The Bushveld Complex

Host to the World's Largest Platinum, Chromium and Vanadium Resources

Morris Viljoen

Bushveld Minerals Limited, Illovo Edge Office Park, cor. Harries and Fricker Road, Illovo, Johannesburg. *E-mail: Morris.viljoen@vmic.co.za*

DOI: 10.18814/epiiugs/2016/v39i2/95777

The geological setting of the Bushveld Complex, the world's largest layered igneous body containing most of the planet's chromium, Platinum Group Elements (PGEs) and vanadium resources, is outlined. The complex is situated in a central position on the ancient Kaapvaal Craton of South Africa, with the mineralisation contained in three large arcuate mafic to ultramafic Limbs, comprised of rocks of the Rustenburg Layered Suite (RLS). The Limbs are overlain by co-magmatic felsic rocks while the floor consists mainly of sediments of the Transvaal Supergroup.

The RLS is divided into the Marginal, Lower, Critical, Main and Upper Zones with the chromium and PGE enriched layers occurring in the Critical Zone and the vanadium mineralisation occurring within titaniferous magnetitite layers of the Upper Zone. The chromitite layers are classed into Lower, Middle and Upper Groups and show a general decrease in chromium content upwards from >46% Cr_2O_3 at the base to <42% Cr_2O_3 at the top. This is accompanied by an increase in iron content upwards and a change in the Cr /Fe ratio from >1.5:1 at the base to <1.3:1 at the top. The Lower Group and Middle Group chromitite layers have, or are currently being, extensively mined.

A noteworthy feature is the presence of PGEs in all the chromitite layers, with an increase from <0.5 ppm in the lower layers to >5 ppm in the uppermost and economically important PGE bearing chromitite layer (the UG2). The economically important Merensky Reef occurs above the UG2 near the top of the Critical Zone. It typically comprises top and bottom chromitite stringers, separated by up to 14 metres of pyroxenite and/or pegmatoidal pyroxenite, with the best mineralisation generally being associated with the top chromitite stringer and where the two chromitite stringers are in close proximity to each other. These stringers can eventually merge towards pothole structures in places, with the top stringer transgressing downward to form a range of pothole Reef features.

The nature and origin of the Merensky Reef in the Eastern and Western Limbs of the Bushveld Complex is discussed. A synthesis and interpretation of a large amount of platinum mine data from the Western Limb, highlights the great variability in the nature of the Merensky Reef in this segment. Evidence suggests that the top chromitite layer represents a magmatic unconformity resulting from thermo-chemical erosion, reconstitution and mineralisation of the immediate footwall layers that it transgressed. The Platreef, a thick, generally feldspathic pyroxenitic and harzburgitic assemblage, occurs on the eastern flank of the Northern Limb and is broadly equated with the Merensky Reef.

About 21 magnetitite layers ranging from massive titaniferous magnetitite, to disseminated and weakly disseminated magnetitite occur within, or are associated with, magnetite gabbro, gabbro and diorite of the Upper Zone. The vanadium content in magnetite is highest in the lowermost magnetitite layers (over 2.2% V_2O_5 in places) dropping to 1.6% V_2O_5 in the overlying Main Magnetitite Layer. An important layer (Layer 21 or the Q Layer), towards the top of the Upper Zone, is enriched in titanium (±13% TiO_2), at the same time having vanadium values of generally less than 0.2% V_2O_5. This layer, which is often over 40 metres thick, contains a huge resource of iron and titanium, as well as vanadium. The mineral apatite appears abruptly at two levels towards the top of the complex, the uppermost occurrence being in a diorite immediately above layer 21 where P_2O_5 values average 4% over several tens of meters.

The use of geophysical and geochemical techniques in exploration and mining in the Bushveld Complex is briefly reviewed and their applicability and effectiveness is illustrated. Given the continuity of layers, including some which extend for well over a hundred kilometres, the resource still present in this unique Complex is vast.

Introduction

The Archaean Kaapvaal and Zimbabwe Cratons of Southern Africa

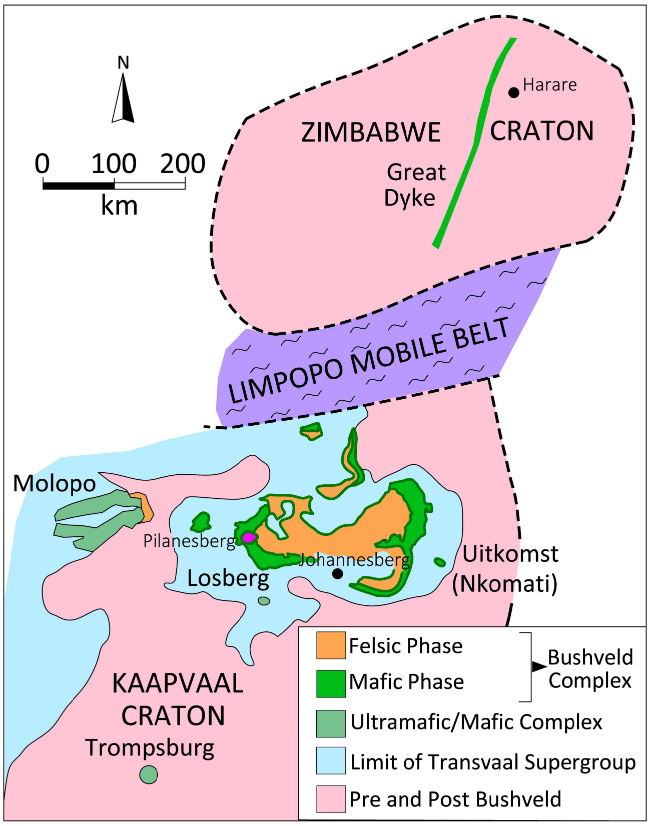


Figure 1. Regional geological setting of the Bushveld Complex and other major mafic/ultramafic layered intrusions of the Kaapvaal and Zimbabwe Cratons.

are host to several major and world renowned layered mafic to ultramafic intrusions. The largest, best-developed and best mineralised are the Great Dyke of the Zimbabwe Craton and the Bushveld Complex of the Kaapvaal Craton. The latter is renowned as host to the world's biggest deposits of the Platinum Group Elements (PGEs), chromium (Cr) and vanadium (V). Several smaller mafic intrusions on the Kaapvaal Craton include the Losberg, Trompsburg and Uitkomst intrusions in South Africa and the Molopo Farms Complex in Botswana (Fig. 1).

The Bushveld Complex is part of a large igneous province made up of three distinct groups of rocks, the oldest of which is the 3.5 km thick felsite-dominated volcanic Rooiberg Group that formed roof rocks to the slightly younger intrusive components, the youngest of which is the Lebowa Granite Suite, that includes a granophyric component. The biggest, and economically the most important component of the Complex is the Rustenburg Layered Suite (RLS) comprised of mafic/ultramafic layered rocks dated at 2.055 Ga (Scoates and Friedman, 2008). The RLS occurs in a series of three main arcuate lobes or Limbs, the best-developed being the Eastern and Western Limbs which are stratigraphically similar to one another and have distinctive layering within each, that can be correlated over a distance of more than 300 km (Figs. 1 and 2). The RLS averages 7 km in thickness and is subdivided into a series of zones that have their most complete development in the Eastern and Western Limbs of the Complex.

At the base of the RLS is the Marginal Zone consisting of variably contaminated norite and pyroxenite. This is followed by the Lower Zone, a sequence of layered dunite, harzburgite and orthopyroxenite. Above this is the Critical Zone, the most strongly layered zone in the RLS, which is characterised by the presence of numerous well defined thinner and more variable PGE-bearing chromitite layers. In the Lower Critical Zone, chromitite layers are hosted by orthopyroxenite and subordinate harzburgite, while in the Upper Critical Zone, they occur in a sequence of interlayered orthopyroxenite, norite and anorthosite. Towards the top of this sequence are the economically important UG2 chromitite and Merensky Reef PGE ore bodies. The overlying noritic to gabbronoritic Main Zone is largely devoid of oxide and sulphide minerals. Above the Main Zone, the Upper Zone is a sequence of ferrogabbronorite, magnetite gabbro anorthosite and ferrodiorite, characterized in particular by the presence of layers of massive and disseminated vanadium-bearing titaniferous magnetite. The magnetitite layers vary from relatively vanadium-rich and titanium-poor near the base of the zone, to vanadium-poor and titanium-rich at the top of the zone.

The Northern Limb differs from the Eastern and Western Limbs in that the Critical Zone correlative along most of its extent, does not contain layers that correlate directly with the Critical Zone of the Eastern and Western Limbs. Instead, the lowermost pyroxenite dominated unit of the RLS, known as the Platreef, is in sharp contact with and transgresses Transvaal Supergroup sediments and Basement granites. This unit is a complex and highly variable sequence of pyroxenite, harzburgite and gabbronorite up to 200 metres thick, xenolithic and contaminated in parts, that hosts significant PGE mineralisation in association with base metal sulphides and minor thin, discontinuous, stringers of chromitite. The Platreef is overlain by Main Zone and Upper Zone sequences that can be correlated with those of the Eastern and Western Limbs.

Main and Upper Zone lithologies are recognised in the Villa Nora occurrence to the north west of the Northern Limb, while in the far west of the Bushveld Complex, an outlier of RLS rocks with Lower and Lower Critical Zone affinities, hosts a series of chromitite layers. In the southeast of the Bushveld Complex, the southeastern or Bethal Limb is obscured by younger cover. It is dominated by relatively iron-rich lithologies.

The Critical Zone of the RLS hosts an estimated 88% of the world's known PGE resources and 72% of the world's chromite ore, whilst the Upper Zone contains approximately 45% of the world's vanadium resources (South African Department of Minerals and Energy, 2003/2004) as well as substantial phosphate mineralisation. Apart from this, significant tin and fluorite deposits are hosted by co-magmatic granites and granophyres of the Bushveld Complex, while magnesite was mined in the past from weathered ultramafic rocks of the Lower Zone of the RLS. The Uitkomst Complex (Fig. 1), a world-class nickel (Ni)-PGE deposit near the contact between the Transvaal Supergroup sediments and the Archaean basement, some 50 km southeast of the Eastern Limb of the Bushveld Complex, is believed to have originated from a similar magma to that which which gave rise to the main Bushveld Complex. In addition to these resources, andalusite is mined in aluminous sedimentary rocks of the Transvaal Supergroup in the metamorphic aureole of the complex.

The Rustenburg Layered Suite

The Rustenburg Layered Suite is subdivided into five zones comprised of rock types ranging from dunite, harzburgite and pyroxenite towards the base, through norite, gabbro and anorthosite to magnetite gabbro towards the top, with the uppermost part

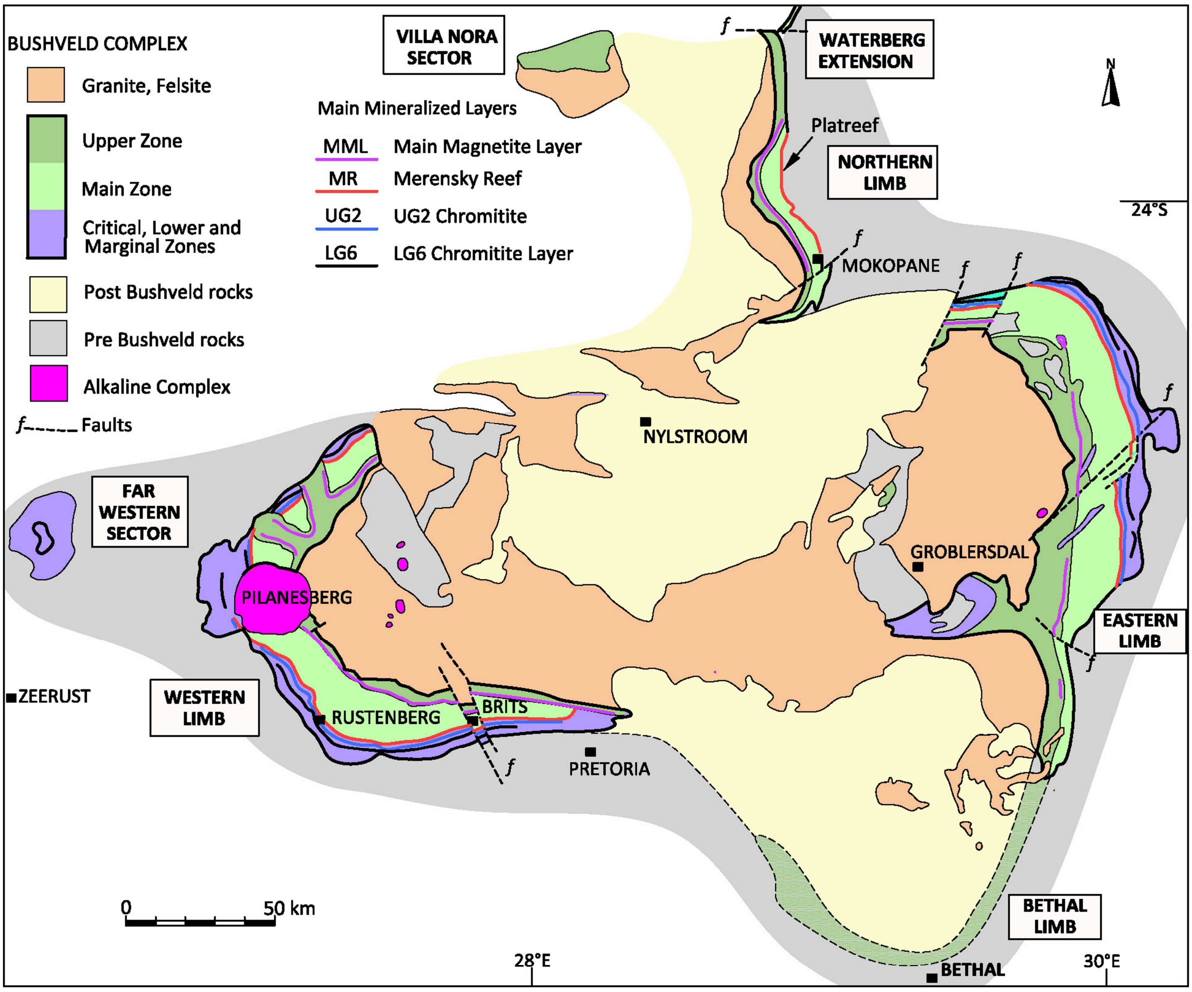


Figure 2. Geological map of the Bushveld Complex showing the distribution of the major mafic/ultramafic zones and the most important mineralised layers within these.

consisting of olivine and apatite-rich diorites. These relatively dense rocks give rise to pronounced gravity anomalies while the magnetite rich Upper Zone also gives rise to a pronounced magnetic anomaly. Generally 3 to 5 of the lithological zones are present in the various Limbs of the complex (Fig. 2). The locations of the main chromium, platinum and vanadium mines are portrayed for the Western and Eastern Limbs in Figs.4 and 5 respectively, while a schematic section through the RLS, showing the various zones and important mineralised layers is given in Fig.6.

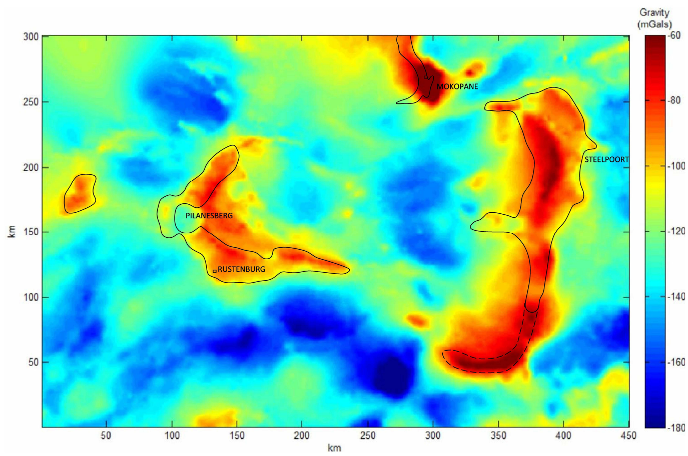


Figure 3. Distribution of the mafic/ultramafic rocks of the Rustenburg Layered Suite in relation to gravity anomalies, highlighting the close correlation between high gravity and dense Bushveld rocks.

Marginal Zone

The Marginal Zone at the base of the Complex is comprised of a noritic and feldspathic pyroxenitic assemblage, which is generally finer grained than the overlying layered rocks and contains abundant country-rock xenoliths. This zone is highly variable in thickness and may be completely absent in some areas. It contains no known economic mineralisation. An extensive suite of co-magmatic diabase to ultramafic sills has, intruded the footwall metasediments of the RLS and these have contributed to the massive thermal metamorphic aureole around the complex. Several distinctive magma types have been proposed for the sills (Harmer and Sharpe, 1985).

Lower Zone

The Lower Zone, where present, overlies the Marginal Zone to form trough like features dominated by orthopyroxenite with associated olivine-rich cumulates, as for example in the northern part

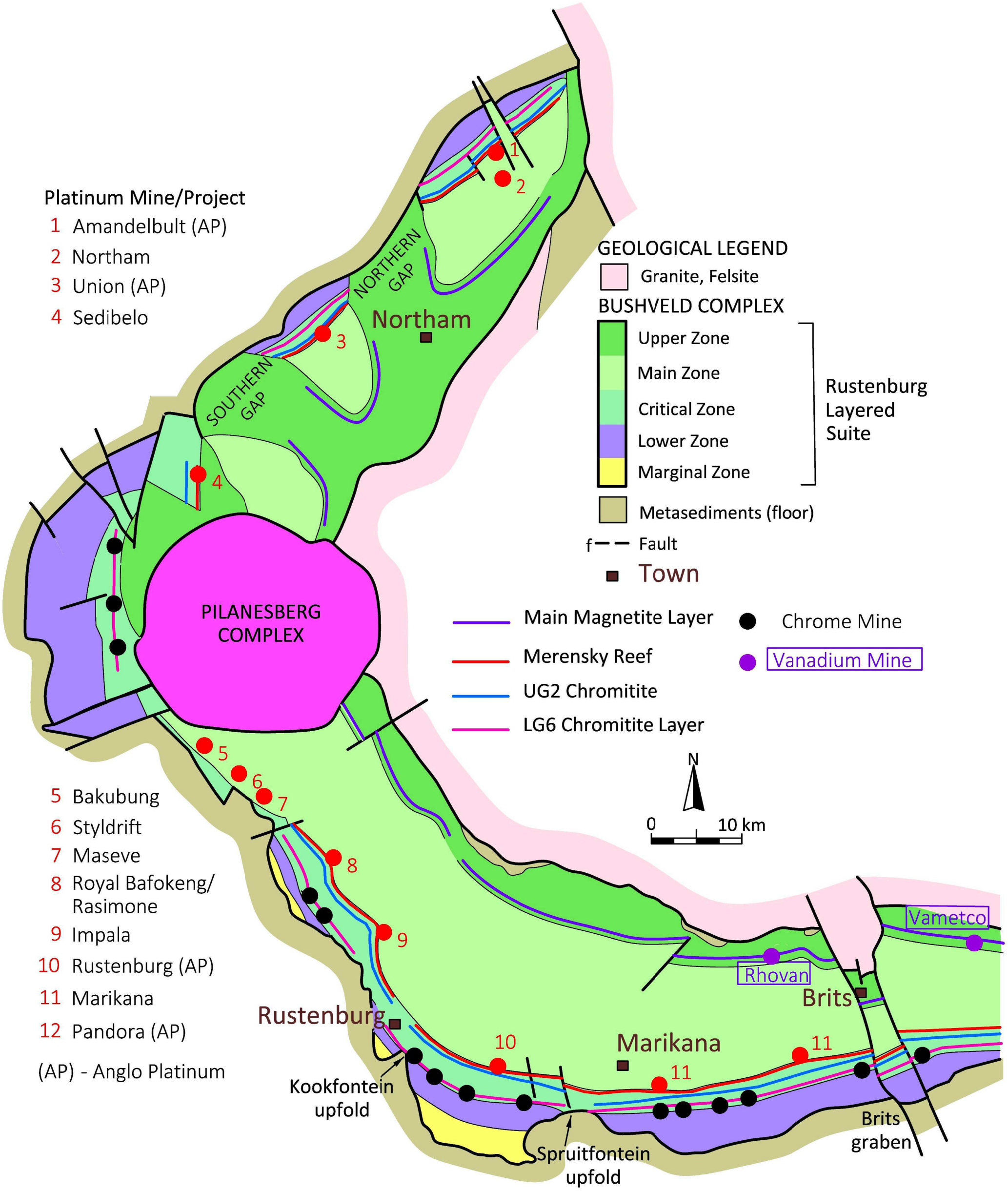


Figure 4. Geological map of the Western Limb depicting the major lithological zones, together with the economically important chromitite, PGE and vanadium-bearing mineralised layers in the Critical and Upper Zones. Localities of the main mines are also shown (after Schurmann et al., 1998 and Viljoen and Schurmann, 1998).

ofthe Eastern Limb where a well exposed and classically layered sequence of Lower Zone ultramafic rock is developed (Figs.5 and 7). Cameron (1978) subdivided the Lower Zone in this area into a Lower Bronzitite, Middle Harzburgite and an Upper Bronzitite, subzone. The pyroxenitic layers form dark, resistant, southward dipping questa ridges, while the olivine-rich lithologies form lower lying lighter toned areas (Fig.7).

Isolated satellite bodies of pyroxenite and harzburgite containing erratic chromitite layers, are intrusive into Archaean granites and Transvaal Supergroup rocks at the base of the Northern Limb of the complex and have been equated with the Lower Zone.

Critical Zone

The appearance of well-defined small layers of cumulus chromite within the ultramafic rocks of the Lower Zone marks the commencement of the Critical Zone which is characterized by regular and often fine-scale rhythmic or cyclic layering. It is host to all the chromitite layers of the Complex, of which up to 25 have been identified and grouped into lower (LG), middle (MG) and upper (UG) groups (Fig.6).

The Critical Zone has been divided into the Lower Critical Zone, which is pyroxenite dominated and the Upper Critical Zone characterized by plagioclase-rich rocks (Fig.6). The contact between the zones occurs in the middle of the Middle Group of chromitite layers and is recognised by the distinctive Middle Group Anorthosite Marker layer (Figs.6 and 8a). The upper Critical Zone, is characterized by a number of units or sequences which generally commence with narrow pyroxenitic horizons, with or without olivine and with chromitite layers at or near to their base.

