CHAPTER ONE: INTRODUCTION

1.1 Statement of the problem

The Platreef represents the most important platinum-group element (PGE) mineralisation associated with the basal contact of the Bushveld Complex. It is still in its early stages of exploitation, with only two Anglo Platinum mines presently operating, namely Potgietersrust Platinums on the farms Sandsloot and Zwartfontein South. However, unpublished company reports indicate that the PGE mineralization extends along most of the strike of the northern limb, from Rooipoort in the south (www.caledoniamining.com) to Aurora and Nonnenwerth in the north (www.Pan Palladium).

Despite an enhanced exploration activity during the last decade, the genesis of the mineralisation in the Platreef remains enigmatic. Past workers have proposed that the sulphides formed in response to assimilation of the floor rocks by the magma (e.g. Buchanan *et al.*, 1981; Gain and Mostert, 1982; Buchanan and Rouse, 1984; Buchanan, 1988), a model that has been applied to the formation of many other examples of similar magmatic sulphide deposits elsewhere e.g. East Bull Lake (Peck *et al.*, 2002) and Portimo (Alapieti and Lahtinen, 2002). However, the Platreef overlies a variety of floor rocks, including quartzite, shale, iron formation, dolomite, and granite-gneiss. It is unclear which of these lithologies, if any, played an important role in magma contamination and sulphide saturation. For example, De Waal (1977) proposed that devolatization of dolomite may increase the O fugacity of the magma, thereby decreasing the activity of Fe^{2+} and the sulphur solubility. Alternatively, sulphide segregation could have been triggered by assimilation of sulphur from the floor rocks, notably shales of the Timeball Hill and Duitschland formations which have been shown to contain up to several percent sulphides (Kinnaird, 2005). Lee (1996) proposed that the Platreef sulphides segregated in a staging chamber at depth followed by entrainment by the ascending silicate magma, and that *in situ* addition of sulphur merely modified the composition of the rocks. One of the reasons for the lack of consensus on a genetic model is the scarcity of compositional studies on the Platreef. Much of the exploration data is confined to a few elements (e.g. Pt, Pd, Ni, Cu) and few complete whole rock compositional analyses, including major elements, sulphur and PGE exist. The present study aims to improve this situation by conducting a detailed compositional study of two Platreef intersections that overlie granite gneiss in the northernmost portion of the northern limb of the Bushveld Complex. The data will be compared with the results of a previous study of the Platreef on the farm Townlands, in the southern part of the northern limb (Manyeruke, 2003) and at other localities, including Drenthe (Stevens, 2004) and Rooipoort (Maier *et al.*, 2007).

1.2 Aims of the study

The present study has two main aims. Firstly, I want to enlarge the database on the Platreef by providing

i) a detailed lithological and petrographic description of the Platreef on the farm Nonnenwerth 421 LR (see Fig. 2.3 and 3.1 for location),

ii) mineral compositional data, focusing on the major silicate minerals (orthopyroxene, clinopyroxene, plagioclase) and the sulphides minerals. Some data on olivine from a serpentinized ultramafic rocks as well as micas and oxides will also be discussed,

iii) comprehensive major and trace element data, including the concentrations of the noble metals,

iii) additional lithophile trace element data from Townlands, in the south of the northern limb, to complement the study of Manyeruke (2003),

iv) a detailed mineralogical investigation of the platinum-group minerals (PGMs) on Townlands and Nonnenwerth 421 LR and a comparison of these data to published PGM data on the Platreef.

v) S- and O- isotopic data of the Platreef on Nonnenwerth 421 LR

Secondly, I will to use the lithophile trace element data to constrain the nature of the magma from which the Platreef crystallized S- and O-isotope data to evaluate the role of floor contamination in triggering sulfide segregation from the magma. In particular, I hope that a comparison of data from different localities, comprising deposits that overlie various types of floor rocks, allows determination of the relative importance of these floor rocks in triggering sulphide saturation. The mineralogical investigation of PGMs will Finally, I aim to place the Platreef mineralization into the broad lithostratigraphic framework of the Bushveld Complex.

