An investigation of mineralisation controls in the upper section of the Platreef in the southern sector, on Turfspruit, Northern Limb, 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.

12 February, 2014

DECLARATION

I declare that this dissertation is my own work, submitted for the Degree of Master of Science at the University of Witwatersrand, Johannesburg. This document has not been submitted for examination or any degree at any other University.

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(Signature of candidate)

Date: 12th day of February 2014

ABSTRACT

Geochemical, mineralogical and tenor variation studies were carried out on the cores from UMT040, UMT064 and UMT063, located in the Flatreef on Turfspruit, in the southern sector of the Platreef. The investigation comprised three objectives (1) to identify controls on mineralisation in the upper section of the Platreef, (2) to construct a 3D PGE tenor model, and (3) to test whether the new geological interpretation on Turfspruit correlates with the eastern and western limbs of the Bushveld Complex. The above-mentioned holes were used for geochemical analyses of major and trace elements; and UMT064 was also used for orthopyroxene microprobe analyses. For construction of the tenor model, a total of 276 drill holes were used. The distance between drill holes for geochemical studies is 145 m and 175 m respectively; and for the tenor model is approximately 100 m.

The outcomes of the study have demonstrated that the upper section of the Platreef comprise at least four lithological units i.e. the topmost portion of T1, lowermost portion of T1, T2 Upper and T2 Lower that can be interpreted to have been formed by four separate pulses of magma. Considering the possibility of the T2 Lower being metamorphosed calc-silicates, this reduces the number of magma pulses to three. This is supported by the mineralogy, geochemical content and tenor variations. The T1 is made up of an orthopyroxenite (feldspathic in places), the T2 Upper comprised a pegmatoidal orthopyroxenite (also feldspathic in places) and the T2 Lower is made up of a harzburgite. High grade PGE, Ni and Cu mineralisation was found to occur within two zones in the upper section of the Platreef i.e. the T1m and T2 (Upper and Lower).

Mineralisation occurs in the form of base metal sulphides such as pyrrhotite, pentlandite and chalcopyrite; and PGEs are dominated by amphoterics (PGE-arsenides, tellurides, antimonides and bismuthinides). These amphoterics are associated with base metal sulphides. The sulphides in both the T1m and T2 are interstitial. PGE minerals such as michenerite, sperrylite, hollingworthite and cooperite are present in the study area. In the T2, an increase in sulphide content and PGE grades are generally associated with the presence of the “main” chromitite stringer/ seam at the contact between a feldspathic pyroxenite (T1) and the coarse-grained to pegmatoidal pyroxenite (T2 Upper). Several other chromitites might be present above and below this contact, and it has been noted that not all of those chromitites are associated with an increase in sulphide content and higher PGE grades. PGE grades were found to be higher in T2 Upper than in T2 Lower, whereas, the base metals (particularly Ni) are generally higher in T2 Lower.

In the T1m, mineralisation occurs close to the contact between the feldspathic pyroxenite and orthopyroxenite, but only the orthopyroxenite hosts the sulphides. Chromitite stringers rarely occur in the T1m. Where present, they generally occur at the top of the mineralised zone. The sulphides in both the T1m and T2 are thought to have resulted from separate and different processes. Those in the

T1m are thought to have resulted from a fractional segregation process, whereas the sulphides in the T2 were thought to have been emplaced in bulk or as a mush.

The 3D PGE tenor model has demonstrated that the tenor in both the T1 and T2 are higher than previously thought for the northern limb of the Bushveld Complex. Tenors in the T1 reach up to 700 ppm, whereas tenors of about 1000 ppm were recorded in the T2. These tenors are comparable to the tenors measured from the sulphide melt inclusions elsewhere in the northern limb. Tenors are the highest in the northwestern part of Turfspruit and they gradually decrease towards the southeast. Both the T1 and T2 are dominated by a tenor of about 100 ppm. In the T1, a tenor of 250 ppm is dominant in the northwestern and southeastern parts of the study area, whereas in the T2 it is only dominant in the northwestern part. Vertical variation in tenors has shown that the tenors are the highest in the topmost portion of the T1 and at the top of T2 Upper (below the T1-T2 contact).

The T1 has been found to be comparable with the Merensky Reef due to the following: (a) similarities with respect to major and trace element compositions of whole rock analyses; (b) Cr/MgO ratios which are greater than 80; and (c) similarities in the pyroxene content excluding the MgO/((MgO)+FeO) ratio and CaO contents; and in the PGE tenor of the sulphides. In addition, the T1 has many of the characteristics of the model proposed by Naldrett et al (2009) for the formation of the Merensky Reef in the western Bushveld. However, the differences between the T1 and the Merensky Reef were also noted i.e. the MgO/((MgO)+FeO) ratios in this study are lower (averaging 0.71) than the Mg# reported for the Merensky Reef ($Mg\#_{78\text{-}83}$), the upper Critical Zone ($Mg\#_{78\text{-}84}$) and elsewhere in the Platreef north of Turfspruit. The CaO levels (representing the wollastonite component of the orthopyroxene) at Turfspruit are higher (>2 wt %) compared to the Merensky Cyclic Unit and other parts of the northern limb where the CaO levels are below 2 wt %. This is an indication that the pyroxene composition at Turfspruit is more evolved compared to the Merensky Reef.

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General introduction of the Bushveld Complex and aims of the study

1.1 General introduction of the Bushveld

1.1.1 Introduction

The mafic rocks of the Bushveld Complex constitute the most voluminous preserved mafic layered intrusion in the world. They underlie an area of 66 000 km^2 from Zeerust in the west to Burgersfort in the east, and from Bethal in the south to Villa Nora in the north, and are exposed for over 12 200 km^2 (Figure 1.1). The Bushveld Complex is famous for its magmatic ore deposits of chromite, platinum group elements (PGEs) and vanadium. Hunter (1975), considered the Bushveld Complex to have a cruciform outline and to consist of five lobes: western, far western, eastern, south-eastern and northern lobes (Figure 1.1). The Bushveld Complex contains the world's three largest platinum bearing horizons: the UG2 Chromitite, Merensky Reef and Platreef (Cawthorn, 1999).

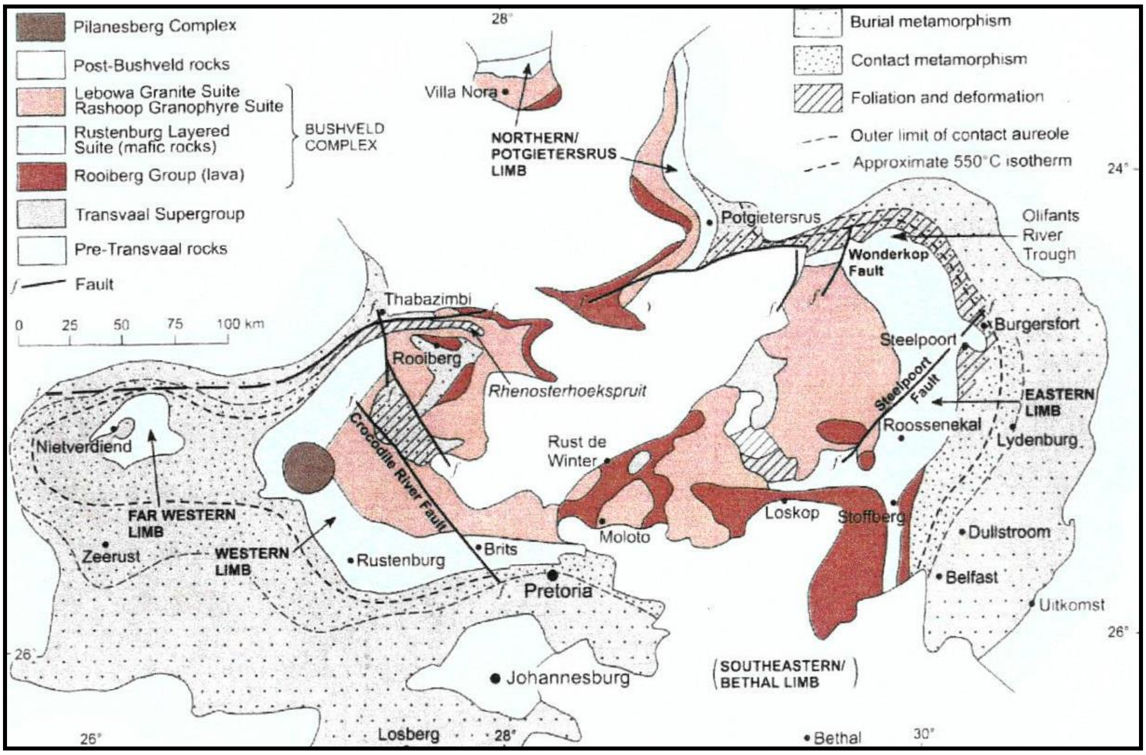


Figure 1.1. Geology of the Bushveld complex (Cawthorn *et al*., 2006)

The subdivisions of the Bushveld Complex have been suggested by SACS (1980) and revised by Hatton and Schweitzer (1995), into the mafic rocks of the Rustenburg Layered Suite, the Lebowa Granite Suite, the Rashoop Granophyre Suite and the Rooiberg Group (Table 1.1). Table 1.2 shows the formal lithostratigraphic classification of the Rustenburg Layered Suite adopted by SACS (1980), as subsequently modified, compared with the standard zonal nomenclature. Note that the use of "bronzite" and "bronzitite" (mineral and rock name respectively) is no longer recommended; the rocks are referred to as pyroxenites.

Table1.1. Currently accepted subdivisions and nomenclature of the Bushveld Complex

<table>
<tr><td>LEBOWA GRANITE SUITE</td><td colspan="2">Nebo, Lease, Makhutso, Klipkloof, Bobbejaankop, Balmoral and Verena Granites</td></tr>
<tr><td>RASHOOP GRANOPHYRE SUITE</td><td colspan="2">Stavoren and Diepkloof Granophyres, Rooikop Porphyritic Granite, Zwartbank Pseudogranophyre</td></tr>
<tr><td rowspan="11">RUSTENBURG LAYERED SUITE</td><td rowspan="3">Upper Zone</td><td>Subzone C (Ol-Ap diorite)</td></tr>
<tr><td>Subzone B (Ol-Mt gabbronorite)</td></tr>
<tr><td>Subzone C (Mt gabbronorite)</td></tr>
<tr><td rowspan="2">Main Zone</td><td>Upper Subzone (gabbronorite)</td></tr>
<tr><td>Lower Subzone (gabbronorite, norite)</td></tr>
<tr><td rowspan="2">Critical Zone</td><td>Upper Subzone (norite, anorthosite, pyroxenite)</td></tr>
<tr><td>Lower Subzone (pyroxenite)</td></tr>
<tr><td rowspan="3">Lower Zone</td><td>Upper Pyroxenite Subzone</td></tr>
<tr><td>Harzburgite Subzone</td></tr>
<tr><td>Lower Pyroxenite Subzone</td></tr>
<tr><td colspan="2">Marginal Zone (norite)</td></tr>
<tr><td rowspan="4">ROOIBERG GROUP</td><td colspan="2">Schrikkloof Formation (flow-banded rhyolite)</td></tr>
<tr><td colspan="2">Kwaggasnek Formation (massive rhyolite)</td></tr>
<tr><td colspan="2">Damwal Formation (dacite, rhyolite)</td></tr>
<tr><td colspan="2">Dullstroom Formation (basaltic andesite)</td></tr>
</table>

Table 1.2. Subsequently modified formal lithostratigraphic classification of the Rustenburg Layered Suite, compared with the standard zonal nomenclature. [1]Walraven (1986), [2]Hulbert and Von Gruenewaldt (1982), [3]Teigler and Eales (1996) suggested that the top of the Lower Zone be taken at the top of the Harzburgite Subzone; [4]Kruger (1994) proposed, on the basis of initial Sr isotopic ratios, that the Upper Subzone of the Main Zone should be included in the Upper Zone

<table>
<tr><th></th><th colspan="2">Standard zonal subdivision (informal)</th><th colspan="6">Nomenclature recommenced by SACS (1980), including subsequent additions</th></tr>
<tr><td rowspan="15">RUSTENBURG LAYERED SUITE</td><td colspan="2">All areas</td><td colspan="2">Eastern limb</td><td colspan="2">Western limb</td><td colspan="2">Northern limb</td></tr>
<tr><td rowspan="3">Upper Zone</td><td>Subzone C</td><td rowspan="3">Roossenekal Subsuite[1]</td><td>Luipershoek Olivine Diorite</td><td rowspan="3"></td><td rowspan="3">Bierkraal Magnetite Gabbro</td><td rowspan="3"></td><td rowspan="3">Molendraai Magnetite Gabbro[1]</td></tr>
<tr><td>Subzone B</td><td>Ironstone Magnetite Gabbro</td></tr>
<tr><td>Subzone A</td><td>Magnet Heights Gabbronorite</td></tr>
<tr><td rowspan="3">Main Zone</td><td>Upper Subzone[4]</td><td rowspan="3">Dsjate Subsuite[1]</td><td>Mapoch Gabbronorite</td><td rowspan="3"></td><td rowspan="3">Pyramid Gabbronorite</td><td rowspan="3"></td><td rowspan="3">Mapela Gabbronorite[1]</td></tr>
<tr><td>Lower Subzone</td><td>Leolo Mountain Gabbronorite</td></tr>
<tr><td></td><td>Winnaarshoek Norite-Anorthosite</td></tr>
<tr><td rowspan="2">Critical Zone</td><td>Upper Subzone</td><td rowspan="2">Dwars River Subsuite[1]</td><td>Winterveld Norite-Anorthosite</td><td rowspan="2">Schilpadnest Subsuite[1]</td><td>Mathlagame Norite-Anorthosite</td><td rowspan="2"></td><td rowspan="2">Grasvalley Norite-Anorthosite[1]</td></tr>
<tr><td>Lower Subzone</td><td>Mooihoek Pyroxenite</td><td>Ruighoek Pyroxenite</td></tr>
<tr><td rowspan="4">Lower Zone[3]</td><td>Upper Pyroxenite Subzone</td><td rowspan="4">Croydon Subsuite[1]</td><td>Serokolo Pyroxenite</td><td rowspan="4">Vlakfontein Subsuite[1]</td><td>Tweelaagte Pyroxenite</td><td rowspan="4">Zoetveld Subsuite[1]</td><td>Moorddrift Harzburgite-Pyroxenite[2]</td></tr>
<tr><td>Harzburgite Subzone</td><td>Jagdlust Harzburgite</td><td>Groenfontein Harzburgite</td><td>Drummondlea Harzburgite[2]</td></tr>
<tr><td rowspan="2">Lower Pyroxenite Subzone</td><td>Rostock Pyroxenite</td><td>Makgope Pyroxenite</td><td rowspan="2">Volspruit Pyroxenite[2]</td></tr>
<tr><td>Clapham Pyroxenite</td><td>Eerlyk Pyroxenite</td></tr>
<tr><td rowspan="2">Marginal Zone</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">Shelter Norite</td><td rowspan="2"></td><td>Kroondal Norite</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Kolobeng Norite</td></tr>
</table>

1.1.2 Rooiberg Group

The Rooiberg Group occurs mainly above the Rustenburg Layered Suite and can be divided into several formations based on lithology and chemistry (Table 1.1). It consists of basalt and basaltic andesite near the base and erratically becomes more felsic upwards, with various pyroclastic and arenaceous layers (Schweitzer *et al*., 1995a). The bulk of the Rooiberg succession comprises generally siliceous volcanic rocks, with sandstone and shale intercalations present in places. The high-Mg felsite magma type occurs at the roof and the floor of the Bushveld mafic sequence, establishing that the volcanic rocks in the roof and the floor are part of the same succession. This is supported by trace element abundances of both the Rooiberg Group and the Lebowa Granite Suite, which display chemical similarity with average upper crust. The Rooiberg volcanic rocks also host minor epigenetic cassiterite and fluorite mineralisation (Schweitzer *et al*., 1995b).

The Rustenburg Layered Suite has been subdivided into 5 zones, the Marginal, Lower, Critical, Main and Upper zones.

1.1.3 Marginal Zone

The Marginal Zone comprises medium-grained, unlayered rocks which encircle most, but not all of the Bushveld Complex. These are mainly norite with minor pyroxenite, containing variable amounts of quartz and biotite, reflecting assimilation of shale. The sequence may reach up to 800 m and probably results from multiple intrusions of magmas, and hence it is not a true chill of the entire intrusion (Cawthorn et al,. 2006).

1.1.4 Lower Zone

In the Olifants River trough (Figure 1.1) in the eastern limb, Cameron (1978) divided the Lower Zone into a Basal subzone (mainly feldspathic pyroxenite), a Lower Bronzitite, a Harzburgite subzone and an Upper Bronzitite. This was subsequently superseded by a threefold subdivision comprising the Lower Pyroxenite, Harzburgite and Upper Pyroxenite Subzones (Table 1.1), all with less than 1 % chromite. In the western limb the lower division contains pyroxenites and olivine-bearing rocks in equal proportions, while the overlying division contains a smaller proportion of pyroxenite (Teigler and Eales, 1996). Structural complexities in the sedimentary floor result in local attenuation of the ultramafic rocks (Sharpe and Chadwick, 1982; Uken and Watkeys, 1997), and also propagate into overlying zones. In the far western limb, Engelbrecht (1985) identified nine cyclic units of dunite-harzburgite-pyroxenite attaining a thickness of 1050 m in the Lower Zone. The Lower and Critical Zone sequences of the northern limb, south of Mokopane (formerly Potgietersrus), are heavily faulted (Barrett et al., 1978). Hulbert and Von Gruenewaldt (1985), assigned a succession of 1700 m of olivine, chromite and orthopyroxene-bearing cumulates, representing 37 cyclic units, to the Lower

Zone in this area. They also reported the occurrence of two chromitite layers (the upper and lower chromitite layers) within the Volspruit subzone of the Lower Zone.

1.1.5 Critical Zone

The Critical Zone carries the world's largest platinum-bearing ore bodies (UG2 Chromitite and Merensky Reefs) and huge deposits of chromite within the Lower (LG), Middle (MG) and Upper (UG) Group chromitite layers (Schurmann et al., 1998). This zone displays spectacular layering of chromitite, pyroxenite, norite and anorthosite on all scales from millimeters to tens of meters (Cameron, 1980, 1982).

The lower Critical Zone contains an 800 m thick succession of pyroxenitic cumulates, with an olivine-bearing interval one-third of the way up. Up to seven chromitite layers, referred to as LG1-7, may be present, individually reaching up to 1 m in thickness (Cawthorn et al,. 2006). Nearly all rocks contain minor disseminated chromite. The Middle Group (MG) comprises a cluster of four chromitites, MG1-4 with MG1 and MG2 in the lower Critical Zone and MG3 and MG4 in the upper Critical Zone. The Upper Critical Zone succession comprises eight cyclic units (Cawthorn et al,. 2006), consisting of partial or complete sequences from a base of ultramafic cumulates (chromitite, harzburgite, pyroxenite) through norite to anorthosite. The top two cyclic units of this sequence are called the Merensky and Bastard cyclic units and have only extremely thin basal chromitite layers. These two cyclic units define a transition to the Main Zone (Cawthorn et al,. 2006).

Economic PGE mineralisation occurs in two layers within the Bushveld Complex, the Merensky Reef and Upper Group 2 (UG2) chromitite in the Critical Zone of both the eastern and western limbs. In the Merensky Reef mineralisation occurs near the base of the Merensky Cyclic Unit, the thinnest of all cyclic units (Cawthorn et al,. 2006). The reef has a very thin (millimetre-thick) chromitite layer, overlain by a feldspathic pyroxenite that may be pegmatitic. A second chromitite layer may occur at the top. The reef contains a heavy dissemination of sulphides that carry about 6 – 8 g/t PGE, 0.15 % Cu and 0.3 % Ni (Lee, 1996). Most of the mineralisation is concentrated close to the chromitite layers, especially the upper one. The UG2 chromitite reef, which may be up to 1.2 m thick, contains minimal sulphides, but still carries similar PGE grade to the Merensky Reef (Cawthorn et al,. 2006). Mineralisation occurrences in the Platreef are discussed in Chapter 2.

Chromite mineralisation occurs entirely in the Critical Zone in both the eastern and western limbs and also occurs in the LZ of the Grasvally area in the northern limb. Chromitite layers contain between 50 and 85 % chromite, the remainder being pyroxene and plagioclase. The highest Cr/Fe values occur in the lowest chromitite layers in the Critical Zone. Chromite mineralisation is also being mined in the Lower Group 6 (LG6), Middle Group 1 (MG1) and (MG2) (Cawthorn et al,. 2006).

1.1.6 Main Zone

In the eastern limb, Von Gruenewaldt (1973) subdivided the Main Zone into three subzones (subzone A, subzone B and subzone C). These subdivisions were based on the nature of the low-calcium pyroxene, whereby an inverted pigeonite-bearing subzone (subzone B) separated a lower subzone (subzone A) and upper subzone (subzone C) from primary orthopyroxene-bearing gabbronorite (Nex et al,. 1998). Von Gruenewaldt (1973) placed a major marker "Pyroxenite Marker" at the boundary between subzone B and subzone C and interpreted it as an injection of undifferentiated magma in the Main Zone. This subdivision was adopted by SACS (1980) as an informal nomenclature for the western Bushveld. Michell (1990) suggested that in the western Bushveld subzone A and subzone B collectively is regarded as the Lower Main Zone and subzone C the Upper Main Zone. However, Nex et al,. (1998), suggested that subzones A and C could be further subdivided into two, leading to five subdivisions of the Main Zone. These subdivisions were based on the variation in relative abundance of different pyroxenes.

Ashwal et al,. (2005) reported a prominent ~4 m thick pyroxenitic horizon about 388 m below the Upper Zone-Main Zone contact. Based on mineralogical data, they suggested that this layer could not be equated to the Pyroxenite Marker of the eastern and western limbs. They concluded that the Pyroxenite Marker could be missing in the northern limb.

1.1.7 Upper Zone

The Upper Zone is the most laterally extensive zone. Its base is defined by the appearance of cumulus magnetite, only a few meters below the lowest magnetite layer in the eastern limb (Molyneux, 1974). It attains a thickness of 2000 m and contains up to 24 magnetitite layers, one of which is 6 m thick; others range from a few centimeters to 2 m in thickness. In the Bellevue core from the northern limb, the thickness of the Upper Zone is 1500 m (Ashwal *et al*., 2005). It is dominated by rocks ranging from gabbronorite to anorthosite, with variable amounts of cumulus Fe-rich pyroxenes and olivine, magnetite and apatite. Magnetite comprises 8 % by volume of the Upper Zone and towards the top of the zone ilmenite may exceed magnetite in abundance (Reynolds, 1985).

On Gezond in the northern limb, the outcrop decreases in width from >1,000 m to <200 m on Jaagbaan in the south (van der Merwe 1978). The base of the Jaagbaan magnetite gabbronorite consists of an 8 m thick anorthosite layer that grade into a magnetite gabbro. All layers dip at approximately 10^o to the west. The number 1 or Main Magnetite Layer (a massive magnetite layer with a 30 cm disseminated sulphide-bearing basal portion) occurs 10 m higher up in the sequence. Three magnetite layers (numbers 2, 3 and 4) have been recorded above the Main Magnetite Layer in this area. The V_2O_5 content of the Main Magnetite Layer over a thickness of 1 m is 2.2 % (van der

Merwe 1976). There are no further indications on surface of magnetitite, gabbro, magnetite gabbro or mottled anorthosite of an Upper Zone sequence further south. A lateral variation is recognised when the Jaagbaan zone is compared with the lower Upper Zone sequence on Gezond in the north. On Gezond, a lower magnetite layer is developed below the Main Magnetite Layer, a mottled anorthosite occurs at the base of the Main Magnetite Layer, and at least seven thin magnetite layers occur in the magnetite gabbro directly above the Main Magnetite Layer. Lateral variations in the layers of the Upper Zone in the rest of the Bushveld Complex are common (Molyneux 1974).

All Bushveld Complex magnetite layers contain vanadium. Vanadium grades (V_2O_5) decreases from 2 % at the base to 0.3 % at the top of the Upper Zone. The 2 m thick Main Magnetitite Layer occurs 130 m above the base of the Upper Zone and is being mined in both the eastern and western limbs (Cawthorn et al,. 2006).

1.2 Aims of the study

The aims of this project are three-fold, (1) to investigate mineralisation controls in the upper section of the Platreef, (2) to produce a 3D PGE tenor (Pt and Pd) model on Turfspruit farm, and (3) to test whether the new geological interpretation for the Turfspruit Reef correlates with the eastern and western limbs of the Bushveld Complex.

There have been two exploration projects within Turfspruit and Macalacaskop farms, an area that was identified as being suitable for opencast mining, termed the 2000 - 2006 open pit, and the 2007 - 2012 (on-going) deep drilling projects (Figure 1.2). This study focuses on the upper section of the Platreef in the deep drilling project in Turfspruit. Reference was given to work conducted on the open pit project due to the amount of research conducted on this project. The study investigates the mineralisation controls in different host rocks/rock units, and was conducted using the research methodology outlined below:

- Detailed logging of drillcore, followed by logging of geological modelling packages, along strike and dip. Geological modelling packages are a unique lithological grouping developed by the project team that are used to build a geological model.
- Sampling for analytical assaying and mineral chemistry.
- Analytical assaying was conducted on every metre sampled through the mineralised zone. Cores were analysed for Pt, Pd, Rh, Au, Ni, Cu, Cr and S.
- Sampling for XRF geochemical analysis: Samples were collected in the different geological units within the upper section of the Platreef, to distinguish the characteristics between

geological units and also to indicate the variation within individual units. This data was compared with the data from the eastern and western limbs to test whether the ore-bearing units from these areas are similar to the Northern Limb.

- Qemscan data analysis: Data from the metallurgical test work conducted in the upper section of the Platreef was used to evaluate the mineralogy, sulphides and PGE composition of the geological units.

- Calculation of tenors in each drill hole and construction of the PGE tenor model throughout the upper section of the Platreef was completed for northern Turfspruit. The resulting tenor patterns were used to identify individual magmatic sills or pulses.

Results from the above were integrated to determine the mineralisation controls in the orebody and also identify areas where there is geological continuity of the high grade ore.

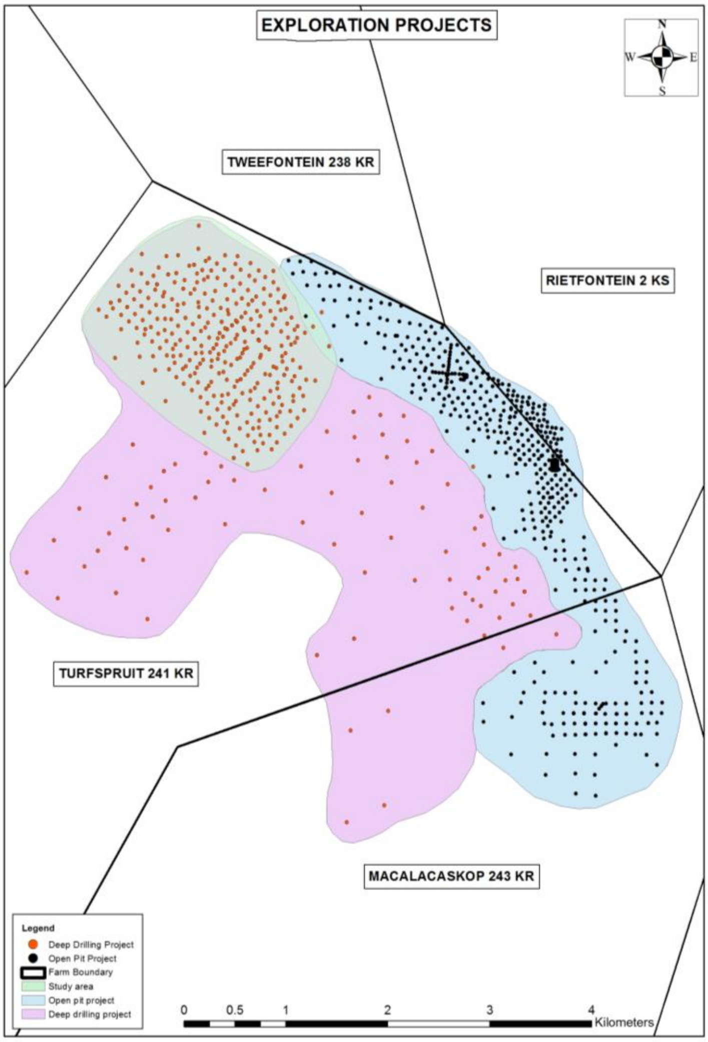


Figure 1.2. Location of exploration projects and study area showing the two exploration areas: the open pit and deep drilling project with location of drillholes in the project

Chapter 2

General geology of the Northern Limb

2.1 Geological setting

The northern limb of the Bushveld Complex intruded Transvaal Supergroup metasediments and Archaean basement at ~2060-2054 Ma (Walraven, 1987, Walraven *et al.*, 1990, Buick et al., 2001). Structurally, the northern limb is separated from the eastern and western limbs by the ENE-WSW trending Thabazimbi-Murchison lineament (TML), a major tectonic boundary formed by the collision of the Pietersburg and Kaapvaal terranes around 2.7 Ga (Griffin et al., 2004; Truter, 1947; de Wit *et al*., 1992; Good and de Wit, 1997; Silver *et al*., 2004). In Mokopane, the TML is marked by the NE-striking Zebediela and Ysterberg-Planknek faults (Figure 2.1).

The northern limb of the Bushveld Complex forms a sinuous outcrop and has a total areal extent of about 7275 km^2. It is <15 km in width and has a strike length of 110 km from the north, where it is covered by younger Waterberg sediments, to the Zebediela fault south of Mokopane, where Karoo sediments are juxtaposed against the layered mafic rocks (Van der Merwe, 1978). South of the Planknek-Ysterberg fault (Figure 2.1) the stratigraphic relationships remain unclear, whereas north of Mokopane, the Lower Zone occurs as satellite bodies and as a thick package locally underlying the Platreef, with Platreef pyroxenites forming the footwall for more than 30 km.

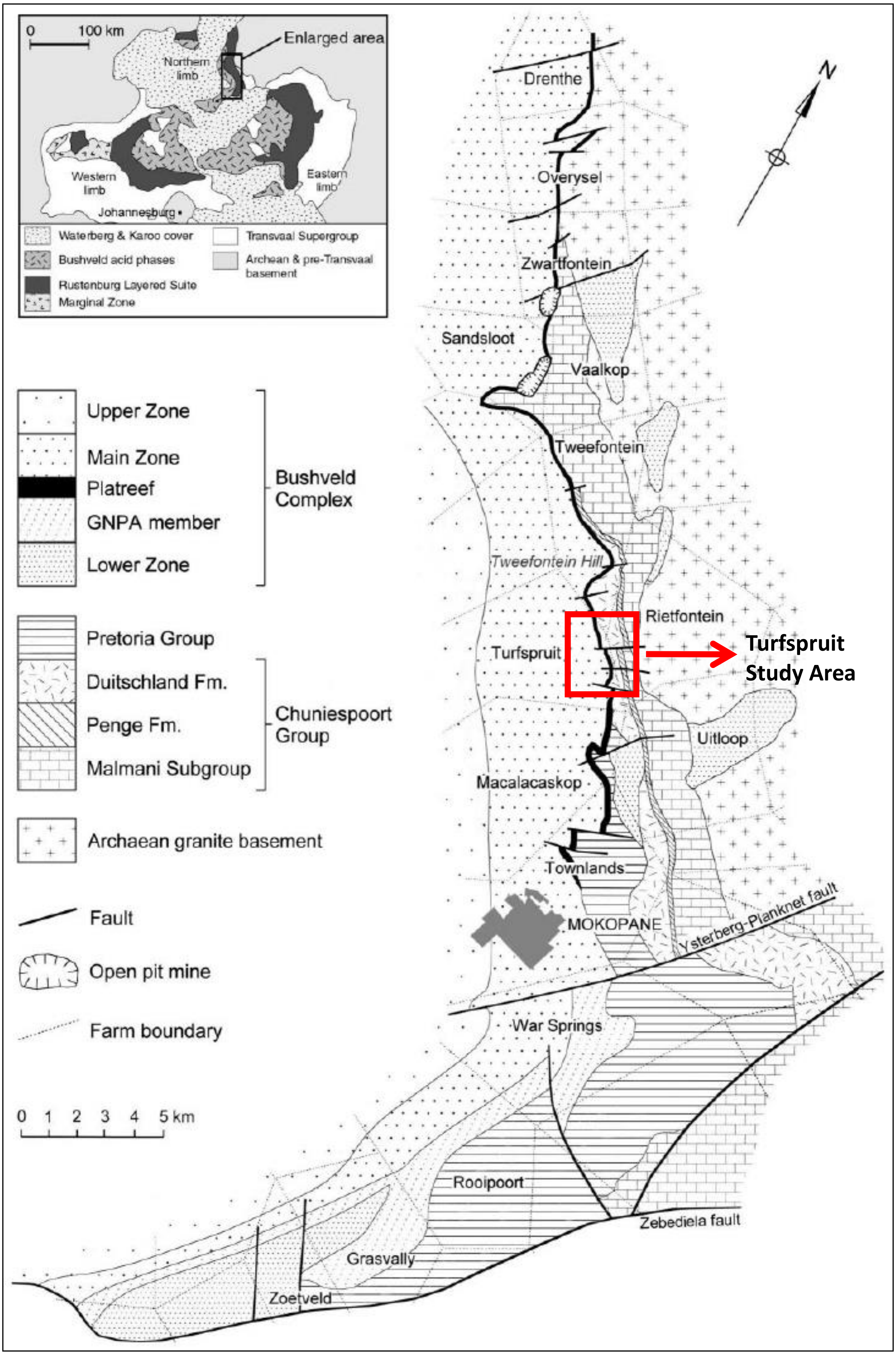


Figure 2.1. Locations of the Ysterberg-Planknek and Zebediela Faults (Holwell *et al.*, 2005)

In relation to both the eastern and western limbs, the Platreef has been equated to the Critical Zone of the Bushveld Complex (Wagner 1929 and White 1994), but several differences have been noted (Van der Merwe 1978 and McDonald *et al*. 2005), as shown in Figure 2.2.

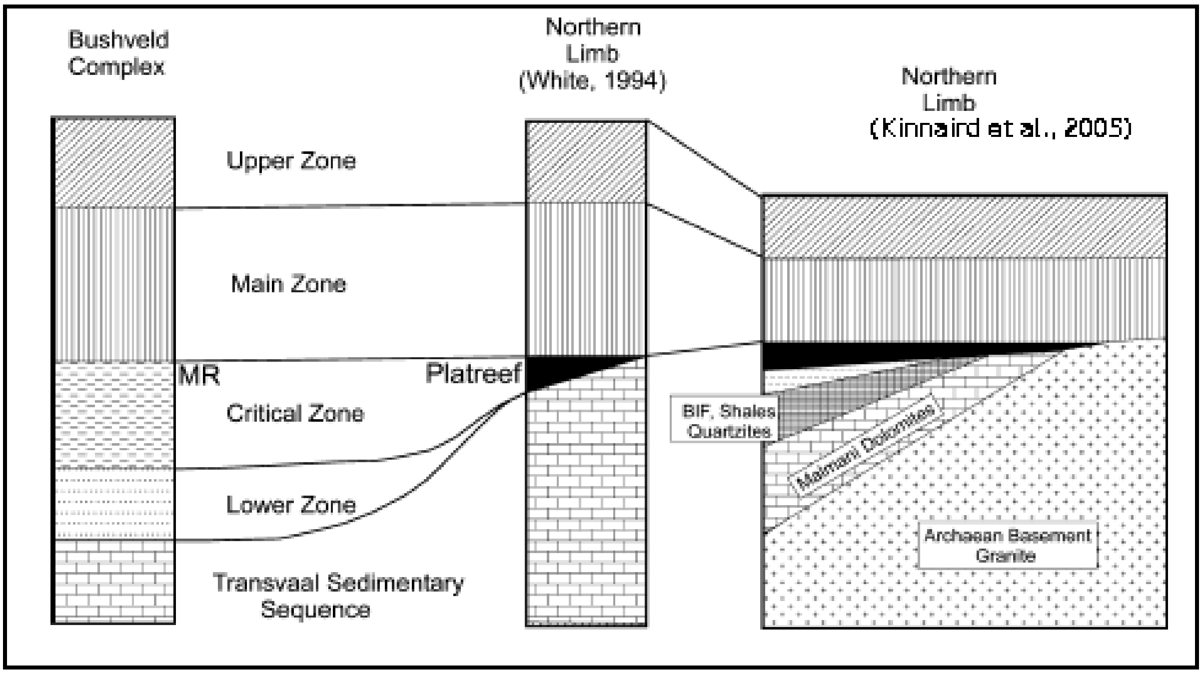


Figure 2.2. Stratigraphic position of the Platreef in relation to the Main Bushveld Complex Kinnaird et al., (2005)

McDonald et al (2005) reported the following differences:

(i) The primary Platreef has different mineral textures than those commonly found in the Merensky Reef. They reported that in the Merensky Reef, the liquidus order is orthopyroxene-plagioclase-clinopyroxene, whereas in the mafic units of the Platreef, clinopyroxene either follows orthopyroxene or crystallises concurrently with it, and generally precedes plagioclase.

(ii) Chromite in the Merensky Reef consistently occurs as the earliest phase, forming layers and inclusions in pyroxenes, whereas in the Platreef it is most commonly post-cumulus.

(iii) The Platreef silicates appear systematically more Fe-rich than their equivalents in the Merensky Reef i.e. Platreef orthopyroxene ($Mg\#_{80}$), olivine ($Mg\#_{76}$) and Merensky Reef orthopyroxene ($Mg\#_{78-84}$) and olivine ($Mg\#_{79-80}$).

(iv) The rare earth element geochemistry in the melanorites of the Merensky Reef at Union Section displayed a much broader range of La/Lu_N ratios (2.8-5.7) and a more pronounced negative Eu anomaly (Eu/Eu* = 0.42-0.80) compared to the reef samples from the Platreef which showed a narrow range of La/Lu_N ratios (1.3-3.3) and small Eu negative Eu anomalies (Eu/Eu* 0.72-0.93).

(v) In the Platreef there is a greater fractionation of low-temperature PGE (Pt and Pd) from high-temperature PGE (Ir and Ru), and all of them are Pd-rich compared with reefs between the UG2 and the Merensky Reef in the eastern and western lobes. In addition, the Platreef silicate rocks with total PGE contents as low as 10 ppb show a lower and more restricted Pt/Pd ratios than in the Upper Critical Zone, where Pt/Pd ratios may exceed those in the northern lobe until well above the level of the Bastard Reef.

2.2 Structural events in the Northern Limb

After the emplacement and consolidation of the Bushveld Complex, the northern limb was subjected to various episodes of faulting. Truter (1947) and de Villiers (1967) recognised the following fault patterns: E to ENE, N to NNW, and NW. Hulbert (1983) recognised four episodes of fault deformation. The earliest generation was an episode of N-S trending reverse faulting. The second generation is portrayed by WNW striking faults. Third generation faults strike NE and are assumed to be post-Waterberg. The fourth and final period of faulting occurred in post-Karoo times and is best demonstrated by the almost EW striking Zebediela fault (Figure 2.3). Northwards, most of the faults strike NE and have a normal displacement with a down throw to the south (White 1994).

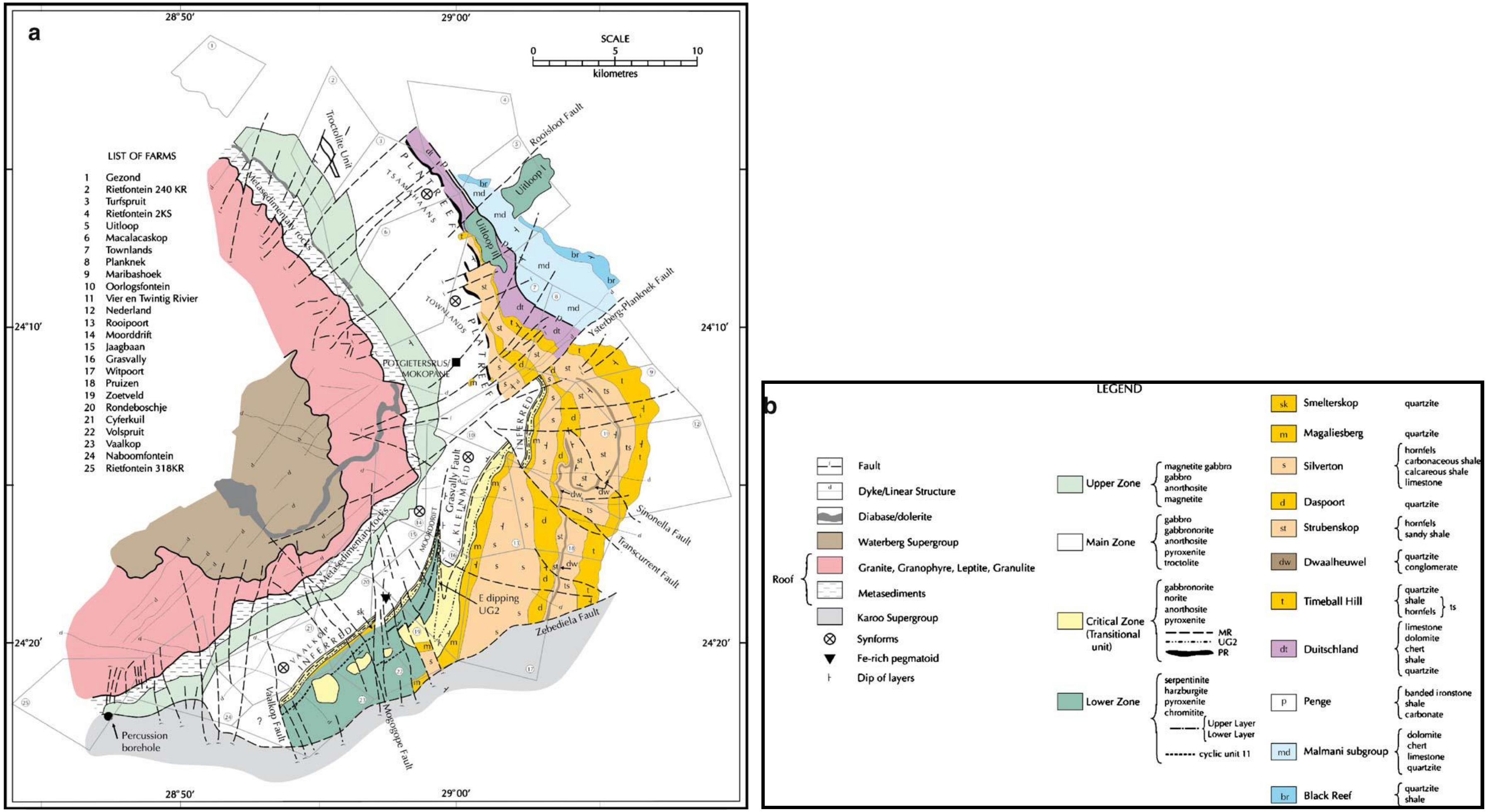


Figure 2.3. A map of the geology and structure of the northern limb at Mokopane, van der Merwe (2008)

Nex, (2005) noted two phases of ductile deformation on Tweefontein Hill. The early phase produced upright folds and the later phase produced dominantly south-west plunging minor folds which reflect the major structure. This ductile deformation pre-dates the intrusion of the Bushveld Complex in the Northern Limb (Nex, 2005).

2.3 Geology of the Platreef in the Northern Limb

The Platreef is a well-known PGE-Ni-Cu rich deposit, located at the base of the northern limb. This pyroxenite-dominated package occurs between the Transvaal metasediments, forming the footwall, and the Main Zone rocks, forming the hangingwall. The Platreef comprises texturally heterogeneous and variably altered pyroxenites with harzburgites, norites and rare anorthosites which onlap onto successively older Transvaal metasedimentary footwall units northwards and eventually transgresses onto Archaean granite. The Platreef varies in thickness from <50 m in the north to ~600 m locally in the south (Kinnaird and Nex, 2012 in press). Generally, the outcrop strikes NNW and dips 40-45^{o} west at surface.

Kinnaird and McDonald, (2005) defined the Platreef as the "mafic units enriched in Ni-Cu-PGE that occur between the Archaean granite-gneiss or the Transvaal Supergroup and the gabbronorites of the Main Zone, north of the Planknek Fault. This definition excludes mineralisation developed in the Main Zone norites and gabbronorites north of farm Drenthe. Mineralisation north of Drenthe has been referred to as "Platreef-style" by Kinnaird *et al* (2005).

Following Merensky (1925), the Platreef can be subdivided into three sectors, according to the footwall lithology and stratigraphic zones (Figure 2.4). The northern sector has a footwall of Archaean granite on farms Overysel 815LR, Drenthe 778LR, Witrivier 777LR and northwards. The central sector is characterised by a dolomitic footwall of the Malmani Subgroup and occurs on farms Zwartfontein 818LR, Sandsloot 236KR, Vaalkop 819LR and Tweefontein 238KR. The southern sector has a footwall composed of Duitschland Formation shales, banded ironstones, calc-silicates, mudstones and siltstones; and extends from Townlands 44KS in the south to Tweefontein 238KR in the north. The Platreef occurs in both the central and southern sectors only (as defined by Merensky), and extends from Mokopane northwards at least 30 km along strike (Kinnaird *et al.*, 2005), as shown in Figure 2.4.

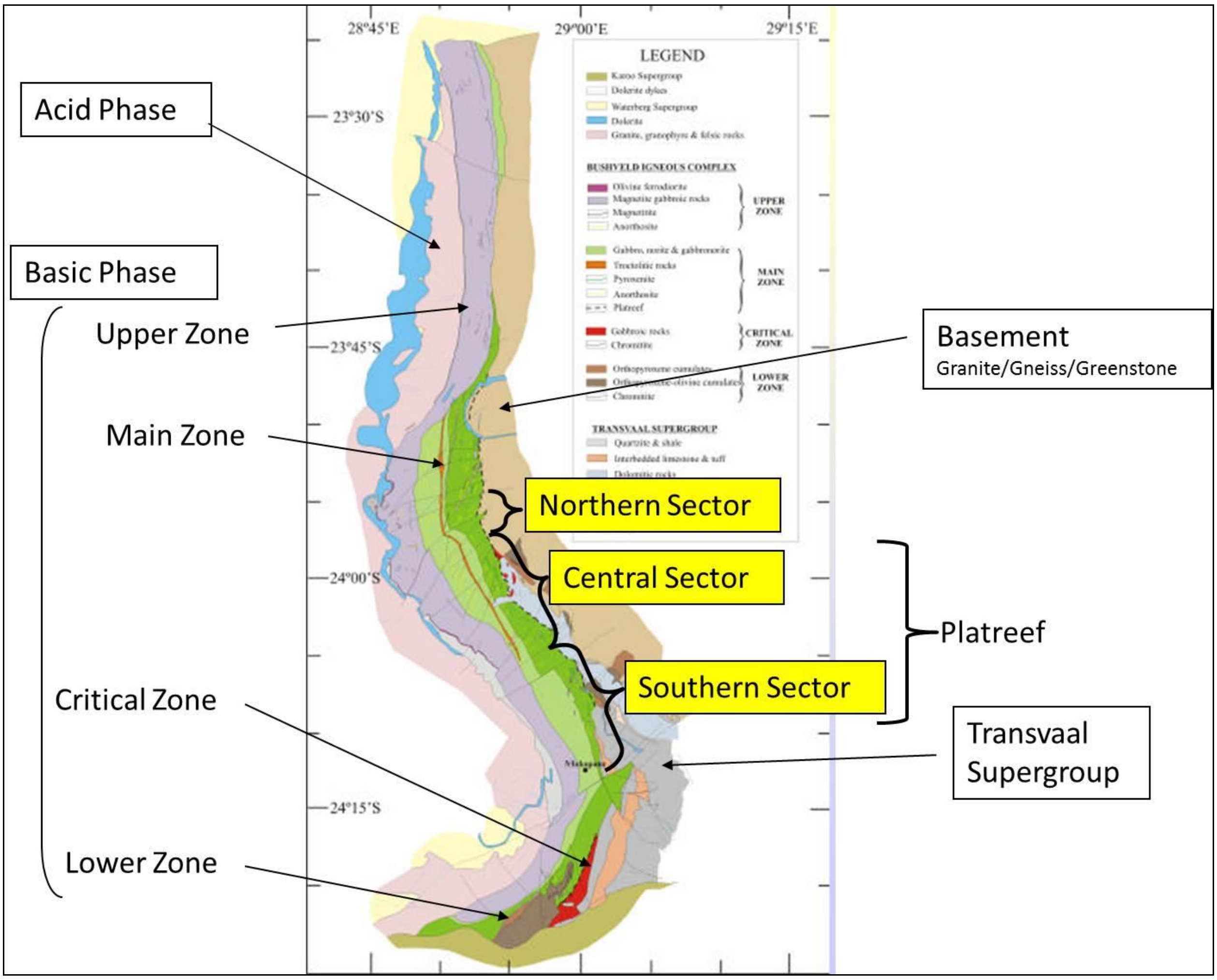


Figure 2.4. Geology of the northern limb of the Bushveld Complex from van der Merwe (1978), modified by Ashwal et al (2005). Note: upper Main Zone shown in light green colour and lower Main Zone in dark green

2.3.1 Footwall lithologies

The Archaean basement consists of tonalitic gneiss intruded by heterogeneous potassic granites (Cawthorn *et al*., 1985) similar to other Archaean exposures on the Kaapvaal craton. The Transvaal Supergroup sediments were deposited on the Archaean basement during the period 2670-2100 Ma (Eriksson *et al*., 2001) and comprise a thin basal clastic unit (Black Reef Formation) followed by a sequence of dolomites, ironstones and minor shales (Malmani Subgroup, Penge Formation, Duitschland Formation). These are overlain disconformably by the Pretoria Group (Timeball Hill Formation) which is dominantly clastic with minor volcanics (Figure 2.5). This Supergroup attains a maximum thickness of 12 km within the Transvaal Basin (Eriksson *et al*., 2001). Examples of footwall lithologies are shown in Figure 2.6.