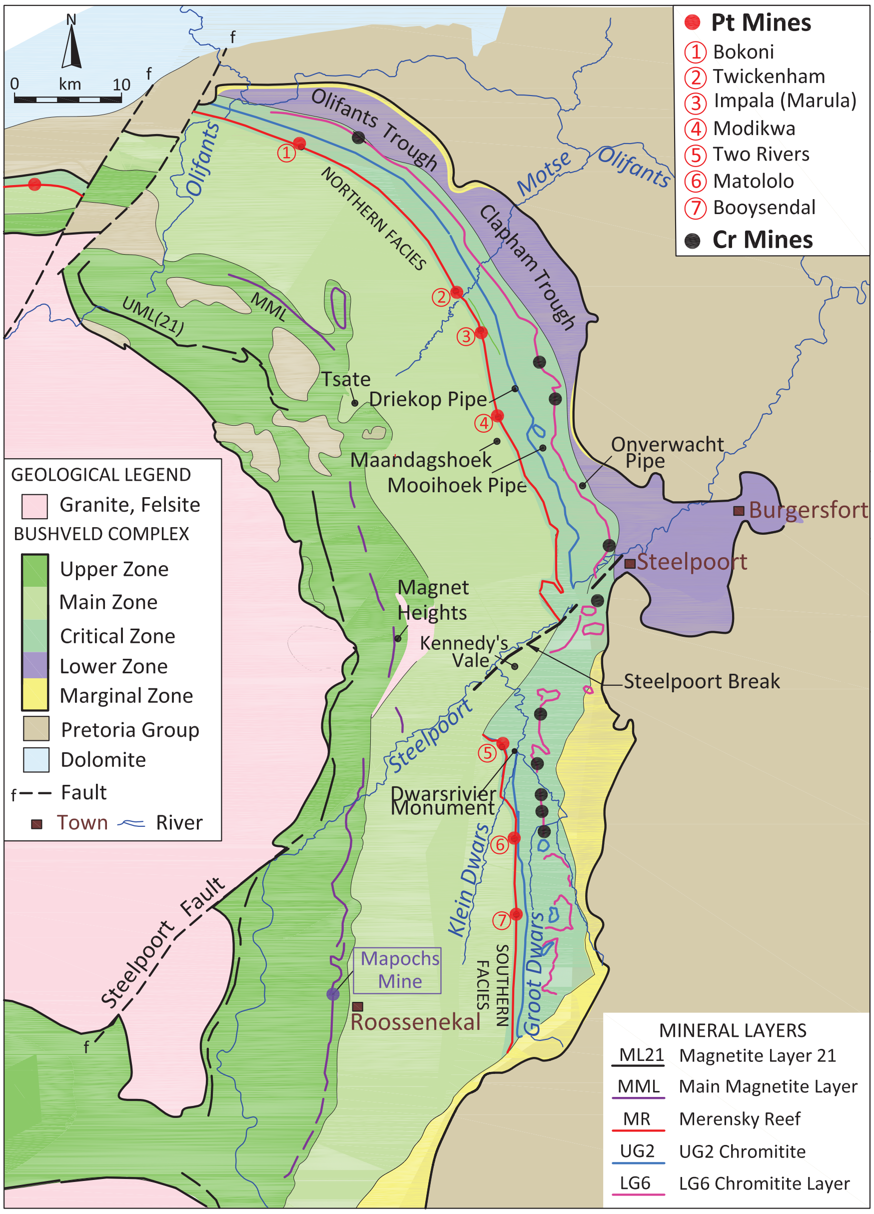


Figure 5. Geological map of the well exposed Eastern Limb of the Bushveld Complex depicting the major lithological zones and major economically important mineralised layers and mines as well as important sites (after Schurmann et al., 1998).

These are generally overlain by norite, leuconorite and anorthosite layers. Chromite (the ore of chromium metal), is mined from selected chromitite layers from all three chromitite groups of the Critical Zone.

The main UG1 chromitite layer, although not economically important as a chromium resource, is a spectacular, persistent unit, consisting of a basal chromitite layer which overlies footwall layers that bifurcate and are interlayered with an underlying anorthosite (Fig. 8b).The UG2 chromitite Layer is a major economic PGE resource as described later.

The two uppermost units of the Critical Zone range from pyroxenite at the base, through norite and anorthosite at the top and include the Merensky and Bastard reefs, the former being of great economic importance as it hosts PGE mineralisation. The top of the Critical Zone is generally taken as the top of a robust anorthosite (the Giant Mottled Anorthosite) that forms the top of the Bastard unit.

A 100-400 metre thick complex pyroxenitic assemblage on the eastern margin of the Northern Limb hosts a number of huge economically exploitable PGE deposits. It is known as the Platreef and is correlated broadly with the Critical Zone, parts having also been likened to a considerably thickened Merensky Reef assemblage (Fig. 2) (Grobler *et al.*, 2012).

Main Zone

The Main Zone is the most robust of the zones of the RLS attaining a thickness of nearly 3 km (Fig.6). It consists of a lower noritic phase overlain mainly by gabbronorites, with interlayered anorthosites. A number of distinctive marker layers have been recognised in the Main Zone and include the Porphyritic Gabbro Marker, Main and Upper mottled anorthosite markers and the Pyroxenite Marker. These have been described from the Eastern Limb (Von Gruenewaldt, 1973 and Molyneux, 1974), the Western Limb (Mitchell, 1990 and Mitchell *et al.*, 1998), as well as from the Northern Limb (Van der Merwe, 2008 and Ashwal *et al.*, 2005).

The resistant gabbro norites of the Main Zone form conspicuous topographic features throughout the exposed Limbs of the Bushveld and are referred to as the Pyramid Hills in the Brits-Pretoria region. They are currently being extensively mined for dimension stone, termed "black and grey granite" in the trade. Low grade PGE mineralisation occurs in places in the Main Zone as discussed later.

Upper Zone

The base of the overlying Upper Zone is defined by the first appearance of cumulus magnetite in ferrogabbro. In the northern portion of the Western Limb, rocks of the Upper Zone truncate the stratigraphy of the lower successions and cut down to the floor rocks in three areas termed the southern, northern and far-northern "Gap" areas (Figs. 2 and 4). In the northern part of the Eastern Limb, a feature is the presence of ovoid domes of floor rock which have penetrated the entire Rustenburg Layered Suite, eventually causing doming and penetrating Upper Zone rocks, which themselves, sharply transgress the underlying layered rocks (Fig.5) (Uken and Watkeys, 1997 and Scoon, 2002).

The Upper Zone consists mainly of noritic rocks towards the base followed by gabbronorite, but including gabbro anorthosite and magnetite gabbro with cumulus, iron-rich olivine appearing at the base of the various subzones (Von Gruenewaldt, 1973 and Molyneux, 1974). Cumulus apatite associated with diorite is a feature of the two uppermost subzones of the Complex, (Scoon and Mitchell, 2012). In all, up to 25 layers of cumulus magnetite containing massive to disseminated magnetite, punctuate the Upper Zone, with the vanadium-rich Main Magnetite Layer near the base being the most

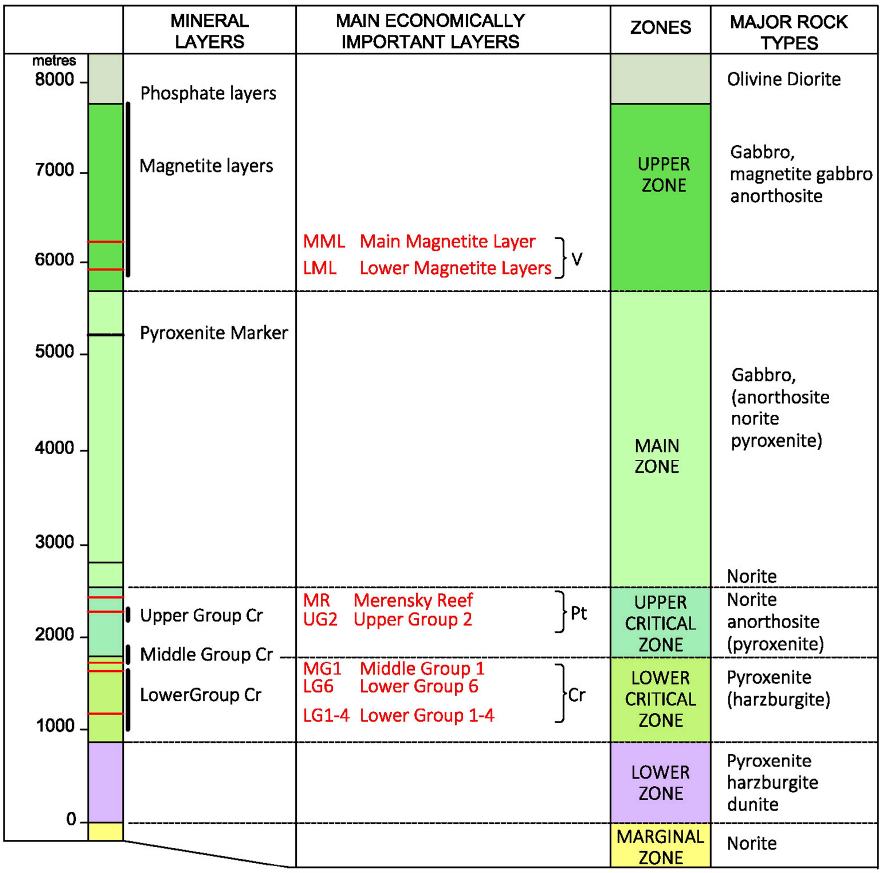


Figure 6. Schematic section through the Rustenburg Layered Suite portraying the major rock types of the five zones and highlighting the most important mineralised layers.

important (Von Gruenewaldt, 1973; Scoon and Mitchell, 2012). Together with its footwall layers in places, the Main Magnetite Layer is exploited for its vanadium (and in places iron) content in the Eastern and Western Limbs of the Bushveld Complex as described later (Figs.2, 4 and 5).

Chromitites of the Critical Zone

Introduction

Bushveld chromite is of the stratiform type occurring as horizontal to subhorizontal layersand is mainly classified as being of the high-iron type (Schurmann *et al.*, 1998). Chrome deposits occur largely in the Eastern and Western Limbs of the Bushveld Complex and as noted, they account for over 80% of the world's chromium resources.

Within the three major chromitite groups of the Critical Zone, the Lower Group contains up to seven chromitite layers (LG1-7), the Middle Group 4 main layers (MG1-MG4) and the Upper Group two main layers (UG1 and UG2) (Fig.6). Though details of these seams vary from sector to sector of the Complex, the major chromitite layers are readily identifiable and often traceable for many kilometres as shown in the stratigraphic columns for the LG and MG chromitite layers of the Eastern Limb of the complex (Fig. 9).

Lower Group Chromitite Layers (LG1-LG4)

Although variable along strike, generally four Lower Group (LG) chromitite layers are recognised in the Eastern, Western and Far Western Limbs (Figs. 2, 4 and 5). They are never more than 0.3 metres thick but have the best chromite grades in the Bushveld Complex with Cr_2O_3contents of generally about 46% and (Cr/Fer atios of >1.8:1). Two harzburgite units are useful markers in correlating the closely associated chromitite layers of the LG Group, with a lower harzburgite unit occurring between the LG2 and LG3 layers and the LG4 layer developed within a harzburgite layer inthe Eastern Limb (Fig. 9). The LG chromitite layers are rarely more than 10mm in thickness in the northern sector (north of the Steelpoort break), while in the southern sector of the Eastern Limb, south of the Steelpoort break, they consist of only very thin chromitite stringers (Fig. 9).

In the Far Western Limb (Nietverdiend sector) (Fig.2), the four chromitite layers mined vary in thickness from 13 to 40 cm, are contained in harzburgite and pyroxenite and are correlated with the LG1 to LG4 chromitites. Here the chromite is more refractory with higher Al_2O_3 and Cr_2O_3 contents (Collins and Human, 1986), and with Cr/Fe ratios of about 1.9:1. (Engelbrecht, 1987). They are all mined in open pit operations in this area.

The two chromitite layers in the area south of Mokopane on the Northern Limb, are associated with olivine and orthopyroxene and have in situ Cr/Fe ratios of over 1.7:1 and grades of over 40% Cr_2O_3. They can broadly be correlated with layers in the LG1 to LG4 succession elsewhere in the Bushveld Complex and have been mined at the Grasvally mine (Hulbert and Von Gruenewaldt, 1986).

Lower Group Chromitite Layers (LG5-LG7)

Economically the most important of the LG layers are the LG5 to LG7, which are well developed in the northern part of the Eastern Limb, north of the Steelpoort break (Figs. 5 and 9). These chromitite layers are absent south of the Steelpoort break which marks an important facies change. The most widely mined chromitite is the LG6 layer which varies in thickness across the northeastern Bushveld Complex from 0.92 to 1. 05m. The LG6A (Leader) has an average thickness of 0.32 metres and is developed, on average 0.81 metres above the LG6 chromitite layer (Fig. 9). The chromitite layers are often associated with disseminated chromite occurring in the immediate hangingwall or footwall orthopyroxenite. The LG6 is also the major chromitite layer mined in the Western Limb of the complex (Figs. 4 and 5) (Schurmann *et al.*, 1998).

The LG6 is a black, shiny layer with coarse granular chromite, constituting 97% of the rock with the remaining 3% being made up of orthopyroxene, clinopyroxene, plagioclase and minor minerals. The chromitite is generally of a friable nature with some patches of "hard lumpy" present. The lumpy to fines (friable) ratio varies throughout the Bushveld Complex. The LG6 has an *in situ* Cr_2O_3 content of between 40% and 44% and Cr/Fe ratios generally above 1.5:1 which, together with its thickness, makes it one of the most economically attractive chromitite mining targets.

Figure 7. Aerial view of the well exposed and well layered Lower Zone in the type section of Cameron (1978). The resistant dark ridges of the Lower and Upper Bronzitite subzones appear on the right and left of the photo respectively, with the light toned Middle Harzburgite subzone in the centre. Olifants trough, northern part of Eastern Limb.

Middle Group Chromitite Layers MG1-MG4

In the Eastern Limb of the Bushveld Complex, Middle Group chromitite layers are well developed south of the Steelpoort break. They are comprised of two lower layers, the MG1 and MG2, within pyroxenite of the Lower Critical Zone and two upper layers, the MG3 and MG4, hosted in plagioclase-dominated norite of the Upper Critical Zone (Fig. 8a). The individual layers can contain silicate interlayers, a feature which is specifically true for the MG2 and MG4 layers. The most important chromitite layer is the MG1 which is generally thicker than the LG6, averaging 1.65 metres. It is hosted in a medium-to coarse-grained pyroxenite and has up to four chromitite "footwall markers", with thicknesses varying from 6 to 48 cm, as well as a hanging wall chromitite leader. The MG2 package south of the Steelpoort structural break usually consists of three distinct chromitite layers, referred to as the MG2A, MG2B and MG2C layers (Fig. 9).

The mineral chromite makes up between 70% and 88% of the MG1 layer, with plagioclase and orthopyroxene being the other major constituents. Some of the MG chromitite layers and in particular the MG1 layer, have Cr_2O_3 contents of between 40% to 44% and Cr/Fe ratios between 1.35 and 1.5:1 and are mineable (Schurmann, *et al.*, 1998). The MG1 chromitite layer is the most important layer mined in the Eastern Limb to the south of Steelpoort.

Upper Group Chromitite Layers (UG1- UG3)

Two very distinctive and continuous chromitite layers, the UG1 and UG2 layers (together with the uppermost UG3 layer in the Eastern Bushveld), constitute the Upper Group and can be traced throughout the Eastern and Western Limbs of the Bushveld Complex. The spectacular but subeconomic UG1 layer has been described earlier (Fig.8b).

The UG2 chromitite layer (0.5-1.0 metres thick) has a Cr_2O_3 content of 43.5% and a Cr/Fe ratio of between 1.26 and 1.40:1. It is however hugely important in that it contains economically exploitable PGE mineralisation in addition to the chromite. The low-grade chromite produced as a by-product of PGM extraction has, until relatively recently (20 years ago), had no market. The UG3 chromitite

Figure 8. (a) The Middle Group Anorthosite Marker straddled by the MG2 and MG3 chromitite layers and defining the contact between the lower and upper critical zones. (b) The spectacular and distinctive UGl chromitite layer with bifurcating footwall layers (black), interlayered with anorthosite (white) and forming characteristic features of the UG1 for over 200 km. Dwars River National monument site, Eastern Bushveld.

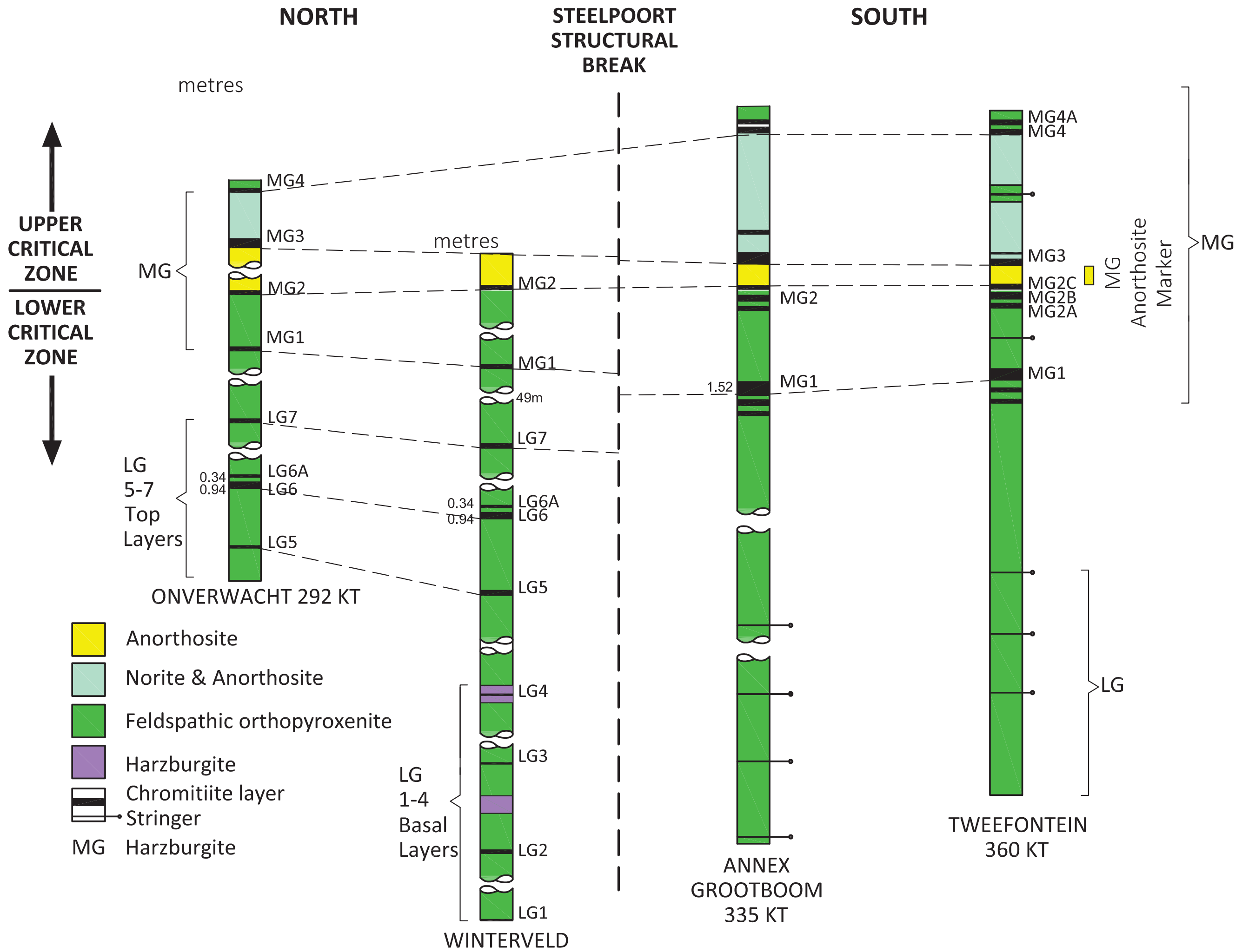


Figure 9. Stratigraphic columns for the lower and middle chromitite groups as developed to the north and to the south of the Steelpoort structural break in the Eastern Limb of the Bushveld Complex (after Schurmann et al., 1998).

layer is part of a classically developed uppermost cycle or unit in the Eastern Limb, where it forms a well-defined 20 cm thick layer that is not exploited.

The economically important PGE-bearing pyroxenitic Merensky Reef and the Platreef are, significantly, also generally characterized by the presence of one or more chromitite stringers with which some of the best PGE grades are associated. The last vestiges of chromite and PGEs in the Critical Zone occur at the base of the uppermost unit, known as the Bastard Reef.

Although having been mined by open pit mining methods in many parts of the Bushveld Complex, the bulk of the current chromite mining uses the board and pillar underground mining method. Scraper mining, breast mining and up-dip mining methods are also used, although at much lower rates as mechanization of mining has increased. The main targets for underground mining are the LG6, MG1, MG2 and UG2 layers. The MG3 and MG4 layers, as well as some of the lowermost LG layers are also being mined, but by open cast methods. The localities of the main chromite mines, past and present, are shown on Figures 4 and 5.

Although chromite ore, (including hard lumpy, small lumps or chips and fines) is trucked and/or railed to the ports of Maputo, Richards Bay and Durban for shipping to export markets, much of the ore is now being beneficiated within the country by smelting it to form a higher value ferrochrome product. Nine Ferrochrome smelters operate in the Eastern and Western Limbs of the Bushveld Complex with four operating outside of the Bushveld, including one at Richard's Bay, while Columbus Steel near Middleburg and Arcelor Mittal (Vanderbijlpark), beneficiate the ferrochrome further to produce stainless steel. Both products have a wide range of industrial uses including in the construction, mining, metallurgical and chemical industries.

PGE Mineralisation in the Critical Zone

Introduction

A striking feature of the Critical Zone is the anomalous PGE values present in all the chromitite layers. This includes the top and bottom chromitite stringers that bound the economically important, pyroxenitic Merensky Reef. There is an overall trend of increasing PGE values from the lowermost to uppermost chromitite layers, ranging from less than 1g/t for the LG 1-4 layers, to over 8g/t for the UG2 layer (Fig. 10) (Scoon and Tiegler, 1994; Mitchell and Scoon, 2007).