1.3 Previous work

The occurrence of platinum in the northern limb of the Bushveld was first reported by a prospector named Adolf Erasmus in 1923. Erasmus panned ground from termite mound on the farms Welgevonden and Rietfontein, 31 km southwest of Potgietersrus (White, 1994). The Pt was derived from mineralized quartz veins within the Rooiberg rhyolites. This was followed by the discovery of platinum by Dr. Hans Merensky on the farms Rietfontein and Tweefontein in January 1925 (White, 1994) which marks the beginning of the exploration history on the Platreef. Mining of the Platreef began in 1926 by Potgietersrus Platinums Limited. The first lithological descriptions of the Platreef were provided by Wagner (1929). He correlated the variably sulphide mineralized, composite rocks at the base of the northern limb of the Bushveld Complex with the Merensky Reef. Based on texture and mineral mode, Wagner distinguished three distinct mineralized layers, which Buchanan (1979) later referred to as the A, B and C reefs, from the base to the top (see section 2.2).

Several studies of the Platreef have emphasized the abundance of xenoliths of metasediments in the intrusive rocks. Buchanan *et al.* (1981) proposed that the Platreef mineralisation on Tweefontein formed as a result of assimilation of sulphur from anhydrite-bearing Malmani dolomite, banded ironstone, argillaceous sediments, and micronoritic sills by Bushveld magma. Buchanan *et al.* (1981) model is based partly on S isotopic studies of Platreef sulphides. In contrast, de Waal (1977) and Gain and Mostert (1982), prefer a mechanism whereby the Bushveld magma was oxidized in response to devolatization of the dolomite. The devolatization released CO_2 into the magma thereby increasing the O fugacity of the magma and, in response, decreasing the sulphur solubility and triggering sulphide supersaturation.

Regional trends in the platinum-group mineralogy of the Platreef where investigated by Kinloch (1982). The author reported that on the farm Zwartfontein the main PGM in the Platreef are platinum-palladium tellurides, sperrylite ($PtAs_2$), platinum- palladium sulphides and palladium alloys. Compared to the Merensky reef and the UG-2 chromitite, the Platreef was shown to be relatively depleted in laurite (RuS_2). Laurite is mostly found in significant amounts in the chromitites-rich Bushveld ores, namely the thin chromitites stringers at the top and base of the Merensky Reef and throughout the UG2 chromitite layer (Kinloch, 1982). Kinloch (1982) attributed the paucity of laurite in the Platreef to the absence or scarcity of chromitites lenses. Alternatively, the Platreef's special emplacement conditions into dolomite of the Transvaal sequence may have played a part. Kinloch (1982) suggested that metamorphism of the dolomite floor rocks due to intrusion of hot Platreef magma released CO_2 from dolomite xenoliths into the Platreef magma resulting in volatization of Ru.

Cawthorn *et al.* (1985) presented major element, trace element and Sr isotope data of the Platreef on the farm Overysel showing a strong, but highly variable crustal component. At this locality, the immediate floor rocks to the Platreef consist of a suite of highly metamorphosed, banded tonalitic gneisses with leucotonalitic veins, which in turn are underlain by basement granite. Through isotope and trace element modeling, Cawthorn *et al.* (op.cit.) suggested that the most likely contaminant of the Platreef magma was a fluid derived from the granite.

White (1994) provided a description of the Platreef at several localities. He reported that the PGE grades in the Platreef are controlled by the nature of the floor rocks. Grades are relatively higher where the floor rocks consist of dolomite, but lower where the floor rocks consist of granite, iron-formation or shale.

In situ formation of the Platreef sulphides was rejected by Lee (1996) who instead proposed that the sulphides segregated in a staging chamber at depth and were subsequently entrained by the ascending Platreef magma. *In situ* addition of S merely modified the composition of the rocks.

Viljoen and Schurmann (1998) produced a comprehensive review of the available data on the Platreef, including information on the geology, the mineralogy and theories of ore genesis.

Harris and Chaumba (2001) conducted a detailed major and trace element investigation as well as H and O isotopic study of the Platreef at Sandsloot. They found evidence for local contamination of Bushveld magma by dolomite, but in addition they suggest that contamination occurred in a staging chamber.

Armitage *et al.* (2002) studied the PGE mineralisation in the Platreef at Potgietersrust Platinums mine, Sandsloot pit, and provided some data on PGE and Au concentrations, and the nature of the PGM. Notably, at this locality, disseminated and vein-type PGE mineralisation is found up to several meters within the sedimentary floor rocks, below the basal contact of the intrusion. Based on scanning electron microscope (SEM) studies of four polished samples, Armitage *et al*. (2002) report the complete absence of PGE sulphides, but the existence of low-temperature semi-metallides and alloys and their high-temperature equivalents. Armitage *et al*. (2002)

also report that PGE ratios in the intrusion and its footwall are broadly similar pointing to similar processes controlling the final PGE distribution in the two packages. They go on to suggest that the PGE were initially concentrated by magmatic sulphides, but were subsequently remobilized by hydrothermal fluids.