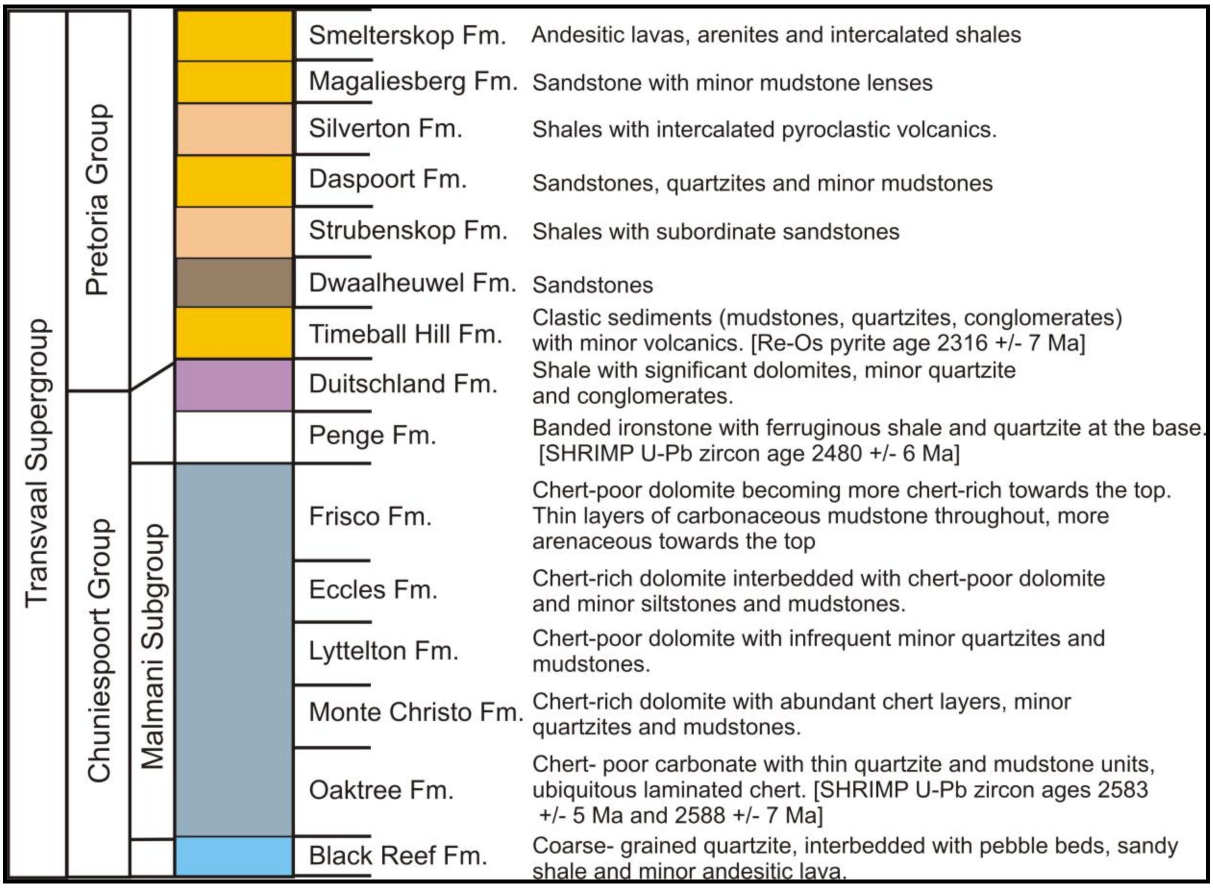


Figure 2.5. Lithostratigraphy of Transvaal Supergroup floor rocks beneath the Platreef from Kinnaird and Nex (2012), with data from Button, (1973); Martini, (1979); Catuneanu and Eriksson (1999); Bekker *et al*., (2001). Age dating from Hannah *et al*., (2004); Nelson *et al*., (1999); Martini *et al*., (1998)

(a) A basement granite core showing variation in potassium content within the basement (NQ core size)

(b) Hornfels displaying porphyroblasts of cordierite-andalusite-pyroxene in a very fine grained groundmass of cordierite-spinel-plagioclase in drill hole ITS097, at a depth of 515.50 m (25 cm sample, NQ core size)

(c) Varied textured dolomite with interbedded chert in drill hole ATS129, at a depth of 185.60 m (25 cm sample, NQ core size)

Figure 2.6. Footwall lithologies (Basement granite and Transvaal metasedimentary rocks)

2.3.2 Lower Zone lithologies

In the central and southern sectors of the Northern Limb the Lower Zone pyroxenites, harzburgites and dunites, which are texturally distinct from the Platreef may form as sills up to 800 m thick between the Platreef and footwall lithologies. They may also form as entirely separate sills and fingers into the footwall metasediments or gneiss that appear isolated on surface, but may be interconnected at depth, such as at Uitloop, Zwartfontein or Bultongfontein (Kinnaird and Nex, 2012 in press). These bodies are erratically serpentinised and occasionally contain thin chromitite seams (Gain and Mostert, 1982). The dunites are remarkably fresh compared to those of the Platreef. They are characterised by rounded cumulus olivines, with minor orthopyroxene with net-textured sulphide blebs or/and chromite; and sometimes by a thin chromitite that grades upward into a chromitiferous dunite and then into a pure dunite. Harzburgites which are also fresh, have varying proportions of olivine, pyroxene and feldspar. Some are lherzolites with minor cumulus clinopyroxene, although generally logged as harzburgites. Feldspathic harzburgites are olivine-rich with intercumulus feldspar, accessory spinel and oikocrysts of clinopyroxene. Pyroxenites of Lower Zone affinity are medium-grained dark-coloured rocks with prismatic medium-grained orthopyroxenes aligned parallel to "layering" and a low percentage of interstitial feldspar (Figure 2.7). On Townlands, pyroxenites, harzburgites and serpentinites with associated high grade chromitites are associated with the Lower Zone (Hulbert and Von Gruenewaldt 1982; Harmer 2004).

South of Mokopane, in the Grasvally-Volspruit area, the Lower Zone consists of >1600 m thick sequence comprising the lower and upper Volspruit Pyroxenite subzone. This subzone is succeeded by harzburgite with chromitites of the Drummondlea subzone and an upper harzburgite-pyroxenite unit known as the Moordrift subzone (Hulbert and Von Gruenewaldt 1982).

(a) Pyroxenite with elongated orthopyroxene showing fabric in drill hole UMT006, at a depth of 1599.17 m (31 cm sample, BQ core size). Oxidised pyrrhotite and pentlandite shown by orange-brown colour

(b) Fine- to medium-grained dunite with > 90 % rounded cumulus olivine in drill hole UMT333, at a depth of 1589.20 m (25 cm sample, NQ core size)

(c) A magnetite-bearing harzburgite with oikocrysts of orthopyroxene in UMT333, at a depth of 1303.15 m (22.5 cm sample, NQ core size). Magnetite occurs in the form of veinlets

Figure 2.7. Lower Zone lithologies below the Platreef

2.3.3 Marginal Zone lithologies

Van der Merwe (1976) reported that generally, exposures of the Marginal Zone are poor in the northern limb, but wherever the contact between the main mass (comprising the Upper, Main, Critical and Lower Zones) and its floor crops out, the Marginal Zone has manifested itself as a zone of noritic to doleritic rock a few centimetres to tens of metres in thickness displaying an intrusive nature. He further reported that the Marginal Zone comprised inclusions of carbonate rock, hornfels, quartzite and granite.

In the southern sector, Kinnaird et al,. (2005) reported a common occurrence of the Marginal Zone norite resting on the hornfels, in areas where the hornfels forms the floor to the Platreef. They further reported that this norite occassionally intruded xenoliths of hornfels. In northern Turfspruit, where the Lower Zone forms the floor to the Platreef, a few metres of Marginal Zone norite occur at the contact between the Platreef and rocks of the Lower Zone, whereas, in southern Turfspruit where the hornfels forms the floor to the Platreef, the Marginal Zone norites range in thickness from a few metres to several tens of metres. Here, the norites appear to have intruded the hornfelses, resulting in repetitive cycles of norite and hornfels (Figure 2.8).

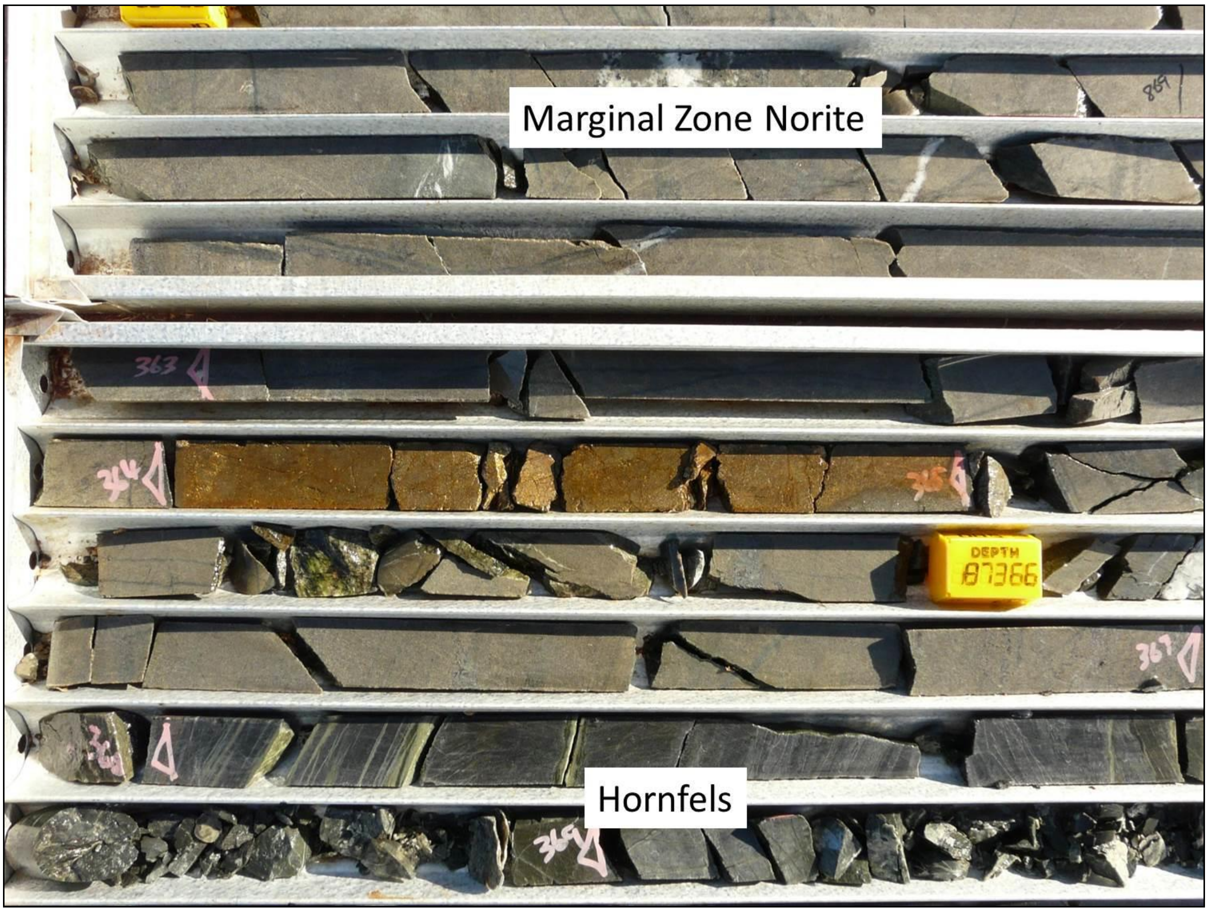


Figure 2.8. Marginal Zone lithologies

2.3.4 Platreef lithologies

Early interpretation of the Platreef classified the rocks into A, B and C reefs (White, 1994). The heterogeneous package at the base was referred to as the A reef, whilst the B reef was regarded as a uniformly textured pyroxenite generally carrying good grades and the C reef as a frequently barren, fine-grained clinopyroxene-bearing feldspathic pyroxenite at the top. However, more recent work (Armitage et al, 2002; McDonald et al, 2005; Kinnaird et al, 2005), which has shown the complexities of the multiphase intrusive nature of the Platreef, has discarded this classification scheme.

2.3.4.1 Pyroxenite and feldspathic pyroxenite

Pyroxenites within the Platreef package vary in grain size from fine- through coarse- to pegmatoidal (Figure 2.9). Pyroxenites and feldspathic pyroxenites immediately below the Main Zone Platreef contact are medium-grained to pegmatoidal in texture, whereas those close to the base of the Platreef are generally fine-grained. Accessory minerals occur in the form of biotite, base metal sulphides and chromite. Biotite is generally dominant in the pyroxenites near the base of the Platreef. The main mineralised zone in the central and northern sectors occurs in these pyroxenites.

(a) Fine-grained clinopyroxene dominant, porphyritic pyroxenite in drill hole UMT063, at a depth of 817.15 m (17.5 cm sample, BQ core size)

(b) Medium- to coarse-grained feldspathic orthopyroxenite in drill hole UMT064, at a depth of 833.38 m (17 cm sample, BQ core size)

(c) Medium- to coarse-grained olivine feldspathic pyroxenite in drill hole ITS004, at a depth of 391.50 m (NQ core size)

(d) Very coarse-grained olivine, biotite, pegmatoidal orthopyroxenite in drill hole UMT312D1, at a depth of 772.75 m (25 cm sample, NQ core size)

Figure 2.9. Pyroxenites in the upper section of the Platreef

2.3.4.2 Norite

Norites occur both within the Platreef package and as chilled micronorite sills often at the base of the package between the Platreef and the floor, or between the Platreef and the Lower Zone; or more rarely within the Platreef package well away from the floor. Some of the norites are described as fingers of Main Zone cutting down into the Platreef (Holwell and Jordaan, 2006), while some are certainly part of the Platreef package. They range from leuconorite (65 - 90 % plagioclase) through norite to melanorite with 65 - 90 % orthopyroxene (Figure 2.10).

(a) Fine- to medium-grained norite with variable amounts of plagioclase in drill hole UMT063, at a depth of 811.68 m (19 cm sample, BQ core size)

(b) Medium-grained olivine norite with interstitial sulphides in drill hole PA002, at a depth of 647.35 m (29 cm sample, NQ core size). Base metal sulphides are pyrrhotite, pentlandite and chalcopyrite

(c) Fine-grained norite with fine-grained sulphides in drill hole UMT060, at a depth of 1198.43 m (20 cm sample, BQ core size). Base metal sulphides are mainly pyrrhotite and pentlandite

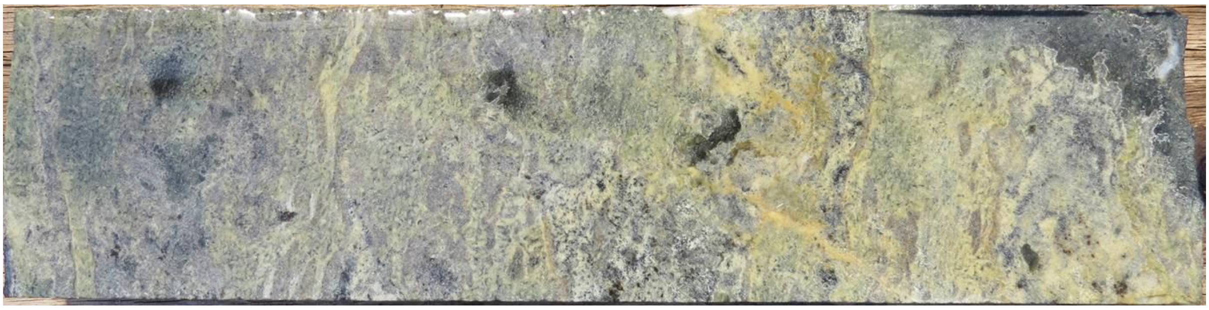
Figure 2.10. Norites within the Platreef

On Turfspruit, cycles consisting of a mafic-rich layer grading into felsic layer upwards, followed by a sharp mafic contact overlying the felsic layer, termed norite cycles occur in the mid to upper Platreef package (Kinnaird *et al*., 2005), but have not been recorded elsewhere.

2.3.4.3 Metamorphosed sedimentary footwall and xenoliths in the Platreef

Xenoliths of calc-silicate (Figure 2.11) and hornfels occur throughout the Platreef and also in the overlying Main Zone. Armitage et al (2002) indicated that at Sandsloot, these xenoliths occur as irregular shaped bodies of variable size from a few decimeters to tens of metres, and are often elongated parallel to the footwall layering, while Gain and Mostert (1982) indicated that the calc-silicates on Drenthe are up to 90 m in diameter. These calc-silicates comprised mineral assemblages of forsterite, diopside and monticellite. Buchanan (1981) suggested that during the emplacement of the Bushveld Complex gabbroic magma intruded into, and reacted with, the floor rocks of dolomite, banded ironstone, argillaceous sediments and micronorite sills giving rise to the 120 m thick Platreef sequence of contaminated pyroxenitic gabbros. He also indicated that considerable amounts of dolomite incorporated into the Platreef magma gave rise to xenoliths of calc-silicate and carbonate-silicate hornfels.

Parapyroxenite, a term first used by Wagner (1929) to describe clinopyroxenites in the northern limb, are common in the central sector of the Platreef package. They vary from a greenish diopsite-hornblende-phlogopite to a pinky-brown diopsite-grossularite assemblage (Figure 2.11). Armitage et al (2002) noted that at Sandloot, these clinopyroxenites occur as elongated lenses and semi-continuous bands concordantly interlayered with calc-silicate hornfels.



(a) Fine grained calc-silicate (metamorphosed dolomite) in drill hole UMT158, at a depth of 521.62 m (19 cm sample, NQ core size)

(b) Fine-grained para-pyroxenite showing assimilated sediments in an olivine rich magma in drill hole UMT158, at a depth of 738.22 m (24 cm sample, NQ core size). A zone of olivine (serpentinised) and plagioclase on the left hand side of the diagram represents a magmatic harzburgite. Preserved sedimentary layering is shown on the right hand side of the diagram

Figure 2.11. Metamorphosed footwall lithologies

2.3.4.4 Granofels lithology

On the farms Overysel and Drenthe, the contact between the Platreef and Archaean granite is marked by an agmatite (locally termed granofels, Figure 2.12), comprising pyroxenite, amphibolite and granite gneiss fragments within a granitic matrix, and developed from the interaction of the Platreef with the footwall (Cawthorn *et al*., 1985; Barton *et al*., 1986). Similar rocks have now been identified in core from Turfspruit.

Figure 2.12. Granofels core with chlorite alteration in drill hole UMT088, at a depth of 1509.57 m (28 cm sample, BQ core size)

2.3.4.5 Felsic vein lithologies

There is a wide variety of granite veins cross-cutting the Platreef. They vary from aplitic (Figure 2.11), through graphic textured, and from fine- to very coarse-grained (Hutchinson *et al*., 2004). They also vary in colour. They may be pinkish where alkali feldspar predominates; white or grey where plagioclase is dominant; to cream, greenish or brown, depending on the accessory mineralogy which may include amphibole, titanite, ilmenite, pyrite, zircon; patches and veinlets of purple fluorite; and the degree of alteration to sericite, chlorite, carbonate or clay minerals (Hutchinson *et al*., 2004) (Figure 2.13). In one white, quartz-poor vein from Turfspruit, accessory zircon, sulphides, monazite, graphite, iridium-osmium alloys (10 um in size) have been identified (Hutchinson *et al*., 2004).

(a) Medium-grained granite vein with pyroxenes and biotite forming a spotted texture in drill hole UMT239, at a depth of 859.31 m (17 cm sample, NQ core size)

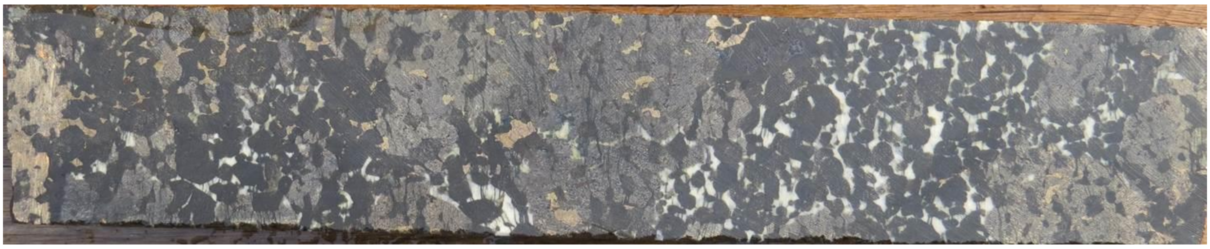
(b) Graphic-textured granite vein with orthoclase and quartz in drill hole UMT158, at a depth of 403.35 m (27 cm sample, NQ core size). Magnetite inclusions are shown by dark spots

Figure 2.13. Medium-grained to pegmatitic granitic veins

2.3.4.6 Olivine-rich lithologies

Most olivine-bearing lithologies in the Platreef are serpentinized. Serpentinization is variable throughout the Platreef i.e. the rocks can be serpentinised to a degree where original mineral textures are destroyed or to a lesser degree where mineral textures are still recognisable (Figure 2.14). Olivine may occur as an early mineral phase or as a late-stage mineral in the rocks of the Platreef. In the latter, McDonald et al (2005) reported the replacement of orthopyroxene by Fe-rich olivine in the southwest corner of the open pit at Sandsloot. They also reported the replacement of plagioclase by Fe-rich clinopyroxenite which led to the development of Fe-rich wehrlites, olivine-lherzolites and harzburgites; and an overall darkening of the rock. Harris and Chaumba (2001) reported the occurrence of olivine in the parapyroxenite at Sandsloot, which they attributed to a metamorphic origin. High grade mineralisation occurs in harzburgites.

(a) Fine-grained serpentinite in drill hole ITS011, at a depth of 132.05 m (14 cm sample, NQ core size). Original texture of minerals is completely destroyed by alteration



(b) Medium- to coarse-grained feldspathic serpentinised harzburgite with orthopyroxene oikocrysts in drill hole UMT239, at a depth of 807.27 m (25 cm sample, NQ core size). Base metal sulphides occur in the form of interstitial pyrrhotite, pentlandite and chalcopyrite

Figure 2.14. Olivine-rich lithologies occurring within the upper section of the Platreef

2.3.5 Main Zone lithologies

Outcrops of Main Zone rocks in the Mokopane area are best developed on Macalacaskop. On Townlands, outcrops are scarce and occur along the farm boundary with Macalacaskop, and to the west and south of town. Main Zone rocks consist of gabbronorite, gabbro and mottled anorthosite layers (Figure 2.15), with a dip of 20^o to 26^o to the west and northwest. The Main Zone thins from a width of >2,400 m in the central sector on Gezond where it is fully developed, to <1,200 m in the south on Moorddrift.

The subdivision of Main Zone rocks is based on schemes proposed by van der Merwe (1976, 1978) for the central sector and Hulbert (1983) and de Klerk (2005) for the southern sector. In the central sector, the upper Main Zone comprises seven mottled anorthosite layers with interlayered gabbro (van der Merwe, 2008). The middle Main Zone consists of gabbronorite and a 110 m thick troctolite unit. The lower Main Zone consists of gabbronorite and norite with four mottled anorthosites and pyroxenite layers. The interlayered gabbro and two of the seven mottled anorthosite layers of the upper Main Zone occupy the area from Gezond in the central sector up to Macalacaskop in the southern sector. Lower down in the middle Main Zone sequence, the troctolite unit occupies the area to the south only as far north as Rietfontein 240KR. The lower Main Zone consisting of units of norite, mottled anorthosite and pyroxenite can be traced in outcrop as far south as Townlands. The above-mentioned marker layers were not traced south of Mokopane in either outcrop or deep exploration borehole intersections. Instead, on Moorddrift, Rooipoort, Oorlogsfontein, Jaagbaan, and further south, the Main Zone is characterised by a 1,200 m thick sequence of gabbronorite and gabbro with three to four mottled anorthosite layers. Hulbert (1983) called it the Rooipoort Gabbronorite zone. Van der Merwe (2008) concluded that the Rooipoort Gabbronorite zone extends north of the Ysterberg-Planknek fault, and it implied that the lateral change of the Rooipoort gabbronorite zone to the zones further north has taken place to the west of Mokopane. Van der Merwe postulated that this lateral change occurred close to a potential feeder.

The contact between the Main Zone and Platreef may be sharp, and is commonly marked by a mottled anorthosite. It may be transitional such that lithologies are interfingered (White, 1994, Wiese, 2010). The lowermost part of the Main Zone overlying the Platreef is commonly a norite. With increasing height above the Platreef, the Main Zone becomes a medium- to coarse-grained gabbronorite. The Main Zone gabbronorite commonly hosts xenoliths of hornfels (rafts), especially towards the base. This has been cited as evidence for the Main Zone pre-dating the Platreef, as these were considered to be the fragments of floor caught up by Main Zone magma. However, often near the base of the Main Zone there is a thick "disturbed zone" for tens of meters above the contact with layers of pyroxenite, norite, gabbronorite, anorthosite and metasedimentary xenoliths. Pyroxene chemistry in the pyroxenites of this disturbed Main Zone is identical to Platreef pyroxenes (Wiese, personal communication, 2010), and contrasts with the mineral chemistry of the "host" Main Zone norite. Kinnaird and Nex (2012, in press) indicated that this suggested that the pyroxenites are xenoliths of Platreef pyroxenite caught up in the Main Zone, supporting the mapping of Holwell and Jordaan (2006) in Zwartfontein pit; and observations of Holwell *et al*., (2005), that the Platreef pre-dated intrusion of the Main Zone. Thus Kinnaird and Nex (2012, in press) suggested that the Transvaal metasedimentary rocks originally formed a roof to the Platreef, and as the Main Zone magma invaded the Platreef, it incorporated xenoliths of hornfels from the roof.

(a) Fine- to medium-grained spotted anorthosite with sub-rounded cumulus orthopyroxenes in drill hole UMT336, at a depth of 1156.20 m (25 cm sample, NQ core size)

(b) Poikilitic inequigranular mottled anorthosite in drill hole UMT335D1, at a depth of 1464.30 m (25 cm sample, NQ core size)

(c) Medium-grained gabbronorite with rounded cumulus orthopyroxenes in drill hole UMT334, at a depth of 1170.70 m (23.5 cm sample, NQ core size)

Figure 2.15. Main Zone lithologies

2.3.6 Upper Zone lithologies

The only outcrops of the Upper Zone (gabbro, magnetite gabbro, magnetitite and mottled anorthosite) in the southern sector of the northern limb occur in the southwestern portion of Townlands and western portion of Jaagbaan, and these appear to represent the lower portions of the Upper Zone. The presence of the zone in this area has been derived mainly on a qualitative basis by recognising images of anomaly patterns bearing Upper Zone signatures, using aeromagnetic survey maps (Geological

Survey of South Africa 1973; Bell 2001). Figure 2.16 below shows a sample of the Upper Zone gabbro at depth.

Figure 2.16. Fine- to medium-grained gabbro of the Upper Zone from the Waterberg Project (Platreef workshop 2012)

2.4 Mineralisation in the Northern Limb

On Grasvally, south of the TML, the Ni-Cu-PGE mineralisation occurs within the Drummondlea harzburgite-chromitite subzone and the Volspruit pyroxenite subzone in the Lower Zone rocks (Hulbert and Von Gruenewaldt, 1982). Sulphide mineralisation in the Drummondlea harzburgite-chromitite subzone is enriched in cycles 24 and 26. These cycles represent chromitite layers i.e. the lower chromitite is called cycle 24 and upper chromitite cycle 26, whereas in the Volspruit pyroxenite subzone, significant sulphide and PGE mineralisation occur in cyclic unit 11 (20 m thick). The highest grade of Ni-Cu-PGE occurs in the basal 6 m of the mineralised zone where sulphides constitute about 3 wt percent of the rock. Average grades are 0.24 % Ni, 0.11 % Cu, 1.39 ppm Pt and 1.73 ppm Pd. The sulphide assemblage consists, in decreasing order, of pyrrhotite, pentlandite, chalcopyrite and cubanite (Hulbert and Von Gruenewaldt, 1982). Another zone of PGE mineralisation occurs in a thin sequence of rocks known as the Grasvally norite-pyroxenite-anorthosite (GNPA) member, which is developed over Lower Zone rocks and sediments of the Pretoria Group south of Mokopane (Hulbert 1983; Hulbert and Von Gruenewaldt 1985, 1986). This sequence contains layered norites, gabbronorites and anorthosites along with a chromitite layer and is termed the "Critical Zone". Hulbert (1983) named this chromitite layer in the GNPA member the "UG2-like" chromitite and it has been correlated with the UG2 chromitite by some authors (e.g. Van der Merwe 1998). The top of the GNPA member is xenolith-rich and hosts PGE mineralisation.

Mineralisation within the Platreef is dominated by disseminated sulphides and associated platinum group minerals (PGMs), although massive sulphides infrequently occur associated with structural downwarps in the footwall (White, 1994; Kinnaird *et al.*, 2005). Mineralisation is bottom-loaded in the southern sector and top-loaded in the central and northern sectors (White, 1994). Where the floor comprises quartzite, as at Townlands, or anhydrous gneiss, such as at Overysel, there is limited fluid activity and PGE distribution is controlled by the behaviour of sulphide liquids producing an intimate PGE-BMS association (Manyeruke *et al*., 2005; Holwell and McDonald, 2006), with high BMS content producing high PGE grades. More commonly, floor rocks are reactive shales or dolomites, and fluid activity related to metamorphism, assimilation and serpentinisation has decoupled PGE from BMS. This has locally transported PGE into footwall alteration zones with semi-metal (Te, Sb, Se, Bi and Ge) - bearing platinum group minerals that are typical of many low-temperature PGE deposits (Armitage et al., 2002). This suggests syn- to postmagmatic crystallisation or redistribution of magmatic PGE by hydrothermal fluids (Hutchinson and Kinnaird, 2005; Zhitova *et al*., 2008). In the south, where dolomite of the Duitschland Formation forms the floor, mineralisation is bottom-loaded in serpentinised peridotite, feldspathic pyroxenite, serpentinised dolomite xenoliths or footwall dolomite (Kinnaird et al, 2005). Elsewhere, where the floor is Lower Zone, hornfels or quartzite, the grade is lower and mineralisation is usually associated with xenoliths of hornfels or with norite and leuconorite, although cyclic norite is selectively mineralised (Kinnaird *et al*., 2005).

The main base metal sulphides present in the Platreef are, in order of abundance, pyrrhotite (sometimes pyrite), pentlandite and chalcopyrite. Minor cubanite, sphalerite, bornite, millerite, cuprite, galena and alabandite also occur (Gain and Mostert, 1982). White (2008) indicated that the PGE grade in the Platreef is often less than 4 g/t although on Sandsloot a thick Platreef zone had a grade (Pt+Pd+Rh+Au) in excess of 10 g/t, and on Akanani a grade of 7.82 g/t occurs over 29 m, with an included higher grade zone of >17 g/t over 6.74 m.

In the southern sector, there is a wide variety of PGE phases, mainly as tellurides, arsenides and antimonides of Pd, Pt, Rh, Ag and variable amounts of Bi occuring as bismuthoantimonides and complex bismuthotellurides (Kinnaird et al., 2005). Armitage et al (2002) reported the occurrence of tellurides and bismuthotellurides in the Platreef and the footwall calc-silicates at Sandsloot. They have also reported that the PGMs are associated with primary silicates, metamorphic silicates, alteration silicates, primary and remobilised sulphides and oxides.

On Tweefontein Hill, massive and net-textured sulphide mineralisation with a cumulative thickness of greater than 0.5 m was intersected in 26 boreholes; with an average thickness of 1.74 m. Nex (2005) reported that later vein style mineralisation containing large sperrylite crystals was hosted by cross-cutting breccia zones within the banded ironstones in this area. He then concluded that the pre-existing fold structure which acted as a trap for the massive sulphide mineralisation pre-dated the Platreef intrusion.

In the central sector, on Tweefontein north, the Ni-Cu-PGE mineralisation is top loaded (White, 1994). Kinnaird et al., (2005) noted a persistent chromitite with sulphides including pyrite, which occurs within 10 m below the hangingwall contact in this area. They further indicated that pyroxenites a few meters below this chromitite are enriched in PGEs. On Sandsloot where the Platreef varies in thickness from a few meters to 30 m in the central and southwestern parts of the open pit (Armitage et al., 2002), discontinuous chromitite lenses occur (Marland, 1997), associated with top loaded mineralisation.

Naldrett (2008) recorded that the tenors (Pt and Pd) in the Platreef sulphides are typically less than 100 ppm, except in the upper sill on Sandsloot where tenors >100 ppm are similar to those of the Merensky Reef. Tenors in the sulphides of the Merensky Reef are at their highest close to the top of the chromite in the northwest of the complex and just south of the Pilanesberg, where tenors in the sulphides reach >3000 ppm (Naldrett et al., 2009).

Beyond the exposed part of the northern limb, north of Harriets Wish farm, high grade PGE mineralisation was reported in the Main Zone rocks which are overlain by the Waterberg sediments. Mineralisation occurs within the T1 reef (harzburgite), T2 reef (norite) (Platinum Group Metals press release November 9, 2011) and the F layer (Platinum Group Metals press release May 23, 2012). In the deeper section (660.0 m) of the property, both T1 and T2 reported 3.47 g/t Pt, Pd and Au (2 PGE+Au) over 3.5 m and 7.00 g/t 2PGE +Au over 5.0 m respectively. Whereas, high grades of 6.32 g/t (2 PGE + Au) over 7.0 m were reported within T2 in the shallower section (322.0 m) of the property. Grade thickness of up to 16.0 m at 6.41 g/t (2 PGE + Au) was reported within the F layer. This layer is located near the bottom of the Bushveld Complex and has metal ratios similar to the Platreef to the south (Platinum Group Metals press release May 23, 2012).

2.5 Discussion

Mineralisation in the northern limb occurs in different stratigraphic levels from the south to the north. On Grasvally, mineralisation occurs in the Lower Zone rocks, in the southern sector it is reported to occur in lithologies near the base of the Platreef, in the central and northern sectors it occurs closer to the Main Zone-Platreef contact, whereas further north of the Platreef, it is reported to occur in the Main Zone rocks. The association of base metal sulphides with the presence of chromitites has been reported on Grasvally, and in the central and northern sectors. In general, mineralisation was reported to be bottom loaded in the southern sector and top loaded in the central and northern sectors.

The base metal sulphides occur in the form of pyrrhotite, pentlandite and chalcopyrite, while the PGE minerals are dominated by tellurides, arsenides and antimonides. In the south, where dolomite of the Duitschland Formation forms the floor, mineralisation is reported to be bottom loaded in serpentinised peridotites, feldspathic pyroxenite, serpentinised dolomite xenoliths or footwall dolomite. In contrast, in Overysel and Townlands where the floor rocks are anhydrous gneiss and quartzite respectively, the PGE distribution is thought to be controlled by the behaviour of sulphide liquids. However, in the central and northern sectors, the highest grade mineralisation (>30 g/t PGE) is reported to be associated with a persistent chromitite near the Main Zone-Platreef contact.

2.6 Summary and conclusions

Previous studies have differentiated the northern and central sectors from the southern sector in that the former comprise top loaded mineralisation and the latter bottom loaded mineralisation. It is the intention of this study to demonstrate that the southern sector of the northern limb on Turfspruit is not only bottom loaded, but also top loaded in mineralisation.

Chapter 3

Geology of Turfspruit

3.1 General geology

A wealth of geological information has been gathered from near-surface resources on Turfspruit focussed along the Platreef sub-outcrop, where the Platreef abuts Transvaal sediments (Figure 3.1). Here, the reef dips at 40^{o} to the southwest (Kinnaird *et al*, 2005). The intermixing of Platreef magma with the sedimentary floor (mainly the Duitschland dolomites and shales) prohibited researchers from obtaining a detailed stratigraphy on Turfspruit. The drilling conducted on the deeper portions of the Platreef, to the southwest of the Platreef sub-outcrop, provided crucial information that enabled the identification of stratigraphy on Turfspruit.

Based on the information from near-surface resources gathered prior to the start of this work, it was believed that the reef dips continuously at 40^{o} to the southwest (Figure 3.2: position of section shown in figure 3.1). However, the information gathered from the deep drilling project indicated that the dip of the reef becomes shallow (10^{o} – 15^{o}) to the southwest (Figure 3.3). This area, which has been chosen for study in this thesis, is referred to as the "Flatreef". The Flatreef is characterised by the following distinguishing factors:

(1) Well-defined geological units that can be correlated for kilometres along dip and strike;

(2) Increased thicknesses of high grade mineralisation with high tenors;

(3) Persistent chromitites associated with the main high grade mineralised zone;

(4) Less contamination in high grade mineralised zones i.e. less mixing of different magmas or mixing of the magma with sediments;

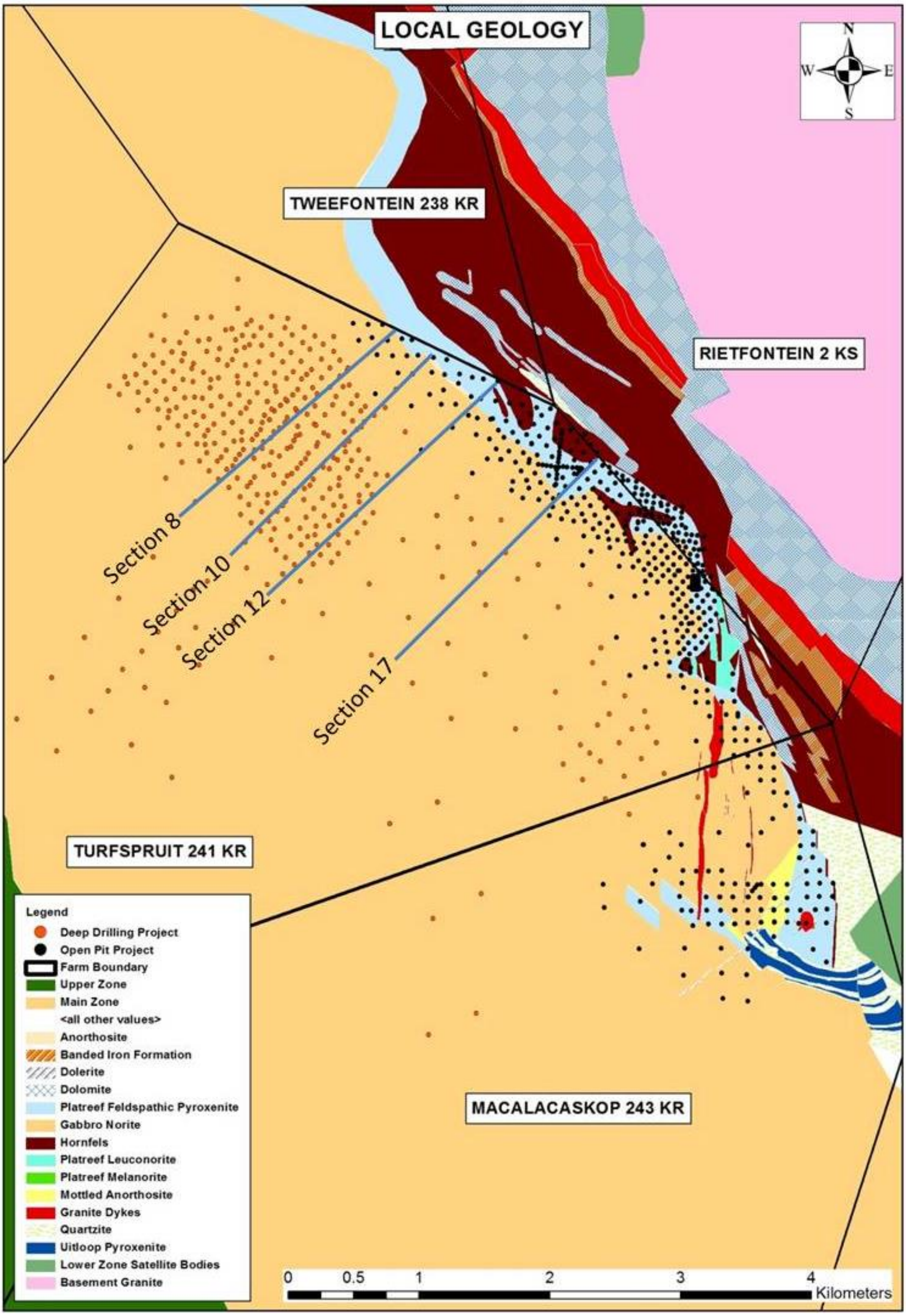


Figure 3.1. Generalised surface geology on Turfspruit showing the section lines which were used for this study. Map courtesy of Ivanplats

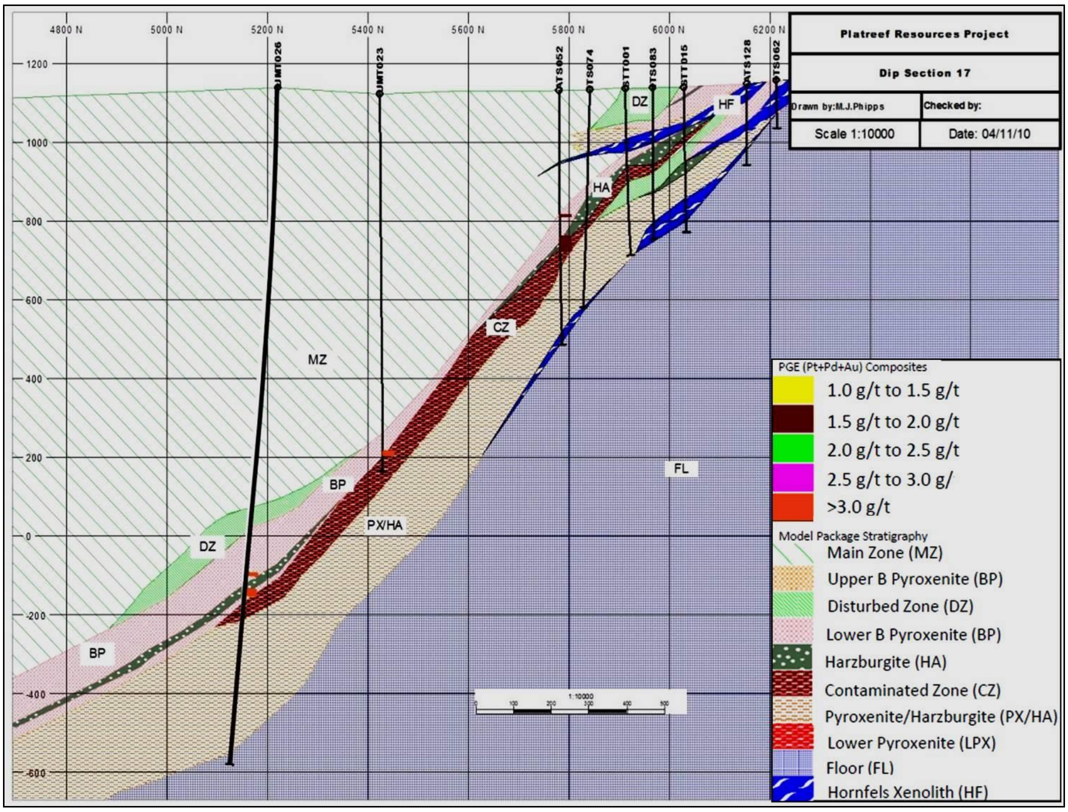
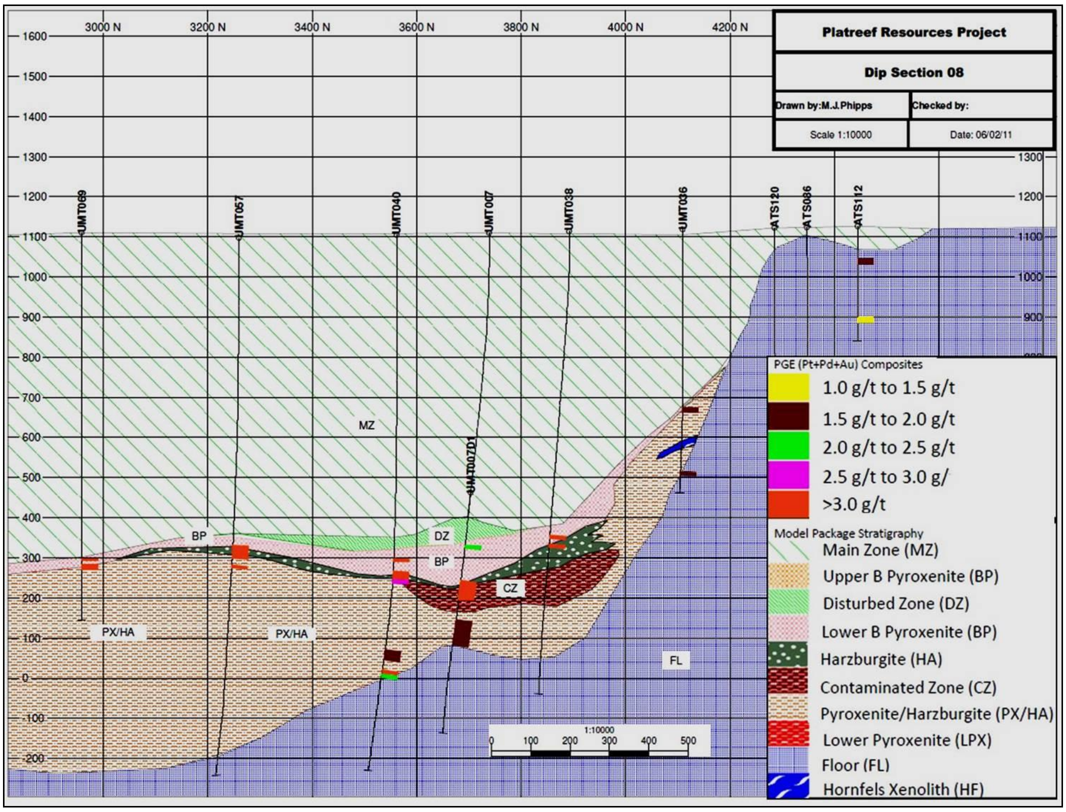
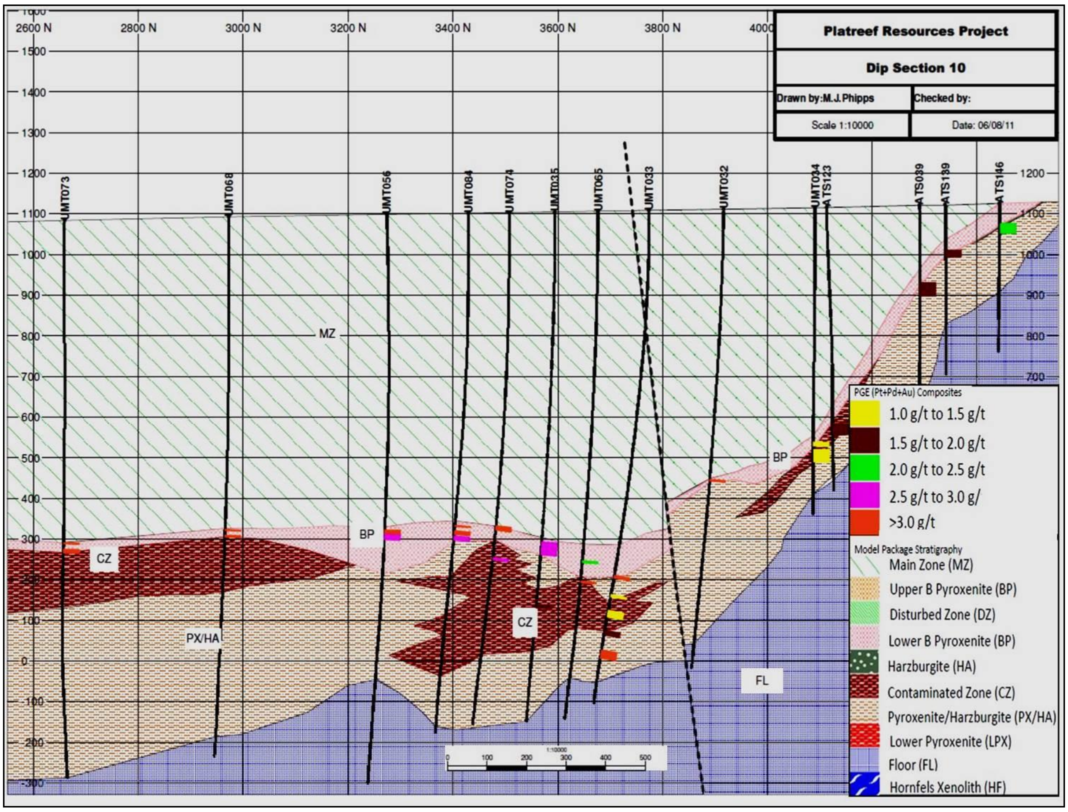


Figure 3.2. Dip section 17 showing estimated dip from shallow resource drill holes. The location of section 17 is shown on Figure 3.1





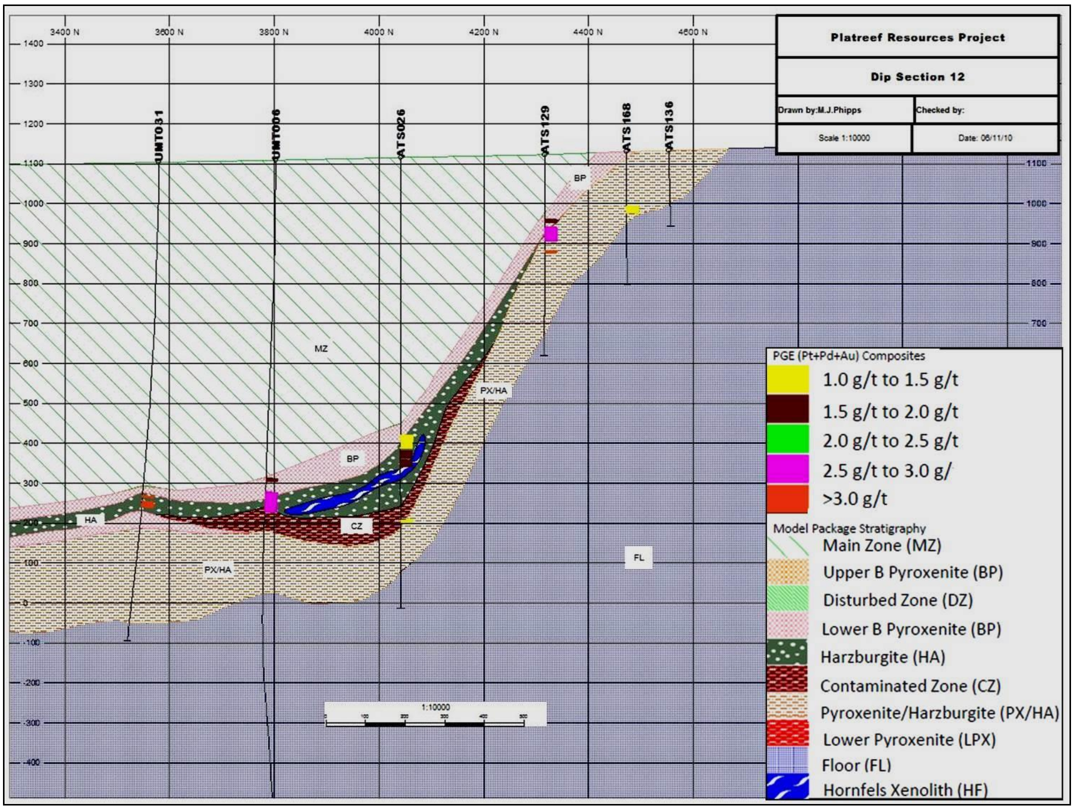


Figure 3.3. Dip sections 8, 10, 12 showing the Flatreef. The location of these sections is shown on Figure 3.1

3.1.1 Floor rocks

Turfspruit comprises variable footwall lithologies from south to north i.e. Duitschland hornfelses and dolomite, Lower Zone (pyroxenites, harzburgite and dunites) and granofels (Figure 3.4). Kinnaird *et al* (2005) identified shales, banded ironstones, calcsilicates, mudstones and siltstones of the Duitschland Formation from near-surface resource drill holes.