In general, the dominant low melting point group of PGEs (platinum[Pt]-palladium[Pd]-rhodium[Rh]) also increase

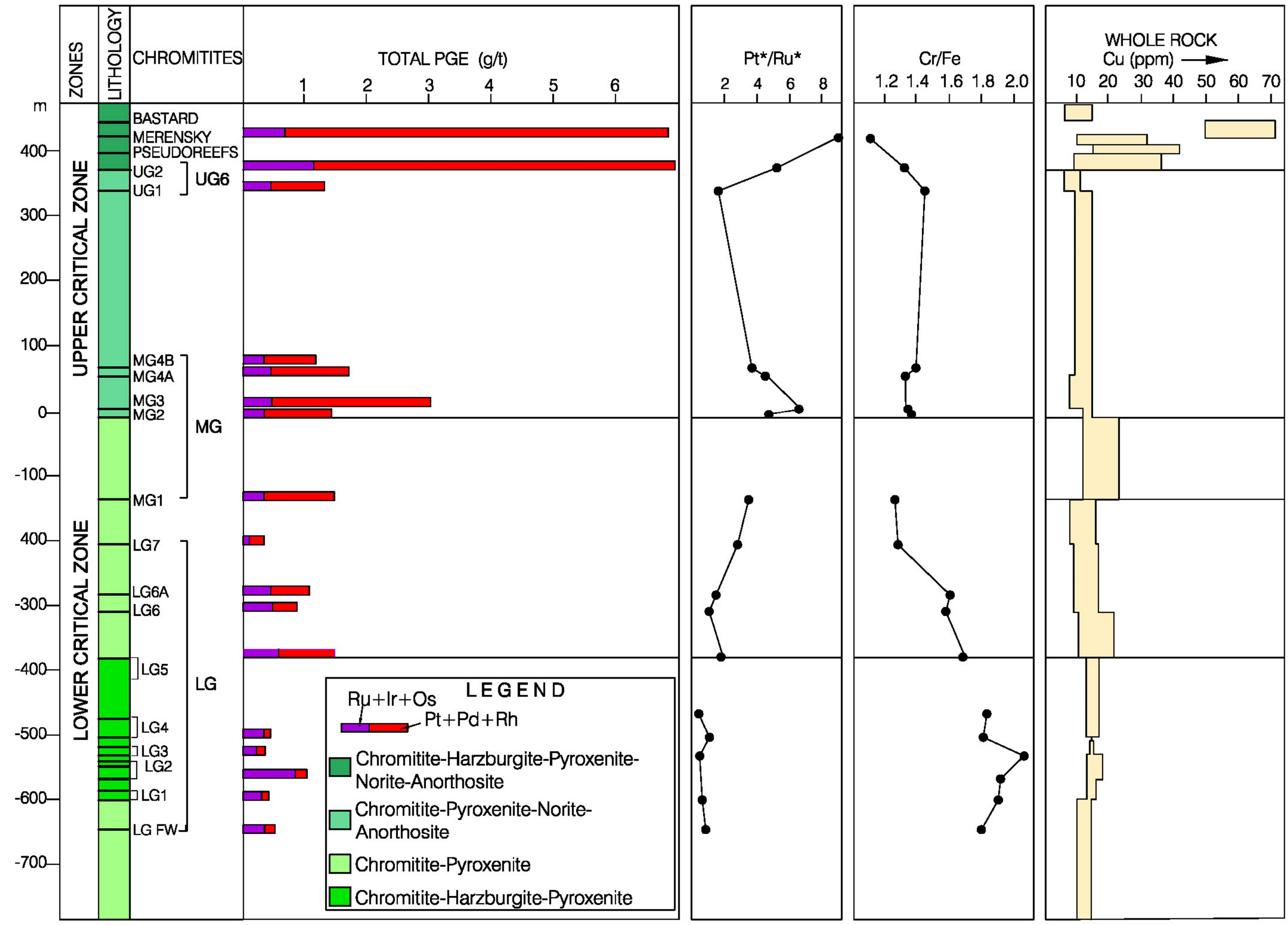


Figure 10. Some geochemical features of the major chromitite layers of the Critical Zone highlighting the increase in overall PGE content as well as in low melting point PGEs (Pt, Pd, Rh), with height and the constancy of the high melting point PGEs (Ru, Ir, O$_s$). The systematic variations in the Pt/Ru and Cr/Fe ratios are also shown (after Scoon and Teigler, 1994; Mitchell and Scoon, 2007; Viljoen et al., 1986a).

systematically from the lower to the upper chromitite layers, with the minor ruthenium (Ru)-osmium(Os)-iridium(Ir) group of PGEs (high melting point elements), being consistently present in all of the chromitite layers, albeit in low concentrations. This is reflected in the overall upward increase in the Pt/Ru ratio in the Critical Zone. The lowermost chromitite layers have Cr/Fe ratios of >1.8:1, whereas the economically important UG2 and Merensky Reef layers have Cr/Fe ratios of <1.3:1. A significant feature is the dramatic increase in copper (Cu) and nickel (Ni) sulphides in the economically important UG2 and particularly the Merensky Reef layers (Fig. 10) (Scoon and Tiegler, 1994).

UG2 Chromitite Layer

Geological Features

The UG2 chromitite contains one of the major PGE resources of the Bushveld Complex and is remarkably similar along its entire 280 km strike extent in the Western and Eastern Limbs of the Bushveld Complex (Figs. 4 and 5). It typically comprises a single main chromitite layer averaging 70 cm but attaining thicknesses of 150 cm in the southern sector of the Eastern Limb (Vermaak, 1985) (Fig. 11). The dip of the UG2, like that of the Merensky Reef, varies from 10° at Rustenburg to over 20° in the Northwestern Limb and up to 65° in the far northern part of the Eastern Limb.

Hulbert and von Gruenewaldt (1986) described a chromitite on the farm Grasvally 393 KR, in the southern sector of the Northern Limb, south of Mokopane, which they referred to as a “UG2-like” chromitite because of its similarity to the UG2 elsewhere in the Bushveld, in terms of geological setting and PGE grade. A possible correlative of the UG2 has also been reported in certain undisturbed portions below the Platreef on the Northern Limb (Grobler *et al.*, 2012).

The UG2 is commonly underlain by a coarse pegmatoidal feldspathic pyroxenite or melanorite, though in places anorthosite forms the footwall. Two to four hangingwall or “leader” chromitite layers, ranging from thin partings to layers over 10 cm in thickness, are invariably developed in the immediate hanging wall feldspathic pyroxenite (Fig. 11). In some areas, the chromitite that elsewhere forms the leader layers or stringers, combines with the top of the main layer to form a thicker composite seam. Rolls, depressions and potholes are common features of the UG2 Chromitite and have been described from all mines that exploit this horizon (Hahn and Ovendale, 1994). These features are generally circular in shape and range from less than 10 metres up to 100 metres in diameter. Whilst somewhat similar to the Merensky Reef potholes, they frequently take the form of gentle down rolls, with their depths generally not as great as is the case with the Merensky Reef potholes.

Mineralogy and Value Distribution

The mineralogy of the UG2 Chromitite is simpler than that of the Merensky Reef with chromite constituting 60-90% of the layer and plagioclase being the second most important mineral. The main base-metal sulphides are pentlandite (commonly cobalt bearing), and chalcopyrite, together with minor phases including pyrrhorite, pyrite, arsenopyrite, bornite, chalcocite, covellite, galena and millerite (Vermaak, 1985). Base-metal sulphide (BMS) contents are typically very low and grains are extremely small, (less than 30 microns). Some 86.5% of the base-metal sulphides are present at grain boundaries, whilst 4.2% occur within chromitite, and the remainder within silicate grains (McLaren and DeVilliers, 1982).

The Platinum Group Mineral (PGM) assemblage of the UG2 Chromitite is dominated by Pt-Pd sulphides (35%), the Ru sulphide laurite (30%), with other PGMs including Pt-Fe alloys and inter-growths (21%), Rh sulphides (11%) and Palladium alloys (3%). The PGMs are also largely interstitial to the chromite grains and are associated with sulphide minerals with the only PGM commonly enclosed by chromite being laurite. PGM grain sizes within the UG2 are the smallest of the Bushveld mineralised sequences with maximum grain sizes of about 50 microns and an average diameter of 9.3 microns (McLaren and DeVilliers, 1982).

A feature of the UG2 is that the Rh content is much greater than in the Merensky Reef. Rhodium is contained in a Pt-Cu-S (sulphur) (Rh, lr, Pd, Ni) mineral which, together with other unnamed Rh-PGMs, can comprise 6-10% of the total PGM assemblage of the UG2 (Lee, 1996). lsoferroplatinum and semi-metal PGM alloys occur where the UG2 is potholed and in areas with ultramafic replacement pegmatoid.

The PGEs are concentrated towards the top, and also towards the base of the UG2 horizon, (Fig. 11). PGE variations within the UG2 around the Bushveld are remarkably constant, a feature being the general constancy of thickness, grade and value distribution.

The Cr_2O_3 content of the UG2 averages 43.5%, while the Cr/Fe ratio ranges between 1.26 and 1.4:1 (Lee, 1996). According to Wagner (1929), PGE contents of the UG2 range from 3.5 to 19.16 ppm with an average of 4-8 ppm. Values of individual PGEs for high-grade layers are typically 3.6 ppm Pt, 3.81 ppm Pd, 0.33 ppm Rh and others 2.26 ppm (Gain, 1985). Copper and nickel values are typically low, being in the order of 1,000 ppm. The Pt/Pd ratio of the UG2 varies with geographic location, an average ratio being 0.94:1 in the Eastern Limb (Gain, 1985) and 2.5:1 in the Western Limb.

Although shallow open pit mining of the UG2 chromitite layer and its hanging wall layers does occur, mining of the UG2 unit is mainly by narrow reef underground mining methods over a stoping width of often not more than 1 metre. Mining problems are caused by the presence of the rolling reef and hangingwall chromitite stringers, which act as natural parting planes inducing hanging wall collapse and dilution of ore. Pothole structures also result in reef loss.

The Merensky Reef

Introduction and Discovery

The Merensky Reef is a PGE enriched zone associated with one or more chromitite stringers at the base of a regionally transgressive pyroxenitic layer occurring close to the top of the Upper Critical Zone in the Eastern and Western Limbs of the Bushveld Complex. Although some early mining took place in the Eastern Limb, close to the discovery site, in the late nineteen twenties, large scale mining of the Merensky Reef commenced in 1929 near Rustenburg in the southern sector of the Western Limb. Mining of the Reef on Swartklip Union Section in the northern part of the Western Limb soon followed and the Western Limb rapidly became the prime platinum producing region of the world, a position it still holds today.

The discovery of the Merensky Reef was preceded by the discovery of alluvial platinum on the farm Maandagshoek on the Eastern Limb of the Bushveld Complex in 1924. The source of this platinum was soon tracked to three cross-cutting platiniferous dunite pipes. The pipes form subvertical features that transgress the layers of the Critical Zone and immediately underlying Lower Zone of the

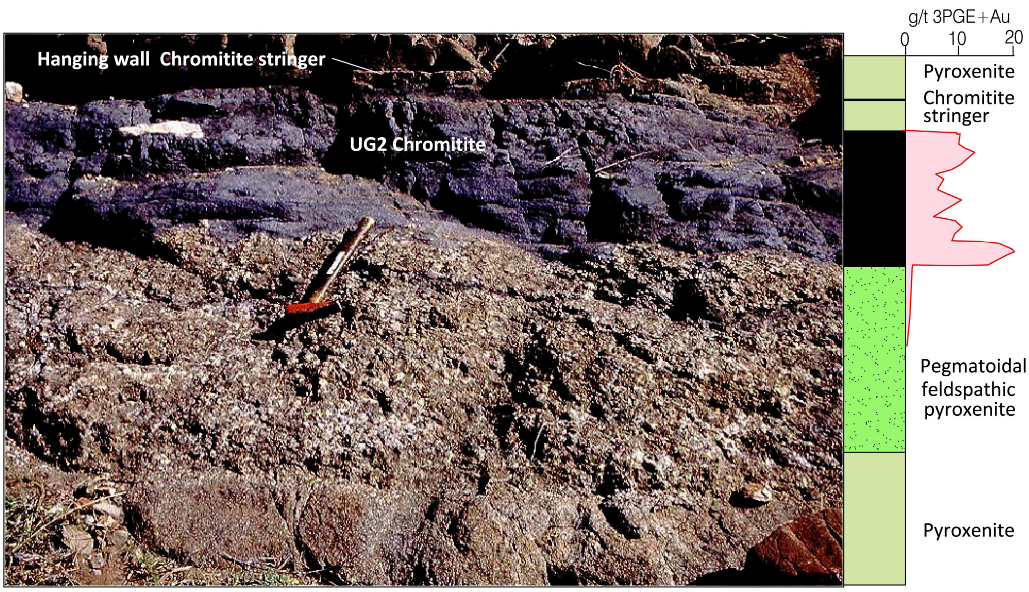


Figure 11. UG2 chromitite layer comprising a 70 cm thick platiniferous chromitite containing an anorthosite xenolith and underlain by a feldspathic pegmatoidal pyroxenite, with a pyroxenite hanging wall. The PGE grade distribution profile is shown with a feature being the highest value occurring consistently in the lower part of the chromitite layer.

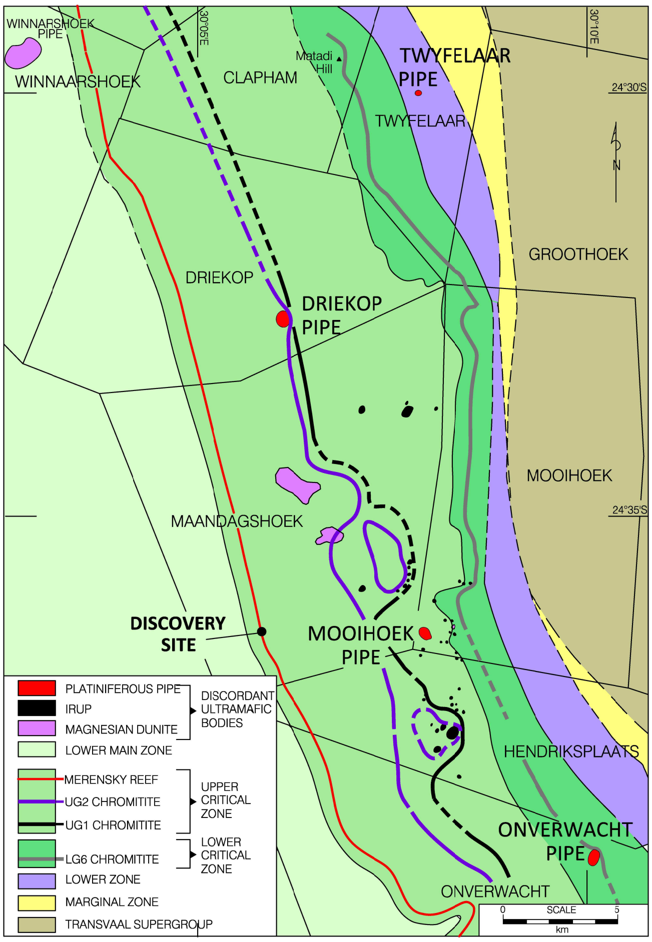


Figure 12. Distribution of platiniferous dunite pipes and iron-rich ultramafic pegmatites (IRUP) in relation to the main mineralised layers of the Critical Zone. Central sector of the Eastern Limb (from Scoon and Mitchell (2004).

central sector of the Eastern Limb (Figs. 5 and 12). They include the well-known Driekop, Onverwacht and Mooihoek pipes, as well as the Twyfelaar pipe, which was never commercially mined (Wagner, 1929). In broad terms each pipe consists of a small, mineralised core of iron-rich dunite and wehrlite, emplaced within a much larger stock-like body of barren magnesian dunite which may include harzburgite. The last mentioned ultramafic rocks are light coloured, fine to medium grained, and partly serpentinised and include accessory Cr spinel. The core of iron-rich hortonolite dunite is associated with clinopyroxenite and accessory Ti-magnetite. This rock is dark and lustrous with clinopyroxenite and accessory titanium (Ti)-magnetite. It is invariably coaser-grained, with a much higher density than the enveloping serpentinised magnesium dunite (Wagner, 1929 and Scoon, 2004).

Wagner (1929) reported the pipe-ores as being characterized by an anomalously high Pt tenor with coarse crystals of Pt-Fe alloy and sperrylite ($Pt\text{-}As_2$) and with a large number of new and unusual PGE minerals sporadically developed within base-metal sulfides. The rare copper iron sulphide mineral Mooihoekite was first described from the Mooihoek pipe (Cabri and Hall, 1972). Metre-sized slabs of chromitite, containing some of the richest platinum ore reported (maximum grade of 1886 g/t Pt; Wagner, 1929), have been recorded in the Onverwacht pipe. The noritic wall rocks to the Driekop pipe are severely disrupted by a kilometre wide downwarped structure, which includes the downwarping of the UG2 and UG1 chromitite layers.

The attention of Dr Hans Merensky was drawn by local farmer Andries Lombard, to well exposed pyroxenitic layers in the Upper Critical Zone, several km west of the Mooihoek dunite pipe and in 1924, one of these layers, subsequently termed the Merensky Reef, returned high PGE values. The layer was quickly traced throughout the Bushveld Complex for 140 km in the Eastern Limb and 145 km in the Western Limb (Scoon, 2009). Seismic surveys have subsequently shown that the Merensky Reef is present as far as 50 km downdip of outcrop, and as deep as 6 km vertically below surface (Du Plessis and Kleywegt, 1987).

Regional Geology

The regional position of the Merensky Reef close to the top of the Critical Zone of the Bushveld Complex is shown in Figures 2, 4, 5 and 6. Unlike other layers in the Bushveld, the Merensky Reef has important regional variations in geological characteristics and mineralisation styles. Some of these variations were first recognised by Wagner (1929), who divided the rocks of the Western Limb into the Swartklip Facies to the north of the Pilanesberg and the Kroondal and Doornspruit facies (now termed the Rustenburg Facies), to the south. The development of the Merensky Reef in the Eastern Limb is also distinctive and although variations do occur, these are not great enough to warrant subdivision into different facies. In broad terms the Merensky Reef may be described as a mineralised feldspathic pyroxenite and/or feldspathic pegmatoidal pyroxenite, olivine-bearing in places, and generally bound by two chromitite stringers when it is known as Normal Reef. The best mineralisation is concentrated in and immediately above, the top chromitite stringer in the overlying feldspathic pyroxenite, with good mineralisation also developed in underlying pyroxenite, including pegmatoidal pyroxenite. Mineralisation may also occur in noritic and anorthositic rocks where they are immediately overlain by the top chromitite, particularly noticeable where it transgresses downward into what are termed pothole structures.

Rustenburg Facies

Geological Features

The Rustenburg Facies of the Merensky Reef, as defined by Wagner (1929), is developed from just south of the Pilanesberg in the west, to beyond Brits in the east. Some important geological features (excluding the more subtle variations) in this sector are schemically portrayed in Figure 13. (Viljoen and Hieber, 1986; Leeb Du Toit, 1986; Viljoen, 1994; Viljoen and Schurmann, 1998). Between the Kookfontein and Spruitfontein floor domes, or upfolds (Rustenburg section of Anglo Platinum mines), "Normal" Merensky Reef is typically a ±25cm thick pegmatoidal, feldspathic pyroxenite layer bounded by top and bottom chromitite stringers (Fig. 14). The lowermost chromitite stringer is well defined and commonly forms a sharp, but irregular or undulose (dimpled) contact, with the footwall norite/anorthosite. The top chromitite is more disseminated and may occur partly in the pegmatoid or in the immediately overlying pyroxenite (Figs. 13 and 14). Locally, the Normal pegmatoidal reef thins due to downward transgression of the top chromitite stringer

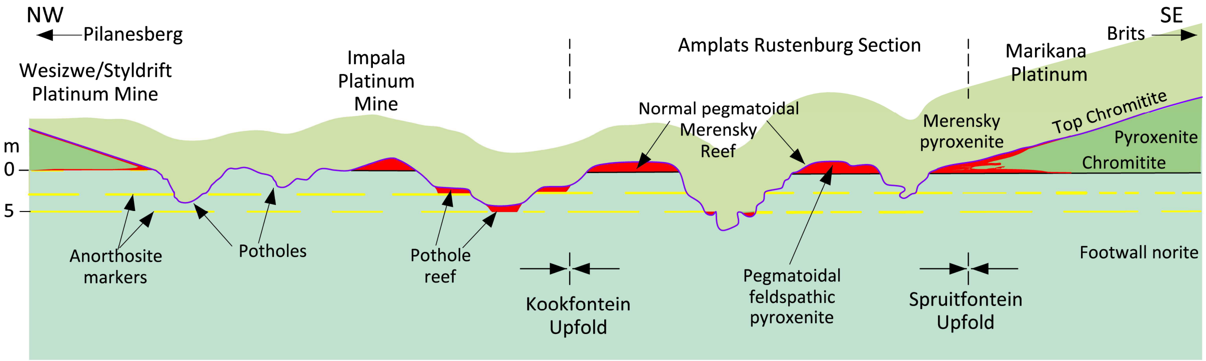


Figure 13. Schematic geological profile portraying the main geological features of the Merensky Reef in the Rustenburg Facies of the Southwestern Limb (after Viljoen 1994 and Viljoen and Schurmann 1998).

and its hanging wall pyroxenite, into pothole structures. The chromitite contact then continues its downward transgression in an irregular manner into the pothole where it may be sporadically associated with pegmatoidal pyroxenite (Fig. 13). Pothole structures which are largely unmineable, occupy about 15% of the Merensky Reef area at Rustenburg section (Viljoen and Hieber, 1986).

To the northwest of the Kookfontein structure, towards the Impala Platinum mine, the reef thins to less than 10 cm and is frequently represented by a single chromitite layer. The potholes in this area (Impala Platinum mine), generally contain well-developed Pothole Reef on two distinctive footwall markers, at levels of about 1 metre and 4 metres below the Normal Reef elevation (Fig. 13). Mineable Pothole reef constitutes about 30% of the Merensky Reef in this area (Leeb Du Toit, 1986). Further northwest towards the Pilanesberg, in the Bafokeng/ Rasimone, Maseve, Styldrift and Bakubung mining areas, a thin Merensky Reef consisting of a chromitite contact only, with about 20% of potholes, is developed (Figs.4 and 13). Locally, pegmatoidal Merensky Reef is developed at a slightly higher elevation than elsewhere in the region. The Reef also thickens downdip and resembles the thicker Merensky Reef style occurring east of Rustenburg section and described below (Fig. 13). Downdip to the north on the farm Styldrift, a relatively abrupt transition of the Merensky Reef into the Swartklip Facies type has been documented (Vermeulen, J; Royal Bafokeng Platinum, pers. comm).

To the east of the Spruitfontein floor dome upfold, towards the Brits graben and beyond (a distance of 40 km), the Merensky Reef widens and grades into a much thicker reef style ranging from less than 50 cm at Rustenburg Section, to 14 metres near Brits (Figs. 4 and 13). Accompanying this thickening, the PGE grades decline and the pegmatoidal texture of the reef largely disappears except for sporadic local development, particularly in the vicinity of the upper and to a lesser extent lower chromitite layer (Figs.4 and 13). The density and size of pothole structures also declines steadily as the thickening takes place and the Merensky Reef becomes subeconomic (Viljoen, 1994).

Mineralogy and Grade Distribution

The pegmatoidal feldspathic pyroxenite of the Normal Merensky Reef in the Rustenburg Facies generally contains between 3% and 10% base-metal sulphides dominated by pyrrhotite, pentlandite, chalcopyrite, pyrite, and cubanite, with minor sulpharsenides, galena, and sphalerite (Kinloch and Peyerl, 1990; Lee, 1996). The ruthenium sulphide, laurite, is commonly associated with, although not confined to, the thin chromitite layers bounding the pegmatoidal Merensky Reef. An average distribution of the PGEs for the Rustenburg facies is:- PGE sulphides, 36%; PGE tellurides, 32%; Ru phases, 15%; PGE alloys, 7%; PGE arsenides, 7%; and Au/Ag phases, 3%. The PGMs are characterised by the presence of the Pt-Pd-sulphide suite, dominated by braggite and cooperite.