Manyeruke (2003) and Manyeruke et al. (2005) conducted a detailed petrographic and geochemical investigation of a borehole core intersection through the Platreef on the farm Townlands. At this locality, the Platreef rests on metasedimentary rocks of the Silverton Formation of the Transvaal Supergroup, and is comprised of three medium-grained units of gabbronorite/feldspathic pyroxenite that are separated by hornfels interlayers. Manyeruke (2003) and Manyeruke et al. (2005) refer to the three platiniferous layers as the Lower, Middle and Upper Platreef. The Middle Platreef is the main mineralized layer, with total PGE contents up to 4 ppm. The Lower and Upper Platreefs are less well mineralized (up to 1.5 ppm). Trace element and S-isotope data show compositional breaks between the different platiniferous layers suggesting that they represent distinct sill-like intrusions of pyroxene and sulphide enriched crystal mushes. Their study also reveals a reversed differentiation trend of more primitive rocks towards the top of the succession, a pattern interpreted to reflect enhanced crustal contamination of the lower Platreef layers. All three Platreef layers are enriched in heavy S (d^{34}S of 2.6 to 9.1 ‰) indicating addition of crustal sulphur, and they have elevated K, Ca, Zr and Y contents and high Zr/Y ratio relative to Critical Zone rocks from elsewhere in the Bushveld Complex, suggesting a model of crustal contamination in ore formation.

McDonald *et al.* (2005) suggested that the Platreef is related to the mixing of Main

Zone magma with differentiates of Lower Zone magma. They highlight that the Platreef has relatively low Pt/Pd and Pt/Au ratios compared to the Merensky Reef. They propose that the low Pt/Pd ratios are an inherent feature of the Platreef magma and that the Platreef and the Merensky Reef are not correlatable.

Ruiz *et al.* (2004) investigated the Re-Os isotopic composition of Platreef sulphides in three samples from a borehole located on the farm Turfspruit 241KR. This was done to constrain the age of the mineralisation and the source of osmium in the sulphides, and by inference, the origin of the PGE mineralisation. Ruiz *et al.* (2004) reported a Re-Os age of 2011 ± 50 Ma and an initial ^{187}Os/^{188}Os value of 0.226 ± 0.021. The initial osmium isotope ratio indicates a crustal component, but the fact that the three samples define a reasonable isochron suggests that this component may have been acquired prior to emplacement.

Holwell *et al.* (2005) studied the relationship between the Platreef and its Main Zone hangingwall at Sandsloot, Zwartfontein South and Overysel. Based on textural evidence such as xenoliths of reef pyroxenite in the Main Zone, they suggest that the hangingwall gabbronorites were emplaced after the Platreef and that there was a significant hiatus between the two intrusive events.

Hutchinson and Kinnaird (2005) investigated the Ni-Cu-PGE mineralisation of the southern Platreef on the farm Turfspruit. They report that S displays a good positive correlation with Ni and Cu, but that Pt and Pd show poor correlations with base metals. Hutchinson and Kinnaird (2005) attribute this to repeated modification of primary sulphides by the introduction of As, Te, Bi and Sb during devolatization of the footwall hornfels and by percolating felsic melts resulting in redistribution of S, Cu and Ni. PGM were found in rims around orthopyroxenes, as discrete grains within secondary silicates and as grains adjacent to, or along the margins of, composite sulphides. More rarely they may occur as inclusions within sulphide minerals.

Kinnaird (2005) studied two borehole cores from the southern sector of the northern limb on the farm Turfspruit and suggested that the Platreef is a complex intrusive body comprising multiple pyroxenite and peridotite sills each with a distinctive chemistry.

Nex (2005) investigated the structural history of the Bushveld Complex in the northern limb by carrying out detailed mapping and structural investigations at Tweefontein Hill. The author suggested that there are two pre-Bushveld ductile deformation events which have resulted in a major south-west plunging fold at Tweefontein Hill. This fold structure primarily controlled the distribution of massive sulphide mineralisation at Tweefontein Hill, a feature unique to this locality.