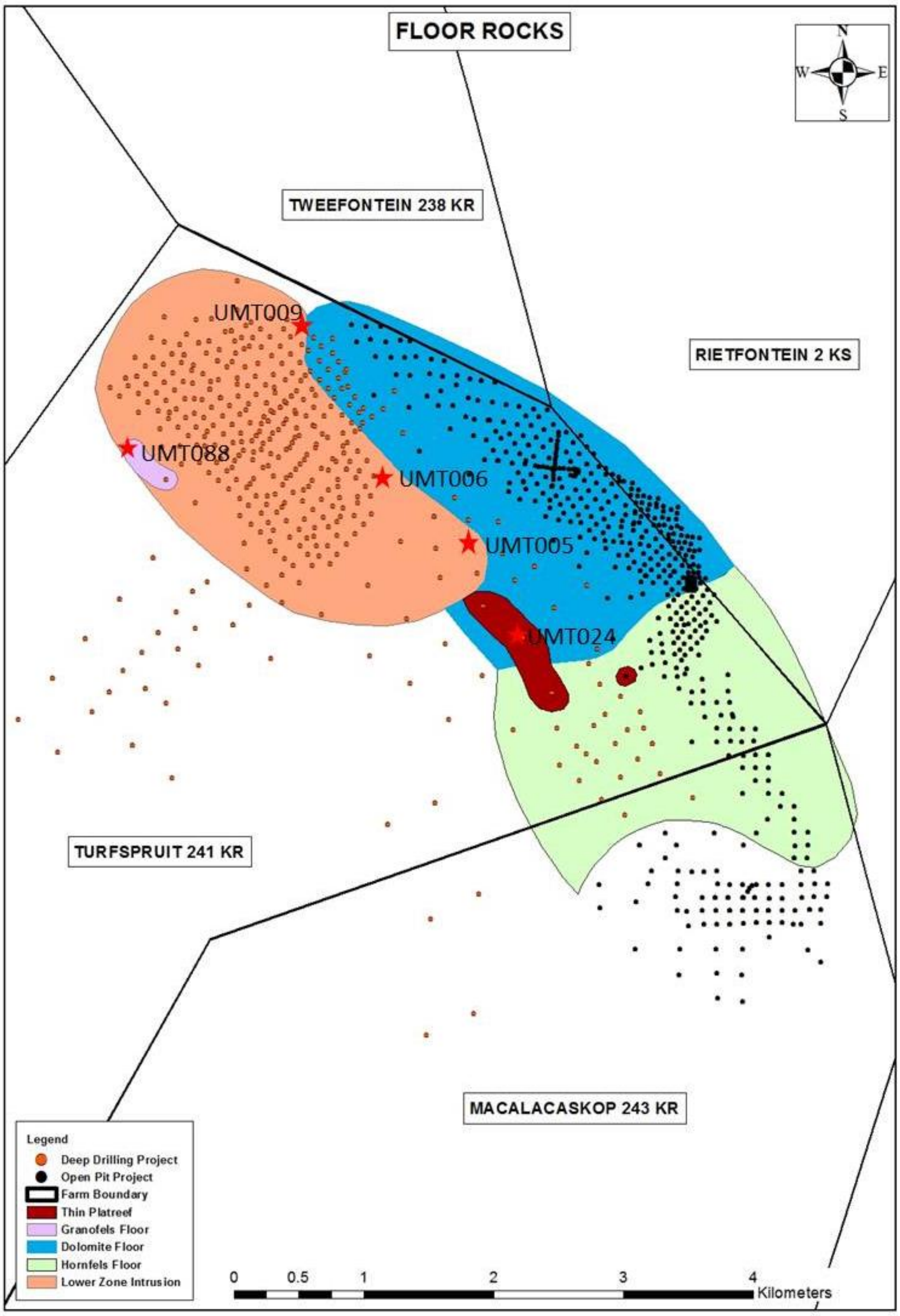


Figure 3.4. Generalised floor rock distribution on Turfspruit and the location of the studied borehole cores

3.1.1.1 Hornfels floor and xenoliths

Hornfelses (metamorphosed shales) form the predominant floor rock lithology in southern Turfspruit. They occur as lenses/slabs in the Platreef and the Main Zone. They also form large rafts (hornfels high) within the Platreef, where large blocks of hornfels, interlayered with fingers of Marginal Zone norite, did not react and mix with the Platreef magmas. In some areas, very thin Platreef is present between the top of the "hornfels high" and base of the Main Zone. This could be a result of the diapirism process as described by Uken and Watkeys (1997). However, in UMT024 (Figure 3.4), 235 m of Platreef were intersected between 200 m of hornfels and the base of Main Zone. Lithological units intersected in this drill hole correlate with those present within the upper section of the Platreef, meaning the lower units of the Platreef did not intrude these sediments, and probably made their way around the sediments.

Kinnaird *et al.* (2005) reported that these hornfelses separate the Platreef sills. This is evident in southern Turfspruit where different lithological units are separated by large hornfels slabs. Some of these slabs are attached to the hornfels floor (Figure 3.5). In northern Turfspruit, hornfels lenses may occur at different positions i.e. at the contact between the Main Zone and the Platreef; within individual lithological units and therefore, resulting in increased thickness of the units (Figure 3.3 – Dip Section 12); across different lithological units (Figure 3.7) and at the contact between the Platreef and the Lower Zone.

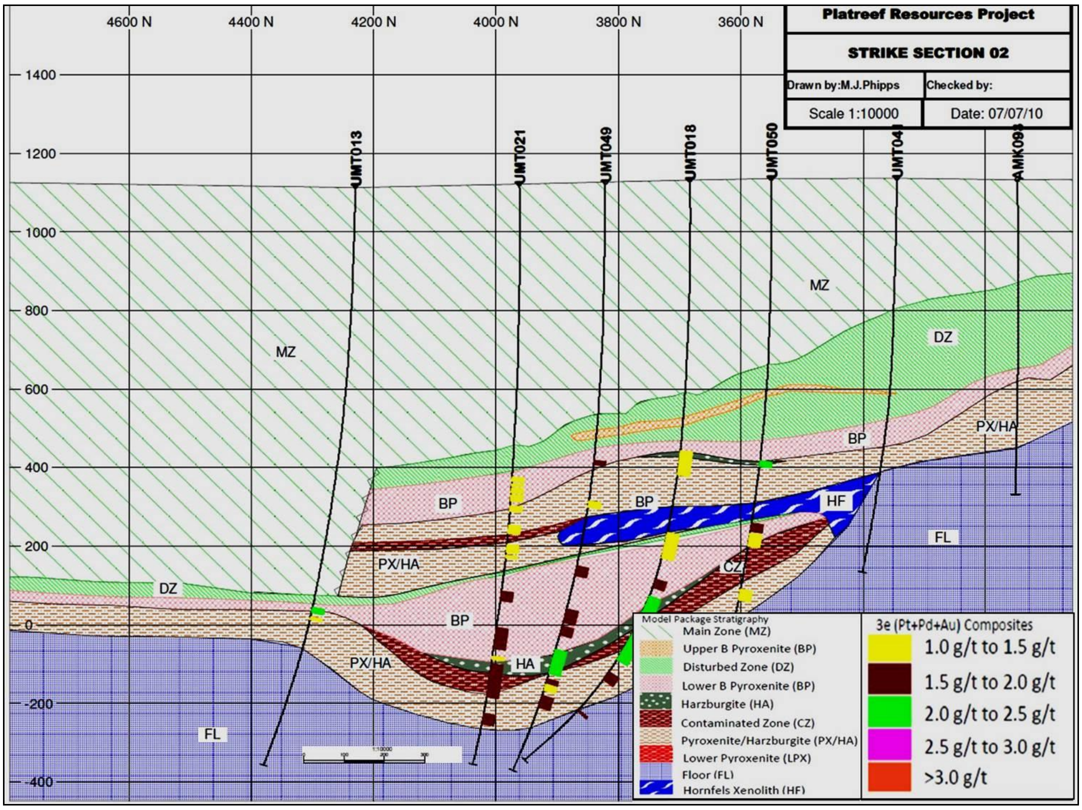


Figure 3.5. Hornfels (HF) separating lithological units

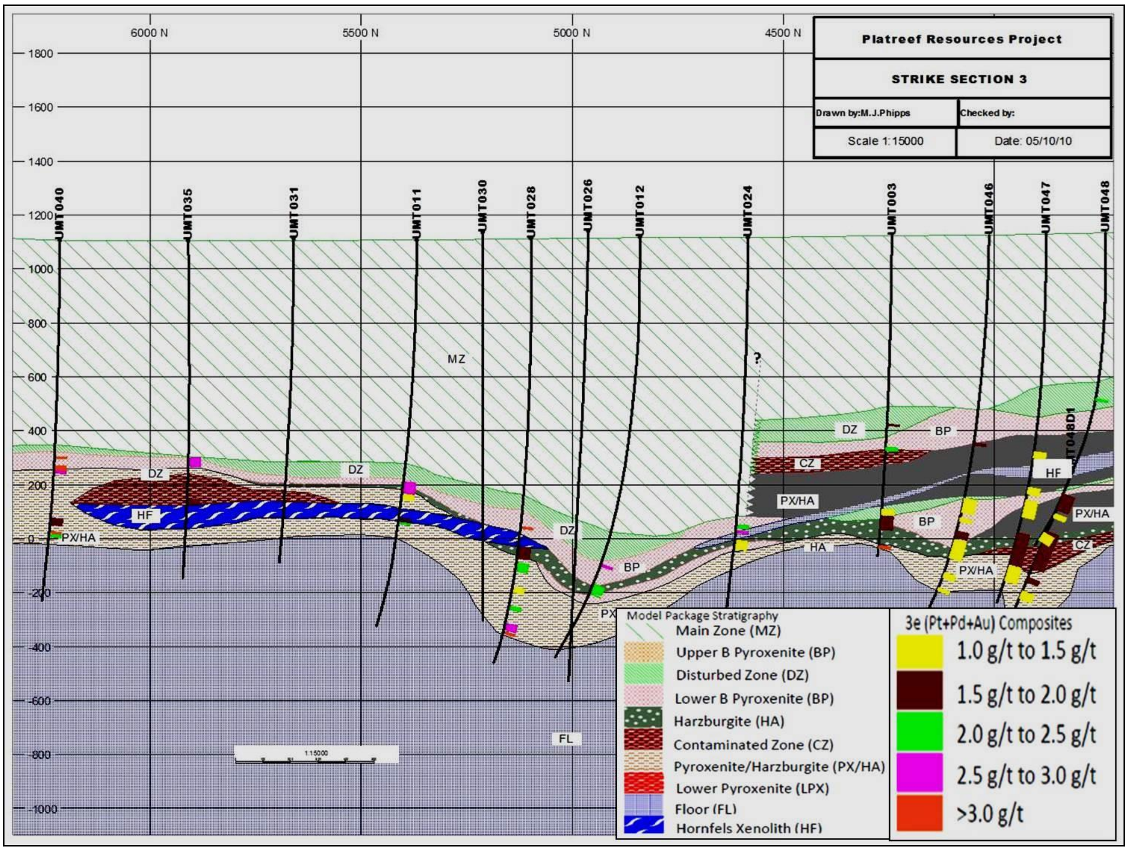


Figure 3.6. Hornfels slab across different lithological units

3.1.1.2 Dolomite floor and xenoliths

Dolomite of the Duitschland forms the floor to most of the central to northern parts of Turfspruit along the eastern boundary of the farm (Figure 3.4). Xenoliths of calc-silicates and parapyroxenites occur in different lithological units within the Platreef. Generally, they form the base/floor to the high grade mineralised zone within the upper section of the Platreef (Figure 3.3 – Dip Section 08). They can occur within the pyroxenite-norite unit in the middle of the Platreef (Figure 3.7). They can be laterally extensive, irregularly-shaped with thickness greater than 200 m (Figure 3.3 – Dip Section 10) or they may have shapes mimicking the floor topography (Figure 3.8). Norites, para-harzburgites and pyroxenites also form the floor to this high grade zone within the study area (discussed later in the chapter). Anhydrite, which may have been derived from the dolomite occurs rarely within the upper section of the Platreef.

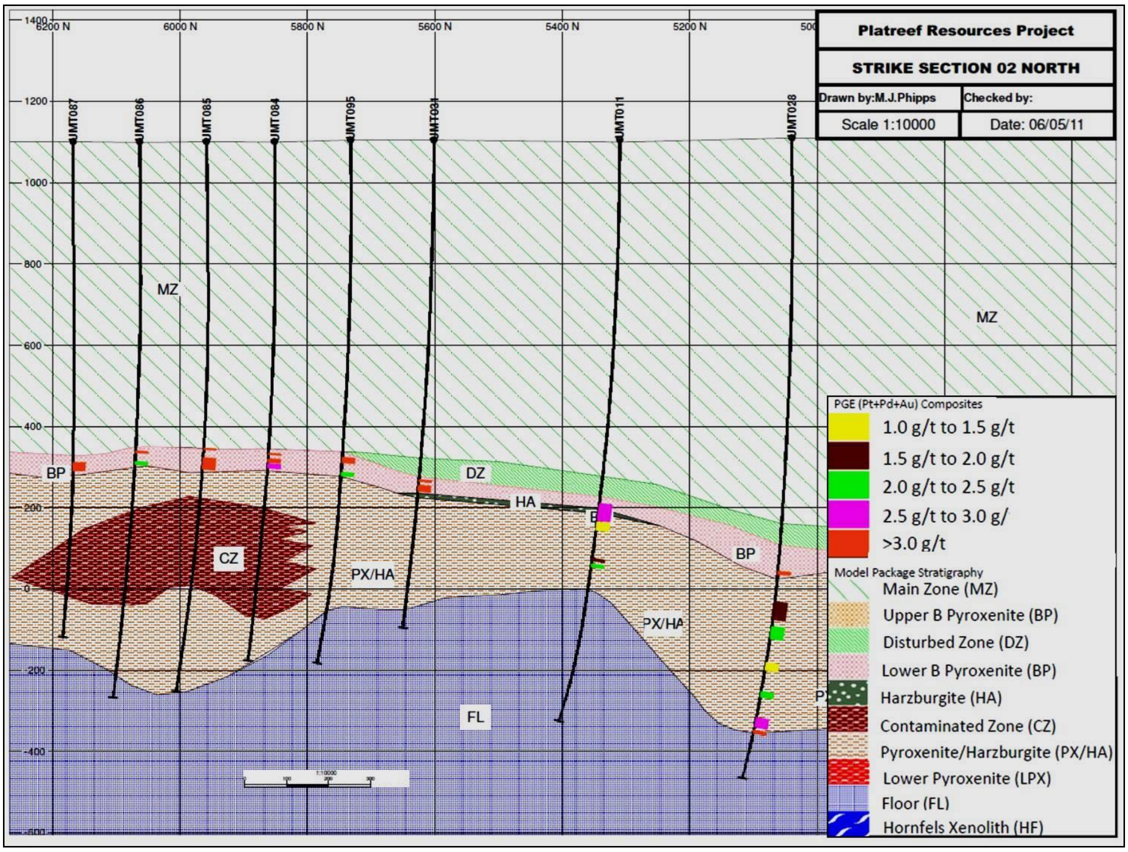


Figure 3.7. Calc-silicate/parapyroxenite xenolith within the middle of the Platreef. Note that the calc-silicate/parapyroxenite zone is labelled "CZ"

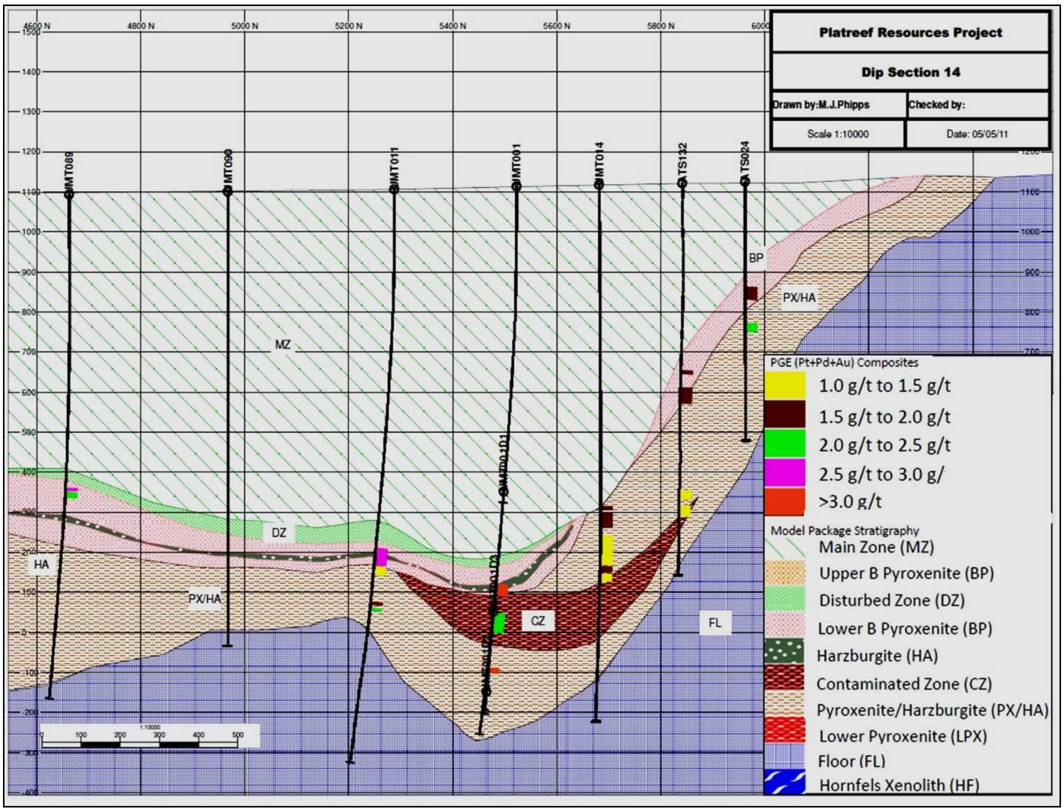


Figure 3.8. Calc-silicate/parapyroxenite xenolith with a shape mimicking that of the base of Platreef topography. Note that the calc-silicate/parapyroxenite zone is labelled “CZ”

3.1.1.3 Granofels

A fine grained granitic rock, petrologically an agmatite, but locally termed granofels occurs in northwestern Turfspruit (Figure 3.4). Kinnaird and Nex (2012) reported the occurrence of agmatite at the contact between the Platreef and Archaean granite on the farms Overysel and Drenthe. Cawthorn *et al*., 1985 and Barton *et al*., 1986 concluded that the agmatite developed from the interaction of the Platreef with the Archaean granite footwall. However, on Turfspruit, the granofels occurs in close proximity with the Lower Zone rocks. More than 250 m of granofels were intersected in UMT088 (Figure 3.4). The majority of the boreholes drilled to below the base of the Platreef in the study area, have intersected the Lower Zone pyroxenites, dunites and harzburgites; whereas in UMT088 the drilling was stopped within the granofels. The drill holes that intersected the Lower Zone are located approximately 100 m away from the UMT088.

3.1.1.4 Lower Zone

A sequence of Lower Zone rocks i.e. pyroxenites, harzburgites and dunites, occupy the central to northwestern parts of Turfspruit (Figure 3.4). These rocks are texturally different from the Platreef pyroxenites. Pyroxenites of Lower Zone affinity are medium- grained with prismatic orthopyroxenes aligned parallel to “layering” and have a low percentage of interstitial feldspar.

Generally, there is a thin layer of hornfels between the Platreef and the Lower Zone pyroxenite. In areas where the hornfels is absent, the Platreef is in direct contact with the Lower Zone pyroxenite. This contact is sometimes difficult to identify when the Marginal Zone norite is in direct contact with the Lower Zone pyroxenite. Xenoliths of hornfels are also present within the Lower Zone sequence. The thickness of the Lower Zone in UMT006 and UMT009 reaches up to 750 m and 800 m respectively (Figure 3.4). To the south, in UMT005, the Lower Zone sequence interfingers with the Platreef and then pinches out. The upper and lower contacts of the Lower Zone pyroxenite with the Platreef norites and pyroxenites are sharp, with dip angles of about 30^{o} and 10^{o} respectively. At the upper contact there is no evidence of chilling, whereas at the bottom contact, the rocks on either side of the contact (for about 30 cm) seem to be finer grained. However, these 30 cm zones are heavily altered with chlorite, making it difficult to determine whether the Lower Zone chills against the Platreef or vice versa.

3.1.2 Platreef rocks

The Platreef consists of feldspathic pyroxenites, harzburgites, pyroxenites and norites with variable textures. Generally, interlayered metasedimentary rocks occur from the middle to the base of the Platreef. The base of the Platreef is characterised by the appearance of the Marginal Zone norite underlain by a thin layer of hornfels; the contact with the footwall rocks (hornfels, dolomite or Lower Zone pyroxenite) may be sharp or gradational. In southern Turfspruit where the footwall is predominantly hornfels, there is a thick unit of repetitive interlayered Marginal Zone norite and hornfels that makes it difficult to mark the contact between the Platreef and the floor rock. In contrast, in northern Turfspruit where the floor rock is predominantly Lower Zone pyroxenite, the contact between the Platreef and the floor is marked by a hornfels layer which may be less than 10 cm thick. Where this hornfels is absent, it is difficult to mark the contact between the Platreef and the floor as the pyroxenite at the base of the Platreef comes in direct contact with the Lower Zone pyroxenite. Where the Marginal Zone norite is present below the Platreef pyroxenite, it is also difficult to mark the boundary between the Platreef and the Lower Zone pyroxenite as there is a gradual change from the Marginal Zone norite to the Lower Zone pyroxenite. Figure 3.9 shows a generalised stratigraphy developed for Turfspruit.

The contact between the Main Zone and the Platreef may be sharp, very often with a mottled anorthosite at the base of the Main Zone. This mottled anorthosite may be a few cm or more than a metre thick. In the study area, granitic sills are often present at the contact between the Platreef and the Main Zone. The contact may also be transitional (Disturbed Zone) or lithologies may interfinger (Kinnaird and Nex, 2012). The Disturbed Zone, a transition zone between the Platreef and the Main Zone, comprises a sequence of interlayered pyroxenites, norites and anorthosites (White, 1994, Wiese, 2010). These rocks form repetitive units that vary in thickness and laterally. Occasionally, very thin (< 1 cm) chromitite stringers occur at the contacts between different lithologies. Wiese (2010) indicated that the chemistry of pyroxenes in the pyroxenites of the Disturbed Zone were identical to the Platreef pyroxenes and; Kinnaird and Nex (2012) added that the chemistry of the Disturbed Zone pyroxenes contrasts with the mineral chemistry of the "host" Main Zone norite. This led Kinnaird and Nex to suggest that the pyroxenites of the Disturbed Zone are xenoliths of the Platreef pyroxenite caught up in the Main Zone. This further supports the mapping of Holwell and Jordaan (2006) in Zwartfontein pit and observations of Holwell et al., (2005) that the Platreef pre-dated the Main Zone intrusion.

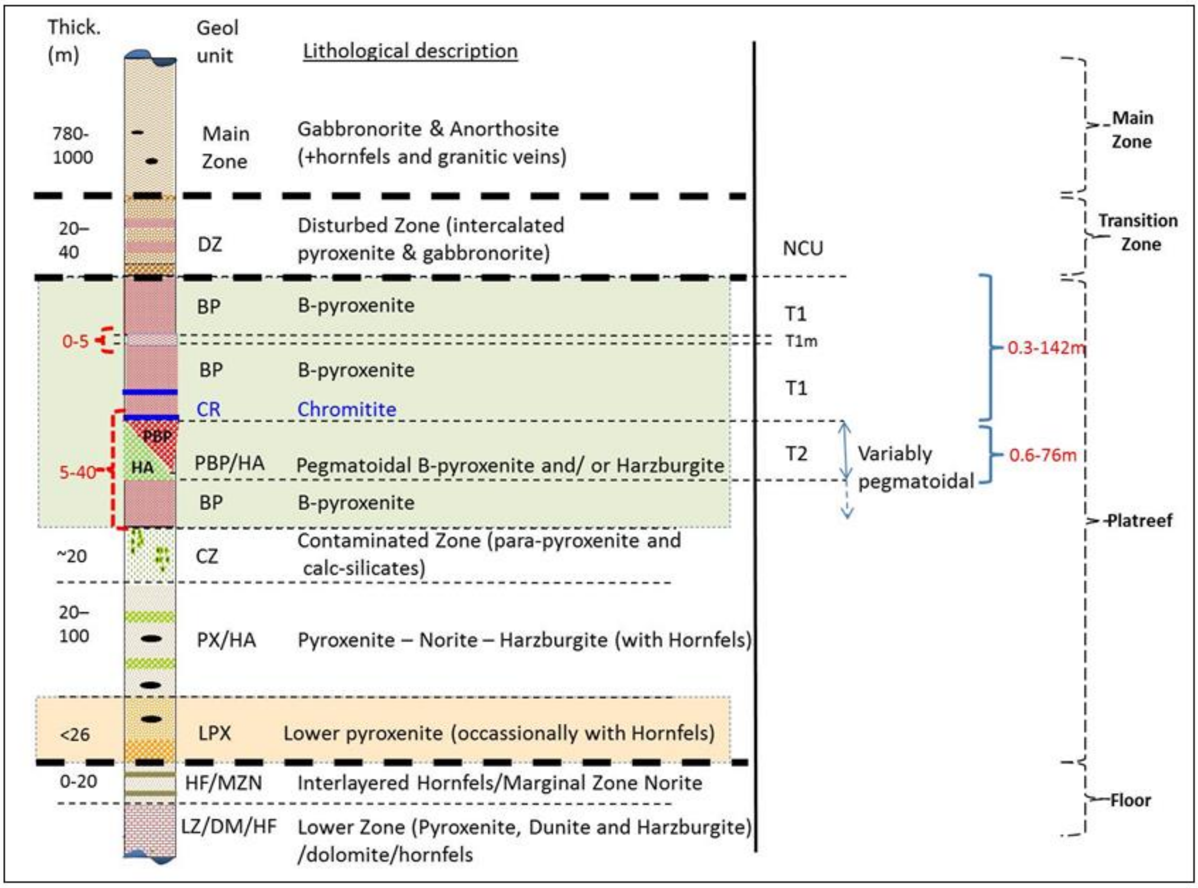


Figure 3.9. Generalised stratigraphy on Turfspruit

In areas where the Disturbed Zone is absent the clinopyroxenite seldom occurs immediately below the Main Zone. The occurrence of clinopyroxenite on Turfspruit is sporadic and as a result, it is difficult to correlate. Hence, it is not listed as a stratigraphic unit in Figure 3.9. Sometimes pyroxenites of the Disturbed Zone consist of both clinopyroxenite and orthopyroxenite. In most parts of Turfspruit, the

Disturbed Zone is well developed on the flat-lying to gentle dipping parts of the Platreef. However, not all flat-lying areas are characterised by an overlying Disturbed Zone.

The B-pyroxenite forms the main mineralised zone within the upper section of the Platreef. Based on lithological variations, the B-pyroxenite has been subdivided into two broad zones, namely, the T1 and T2 Upper (Grobler and Nielsen, 2012). They also renamed the harzburgite or an olivine-bearing pyroxenite which often occurs below the T2 Upper to T2 Lower. The mineralised portion of the T1 was assigned to T1m. Well mineralised zones in the T2 are associated with the pegmatoidal texture. It is noted that the T1 and T2 zones referred to in this study are in no way related to those reported by PTM further north of the Platreef.

The T1 consists of a fairly homogeneous feldspathic pyroxenite that ranges in thickness from a few meters to several tens of meters, but the mineralised zone (T1m) has an average thickness of 5 m. There is a slight variation in the plagioclase content within this pyroxenite. It is uncontaminated, i.e. not mixed with calc-silicates or para-pyroxenites, and is weakly altered. Chromitite stringers very seldom occur in this lithological unit.

The T2 Upper comprises a slightly pegmatoidal pyroxenite at the top that grades into a fully developed pegmatoidal pyroxenite towards the base. Chromitite seams, stringers and blobs of variable thicknesses normally occur at the contact between the feldspathic pyroxenite (T1) and the pegmatoidal pyroxenite (T2 Upper) (Figure 3.10). This contact can also be recognised due to textural differences between the two rock types. Thus, in areas where the chromitite is non-existent, the contact can still be recognised. Often, more than one chromitite stringer (up to six stringers in places) occurs above and below this contact (Figure 3.11). In areas where the T2 Lower occurs below the T2 Upper, chromitite stringers often occur at the top and base of the T2 Upper. Disseminated chromite sometimes occurs within the T2 Lower. Where the T2 Upper is absent or very thin, the T1 comes into contact with or closer to the T2 Lower and the chromitite stringer occurs in contact or just above the T2 Lower. The T2 Lower has a magmatic texture and consists of orthopyroxene oikocrysts (giving them a pegmatoidal texture). Often, the fully developed pegmatoidal pyroxenite extends below the T2 Lower and it is sometimes well mineralised. Chromitites occur as compact seams (up to 30 cm thick) and stringers or as disseminations (more than 1 m thick).

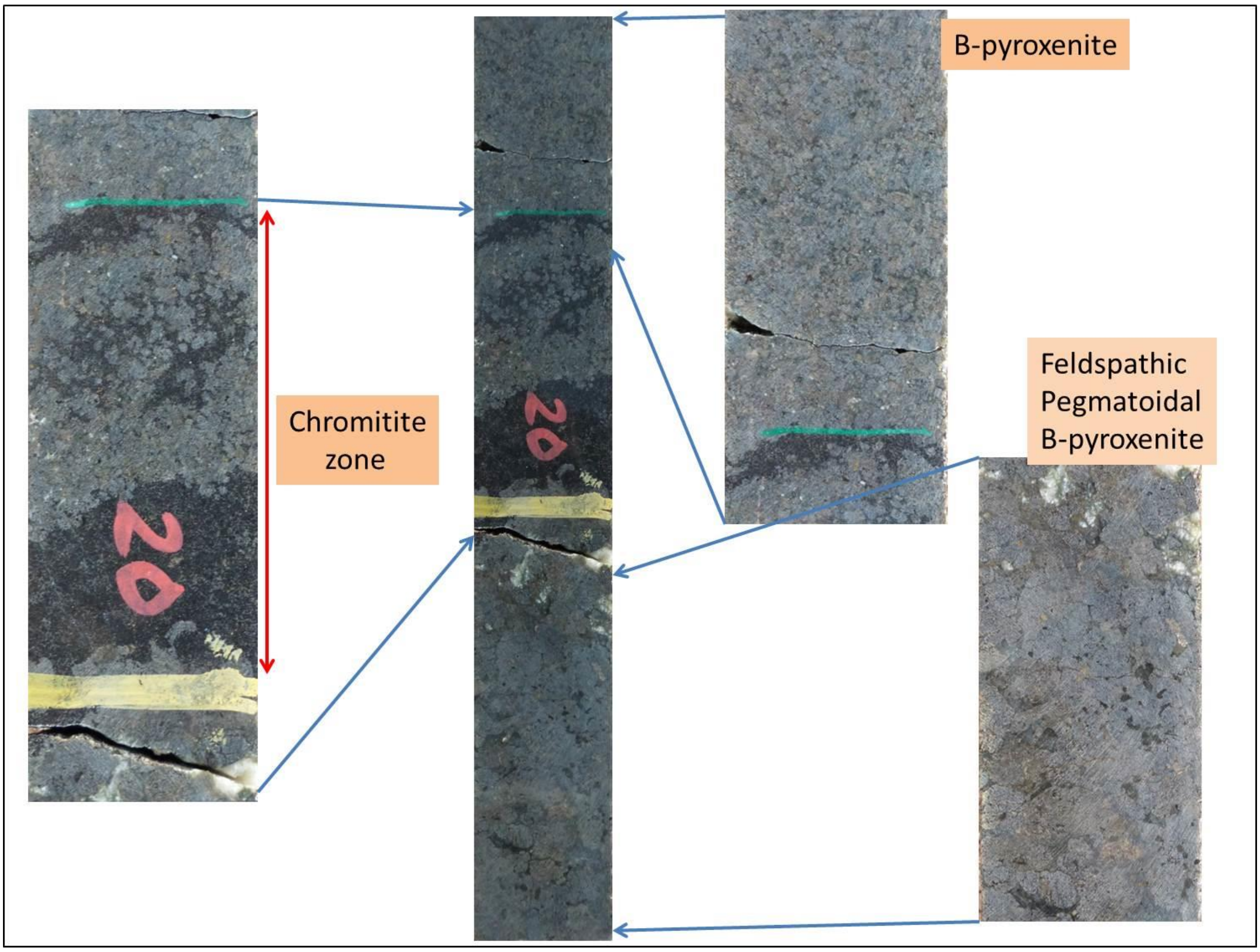


Figure 3.10. B-pyroxenite/pegmatoidal B-pyroxenite contact marked by chromitite stringer (UMT209 at 750.50 m)). The sample is 35 cm long and the chromitite is 12 cm thick. The compact part of the chromitite is about 4 cm in thikness

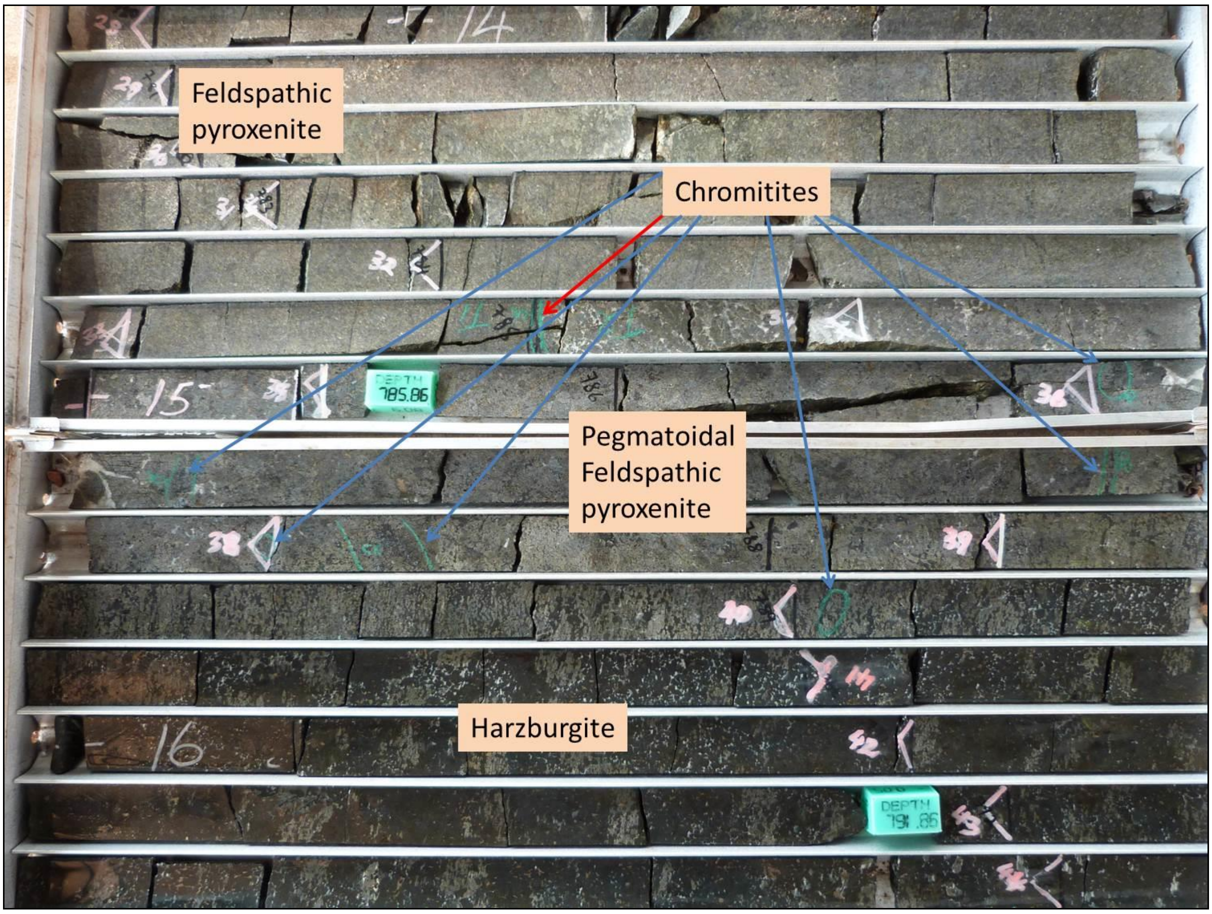


Figure 3.11. Multiple occurrences of chromitites within the upper section of the Platreef in UMT278, between depths of 785 m – 789.05 m. Chromitite locations are indicated by the green marks on the drill core. They occur in the form of stringers, blobs and disseminations. The main chromitite that marks the boundary between the feldspathic pyroxenite (T1) and the pegmatoidal pyroxenite (T2 Upper) is indicated by the red arrow. The stringers range in thickness from <1 cm to 10 cm

Yudovskaya and Kinnaird (2010) reported the occurrence of chromitites in the Upper Chromitite zone (UCR) in the central and northern sectors of the Platreef. In both sectors, the chromitites occur approximately 17 – 20 m below the top contact of the Platreef. However, on Turfspruit the distance between the chromitites and the top Platreef contact is also variable and much greater (several tens of meters) than in the central and northern sectors. The minimum distance of the chromitite below the top Platreef contact is 0.32 cm (in UMT297) in the northwestern part of the study area, whereas the maximum distance of 142.33 m was observed in UMT196 in the central part (Figure 3.12). The average depth to chromitite is 37 m.

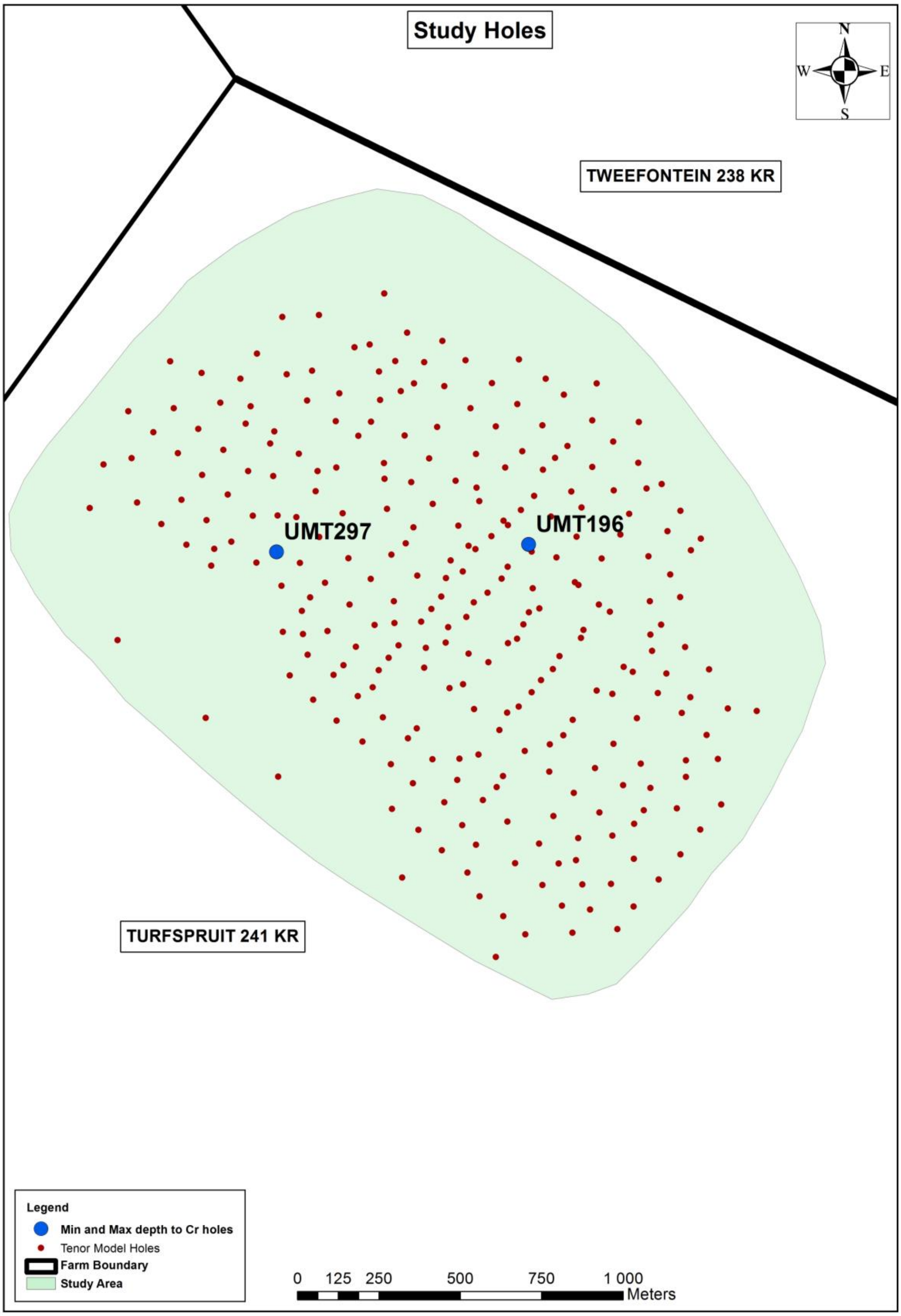


Figure 3.12. Location of holes with minimum and maximum distances between top of Platreef contact and chromitite. The minimum distance of 0.32 cm between the top of Platreef contact and the chromitite was observed in UMT297, whereas the maximum distance of 142.33 m was noted in UMT196

Different lithologies underlie the T2. In other parts of the study area, several metres of feldspathic B-pyroxenite occur below the T2 Upper or T2 Lower. Other lithologies include the norites, pyroxenites, olivine-bearing pyroxenites, calc-silicates and para-pyroxenites. Where pegmatoidal B-pyroxenite is absent below the T2 Lower, the T2 Lower grades into a non-pegmatoidal lithology and is often contaminated i.e. mixed with calc-silicates and para-pyroxenites. In this case, the boundary between the pegmatoidal and the non-pegmatoidal facies of the T2 Lower is taken to mark the base of the T2 (Grobler and Nielsen, 2012).

Variable thicknesses of calc-silicates and para-pyroxenites occur below the T2, and collectively they are called the Contaminated Zone (CZ). These lithologies have an average thickness of 20 m in the study area. A mixed zone of norites, pyroxenites (olivine-bearing in places) and harzburgites with xenoliths of hornfels and granitic dykes occur below the CZ. This zone is referred to as the PX/HA and ranges in thickness from 20 – 100 m. The pyroxenites and norites of the PX/HA are visually distinct, but petrographically similar. Both the CZ and PX/HA form the floor to the T2.

The base of the Platreef is marked by a fairly continuous, homogeneous and fine grained pyroxenite, called the Lower Pyroxenite (LPX) (Figure 3.13). Sometimes this pyroxenite contains fair amounts of plagioclase (approx. 2 - 3 %). It comprises mainly clinopyroxene and biotite. The mineralised zone of this lithological unit constitutes the basal mineralised zone of the Platreef (not a focus for this study). The unit thickness reaches several tens of metres, but the well mineralised zone within it is up to 26 m thick.

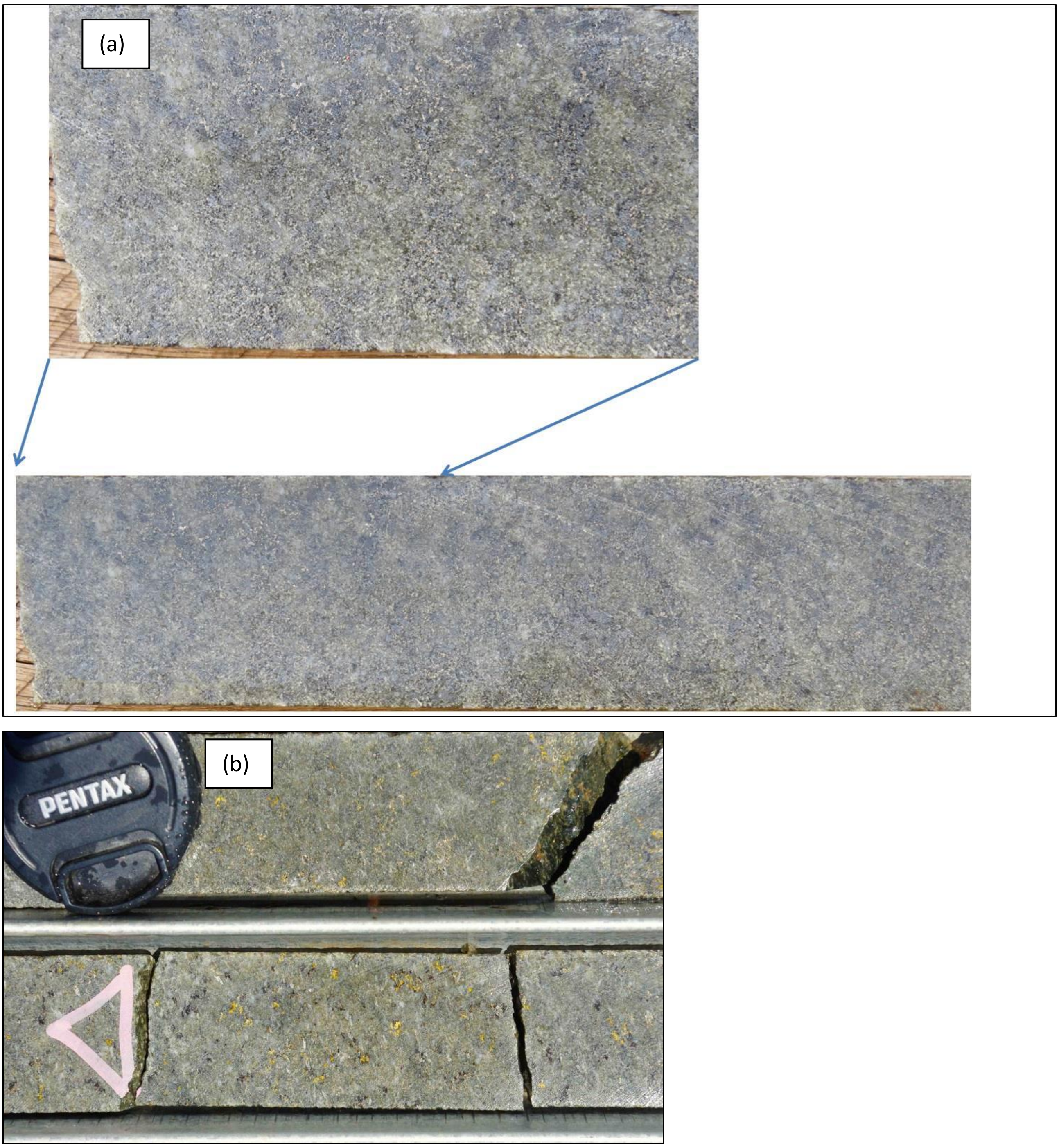


Figure 3.13. Pyroxenite of the basal unit of the Platreef. (a) shows fine grained pyrrhotite and pentlandite associated with the more mafic portions of the rock. (b) shows biotite-rich rock (darker spots) with chalcopyrite mineralisation

3.1.3 Hanging-wall rocks

The hanging-wall lithologies comprise gabbronorites, anorthosites and mottled anorthosites of the Main Zone. Gabbronorites often host xenoliths of hornfels, especially towards the base (Kinnaird and Nex, 2012). Late granitic intrusions are also present in the Main Zone. They may occur as flat-lying sills or cross-cutting veins. In the study area, the average thickness of the Main Zone is about 780 m, whereas in central and southern Turfspruit the Main Zone thickness is about 1100 m and 600 m respectively.