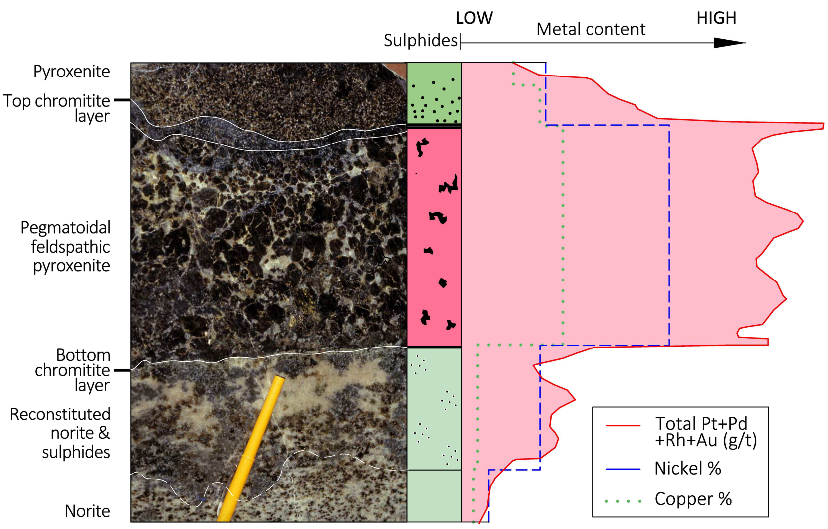


Figure 14. Normal Merensky Reef from the Rustenburg Facies with hanging wall pyroxenite underlain by pegmatoidal feldspathic pyroxenite bounded by thin chromitite stringers. The footwall is a patchy anorthosite with grey patches containing finely disseminated sulphide mineralisation. The size of sulphide particles in the different reef components, together with the broad PGE and base metal distribution profiles is also shown.

The texture and size of sulphide accumulations vary from coarse-grained aggregates, averaging from 0.5 to 1 cm in the pegmatoidal pyroxenite, to smaller disseminated grains in the hangingwall pyroxenite and fine disseminations in blotchy grey patches within anorthosite, in what is interpreted as thermo-chemically reconstituted footwall noritic rocks (Fig. 14). Where the Normal Reef is thin or only a chromitite contact, this “blotchy mineralisation” can extend for up to a metre into the footwall.

Mining of the Merensky Reef in the Rustenburg

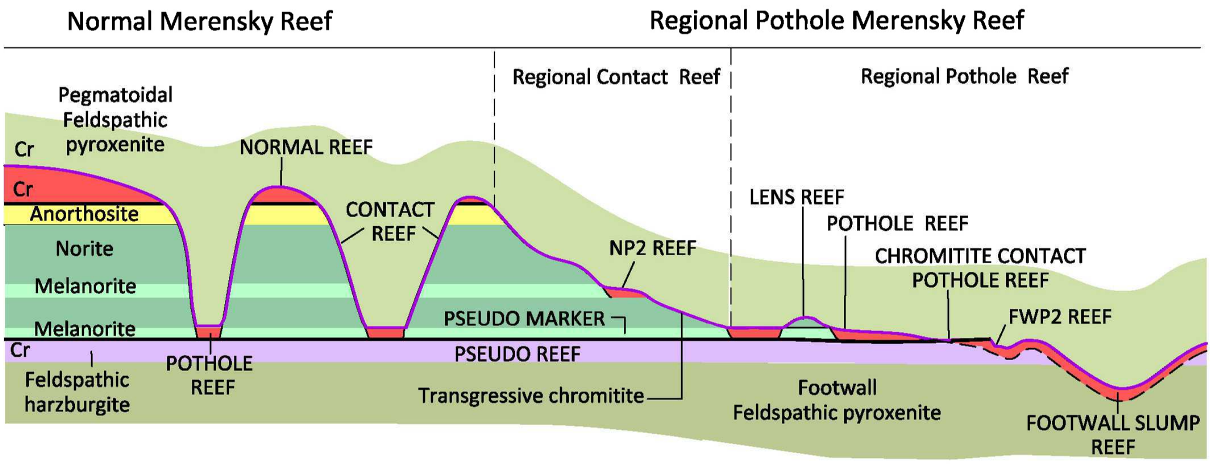


Figure 15. Schematic regional geological profile of the Merensky Reef in the northern part of the Swartklip Facies portraying some of its major characteristics from Normal Reef in the northwest (updip areas of Union and Amandelbult sections), to Regional Pothole Reef in the southeast (downdip areas of Union and Amandelbult sections) and Northam Platinum mine. The top chromitite layer is interpreted as a regional, thermochemical unconformity which reconstituted and mineralised its footwall.

Facies is typically by narrow-reef underground methods. Deep and irregular potholes are generally not mined, whereas regular, relatively shallow Pothole Reef layers, at depths of no more than 4 metres, are frequently mined. As the Merensky Reef thickens, the grade diminishes and stoping is focussed on the top chromitite. Finally, in the east beyond Marikana the thin, low grade zone of mineralisation associated with the top chromitite layer of the thick reef, becomes sub-economic.

Swartkilp Facies

The Swartklip Facies is confined to the northern section of the Western Limb of the Bushveld Complex to the north of the Pilanesberg and is well documented at Union, Amandelbult, and Northam Platinum Mines, (Fig. 4). Normal Merensky Reef (with some potholes) occurs in the updip areas on these mines, while a Regional Contact and Pothole Reef is developed downdip, as well as in a segment immediately north of the Pilanesberg (Figs. 4 and 15) (Viljoen, 1994; Viljoen and Schurmann, 1998; Viring and Cowell, 1999; Lomberg *et al*., 1999). Swartklip Facies type reef as noted, has also been described at depth, immediately south of the Pilanesberg (Vermeulen, pers. comm., 2015).

Normal Merensky Reef

Merensky Reef on normal elevation in the Swartklip facies at Union and Amandelbult sections of Anglo Platinum mines, consists of a pegmatoidal feldspathic pyroxenite bounded by two chromitite layers with a pyroxenite hanging wall and an anorthositic footwall (Figs. 15 and 16a). The Reef is considerably thicker on average (0.5-7.0 metres) than in the Rustenburg facies and is olivine-bearing (Viljoen and Schurmann, 1998). Normal Merensky Reef in the updip regions of the Amandelbult and Union sections is thickest approaching the outcrop in the northwest in these two mining sectors (Figs. 4 and 29).

Potholes are present throughout the area of Normal Reef development, generally increasing in size and frequency downdip as the Normal Reef thins regionally (Fig. 15). A systematic thinning of

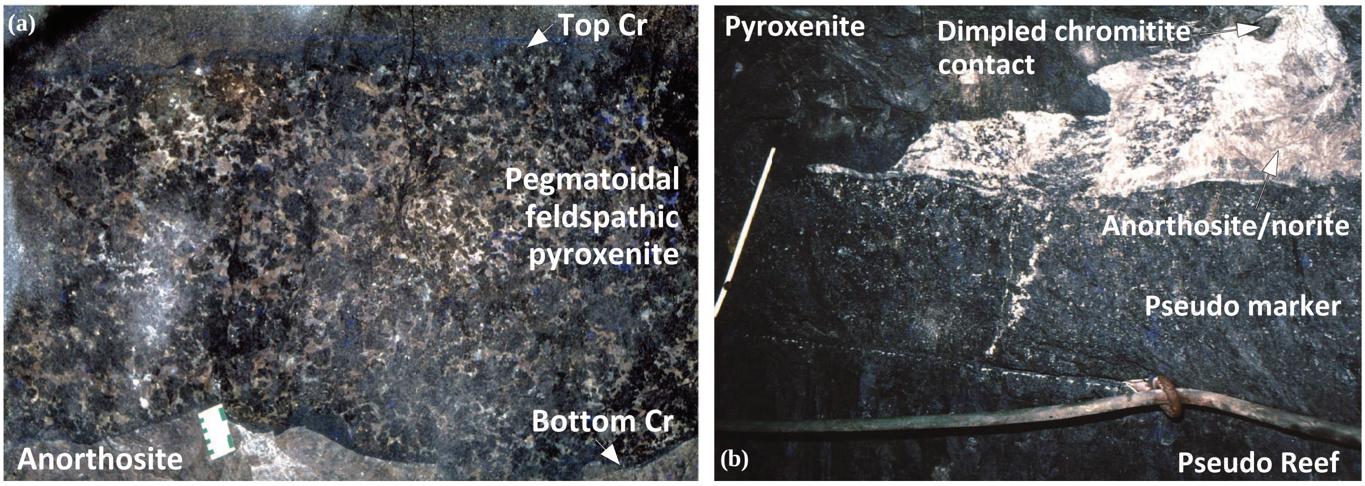


Figure 16. (a) Normal Merensky Reef of Swartklip Facies consisting of a pegmatoidal feldspathic pyroxenite bounded by chromitite stringers. Union Section of Anglo Platinum. (b) Chromitite Contact Reef coming to rest on the Pseudo Marker to form pegmatoidal Pothole Reef. Union Section of Anglo Platinum.

the Normal Reef also takes place towards individual pothole edges due to downward transgression of the top chromitite layer, until the pegmatoidal pyroxenite disappears and only a chromitite contact is present around the periphery of the pothole structure. Sulphide content and grade increase significantly in this narrow reef around the pothole edge.

From the pothole edge, the chromitite contact then transgresses the footwall layers of anorthosite/feuconorite, leuconorite (Fig. 16b) up to a well-defined feldspathic harzburgite layer termed the Pseudo Reef (also known as the "Tarentaal" or "Guinea fowl" rock because of its speckled appearance). Immediately above the Pseoudo Reef, the contact chromitite settles on to a 60 cm thick pyroxenite/partially pegmatoidal pyroxenite layer termed the Pseudo Marker. The marker becomes totally reconstituted and mineralised to form a pegmatoidal pyroxenite, now termed Pothole Reef, with the chromitite now forming its top contact.The chromitite layer at the top of the underlying Pseudo Reef then forms the lower chromitite of the Pothole Reef (Viljoen *et al.*, 1986a) (Figs. 15 and 16b).

Regional Pothole Merensky Reef

Downdip from the Normal Merensky Reef, and on a more regional scale, the upper chromitite transgresses the various footwall markers mentioned above, to form what is termed *Regional Pothole Merensky Reef* (Fig. 15). This initially takes the form of a Regional Contact Reef and is followed downdip by the formation of Regional Pothole Reef, the latter forming when the chromitite contact eventually comes to rest on the Pseudo Marker, converting it to mineralised pegmatoid as in the case of potholes occurring within the Normal Merensky Reef (Figs. 15 and 16b).

Some of the more important variants within the Regional Pothole Merensky Reef are schematically depicted in Figure 15. They include a "perched" pegmatoidal Pothole Reef (termed NP2 Reef, at Northam Platinum Mine), Lens Reef and Chromitite Contact Pothole Reef. Further transgression of the chromitite contact onto the Pseudo Marker results in the latter becoming well mineralised to form Chromitite contact Pothole Reef (Viljoen, 1999). Irregular transgression into the Pseudo Reef has resulted in the formation of FW-P2 Reef, documented at Northam Platinum Mine (Viring and Cowell, 1999). Further transgression into the pyroxenite underlying the Pseudo Reef has resulted in the development of mineralised pegmatoidal pyroxenite below the chromitite layer, well into the footwall in a so-called Footwall Slump Structure at Union Section (Fig. 15) (Viljoen *et al.*, 1986b). The transgressive mineralising top chromitite layer is thus of fundamental importance in forming both Regional Contact and Regional Pothole Reef types.

Mineralogy and Grade Distribution

PGMs in the Normal Merensky Reef of the Swartklip facies are dominated by intricate eutectic-like intergrowths of Pt-Fe alloys associated with the base-metal sulphides and silicates, together with minor PGM sulphides. As is the case in the Rustenberg Facies of the Merensky Reef, laurite is once again associated with the thin Merensky Reef chromitite layer. High PGE values in solid solution in pentlandite, are also characteristic of this type of reef (Kinloch and Peyerl, 1990). The PGM mineralogy of the Regional Pothole Reef is Pt/Fe alloy-dominant, with abnormally high contents of PGE in solid solution in base-metal sulphides.

In the Swartklip facies of the Merensky Reef (as in case of the Rustenburg facies) high PGE values are always associated with the top chromitite layer, with mineralisation spreading into the various footwall lithologies where the only recognisable feature of the Merensky Reef is a thin, irregular chromitite contact, with its overlying pyroxenite.

Mining of Normal Merensky Reef and Regional Pothole Reef is relatively straightforward with standard narrow underground reef mining methods used. Re-development is necessary up to 13 metres below Normal Reef elevation to access Pothole Reef and this is only justified if the volume and grade of the Pothole Reef is large enough. The irregular, steep, Contact Reef forming the periphery of smaller potholes, is largely unmineable. The regional transgressive Chromitite Contact Reef has a relatively shallow dip and is fairly extensively mined, particularly because of its high grade (>50 g/t PGEs in places). High grade but irregular second order pothole reef (FWP2 Reef) in the Swartklip facies, is difficult to mine.

Eastern Limb Facies

The Merensky Reef in the Eastern Limb differs somewhat from the Reef in the Western Limb with the mineralised interval being broadly equated to the wide reef style of the Rustenburg Facies (Mitchell and Scoon, 2007). PGE mineralisation is largely confined to a relatively thick succession of non-pegmatoidal feldspathic orthopyroxenite, bounded by two chromitite stringers. These are spaced between 0.5 metres (Lebowa Platinum mine) and 2 metres apart (Maandagshoek and Winnaarshoek) and the immediate hanging wall is also a feldspathic ortho pyroxenite (Figs. 17a and 17b). A pegmatoidal feldspathic pyroxenite, ranging in thickness from 30 cm in the Maandagshoek area to 1.5 metres at Lebowa platinum mine in the northern part of the Eastern Limb, forms the immediate footwall to the lower chromitite. The footwall pegmatoid is weakly and sporadically mineralised with better, but still subeconomic PGE values occurring in the Lebowa (Bakoni) platinum mine area (Mossom, 1986). The paucity of mineralisation in the pegmatoidal pyroxenite is in contrast to the Western Limb, where much of the well mineralised reef zone is dominated by pegmatoidal pyroxenite. A geological section with PGE grade distribution profiles for the Merensky Reef on Winnaarshoek, is presented in Figure 17a. There is a significant variation in PGE and nickel grade distribution in the Merensky Reef over short distances, with the only relatively consistent mineralisation being that associated with the remarkably persistent upper chromitite layer (Fig. 17b) (Mitchell and Scoon, 2007).

The Platreef

Introduction

The Platreef, although not as laterally extensive as the Merensky Reef, is more than 20 times as thick as the latter and over a distance of 30 kilometres represents by far the largest PGE concentration known. Historically it has been described as a complex, thick (over 200 metres at its broadest) and variably mineralised (PGE, Ni and Cu-bearing), composite pyroxenitic assemblage that, unlike the thin Merensky Reef in the Western and Eastern Limbs, is developed on, or close to, the eastern floor contact of the Northern Limb of the Complex (Fig. 18a). It extends northward from Mokopane for a distance of at least 35 km and dips at 40° to the west.

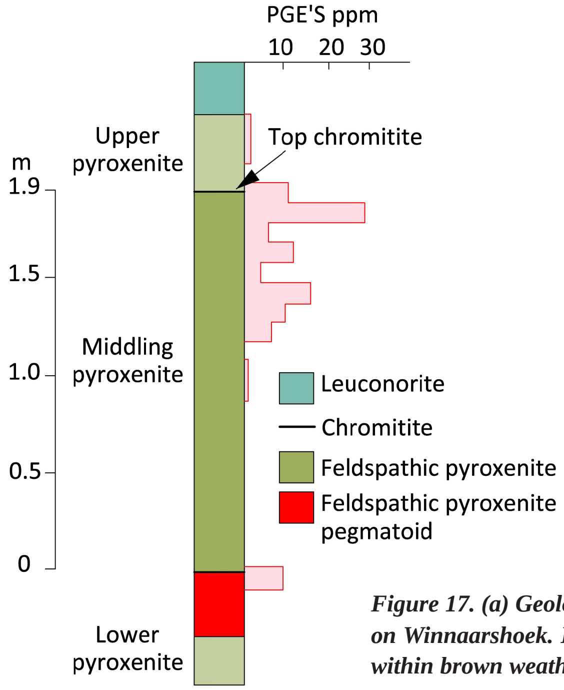


Figure 17. (a) Geological section and PGE value profile for the Merensky Reef in the Eastern Limb on Winnaarshoek. Mitchell and Scoon, (2007). (b) Thin top chromitite layer of the Merensky Reef within brown weathering orthopyroxenite, traceable for over 130 km in the Eastern Limb.

From south to north, the Platreef transgresses quartzite and shale formations of the Pretoria Group (Timeball Hill and Duitschland formations) just north of Mokopane, then, further north on the farm Tweefontein, it transgresses onto the Penge banded iron formation and on northern Tweefontein, onto the underlying dolomitic Malmani subgroup. It is underlain by dolomite for 9 km before transgressing onto Archaean Basement granite on northern Zwartfontein, (Fig. 18a) (Van der Merwe, 1978 and 2008). The full Platreef pyroxenitic assemblage varies from about 100 metres to over 250 metres in thickness and has a variable and irregular footwall contact. It has a generally sharp contact with the overlying gabbro, norite and anorthosite, at the base of the Main Zone (White, 1994). The different footwall rocks have had a significant effect on the nature, PGE grades and possibly even the thickness of the lower Platreef succession. In the Ivanplats project area of the southern sector, the Platreef diverges from the floor rocks and at a depth of about 500 metres flattens out. This so called "Flatreef" extends for over 1.5 km to the west before steepening again further to the west (Fig.18b) (Grobler *et al.*, 2012).

Although not as extensive, a similar localized flattening of dip of the Platreef is evident in the central and northern sectors, in the Mogalakwena Mine lease area. This could be a fault controlled feature (J. Winch - Anglo American Platinum, 2013).

Normal Platreef

Although complex and variable along strike, the Platreef displays a certain broad, consistent, magmatic stratigraphy, particularly in deeper areas away from the immediate footwall contact and in areas displaying lesser contamination, such as on the farms Macalacaskop, Turfspruit and Tweefontein (Buchanan and Rouse, 1984; Grobler *et al.*, 2012; Yudovskaya *et al.*, 2013; Stephenson *et al.*, 2015).

The uppermost unit of the Platreef is a medium-grained, brownish green feldspathic pyroxenite of variable thickness but averaging 10-20 metres in width and known as the T1 feldspathic pyroxenite on the farm Turfspruit (Grobler *et al.*, 2012), which is correlated with the "C-Reef" on the farm Tweefontein to the north (Fig. 19). At the base is a chromitite stringer (not always present in the northern areas), overlying a thick (average 17 metres) coarse-grained mineralised orthopyroxenite, that is frequently pegmatoidal and is termed the T2 pegmatoidal pyroxenite zone on Turfspruit (Grobler *et al.*, 2012) and the "B Reef" on Tweefontein (Fig. 20a). The lower part of the succession contains olivine-bearing harzburgitic assemblages which are also a feature of the Platreef at depth on the farms Zwartfontein and Moordkopjie, of the Akanani Project Area (Fig.18a) (Mitchell and Scoon, 2014). In places a chromitite stringer also occurs at the base of this pyroxenitic assemblage. Based on geochemical data, Nodder *et al.*, (2015) concluded that the T2 Reef zone is a much thicker development of the Merensky cyclic unit (MCU) as seen in the Eastern and Western Limbs of the Bushveld Complex. The B Reef of the Platreef specifically, and the Merensky Reef, are considered by Kruger (2010), to be co-magmatic and coeval.

At surface and in shallower areas a heterogeneous, vari-textured, highly feldspathic pyroxenite occurs below the T2 Reef. It is known as the "Contaminated Zone" or "zone of magma-sediment interaction" on Turfspruit (Grobler, pers. comm.) and as the A Reef on Tweefontein. This enigmatic rock contains graphic inter-growths of plagioclase feldspar and quartz and often contains mineralisation including fairly large blebs of massive sulphides (Fig. 20b). In areas where contamination is absent, a set of norite cycles is developed and these have been interpreted as the normal footwall lithology to the T2 reef zone. Deeper drilling has intersected a massive chromitite layer up to 1.5 metres thick, within norite cycles and this has been equated with the UG2 chromitite layer (Grobler *et al.*, 2012 and Dunnett *et al.*, 2012) (Fig. 18b). Similar distinctive footwall layers have been described from below the T2/B Reef equivalent at depth, on the farms Moordkopje and Swartfontein (Mitchell and Scoon, 2014).

Very similar PGE, Ni and Cu grade distribution profiles are evident for Tweefontein north and Turfspruit (Fig. 19). The uppermost feldspathic pyroxenite (T1/C Reef) is normally barren but in some

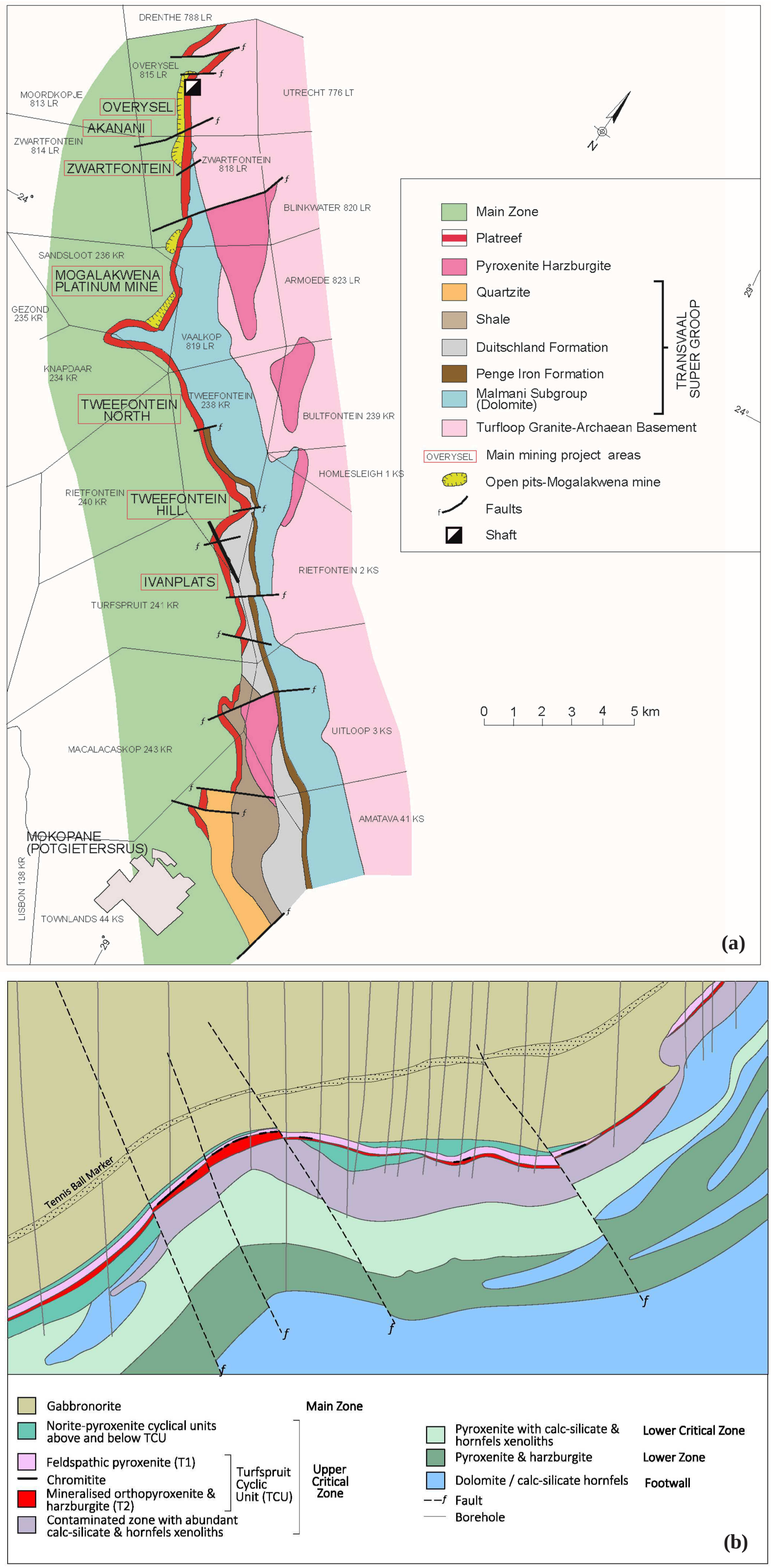


Figure 18. (a) Geological settingof the well mineralised sector of the Platreef between Mokopane (Potgietersrus) and Overysel, a distance of 27 km, showing localities and major PGE mining/mineral projects (after Viljoen and Schurman, 1998).(b) East-west geological section through the Platreef and portraying the "Flatreef" development on the farm Turfspruit in the Ivanplats project area (simplified after unpublished map, D. Grobler, Ivanplats, 2015).