Sharman-Harris *et al.* (2005) performed sulphur and oxygen isotope analysis on a range of Platreef and footwall rocks on the farm Turfspruit. Their study revealed that the Platreef sulphides at this locality contain a significant component of crustal S, which they propose to be derived from the adjacent shales of the Duitschland Formation. The heaviest S isotopic signatures occur closest to the footwall contact whereas lighter signatures, more similar to that expected for magmatic sulphur, occur near the top of the Platreef.

A recent study by Holwell *et al.* (2006) on the PGM assemblage in the Platreef at Sandsloot mine revealed that the pyroxenites and pegmatites of the reef contain a PGM assemblage dominated by Pt and Pd tellurides (kotulskite and moncheite), electrum and some arsenides. Portions of the reef that have been replaced by olivine are characterised by the presence of Pt-Fe alloys, Pd-alloys and Pd-tellurides. The metamorphosed footwall rocks that contain PGE mineralisation are characterised by arsenides, bismuthides and antimonides. Holwell *et al.* (2006) suggest that the variety of PGM assemblages in the different Platreef rocks at Sandsloot reflects the late magmatic and hydrothermal processes which affected the Platreef during and after emplacement.

1.4 Methodology

The initial step of this investigation involved the examination and logging of two borehole cores (borehole 2121 and 2199) drilled in 1994 by Gencor on the farm Nonnenwerth. More than one hundred samples of the Platreef and its floor rocks were collected representing the different lithologies and mineralization. Seventy one quarter core samples, 10-30 cm in length, were selected for detailed study. Polished thin sections were prepared for all 71 samples. In relatively unaltered samples, the modal proportions of mineral phases were estimated by point counting. Thirty nine (39) samples were pulverised using a C-steel jaw-crusher and a C-steel milling vessel. The samples were analysed for major and trace elements by X-ray fluorescence spectroscopy (XRF) at the University of Pretoria. The PGE concentrations were determined at the Université du Quebec à Chicoutimi, Canada, by Ni-sulphide fire assay followed by Instrumental Neutron Activation Analysis (INAA). Details of the method are given in Bédard and Barnes (2002). The compositions of selected minerals were determined by electron microprobe at the University of Pretoria, South Africa. S and O isotope analyses on selected samples were performed at Indiana University, Bloomington, USA. The compositions of few chromites from the serpentinised peridotite and magnesian gabbronorite were obtained using a CAMECA SX-100 electron probe micro-analyser at the University of Pretoria, South Africa. The analytical results were corrected for Fe^{3+} content using the method of Finger (1972). Twenty-five polished sections were investigated by reflected light microscopy and scanning electron microscopy at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany to investigate the nature of the platinum-group minerals, the host phases of Pd and Pt and the composition of the base metal sulphides. Quantitative electron microprobe analyses of sulphides and PGM were performed using a CAMECA SX 100 at the Federal Institute for Geosciences and Natural Resources in Hannover, Germany. All analytical details are given in Appendix 1e.

CHAPTER TWO: OVERVIEW OF THE BUSHVELD COMPLEX

2.1 General

The Bushveld Complex, ca. 2055 - 2060 Ma (Rb-Sr whole rock age, Walraven et al., 1990; U-Pb on zircons, Harmer and Armstrong, 2000; U-Pb titanite age, Buick et al., 2001), consists of at least two distinct phases, including the largest mafic-ultramafic layered intrusion on Earth (the Rustenburg Layered Suite (R.L.S), measuring ca. 65 000 km^2 in outcrop/sub-surface outcrop), and one of the largest A-type granites on Earth (the Lebowa Granite suite measuring ca. 60 000 km^2; Kleeman and Twist, 1989) (Fig. 2.1). Extrusive rhyolitic pyroclastics of the Rooiberg Group are broadly of the same age and may equally form part of the Bushveld event (Harmer and Armstrong, 2000). The Bushveld Complex is located in the northern portion of the Kaapvaal craton. It lies almost entirely within the bounds of the Transvaal sedimentary Supergroup. The latter represents a supracrustal volcanosedimentary sequence estimated to have a total stratigraphic thickness of >15 km (S.A.C.S, 1980). It consists, from the base to the top, of (a) the protobasinal Wolkberg and Buffelsfontein Groups, (b) the carbonaceous Chuniespoort Group, and (c) the largely pelitic Pretoria Group. The Transvaal Supergroup is underlain by Archaean greenstones and basement granite- gneiss. Both the intrusive and the sedimentary rocks possibly formed in response to intracratonic rifting (Eriksson et al. 1991). The mafic-ultramafic sequence contains approximately 80% of the world's resources of PGE (Morrissey, 1988), as well as abundant reserves of Cr and V. The felsic rocks of the Complex host some important Sn and F deposits (Bailie and Robb, 2004).