3.1.4 Variation in geology in the upper section of the Platreef

There is considerable variation in lithological units and their thicknesses within the upper section of the Platreef. It occurs in the footwall to the T2, within the T2, T1 pyroxenite and at the contact between Platreef and the Main Zone. The footwall lithologies vary between the footwall norites (FWN: norites, pyroxenites and olivine-bearing pyroxenites) and calc-silicates (CS: calc-silicates, para-harzburgites and para-pyroxenites) (Figure 3.14).

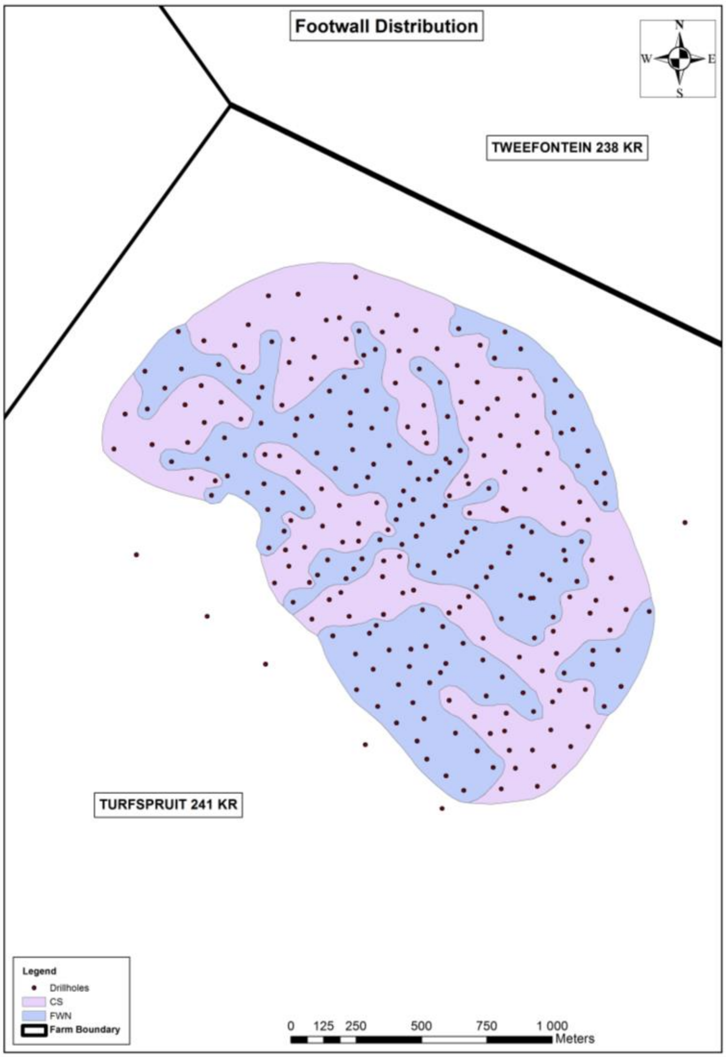


Figure 3.14. Distribution of footwall lithologies below the T2 in the study area.
CS = calcsilicate and FWN = footwall norite

Both the T2 Upper and Lower are very well represented within the study area. However, one or both units may be absent in some parts of the study area. This variation is largely attributed to erosion by the incoming Main Zone magma. Figure 3.15 shows an E-W strike section through the study area displaying erosion of the T1 in UMT063. The Main Zone magma has eroded the upper portion of the T1, taking away the T1m. In other parts of the study area, the erosional levels have cut down into the T2 Lower, removing the entire T1 (including T1m) and T2. The fact that (1) some holes have the T1 (including the T1m) and others don't; and (2) in some holes the T1m occurs within the Disturbed Zone, suggests that probably not all of the T1 or T1m (and maybe some of the T2) intersected in the drill holes are currently sitting in their original positions after the intrusion of the magma. In other words, the incoming Main Zone eroded parts of the T1, T1m and T2 from their original positions and moved them to new locations. And probably the Disturbed Zone was formed during this movement.

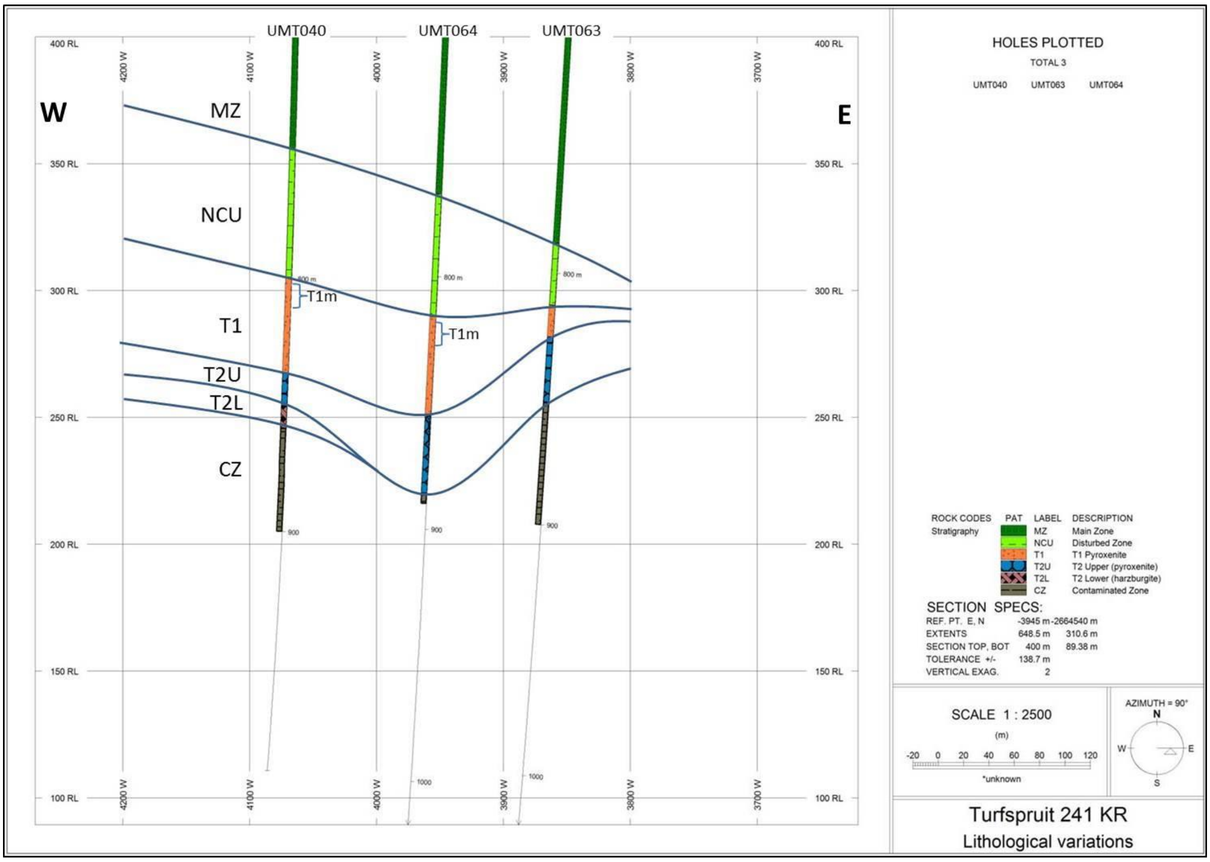


Figure 3.15. Geological variation in lithological units along strike. Note that drillholes are plotted from a depth of 700 m below surface

3.2 Mineralisation

Previous studies conducted along the near-surface resources (open pit project) on Turfspruit have shown that mineralisation in the Platreef is generally of the type represented by that shown in the pyroxenite at the base of the Platreef (Figure 3.13) (Kinnaird *et al*., 2005). It was further indicated by Kinnaird *et al*., (2005), that in areas where the floor comprises dolomites of the Duitschland Formation, mineralisation occurs in serpentinised peridotites, feldspathic pyroxenite, serpentinised dolomite xenoliths, or footwall dolomite. The occurrence of significant PGE grades in the upper section of the Platreef was noted in other parts of the open pit project area by Kinnaird (2005) and Hutchinson and Kinnaird (2005).

In the study area, mineralisation in the upper section of the Platreef occurs within what has been referred to as the T1m and T2 pegmatoid (Grobler and Nielsen, 2012). The separation between the two mineralised zones is variable along strike and along dip. It varies from more than 60 m to less than 1 m. Sometimes, these mineralised zones are in contact with each other, resulting in huge thicknesses of mineralised zone (up to 40 m). Compositions of the different mineralised zones and their footwall are discussed below.

3.2.1 Mineralisation in the footwall

Generally, the footwall rocks are poorly mineralised, but sometimes the T2 mineralisation extends into the footwall rocks (contaminated zone), resulting in increased thicknesses of mineralised zones, whereas, in a few areas, the T2 is absent and the mineralisation occurs in the footwall norites and pyroxenites. Both PGE and base metal grades drop at the contact between the T2 and the footwall rocks. However, intervals with PGE (Pt, Pd + Au) grades above 12 g/t occasionally occur in para-pyroxenites.

3.2.2 Mineralisation in the T2 pegmatoid (T2)

High grade PGE mineralisation in the T2 is associated with the base metal sulphides (Figure 3.16). Hutchinson and Kinnaird (2005) categorised the associations of sulphide minerals on Turfspruit into four groups: *(1) Early magmatic sulphides, (2) Late magmatic sulphides associated with interstitial felsic assemblages, (3) Late magmatic sulphides associated with granite dykes, and (4) Sulphides within secondary silicate assemblages.*

The majority of sulphides in the T2 is magmatic (Figure 3.17) and can be associated with the above categories. However, semi-massive to massive sulphide veins (pyrrhotite dominant) associated with the late hydrothermal fluids occurs rarely in the T2 pegmatoid. Average grades of 4.56 g/t PGE, 0.41 % Ni and 0.20 % Cu were reported in the study area (AMEC 43-101 Technical report, 2011). Intervals of up to 41 g/t PGE, 6 % Ni and 7 % Cu also occur in the T2. Pt/Pd ratios are the highest (up to 2) in T2 Upper and are lower in T2 Lower. Similar base metal sulphides reported for the mineralisation occurring towards the base of the Platreef on Turfspruit, also occur in the T2, with a similar order of abundance i.e. pyrrhotite, pentlandite and chalcopyrite. However, accessory sulphides in the T2 include only millerite, bornite, sphalerite and galena (Lotter *et al*., 2011). The difference in sulphide mineralogy between the mineralisation at the base of the Platreef and that in the upper section of the Platreef is marked by the abundance of accessory sulphides in that they are less abundant and more restricted in composition in the upper section of the Platreef.

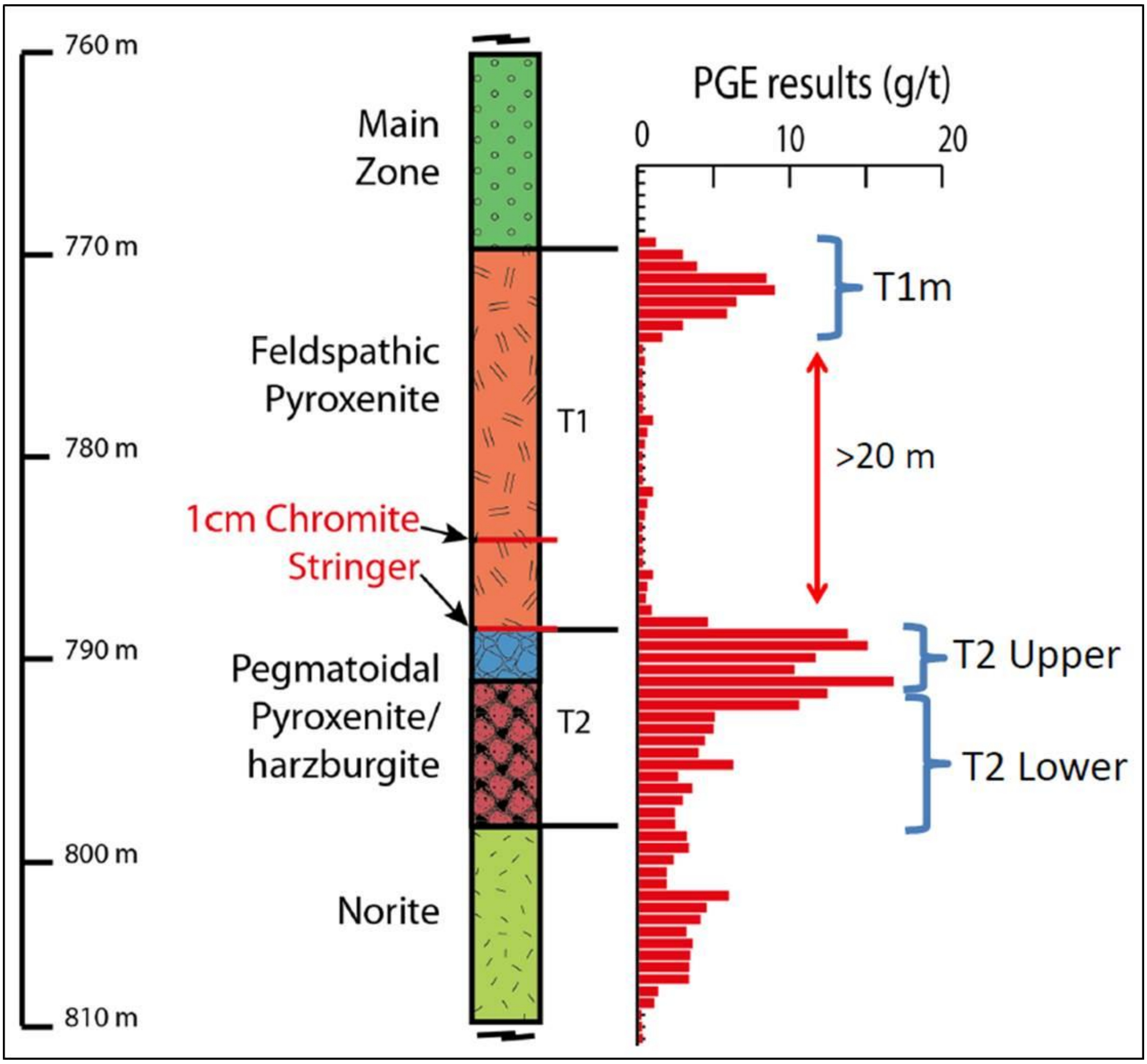


Figure 3.16. Schematic lithological log showing the relative positions of the T1m, T2 Upper and Lower, the location of the high grade mineralised zones within the upper section of the Platreef (Modified after Grobler and Nielsen, 2012). Mineralisation occurs within the T1m and T2 pegmatoid. The separation between the two mineralised zones is variable along strike and along dip. It varies from more than 60 m to less than 5 m

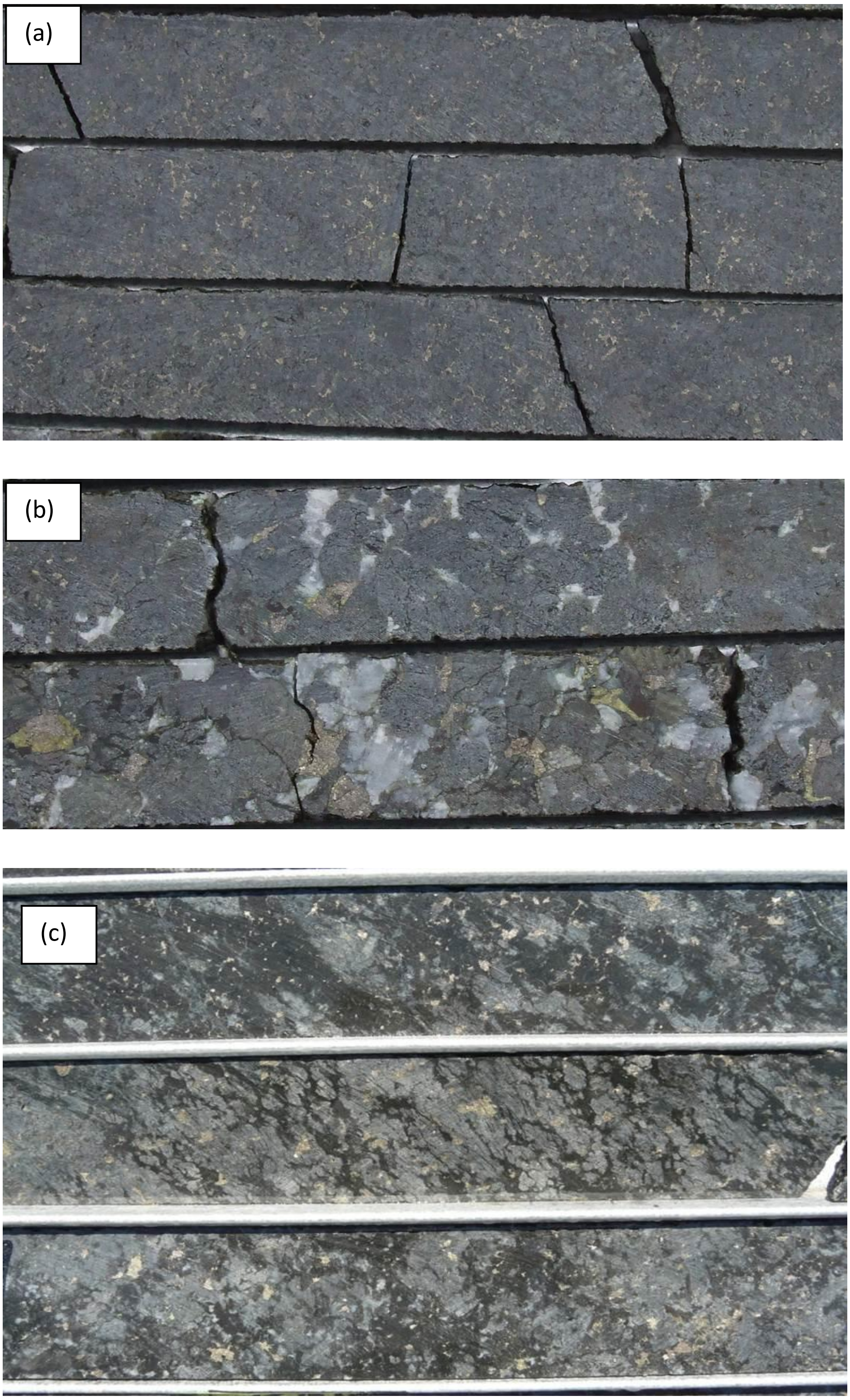


Figure 3.17. Mineralisation in T2 Upper and T2 Lower. (a) Interstitial fine-grained sulphides in orthopyroxenite, T2 Upper. (b) Interstitial coarse-grained sulphides in pegmatoidal B-pyroxenite, T2 Upper. (c) Fine to medium grained interstitial sulphides in serpentinised harzburgite, T2 Lower. In all the samples, the sulphides are dominated by pyrrhotite, followed by pentlandite and chalcopyrite

The increase in sulphide content and PGE grades in the T2 are generally associated with the presence of the "main" chromitite stringer/ seam at the contact between the feldspathic pyroxenite (T1) and the coarse- grained to pegmatoidal pyroxenite (T2 Upper) (Figure 3.18). Even when the chromitite is absent/ not visible at this contact, there is still an increase in sulphide content and PGE grades, a feature also noted by Yudovskaya and Kinnaird (2010) in the central sector of the Platreef. Sometimes the increase in sulphide content starts a few centimeters above the "main" chromitite, but the highest PGE grades occur within and below the samples hosting the "main" chromitite. Not all chromitites are associated with an increase in sulphide content and higher PGE grades. Other chromitites that occur above and (sometimes) below the "main" chromitite may or may not be associated with high sulphide content and PGE grades. Yudovskaya *et al.*, (2011) noted similarities in the composition of chromitites in the feldspathic pyroxenite (equivalent of T2 Upper) and the harzburgite (equivalent of T2 Lower) in the central sector of the Platreef. They concluded that these chromites are similar in composition and comparable with the Merensky chromite composition.

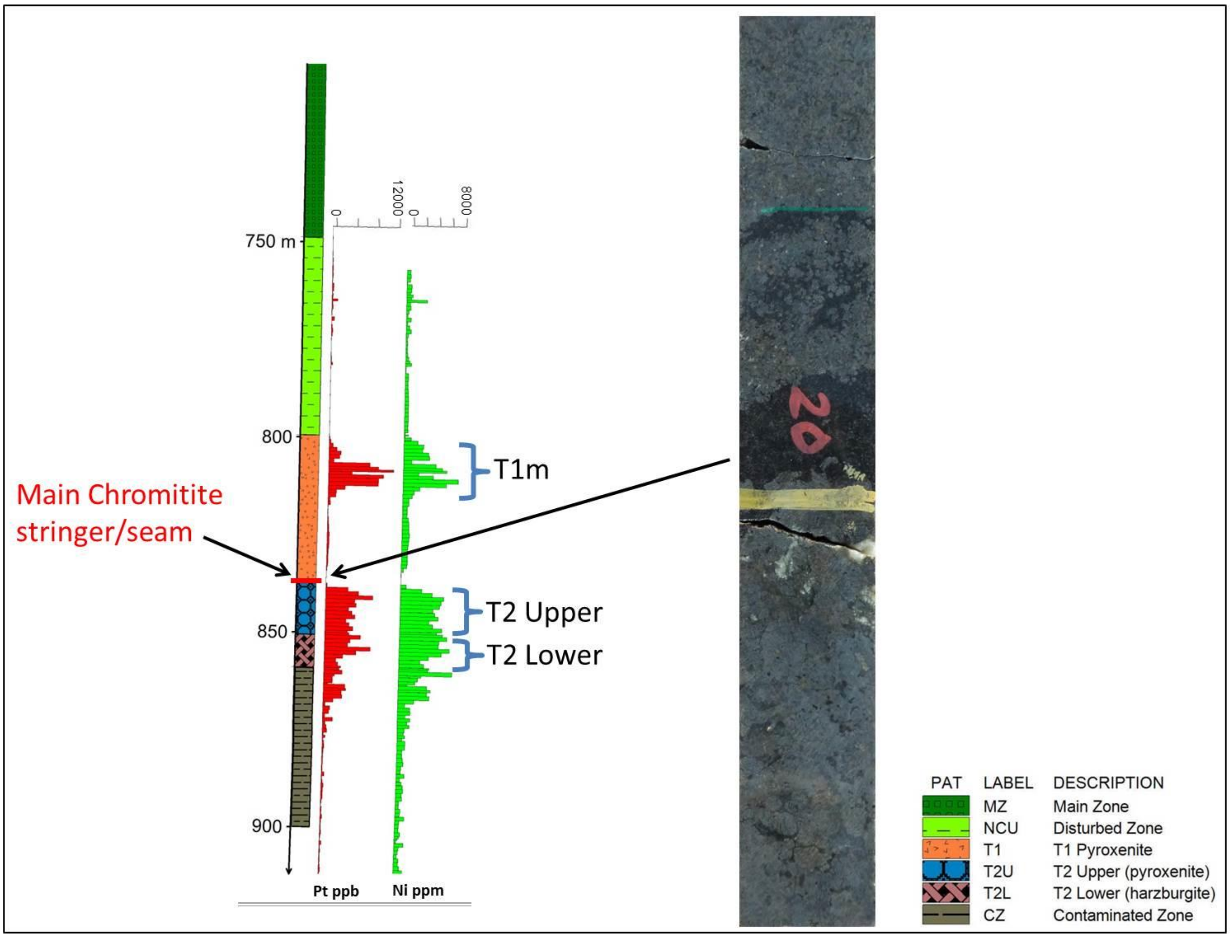


Figure 3.18. PGE grade and chromitite association

3.2.3 Mineralisation in the T1m pyroxenite

The T1m is a sulphide-rich zone that occurs within sulphide-poor feldspathic to orthopyroxenite lithologies. Mineralisation occurs close to the contact between the feldspathic pyroxenite and orthopyroxenite, but only the orthopyroxenite hosts the sulphides (Grobler and Nielsen, 2012). Chromitite stringers rarely occur in the T1m. Where present, they generally occur at the top of the mineralised zone. This is supported by the elevated chrome assays at this location. The sulphides are interstitial and sometimes net-textured (Figure 3.19).

Figure 3.19. T1m sulphide mineralisation showing interstitial blebs of pyrrhotite and pentlandite. Sample length is 22 cm

3.2.4 Variation in T1m and T2 pegmatoid

The dip and separation between T1m and T2 are variable across the study area (Figure 3.20). Generally, the dip of T1m mimics that of the T2. A major change in dip occurs west of the study area, across a major fault. The entire T1 is up to 142 m thick and the T1m within it is about 5 m thick, whereas the T2 is up to 76 m in thickness and the mineralised zone within it is up to 40 m in places.

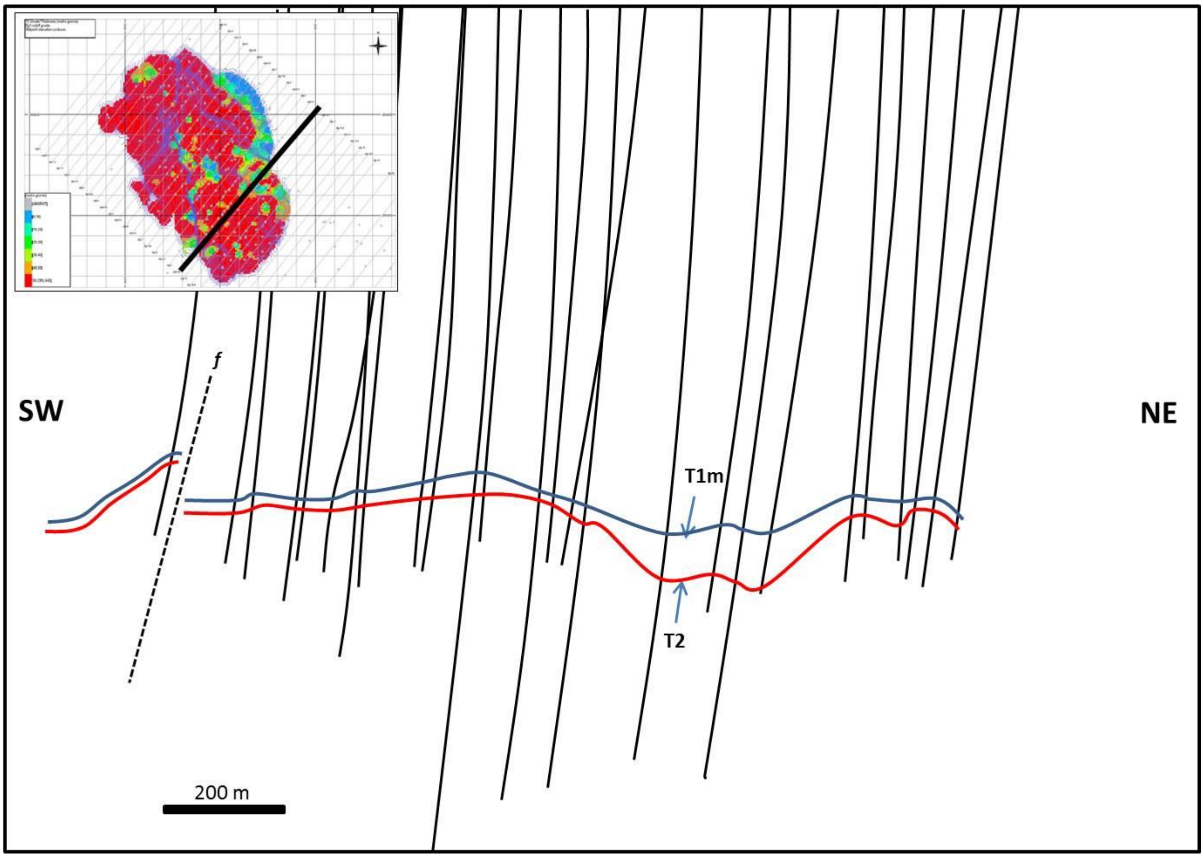


Figure 3.20. Section showing the separation of the mineralised units T1m (blue line) and T2 (red line) across the study area (Modified after Nielsen, 2012). Note the change in dip across the major fault in the west. Drill holes are indicated by the black solid traces, whereas the fault is shown by the dashed black line. Location of section is indicated by the thick solid black line on the map insert

3.3 Discussion

The upper section of the Platreef in the study area comprises different floor rocks i.e. calc-silicates and parapyroxenites (CZ), and also norites and pyroxenites (FWN – footwall norite). The main lithologies forming the upper section of the Platreef are the T1 (feldspathic orthopyroxenite), T2 Upper (pegmatoidal orthopyroxenite) and T2 Lower (harzburgite). These lithological units are overlain by the Disturbed Zone (NCU) and then the Main Zone. The Disturbed Zone (a transition zone between the Main Zone and the Platreef) is thought to be formed by the reaction and mixing of the incoming Main Zone magma with lithological units of the upper section of the Platreef. The erosional levels of these lithological units are variable within the study area: (a) sometimes only the top portion of the T1 is eroded and the T1m (sulphide-rich portion of the T1) is not eroded; (b) sometimes the T1m is eroded including the lower portion of the T1 below the T1m and thereby resulting in the Main Zone sitting closer to the T2 Upper; (c) where the erosion was severe, the entire T1, T2 Upper and Lower were eroded and in this situation the Main Zone rests directly on top of the floor rocks.

This erosional effect of the Main Zone has resulted in certain areas of the Flatreef missing parts of the stratigraphy. Or in areas where most of the Platreef lithologies were eroded by the Main Zone, very thick Disturbed Zones were formed. The after effect of this erosional episode/s poses a challenge to the logging geologist during interpretation.

Previous studies on Turfspruit suggested that good PGE mineralisation occurred near the base of the Platreef, especially where the Duitschland dolomites formed the floor to the Platreef. In this study, it is shown that the Platreef is much better mineralised within its upper section in the Flatreef area. Here, mineralisation is hosted within the T1m and the T2 (T2 Upper and T2 Lower). In both zones, mineralisation occurs in the form of base metal sulphides dominated by pyrrhotite, pentlandite and chalcopyrite. In the T2, the base metal sulphides are associated with the presence of the main chromitite which occurs at the boundary between the T1 and T2 Upper. The majority of the sulphides occur below this chromitite. Sometimes, sulphides do occur above the chromitite as well. PGE grades are generally higher in T2 Upper than in T2 Lower, whereas the base metals (particularly Ni) are generally higher in T2 Lower than in T2 Upper.

Mineralisation in the upper section of the Platreef is interesting in that: (a) it occurs within well-defined geological units which can be correlated for kilometers along dip and strike, unless disrupted by the erosion of the Main Zone magma; (b) it has huge thicknesses (up to 40 m) of high grade PGEs and Ni; (c) it persistently occurs at the contact between the T1 and T2 Upper, a contact marked by the presence of chromitite stringers, seams or blobs; (d) it has high Pt/Pd ratios; and (e) there is less contamination in the high grade zone.

3.4 Summary and conclusions

It has been demonstrated that on Turfspruit, the Platreef is better mineralised within its upper section. The mineralisation occurs within well-defined geological units which are laterally extensive and have great thicknesses. Compared to previous mineralisation studies on Turfspruit, this study has shown that the high grade mineralisation within the upper section of the Platreef have resulted from magmatic processes and not from the interaction of the Platreef with the dolomite floor. This is supported by the lack of contamination within the high grade zones and the abundance of interstitial sulphides.

Chapter 4

Core logging

4.1 Introduction

Prior to undertaking sampling for geochemical analysis and tenor calculations, three cores were selected for more detailed lithological logging than would normally be undertaken as part of the routine logging for company purposes. The location of these holes is shown in Figure 4.1.

The holes in the study area were logged using the detailed logging scheme, lithological groupings and the new interpretation as discussed in chapter 3. These logging schemes are unique to the project. Logging was conducted from the Main Zone Gabbronorites through the upper section of the Platreef into the footwall lithologies (to the upper section of the Platreef) as discussed in Chapter 3. The logging technique included lithological variations, alteration, significant structural features and sulphide mineralisation (including mineralisation style and abundance).

4.2 Lithological variations in the selected cores

The selected cores i.e. UMT040, UMT064 and UMT063 cover a range of different lithologies within the upper section of the Platreef and they are located 145 m and 175 m apart, respectively. All the holes comprised the Main Zone (MZ), Disturbed Zone (NCU), T1 and T2 Upper (Figure 4.2). In addition, UMT040 comprised the T2 Lower and footwall norites of the Contaminated Zone; UMT064 comprised two lithologies of the T2 Upper i.e. the pegmatoidal pyroxenite forming the top portion of T2 Upper and olivine-bearing pyroxenite forming the base (all are plotted as T2 Upper). The footwall in UMT064 consists of norites of the Contaminated Zone, while in UMT063 the footwall is made up of the para-pyroxenites. T2 Lower is missing in both UMT064 and UMT063. The T1m (sulphide rich portion of the T1) is present in both UMT040 and 064, and is missing in UMT063. No petrographic studies were conducted on these cores; however, their petrography is typical of the rocks described in Chapter 3.

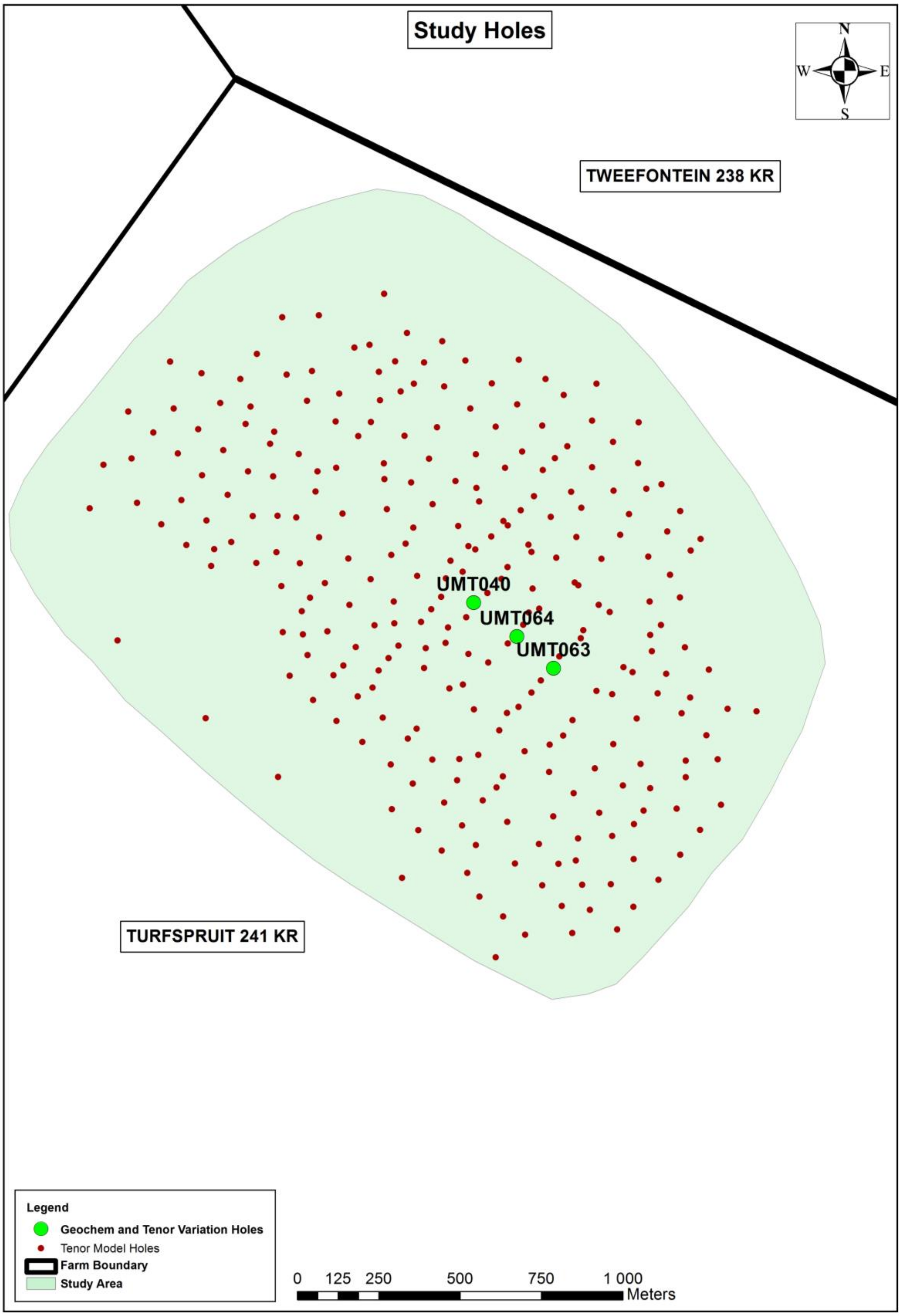


Figure 4.1. Plot showing the location of the three cores selected for geochemical analysis (green circles)

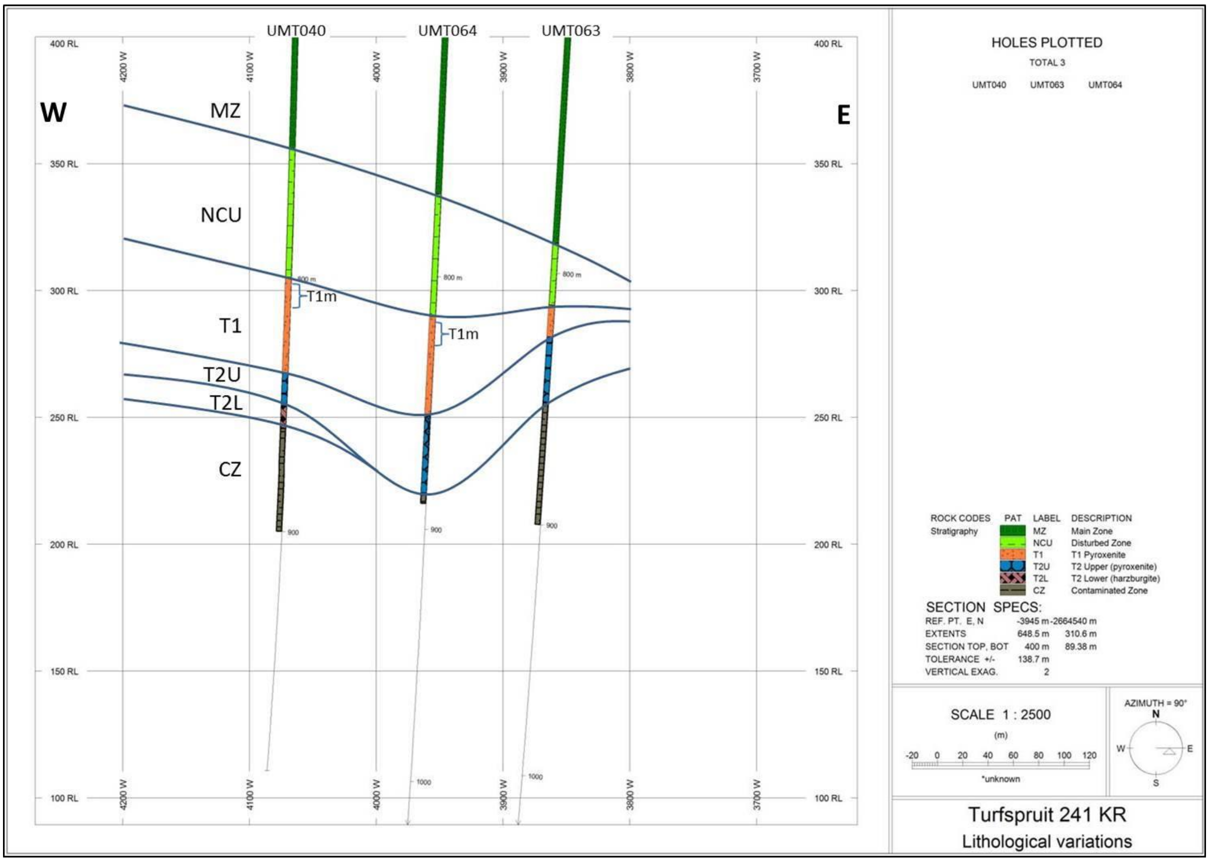


Figure 4.2. Lithological variations in the selected cores along strike. Note that the holes were plotted from a depth of about 700 m below surface in order to allow better visualisation of the interpretation. The approximate positions of the mineralised portions of the T1 in both UMT040 and 064 are indicated by T1m

4.3 Qemscan data analysis

Lotter *et al*., (2011) conducted Qemscan (Quantitative Evaluation of Materials by Scanning Electron Microscope) and EPMA (Electron Probe MicroAnalyser) studies on five lithological units within the upper section of the Platreef i.e. the T1m - pyroxenite, T2 Upper - pyroxenite (with a well developed pegmatoid), T2 Upper - pyroxenite (pegmatoid not well developed), T2 Lower - harzburgite and the Contaminated Zone comprising calc-silicates. The objective of the study was to determine the metallurgical responses and mineralogical compositions of each lithological unit. The metallurgical responses fall outside the scope of this study and therefore only mineralogical compositions are discussed.

Samples from different drill holes (Figure 4.3) were composited for each lithological unit, processed (crushed and milled) and then treated as “feed to mill”. They were processed and analysed at Xstrata Process Support Laboratory in Ontario, Canada.

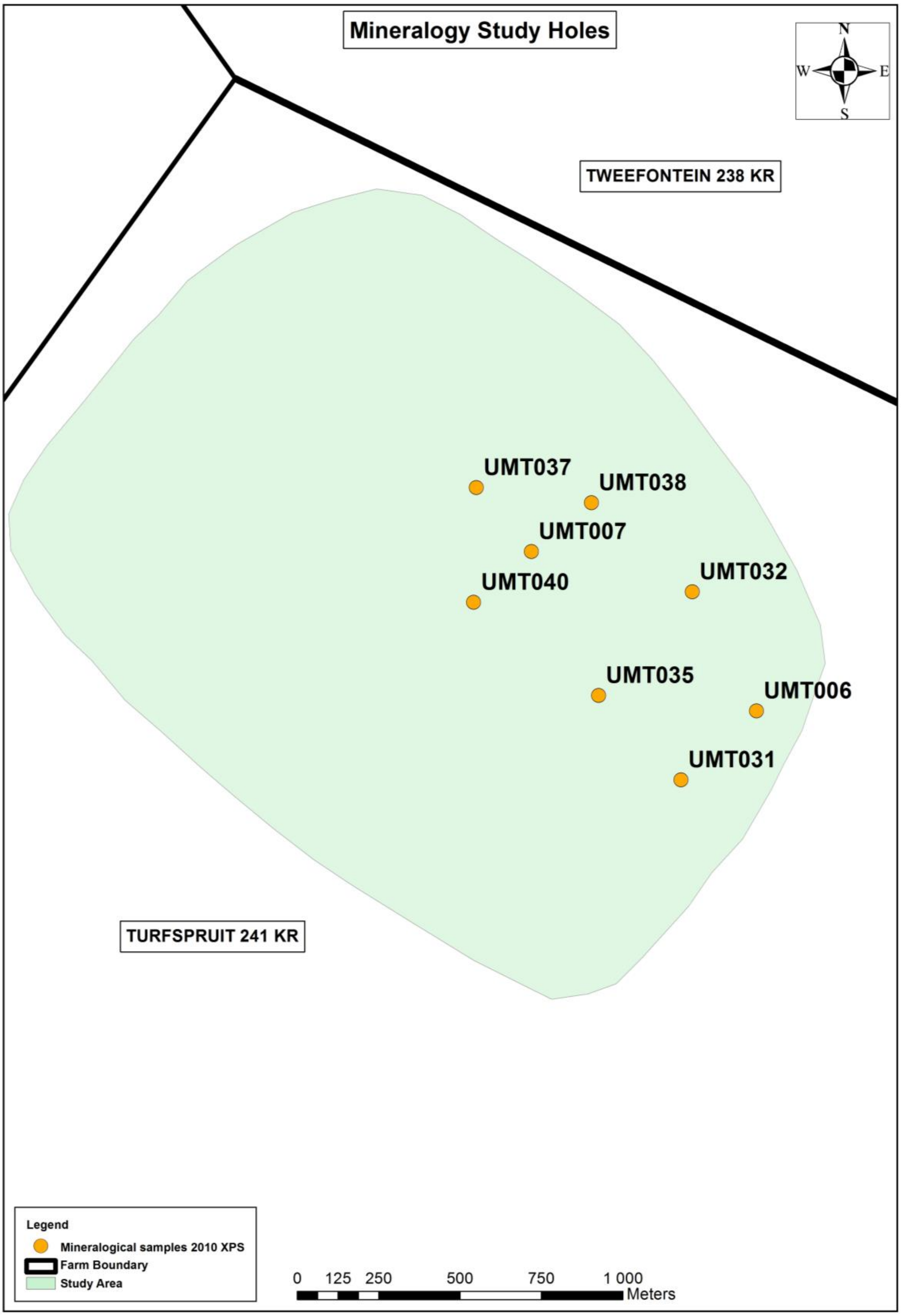


Figure 4.3. Location of samples for mineralogical testwork

Results of Qemscan studies revealed the following:

(1) The Contaminated Zone was dominated by augite, plagioclase and actinolite, with lesser amounts of orthopyroxene, chlorite and serpentine (Figure 4.4). Slightly elevated levels of muscovite, orthoclase and chromite were also noted.

(2) T2 Lower contained relatively equal proportions of serpentine and orthopyroxene as well as significant relic olivine textures, elevated talc and magnetite content. In comparison with the T1m and T2 Upper, the T2 Lower contained the highest serpentine, lower orthopyroxene and almost similar amounts of talc.

(3) T1m and T2 Upper have shown similar mineralogical compositions even though they occur at different stratigraphic levels. They are dominated by orthopyroxene, plagioclase, augite, amphibole (actinolite/tremolite), chlorite and talc. T2 Upper contained slightly elevated levels of serpentine and olivines.

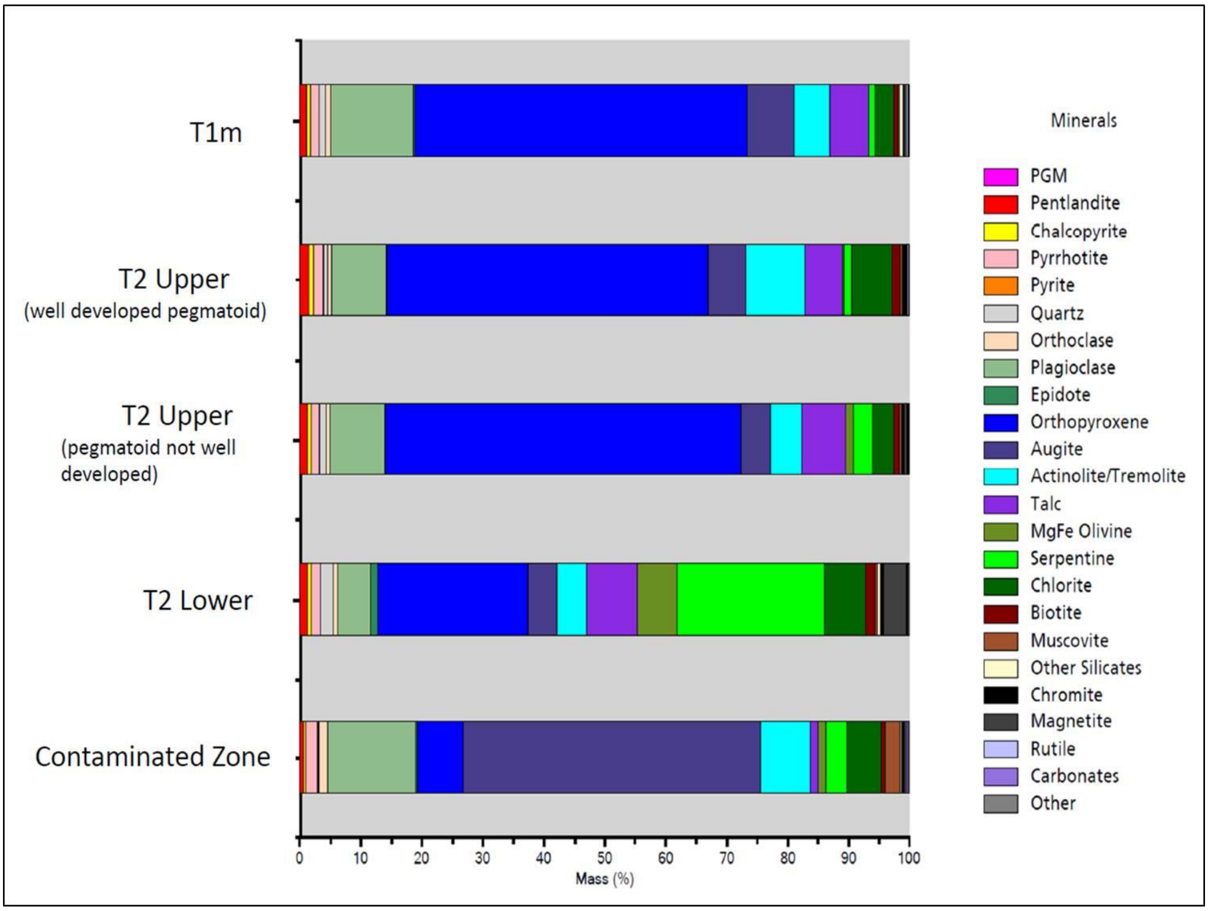


Figure 4.4. Modal mineralogy of lithological units within the upper section of the Platreef (modified after Lotter et al., 2011). Note that portions of the T2 Upper with a well-developed pegmatoid and that without a well-developed pegmatoid were sampled individually and treated as separate lithological units during processing

The sulphide mineralogy of the T1m, T2 Upper (with a well developed pegmatoid and where the pegmatoid is not well developed), T2 Lower and the Contaminated Zone, reported similar base metal content ranging between 3 - 4 % by mass, Lotter *et al*., (2011) (Figure 4.5). They further reported that the T2 Upper hosted the highest overall sulphide content, followed by the T2 Lower. And that almost similar amount of pentlandite and chalcopyrite occurred in the T1m and T2, and lower concentrations in the Contaminated Zone.