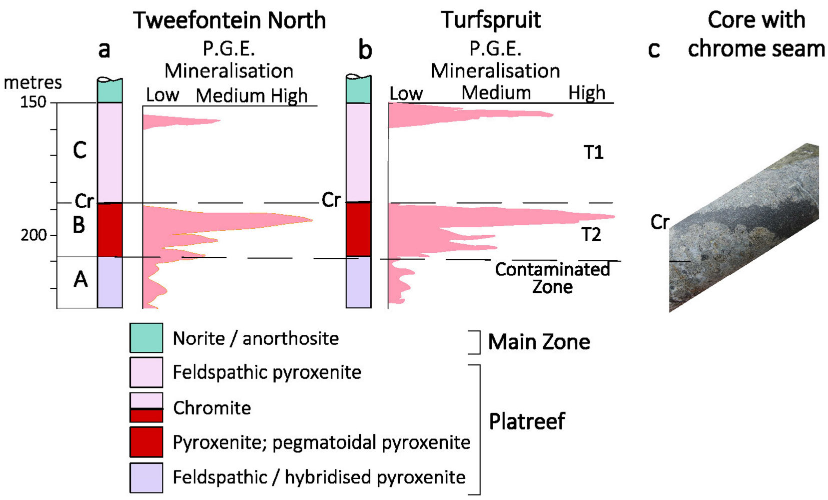


Figure 19. (a) Geological log with PGE, grade distribution, of the Platreef on northern Tweefontein with classification into A, B and C Reef types and with a thin chromitite layer at the top of the B Reef. (Viljoen and Schurmann 1998). (b) Geological log with PGE grade distribution of the Platreef on Turfspruit (Grobler et al., 2012; Dunnet et al., 2012; Stephenson et al., 2015). (c) Top chromitite layer of the pegmatoidal feldspathic pyroxenite (T2) of the Platreef in sharp contact with overlying feldspathic pyroxenite (T1) and equated with the top chromitite contact of the Merensky Reef, in the Eastern and Western Limb. Northern Turfspruit (Dunnet et al., 2012). Suggested correlations are shown.

boreholes mineralisation occurs in its upper part. This mineralisation could perhaps be correlated with that in the Bastard Reef unit elsewhere in the Eastern and Western Limbs of the Bushveld. The best mineralisation occurs in the T2/B Reef, with highest values associated with the top chromitite layer and therefore analogous to the Merensky Reef grade profile elsewhere in the Bushveld, only much thicker. The Contaminated Zone/A Reef contains scattered, generally low grades throughout (Fig. 19).

What is considered to be immiscible sulphide settling has taken place in the Tweefontein Hill area, where a pronounced structural downwarp appears to have acted as a structural trap site for settling sulphides. This has resulted in significant accumulations of massive, to heavily disseminated base-metal sulphides, close to the footwall contact. Narrow copper sulphide-rich veins have penetrated the footwall rocks on Tweefontein Hill which was the site of early copper mining activity. A notable feature is the presence of perfectly formed sperrylite crystals in the gossanous near surface alteration of the veins. The PGE, Ni and Cu value profiles reflect the features described above for Tweefontein Hill and in particular a shift in mineralisation and specifically base metal mineralisation, towards the basal part of the A reef and as veins into the footwall hornfels (Viljoen and Schurmann, 1998).

Contaminated Platreef

While some form of contamination is present throughout the Platreef, significant contamination, metasomatic overprinting and interaction with the footwall is present where the Platreef is underlain by, or incorporates as entrained xenoliths, reactive lithologies such as dolomite, particularly on the farms Sandsloot and southern Zwartfontein (Figs.18a and b) (White, 1994; Viljoen and Schurmann, 1998; Grobler *et al.*, 2012).

In the Sandsloot open pit where mining first started in 1994, as well as at the Overysel trial mining shaft (now the primary mining area), the Platreef, although still broadly divisible into A, B and C reef components, is dominated by the effects of reaction with the dolomite floor rocks and in the case of the latter, also granitic footwall. In the Sandsloot and Zwartfontein areas the Platreef contains many calc-silicate (originally dolomite) xenoliths, surrounded by haloes of serpentine containing altered olivine and magnetite (Fig. 21a) (White, 1994; Viljoen and Schurmann, 1998). Carbonate floor rocks in immediate contact with the basal Platreef have been altered to mineralised “parapyroxenites” (equigranular diopside) and calc-silicates (typically garnetiferous magnesian skarn), formed during extensive syn-magmatic interaction with high magnesium silicate melts (Viljoen and Schurmann 1998; J. Winch, pers. comm., 2015) (Fig. 21b). While calc-silicate contamination dilutes PGE grades and dramatically affects benefication, reaction haloes of serpentinite in the surrounding magmatic material often contain localized erratic sulphide concentrations with high Cu, Ni and PGE values (Lee, 1996).

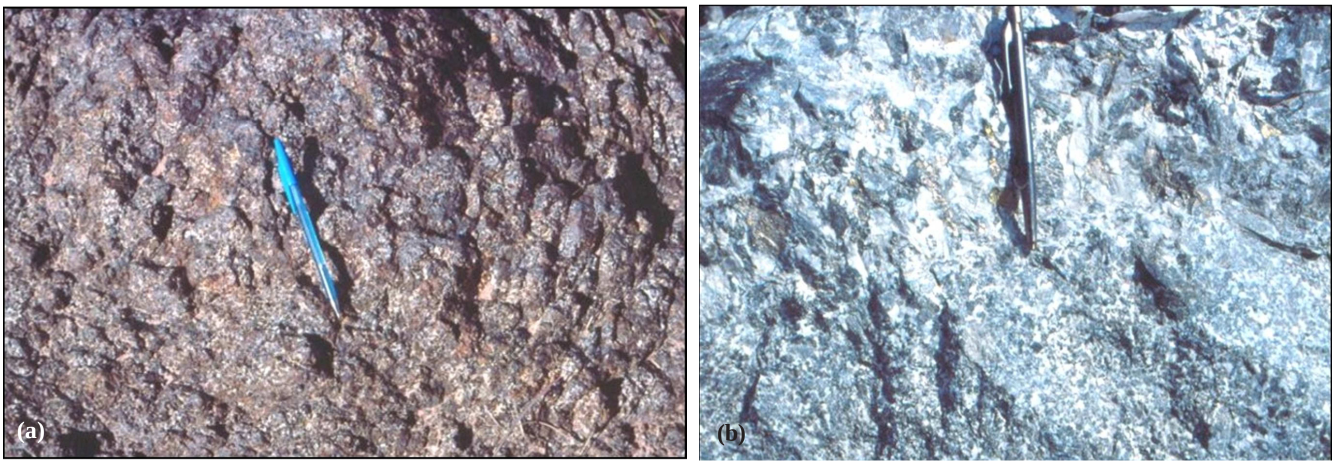


Figure 20. (a) Typical B reef feldspathic pyroxenite outcrop with small oxidized sulphide blebs (now limonite), Tweefontein. (b) Contaminated vari-textured feldspathic pyroxenite (A Reef) with mineralisation in the form of irregular sulphide blebs. Sandsloot open pit mine.

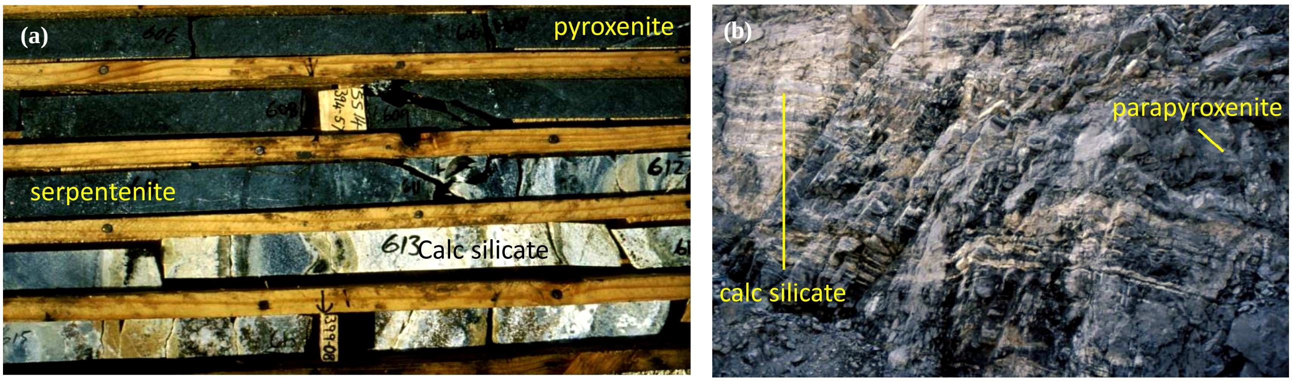


Figure 21. (a) Calc silicate xenoliths grading into serpentinite and finally B Reef pyroxinite (Overysel). (b) Mineralised parapyroxenite (dark, dense, hard equigranular diopsidite) interlayered with calc-silicate (typically garnetiferous magnesian skarn). Immediate footwall of Platreef, Sandsloot open pit mine

Argillite xenoliths and autoliths are more common in the southern Platreef area and have been thermally metamorphosed into hercynite + cordierite ± plagioclase ± hypersthene hornfels. The assemblage has resulted from partial to complete melting of the argillaceous units which are normally located within magmatic units of feldspathic pyroxenite and norite. This is due to the incorporation of silica-rich fluids, derived from melting of these clasts into the magmatic melt (Sluzhenikin *et al*., 2015). Evidence also exists for the inclusion of meta-quartzite within magmatic units, mainly in the southern part of the area (Fig. 18b).

Where the Platreef is underlain by Archaean granite, partial melting of the granitic gneiss floor has resulted in the formation of a rock described as a granofels (Cawthorn *et al.*, 1985). The granofels frequently exhibits an agmatitic texture (rheomorphic breccia) and contains dark-green mafic schlieren that often host PGE mineralisation. This is classically seen in the open pit on Overysel (Figs. 22a and b) where granofels predominates in an extensive interaction zone developed between the base of the Platreef and the underlying Basement granitic rock. Chilled basal mafic lithologies of the Platreef were invaded by an extensive network of leuco granitic melt, generated by the heat imparted from the intrusive that invaded the already solidified and brecciated, darker Platreef material, to form the widely developed rheomorphic breccia (Fig. 22b). In places the deformation was sufficiently plastic and the incorporation and assimilation of Platreef material in this leucocratic footwall partial melt so extensive, that the material more closely resembles a gneiss. (J. Winch, pers. comm., 2015). Massive sulphide mineralisation in the form of downward penetrating veins, blebs and patches, often occurs close to the footwall contact of the Reef in this area.

Within the open pits of the Mogalakwena Platinum Mine, situated on the farms Sandsloot, Zwartfontein and Overysel, the better grades for the Normal Platreef are hosted largely in the B reef pyroxenite. Lower grade and more erratic mineralisation occurs in the underlying possibly quenched A Reef (J. Winch, pers. comm., 2015). Copper and nickel range between 0.1-0.25% and 0.15-0.35% respectively, while PGEs range from < 2.5 ppm to 15 ppm and in places up to 25 ppm. The ratio of Pt to Pd is approximately 1:1 (Lee, 1996). The variations in the nature and mineralisation styles of the Platreef described above are schematically portrayed in Figure 23.

Possible Platreef and Other Extensions

An enigmatic unit of layered rocks lies beneath the Main Zone, south of Mokopane, where the Platreef *sensu stricto* is not present. Instead Ni-Cu-PGE sulphide mineralisation is present as sporadic disseminations within a vari-textured succession of pyroxenites, norites, anorthosites and chromitites, within an 800 metre thick unit that extends for 30 km and is referred to as the Grasvally norite-pyroxenite-anorthosite (GNPA) member (Hulbert and Von Gruenewaldt, 1982; Smith *et al.*, 2014). The GNPA member and the Platreef are considered to have formed concurrently, from compositionally similar and related magma, with a transition occurring between the two (Holwell *et al.*, 2015).

An apparent extension of the Northern Limb has recently been discovered below a cover of flat lying, 2 billion year old Waterberg Group red bed sediments, north of the known outcrop (Fig. 2) (Muller, 2015). Two zones of PGE mineralization known as the T and F zones occur over a strike distance of 17 km. The T Zone lies within the Main Zone, beneath the contact of the overlying Upper Zone and contains two potentially economic layers, namely the T1 and T2 Zones. T1 mineralisation is hosted in olivine bearing troctolite and harzburgite as well as in pyroxenite and pegmatoidal gabbro, while T2 mineralisation is hosted in norite and gabbro norite. PGE grades in these two layers are typically 3.47 g/t PGE over 2.4 metres and 3.95 g/t over 3.87 metres respectively. The PGEs have an unusual metal ratio of 50% Pd, 30% Pt and anomalously high Au (20%), with 0.1% Ni and 0.17% Cu (Muller, 2015).

The F reef occurs at the base of the Main Zone and could perhaps be equated with the Platreef. It is hosted in alternating units of serpentinised troctolite/harzburgite and pyroxenite, averaging 100 metres in thickness. The F Zone is divided into the FH and FP layers. The mineralised FH layer has significantly high volumes of olivine, in contrast to the lower FP layer which is predominantly pyroxenite. The FH layer is divided into six cyclic units identified by their geochemical signatures, particularly chromium. Mineralisation is typically over less than 10 metres in thickness within the central portion, with grades of 3 g/t PGE and containing 65% Pd, 30% Pt and 5% Au with 0.07% Ni and 0.17% Cu and with a strong Cr enrichment associated with the highest PGE concentrations. The current inferred resource (PTM, April 2015) over 10 km strike and down to 100 metres, is 287 million tonnes grading 3.15 g/t PGE and containing 29 million ounces of PGE (Muller, 2015).

It should be noted that low grade PGE mineralisation has recently been defined associated with the Troctolite Marker situated towards the Upper part of the Main Zone of the Northern Limb

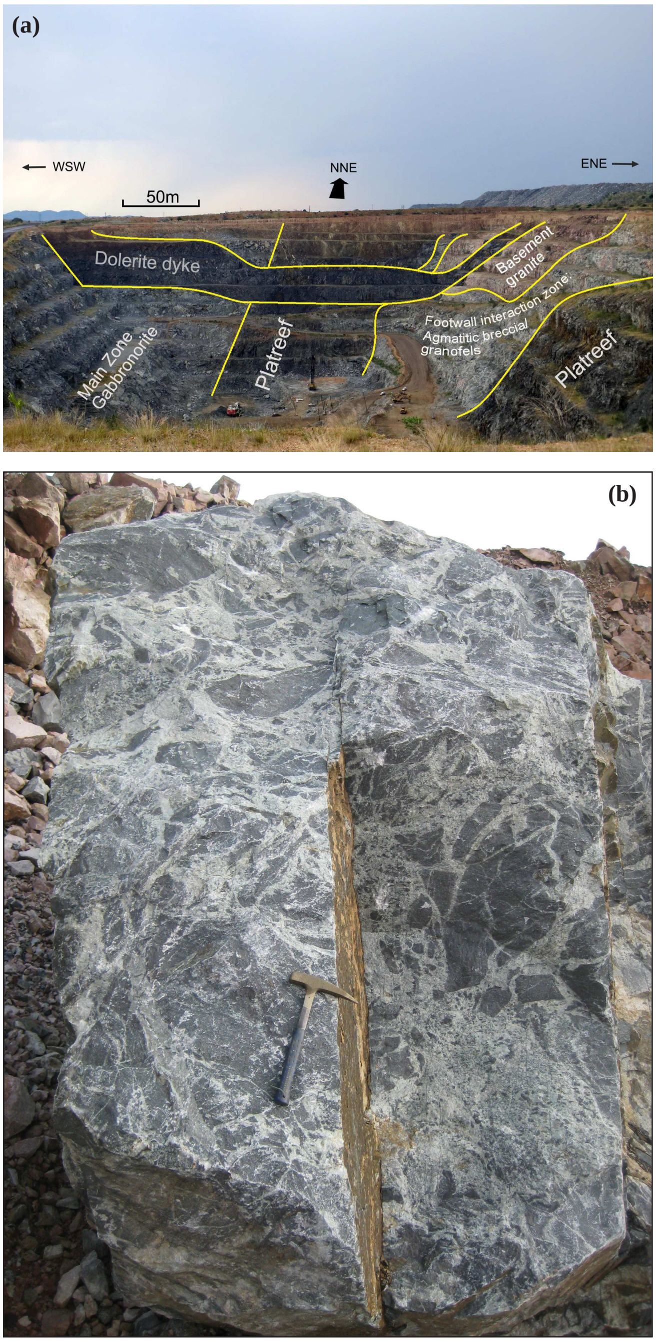


Figure 22.(a) General view of open pit mine on Overysel showing the main mineralised B Reef (Merensky Reef equivalent) - dark green with underlying A Reef and granofels footwall to the right. A major fold in the B reef results its re-appearance in the right foreground. The whole succession is cut by an E-W trending dolerite dyke (Photo. James Winch, Anglo Platinum). (b) Agmatite or rheomorphic breccia in the footwall of the Platreef. (Photo J. Winch, Anglo Platinum).

and attains its best development in the central sector, with fine disseminated sulphides hosted within the troctolite itself, as well as in overlying olivine-bearing noritic units closely associated with anorthosite layers. Up to five mineralised units have been identified with the highest PGE value being 3.68 g/t within a 3.23 metre wide zone that averages 1.15 g/t PGE (Bushveld Minerals, 2010).

Vanadiferous Magnetitites of the Upper Zone

Introduction

The bulk of South Africa's vanadium is hosted in the vanadium enriched titaniferous magnetitite layers (magnetite -bearing layers, referred to from hereon as magnetite layers for simplicity) of the Upper Zone of the Bushveld Complex, where the presence of vanadium has been known since the turn of the 20th century. In 1921 Cornelius Delfos attempted to smelt these ores in a blast furnace in Pretoria, but discovered that the titanium carbides and nitrides choked the furnace. No further attempts were made to exploit this resource until 1957 when vanadium-pentoxide (V_2O_5) production commenced using a salt-roast leach technique on ore extracted from the Main Magnetite Layer near Stoffberg in the Eastern Limb, by the Vanadium Transvaal (VANTRA) Company (Schurmann and Marsh, 1998). Vantra subsequently changed its source of ore to the higher grade Kennedy's Vale magnetite pipe, in the Eastern Limb near Steelpoort (Fig. 5). When it became feasible to produce iron and steel from the Bushveld ores, Highveld Steel and Vanadium Corporation Ltd was established, with steel and vanadium plants near Witbank. At the same time a company called Vanchem was established to beneficiate the vanadium product to high-grade fused vanadium pentoxide from roast leaching. Ore to feed the plants was obtained from the Mapochs Mine, which exploits the Main Magnetite Layer at Roossenekal (Fig. 5). Kennedy's Vale mine closed in 1972 after the Mapochs Mine came into production. The mine reopened with a processing plant in 1988 installed by VANTRA. After closing again in 1990, the mine was reopened by Vanadium Technology (Pty) Ltd. (VANTECH) in 1992, but having been largely mined out, it was finally closed in 2004 by the company Xstrata. A number of companies have, or are still mining in the Southwestern Limb of the Upper Zone of the Bushveld Complex. They include Vametco, which started in 1968 and Rhovan, which started in 1989 (Schurmann and Marsh, 1998) (Fig. 4).

No discrete vanadium bearing minerals have thus far been positively identified in the ore layers of the Bushveld Complex (Reynolds, 1986) with the vanadium being present in solid solution in the magnetite (Hiemistra and Liebenberg,1964), as a substitution of V_3^+ for Fe_3^+. Vanadium pentoxide is the commercially extracted end product as V^+_3 and not as V^+_5 (Eales and Cawthorne, 1996). Most vanadium used in industry is in the form of vanadium-pentoxide (V_2O_5), which is produced by blending milled ore, slag or concentrate, with sodium salt and then roasting and leaching it. The steel industry consumes most of the vanadium in the form of ferrovanadium as an essential alloying metal that imparts strength, hardness and resistance to both mechanical and chemical corrosion, to steels. Vanadium pentoxide, ammonium vanadate, vanadium tetrachloride etc. are used as catalysts in oxidation reactions in the chemical industry and vanadium is becoming increasingly important in storage batteries, particularly in combination with renewable energy generation.

South Africa's reserves of vanadium-bearing titaniferous magnetites in the Upper Zone of the Bushveld Complex are vast and are estimated by the Minerals Bureau (Grohman, 1994) to be 12.5 million tonnes of vanadium metal (to a depth of 50 metres), which is about 45% of the estimated world reserves.

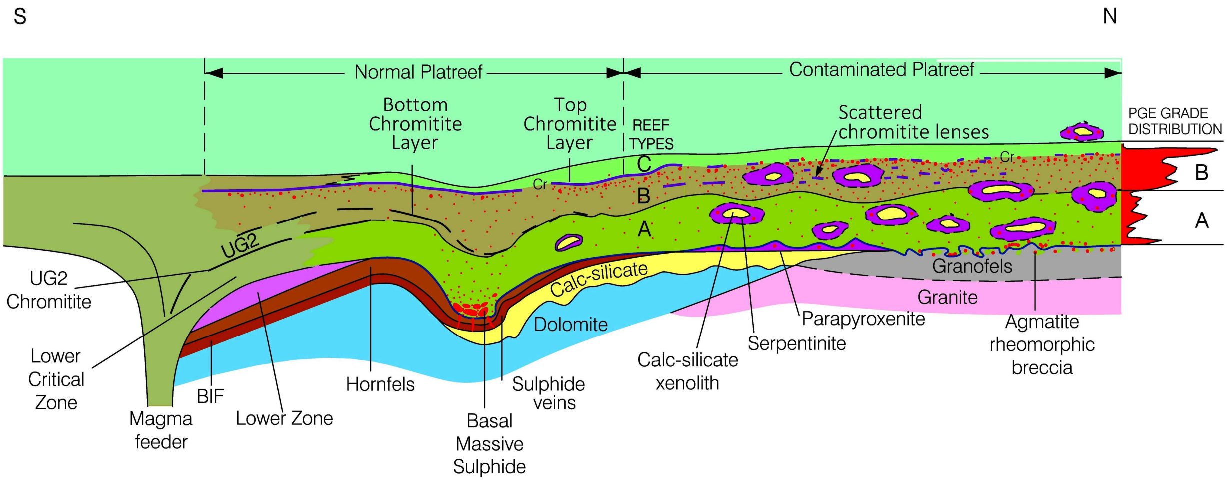


Figure 23. Schematic north-south geological profile of the Platreef, close to surface, depicting the nature and styles of PGE mineralisation.