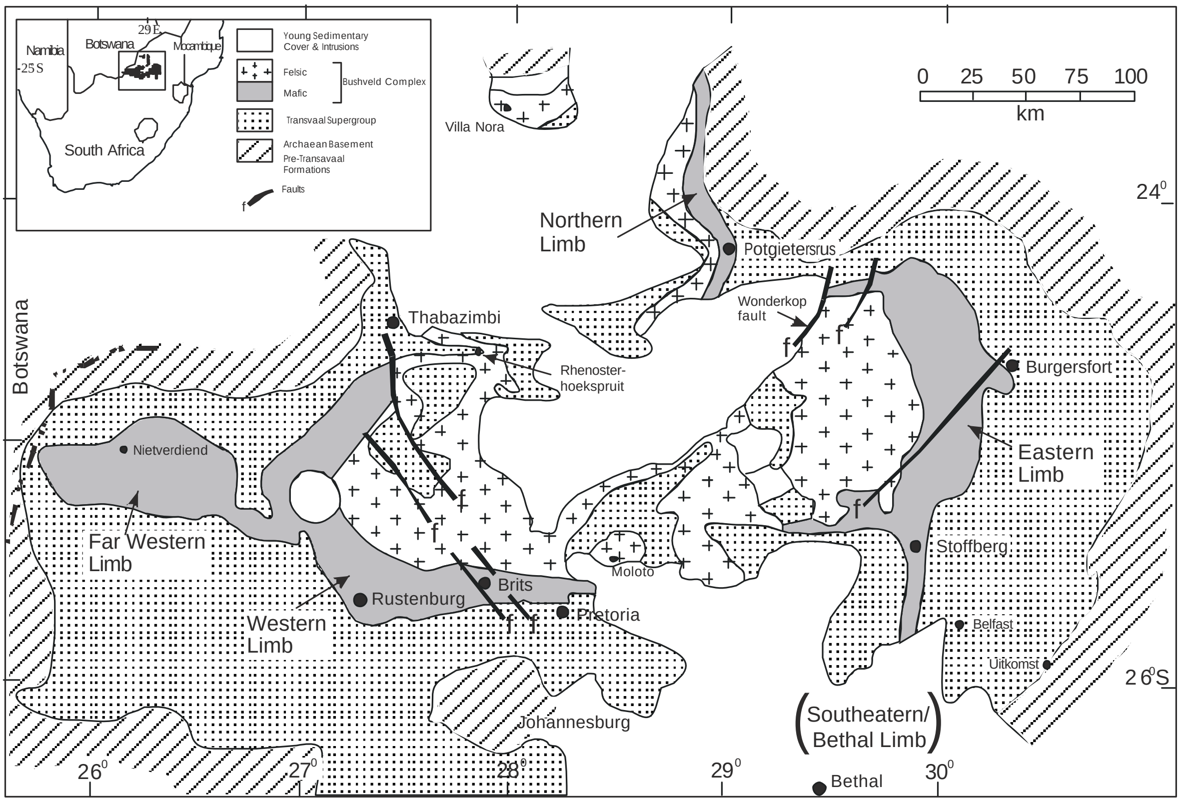

Fig. 2.1: Geologic map of the Bushveld Complex showing the different limbs (Modified after Reczko et al., 1995).

The R.L.S intruded the 2550 – 2060 Ma (Nelson et al., 1999) Transvaal Supergroup largely along an unconformity between the Magaliesberg quartzite of the Pretoria Group and the overlying Rooiberg felsites. However, in the eastern lobe of the Complex south of the Steelpoort fault the Complex transgressed upwards through more than 2 km of sediments. In the northern limb, the Complex intruded at the level of the Magaliesberg quartzite in the south, but transgressed progressively lower members of the Transvaal Supergroup towards the north, until the mafic rocks abut Achaean granitic gneiss (Eales and Cawthorn, 1996).