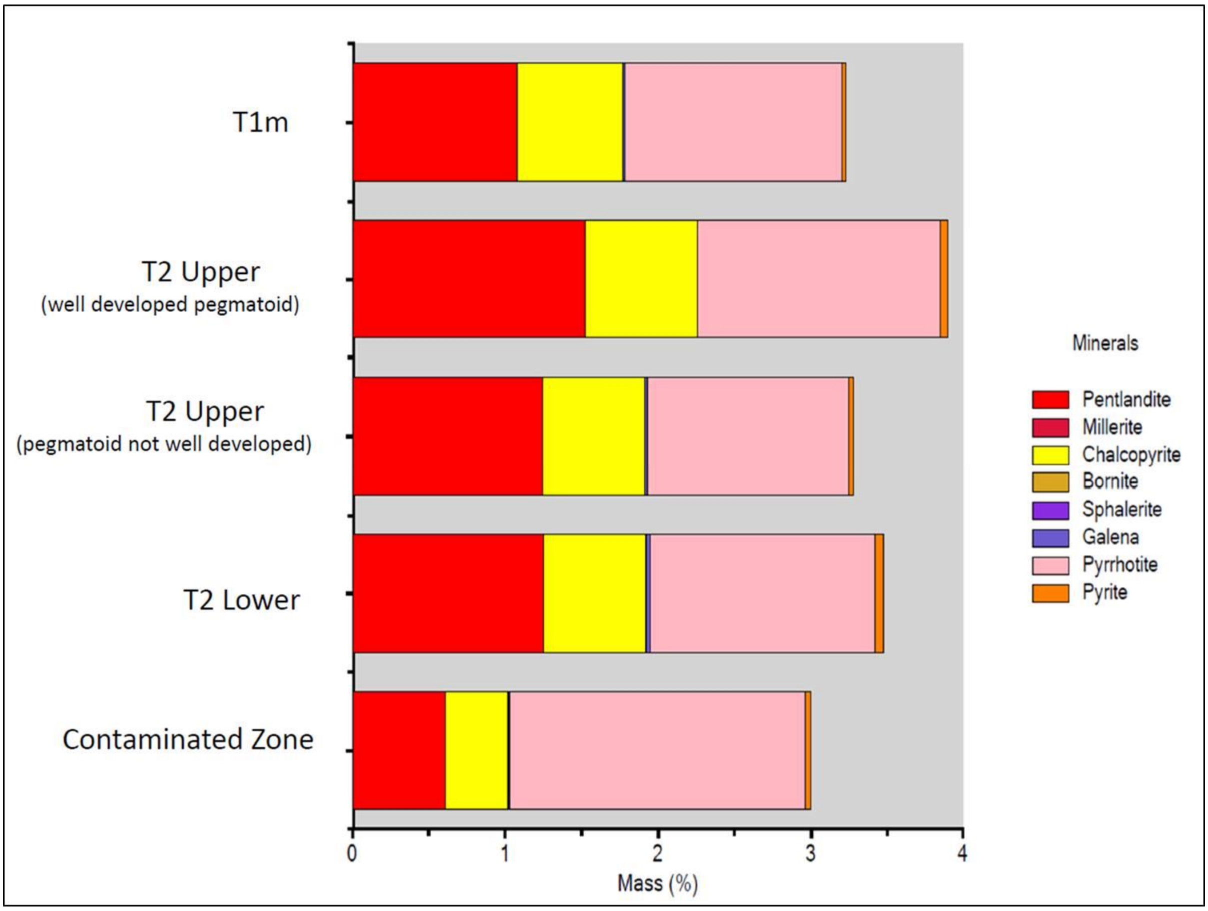


Figure 4.5. Qemscan analysis of the sulphide modal mineralogy (modified after Lotter *et al.*, 2011). The T2 Upper with a well developed pegmatoid hosts the highest overall sulphide content. Pyrrhotite tends to dominate although in the T2 Upper where the pegmatoid is not well developed there is an approximately equal proportion of pentlandite and pyrrhotite. Accessory sulphides such as millerite, bornite, sphalerite and galena occur in smaller quantities and hence, they are not visible on the plot

The T1m and T2 comprise PGE minerals of types that are usually formed at high and also at low temperatures in the Bushveld Complex. PGMs and Pt-Pd sulphides are associated with the presence of base metal sulphides. Lotter *et al*., (2011) reported that greater than 98 % PGE minerals mass distribution observed in the T1m, T2 and the Contaminated Zone was dominated by amphoterics (PGE-arsenides, tellurides, antimonides and bismuthinides), and that limited Pt or Pd sulphide species were identified (Figure 4.6). The PGE minerals identified were michenerite, sperrylite, hollingworthite and cooperite. Electrum grains were also reported. The T2 Lower contained the highest concentration of Pt and Pd sulphides compared to other lithological units. Au and Ag were more abundant in the T2 Upper, (Lotter *et al*., 2011). In a separate study, Onishi (2012, unpublished) identified additional PGE minerals to those reported by Lotter *et al.,* (2011) in the upper section of the Platreef. They are moncheite, kotulskite, tetraferroplatinum, zveyagintsevite and plumbopalladinite. A laser ablation study by Hutchinson and McDonald (2008) indicated the occurrence of tellurium (in solid solution) and bismuth (in solid solution or as discrete phases) in both chalcopyrite and pentlandite. Hutchinson and Kinnaird (2005) suggested that the PGEs were originally associated with large composite sulphides, and that later hydrothermal alteration led to the remobilisation and subsequent redeposition of PGEs within secondary silicate assemblages of talc, tremolite and serpentine. They further suggested that the localised remobilisation of metals may have accounted for the decoupling of Cu+Ni from Pt and Pd. Hutchinson and McDonald (2008) also reported that the PGE distribution between the base metal sulphides and the platinum group minerals in the Platreef pyroxenites were consistent with fractional crystallization of a sulphide liquid.

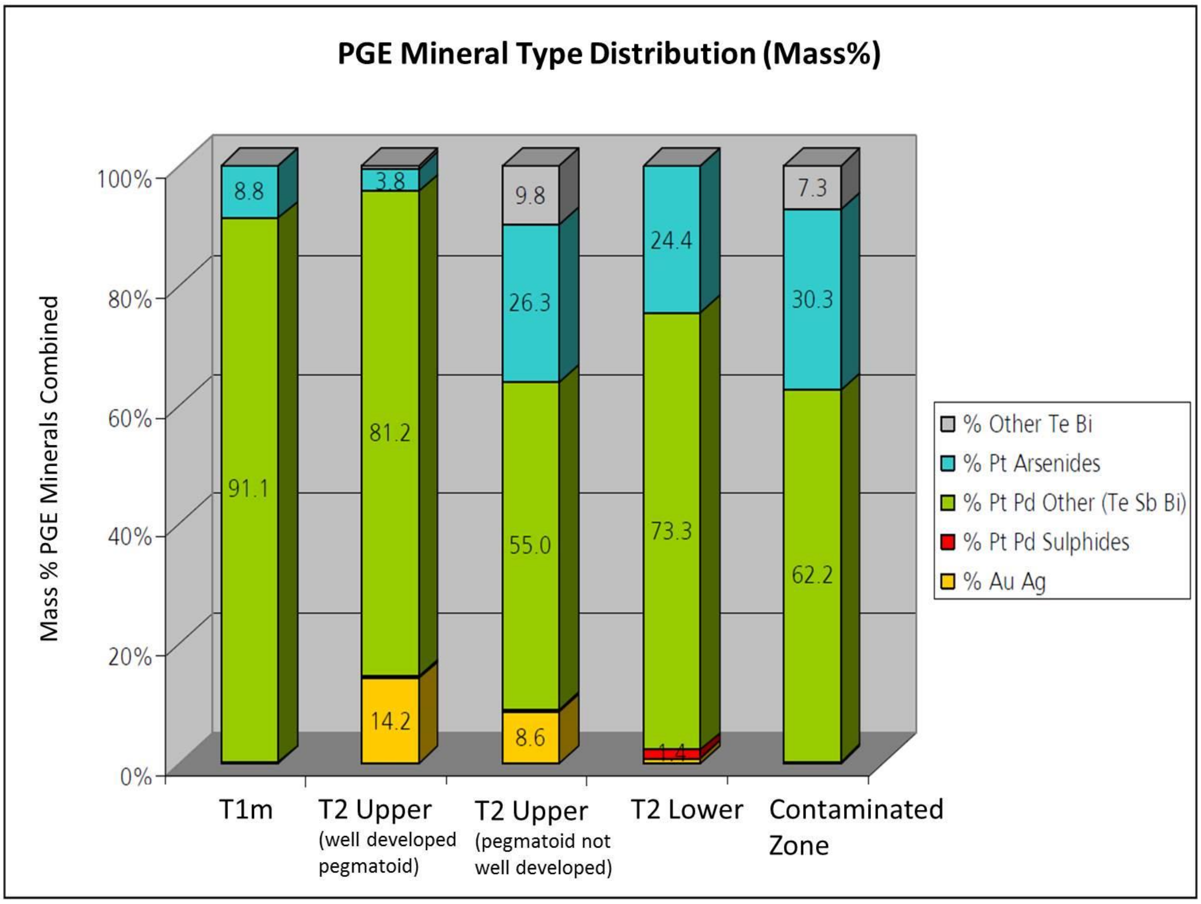


Figure 4.6. PGE mineral type distribution showing the dominance of Pt-Pd antimonides, bismuthotellurides and minor contribution of PGE sulphides and electrum as determined by QEMSCAN studies (modified after Lotter *et al*, 2011)

4.4 Lithological and mineralogical variability

Lithological variations in the study area are more variable than those shown in Figure 4.2 above. However, this figure displays some of the variations present. The thickness of the Disturbed Zone becomes thinner towards the east and the Main Zone thickens. The T1 is also thinning towards the east and in UMT063 it is missing the T1m. This is thought to be a result of the incoming Main Zone magma cutting through and reacting with the upper portion of the Platreef (specifically the T1) and thereby forming the Disturbed Zone. It is noted that the direction of the thinning of both T1 and the Disturbed Zone as shown above is not representative of the study area.

The T2 Upper is thinning towards the west, however, in UMT040 it is underlain by the T2 Lower. Considering the thickness of the T2 Lower in UMT040, the overall thickness of the T2 in all three drill holes would be almost similar. All the footwall lithologies were collectively called the Contaminated Zone. Variation in depths at the contact of the Contaminated Zone with the overlying T2 is thought to be a result of the floor or Lower Zone topography.

The Qemscan studies have indicated high serpentine and lower orthopyroxene contents in the T2 Lower than in the T1m and T2 Upper. Similar mineralogical compositions dominated by orthopyroxene, plagioclase, augite, amphibole (actinolite/tremolite), chlorite and talc were observed in the T1m and T2 Upper. However, the T2 Upper contained slightly elevated levels of serpentine and olivines.

Having undertaken a lithological and mineralogical study, a geochemical study was also undertaken to evaluate any chemical changes within and between the different lithologies.

4.5 Summary and conclusions

Occurrences of the T1m and T2 Lower are not present throughout the study area. The absence of the T1m is attributed to erosion of the T1 by the Main Zone magma, whereas that of the T2 Lower could be because the T2 Lower pulse did not reach other places during its emplacement. Mineralogical similarities in the T1m and T2 Upper as shown by the Qemscan data suggest that these lithological units could have been formed from a single magma pulse or multiple pulses of similar composition.

PGE mineralisation occurs in association with the base metal sulphides. A Qemscan study has shown that very little PGE sulphides occur within the upper section of the Platreef. Instead, the PGEs are hosted in arsenides, tellurides, antimonides and bismuthinides. This study has also shown that the majority of base metal sulphides are hosted within the T2 Upper with a well developed pegmatoid followed by the T2 Lower. The T1m and T2 Upper comprised similar amounts of pyrrhotite and pentlandite. Hutchinson and Kinnaird (2005) suggested that the PGEs were originally associated with composite sulphides and they were later remobilised and redeposited within secondary silicate assemblages of talc, tremolite and serpentine by hydrothermal alteration. They further suggested that the local remobilisation of metals may have accounted for the decoupling of Cu+Ni from Pt+Pd. This process is thought to have taken place within the upper section of the Platreef. It is supported by the results of the Qemscan study showing that the PGEs are hosted within arsenides, tellurides, antimonides and bismuthinides; and the fact that the PGEs occur in areas where the base metal sulphides are present.

Chapter 5

The distribution of tenors and construction of a 3D PGE tenor model

5.1 Introduction

The Bushveld Complex contains about 75 % of the world's resources of Pt, 52 % of Pd, 82 % of Rh and 16 % of Ni (Naldrett, 2004). Economic concentrations of these metals occur principally in three stratigraphic units, the UG-2 chromitite, the Merensky Reef (MR) and the Platreef (Naldrett *et al.*, 2009). The UG-2 and the MR in the eastern and western Bushveld were studied extensively with respect to both the chemistry and tenors. However, there is limited information on tenors for the Platreef. PGE tenors are described as the concentrations of metals (Pt, Pd, Rh, Ru, Ir and Os) in 100 % sulphide (Naldrett *et al*., 2011). Furthermore, Naldrett *et al*., (2011) described the tenor as a representative concentration of a particular metal in the original sulphide droplet, after the sulphide droplet has segregated from its host magma. Hutchinson and McDonald (2006) reported that the Pt tenor of sulphides in the Upper Platreef on Turfspruit, is less than 50 ppm. Naldrett (2008) recorded that the tenors (Pt and Pd) in the Platreef sulphides are typically less than 100 ppm, except in the upper sill on Sandsloot where tenors >100 ppm are similar to those of the Merensky Reef. Naldrett *et al*., (2009a), also noted that the tenors in the sulphides of the Merensky Reef are at their highest close to the top of the chromite in the northwestern part of the Bushveld Complex and just south of Pilanesberg, where tenors in the sulphides reach >3000 ppm. This study presents the new data on the distribution of the PGE tenors (Pt and Pd) in the upper section of the Platreef.

5.2 Selected holes for tenor calculations

For this research programme, 276 holes were sampled and data used in the construction of the 3D PGE tenor model. In order to study the variation in tenors within the upper section of the Platreef, three holes (UMT040, 063 and 064) were selected along strike in the study area (Figure 5.1). Half core samples were collected from approximately 5 m above the Main Zone-Platreef contact, through the upper section of the Platreef into the footwall lithologies (to the upper section of the Platreef). Samples were taken within lithological boundaries. The nominal sample length was 1 m, with a minimum of 0.3 m and a maximum of 1.25 m. Both NQ (47.6 mm diameter) and BQ (36.4 mm diameter) cores were sampled in this programme. Strict quality assurance and quality control (QAQC) measures were applied to ensure sample integrity prior to sending the samples to the assay laboratory. This includes the insertion of blank material and duplicate samples.

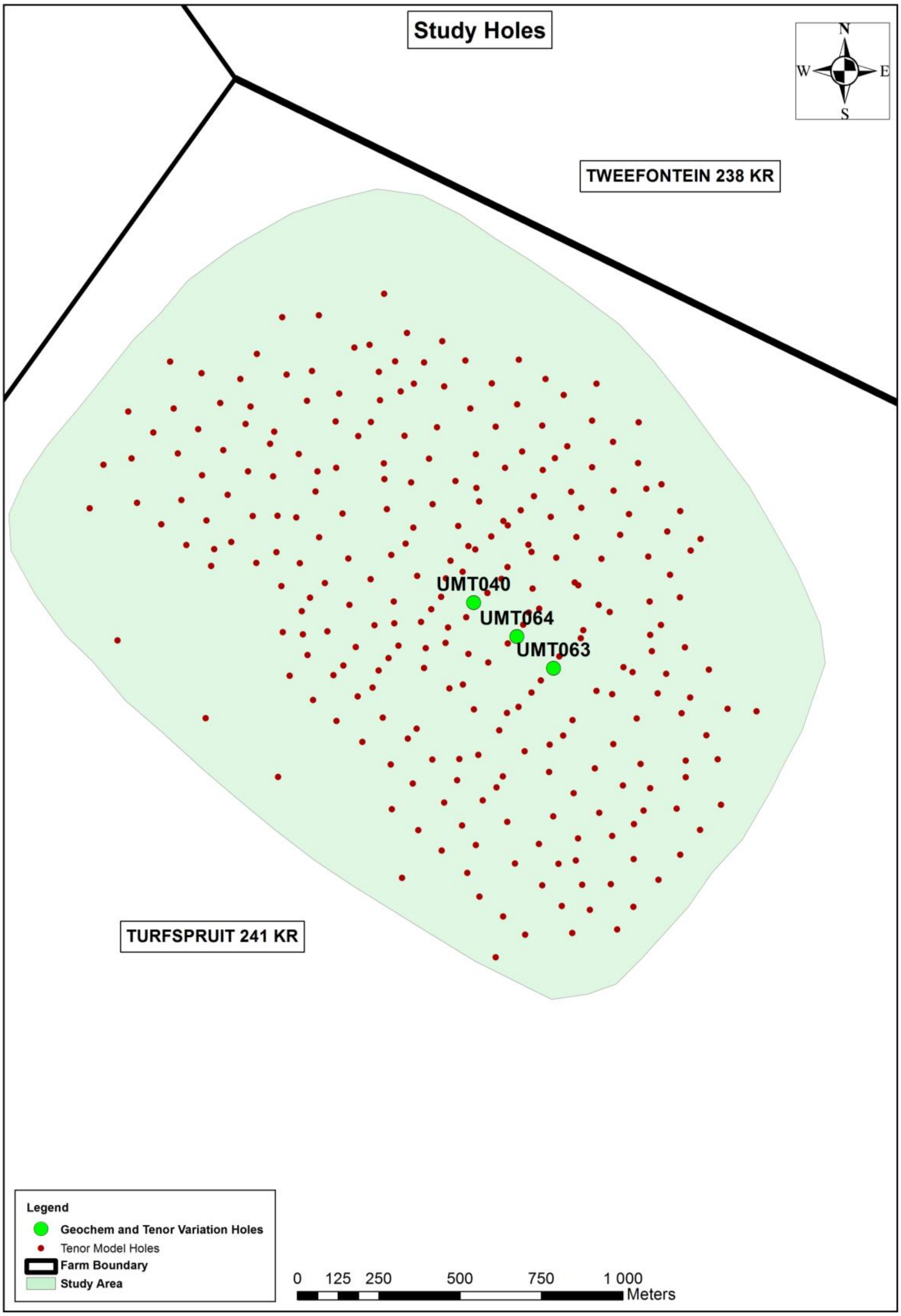


Figure 5.1. Location of holes studied

5.3 Calculation of tenors

The tenor values were determined by taking the sulphur content of the sample, calculating all the copper in the sample as chalcopyrite and subtracting the sulphur involved from the total sulphur, all nickel in the sample as pentlandite and similarly subtracting the sulphur from the total, and calculating the remaining sulphur as pyrrhotite (Naldrett *et al*,. 2011). The amount of sulphide present in a sample can be calculated by adding the chalcopyrite, pentlandite and pyrrhotite together, assuming that the other sulphide minerals present are negligible. However, when the amount of sulphide is low, much of the Ni will be in the silicate, not sulphide, and if one calculates the Ni as pentlandite, this figure will be too high. Since the amount of pyrrhotite is determined by subtracting the sulphur in chalcopyrite and pentlandite from the total sulphur, sulphur may be negative, giving a negative pyrrhotite, which distorts the calculation. In this case the 2.65 x sulphur method is used (Naldrett *et al*., 2000). The tenor calculation is based on the following assumptions (as described by Naldrett *et al*,. 2011): (1) The present sulphur content in the sample is equal to the original sulphur content in the magma, (2) All Cu and Ni are present in the sulphides, and (3) All PGEs are hosted in sulphides and not in other phases. However, Qemscan studies (Lotter *et al.*, 2011) revealed that on Turfspruit there are only minor Pt and Pd in sulphides; with the bulk in amphoterics (arsenides, antimonides, tellurides and bismuthinides). These amphoterics are associated with the sulphides (Kinnaird 2005). Kinnaird *et al*., (2005) indicated that the PGEs were remobilised from the sulphides to the amphoterics by hydrothermal fluid activity. Evidence for such fluids is shown by the presence of serpentinisation, tremolite, chlorite and talc. By calculating the S/Se ratios Naldrett *et al*., (2009) indicated that the occurrence of Pt and Pd in amphoterics did not affect the sulphide tenors significantly.

5.4 Tenor variations in selected drill cores

Variations in tenors were described based on the tenor populations/patterns, metals grades (high or low) and the proportions of Pt vs Pd in each lithological unit. To address the metal grades a reference line was drawn on the 100 000 ppb (100 ppm) mark, on the tenor plots for each drill hole. This reference line was based on the indications by Naldrett et al (2009) that the Merensky Reef tenors are generally above 100 ppm. Tenor plots for UMT040, UMT063 and UMT064 are shown in Figures 5.2 – 5.4. The vertical grey-shaded area on the diagrams outlines a zone corresponding to the amount of sulphide that would be contributed by 10 – 40 % of trapped, sulphide-saturated intercumulus silicate liquid (as defined by Naldrett et al, 2009). Where the calculated sulphide content of the study samples lies well to the right of the shaded area, it is likely that this is due to the presence of excess sulphide; and where the sample points fall within or to the left of the shaded area, excess sulphides are unlikely to have been present.

In UMT040, the Disturbed Zone (NCU) consists of low tenors in the range of 1 – 80 ppm, low sulphide content and low Pt/Pd ratios (Figure 5.2).

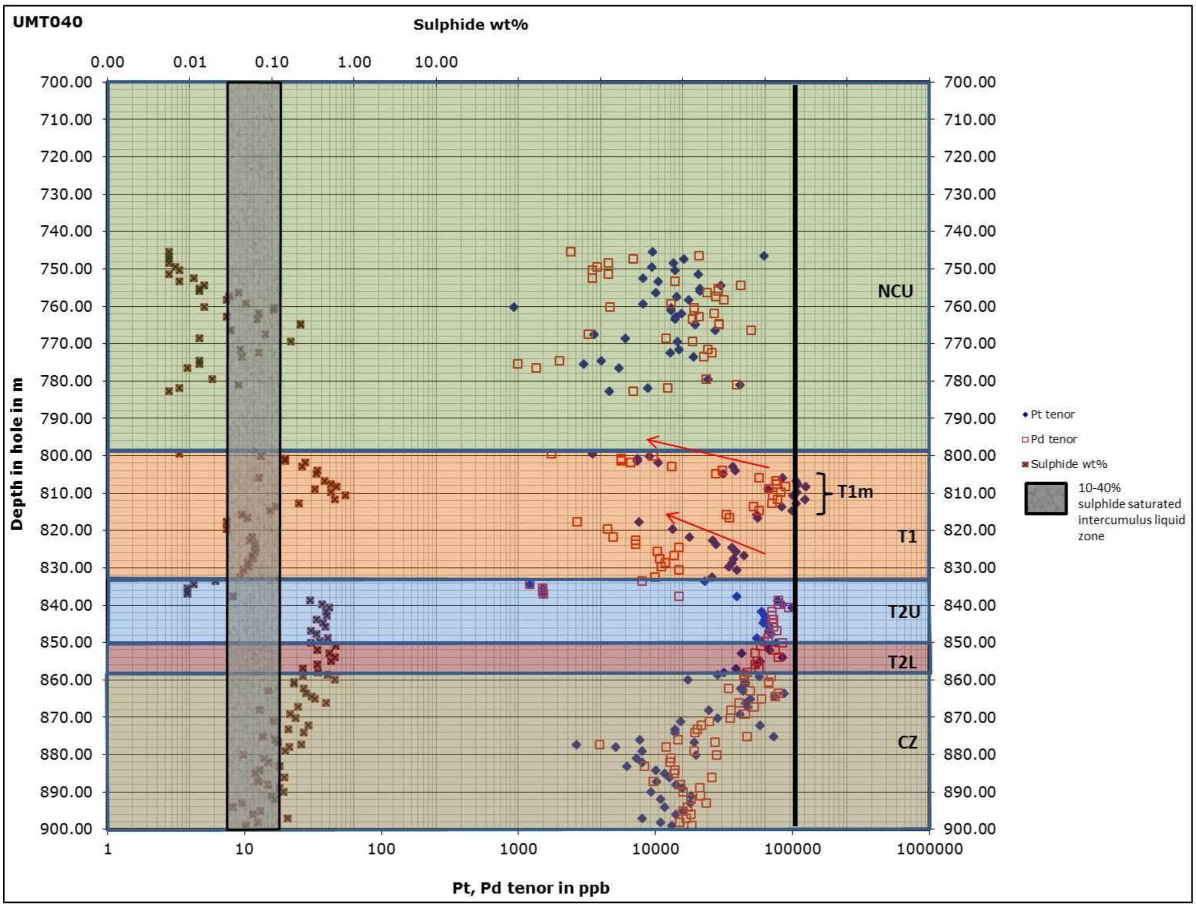


Figure 5.2. UMT040 tenor plot showing Pt and Pd tenors; and sulphide wt %. A decrease in tenor grade within T1 is indicated by a red arrow

Tenors in the T1 can be divided into two broad zones, the topmost portion comprising high tenors in the range of 80 – 105 ppm, with an upward decrease; and the lowermost portion comprising low tenors of about 2 – 70 ppm, also decreasing upwards. The lowermost portion of the T1 is characterised by high Pt/Pd ratios (>1) and low sulphide content; whereas the topmost portion comprises high tenors at the base and they decrease upwards. This topmost portion also comprises high sulphide content and high Pt/Pd ratios.

The T2 Upper and T2 Lower consist of tenors in the range of 70 – 100 ppm with an upward increase, low Pt/Pd ratios and high sulphide content. The Contaminated Zone also comprises low tenors ranging from 8 – 90 ppm, and low Pt/Pd ratios. The sulphide content in the Contaminated Zone ranges from low to high from the base of the lithological unit upwards.

The Disturbed Zone in UMT063 comprises low tenors in the range of 1 – 90 ppm, low Pt/Pd ratios and low sulphide content (Figure 5.3). The T1 is characterised by low tenors in the range of 9 – 90 ppm with an upward decrease, high Pt/Pd ratios and high sulphide content. The T2 Upper consists of

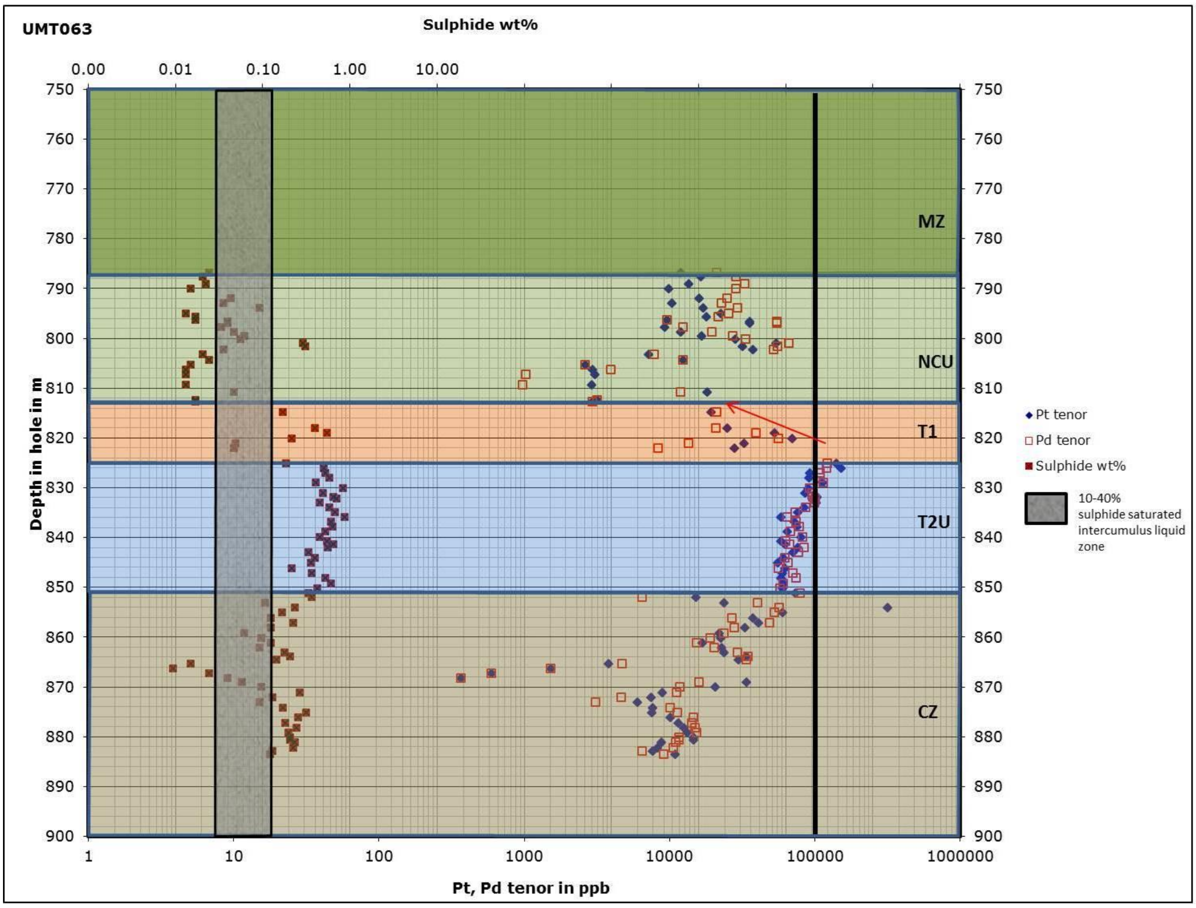


Figure 5.3. UMT063 tenor plot showing Pt and Pd tenors; and Sulphide wt %. A decrease in tenor grade within T1 is indicated by a red arrow

an upward increase in tenors from low (about 85 ppm) at the base, to high (about 110 ppm) at the top of the lithological unit. The Pt/Pd ratios are about 1 from the base of the unit and become higher (>1) across the 100 ppm mark. The entire T2 Upper consists of high sulphide content. T2 Lower is absent in this drill hole. The Contaminated Zone consists of low tenors from about 6 – 85 ppm with an upward increase, low Pt/Pd ratios and high sulphide content.

In UMT064, the Disturbed Zone comprises low tenors in the range of 1 – 90 ppm, low Pt/Pd ratios and low sulphide content (Figure 5.4). The T1 can be divided into two sub-units, the topmost portion comprising high tenors of about 90 – 105 ppm and the lowermost portion comprising low tenors in the region of 10 – 90 ppm.

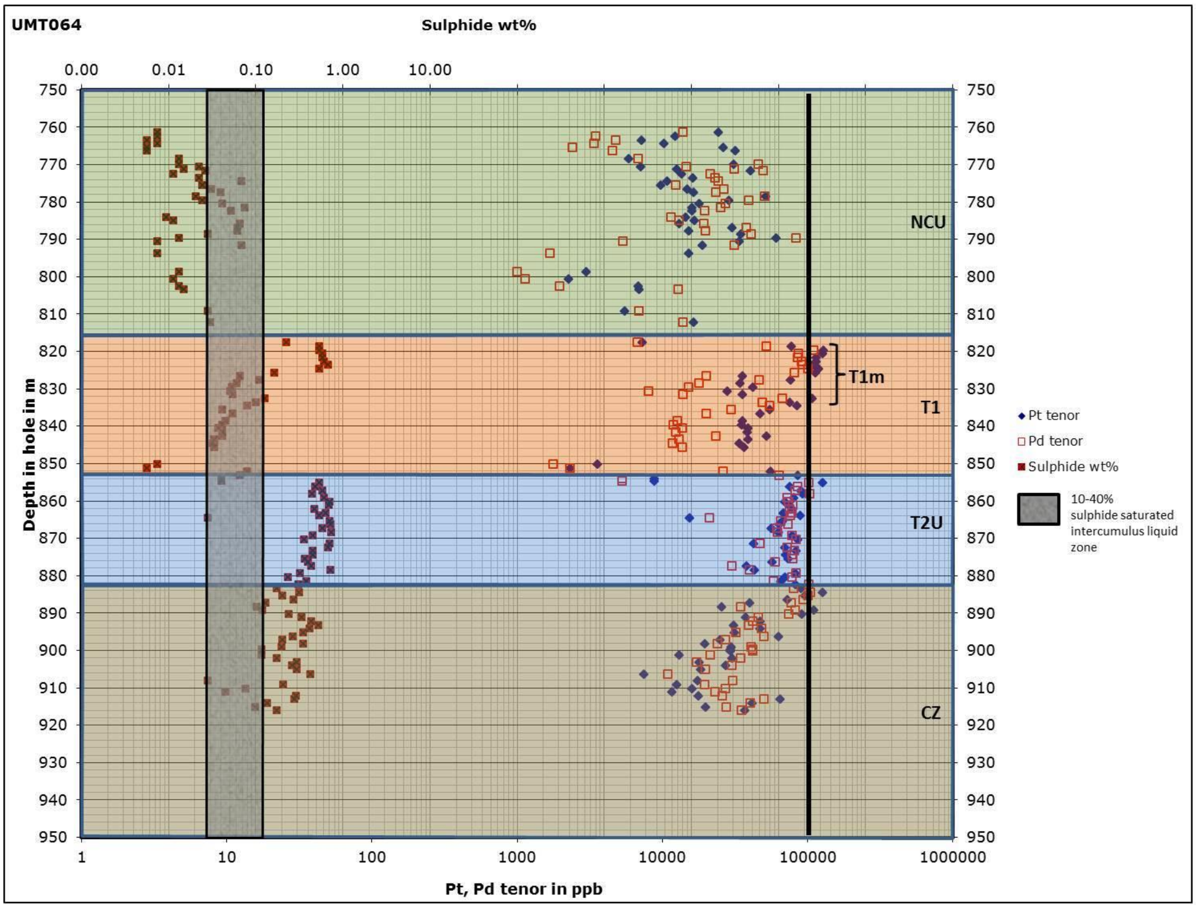


Figure 5.4. UMT064 tenor plot showing Pt and Pd tenors; and Sulphide wt %

The lowermost portion is also characterised by high Pt/Pd ratios and low sulphide content, whereas the topmost portion comprises high tenors, high Pt/Pd ratios and high sulphide content. The T2 Upper comprises low tenors (about 70 ppm) from the base becoming high (about 105 ppm) at the top of the lithological unit. Pt/Pd ratios are about 1 and becoming high (>1) towards the top of the lithological unit. The sulphide content is high throughout the unit. T2 Lower is absent in this drill hole. The Contaminated Zone comprises low tenors (about 9 ppm) at the base, becoming high (105 ppm) towards the top of the lithological unit. Pt/Pd ratios are low, becoming high towards the top of the unit. Sulphide content is also high.

5.5 Construction of the tenor model

The model was constructed using Geosoft Target software. A total of 276 drill holes were used in the model. The drillhole depths were restricted to a few meters within the Contaminated Zone. This was done because the study is focused on the upper section of the Platreef, above the Contaminated Zone.

The inverse distance squared interpolation method was used to grid the data. A search radius of 80 m from the centre of each drill hole was used and the model blocks were 20 x 20 x 20 m in size. Most of the area is covered by a drill hole spacing of about 100 m. In order to explain the lateral variation in PGE tenor in the study area, the T1 and T2 were modeled separately. It is noted that the T1 model includes both the topmost and lowermost portions of the T1 unit as described above. For each of the lithological units (T1 and T2), a set of three datasets i.e. PGE tenor, PGE grade in ppb and sulphide wt % were compiled and gridded. Isosurfaces were then generated for each dataset. An isosurface is a 3 dimensional surface that represents points of a constant value or points with equal values in a 3 dimensional data distribution. It is formed by joining these data points laterally and vertically. The cut-offs applied on the isosurfaces in both the T1 and T2 were as follows: 100 ppm for the PGE tenor, 2 ppm for the PGE grade and 0.1 wt% for the sulphide content. This information is available in an electronic format in Appendix 1.

5.5.1 T1 model

The PGE tenor is the highest (about 700 ppm) in the northwestern part of the study area, an area where the reef was intersected at depths of about 1000 – 1100 m (Figure 5.5 and 5.6). In most of the study area, the Main Zone – Platreef contact occur at depths of about 750 m. This northwestern area was interpreted to be a downward faulted (by a N-S trending fault) portion of the Platreef. The tenor gradually decreases towards the southeast. The lowest tenor (about 2.4 ppm) was observed on the eastern side of the study area. Figure 5.7 shows the tenor isosurfaces. The T1 is dominated by a tenor of about 100 ppm (grey isosurface), whereas a tenor of about 250 ppm forms a regional NW-SE trend.

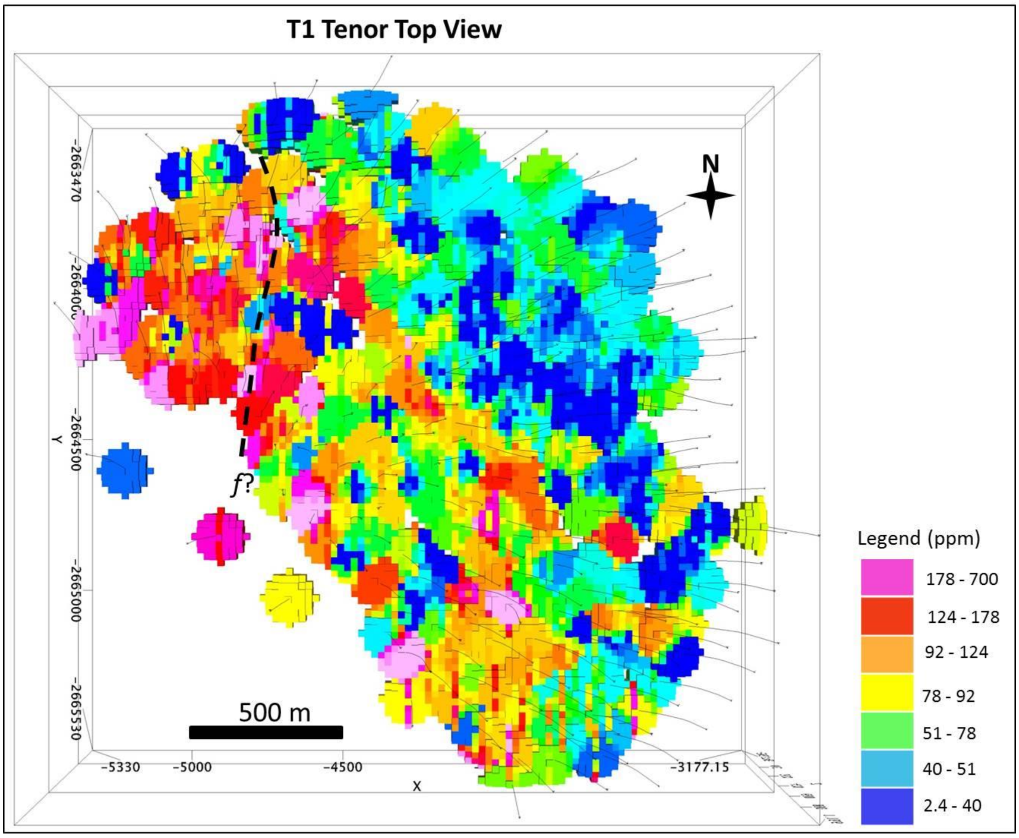


Figure 5.5. Diagram showing the lateral distribution in PGE tenor in T1 as viewed from the top. Drill holes are indicated by solid black traces and the interpreted fault by the dashed black line. A tenor cut-off of 2.4 ppm PGE was applied over a thickness of 20 m

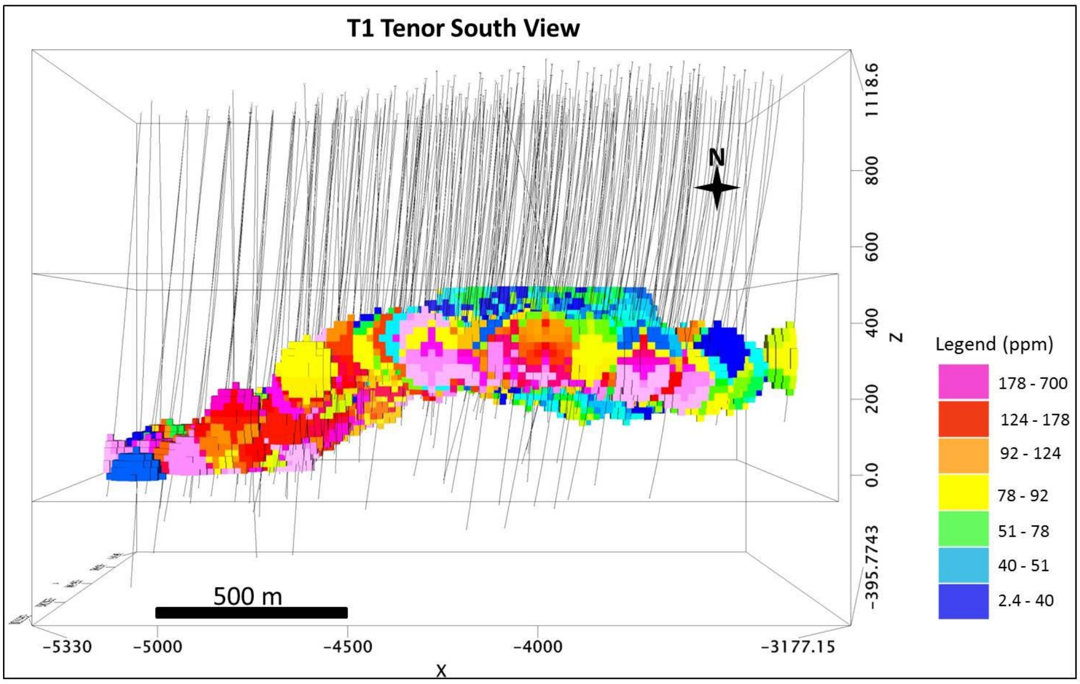


Figure 5.6. Diagram showing the lateral distribution in PGE tenor in T1 as viewed from the south. Drill holes are indicated by black traces. A tenor cut-off of 2.4 ppm PGE was applied over a thickness of 20 m

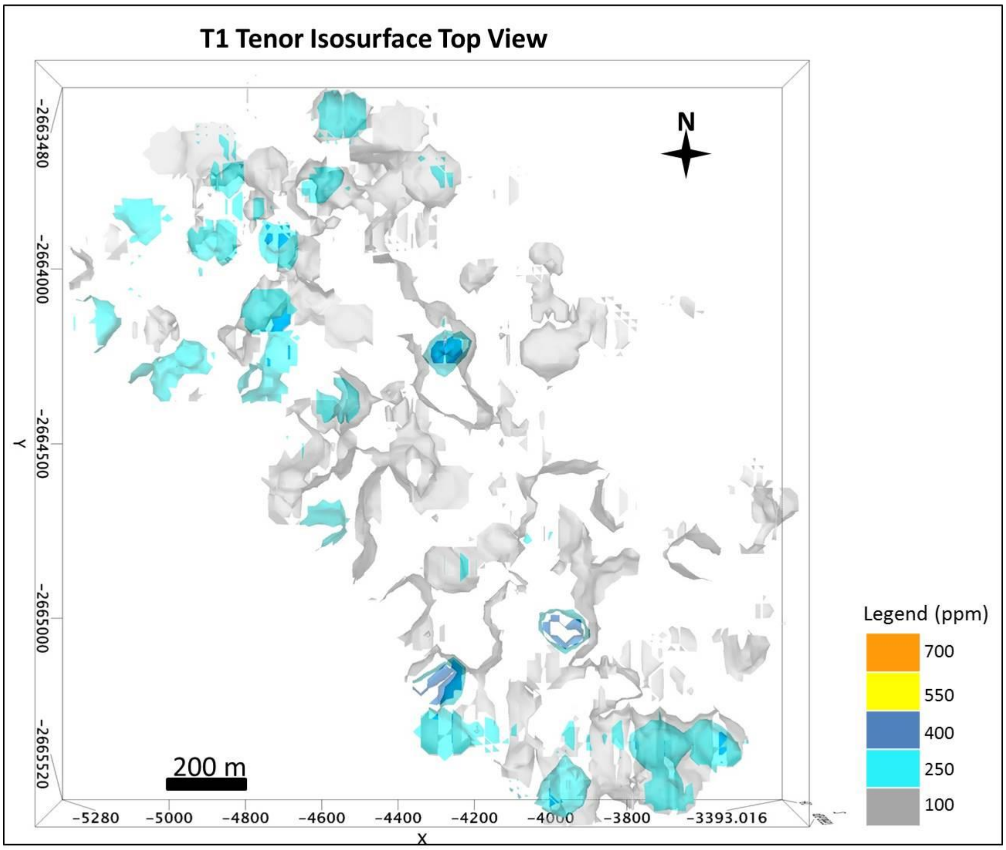


Figure 5.7. Diagram showing the PGE tenor distribution as isosurfaces in the T1. The diagram shows the distribution as viewed from the top. A tenor cut-off of 100 ppm PGE was applied over a thickness of 20 m

The PGE grade (in ppb) distribution in the T1 is shown in Figure 5.8. The area is dominated by grades of about 2000 ppb (2 ppm); grades above 2 ppm are sporadic. The T1 generally comprises a sulphide content in the range of 0.1 wt % (grey isosurface) to 0.3 wt % (light blue isosurface) (Figure 5.9).

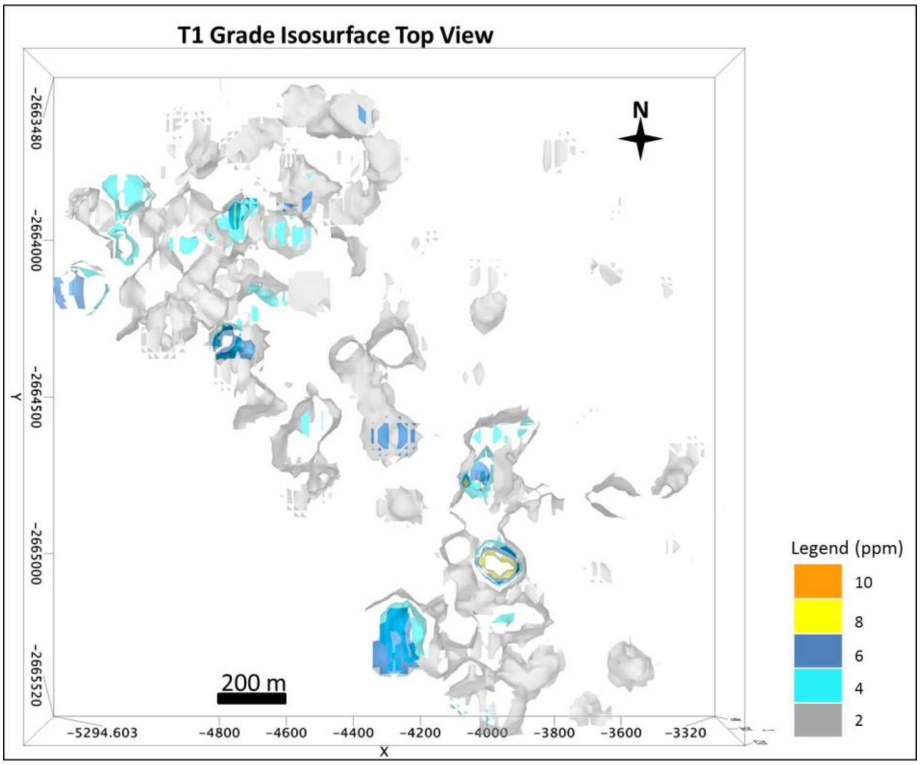


Figure 5.8. Diagram showing the PGE grade distribution as isosurfaces in the T1 as viewed from the top. A grade cut-off of 2 ppm PGE was applied over a thickness of 20 m

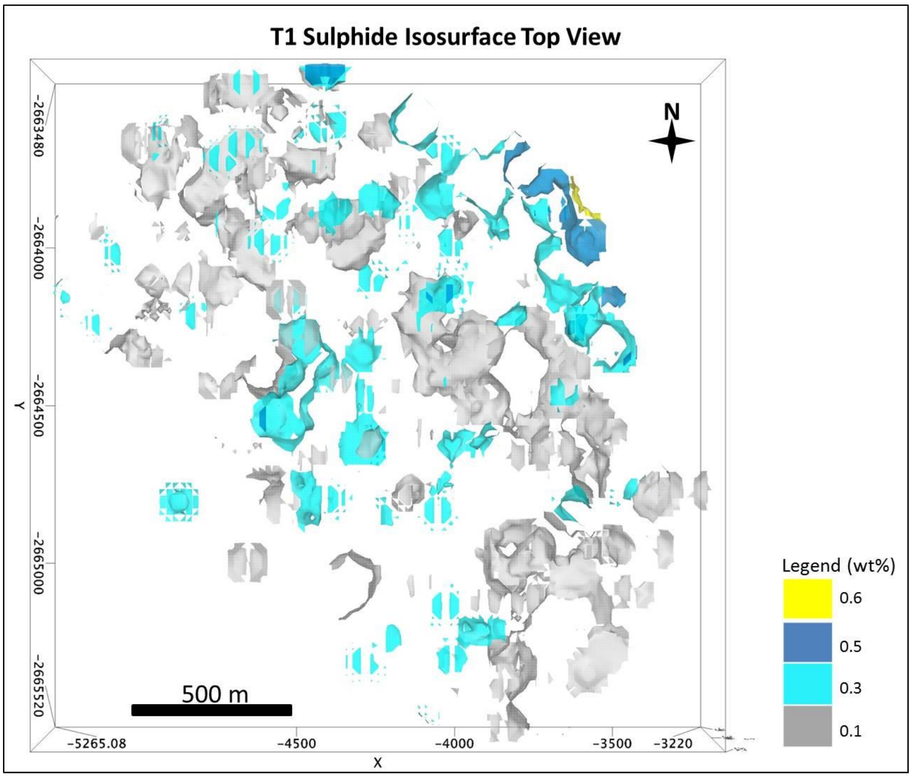


Figure 5.9. Diagram showing sulphide distribution as isosurfaces in the T1. The diagram shows the distribution as viewed from the top. A sulphide content cut-off of 0.1 wt% was applied over a thickness of 20 m

5.5.2 T2 model

The PGE tenor in the T2 is variable, but the profiles shown in the drill holes UMT040, 063 and 064 are typical of those that are found in the study area. It is noted that the T2 includes both the T2 Upper and T2 Lower. The highest tenor in the T2 is about 1000 ppm and occurs in the northwestern part of the study area. The lowest tenor of about 20 ppm is dominant on the northeastern side of the study area. Generally, two high tenor zones trending NW-SE occur in the T2 (Figure 5.10). The tenor distribution as viewed from the south is shown in Figure 5.11. These high tenor zones are separated by a zone of low tenor which seems to disappear at a location approximate to the N-S trending fault. The high tenor zones also display a gradual decrease in tenor towards the southeastern part of the study area. The T2 is dominated by a tenor of about 100 ppm, as shown by the grey isosurfaces (Figure 5.12). A tenor of about 250 ppm is dominant in the northwestern part.