Geological Setting

Bushveld vanadiferous magnetite mineralisation of the Upper Zone occurs as concordant, massive and disseminated layers, and as cross cutting magnetite plugs, or pipes, mainly in magnetite gabbro of the Upper Zone. The latter are part of a suite of iron-rich ultramafic pegmatite bodies (IRUPs) (Viljoen and Scoon, 1985).

The magnetite layers are concordant over considerable distances, both along strike and downdip. They vary in thickness, as well as in the number of associated layers and in their magnetite, V_2O_5 and TiO_2 contents. Between 20 and 25 layers of Ti-magnetite (including both massive and disseminated components) have been recognised and are often closely associated with anorthosite layers. Numbering has been subjective so that multiple layers occurring in close proximity were not necessarily given separate numbers. In reality there are far more, minor individual layers, than generally portrayed (Schurmann and Marsh, 1998).

Molyneux (1974) defined the base of the Upper Zone in the Eastern Limb of the Bushveld Complex as an anorthosite layer in which cumulus Ti-magnetite first appears in the sequence, some 30 metres below the lowermost Ti-magnetite layer. Although apparently conformable in places, the Upper Zone can dramatically transgress its footwall rocks to form a major unconformity. Clear evidence for this unconformity comes from the so called Gap areas of the Western Limb, north of the Pilanesberg, as well as from "the floor domes" in the northern part of the Eastern Limb (Figs. 4 and 5).

Magnetite of the Upper Zone is invariably black and highly magnetic, with the best magnetite concentration over reasonable thicknesses occurring in the Main Magnetite Layer (MML) which is developed in all of the Limbs of the complex. Some of the highest vanadium grades (>2%V_2O_5) occur in disseminated and massive footwall layers to the MML, with the V_2O_5 content decreasing upward to about 0.25% V_2O_5 for the uppermost layers. The titanium content in the Upper Zone varies in inverse proportion to that of vanadium, from about 11% in the lowest layer, up to about 18% TiO_2 in some of the top layers. The formation of magnetite layers in the Upper Zone has been ascribed to a number of processes, including changes in oxygen fugacity during fractional crystallization, pressure change, magma chamber replenishment, basal boundary layer crystallization and the formation of immiscible liquids.

The IRUP's are randomly distributed, cross-cutting structures of widely differing sizes, and range from dyke-like to pipe-like in form (Fig.12) (Viljoen and Scoon,1985; Scoon and Mitchell, 1994). IRUP's have a spatial and genetic association with titaniferous magnetite layers of the Upper Zone but are also widespread in the Main Zone where they bear a relationship to anorthosite layers (Viljoen *et al.*, 1986a and c). They have similar compositions to the layered magnetites immediately above them and are considered to represent pure Fe-Ti oxide melts that drained downward along structures from the associated overlying layers (Scoon and Mitchell, 1994). The Kennedy's Vale pipe is a zoned body, 300 by 100 metres in size, which had a core of massive, vanadium-rich Fe-Ti oxide pegmatite, enveloped by disseminated Fe-Ti oxides and clinopyroxenite pegmatite (Fig. 24). The iron-rich core which was mined for vanadium, is carrot-shaped, pinching out at depth, which can be taken as supporting the proposed downward draining origin. The pipe occurs in the lower part of the Main Zone and is stratigraphically the

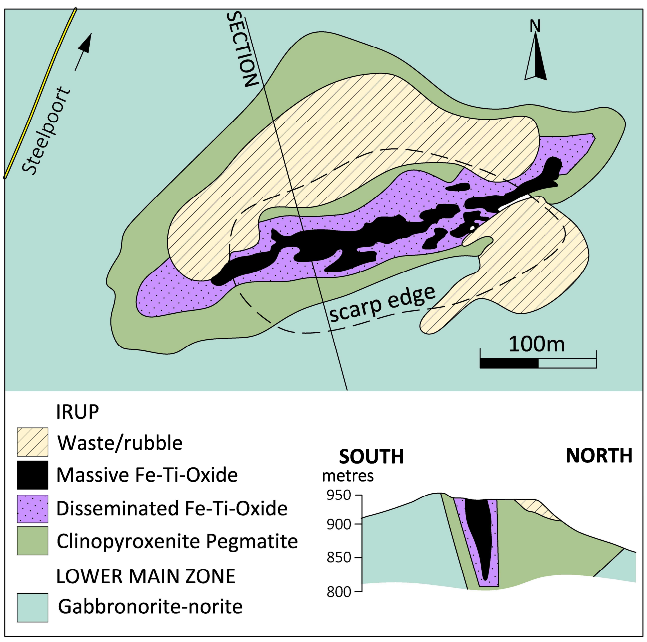


Figure 24. Geological map and section through the Kennedy's Vale zoned, vanadiferous magnetite pipe, site of one of the earliest vanadium producing mines (after Scoon and Mitchell, 2004).

lowermost occurrence of vanadium ore in the Bushveld. With a V_2O_5 content of 2.5%, it was one of the first and richest vanadium deposits to be mined.

Magnetite Layers with Special Reference to the Eastern and Northern Limbs

Introduction

Geological mapping and geochemical studies have been undertaken across much of the Upper Zone of the Bushveld Complex in the Roossenekal / Mapochs mine area of the Eastern Limb (Von Gruenewaldt, 1973; Molyneux, 1974 and Scoon and Mitchell, 2012) (Fig. 5). The first two authors divided the Limb into 4 subzones A to D, with the last mentioned authors adding a further subzone E, at the top (Fig. 5). In the poorly exposed Northern Limb, details of the Upper Zone have been based on a section line constructed from six boreholes, where it has also been divided into subzones A to E (Figs. 25a and b) (Bushveld Minerals, pers. comm.).

Three groupings of magnetite layers are evident in the Eastern and Northern Limbs and these can be broadly divided into Lower, Middle, and Upper Magnetite Groups (Fig. 25a). The Lower Magnetite Group straddles subzones A and B, and contains the important Main Magnetite Layer (MML) which is vanadium-rich. The Upper Group of layers occurs towards the top of subzone D and are titanium-rich with lower vanadium contents. A robust, titanium-rich magnetite layer at the top of the Upper Magnetite Group is referred to as Layer 21 in the Eastern Limb and as the Q layer in the Northern Limb. The Middle Group cluster of thin layers occurs in subzone C and contains intermediate vanadium and titanium grades. Most of the magnetite layers are closely associated with anorthosite layers. The magnetite layers are described sequentially from the base to the top of the Upper Zone.

Lowermost Magnetite Layers

Within subzone A of the Eastern Limb in the Roossenekal area, 4 thin magnetite layers occur below the MML, while in the Northern Limb a robust 10 metre thick layer of disseminated magnetite is developed, with a geochemical profile suggesting that it is comprised of 3 adjoining horizons with the presence of layer 1 (based on aeromagnetic data) not as yet tested (Fig. 25b).

In the Southwestern (Rustenburg) Limb of the Bushveld Complex, 3 to 5, somewhat discontinuous, mainly disseminated magnetite layers occur (Van der Merwe, M., pers. comm.). The V_2O_5 content in the magnetite of these lower layers ranges from between 2.0 to 2.2% V_2O_5 for the lower part of individual cycles, to just over 1.8% V_2O_5,

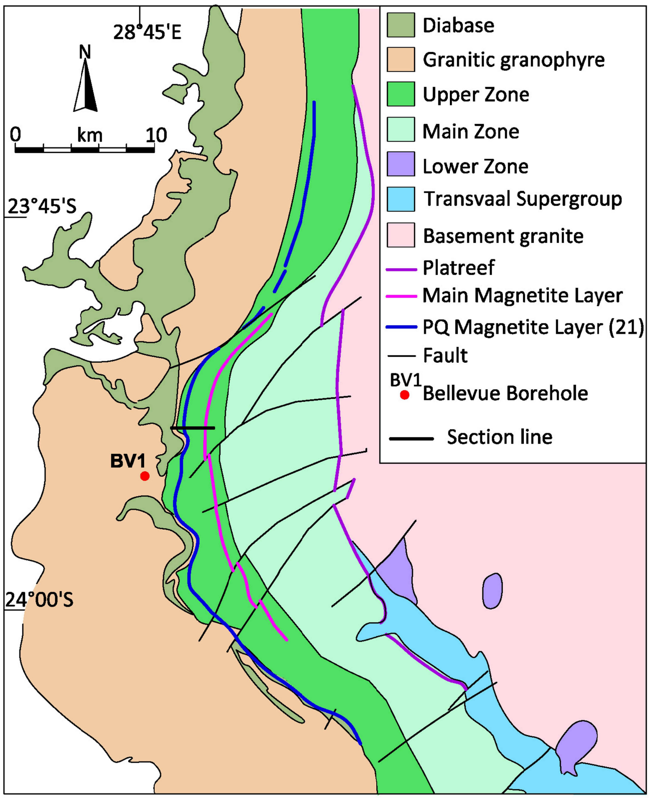


Figure 25. (a) Geological setting of the Upper Zone in the central sector of the Northern Limb highlighting the Main Magnetite Layer (MML) and Q layer (Layer 21) as well as the locality of the geological section.

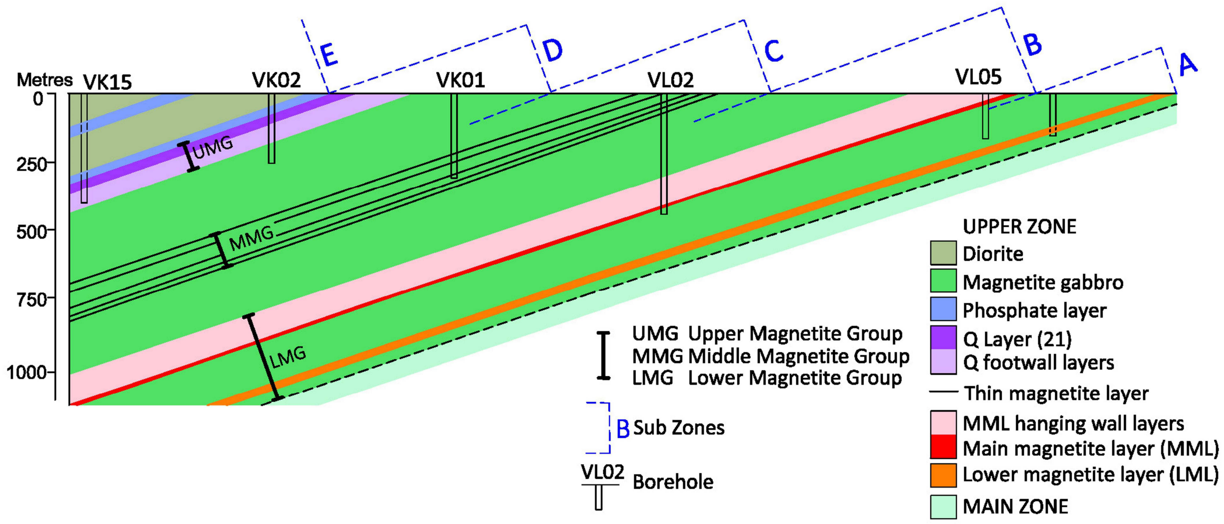
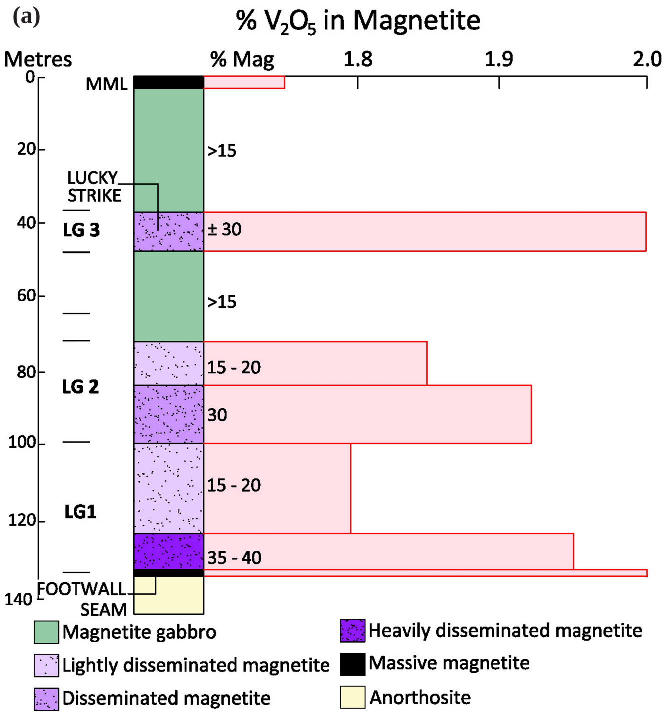


Figure 25. (b) Geological section through the Upper Zone of the Northern Limb showing the major subzones and magnetite groups together with the MML and Layer 21, after Bushveld Minerals.



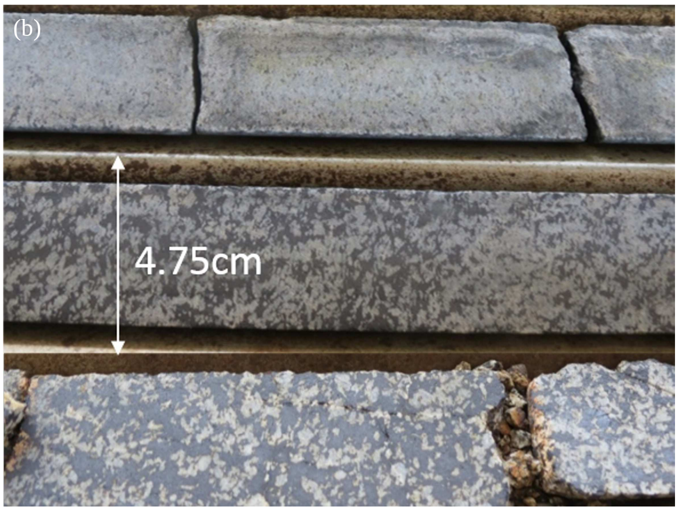


Figure 26. (a) Section through the lowermost magnetite layers with portrayal of amount of disseminated magnetite and V_2O_5 grade of the magnetite. Rhovan Vanadium Mine (M. Maseti- Rhovan Mine). (b) Examples of heavily disseminated to slightly disseminated magnetite typical of the vanadium-rich lowermost magnetite layers. Rhovan mine, Southwestern Limb.

for the uppermost cycle, with a value of 2.4% V_2O_5 having been recorded in the lowermost of the layers (Van der Merwe, M., pers. comm.).

The general enrichment of vanadium in magnetite and its decrease from the base upwards, is well demonstrated in the case of the Rhovan Vanadium Mine (Fig. 26a). Here, a series of three disseminated but generally recognisable layers occur over an interval of 130 metres below the MML (Figs. 26a and b). A one metre thick footwall layer of nearly massive magnetite averaging 2% V_2O_5 is overlain by heavily and then slightly, disseminated magnetite zones averaging 1.96 and 1.8% V_2O_5 respectively. An overlying cycle has a lower disseminated magnetite component averaging 1.92% V_2O_5, which passes up into a lightly disseminated upper sector averaging 1.84% V_2O_5. The uppermost third layer, known as the Lucky Strike, averages 30% magnetite with a grade of 2.0% V_2O_5 (M. Maseti-Rhovan, pers. comm.).

The lower magnetite layers, although consisting largely of disseminated magnetite, are of economic importance because of the high V content of the magnetite. Lower magnetite layers of the Vametco Mine show a broadly similar layered succession.

The Main Magnetite Layer

The Main Magnetite Layer (MML) in the Eastern Limb is a 2 metre thick massive layer with a disseminated magnetite parting in the middle (Figs. 27a and b). The contact with the footwall mottled anorthosite is sharp, whereas the hangingwall contact is gradational. This layer may include disseminated base metal sulphides (Von Gruenewaldt, 1973 and Page *et al.*, 1982). The MML contains between 1.61% and 1.8% V_2O_5 in the magnetite and is mined as a vanadium and iron ore at the Mapochs mine near Roossenekal (Figs. 5 and 27b). In the Northern Limb the MML is 8 metres thick with a 2 metre disseminated magnetite gabbro parting.

Detailed logging and sampling of the 130 metre thick magnetite bearing hanging wall succession of the MML in the Northern Limb

Figure 27. (a) The 2 metre thick Main Magnetite Layer (MML) consisting of massive magnetite. Exposure in a stream bed northwest of Roossenekal. (b) Mapochs mine, where the dip slope comprised of the resistant MML has been stripped off by early mining activities.

has revealed the presence of eleven discrete, heavily to moderately disseminated vanadiferous magnetite layers. Many of these have sharp basal contacts overlying anorthosite or leucogabbro and have graditional upper contacts. V_2O_5 grades are mainly above 0.55%, with several layers spiking above 1.3% V_2O_5. A remarkable feature of the MML and its distinctive, often very thin hanging wall markers, is their continuity over large distances of at least 3 km, where studied in the Northern Limb (Bushveld Minerals, 2014). This continuity of layers epitomizes the layering style in the Bushveld Complex.

Layer 21 (Q Layer)

Layer 21 (referred to as the Q Layer in the Northern Limb by Bushveld Minerals) forms a distinctive assemblage of magnetite layering averaging over 45 m in thickness and consisting of massive, disseminated and stringer magnetite. It represents a major potential iron and titanium resource that is recognisable in most of the exposed Limbs of the Bushveld Complex. A feature of the Upper Magnetite Group is the low P_2O_5 content (<0.05%).

A sharp, well defined contact is present at the top of the Q Layer (Layer 21) in both the Eastern and Northern Limbs and marks the contact between the D Zone and overlying E Zone.

Phosphatic D and E Subzones

The sudden appearance of phosphate in the form of apatite, defines the base of the D and E Subzones of the Upper Zone. This is portrayed by the P_2O_5 content of silicate rocks for the Eastern Limb (Scoon and Mitchell, 2012) (Fig. 28). In the D zone P_2O_5 values average 2.5% but decline dramatically in anorthosite layers and in the Upper Magnetite Group layers. A second, sudden appearance of P_2O_5 of up to 5%, occurs at the base of the E-zone and decreases steadily to zero at the top of the E zone and the top of the RLS (Fig. 28).

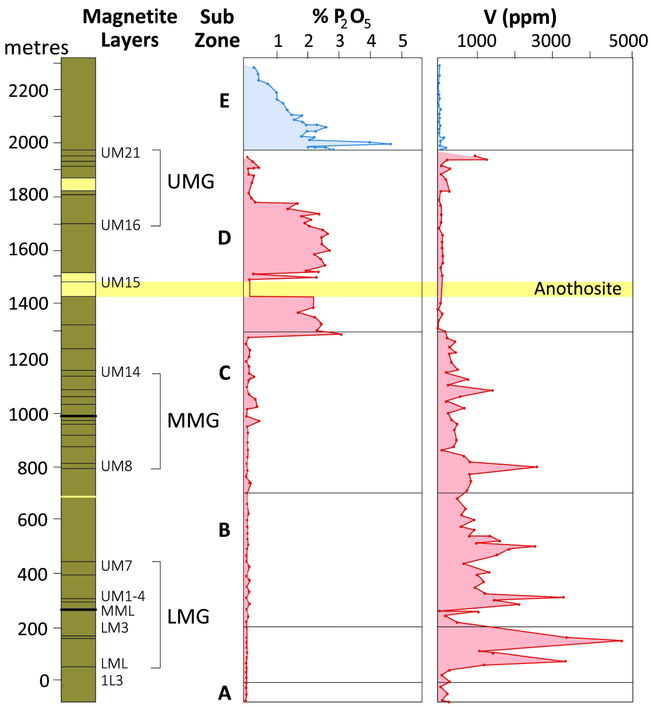


Figure 28. Regional geochemical trends for phosphate and vanadium in silicate rocks of the Upper zone based on 20 m sample intervals, in relation to Subzones. Roossenekal area of the Eastern Limb. After Scoon and Mitchell, 2012.

In the Northern Limb, the base of the distinctive, greenish brown dioritic E zone is marked by the Hanging Wall Marker which immediately overlies disseminated magnetite of the top of the Q layer or layer 21 (Bushveld Minerals unpublished report; Viljoen, M). The lower part of subzone E in the Northern Limb has two robust magnetite-bearing diorite layers averaging up to 5% P_2O_5. The E zone is overlain by a hybrid zone followed by the Rooiberg Felsite, the roof rock of the Rustenburg Layered Suite.

Exploration

Geophysical techniques, in particular gravity, magnetics and seismics, together with soil geochemistry, have been applied successfully, in combination with detailed geological mapping, to exploration and mining projects in the Bushveld Complex and have been used to establish and constrain models for the nature and origin of Rustenburg Layered Suite and its mineralisation (Campbell, 1990, 2006 and 2011 and Viljoen, 1999).

Gravity

The importance of gravity in defining the major Limbs of the Bushveld Complex has been referred to earlier (Fig. 3). High-Gravity anomalies in the Western Limb have been shown to correlate with areas of greater potholing and thermo-chemical reaction of the Merensky Reef (Viljoen, 1999). In the Swartklip Facies, areas of highest gravity correlate with Regional Pothole Reef in the downdip area and suggest a possible magma feeder and/or thickening of magmatic rocks closer to this, probably higher temperature domain (Fig. 29) (Viljoen, 1999). In the Rustenburg Facies, higher gravity also correlates with generally thinner, more potholed and higher grade Merensky Reef types. A region of lower gravity towards Brits, corresponds to the non-pegmatoidal, largely non-potholed and low grade, wide Merensky Reef type (Figs. 2, 3, 4 and 29).

It is evident that the region of highest gravity in the Bushveld Complex, towards the southern sector of the Northern Limb, to the immediate northwest of Mokopane, corresponds to the area of thickest, best developed and highest PGE enriched rocks in the Bushveld Complex (Figs. 2 and 3). This, it is suggested, could reflect the locality of one of the more important higher temperature magma feeders to the Rustenburg Layered Suite, in this area (Viljoen, 1999).