2.1.1 Rustenburg Layered Suite

The Rustenburg Layered Suite is an approximately 8 km thick succession of layered mafic and ultramafic rocks, exposed in five major lobes, i.e., the eastern-, western-, and far-western lobes, the northern or Potgietersrus - Villa Nora lobe, and the Bethal lobe. The latter is hidden below younger sedimentary cover. It was identified on the basis of a gravity high and is only known from borehole core (Buchanan, 1975). Drilling also established extensions of the western limb of the Complex at its northern end beneath the Bushveld granite, and of the eastern limb beneath the Karoo sedimentary cover to the west of the Wonderkop fault (Eales and Cawthorn, 1996).

There is still controversy as to whether the limbs are joined at depth. Such a model was initially proposed by Hall (1932) based on the lithological similarity between the lobes. However, gravity data collected in the 1950's showed that the centre of the Complex lacks a positive anomaly suggesting that the mafic-ultramafic rocks were not continuous at depth (Cousins, 1959). Cawthorn and Webb (2001) and Webb et al. (2004) reinterpreted the gravity data based on seismic evidence suggesting a thickened crust beneath the Bushveld Complex (James, et al., 2004). As a result the gravity data are consistent with a model of connectivity of the lobes at depth.

The mode of emplacement of the layered suite was one of repeated injections of magma. This is suggested by the frequent reversals in the trend of differentiation towards higher Mg# and Cr contents (Eales & Cawthorn, 1996), in the initial Sr – isotopic ratio towards more mantle-like values, and by textural evidence such as resorbed plagioclase inclusions in olivine and pyroxene (Eales et al. 1986).

The Rustenburg Layered Suite is generally sub-divided into five zones on the basis of mineralogical and petrological variations (Hall, 1932): at the base is the Marginal Zone which is overlain by the Lower Zone, the Critical Zone, the Main Zone, and the Upper Zone. A simplified stratigraphic column is shown in Fig. 2.2. The basal Marginal Zone consists of poorly layered, fine- to medium grained, heterogeneous gabbronoritic rocks. Marginal Zone rocks contain variable amounts of quartz and biotite, reflecting assimilation of the underlying shale. It varies in thickness between 0 and 250 m (western Bushveld Complex, Coertze, 1974). The rocks of the Marginal Zone are generally unmineralized (Viljoen and Schurmann, 1998). They may represent composite sills or rapidly cooled derivatives of the parental magmas to the Complex (Eales and Cawthorn, 1996). The Lower Zone reaches a thickness of approximately 800 m In the western limb, it comprises three main intervals. At the base occur interlayered olivine-rich and orthopyroxene-rich cumulates ca. 450 m, in the form of harzburgites and dunites (Eerlyl bronzitite of SACS, 1980). This is overlain by predominantly orthopyroxenite, ca. 100 m, (Makgope bronzitite of SACS, 1980), and at the top, some 300 m of mainly harzburgite and dunite (Groenfontein harzburgite of SACS, 1980). In the eastern limb, the Lower Zone is dominated by orthopyroxene-rich rocks (Eales and Cawthorn, 1996).

The Critical Zone is ca. 1.2 km thick and contains two economically important PGE-layers (the Merensky Reef and UG2 chromitite) and a total of 13 major chromite layers. The Critical Zone is sub-divided into two compositionally contrasting subzones, namely the Lower Critical Zone and the Upper Critical Zone (Cameron, 1980, 1982). The base of the Lower Critical Zone is characterised by an increase in