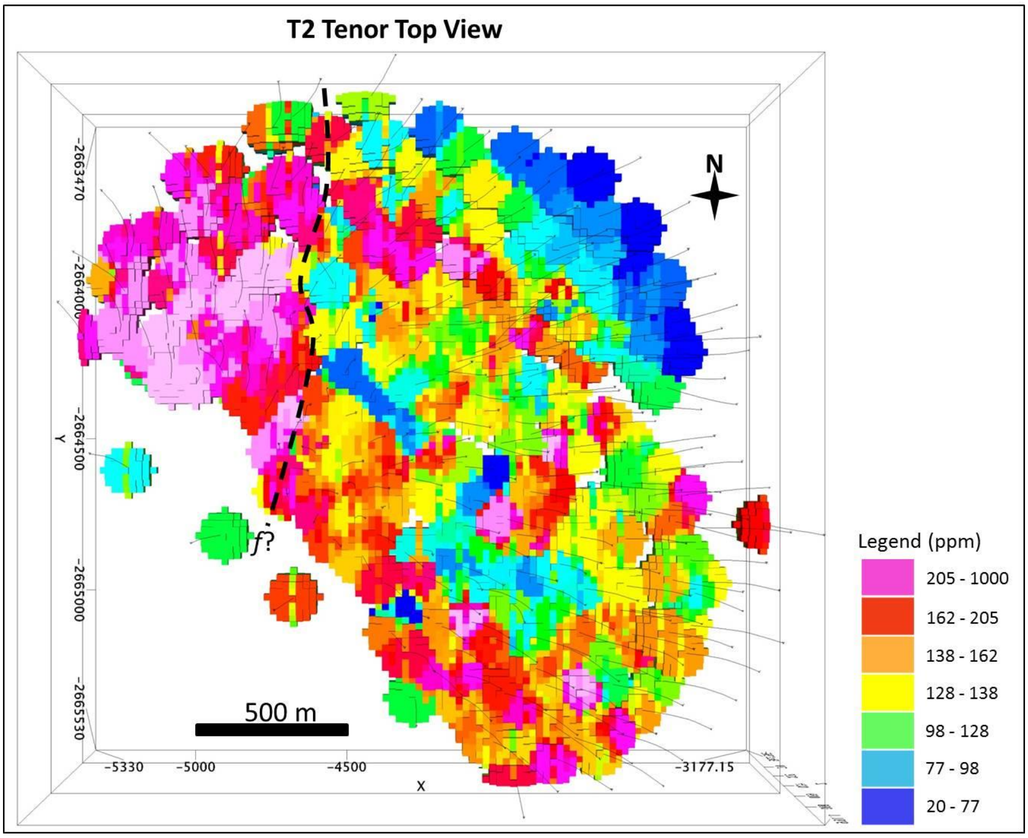


Figure 5.10. Diagram showing the lateral distribution in PGE tenor in the T2 as viewed from the top. Drill holes are indicated by black solid traces and the fault by a dashed black line. A tenor cut-off of 20 ppm PGE was applied over a thickness of 20 m

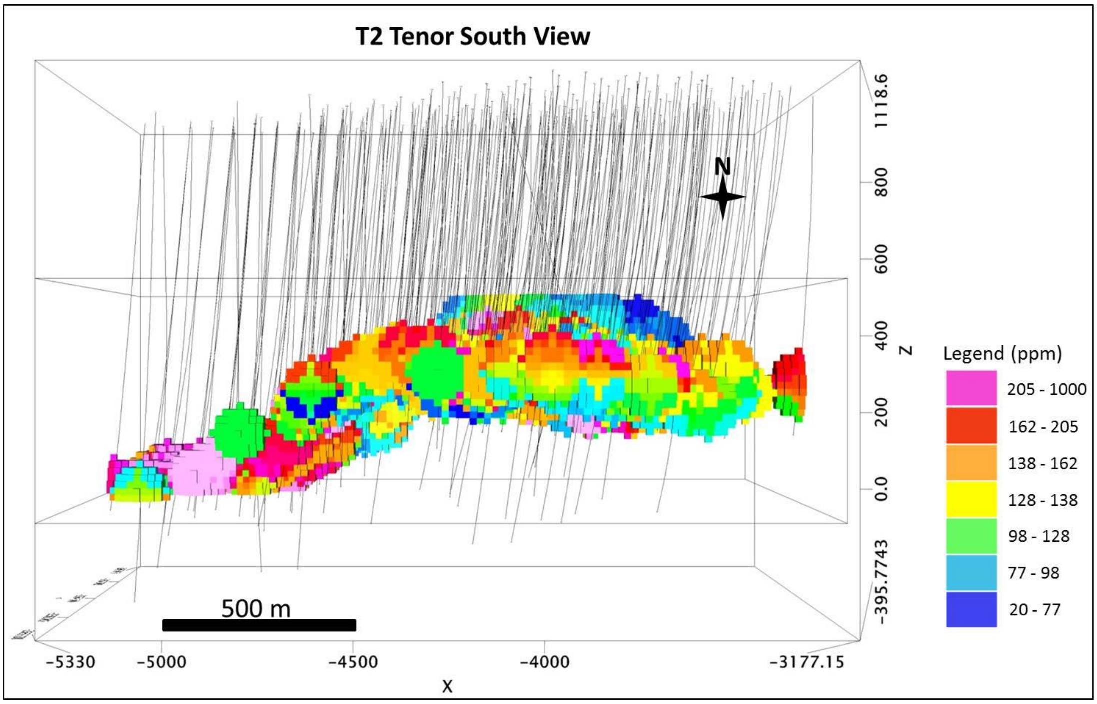


Figure 5.11. Diagram showing the lateral distribution in PGE tenor in the T2 as viewed from the south. Drill holes are indicated by black traces. A tenor cut-off of 20 ppm PGE was applied over a thickness of 20 m

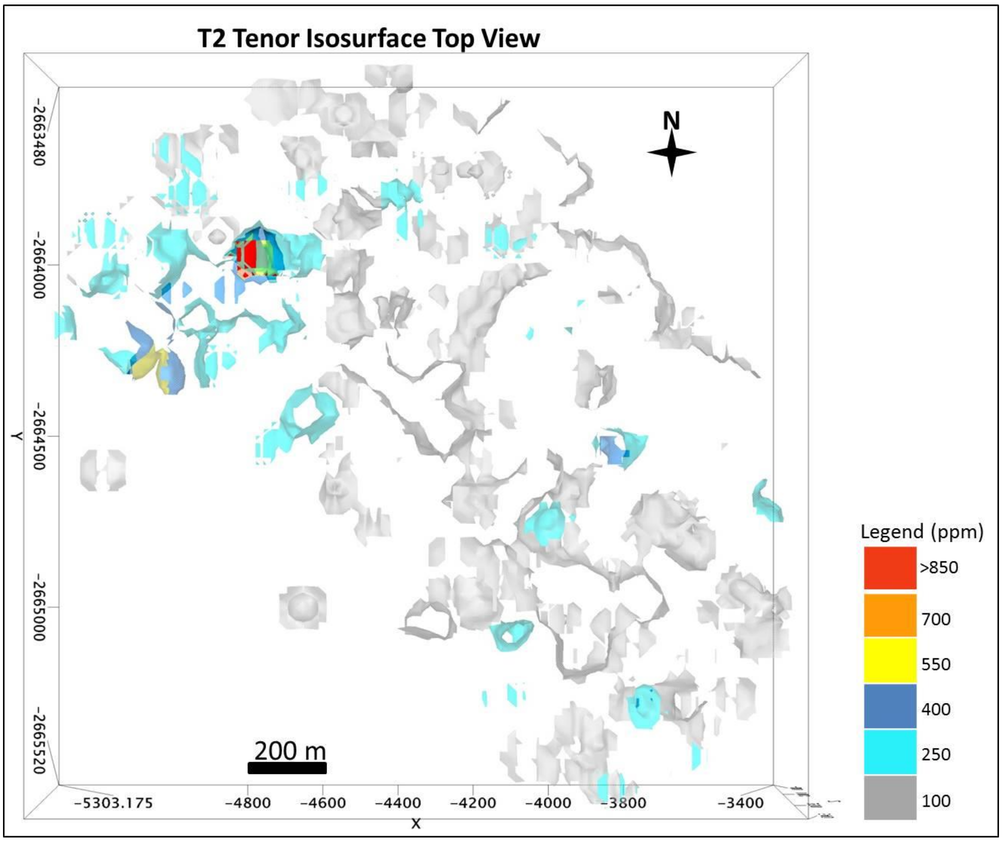


Figure 5.12. Diagram showing PGE tenor distribution as isosurfaces in the T2. The diagram shows the distribution as viewed from the top. A tenor cut-off of 100 ppm PGE was applied over a thickness of 20 m

The dominant PGE grade in the T2 ranges from 2000 – 4000 ppb (2 – 4 ppm) (Figure 5.13). The highest grades of up to more than 12000 ppb (12 ppm) occur in the northwestern part. The T2 is dominated by sulphide content in the range of 0.3 – 0.5 wt % (Figure 5.14). The highest sulphide content of about 1.1 wt % was observed towards the centre of the study area.

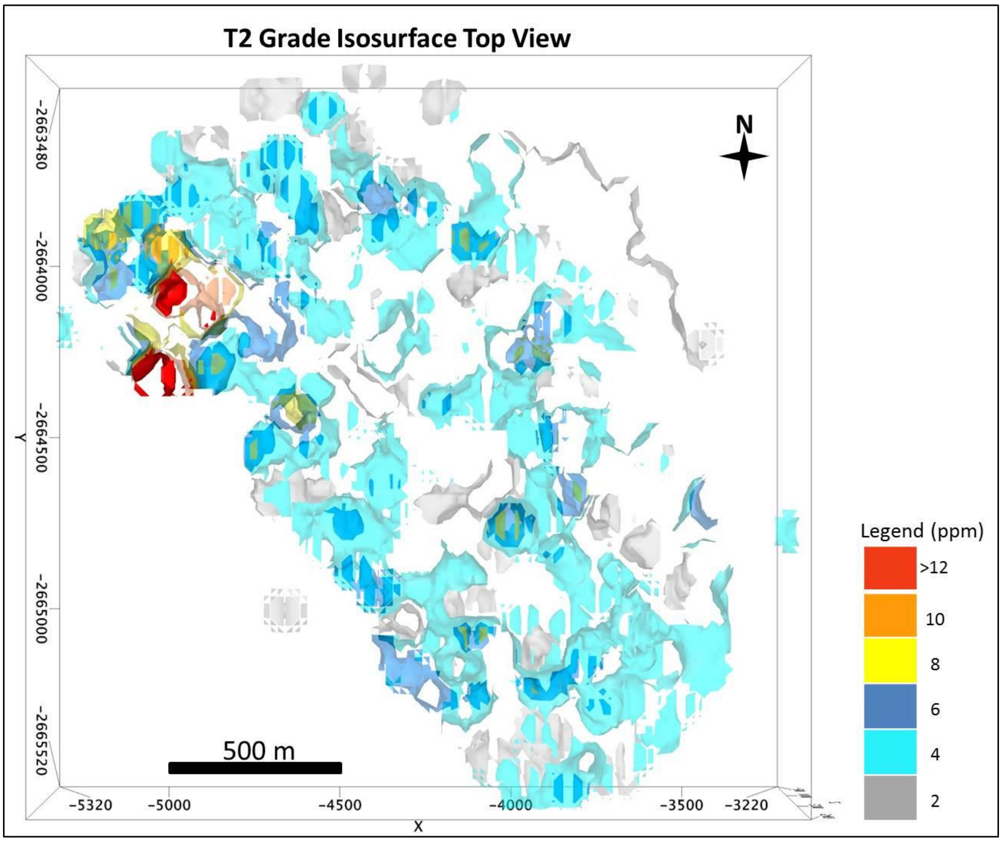


Figure 5.13. Diagram showing PGE grade distribution as isosurfaces in the T2. The diagram shows the distribution as viewed from the top. A grade cut-off of 2 ppm PGE was applied over a thickness of 20 m

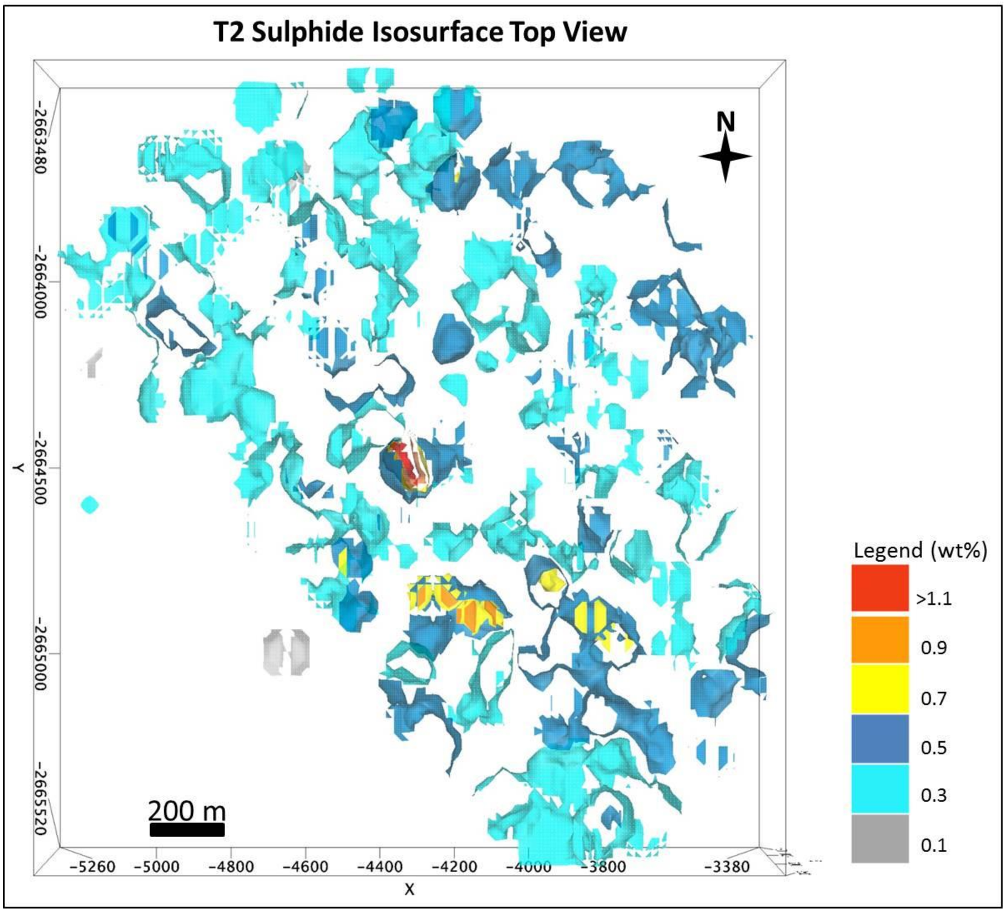


Figure 5.14. Diagram showing sulphide distribution as isosurfaces in the T2. The diagram shows the distribution as viewed from the top. A sulphide content cut-off of 0.1 wt% was applied over a thickness of 20 m

5.6 Discussion

5.6.1 Variation in tenor in UMT040, 063 and 064

In all the drill holes, there is a general upward increase in tenors and sulphide content from the Contaminated Zone to the top of the T2 Upper. A major break in tenors occurs at the contact between the T1 and T2. In general, the Disturbed Zone comprises low tenors in the range of 1 - 90 ppm, low Pt/Pd ratios and low sulphide content.

In UMT040 and 064, the T1 can be divided into two sub-units based on the tenor patterns. The topmost portion comprising high tenors in the range of 80 – 105 ppm with an upward decrease, high Pt/Pd ratios and high sulphide content; and the lowermost portion characterised by low tenors of about 2 – 90 ppm also with an upward decrease, high Pt/Pd ratios and low sulphide content. This lower portion of the T1 is comparable with the T1 in UMT063 in that it has low tenors with an upward decrease and high Pt/Pd ratios. This could suggest that the T1 is made up of at least two pulses of magma; the first magma which is poor in sulphides (lowermost portion of T1) and the second magma which is rich in sulphides (topmost portion of T1). The upward decrease in tenor from the base of the lowermost portion of the T1 in all the drill holes is attributed to fractional segregation of sulphides in the magma.

The topmost portion of the T1 was intersected in UMT040 and 064, and not in UMT063. This could be caused by erosion of the incoming Main Zone magma. This top portion can be interpreted as a new wave of magma that had picked up some PGE-rich sulphides during its emplacement. This magmatic pulse comprises a higher sulphide content than can be accommodated by the intercumulus liquid, suggesting that additional sulphide has been added to the magma. The upward decrease in tenors can be attributed to the static exhaustion of magma due to segregation of sulphides. The sulphide rich-zone/interval of this T1 has been called the T1m by the logging geologists at the project site. In both the topmost and lowermost portions of the T1, the upward decrease in tenor coincides with the upward increase in the Cu/Pd ratio within the same intervals in the lithological unit (Figures 5.15 and 5.16), another feature that would be expected to result from in situ fractional segregation of sulphide.

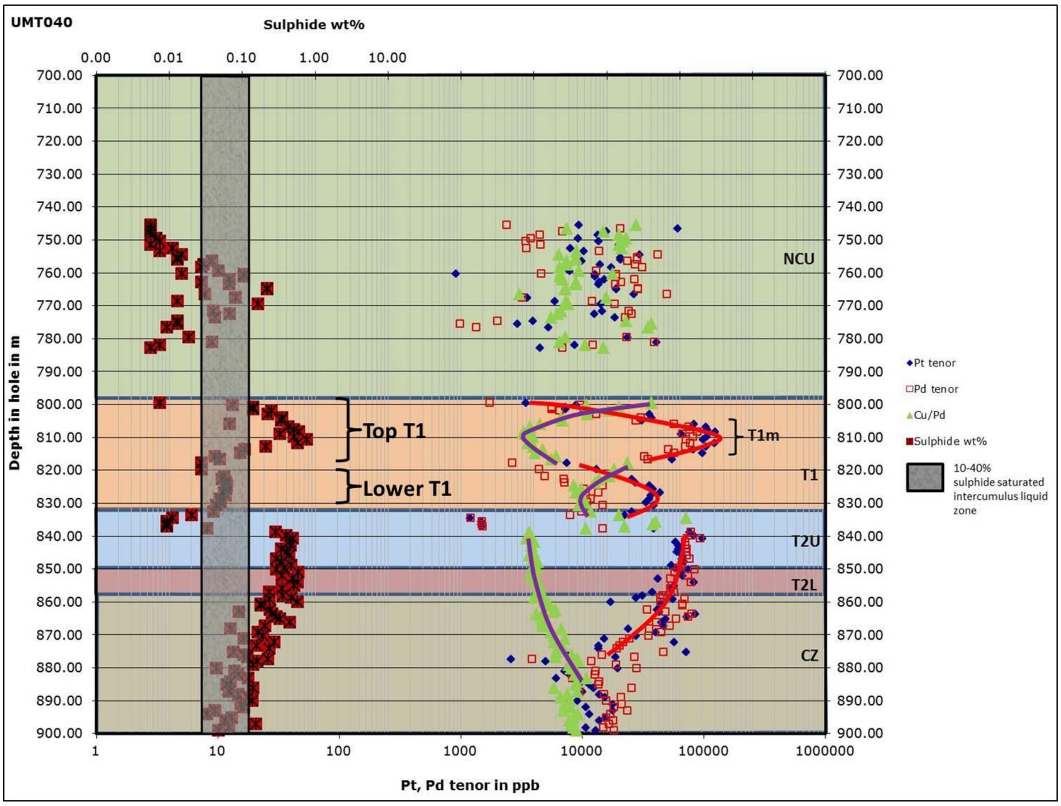


Figure 5.15. Diagram showing variations in PGE tenor and Cu/Pd ratios in UMT040. The topmost part of the T1 comprises a high sulphide content with high tenor, whereas the lowermost part has low sulphide content and low tenor. In both sections of the T1, an upward decrease in tenor coincides with an upward increase in Cu/Pd ratio

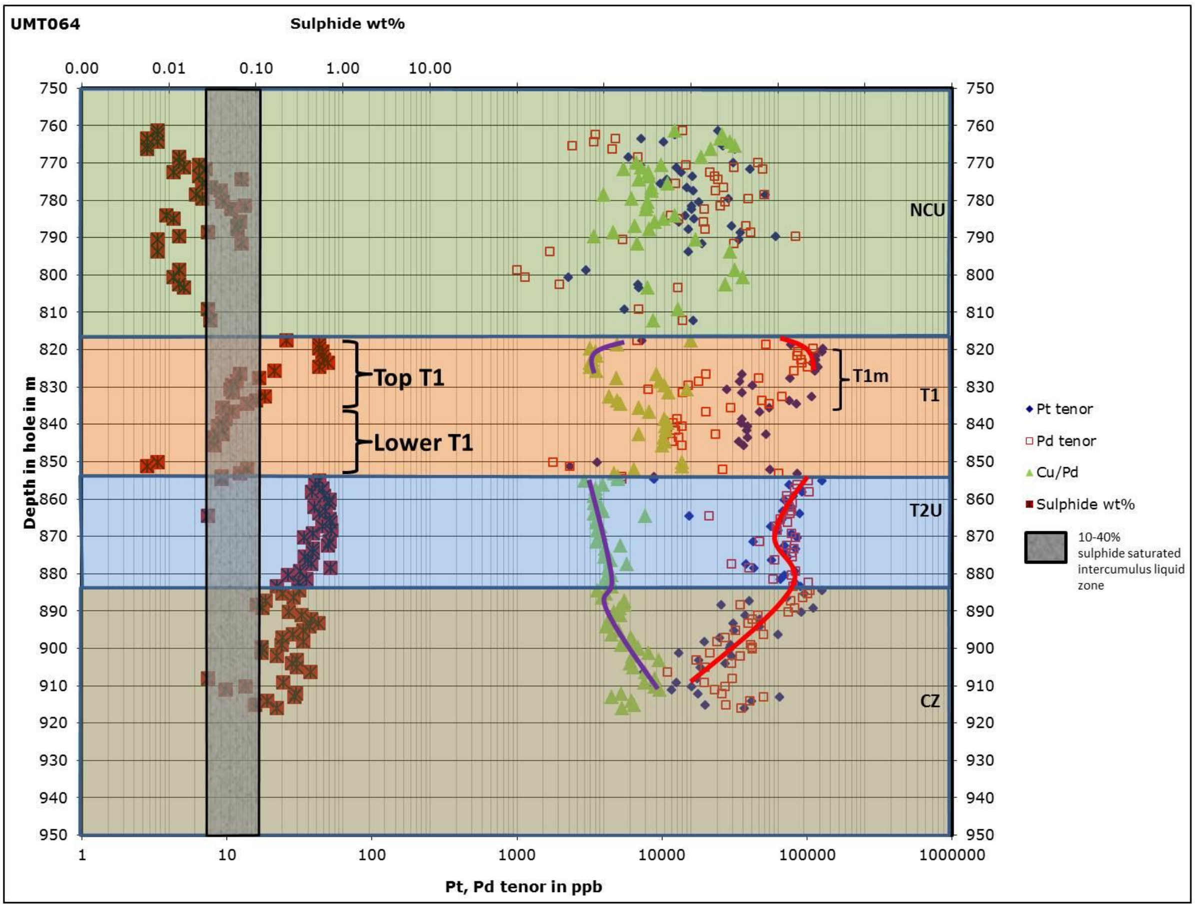


Figure 5.16. Diagram showing variations in PGE tenor and Cu/Pd ratios in UMT064. It is envisaged that the upper portion of the T1 has been partially eroded by the incoming Main Zone magma and thereby removing the upper section which would have displayed the exponential upward decrease in tenor and a coincidental upward increase in Cu/Pd ratio. The tenor and Cu/Pd ratios in the lowermost portion of the T1 are hard to explain, however, the Pt/Pd ratios are typical of those found in the lowermost portion of the T1 in UMT040 and 063

In order to explain the PGE tenor and Cu/Pd ratio variations described above, possible scenarios that could have resulted from the perfect Rayleigh fractional segregation are shown (Figure 5.17).

Scenario (a) in Figure 5.17 can be compared with the lowermost portion of the T1 in UMT040 and 063, where the tenor of the sulphides decreases upwards. This could represent an initial magmatic pulse of the T1 with low sulphide content and low tenor. Whereas, scenario (c) could be compared with the entire T1 in both UMT040 and 064, where the T1 can be divided into two sub-units based on the tenor patterns. The sulphides are thought to have segregated from each batch of magma resulting in a progressive upward decrease in tenor. Cu/Pd ratios show an upward increase coincidental with the progressive decrease in tenor. Naldrett et al (2009) indicated that this would be expected if the sulphides segregate fractionally from a body of magma and the PGE become depleted in the magma much more rapidly than the base metals such as Cu. This occurs because although both PGE and Cu partition into a sulphide phase once it develops, PGE partition more strongly than Cu.

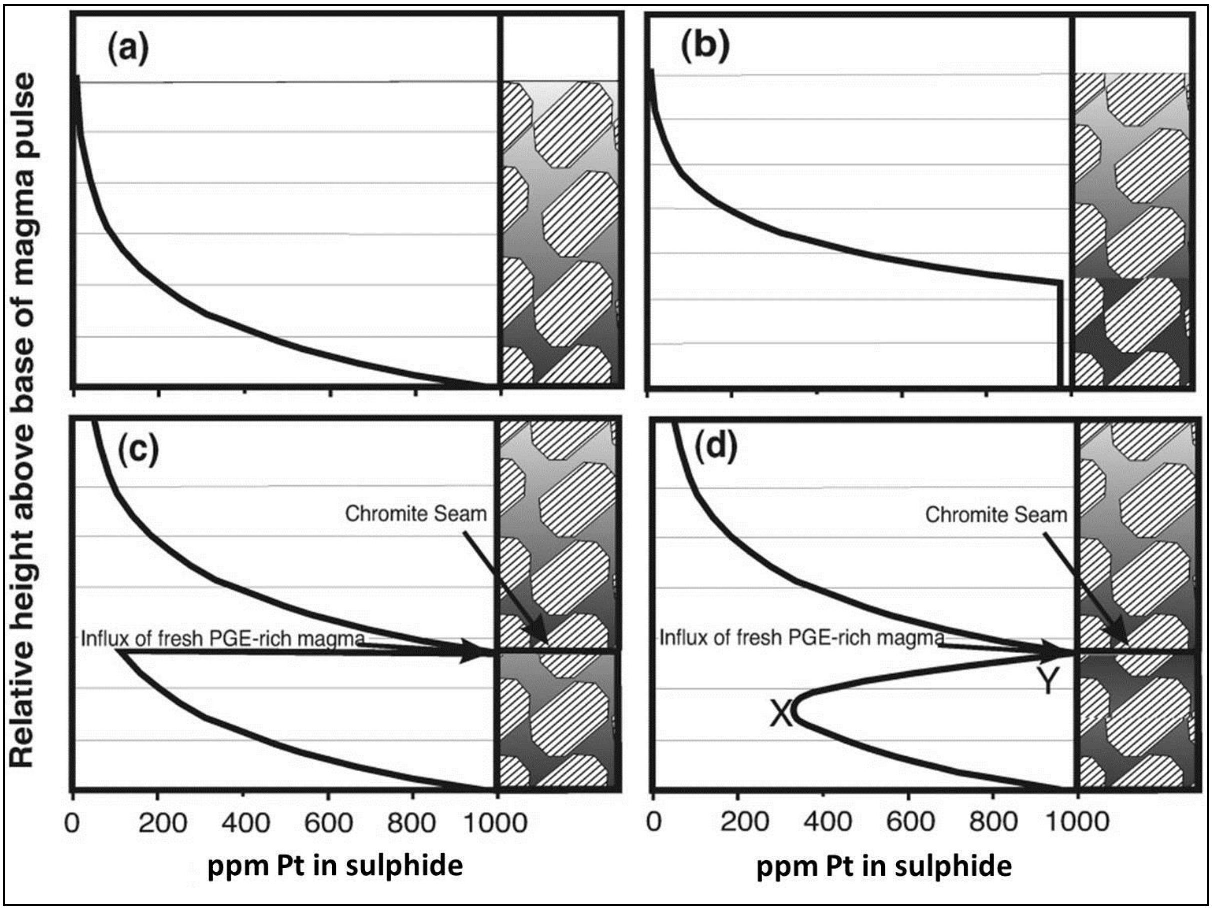


Figure 5.17. Theoretical scenarios involving fractional segregation of sulphide (after Naldrett et. al, 2009). (a) An illustration of the exponential upward decrease in sulphide PGE tenor over a vertical profile as a result of simple segregation. (b) An illustration of the profile to be expected if the magma intruded carrying a bottom load of sulphide of uniform composition and then continued segregating sulphide in situ. (c) A scenario involving emplacement of a second pulse of fresh, undepleted magma. (d) Same scenario as illustrated in (c), but modified by the settling of high PGE tenor sulphide associated with the second pulse and mixing of sulphides from the two pulses.

Following the staging chamber model for the development of PGE-enriched magma with a low Cu/Pd ratio as proposed by Naldrett et al (2009), it is envisaged that the topmost portion of the T1 resulted from one of the later batches of magma that was enriched in PGE, Ni and Cu.

The T2 comprises low tenors of about 70 ppm at the base, increasing upwards to high levels of about 110 ppm towards the top of the lithological unit in the drill holes. Pt/Pd ratios range from below to about 1 through most of the unit and become high (>1) towards the top of the unit. The sulphide content is higher than can be dissolved by the intercumulus liquid. This could suggest that the T2 magma was already rich in PGE sulphides when entering the magma chamber, and the sulphides have gained their tenor elsewhere, rather than in situ. These sulphides were deposited as a mush or in bulk, and did not undergo any segregation. This is supported by the lack of an upward decrease in tenors as observed in the T1.

Generally, the Contaminated Zone comprises low tenors in the range of 6 – 90 ppm, increasing upwards, and high sulphide content. However, tenors above 105 ppm were observed towards the top of the Contaminated Zone in UMT064.

5.6.2 Lateral variation in PGE tenor in the study area

The following observations were made in the T1 and T2:

(a) The highest tenor in T1 is 700 ppm and about 1000 ppm in T2;

(b) Both the T1 and T2 have the highest tenor in the northwestern part of the study area, and the tenor gradually decreases towards the southeast;

(c) Two high tenor zones (trending NW-SE) separated by a zone of low tenor were observed in the T2, whereas in the T1 only one high tenor zone with a similar trend was observed;

(d) Both the T1 and T2 are dominated by a tenor of about 100 ppm. In the T1, a tenor of 250 ppm is dominant in the northwestern and southeastern parts of the study area, whereas in the T2 a 250 ppm tenor is only dominant in the northwestern part;

(e) The dominant PGE grades in the T1 are about 2000 ppb (2 ppm), whereas in the T2 they range from 2000 – 4000 ppb (2 – 4 ppm);

(f) The dominant sulphide content in the T1 ranges from 0.1 – 0.3 wt %, whereas in the T2 it ranges from 0.3 – 0.5 wt %;

In addition, there is no correlation between the sulphide content and the tenor. In other words, where the sulphide content is high, the tenor is not at its highest. However, there seem to be a correlation between tenor and grade, particularly in the case of the T2. Areas with moderate to high tenor (250 - >850 ppm) seem to occur where the grade is also moderate to high (4 - >12 ppm), although this does not apply in all the holes.

The tenor can only decrease where there is sulphur addition or through progressive segregation of sulphide from a body of magma. In the second case, if the body of magma is moving there will be a lateral decrease in tenor in the direction of movement, as Naldrett et al. (2009) proposed for the difference in tenor between the northwest and southwest areas of the western Bushveld. If the body of magma is stationery there will be a vertical upward decrease in tenor as it was also observed in the Merensky Reef (Naldrett, personal communication, 2013). A scenario relating to the upward decrease in tenor was observed in the T1. Therefore, it can be concluded that the process that formed the T1 is similar to the one that formed the Merensky Reef. In general, the lateral variation in tenor in both the

T1 and T2 show a gradual decrease towards the southeast, which could suggest that these magmas probably came in from the northwesterly direction.

McDonald et al (2011) reported that the sulphide inclusions with inverse crystal shapes in early Platreef chromite carried extremely high PGE tenors (Pt up to 900 ppm, Pd up to 680 ppm). They then suggested that these sulphide inclusions represented the trapped droplets of this early PGE-rich sulphide liquid. In order to provide evidence that the PGEs on Turfspruit were originally hosted in sulphides, PGE tenors of McDonald et al (2011) were compared with PGE tenors in the T1 and T2. The highest PGE tenors in the T1 (Pt up to 856 ppm, Pd up to 402) occur in the feldspathic pyroxenite and chromite samples, respectively; whereas in the T2, the highest PGE tenors (Pt up to 1021 ppm, Pd up to 520 ppm) occur in the chromite sample.

5.7 Summary and conclusions

This study has revealed that the tenors on Turfspruit are higher than previously thought. Tenors in the T1 reach up to 700 ppm, whereas tenors of about 1000 ppm were recorded in the T2. Tenors are the highest in the northwestern part of the study area and they gradually decrease towards the southeast. Both the T1 and T2 are dominated by a tenor of about 100 ppm. In the T1, a tenor of 250 ppm is dominant in the northwestern and southeastern parts of the study area, whereas in the T2 it is only dominant in the northwestern part.

The T2 is dominated by PGE grades in the range of 2 – 4 ppm and a sulphide content of 0.3 – 0.5 wt %, whereas the T1 is dominated by grades of about 2 ppm and sulphide content of 0.1 – 0.3 wt %.

Based on the tenor patterns and behaviour, the T1 can be divided into two sub-units i.e. the topmost and lowermost portions. The topmost portion comprises a high sulphide content, high tenor and high Pt/Pd ratios, whereas the lowermost portion comprises low sulphide content, low tenor and high Pt/Pd ratios. The T2 comprises high tenors towards the top of the lithological unit. At least two sulphide emplacement processes are envisaged for the study area i.e. (1) the sulphides in the T2 are thought to have been emplaced in bulk compared to (2) the sulphides in the T1 that have segregated from batches of magma. The process responsible for the formation of the T1 is interpreted to be similar to that which formed the Merensky Reef. PGE tenors on Turfspruit are comparable to the PGE tenors measured from the sulphide melt inclusions elsewhere in the northern limb.

Chapter 6

Geochemistry

6.1 Introduction

In order to investigate whether the upper section of the Platreef has resulted from the same or separate magma pulses, geochemical analyses were completed from three holes (along strike) in the study area (Figure 6.1). This data was also used to prove or disprove the correlation of the upper section of the Platreef with the Merensky Cyclic Unit (MCU).

Sample selection was guided by lithological units, alteration and variation in PGE tenor. Quarter core samples were taken from BQ cores. In order to maintain consistency, the sample lengths were kept at 15 cm, but smaller samples were also collected. At least two samples were taken above and below areas with variations in alteration and a change in tenor pattern/population. Samples were also taken in one tenor pattern/population within a specific lithological unit. A total of 124 samples were collected from all three drill holes.

Base metal and precious metal analyses were undertaken by multi-acid digestion followed by ICP-MS (and OES), whereas, the major and trace element whole rock analyses were undertaken by XRF. The pyroxene chemistry was analysed by wavelength dispersive electron microprobe.

6.2 Fire assay with ICP-MS

The majority of the drill holes were drilled during the peak of the exploration program and three analytical laboratories were used to process the large number of samples. All samples were analysed by the UltraTrace and Genalysis Laboratories in Perth, Australia and SetPoint Laboratory in Johannesburg, South Africa. Samples were analysed for Pt, Pd, Rh, Au, Ni, Cu, Cr and S. Analytical methods used by each laboratory are listed below.

SetPoint:

Fire assay lead collection followed by ICP-MS to determine Au, Pt and Pd;
Total Acid Digestion followed by ICP-OES to determine Cu and Ni;
Sulphur by Leco;
Fire assay Pd collector followed by ICP-MS to determine Au, Pt and Rh;
Fire assay NiS collector to determine Au, Pt, Pd, Rh, Ir, Ru, Os (used as a check on the Pd collector).

UltraTrace:
Multi-acid digestion followed by ICP-OES to determine Ni, Cu, Cr and sulphur;
Fire assay lead flux collector followed by ICP-MS to determine Pt, Pd and Au.
Fire assay Pd collector followed by ICP-MS to determine Rh, Pt and Au.

Fire assay NiS collector to determine Au, Pt, Pd, Rh, Ru, Os and Ir (used as a check on the Pd collector).

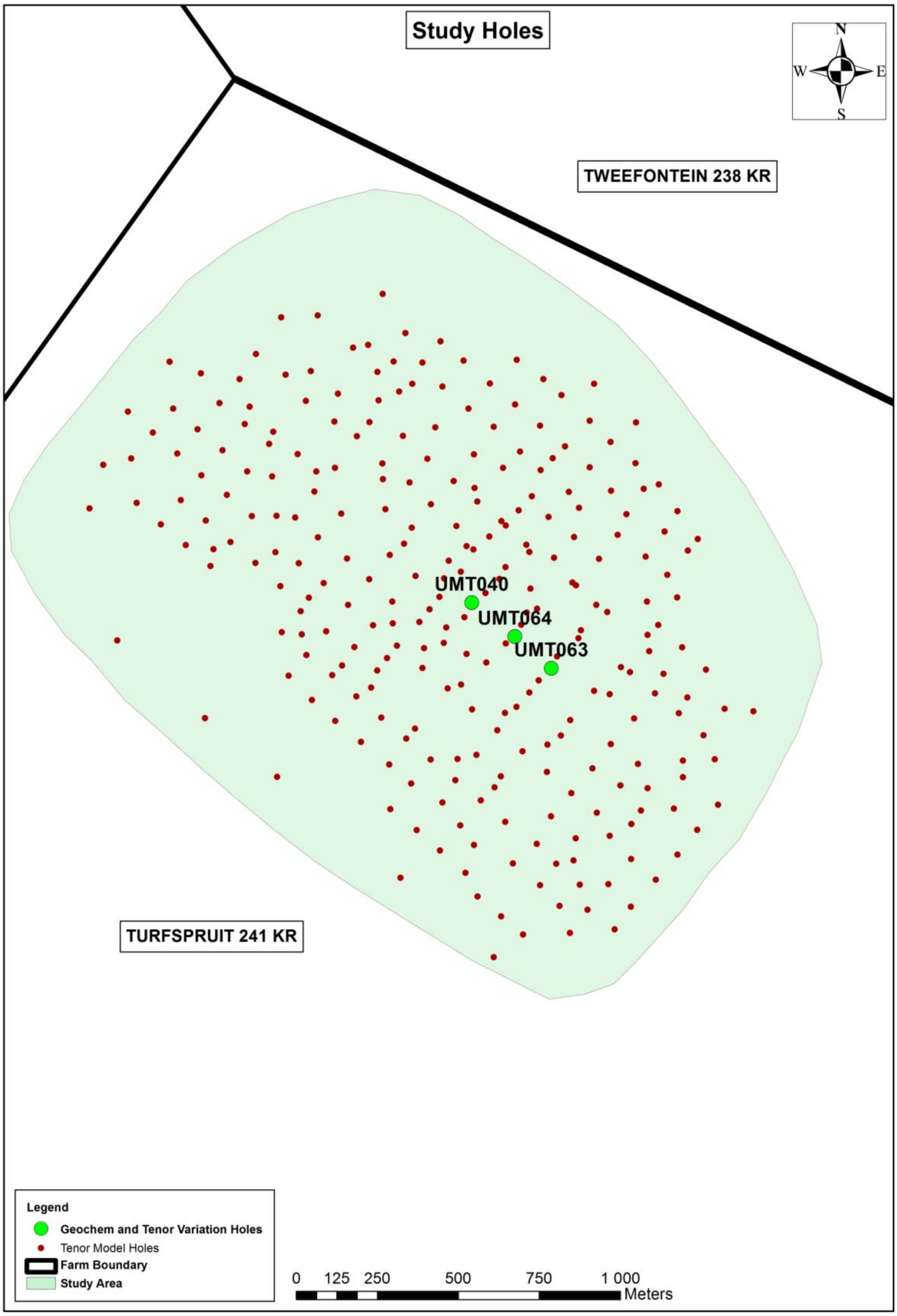


Figure 6.1. Location of holes sampled for geochemical analysis

Genalysis (Perth):

Fire assay lead collection followed by ICP-MS to determine Au, Pt and Pd;
Multi-acid digestion followed by ICP-OES to determine Cu, Cr, Ni and S.

Genalysis (Johannesburg):

Fire assay Pd collector to determine Rh;
Fire assay NiS collector to determine Au, Pt, Pd, Rh, Ru, Os and Ir (used as a check on the Pd collector).

6.3 Major and trace element (XRF) data analysis

The major and trace element analyses were conducted on quarter cores from UMT040, UMT063 and UMT064. Samples were analysed at the University of the Witwatersrand using standard laboratory practice. The major elements were determined using the XRF on fused beads and trace elements determined by pressed powder pellets. Reproducibility for major and trace elements is excellent. The detection limits for most trace elements are low i.e. for Cu, Co, Ni and Zn are 6 ppm, for Rb, Sr, Y and Nb are 3 ppm and; for V, Cr, Ba, Pb, Ga, La, Se, Sc, Th, As, U and Zr are less than 12 ppm.

6.3.1 Major elements

To test whether the upper section of the Platreef resulted from the same or separate magma pulses, MgO and Cr/MgO ratio were plotted for the three drill holes. Other major element data showed less variation between the Disturbed Zone (NCU), T1, T2 Upper, T2 Lower and the Contaminated Zone and hence, the data is not presented here. However, the overall average major element data per lithological unit for the three holes (Table 6.1) display slight differences in Al_2O_3, FeO (expressed as total FeO), CaO and Na_2O contents between lithological units. In general, the Disturbed Zone is higher in Al_2O_3 and Na_2O; and lower in FeO compared to the T1, T2 Upper, T2 Lower and the Contaminated Zone. This is also supported by the CIPW norms which indicate higher amounts of modal plagioclase in the Disturbed Zone (discussed below). CaO is slightly higher in the Disturbed Zone and Contaminated Zone; and lower in T1, T2 Upper and T2 Lower. Both T2 Upper and T2 Lower contain high Ni content than the Disturbed Zone, T1 and Contaminated Zone. A complete dataset of major elements is shown in Appendix 2.

Figure 6.2 shows the MgO (wt %) plot for the three holes, UMT040, UMT063 and UMT064. Note that the plots were generated using the absolute values, not averages. In all the holes the MgO in the Disturbed Zone ranges from 3 – 22 wt %. In UMT040 and UMT064, the MgO in the T1 is generally constant around 20 wt %, whereas in UMT063 there is a slight upward decrease. The T2 Upper in UMT040 comprises around 20 – 25 wt %, whereas in UMT063 and 064, the T2 Upper can be divided into two sub-units i.e. the topmost and lowermost portions. The topmost portion comprises 16 – 25 wt % MgO, whereas the lowermost portion comprises values ranging from 20 - 32 wt % MgO and are increasing upwards. The T2 Lower in UMT040 comprises values from 28 - 34 wt % MgO, and they are also increasing upwards. The Contaminated Zone ranges in composition from 14 – 26 wt % MgO.

Table 6.1. Average major elements data (wt %) per lithological unit. NCU = Disturbed Zone, T1 = Feldspathic orthopyroxenite, T2 Upper = Pegmatoidal (feldspathic) pyroxenite, T2 Lower = Harzburgite, CZ = Contaminated Zone

	NCU	NCU Range	T1	T1 Range	T2 Upper	T2 Upper Range	T2 Lower	T2 Lower Range	CZ	CZ Range
	21 samples		54 samples		32 samples		4 samples		11 samples	
SiO2	52.75	49.92-54.60	53.99	52.48-57.11	51.39	42.13-54.30	43.30	41.34-47.08	50.22	46.20-52.59
Al2O3	14.55	5.67-27.59	6.09	2.76-10.28	5.25	2.20-23.49	4.01	3.49-4.49	6.52	3.92-9.34
Fe2O3	0.91	0.27-1.34	1.24	0.95-1.58	1.45	0.54-2.19	1.91	1.82-1.98	1.25	0.75-1.63
FeO	7.35	2.15-10.85	10.06	7.69-12.82	11.74	4.37-17.70	15.42	14.71-16.04	10.14	6.09-13.16
Tot FeO	8.17	2.39-12.06	11.18	8.54-14.24	13.04	4.86-19.67	17.14	16.35-17.82	11.26	6.76-14.63
MnO	0.15	0.05-0.23	0.20	0.14-0.23	0.20	0.09-0.23	0.18	0.16-0.22	0.19	0.15-0.22
MgO	13.76	2.80-22.14	22.00	14.59-25.53	23.30	4.33-31.40	30.72	28.65-33.07	21.21	14.18-26.27
CaO	8.29	4.20-13.70	4.71	3.74-5.51	4.78	2.06-12.44	2.92	2.59-3.56	8.55	3.38-18.42
Na2O	1.48	0.69-2.47	0.73	0.41-1.76	0.45	0.05-2.46	0.26	0.15-0.40	0.44	0.12-0.75
K2O	0.40	0.14-1.20	0.30	0.11-1.72	0.26	0.04-0.75	0.13	0.06-0.20	0.19	0.01-0.46
TiO2	0.28	0.14-0.51	0.26	0.15-0.64	0.25	0.12-0.37	0.13	0.09-0.18	0.24	0.14-0.41
P2O5	0.04	0.02-0.08	0.03	0.01-0.17	0.03	0.01-0.05	0.03	0.02-0.04	0.02	0.01-0.03
Cr2O3	0.18	0.02-0.34	0.36	0.25-0.46	0.30	0.03-0.41	0.08	0.04-0.13	0.35	0.19-0.70
NiO	0.05	0.01-0.12	0.23	0.07-1.29	0.71	0.02-3.59	0.61	0.41-0.91	0.27	0.05-0.59
TOTAL	100.19	97.66-101.26	100.21	98.91-102.13	100.10	98.53-101.27	99.68	99.52-99.86	99.59	97.34-100.33
LOI	0.41	(-0.37)-3.43	0.23	(-0.38)-1.60	2.14	0.06-6.69	7.86	6.57-9.80	2.24	0.44-4.72
SiO2/Al2O3	4.97	1.82-9.31	9.26	5.48-19.01	11.97	2.20-24.20	10.96	9.21-13.49	8.31	5.13-12.00
Al2O3/ FeO+MgO	1.38	0.18-5.36	0.19	0.07-0.46	0.21	0.06-2.70	0.09	0.08-0.09	0.22	0.11-0.42
CaO/Al2O3	0.62	0.47-0.76	0.80	0.50-1.49	1.01	0.53-2.23	0.73	0.64-0.84	1.32	0.65-2.94
MgO/FeO	1.75	1.03-2.32	2.20	1.59-2.55	1.99	0.99-2.34	1.99	1.86-2.17	2.12	1.80-2.33

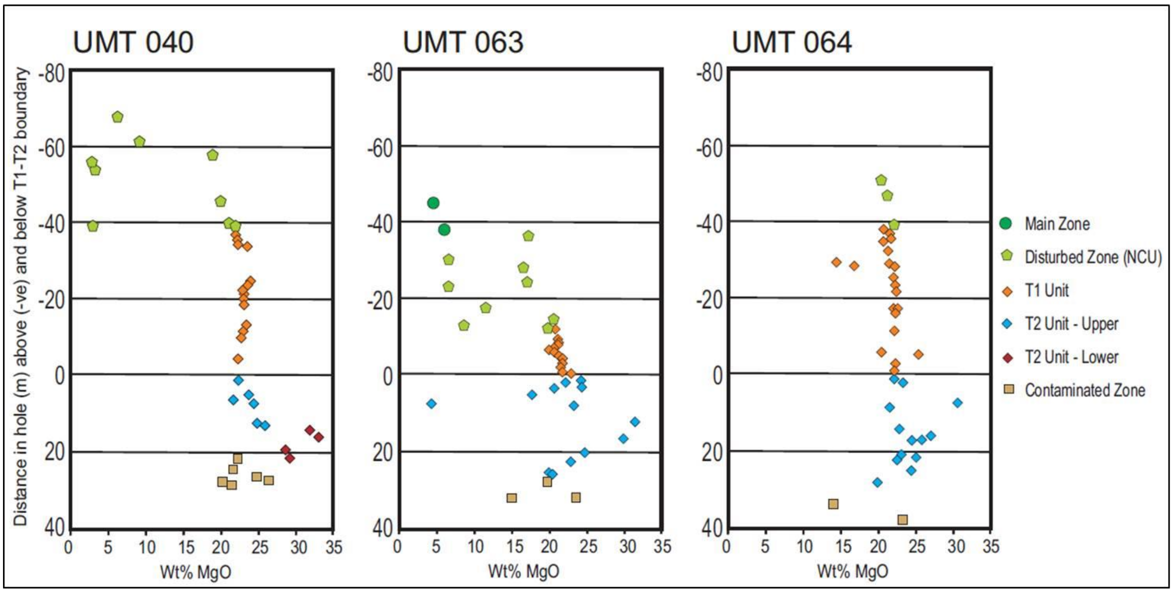


Figure 6.2. Plot of the MgO (wt %) distribution in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

The Cr/MgO ratios in the Disturbed Zone range from 100 – 50 in all drill holes, and show a general upward decrease (Figure 6.3). The T1 comprises ratios ranging from 95 – 130. The T2 Upper in UMT040 comprises ratios from 70 – 120 and they are increasing upwards. In UMT063 and 064, the topmost portion of the T2 Upper consist of ratios ranging from 80 - 120 (with an upward increase in UMT063), whereas the lowermost portion comprises ratios in the range of 125 – 5 (decreasing upwards). In UMT040, the T2 Lower comprises ratios from 40 – 5, also decreasing upwards. The Contaminated Zone comprises ratios between 50 and 155.