Seismics

Seismic profiling has been used since the early 1980s in various sectors of the Bushveld to determine the regional structure of the layering at depth, while 3D seismics has been used to determine the structural features of the Merensky Reef, including the distribution, shape and size of pothole structures. A seismic line across the Southwestern Limb (Fig. 29) reveals pronounced seismic reflectors demarcating the Upper Zone, the upper Critical Zone, (including the Merensky Reef) and the base of the Lower Zone. No reflectors are present in the overlying homogeneous Bushveld granite. The seismic data suggest a broad basinal structure for the Southwestern Limb, with a broad arcuate, trough-like form, the inner part of which occurs below Bushveld granite. A local updome below an inner gravity

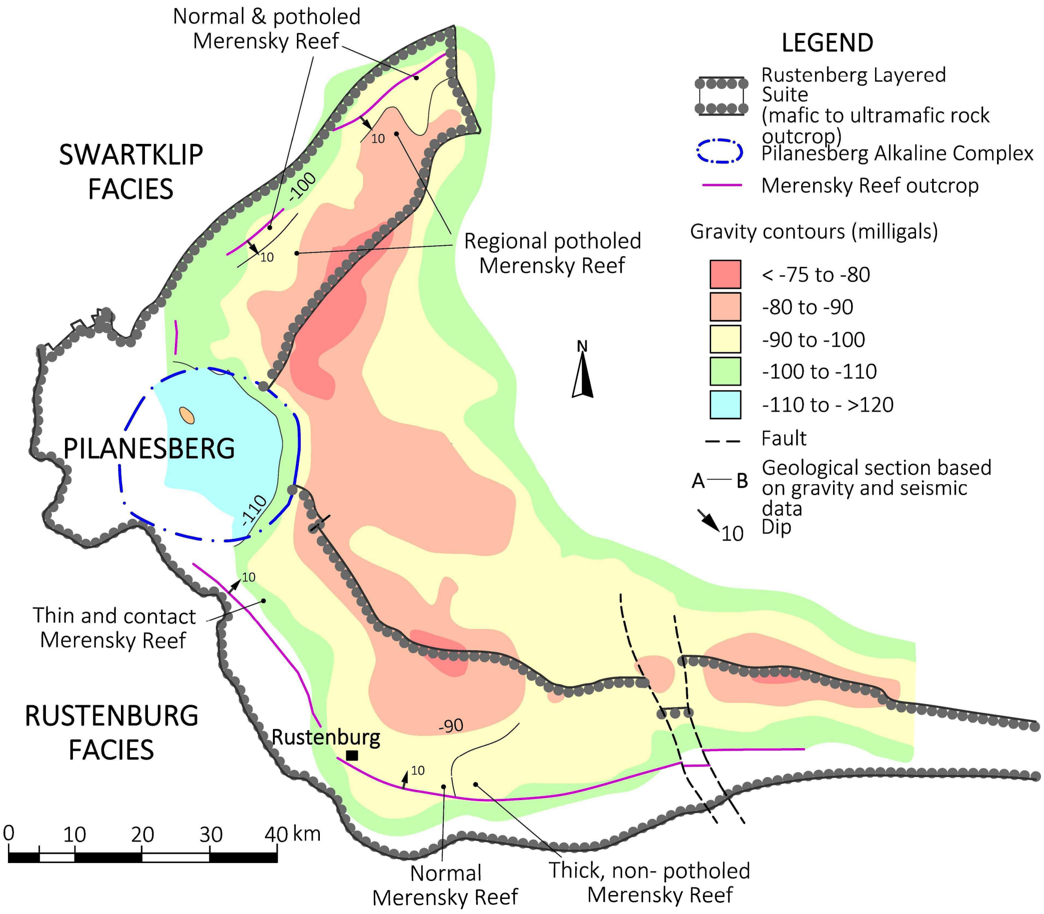


Figure 29. Gravity anomalies of the Western Limb of the Bushveld Complex in relation to the distribution of Merensky Reef types including Normal and Potholed, Thin Contact as well as Wide Reef types. Schematic cross section through the Western Limb of the Complex based on gravity, seismic and aeromagnetic data, highlighting the position of the Upper Zone and Merensky Reef (Viljoen, 1999).

anomaly west of the Pilansberg, suggests that the Merensky Reef occurs at a depth of 6 km below surface in an updomed area below Bushveld granite (Campbell, 1990 and Viljoen, 1999) (Fig. 29).

Magnetics

Aeromagnetics is important in demarcating the regional distribution of the magnetite-rich Upper Zone of the Bushveld. Magnetics, including ground magnetics, have also been extensively used to identify and map important marker horizons, particularly in the Critical, Main and Upper zones. In the Rustenburg area, an airborne magnetic survey clearly demarcates stratigraphic magnetic anomalies in the Main Zone (Fig. 30) whilst IRUP dykes and mine infrastructure are also clearly demarcated in this area of poor exposure.

Remote sensing

Rocks of the Rustenburg Layered Suite in the Western Limb are poorly exposed and are invariably covered by a relatively thin, clay-rich residual soil. This is often of the vertisol type, giving rise to a "black turf" soil cover over all but the Upper Zone of the Bushveld, which, due to oxidation of iron-rich minerals, has developed a distinctive reddish-brown soil. These soil types are clearly defined on false colour satellite imagery (Fig. 31) which also highlights a region of light sandy soil developed on Bushveld granite rocks to the north.

Soil Geochemistry

Soil geochemistry is extremely effective over the thin residual soils of the Bushveld Complex. This is illustrated by the results of a survey on a 1 km^2 grid undertaken by the Council for Geoscience over the Southwestern Limb of the complex that is also covered by the satellite image (Figs.32a and b) (Wilhelm *et al.*, 1997). Whilst contamination is widespread around smelters, refineries and other mining infrastructure, important geological trends are nevertheless evident. These include anomalous chromium geochemistry (>1,700 ppm) over the Lower and Critical zones, as well as copper (>75 ppm) which is sporadically present along the outcrop region of the Merensky Reef and with a clear enrichment over the Upper Zone (Fig. 32a). Platinum is enriched (30 ppm and peaking at over 125 ppm) along the outcrop region of the Merensky Reef, with Pt, Pd and Au geochemistry also having defined the presence of a new platinum enriched layer, albeit of low grade, near the top of the Main Zone (Fig. 32b) (R. Viljoen, pers. comm.).

A combination of aeromagnetics and soil geochemistry was also effective over the poorly exposed Upper Zone in the Northern Limb. Pronounced aeromagnetic anomalies demarcated the MML and its hanging wall layers as well as the robust Q layer (layer 21). The magnetics were complemented by soil geochemistry with, for example, a pronounced vanadium anomaly occurring over the former and iron and titanium anomalies over the latter (Fig. 33).

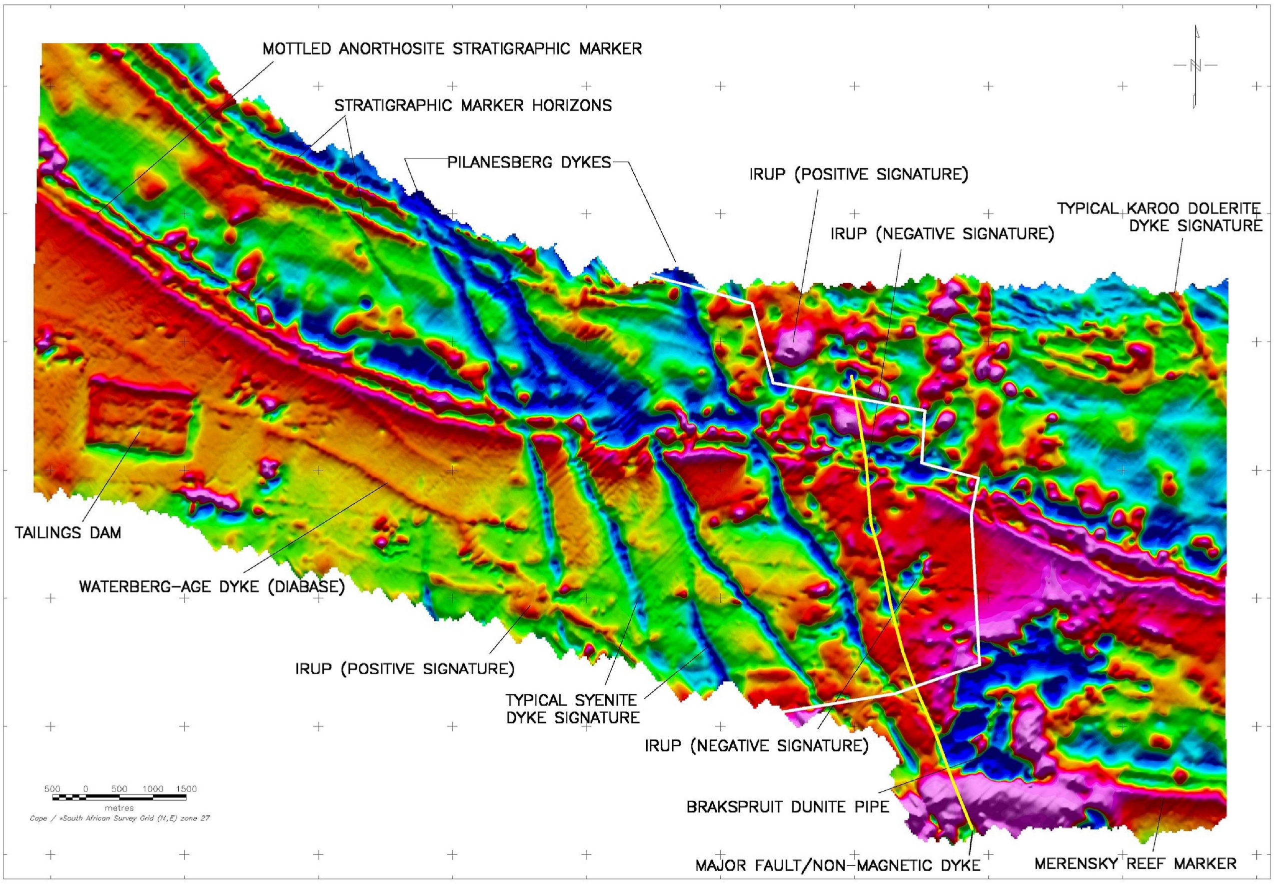


Figure 30. Aeromagnetics over the Main Zone in the Rustenburg area of the Southwestern Limb highlighting stratigraphic magnetic anomalies reflecting magnetite-bearing anorthosite layers. Also evident are smaller, roughly circular anomalies indicative of the presence of iron-rich ultramafic pegmatites (IRUP's). Anomalies caused by younger cross cutting dykes as well as by mining infrastructure including tailings dam (to the left) are also highlighted (G. Campbell, GAP Geophysics).

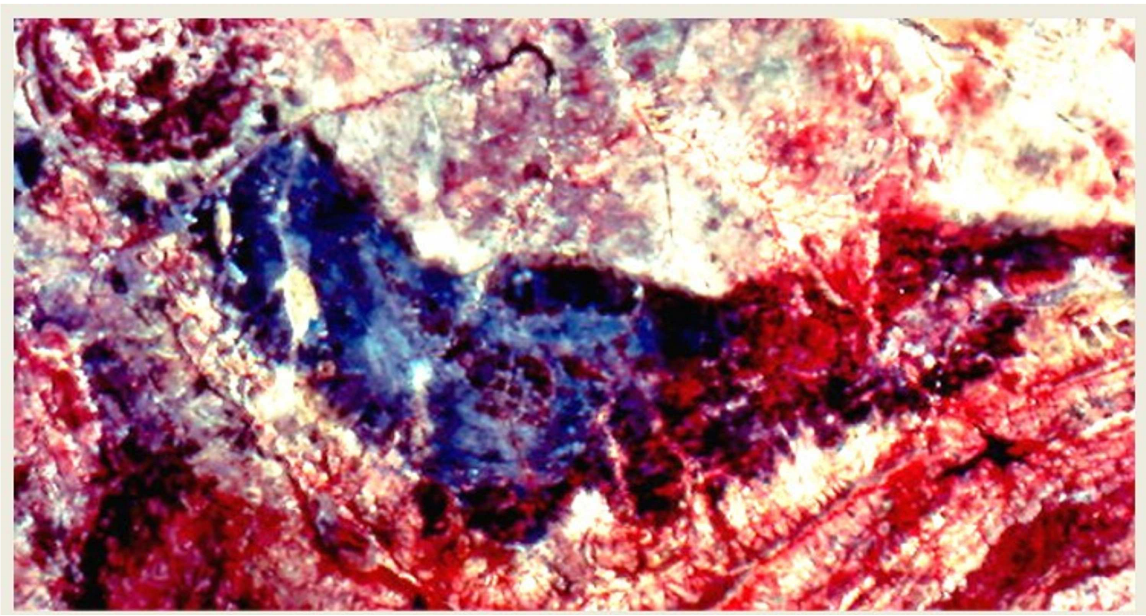


Figure 31. Landsat false colour composite image enhancing the distribution of mafic/ultramafic rocks of the Rustenburg Layered Suite consisting of the Marginal, Lower Critical and Main Zones, on which a dark podsolic ("black turf") soil is developed (blue/dark blue signature) and the Upper Zone on which a dark reddish brown soil is developed (dark green signature). Granophyric and granitic rocks to the north have a light signature and green leafy vegetation a red signature. Southwestern Limb of the Bushveld Complex with the Pilanesberg intrusion at the top left.

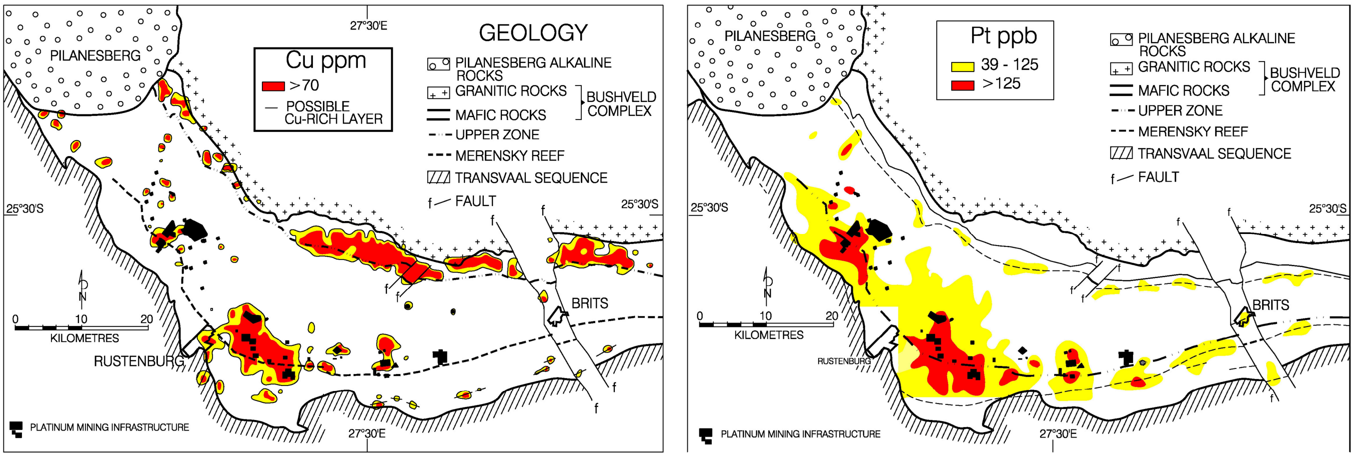


Figure 32. Distribution of soil geochemical anomalies on the southwestern limb of the Bushveld Complex for selected elements (Wilhelm et.al., 1997). Main mining infrastructure including smelters causing platinum and chromium anomalies are also shown. (a) Cu occurs sporadically along the outcrop region of the Merensky Reef and particularly around mine infrastructure. A clear Cu enrichment in the Upper Zone is evident. (b) Pt occurs sporadically along the outcrop region of the Upper Critical Zone and associated with mine infrastructure. Anomalies are strung out along the upper part of the Main Zone and were the basis for the discovery of a new PGE bearing layer.

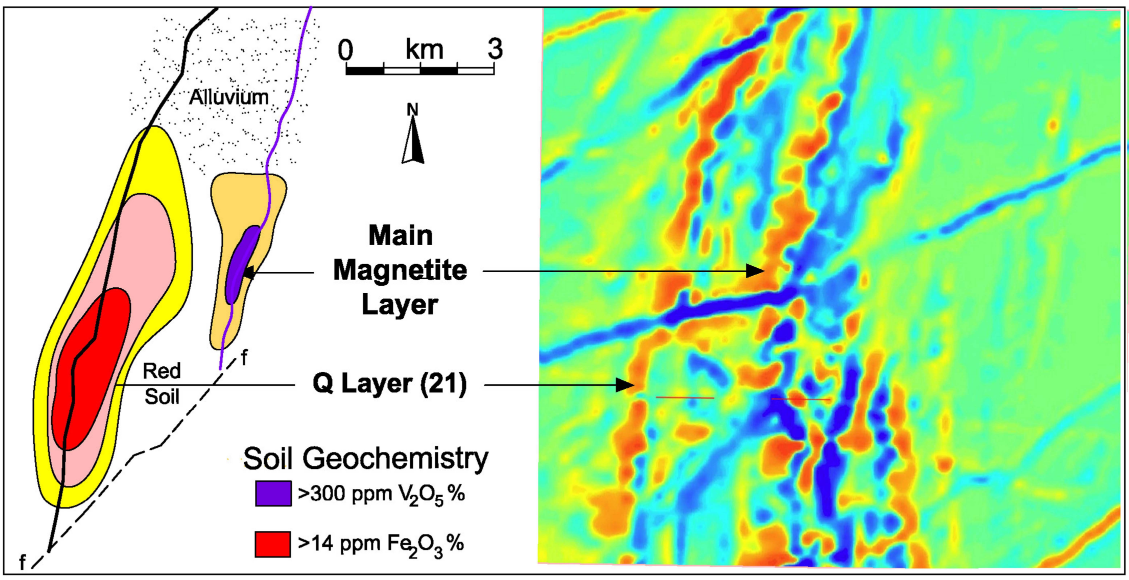


Figure 33. Soil geochemical and airborne magnetic anomalies over the central sector of the Northern Limb, demarcating the positions of the MML and Q layer (Layer 21) in this poorly exposed, soil covered area (Bushveld Minerals, unpublished report).

Conclusions

The Bushveld Complex represents a huge and as yet not fully understood layered magmatic system. This contribution has focused on describing the main geological and mineralisation features as obtained from mines and exploration projects, as well as from the vast literature base that exists. It is evident however that because of length constraints, much detail has of necessity been omitted, as has any in-depth discussion on the genesis of the layering and in particular, the origin of the remarkable economic mineral layers.

Acknowledgements

Numerous individuals and companies have provided valuable input to this chapter with specific contributions having been acknowledged in the text and reference list. I would like to thank the many mine geologists on Anglo Platinum mines in particular, with whom I worked and from whom I learned a great deal about platinum mineralisation in the Bushveld Complex. Many were co-authors on earlier papers dealing with aspects of the geology of the platinum mines of Anglo Platinum.

I would like to thank Jan Grabe, of Xstrata, James Winch of Mogalakwena mine, Jaco Vermeulen and his team at Royal Bafokeng, Danie Grobler of Ivanplats, Fred Mphephu and M. Maseta of Rhovan vanadium mine and Mauritz Van der Merwe. The paper was reviewed by Chris Lee, Andrew Mitchell, Richard Viljoen and Mike Wilson who also edited the manuscript. I acknowledge their valuable comments and input which considerably improved this contribution. Drafting of maps was done by Lynda Whitfield and Margaret Sherwood of VMIC and Belinda Oosthuizen of the Council for

Geoscience, while typing and preparation of the manuscript was undertaken by Sammy Mnkandla and Makabele Fosa.

Finally VMI and Bushveld Minerals and their Directors are thanked for allowing a large amount of unpublished data to be presented and for affording me the time and the facilities to prepare and write this chapter.

References

Anglo American Platinum Limited 2013. Focused on delivery, restructuring for prosperity. Annual report.

Armitage, P.E.B, McDonald, I., Edwards, S.J., Manby, G.M., 2002. Platinum-group element mineralisation in the Platreef and calc-silicate footwall at Sandsloot, Potgietersrus District, South Africa: Transactions Institute of Mining and Metallurgy, 111, B36-45.

Ashwal, L.D., Webb, S.J. and Knoper, M.W., 2005. Magnetic stratigraphy in the Bushveld northern Lobe: continuous geophysical and mineralogical data from the 2950 metre Bellevue drill core. South African Journal of Geology, 108, 199-232.

Buchanan, D.L., 1975. The petrography of the Bushveld Complex intersected by boreholes in the Bethal area. Transactions, Geological Society of South Africa, 73, 335-348.

Buchanan, D.L., 1998. Platinum-group element exploration. Dev. Economic Geology, Elsevier, Amsterdam, 26, 184pp.

Bushveld Minerals, 2010. Unpublished drilling report.

Bushveld Minerals, 2012. Unpublished report.

Cabri, L.J. and Hall, S.R., 1972. Mooihoekite and Haycockite, Two New Copper-Iron Sulphides and their Relationship to Chalcopyrite and Talnakhite. Canadian Minerologist, 57, 689-708.

Cameron, E.N., 1964. Chrome deposits of the eastern part of the Bushveld Complex. In: The Geology of Some Ore Deposits in Southern Africa (S.H. Haughton, ed.), Special Publication, Geological Society of South Africa, 2, 131-168.

Cameron, E.N., 1978. The lower zone of the Eastern Bushveld Complex in the Olifants River trough. Journal of Petrology, 19, 437-462.

Cameron, E.N., 1980. Evolution of the Lower Critical Zone, central sector, eastern Bushveld Complex, and its chromitite deposits. Economic Geology, 75, 845-871.

Cameron, E.N., 1982. The upper Critical Zone of the eastern Bushveld Complex, precursor of the Merensky Reef. Economic Geology, 77, 1307-1327.

Cameron, E.N. and Desborough, G.A., 1964. Origin of certain magnetite-bearing pegmatites in the eastern part of the Bushveld Complex, South Africa. Economic Geology, 59, 197-225.

Cameron,E.N. and Desborough G.A., 1969. Occurrence and characteristics of chromite deposits, eastern Bushveld Complex. Economic Geology, 4, 23-40.

Campbell, G., 1990. The seismic revolution in gold and platinum prospecting. South African Geophysical Association Yearbook, B.P.I. Geophysics, University of Witwatersrand, Johannesburg. 37-45.

Campbell, G., 2006. High resolution aeromagnetic mapping of “loss” of ground features at platinum and coal mines in South Africa. South African Journal of Geology, 109, 439-458.

Campbell, G., 2011. Exploration geophysics of the Bushveld Complex in South Africa. The Leading Edge, 30(6), 622-638

Carr, H.W., Groves, D.I. and Cawthorn, R.G., 1994. The importance of synmagmatic deformation in the formation of Merensky reef potholes in the Bushveld Complex. Economic Geology, 89, 1398-1410.

Cawthorn, 1999. Platinum-group element mineralisation in the Bushveld Complex; a critical reassessment of geochemical models. South African Journal of Geology, 102, 268-281.

Cawthorn, R.G., Barton, J.M. Jr. and Viljoen, M.J., 1985. Interaction of floor rocks with the Platreef on Overysel, Potigietersrus, Northern Transvaal. Economic Geology, 80, 88-1006.

Cawthorn, R.G. and Molyneux, T.G., 1986. Vanadiferous magnetite deposits of the Bushveld Complex. In: Mineral Deposits of Southern Africa (C.R. Anhaeusser and S. Maske, eds.), Geological Society of South Africa, Johannesburg. 1251-1266.

Cawthorn, R.G., Merkle, R.K.W. and Viljoen, M.J., 2001. Platinum-Group element deposits in the Bushveld Complex, South Africa. In: The geology, geochemistry, mineralogy and benefication of platinum-group elements (Ed. L.J. Cabri). CIM Special Volume 54, Canadian Institute of Mining, Metallurgy and Petroleum.

Cawthorn, R.G. and Webb, S.J., 2001. Connectivity between the Western and Eastern Limbs of the Bushveld Complex. Tectonophysics, 330, 195-209.

Cawthorn, R.G. and Boerst, K., 2006. Origin of the pegmatitic pyroxenite in the Merensky unit, Bushveld Complex, South Africa. Journal of Petrology,47,1509-1530.

Cawthorn, R.G., Eales, H.V., Walraven, F., Uken, R.I. and Watkeys, M.K., 2006. The Bushveld Complex. In: Geology of South Africa.

Cheney, E.S. and Twist, D., 1991. The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa, Precambrian Research, 74, 203-223.

Coertze, F.J., 1974. The geology of portion of the Western Bushveld Igneous Complex. Memoir, Geological Survey of S.A., 66, 148.

Coertze, F.J. and Coetze, C.B., 1976. Chromium. In: Mineral Resources of the Republic of South Africa (C.B. Coetzee, ed.), Handbook, Geological Survey of South Africa, 7, 117-122.

Collins, L.A. and Human, D.R., 1986. The Groot-Marico chromitite deposit, Western Transvaal. In: Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.), Geological Society of South Africa, Johannesburg, 1229-1235.

Cousins, C.A., 1959. The structure of the mafic portion of the Bushveld Igneous Complex. Transactions of the Geological Society of South Africa, 62, 174-189.

Cousins, C.A. and Feringa, G., 1964. The chromite deposits of the western belt of the Bushveld Complex. In: The Geology of Some Ore Deposits in Southern Africa. (S.H. Haughton, ed.), Special Publication, Geological Society of South Africa, 2, 183-202.

Dunnett, T., Grobler, D.F. Simmonotti, N.M., and Mapeka, J.M., 2012. Lithological variations within upper Critical Zone stratigraphy, Turfspruit 214 K,R. Northern Limb, Bushveld Complex. Abstract volume, 5th Platreef workshop, Mokopane.

Du Plessis, A. and Kleywegt, R.J., 1987. A dipping sheet model for the mafic lobes of the Bushveld Complex. South African Journal of Geology, 90, 1-6.

Eales H.V., 2014. The Bushveld Complex. An introduction to the geology of the Bushveld Complex, 2nd Edition. Council for Geoscience 214pp.

Eales, H.V., Field, M., De Klerk, W.J. and Scoon, R.N., 1988. Regional trends of chemical variations and thermal erosion in the Upper Critical Zone, Western Bushveld Complex. Mineralogy Magazine, 52, 63-79.

Eales, H.V, and Cawthorn, R.G., 1996. The Bushveld Complex. In:- Layered Intrusions. (R.G. Cawthorn, ed.). Developments in Petrology, Elsevier. 15. 531pp.

Farquhar, J., 1986. The Western Platinum Mine. In:- Mineral Deposits of Southern Africa. v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1135-1142.

Gain, S.B. and Mostert, A.B., 1982. The geological setting of the platiniferous UG2 chromitite layer on the farm Maandagshoek, eastern Bushveld Complex. Economic Geology, 80, 925-943.

Gain, S.B. 1985. The geological setting of the platinoid and base metal sulphide mineralisation in the Platreef of the Bushveld Complex on Drenthe, north of Potgietesrus. Economic Geology, 77, 1395-1404.

Grobler, D.F., Nielsen, S.A., and Broughton, D.W., 2012. Upper Critical Zone (Merensky Reef-UG2) correlates within the Platreef on Turfspruit 241 KR, Northern Limb, Bushveld Complex. 5th Platreef workshop, Mokopane.

Grobler, N.J. and Whitfield, G.G., 1970. The olivine-apatite magnetite and related rocks in the Villa Nora occurrence of the Bushveld igneous complex. Special Publication 1, Geological Society of South Africa, 1, 36-45.

Grohmann, G., 1994. Vanadium in South Africa's Mineral Industry: Report, Minerals Bureau, Department of Mineral and Energy Affairs, 74-76.

Hahn, U.F. and Ovendale, B. (1994). UG2 chromitite layer potholes at Wildebeestfontein North Mine, Impala Platinum Limited. XVth CMMI Congress, Johannesburg. South African Institute Mine Metall, 3, 195-200.

Hall, A.L., 1932. The Bushveld Igneous Complex of the Central Transvaal. Memoir, Geological Survey of South Africa, 28, 560pp.

Harmer, R.E. and Sharpe, M.R., 1985. Field relations and strontium isotope systematics of the marginal rocks of the eastern Bushveld Complex. Economic Geology, 80, 813-837.

Hatton, C.J., and Von Gruenewaldt, G., 1987. The geological setting and petrogenesis of the Bushveld chromitite layers. In: Stowe, C.W., ed., Evolution of chromium ore fields. New York, N.Y., Van Nostrand Reinhold, 109-143.

Hiemstra, S.A., 1986, The distribution of chalcophile and platinum-group elements in the UG-2 chromitite layer of the Bushveld Complex. Economic Geology, 81,7 5-76.

Holwell, D.A., Smith, J.W. and McDonald, I., 2015. GNPA-Hosted mineralisation South of Mokopane, Platreef, Merensky Reef, or neither. Abstract, 6th Platreef workshop, Mokopane.

Hulbert, L.J. and Von Gruenewaldt, G., 1982. Nickel, copper and platinum mineralisation in the Lower Zone of the Bushveld Complex, south of Potgietersrus. Economic Geology, 77, 1296-1306.

Hulbert, LJ. and Von Gruenewaldt. G., 1986. The structure and petrology of the Upper and Lower Chromitite layers on the farms Grasvally and Zoetveld, south of Potgietersrus. In: Mineral Deposits of Southern Africa v.II (CR. Anhaeausser and S. Maske eds.). Geological Societyof South Africa, Johannesburg, 1237-1249.

Ireland, K.L., 1986. The Winterveld (TCL) Chrome Mine Limited, eastern Bushveld Complex. In Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1183-1188.

Kekana, S.M., 2015. Geochemical Mineralogical and tenor variations in the upper section of the Platreef, Northern Limb, Bushveld Complex and Correlation with the Merensky Reef. 6th Northern Limb and Platreef workshop. Abstract.

Kinloch, E.D., 1982. The regional trends in platinum group mineralogy of the Critical Zone of the Bushveld Complex, South Africa. Economic Geology, 77, 1328-1347.

Kinloch, E.D. and Peyerl, W., 1990. Platinum-group minerals in various rock types of the Merensky Reef; genetic implications. Economic Geology, 85, 537-555.

Kinnaird, J.A., 2004. An overview of the Platreef. Abstact Volume, Geoscience Africa, Johannesburg, July 2004.

Kinnard. J.A., White, J.A. and Schurmann, L.W., 2005. Multiple emplacement of the Platreef, Northern Bushveld, South Africa. Abstract, 10th Platinum Symposium, Oulu, Finland, 7-9th August 2005.

Kinnaird, J.A., Yudovskaya, M. and Botha, M.J., 2015. There's life in the old dog yet. The Waterberg PGE deposit. Abstract volume, 6th Platreef workshop, Mokopane.

Kruger, F.J., 1992. The origin of the Merensky cyclic unit; Sr-isotopic and mineralogical evidence for an alternative orthomagmatic model. Australian Journal of Earth Sciences, 39, 255-261.

Kruger, F.J., 2010. The Merensky and Bastard cyclic units and the Platreef of the Bushveld Complex;consequences of Main Zone magma influxes and dynamics. The 4th International Platinum Conference, the SA. Insitute of Mining and Metalurgy.

Lee, C.A., 1996. A review of mineralisation in the Bushveld Complex and some other layered intrusions. In: -Layered Intrusions (R.G. Cawthorn, ed.), Elsevier, Amsterdam, 103-146.

Lee, C.A. and Parry, M.S.J., 1988. Platinum-group element geochemistry of the lower and middle group chromitites of the eastern Bushveld Complex. Economic Geology, 85, 877-883.

Leeb, Du Toit, A., 1986. The Impala Platinum Mines. In: Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1091-1106.

Liebenberg, L., 1970. The sulphides in the layered sequence of the Bushveld Igneous Complex. Geological Society of South Africa, Special Publication, 1, 108-207.

Lomberg, K.G., Martin, E.S., Patterson, M.A., d Venter, J.E., 1999. The morphology of potholes in the UG2 chromitite layer and Merensky reef (pothole facies) at Union section, Rustenburg Platinum Mines. South Arican Journal of Geology, 102, 209-220.

Luyt, J.F.M., 1976. Vanadium. In: Mineral Resources of the Republic of South Africa (C.B. Coetzee, ed.). Handbook, Geological Survey of South Africa, 7, 462pp.

Maier, W.D. and Eales, H.V.,1994. A facies model for the interval between the UG2 and Merensky Reef, Western Bushveld Complex. Transactions Institute of Mining and Metallurgy, 103, B22-B30.

McCandless, T.E., Ruiz, J., Adair, B.I., and Freydier, C., 1999. Re-Os isotope and Pd/Ru variations in chromitites from the Critical Zone, Bushveld Complex, South Africa, Geochimica et Cosmochimica Acta, 63(6), 911-923.

McLaren, C.H. and De Villiers, J.P.R., 1982. The platinum-group chemistry and mineralogy of the UG2 chromitite layer of the Bushveld Complex. Economic Geology, 77, 1348-1366.

Meyer, R. and de Beer, H., 1987. Structure of the Bushveld Complex from resistivity measurements. Nature, 325, 610-612.

Mitchell, A.A. 1990 The Stratigraphy Petrology and mineralogy of the Main Zone of the northwestern Bushveld Complex. South African Journal of Geology, 93, 971-1009.

Mitchell, A.A. and Scoon, R.N.,2007 The Merensky Reef at Winnaarshoek, Eastern Bushveld Complex. A primary Magmatic Hypothesis Based on a Wide Reef Facies. Economic Geology, 102, 818-831.

Mitchell, A.A. and Scoon, R.N., 2014. The Platreef of the Bushveld Complex, South Africa. A new Hypothesis of multiple, non-sequential magma replenishment based on observations at the Akanani project, northwest of Mokopane. South African Journal of Geology, 115(4), 535-550.

Molyneux, T.G., 1970. The geology of the area in the vicinity of Magnet Heights, Eastern Transvaal, with special reference to magnetite iron ore In:- Symposium on the Bushveld Igneous Complex and Other Layered Intrusions (D.J.L. Visser and G. von Gruenewaldt, eds.). Special Publication, Geological Society of South Africa, 1, 28-41.

Molyneux, T.G., 1974. A geological investigation of the Bushveld

Complex in Sekhukhuneland and part of the Steelpoort Valley. Transactions of the Geological Society of South Africa, 77, 329-338.

Mossom, R.J., 1986. The Atok Platinum Mine.In:- Mineral Deposits of Southern Africa, v.ll (C.R Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg,1143-1154.

Muller, C.J., 2015. An independent technical report on the Waterberg Project located in the Bushveld Igneous Complex, South Africa. Unpublished report, Waterberg Platinum.

Nicholson, D.M. and Mathez, E.A., 1991. Petrogenesis of the Merensky reef in the Rustenburg section of the Bushveld Complex. Contributions to Mineralogy and Petrology, 293-309.

Nodder, S., McDonald, I. and Grobler, D., 2015. Correlating the Northern Limb with Western and Eastern Limbs;a geochemical and petrological study of Turfspruit core. Abstract volume, 6th Platreef workshop, Mokopane.

Page, N.J., Von Granewaldt, G., Haffty, J., and Aruscavage, P. J., 1982. Comparison of Platinum, Palladium and Rhodium distributions in some layered intruisions with special reference to the late differentiates (Upper Zone) of the Bushveld Complex, South Africa. Economic Geology, 91, 439-450

Reynolds, I.M., 1985. Nature and origin of titaniferous magnetite rich layers in the Upper Zone. Economic Geology, 80, 1089-1108.

Reynolds, I.M., 1986. The mineralogy and petrography of the Bushveld titaniferous magnetite layers. In: Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1267-1286.

Schurmann, L.W. and Von Gruenewaldt, G., 1998. The petrogenesis of the upper Critical Zone in the Boshoek section of the Western Bushveld Complex.Abstracts, Symposium on Layering in Igneous Complexes, Wager and Brown, 25th Anniversary commemorative meeting, Johannesburg, 8thto 10th September.

Schurmann, L.W. and Marsh, S., 1999. Vanadium. In: The Mineral Resources of South Africa. Handbook(Wilson, M.G.C. and Anhaeusser C.R. eds.). Council for Geoscience, 16, 659-66.22/6.

Schurmann, L.W., Grabe, P.J. and Steenkamp,C.J., 1998. Chromium. In: The Mineral Resources of South Africa. Handbook (Wilson, M.G.C. and Anhaeusser C.R. eds.). Council for Geoscience,16., 740pp.

Scoates, J.S. and Friedman, R.M., 2008. Precise Age of the platiniferous Merensky Reef, Bushveld Complex., South Africa,by the U-Pb zircon chemical abrasion 10 Tims technique. Economic Geology, 103, 465-471.

Scoon, R.N., 2002. A new occurance of Merensky Reef on the flanks of the Zaaikloof dome, northeastern Bushveld Complex: Relatiolnship between diapirism and magma replenishment. Economic Geology, 97, 1037-1049.

Scoon, R.N., 2004a. The platiniferous dunite pipes in the Eastern Limb of the Bushveld Complex. Review and comparison with unmineralised discordant ultramafic bodies. South African Journal of Geology, 107, 505-520.

Scoon, R.N., 2009. Discovery and geology of the platinum group element deposits of the Bushveld Complex, South Africa. Society of Economic Geologistsnewsletter no.78, 13-9.

Scoon, R.N., and Eales, H.V., 1989. Platinum group element mineralisation in the Critical Zone of Bushveld Complex. South Africa.Distribution and mineralisation types. 28thInternational Geological Congress, Washington, Extended Abstracts, 361-62.

Scoon, R.N. and Mitchell; A.A., 1994. Discordant iron-rich ultramafic pegmatites in the Bushveld Complex and their relationship to iron-rich intercumulus and residual liquids. Journal of Petrology, 35, 881-917.

Scoon, R.N. and Mitchell, A.A., 2004. The platiniferous dunite pipes in the Eastern Limb of the Bushveld Complex,review and comparison with unmineralised discordant ultramafic bodies. South African Journal of Geology, 107, 505-520.

Scoon, R.N. and Mitchell, A.A., 2013. The Upper Zone of the Bushveld Complex at Roossenekal., South Africa, geochemical stratigraphy and evidence of multiple episodes of magma emplacement. South African Journal of Geology, 115, 515-534.

Scoon, R.N. and Teigler, B., 1994. Platinum- group element mineralisation in the critical zone of the Western Bushveld Complex: 1 Sulfide-poor chromitities below the UG2. Economic Geology, 89, 1094-1121.

Sluzhenikin, S., Yadovskaya, M., Grobler, D.F., Brits, J.A.N. and Costin, G., 2015. Contact metamorphic and contact metasomatic rocks in the Platreef footwall on Turfspruit (preliminary data). Abstract volume, 6th Platreef Workshop, Mokopane.

Smith, D.S. and Basson, I.J., 2006, Shape and distribution analysis of Merensky reef potholing, Northam Platinum Mine, Western Bushveld Complex.Implications for pothole formation and growth, Mineralium Deposita, 41, 281-295.

Smith, D.S., Basson, I.J. and Reid, D.L., 2004. Normal reef subfacies of the Merensky reef at Northam Platinum Mine, Zwartklip facies, Western Bushveld Complex, South Africa. Canadian Mineralogist, 42, 243-260. Abstract volume, 6th Platreef Workshop, Mokopane.

Smith, J. W., Holwell, D. A., and McDonald, I., 2012. An Overview of PGE and BMS Mineralisation within the GNPA member. 5th Platreef Workshop, Mokopane. Abstract.

South African Mineral Industry 2003/4. South African Department of Minerals and Energy, Directorate of mineral Economics.

Stephenson, H., McDonald, I. and Grobler, D., 2015. Platinum-group element mineralogy in the Platreef deposit on Turfspruit, northern Bushveld Complex. Abstract volume, 6th Platreef Workshop, Mokopane.

Teigler, B. and Eales, H.V., 1993. Correlation between chromite composition and PGE mineralisation in the Critical Zone of the Western Bushveld Complex.Mineralium Deposita, 28, 291-302.

Tredoux, M., Lindsay, N.M., Davies, G. and McDonald, I., 1995. The fractionation of platinum-group elements in magmatic systems, with the suggestion of a novel causal mechanism. South African Journal of Geology, 98,157-167.

Uken, R., and Watkeys, M.K., 1997. Diapirism initiated by the Bushveld Complex. Geology, 25, 723-726.

Van der Merwe, M.J., 1978. The layered sequence of the Potgietersrus Limb of the Bushveld Complex.Ph.D. thesis. University of Witwatersrand, Johannesburg, 176pp. (unpub).

Van der Merwe, M.J., 2008. The geology and structure of the Rustenburg Layered Suite in the Potgietersrus - Mokopane area of the Bushveld Complex, South Africa. Mineralium Deposita, 43, 405-419.

Vermaak.C.F., 1976. The Merensky reef - thoughts on its environment and genesis. Economic Geology, 71, 1270-1298.

Vermaak, C.F., 1985. The UG2 Layer. South Africa’s slumbering chromitite giant. Chromium Review, 5, 9-23.

Vermaak, C.F., 1986. Summary aspects of the economics of chromium with special reference to Southern Africa. In: Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1155-1181.

Vemaak, C.F., 1995. The Platinum-Group Metals, Mintek.

Viljoen, M.J., 1994. A review of regional variations in facies and grade distribution of the Merensky Reef, Western Bushveld Complex, with some mining implications. Proceedings, 15th CMMI Congress, South African Institute of Mining and Metallurgy, 183-194.

Viljoen, M.J., 1999. The nature and origin of the Merensky Reef of the Western Bushveld Complex based on geological facies and geophysical data. South African Journal of Geology, 102 (3), 221-239.

Viljoen, M.J.and Scoon, R.N., 1985. The distribution and the main geologic features of discordant bodies of iron-rich ultramafic pegmatite in the Bushveld Complex. Economic Geology, 80, 1109-1128.

Viljoen, M.J. and Hieber, R.W., 1986a. The Rustenburg Section of Rustenburg Platinum Mines Limited, with reference to the Merensky Reef in Mineral Deposits of Southern Africa. v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1107-1134.

Viljoen, M.J., De Klerk, W.J., Coetzer, P.M., Hatch, N.P., Kinloch, E.D. and Peyerl, W., 1986b. The Union Section of Rustenburg Platinum Mines Limited, with reference to the Merensky Reef in Mineral Deposits of Southern Africa. v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1061-1190.

Viljoen, M.J., Theron, J., Underwoord, B., Walters, B.M., Weaver, J. and Peyerly, W., 1986c. The Amandelbult Section of Rustenburg Platinum Mines Limited, with reference to the Merensky Reef. In: Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Society of South Africa, Johannesburg, 1041-1060.

Viljoen, M.J. and Schurmann, L.W., 1998 Platinum group metals.In:- The Mineral Resources of South Africa; Handbook. (Wilson, M.G.C., and Anhauesser, C.R., eds.). Council for Geoscience, 16, 532-568.

Viring, R.G. and Cowell, M.W., 1999. The Merensky Reef on Northam Platinum Mine. South African Journal of Geology, 102, 192-208.

Von Gruenewaldt, G., 1973. The Main and Upper zones of the Bushveld Complex in the Roossenekal area, Eastern Transvaal. Transactions of the Geological Society of South Africa, 76, 207-227.

Von Gruenewaldt, G., Hatton, C.J., Merkle, R.K.W. and Gain, S.B., 1986. Platinum group element-chromitite associations in the Bushveld Complex. Economic Geology, 81, 1067-1079.

Von Gruenewaldt, G., Sharpe, M.R. and Hatton, C.J., 1985. The Bushveld Complex, introduction and review. Economic Geology, 80, 803-812.

Wagner, P,A., 1929. The Platinum Deposits and Mines of South Africa. Oliver and Boyd, Edinburgh, 326pp.

Waterberg Project, 2014. Amended and restated Technical Report for the update on exploration drilling at the Waterberg Joint Venture and Waterberg extension projects, South Africa. Unpublished Report.

White, J.A., 1994. The Potgietersrus project, geology and exploration history. Proceedings, 15th CMMI Congress, South African Institute of Mining and Metallurgy, 173-182.

Wilhelm, H.J., Zhang, H., Chen, F.L., Elsenbroek, J.H., Lombaard, M. and De Bruin, I.D., 1997. Geochemical exploration for platinum-group elements in the Bushveld Complex, South Africa. Mineralium Deposita, 32, 349-361.

Willemse, J., 1969. The geology of the Bushveld Igneous Complex. The largest repository of magmatic ore deposits in the World. Economic Geology, Monograph, 4, 1-22.

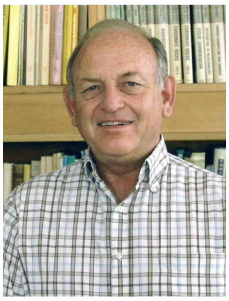
Willemse, J., 1969. The vanadiferous magnetite iron ore of the Bushveld igneous complex. Monograph, Economic Geology, 4, 1987-208.

Wilson, A.H. and Chunnett, G., 2006. Trace element and platinum group element distribution and the geneis of the Merensky reef, Western Bushveld Complex, South Africa. Journal of Petrology, 47, 2369-2403.

Worst, B.G., 1986a. The chromite deposits of the Montrose and Groothoek mines. Eastern Bushveld Complex. In: Mineral Deposits of Southern Africa v.II (C.R. Anhaeusser and S. Maske, eds). Geological Societyof South Africa, Johannesburg, 1189-1195.

Worst, B.G., 1986b. The chromitite deposits at Kroondal chrome mine, Western Bushveld Complex. In: Mineral Deposits of Southern Africa, v.II (C.R. Anhaeusser and S. Maske, eds.). Geological Societyof South Africa, Johannesburg, 1209-1215.

Yudovskaya, M. A., Kinnaird, J.A., Sobolev, A., Kuzmin, D.V., McDonald, I. and Wilson, A.H., 2013. Petrogenesis of the Lower Zone olivine-rich cumulates beneath the Platreef and their correlation with recognised occurrences in the Bushveld Complex. Economic Geology, 108, 1923-1952.



Morris Viljoen *is a graduate of the University of the Witwatersrand. His Ph.D studies in the Barberton greenstone belt led to the discovery, jointly with Richard Viljoen, of the new rock type komatiite. Most of his career has been in mineral exploration and mining geology in southern Africa. This has included extensive work on mineralisation in greenstone belts, the Witwatersrand gold deposits and mineralisation in the Bushveld Complex. He has published extensively on these topics. He also spent 15 years as professor of mining and exploration geology at Wits University. His current interests include geoheritage and geotourism, mining history and environmental geoscience.*