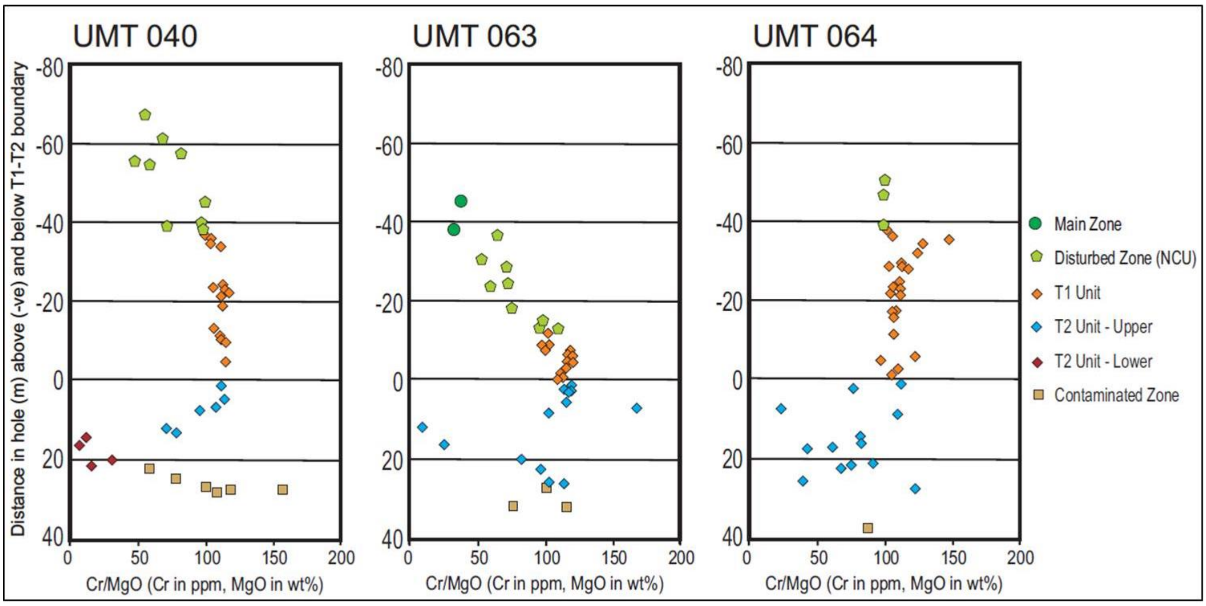


Figure 6.3. Plot of the distribution of the Cr/MgO ratios in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

In order to test whether the major element oxides are related to the changes in mineralogy, the CIPW norms were calculated. Average values for the dominant minerals are shown in Table 6.2 below, a complete dataset is included in Appendix 2. In general, the Main Zone comprises higher modal plagioclase than all other lithological units, followed by the NCU. This corresponds with higher concentrations of Al_2O_3 and Na_2O in these lithological units. Hypersthene which is related to higher concentrations of MgO, is dominant in the NCU, T1 and T2 Upper, whereas the olivine, which is also related to higher amounts of MgO, is the highest in T2 Lower. The T2 Upper in both UMT063 and UMT064 comprise higher modal olivine compared to the NCU and the T1. However, based on the olivine content these holes can be divided into two sub-units, i.e. the topmost portions that are poorer in olivine content and the lowermost portions with higher olivine content. Magnetite which is related to the iron content is generally higher in the T2 Upper and T2 Lower.

Table 6.2. Average CIPW norms (%) per lithological unit. NCU = Disturbed Zone, T1 = Feldspathic orthopyroxenite, T2 Upper = Pegmatoidal (feldspathic) pyroxenite, T2 Lower = Harzburgite, CZ = Contaminated Zone

UMT040										
	NCU	NCU Range	T1	T1 Range	T2 Upper	T2 Upper Range	T2 Lower	T2 Lower Range	CZ	CZ Range
	9 samples		18 samples		6 samples		4 samples		6 samples	
Plagioclase	52.24	19.94-82.83	16.78	10.73-19.66	12.07	6.50-19.05	11.69	9.96-12.99	19.18	12.84-27.49
Diopside	6.54	2.89-9.18	8.03	5.22-12.66	8.72	5.21-11.78	4.00	2.26-6.52	8.11	4.27-14.21
Hypersthene	35.58	3.42-67.48	70.92	68.55-73.57	72.23	64.01-76.11	23.84	13.19-47.21	61.55	57.56-68.88
Olivine	0.86	0.00-4.34	0.41	0.00-2.49	3.02	0.00-6.31	56.59	35.10-68.49	7.89	3.88-14.82
Magnetite	1.14	0.39-1.90	1.88	1.67-2.10	2.17	1.74-2.51	2.79	2.67-2.91	1.99	1.68-2.16

UMT063										
	MZ	MZ Range	NCU	NCU Range	T1	T1 Range	T2 Upper	T2 Upper Range	CZ	CZ Range
	2 samples		9 samples		13 samples		13 samples		3 samples	
Plagioclase	60.26	53.81-66.70	42.87	22.43-67.36	20.85	14.51-25.51	20.16	9.70-72.40	19.69	13.44-25.12
Diopside	16.30	10.24-22.36	7.86	5.81-9.11	8.73	6.29-12.76	10.29	2.86-31.55	41.14	23.98-53.9
Hypersthene	13.10	10.94-15.25	44.15	20.80-64.83	66.04	59.87-67.91	52.41	14.20-74.32	14.32	0.00-26.04
Olivine	0.00	0.00	0.01	0.00-0.06	0.74	0.00-3.01	13.29	0.00-64.18	21.91	12.74-35.68
Magnetite	0.87	0.80-0.93	1.40	0.86-1.94	1.78	1.61-2.20	2.08	0.78-3.35	1.57	1.20-1.87

UMT064								
	NCU	NCU Range	T1	T1 Range	T2 Upper	T2 Upper Range	CZ	CZ Range
	2 samples		13 samples		23 samples		3 samples	
Plagioclase	19.59	17.43-21.49	18.36	8.64-30.11	14.27	7.30-23.88	18.09	12.16-24.01
Diopside	7.89	7.67-8.25	9.10	5.04-16.68	10.18	2.18-34.54	34.06	17.67-50.45
Hypersthene	66.52	64.74-69.32	65.10	44.88-70.11	56.15	24.12-73.02	27.35	18.17-36.52
Olivine	0.12	0.00-0.36	0.96	0.00-10.11	14.25	0.00-56.68	15.59	2.72-28.45
Magnetite	1.74	1.70-1.77	1.76	1.38-2.32	2.12	1.73-2.84	1.78	1.10-2.45

6.3.2 Trace elements

The variation in trace element abundances was also examined in the different lithologies of the upper section of the Platreef. Again as with the major element data, only parameters with significant geochemical variations across lithological units are presented. PGE (Pt, Pd + Au), Ni, Cu and S data were also used in this evaluation and are located in Appendix 3. The PGE, Ni, Cu and S data were taken from metre samples throughout the upper section of the Platreef and not from the quarter core samples used for major elements analyses i.e. different dataset from the same holes. Average trace element abundances per lithological unit are shown in Table 6.3.

In general, the Disturbed Zone consists of lower amounts of Co, Pb, Ni and Cu; and higher amounts of Sr than the T1, T2 Upper, T2 Lower and the Contaminated Zone. Whereas, the T2 Lower comprises lower amounts of Sc and Cr compared to the Disturbed Zone, T1, T2 Upper and the Contaminated Zone.

Table 6.3. Average trace elements (ppm) per lithological unit. NCU = Disturbed Zone, T1 = Feldspathic orthopyroxenite, T2 Upper = Pegmatoidal (feldspathic) pyroxenite, T2 Lower = Harzburgite, CZ = Contaminated Zone

	NCU	NCU Range	T1	T1 Range	T2 Upper	T2 Upper Range	T2 Lower	T2 Lower Range	CZ	CZ Range
	21 samples		54 samples		32 samples		4 samples		11 samples	
Sc	25.90	12.81-35.04	30.70	21.70-39.07	27.02	8.93-45.52	13.13	9.29-19.84	32.28	21.88-60.52
V	125.96	35.55-190.79	149.55	108.54-230.49	163.93	39.66-502.42	123.50	48.01-219.90	343.29	146.60-617.22
Cr	1125.07	130.82-2186.17	2422.05	1619.86-3205.83	1935.32	309.50-2895.65	465.24	228.79-844.53	2242.90	1297.35-4058.79
Co	61.41	12.33-92.95	104.87	81.23-229.03	177.67	63.31-579.28	216.90	159.22-264.00	135.51	64.01-211.81
Ni	392.63	61.26-965.74	1694.26	534.68-10415.70	5587.62	703.75-30707.40	4226.23	2855.71-6243.07	2029.23	355.30-4503.67
Cu	65.80	13.43-264.36	699.76	26.99-6178.11	2591.04	163.16-11895.90	2000.87	1250.55-2491.19	923.39	201.93-1638.43
Zn	63.21	16.43-97.65	82.64	57.82-104.81	80.03	21.32-104.00	86.95	72.85-103.64	66.25	33.08-92.69
Ga	12.92	6.42-20.14	6.81	3.75-11.31	5.72	1.90-15.46	3.87	2.92-4.41	6.58	3.73-9.40
Rb	12.40	2.86-49.16	11.15	3.93-106.99	9.13	2.53-39.38	5.13	1.00-8.47	5.77	0.50-9.56
Sr	184.75	50.55-364.02	63.62	22.15-126.50	39.55	3.33-170.20	32.80	21.01-41.29	80.67	4.11-177.42
Y	6.60	1.67-9.71	6.16	2.63-13.57	4.36	1.52-9.17	2.46	1.45-3.58	4.90	1.10-11.06
Zr	26.61	9.90-63.17	21.38	8.67-98.52	20.89	5.86-78.64	21.02	7.77-33.80	16.42	6.67-52.70
Nb	2.43	0.58-5.72	2.46	0.13-11.03	2.22	0.00-7.30	2.20	1.41-2.88	1.32	0.48-1.97
Mo	0.46	0.00-1.33	0.81	0.00-2.21	0.91	0.00-2.49	0.76	0.00-2.18	1.04	0.28-2.60
Ba	118.46	42.52-216.42	78.97	42.17-708.89	49.15	6.58-114.82	36.34	16.46-52.95	84.07	7.56-221.03
Pb	2.13	0.00-4.94	4.56	0.94-28.34	8.39	0.74-35.99	7.09	5.48-9.31	6.10	0.00-34.50
Th	3.77	0.51-7.09	3.47	0.00-10.37	3.65	0.11-7.58	5.15	4.02-6.55	2.64	0.05-6.88
U	0.83	0.00-3.01	0.00	0.00-5.26	0.00	0.00-4.33	0.00	0.00	0.00	0.00
Cr/V	7.94	2.49-15.12	16.64	11.20-23.18	13.01	4.87-23.98	4.24	2.95-7.04	7.21	3.52-13.58
Nb/Th	0.80	0.34-2.51	1.07	0.18-12.00	0.88	0.00-5.47	0.42	0.35-0.56	1.92	0.17-9.60
Ba/Zr	5.92	1.30-17.15	3.88	1.06-12.16	3.14	0.56-13.86	2.09	1.50-2.36	6.46	1.13-12.49

Trace element of V, Cr/V and Cu/Pd ratios were used to describe the differences between and within the lithological units. In all the drill holes, the V content in the Disturbed Zone ranges from 50 – 200 ppm, whereas in the T1 it ranges from 110 – 200 ppm (Figure 6.4). In UMT040, the T2 Upper contains V in the range of 150 – 210 ppm. In UMT063 and 064, the T2 Upper can be divided into two sub-units. The topmost portions contain V ranging from 50 – 200 ppm, while the lowermost parts contain 280 – 10 ppm, decreasing upwards. The T2 Lower in UMT040 contains V ranging from 210 – 20 ppm, and it decreases upwards. The Contaminated Zone comprises V in the range of 150 – 650 ppm.

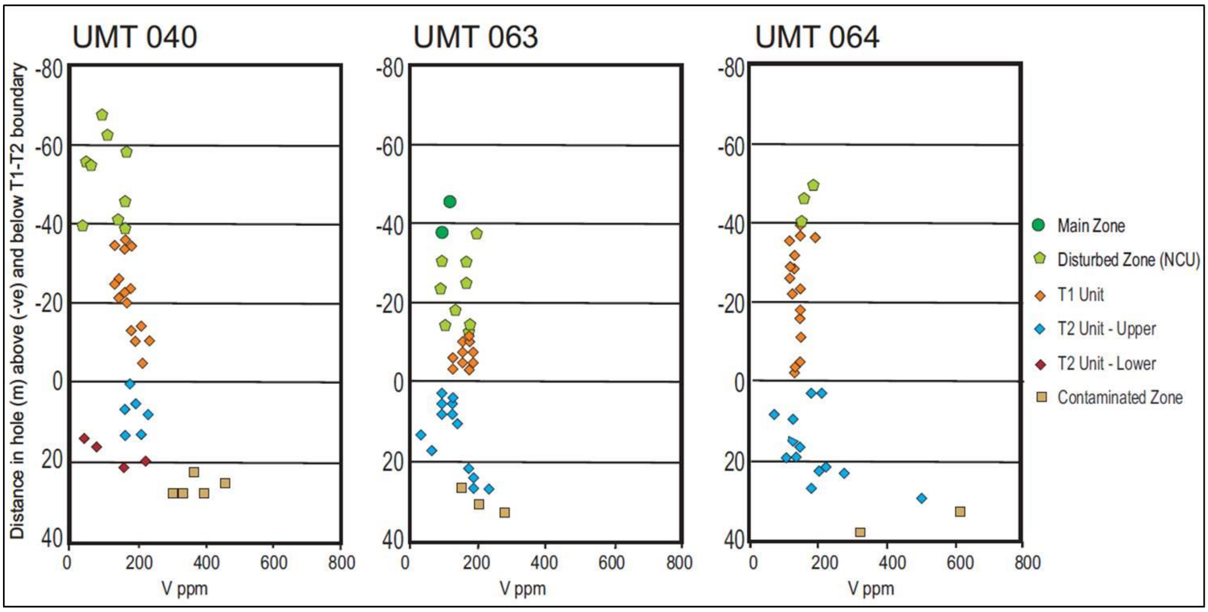


Figure 6.4. Plot showing the distribution of V in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

The Cr/V ratio in the Disturbed Zone ranges from 1 – 15, whereas in the T1 it ranges from 10 – 25 (Figure 6.5). In UMT040, the T2 Upper contains Cr/V ratios in the range of 9 – 15, increasing upwards. In UMT063 and 064, the T2 Upper can be divided into two sub-units. The topmost portions contain Cr/V ratios ranging from 13 – 25, while the lowermost parts contain ratios in the range of 4 – 15. The T2 Lower in UMT040 contains Cr/V ratios ranging from 2 – 8, and it increases upwards. The Contaminated Zone comprises Cr/V ratios in the range of 2 – 14.

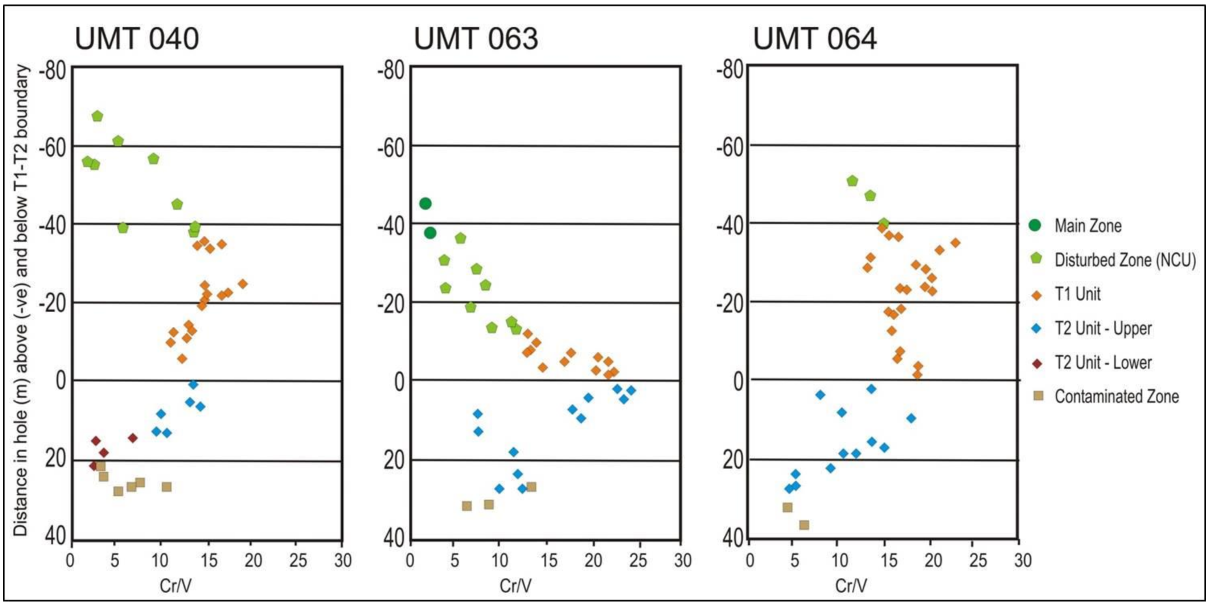


Figure 6.5. Plot showing the distribution of Cr/V ratios in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

The Cu/Pd ratio in the Disturbed Zone ranges from 700 – 70 000 in the drill holes (Figure 6.6). In UMT040, the T1 can be divided into two sub-units i.e. the topmost portion comprising Cu/Pd ratios from 800 – 12 000, and the lowermost portion comprising ratios in the range of 7000 – 120 000. The ratios in the topmost portion are decreasing upwards from the base of the unit and they become constant, and then they increase upwards towards the top of the unit. The basal portion of the lowermost portion of the T1 comprises ratios in the range of 120 000 – 10 000, which decreases upwards and thereafter followed by an upward increase. In UMT064, the T1 can also be divided into two sub-units i.e. the topmost portion comprising ratios in the range of 800 – 10 000, increasing upwards; and a lowermost portion comprising ratios from 1000 – 10 000. UMT063 comprises ratios in the range of 1000 – 10 000.

In all the drill holes, both the T2 Upper and T2 Lower comprise ratios ranging from 3000 – 800, and they decrease upwards. The Contaminated Zone comprises ratios in the range of 6000 – 900, and they are also decreasing upwards.

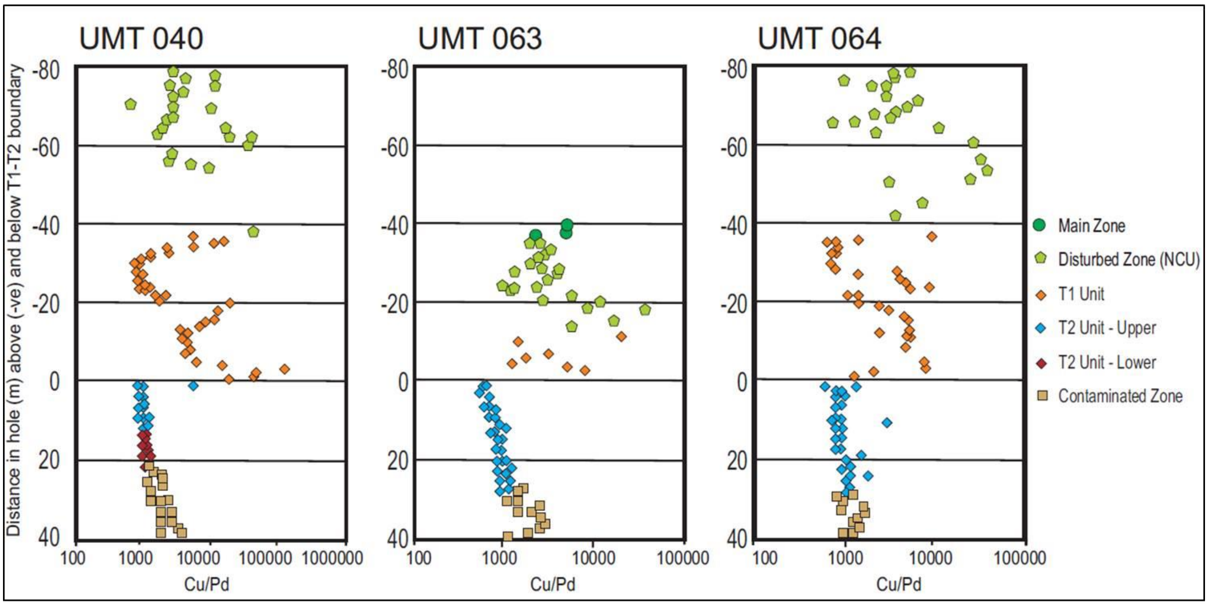


Figure 6.6. Plot showing the distribution of Cu/Pd ratios in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

6.4 Mineral Chemistry

A total of 15 samples were collected within the T1 and T2 Upper in UMT064 for orthopyroxene microprobe analyses, with the objective to investigate whether there is a significant chemical compositional variation in the two lithologies. Samples were prepared at the University of Witwatersrand and processed at Rhodes University. They were analysed using an automated Jeol JXA 8230 (electron-probe microanalyser) Superprobe. The sample suite comprised 11 samples in T1 (including 5 samples in T1m) and 4 samples in T2 Upper. Each orthopyroxene grain was analysed three or four times. Table 6.4 below shows the averaged results per sample. A complete dataset can be found in Appendix 4.

This investigation was particularly focussed on the nickel concentration of the orthopyroxenes in the two geological units (Figure 6.7). However, variations in MgO/((MgO)+FeO) ratio were also observed. In the T1, the MgO/((MgO)+FeO) ratio ranges from 0.7 – 0.725 and shows a slight upward increase through the lithological unit, whereas, in the T2 Upper the ratio ranges from 0.68 – 0.73 and increases upwards. The Ni content in the T1 ranges from 550 – 850 ppm and display a steady upward increase, while in the T2 Upper it ranges from 1010 – 700, decreasing upwards.

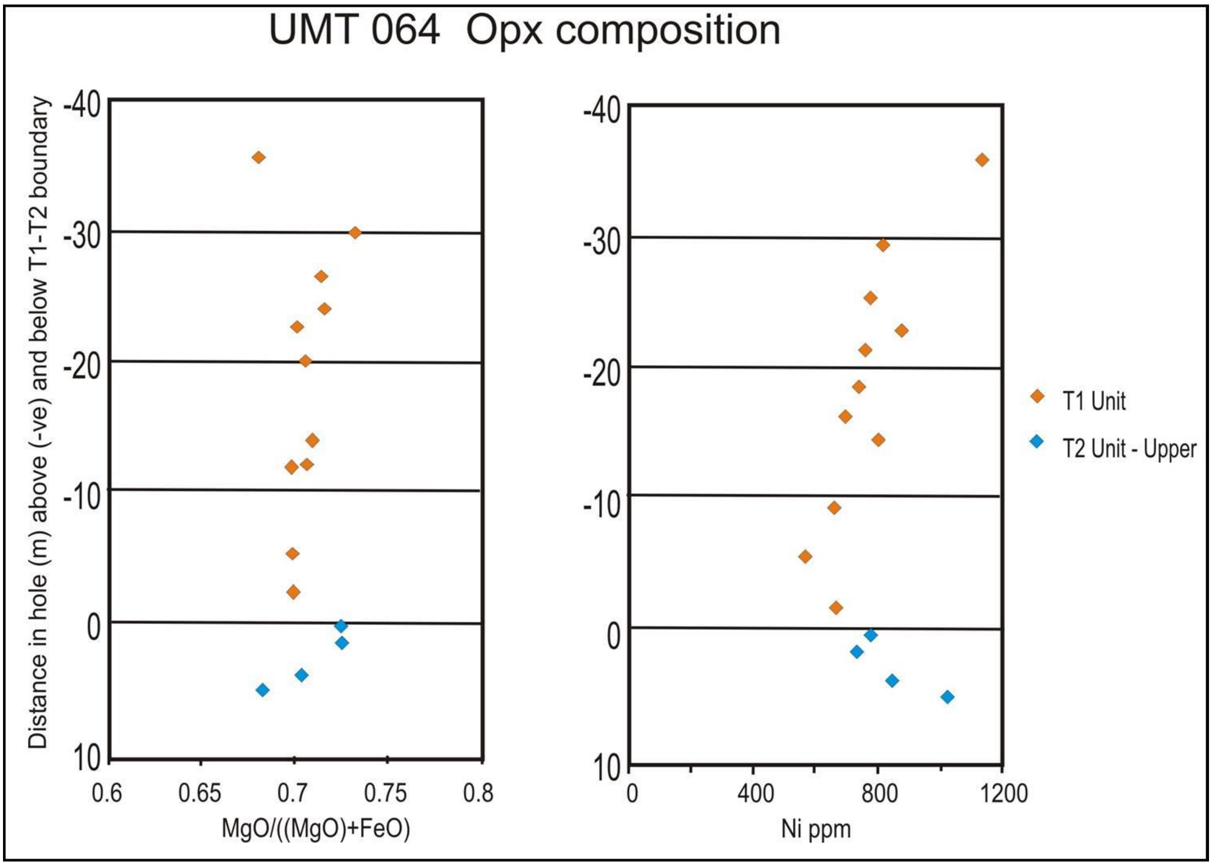


Figure 6.7. Diagram showing the distribution of MgO/((MgO)+FeO) ratio and Ni (ppm) in UMT064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

Table 6.4. UMT064 Orthopyroxene microprobe data (wt %)

Sample no.	SO43 064	SO45 064	SO46 064	SO47 064	SO48 064	SO49 064	SO50 064	SO52 064	SO54 064	SO56 064	SO57 064	SO58 064	SO59 064	SO60 064	SO61 064
Depth (m)	819.29 - 819.44	825.75 - 825.90	829.70 - 829.85	832.21 - 832.38	833.68 - 833.86	836.50 - 836.69	838.7 - 838.86	840.55 - 840.74	845.52 - 845.68	849.23 - 849.38	853.11 - 853.26	855.27 - 855.43	856.53 - 856.69	858.80 - 858.95	860.05 - 860.20
SiO2	54.66	55.18	55.07	55.72	56.57	55.47	55.62	55.47	55.36	55.40	55.97	55.51	55.66	55.86	55.52
Al2O3	1.33	1.73	1.36	1.34	3.62	1.45	1.26	1.25	1.53	1.47	1.25	1.56	1.41	1.32	1.26
FeO	12.99	10.18	11.47	11.71	9.82	12.26	11.98	12.55	12.17	12.42	12.47	11.24	11.46	12.39	13.40
MnO	0.25	0.22	0.22	0.25	0.16	0.24	0.26	0.25	0.26	0.23	0.25	0.22	0.22	0.24	0.24
MgO	27.41	27.86	28.51	29.26	24.74	29.05	28.93	28.64	28.97	28.54	28.67	29.15	29.95	29.10	28.54
CaO	2.31	4.45	2.85	1.70	2.72	1.53	1.60	1.40	1.29	1.95	1.43	1.99	1.44	1.48	1.32
Na2O	0.03	0.07	0.04	0.03	0.15	0.03	0.02	0.02	0.01	0.02	0.01	0.03	0.02	0.01	0.02
K2O	0.02	0.02	0.02	0.02	1.74	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02
TiO2	0.21	0.13	0.12	0.17	0.14	0.13	0.14	0.12	0.12	0.14	0.15	0.11	0.11	0.15	0.16
Cr2O3	0.44	0.56	0.44	0.45	0.28	0.45	0.43	0.44	0.46	0.39	0.40	0.48	0.37	0.43	0.35
NiO	0.14	0.09	0.10	0.11	0.12	0.09	0.09	0.10	0.08	0.07	0.08	0.10	0.09	0.11	0.13
Total	99.79	100.50	100.20	100.75	100.09	100.73	100.33	100.26	100.27	100.65	100.70	100.43	100.74	101.11	100.96
MgO/((MgO)+FeO)	0.68	0.73	0.71	0.71	0.72	0.70	0.71	0.70	0.70	0.70	0.70	0.72	0.72	0.70	0.68

6.5 Discussion

There is a disagreement between the interpretation of the geological logging and the chemistry of the rocks. In UMT040, the geological logging has broken down the T2 unit into T2 Upper (orthopyroxenite – (feldspathic in places)) and T2 Lower (harzburgite), whereas in UMT063 and 064 the entire T2 unit has been logged as T2 Upper. However, the lowermost portions of the T2 in both UMT063 and 064 have many of the characteristics of the T2 Lower in UMT040. These include high MgO, and in places lower Cr/MgO and Cr/V ratios; and lower V content. The T2 Upper in UMT040 and the topmost portions of the T2 Upper in UMT063 and 064 display a general upward increase in Cr/MgO ratio (Figure 6.8) and a decrease in V content (except in UMT064) (Figure 6.9). Whereas, the T2 Lower in UMT040 and the lowermost portions of the T2 Upper in UMT063 and 064 show a general upward increase in MgO (Figure 6.10), a decrease in V content (Figures 6.9), and a decrease in Cr/MgO ratio (Figure 6.8). The topmost portion of the T2 Upper in UMT063 displays an upward increase in Cr/V ratios similar to the T2 Upper in UMT040, whereas in UMT064, the lowermost portion also displays an upward increase in Cr/V ratios similar to the T2 Lower in UMT040 (Figure 6.11). The observed differences between the T2 Lower in UMT040 and the lowermost portions of the T2 Upper in UMT063 and 064 shows that the criteria used to distinguish the T2 Upper and Lower were not definitive, and therefore are not reliable.

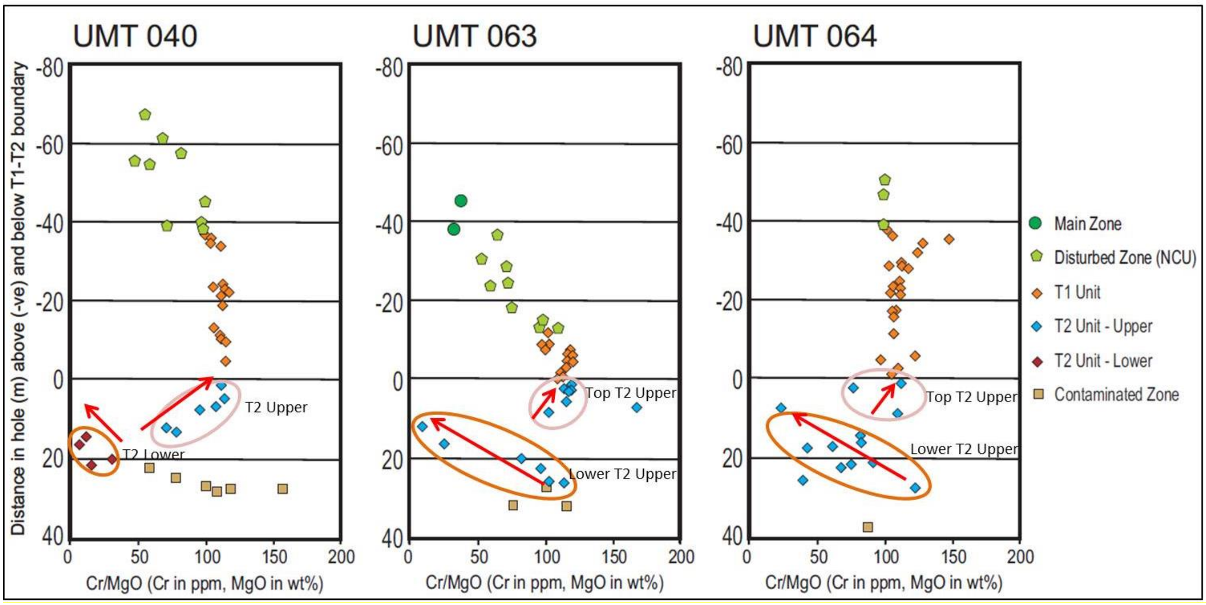


Figure 6.8. Interpreted zones of Cr/MgO ratio in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

The Cu/Pd ratios do not display the differences in the T2 unit as observed in figure 6.8 above. However, they do show different patterns within the T1 in UMT040 (Figure 6.12). As discussed in chapter 5, these trends are attributed to the fractional segregation of sulphides from at least two batches of magma, whereas, the trends observed in the T2 are thought to represent the sulphides that were emplaced as a mush or in bulk and did not undergo any segregation. The upward decrease in Cu/Pd ratio in the T2 suggests that the sulphides were in equilibrium with a magma that was gradually getting PGE enriched.

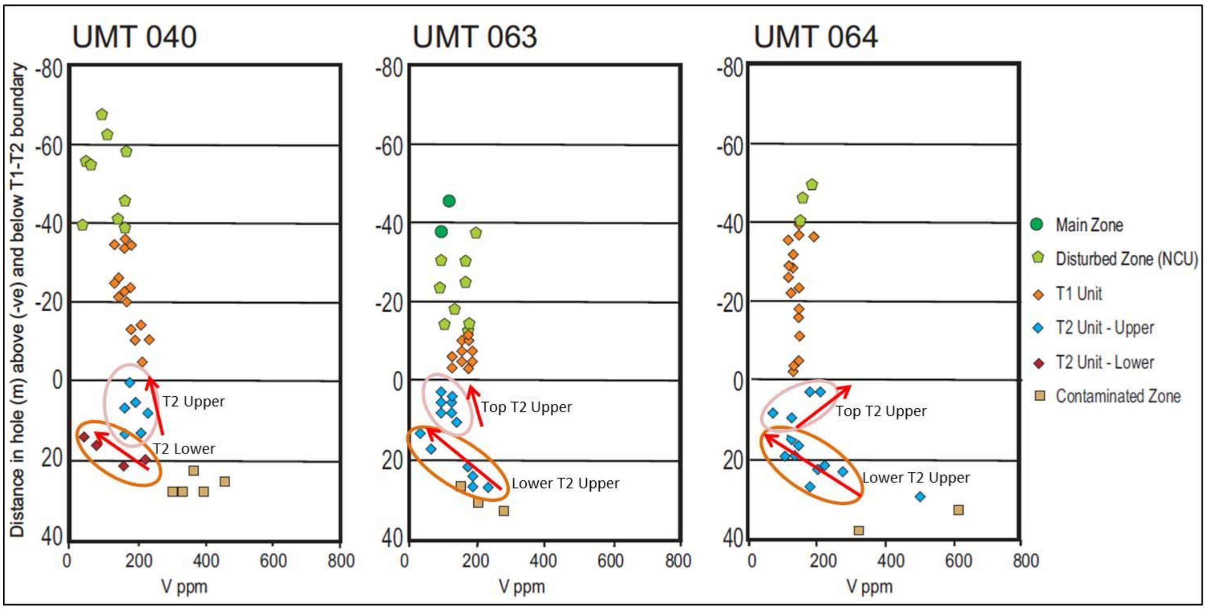


Figure 6.9. Interpreted zones of V content in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

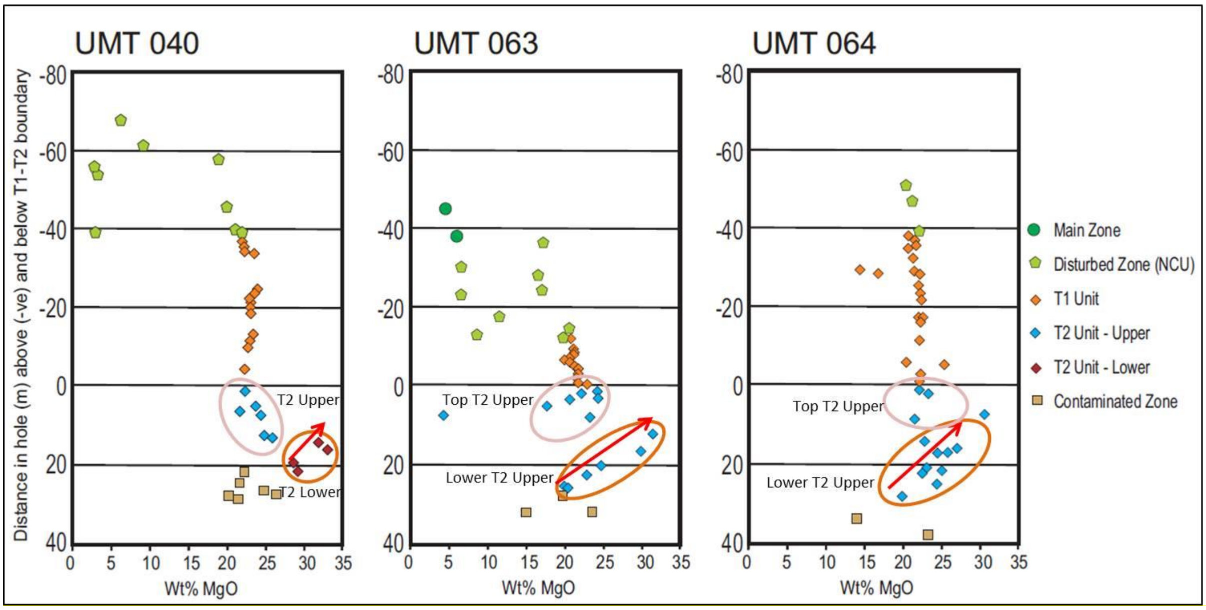


Figure 6.10. Interpreted zones of MgO content in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

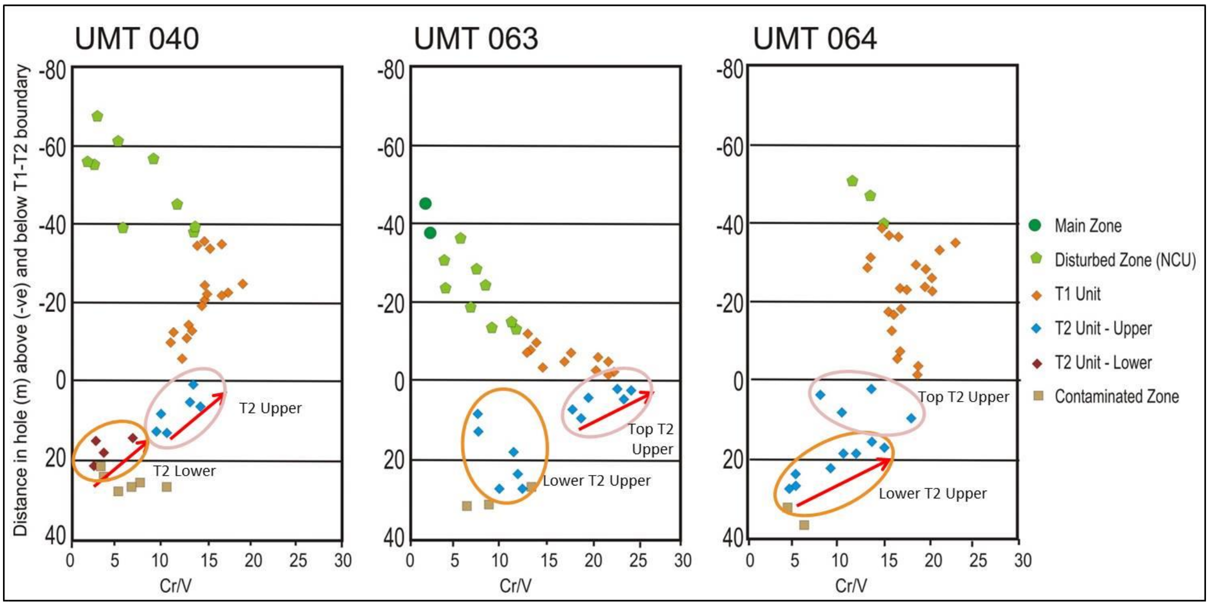


Figure 6.11. Interpreted zones of Cr/V ratio in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

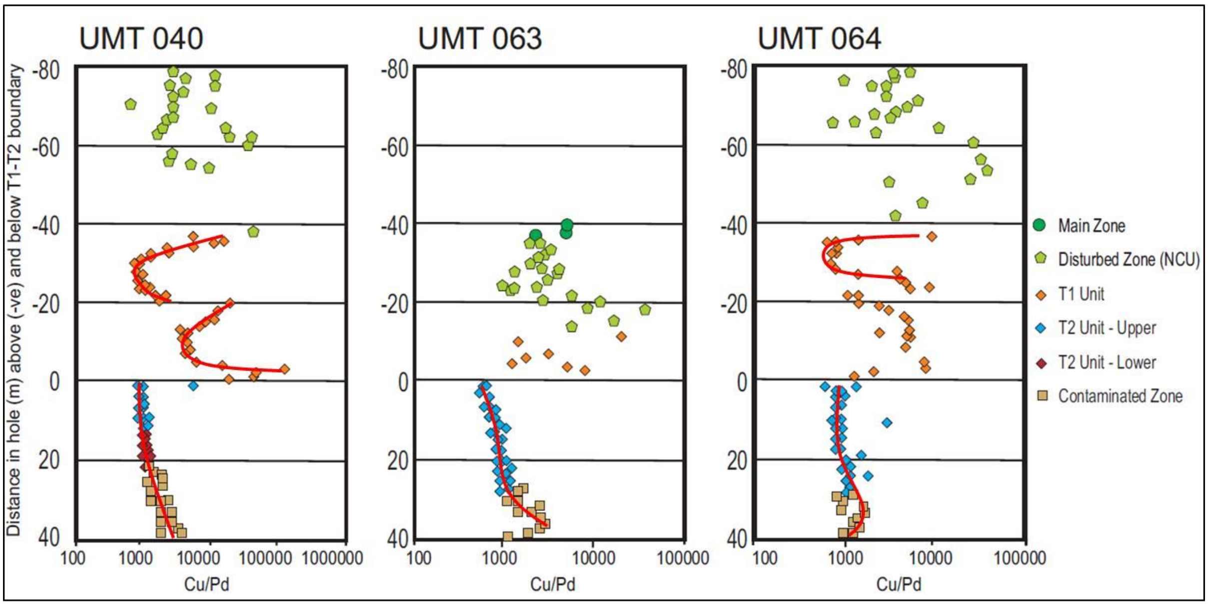


Figure 6.12. Interpreted Cu/Pd ratio trends in the T1 and T2 units. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

The Ni content and the MgO/((MgO)+FeO) ratio of the orthopyroxenes in both T1 and T2 have demonstrated that these lithological units were formed by magmatic pulses of different chemical compositions (Figure 6.13).

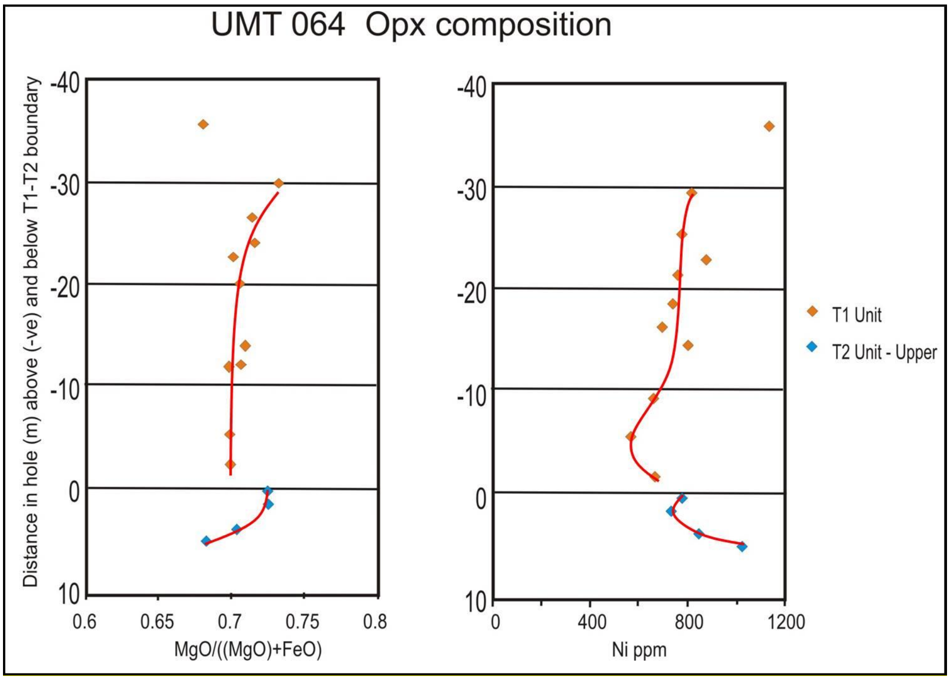


Figure 6.13. Interpreted trends of Ni (ppm) and MgO/((MgO)+FeO) ratio in the orthopyroxenes. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e. T1-T2 boundary = 0

6.6 Comparison of geological logs and the chemistry of the rocks

The harzburgites below the T2 Upper show an unusual chemistry. They have high MgO values >30 wt%, but corresponding low Cr values (228 – 845 ppm) in contrast to the Cr values of the T1 feldspathic pyroxenite (~>2000 ppm). These low Cr values of the harzburgites result in Cr/MgO values of 7 – 29 (compared to values of >100 for the T1) and low Cr/V values of 3 – 7 in contrast to the feldspathic pyroxenite of >10. This might suggest that the harzburgite is a raft of serpentinised calc-silicates. However, texturally the harzburgites appear igneous and; the high Cu and Ni values of these rocks which are greater than most of the T1 rocks would support. Thus the harzburgite has Ni values of 2856 – 6243 ppm and Cu values of 1250 – 2491 ppm as shown in Appendix 3. In comparison with the geochemical data of McDonald et al (2005), the harzburgite is comparable to the serpentinised para (clino) pyroxenite, calc-silicates and footwall hybrid with respect to the SiO_2 and Cr contents. Their silica content ranges from ~39 – 44 wt% (compared to values of 41 – 47 in the harzburgite in UMT040) and the Cr is about 20 – 835 ppm. It is noted that even though the rock chemistry suggests that the lowermost portions of the T2 Upper in UMT063 and 064 should be logged as T2 Lower, this will create a challenge for the logging geologist as the samples showing the characteristics of the T2 Lower in these drill holes are actually serpentinised feldspathic pegmatoidal orthopyroxenites. The olivines in these samples are not completely serpentinised (not black in colour) as it is the case in the harzburgites (T2 Lower "proper") and therefore with a naked eye there is no justification to naming these rocks as harzburgites, but chemically they are harzburgites. Most of the samples in these lowermost portions have Cr values similar to those in the T1 feldspathic pyroxenite. Further systematic geochemical analyses are warranted through the serpentinised feldspathic pegmatoidal orthopyroxenites in order to determine the actual boundaries of this change in chemistry.

6.7 Summary and conclusions

Based on the Cu/Pd ratios there is sufficient evidence to suggest that the T1 unit was formed from at least two pulses of magma. The lack of differences in the Ni and MgO/((MgO)+FeO) in the orthopyroxenes within the T1 suggests that these two pulses comprised the same chemical composition. The lowermost portions of the T2 Upper in UMT063 and 064 should be logged as T2 Lower. This separation of the T2 Upper into the topmost and lowermost portions is supported by the chemistry of the rocks as shown by the MgO and V contents, the Cr/MgO and Cr/V ratios; and the olivine content from the CIPW norms. The disagreement between the geological logging and the chemistry of the rocks can be better understood by conducting a further systematic sampling through the serpentinised feldspathic pegmatoidal orthopyroxenites and analyzing the samples for major and trace elements. Petrographic studies will also play an important part in addressing this challenge.

6.8 Comparison with the Critical Zone (Merensky Reef)

In 2012, Grobler and Nielsen correlated the upper section of the Platreef with the Merensky Cyclic Unit (MCU) of the eastern and western limbs. They then called the upper section of the Platreef the Turfspruit Cyclic Unit (TCU). The TCU was specifically correlated with the Upper Critical Zone of the Amandelbult – Union Section – Northam mines in the northwestern Bushveld and the northwestern sector of the eastern Bushveld southeast of Mokopane. In comparison with the Swartklip facies of the western Bushveld, they correlated the Disturbed Zone (NCU) of the TCU with the Bastard Cyclic Unit, the T1 and T2 Upper with the Merensky Cyclic Unit, T2 Upper was directly correlated with the Merensky Reef; and the T2 Lower was correlated with the Tarentaal harzburgite (Figure 6.14). Furthermore, Grobler and Nielsen have interpreted the T2 Lower to occur in areas that are thought to be potholes.

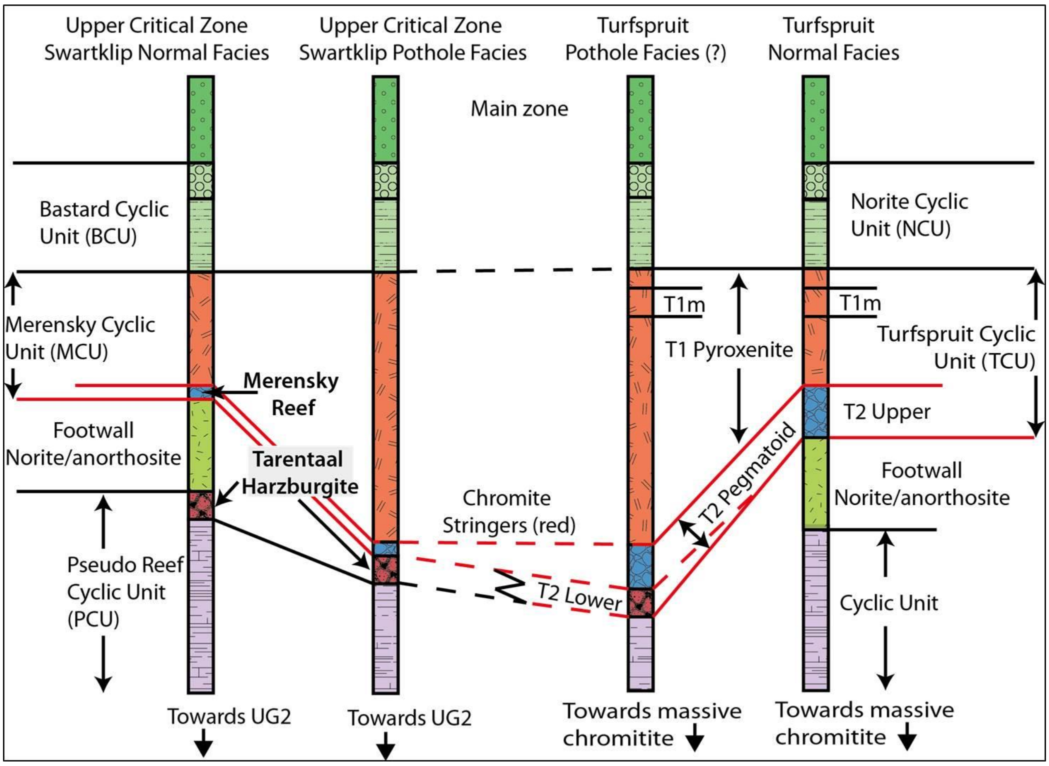


Figure 6.14. Correlation of the upper section of the Platreef with the Swartklip facies of the western Bushveld (After Grobler and Nielsen, 2012). Note that the Disturbed Zone is equated to the Norite Cyclic Unit (NCU)

In order to validate the comparison between the TCU and MCU, the major and trace elements data discussed above were compared with the data from the Merensky Cyclic Unit in the eastern and western Bushveld Complex. Ni and Cu analyses were excluded from these comparisons due to their elevated concentrations in the Platreef. Using the Cr/MgO parameter of Seabrook et al., (2005), the T1 and T2 Upper show values above 80 (Table 6.5). This is comparable to the Critical Zone in the eastern and western limbs and to the Platreef data of Kinnaird (2005). In addition, the averaged data of Seabrook show that SiO_2, TiO_2 and P_2O_5 contents in the Merensky pyroxenite are comparable to those in the T1 and T2 Upper. Similar P_2O_5 content was also observed in the T2 Lower.

Table 6.5. Comparison of major element data (wt %) for the Merensky Reef and the upper section of the Platreef (TCU). Merensky analyses were compiled by Seabrook et al (2005). Note that the original data of Seabrook were averaged. T1 = Feldspathic orthopyroxenite, T2 Upper = Pegmatoidal (feldspathic) pyroxenite, T2 Lower = Harzburgite, CZ = Contaminated Zone

	MR pyroxenite analyses	Range	Platreef TCU analyses							
			T1	Range	T2U	Range	T2L	Range	CZ	Range
SiO2	51.28	48.32-53.53	53.99	52.48-57.11	51.39	42.13-54.30	43.30	41.34-47.08	50.22	46.20-52.59
TiO2	0.20	0.12-0.36	0.26	0.15-0.64	0.25	0.12-0.37	0.13	0.09-0.18	0.24	0.14-0.41
Al2O3	16.49	5.80-29.03	6.09	2.76-10.28	5.25	2.20-23.49	4.01	3.49-4.49	6.52	3.92-9.34
FeO	3.34	2.40-12.55	6.32	7.69-12.82	5.48	4.37-17.70	4.12	14.71-16.04	6.73	6.09-13.16
MnO	0.13	0.04-0.21	0.20	0.14-0.23	0.20	0.09-0.23	0.18	0.16-0.22	0.19	0.15-0.22
MgO	13.53	1.70-22.23	22.00	14.59-25.53	23.30	4.33-31.40	30.72	28.65-33.07	21.21	14.18-26.27
CaO	8.76	4.31-14.40	4.71	3.74-5.51	4.78	2.06-12.44	2.92	2.59-3.56	8.55	3.38-18.42
Na2O	1.42	0.70-2.61	0.73	0.41-1.76	0.45	0.05-2.46	0.26	0.15-0.40	0.44	0.12-0.75
K2O	0.09	0.02-0.17	0.30	0.11-1.72	0.26	0.04-0.75	0.13	0.06-0.20	0.19	0.01-0.46
P2O5	0.03	0.02-0.04	0.03	0.01-0.17	0.03	0.01-0.05	0.03	0.02-0.04	0.02	0.01-0.03
Cr/MgO	167.56	109.00-274.00	109.99	97.07-146.92	92.16	9.86-164.75	15.59	6.92-29.48	108.69	58.36-201.61

Considering the averaged data of Cawthorn and Boerst (2006) in the samples from Impala Platinum Mine, the following similarities were noted: (1) SiO_2 and TiO_2 contents in the Merensky pyroxenites are comparable to those found in the T1 and T2 Upper in all samples; (2) Zr content in the Merensky pyroxenites is comparable to that found in the T1, T2 Upper and T2 Lower; (3) MnO, Rb, Cr, MgO, Al_2O_3, CaO and Na_2O in the T1, T2 Upper and T2 Lower were also comparable to some of the Merensky pyroxenite samples.

In the averaged data of Arndt et al (2005) from the western Bushveld, SiO_2, TiO_2 and MnO contents in the Merensky pyroxenite were found to be comparable to those in the T1 and T2 Upper, whereas the Y and Cr contents were comparable with those in the T1 (Table 6.6).

Table 6.6. Comparison of major element data (wt %) for the Merensky Reef and the upper section of the Platreef (TCU). Merensky analyses were compiled by Arndt et al (2005). Note that the original data of Arndt were averaged. T1 = Feldspathic orthopyroxenite, T2 Upper = Pegmatoidal (feldspathic) pyroxenite, T2 Lower = Harzburgite, CZ = Contaminated Zone. NB: trace elements reported in ppm

	MR pyroxenite analyses	Platreef TCU analyses							
		T1	Range	T2U	Range	T2L	Range	CZ	Range
SiO2	53.93	53.99	52.48-57.11	51.39	42.13-54.30	43.30	41.34-47.08	50.22	46.20-52.59
TiO2	0.35	0.26	0.15-0.64	0.25	0.12-0.37	0.13	0.09-0.18	0.24	0.14-0.41
MnO	0.16	0.20	0.14-0.23	0.20	0.09-0.23	0.18	0.16-0.22	0.19	0.15-0.22
Na2O	1.02	0.73	0.41-1.76	0.45	0.05-2.46	0.26	0.15-0.40	0.44	0.12-0.75
K2O	0.98	0.30	0.11-1.72	0.26	0.04-0.75	0.13	0.06-0.20	0.19	0.01-0.46
P2O5	0.19	0.03	0.01-0.17	0.03	0.01-0.05	0.03	0.02-0.04	0.02	0.01-0.03
Rb	44.30	11.15	3.93-106.99	9.13	2.53-39.38	5.13	1.00-8.47	5.77	0.50-9.56
Ba	176.00	78.97	42.17-708.89	49.15	6.58-114.82	36.34	16.46-52.95	84.07	7.56-221.03
Sr	121.00	63.62	22.15-126.50	39.55	3.33-170.20	32.80	21.01-41.29	80.67	4.11-177.42
Th	6.90	3.47	0.00-10.37	3.65	0.11-7.58	5.15	4.02-6.55	2.64	0.05-6.88
U	1.10	0.00	0.00-5.26	0.00	0.00-4.33	0.00	0.00	0.00	0.00
Pb	10.80	4.56	0.94-28.34	8.39	0.74-35.99	7.09	5.48-9.31	6.10	0.00-34.50
Nb	4.10	2.46	0.13-11.03	2.22	0.00-7.30	2.20	1.41-2.88	1.32	0.48-1.97
Zr	124.00	21.38	8.67-98.52	20.89	5.86-78.64	21.02	7.77-33.80	16.42	6.67-52.70
Y	7.00	6.16	2.63-13.57	4.36	1.52-9.17	2.46	1.45-3.58	4.90	1.10-11.06
Cr	2646.00	2422.05	1619.86-3205.83	1935.32	309.50-2895.65	465.24	228.79-844.53	2242.90	1297.35-4058.79
Ni	1177.00	1694.26	534.68-10415.70	5587.62	703.75-30707.40	4226.23	2855.71-6243.07	2029.23	355.30-4503.67
Cu	598.00	699.76	26.99-6178.11	2591.04	163.16-11895.90	2000.87	1250.55-2491.19	923.39	201.93-1638.43
Zn	64.00	82.64	57.82-104.81	80.03	21.32-104.00	86.95	72.85-103.64	66.25	33.08-92.69
Co	75.00	104.87	81.23-229.03	177.67	63.31-579.28	216.90	159.22-264.00	135.51	64.01-211.81
V	116.00	149.55	108.54-230.49	163.93	39.66-502.42	123.50	48.01-219.90	343.29	146.60-617.22
Sc	17.00	30.70	21.70-39.07	27.02	8.93-45.52	13.13	9.29-19.84	32.28	21.88-60.52

The average pyroxene composition in the T1 and T2 Upper were found to be comparable to the average compositions of pyroxenes in the pyroxenites, feldspathic pyroxenites, harzburgites and melanorites from Sandsloot, Turfspruit, Akanani, Union Section and other parts of the Rustenburg area (Tables 6.7 and 6.8). Interestingly, the pyroxene compositions in the T1 and T2 Upper are comparable to those in the Critical Zone and the Platreef with respect to SiO_2, Al_2O_3, FeO, MnO, MgO, Na_2O, K_2O, TiO_2, Cr_2O_3 and NiO, compared to the major element compositions of whole rock analyses. However, the MgO/((MgO)+FeO) ratios in this study are lower (averaging 0.71) than the Mg# reported for the Merensky Reef ($Mg\#_{78\text{-}83}$), the upper Critical Zone ($Mg\#_{78\text{-}84}$) (McDonald et al, 2011) and elsewhere in the Platreef north of Turfspruit. The CaO levels (representing the wollastonite component of the orthopyroxene) at Turfspruit are higher (>2 wt %) compared to the Merensky Cyclic Unit and other parts of the northern limb where the CaO levels are below 2 wt %. This is an indication that the pyroxene composition at Turfspruit is more evolved compared to the Merensky Reef. The Cr content in the T2 Lower is much lower (~465 ppm) compared to that of the Merensky Pyroxenite (>2000 ppm).

Table 6.7. Average pyroxene composition in the T1 and T2 Upper (wt %)

	T1 11 samples	Range	T2 Upper 4 samples	Range
SiO2	55.50	54.51-59.30	55.64	55.39-55.97
Al2O3	1.60	1.11-8.77	1.39	0.93-1.52
FeO	11.82	3.57-13.74	12.12	10.65-13.65
MnO	0.24	0.01-0.30	0.23	0.20-0.25
MgO	28.23	17.80-29.55	29.19	28.47-30.21
CaO	2.11	0.73-9.48	1.56	0.93-1.89
Na2O	0.04	0.00-0.41	0.02	0.01-0.03
K2O	0.18	0.01-5.18	0.02	0.01-0.03
TiO2	0.14	0.04-0.25	0.13	0.05-0.21
Cr2O3	0.43	0.17-0.63	0.41	0.28-0.50
NiO	0.10	0.07-0.19	0.11	0.08-0.12
MgO/((Mg)+FeO)	0.71	21.37-43.29	0.71	39.12-43.85

Table 6.8. Average pyroxene data (wt %) in the Platreef and the Merensky Cyclic Unit in the western Bushveld (from unpublished data of Yudovskaya)

Area	Sandsloot		Turfspruit		Akanani							
Hole	SS371		UMT006		ZF116							
Rock Type	Pyroxenite		Harzburgite		Melanorite		Harzburgite		Feldspathic Pyroxenite		Harzburgite	
	2 samples	Range	1 sample	Range	2 samples	Range	3 samples	Range	3 samples	Range	1 sample	Range
SiO2	55.04	54.68-55.53	54.49	54.26-54.88	54.84	54.36-55.34	54.88	53.93-56.28	54.91	53.70-56.20	55.07	54.81-55.30
Al2O3	1.36	0.94-1.67	1.48	1.32-1.68	1.48	1.00-1.78	1.51	0.48-2.08	1.55	0.63-2.57	1.57	1.56-1.58
FeO	12.19	10.28-13.70	11.89	11.27-12.58	11.62	11.06-12.29	10.84	10.31-11.57	11.37	9.90-14.99	10.28	9.99-10.88
MnO	0.27	0.21-0.31	0.27	0.25-0.28	0.25	0.23-0.27	0.26	0.22-0.30	0.27	0.24-0.32	0.28	0.25-0.33
MgO	28.86	27.67-30.20	28.47	27.87-29.29	29.67	28.95-30.00	30.57	27.94-32.01	29.93	26.34-32.83	30.33	30.14-30.48
CaO	1.73	0.51-2.67	2.44	0.80-4.14	1.40	0.84-2.40	1.19	0.25-3.63	1.39	0.12-3.65	1.85	1.17-2.34
Na2O	0.03	0.00-0.08	0.04	0.02-0.05	0.03	0.01-0.07	0.02	0.00-0.10	0.02	0.00-0.08	0.05	0.01-0.07
TiO2	0.15	0.09-0.22	0.16	0.12-0.18	0.14	0.08-0.31	0.12	0.02-0.29	0.11	0.01-0.28	0.12	0.10-0.16
Cr2O3	0.46	0.32-0.59	0.42	0.32-0.49	0.54	0.44-0.68	0.35	0.07-0.62	0.39	0.02-0.64	0.49	0.36-0.57
NiO	0.10	0.08-0.10	0.07	0.06-0.07	0.10	0.10-0.11	0.10	0.05-0.12	0.07	0.02-0.14	0.05	0.05
MgO/((Mg)+FeO)	0.70	0.69-0.73	0.71	0.70-0.71	0.72	0.71-0.72	0.74	0.73	0.72	0.69-0.73	0.75	0.74-0.75

Table 6.8. Average pyroxene data (wt %) in the Platreef and the Merensky Cyclic Unit in the western Bushveld (from unpublished data of Yudovskaya), continued

Area	Union Section								Rustenburg			
Hole												
Rock Type	Harzburgite		Harzburgite		Feldspathic Pyroxenite		Harzburgite		Feldspathic Pyroxenite		Harzburgite	
	1 sample	Range	1 sample	Range	1 sample	Range	1 sample	Range	2 samples	Range	1 sample	Range
SiO2	54.60	54.08-55.23	54.67	54.34-55.33	54.60	54.36-54.79	54.76	54.46-55.16	54.33	53.63-55.21	54.94	54.27-55.58
Al2O3	1.53	1.08-1.73	1.46	1.15-1.76	1.62	1.42-1.83	1.30	0.83-1.67	1.35	0.88-1.71	1.56	1.09-1.92
FeO	11.30	10.61-11.83	11.68	11.31-12.09	11.46	10.77-11.92	11.88	11.30-12.52	12.44	10.60-13.31	11.09	9.99-12.45
MnO	0.24	0.23-0.26	0.25	0.24-0.26	0.25	0.23-0.26	0.25	0.24-0.27	0.27	0.23-0.29	0.22	0.19-0.25
MgO	29.93	28.90-30.83	29.80	29.13-30.78	29.80	28.33-30.59	29.92	29.17-30.53	29.11	27.97-30.15	29.67	27.96-30.50
CaO	1.67	0.49-3.37	1.63	0.49-2.78	1.52	0.50-3.23	1.40	0.78-2.24	1.50	0.65-4.24	1.78	0.70-4.26
Na2O	0.03	0.00-0.07	0.02	0.00-0.05	0.04	0.01-0.09	0.01	0.00-0.04	0.02	0.00-0.07	0.01	0.00-0.03
TiO2	0.15	0.12-0.18	0.19	0.13-0.28	0.16	0.11-0.24	0.27	0.11-0.36	0.21	0.12-0.32	0.21	0.15-0.28
Cr2O3	0.46	0.27-0.56	0.36	0.20-0.51	0.47	0.38-0.53	0.23	0.10-0.57	0.44	0.27-0.56	0.42	0.33-0.49
NiO	0.10	0.09-0.12	0.09	0.08-0.11	0.10	0.10-0.11	0.09	0.09-0.10	0.12	0.09-0.14	0.10	0.09-0.12
MgO/((Mg)+FeO)	0.73	0.72-0.73	0.72	0.72	0.72	0.72	0.72	0.71-0.72	0.70	0.69-0.73	0.73	0.71-0.74

6.8.1 Summary and conclusions

Major element compositions of whole rock analyses for the T1 and T2 Upper are comparable to those of the Merensky pyroxenites mainly with respect to SiO_2, TiO_2 and P_2O_5. The Cr/MgO ratio in the T1 and T2 Upper are greater than 80, similar to those of the Critical Zone in the eastern and western limbs and also for the Platreef elsewhere. The pyroxene data, excluding the MgO/((MgO)+FeO) ratio, Cr (in T2 Lower) and CaO contents, in the T1 and T2 Upper is comparable to that of the Merensky pyroxenites and other parts of the northern limb. The PGE tenors in the T1 and T2 have shown maximum values of up to 700 ppm and about1000 ppm respectively (chapter 5). These values are comparable to the PGE tenor of Naldrett et al (2009) in the western Bushveld.

Considering the process that gave rise to the formation of the Merensky Reef as discussed by Naldrett et al (2009), the whole rock geochemistry, mineral chemistry and PGE tenor, it is suggested that only the T1 can be compared with the Merensky Reef. The T2 Upper, in spite of the similarity between the whole-rock geochemistry and mineral chemistry to that of the Merensky pyroxenites, in this study it is interpreted to have been formed from a separate and different process than the T1. It is noted that the difference in thickness between the Merensky Reef and the T1m still needs to be accounted for.

Chapter 7

Discussion and conclusion

7.1 Discussion

7.1.1 Introduction

The lithological, mineralogical, geochemical and tenor variations of the upper section of the Platreef have been studied both to contribute to a greater understanding of the distribution of rock types and to gain a greater understanding on the nature of the mineralisation. By using a combination of the data it is the intention to comment on processes in the emplacement and subsolidus processes in part of the Platreef.

7.1.2 Discussion of results

There is a disagreement between the geological logging and the chemistry of the rocks. In UMT040, the geological logging has broken down the T2 unit into T2 Upper (orthopyroxenite – (feldspathic in places)) and T2 Lower (harzburgite), whereas in UMT063 and 064 only the T2 Upper was identified. However, the lowermost portions of the T2 Upper in both UMT063 and 064 have many of the characteristics of the T2 Lower in UMT040. These include high MgO (resulting in high olivine content as shown by the CIPW norms), and in places lower Cr/MgO and Cr/V ratios; and lower V contents. The T2 Upper in UMT040 and the topmost portions of the T2 Upper in UMT063 and 064 display a general upward increase in Cr/MgO ratio (Figure 7.1) and a decrease in V content (except in UMT064) (Figure 7.2). Whereas, the T2 Lower in UMT040 and the lowermost portions of the T2 Upper in UMT063 and 064 show a general upward increase in MgO (Figure 7.3), a decrease in V content (Figure 7.2), and a decrease in Cr/MgO ratio (Figure 7.1). Based on these observations it is compelling to say that the lowermost portions of the T2 Upper in both UMT063 and 064 should be logged as T2 Lower (harzburgites).

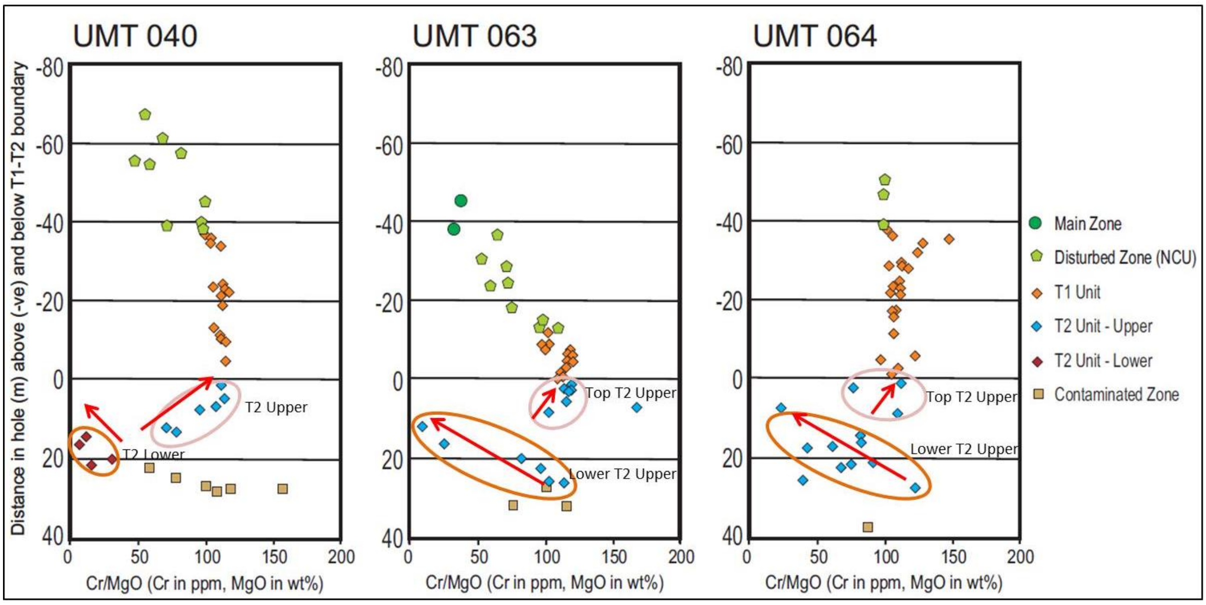


Figure 7.1. Interpreted zones of Cr/MgO ratio in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

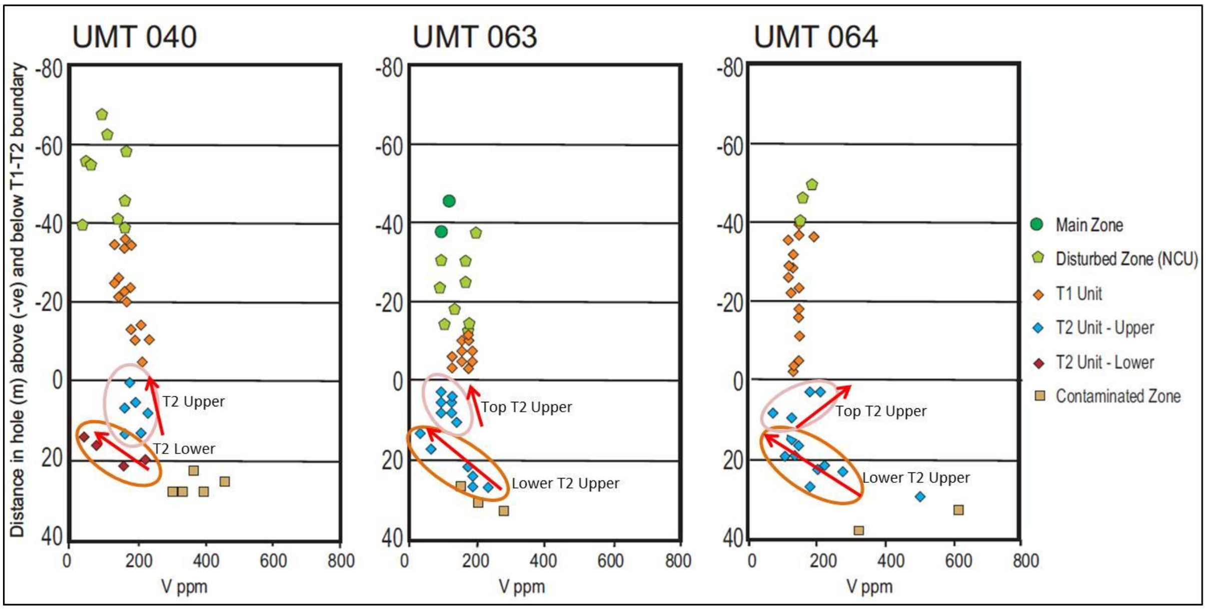


Figure 7.2. Interpreted zones of V content in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

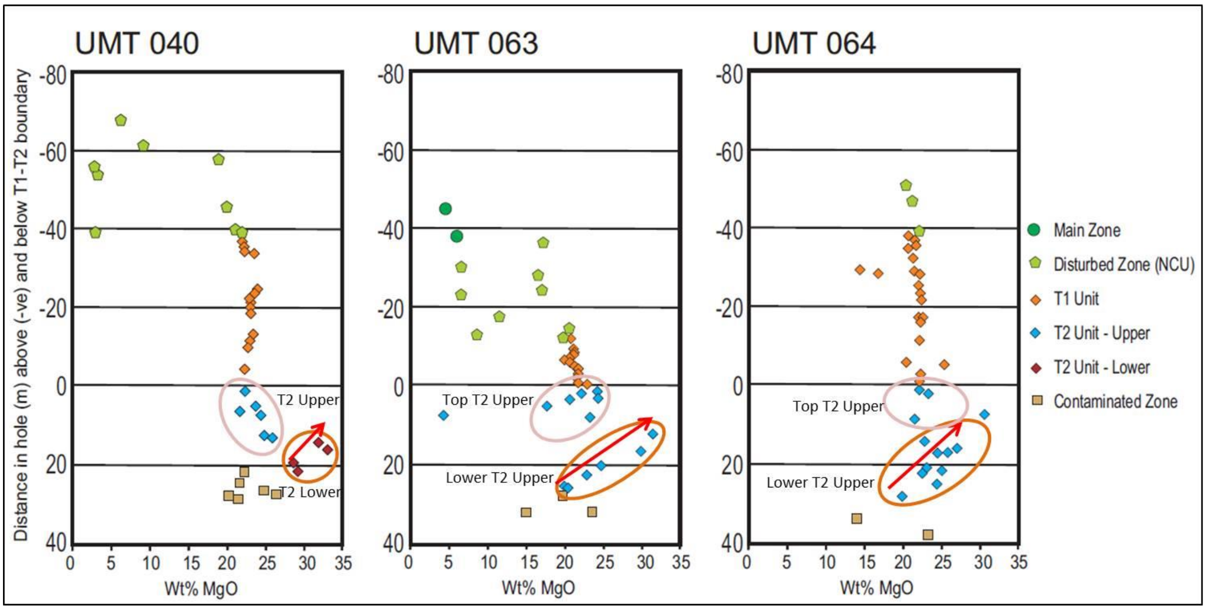


Figure 7.3. Interpreted zones of MgO content in UMT040, 063 and 064. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

However, the harzburgites below the T2 Upper show an unusual chemistry. They have high MgO values >30 wt%, but corresponding low Cr values (228 – 845 ppm) in contrast to the Cr values of the T1 feldspathic pyroxenite (~>2000 ppm). These low Cr values of the harzburgites result in Cr/MgO values of 7 – 29 (compared to values of >100 for the T1) and low Cr/V values of 3 – 7 in contrast to the feldspathic pyroxenite of >10. This might suggest that the harzburgite is a raft of serpentinised calc-silicates, meaning that these harzburgites are metamorphic in nature. However, texturally the harzburgites appear igneous, supported by the high Cu and Ni values which are greater than most of the T1 rocks. In comparison with the geochemical data of McDonald et al (2005), the harzburgite is comparable to the serpentinised para (clino) pyroxenite, calc-silicates and footwall hybrid with respect to the SiO_2 and Cr contents. Their silica content ranges from ~39 – 44 wt% (compared to values of 41 – 47 in the harzburgite in UMT040) and the Cr is about 20 – 835 ppm.

The orthopyroxene data have shown a slight difference in the composition of the T2 Upper (topmost portion) and the T1 unit in UMT064. These differences were indicated by the Ni content and MgO/((MgO)+FeO) ratio (Figure 7.4). However, the Qemscan data have shown that the mineralogical composition of the T1m and that of the T2 Upper were similar.

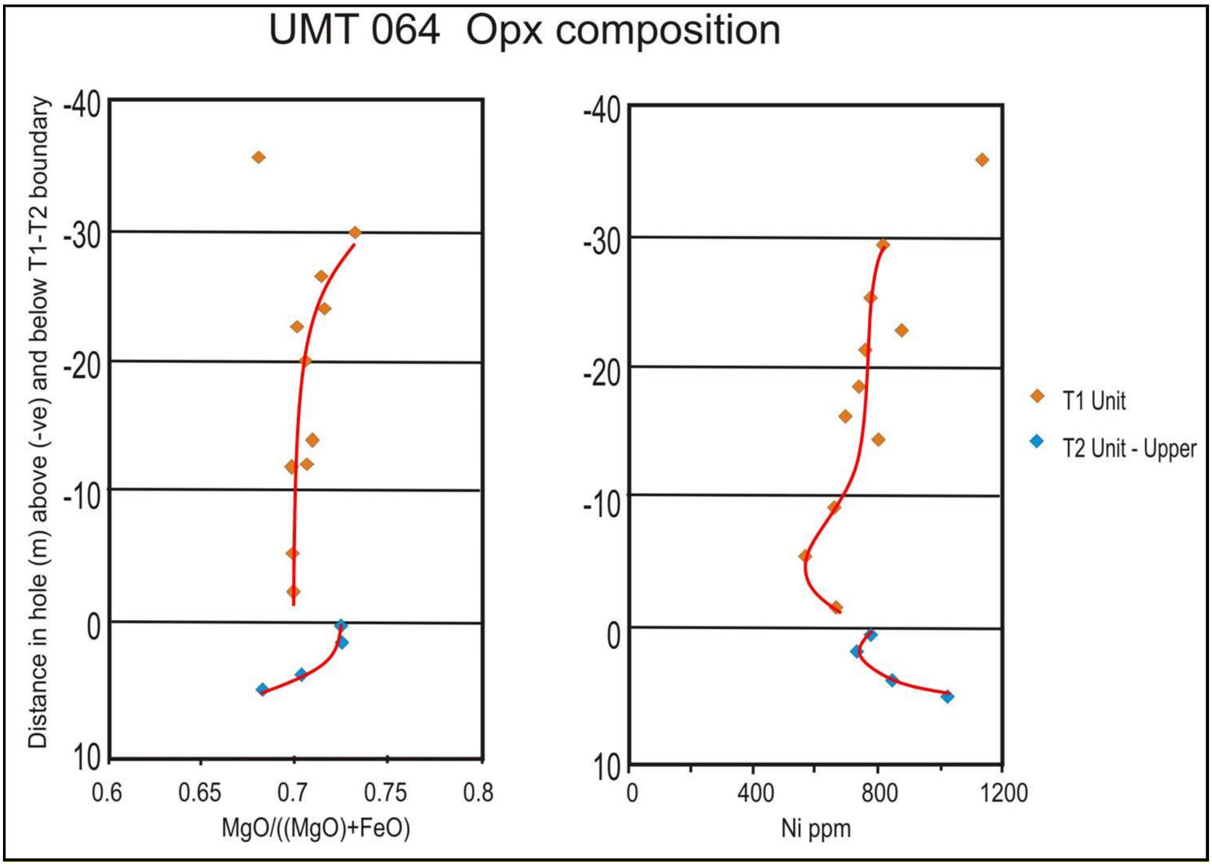


Figure 7.4. Interpreted trends of Ni (ppm) and MgO/(MgO)+FeO ratio in the orthopyroxenes. Note that the sample depths are plotted using the boundary between the T1 and T2 as a reference point i.e T1-T2 boundary = 0

Considering the tenor variations and Cu/Pd ratios the T1 in UMT040 and 064 can be divided into two sub-units i.e. the topmost and lowermost portions. The lowermost portions of the T1 in these drill holes comprise low tenors in the range of 2 – 90 ppm. Whereas, the topmost portions of the T1 are characterised by high tenors ranging from 80 - 105 ppm. The topmost portions in both drill holes also comprise high sulphide content and high Pt/Pd ratios, whereas the lowermost portions comprise low sulphide content and high Pt/Pd ratios (Figures 7.5 and 7.6). The Cu/Pd ratio patterns in UMT040 and the high tenor within the topmost portion of the T1 can only be explained by the emplacement of new waves/batches of magma. The exponential upward decrease in tenor and a coincidental upward increase in Cu/Pd ratio have been attributed to the process of fractional segregation of sulphides from a body of magma (Naldrett et al,. 2009).

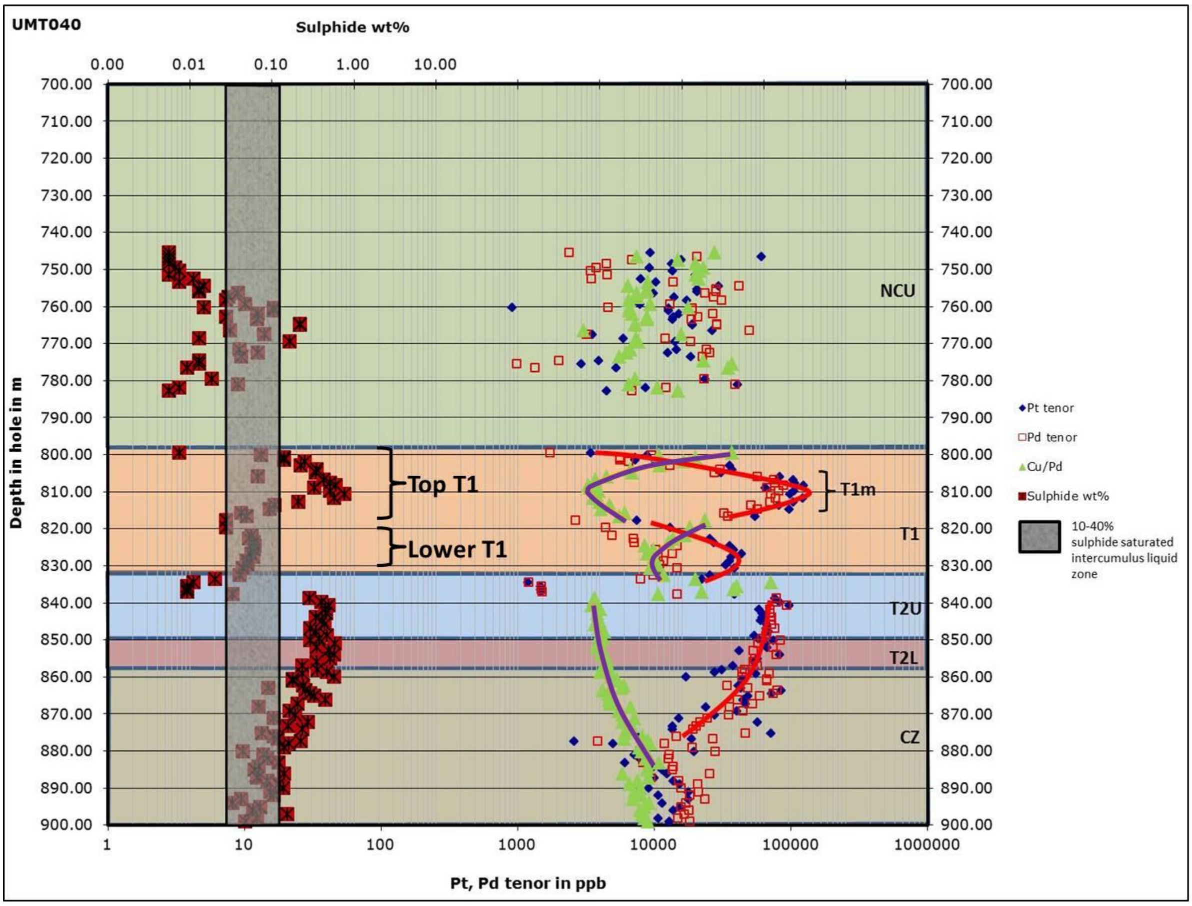


Figure 7.5. Diagram showing variations in PGE tenor and Cu/Pd ratios in UMT040. The topmost part of the T1 comprises high sulphide content and has high tenor, whereas the lowermost part has low sulphide content and low tenor. In both sections of the T1, an upward decrease in tenor coincides with an upward increase in Cu/Pd ratio

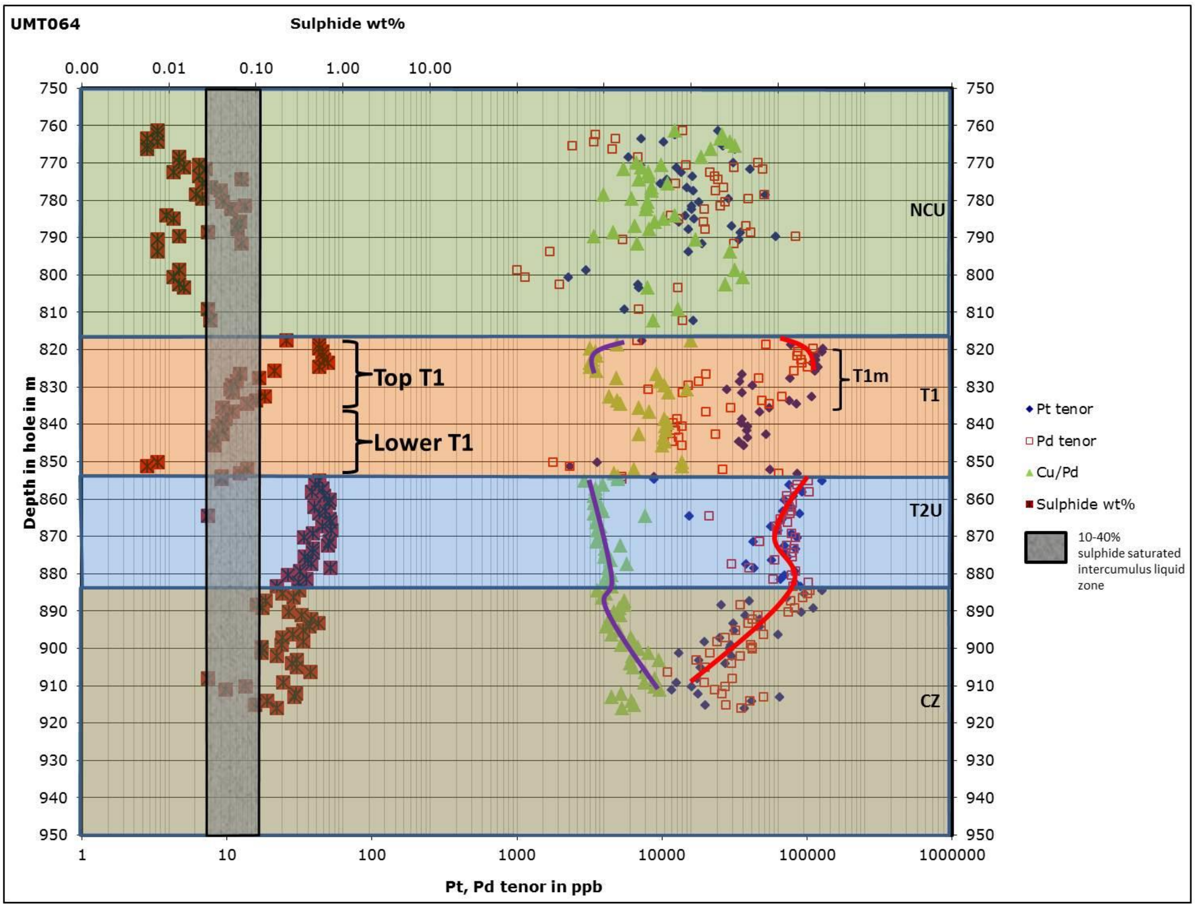


Figure 7.6. Diagram showing variations in PGE tenor and Cu/Pd ratios in UMT064. It is envisaged that the upper portion of the T1 has been partially eroded by the incoming Main Zone magma and thereby removing the upper section which would have displayed the exponential upward decrease in tenor and a coincidental upward increase in Cu/Pd ratio. The tenor and Cu/Pd ratios in the lowermost portion of the T1 are hard to explain, however, the Pt/Pd ratios are typical of those found in the lowermost portion of the T1 in UMT040 and 063

Considering the staging chamber model of Naldrett et al (2009) for their study on the Merensky Reef in the western Bushveld it is suggested that a similar process have taken place during the emplacement of the T1. This model suggests that the sulphide that was upgraded to produce the PGE-enriched magmas of the upper Critical Zone, was deposited from early batches of magma in a staging chamber (Figure 7.7) that subsequently became a conduit for later magma. Successive batches of magma passing through this chamber dissolved FeS, leaving the residual sulphide progressively more enriched in Ni, Cu and PGE. As time progressed, the sulphides developed an unusually low Cu/Pd ratio (because Cu was dissolved by the successive pulses of magma more readily than Pd) and this ratio was impressed on later batches of magma passing through the system. These batches were not necessarily sulphide saturated but their Ni, Cu and PGE contents reflected the sulphides with which they had interacted. Following this process it is suggested that the topmost portion of the T1 represents a later batch of magma that had dissolved the sulphide that segregated during an earlier episode, and became enriched in PGE and developed a low Cu/Pd ratio.

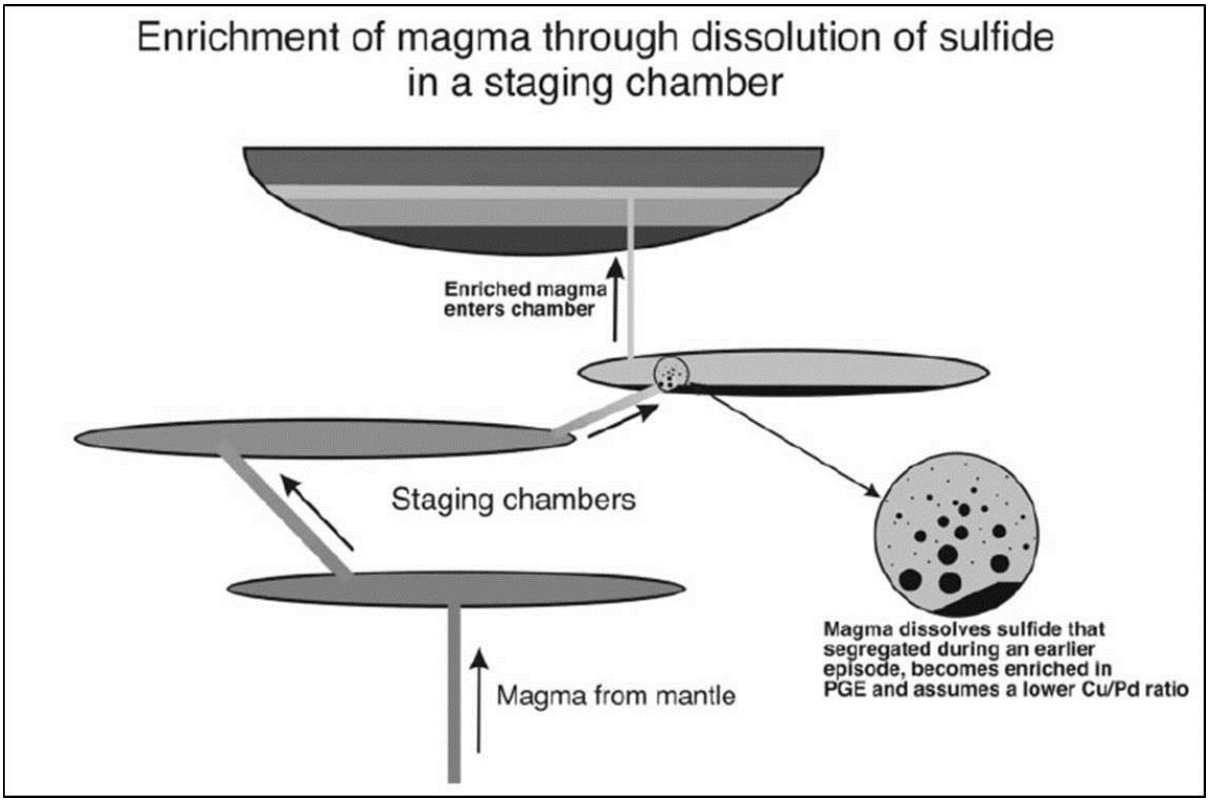


Figure 7.7. Staging chamber model for the development of PGE-enriched magma with a low Cu/Pd ratio (After Naldrett et al,. 2009)

Given the above characterictics, it is suggested that the topmost and lowermost portions of the T1 be considered as separate lithological zones during geological logging.

In comparison with the proposed model of McDonald et al (2011) for the emplacement of the Platreef, the model of Naldrett et al (2009) is the preferred model because it supports the processes that are thought to have taken place during the emplacement of the T1. McDonald et al (2011) suggested that the model of Naldrett would be correct if the Platreef transformed laterally into a UG2-Merensky sequence and; a thicker and more complete Critical Zone sequence developed downdip towards the centre of the northern limb. They further reported that based on the limited picture provided by the drilling at Akanani, showing that the Platreef intruded directly onto the Lower Zone or basement granite-gneisses, with no development of the Critical Zone, their suggestion for the model of Naldrett, remained unproven. Grobler and Nielsen (2012) reported the occurrence of the UG2 and Merensky equivalents in UMT081 and 094 downdip of the Flatreef area. This provides evidence to the much needed support by McDonald et al (2011) to validate the model of Naldrett as correct for the northern limb. The only criticism to the model of McDonald is that not all sulphides were emplaced into the Platreef as a mush. This study has shown that in the T1 the sulphides have undergone a fractional segregation process.

7.2 Conclusion

Based on the above discussion, it is concluded that the upper section of the Platreef comprise at least four lithological units i.e. the topmost portion of T1, lowermost portion of T1, T2 Upper and T2 Lower that can be interpreted to have been formed by four separate pulses of magma. Considering the possibility of the T2 Lower being metamorphosed calc-silicates, this reduces the number of magma pulses to three. This is supported by the mineralogy, geochemical content and tenor variations. High grade mineralisation occurs within the T1m and T2 (Upper and Lower). In the T2, an increase in sulphide content and PGE grades are generally associated with the presence of the "main" chromitite stringer/ seam at the contact between a feldspathic pyroxenite (T1) and the coarse-grained to pegmatoidal pyroxenite (T2 Upper). Several other chromitites are present in places above and below this contact, and it has been noted that not all of those chromitites are associated with an increase in sulphide content and higher PGE grades. PGE grades are generally higher in T2 Upper than in T2 Lower, whereas, the base metals (particularly Ni) are generally higher in T2 Lower.

In the T1m, mineralisation occurs close to the contact between the feldspathic pyroxenite and orthopyroxenite, but only the orthopyroxenite hosts the sulphides. Chromitite stringers rarely occur in the T1m. Where present, they generally occur at the top of the mineralised zone. The sulphides in both the T1m and T2 are interstitial and sometimes net-textured.

This study presents the first 3D PGE tenor model for the northern limb of the Bushveld Complex**.** The model has demonstrated that the tenors in both the T1 and T2 are higher than previously thought. Tenors in the T1 reach up to 700 ppm, whereas tenors of about 1000 ppm were recorded in the T2. These tenors are comparable to the tenors measured from the sulphide melt inclusions elsewhere in the northern limb. Tenors are the highest in the northwestern part of Turfspruit and they gradually decrease towards the southeast. Both the T1 and T2 are dominated by a tenor of about 100 ppm. In the T1, a tenor of 250 ppm is dominant in the northwestern and southeastern parts of the study area, whereas in the T2 it is only dominant in the northwestern part. Vertical variation in tenors has shown that the tenors are the highest in the topmost portion of the T1 and at the top of T2 Upper (below the T1-T2 contact).

Major element compositions of whole rock analyses for the T1 and T2 Upper are comparable to those of the Merensky pyroxenites mainly with respect to SiO_2, TiO_2 and P_2O_5. The Cr/MgO ratio in the T1 and T2 Upper are greater than 80, similar to those of the Critical Zone in the eastern and western limbs. The pyroxene data excluding the MgO/((MgO)+FeO) ratio, Cr (in T2 Lower) and CaO contents, in the T1 and T2 Upper is comparable to that of the Merensky pyroxenites and other parts of the northern limb. The MgO/((MgO)+FeO) ratios in this study are lower (averaging 0.71) than the Mg# reported for the Merensky Reef ($Mg\#_{78-83}$), the upper Critical Zone ($Mg\#_{78-84}$) and elsewhere in the Platreef north of Turfspruit. The CaO levels (representing the wollastonite component of the orthopyroxene) at Turfspruit are higher (>2 wt %) compared to the Merensky Cyclic Unit and other parts of the northern limb where the CaO levels are below 2 wt %. This is an indication that the pyroxene composition at Turfspruit is more evolved compared to the Merensky Reef. The Cr content in the T2 Lower is much lower (~465 ppm) compared to that of the Merensky Pyroxenite (>2000 ppm). The PGE tenor in the T1 and T2 have shown maximum values of up to 700 ppm and >1000 ppm respectively. These values are comparable to the PGE tenor of Naldrett et al (2009) in the western Bushveld.

Considering the process that gave rise to the formation of the Merensky Reef as discussed by Naldrett et al (2009), the whole rock geochemistry, mineral chemistry and PGE tenor, it is suggested that only the T1 can be compared with the Merensky Reef. The process that led to the emplacement of the T1 was interpreted to be similar to the one that formed the Merensky Reef. The T2 Upper, even though it has geochemical signatures and mineral chemistry that is similar to that of the Merensky pyroxenites, in this study it is interpreted to have been formed from a separate and different process than the T1. However, the thickness difference between the Merensky Reef and the T1m still needs to be addressed.

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APPENDICES