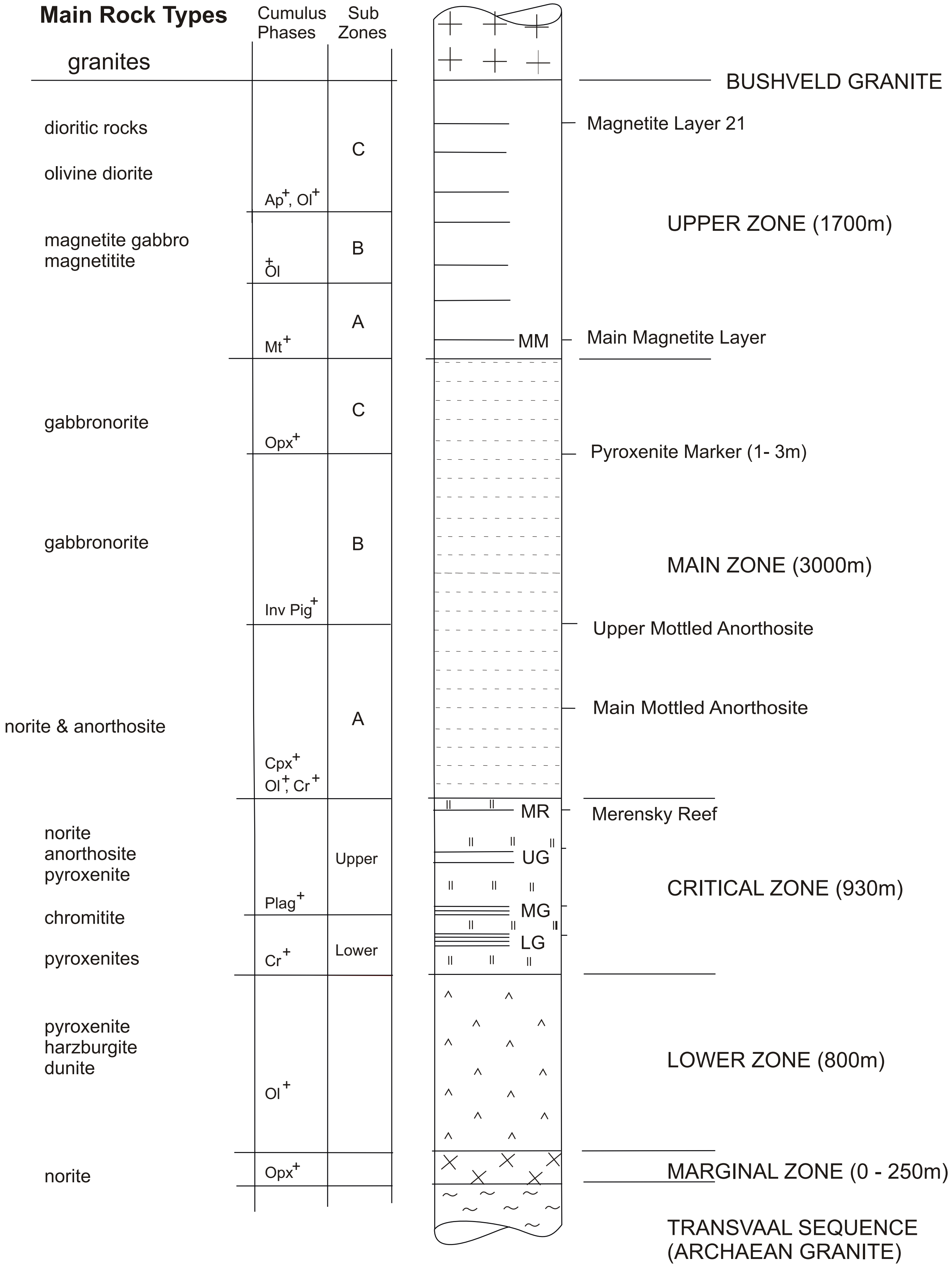

Fig. 2.2: Stratigraphy of the Rustenburg Layered Suite in the western Bushveld Complex (from Mithcell, 1990)

the proportion of interstitial plagioclase, from 2 to 6 % (Cameron, 1978). The boundary between the Lower Critical Zone and the Upper Critical Zone is defined by the appearance of cumulus plagioclase, forming an anorthosite layer between the MG2 and MG3 chromitites. The Upper Critical Zone is characterised by a number of cyclic units consisting of basal chromitite, overlain by harzburgite and/or pyroxenite, norite and anorthosite (Eales et al., 1986).

According to the most widely accepted subdivision, the base of the Main Zone may be placed at the top of the Giant Mottled Anorthosite with large oikocrysts of pyroxene at the top of the Bastard unit, although the exact position is somewhat controversial (Kruger, 1990; Mitchell and Scoon, 1991). The Main Zone is ca. 3000 m thick and consists mainly of norite in the basal and uppermost portions, but gabbronorite in the intervening central portion (Mitchell, 1990). Anorthosite constitutes some 5 % of the rocks, while pyroxenite is rare. The rocks are mostly poorly layered. Cumulus olivine and chromite are absent and magnetite occurs only near the top of the zone. The Main Zone onlaps the floor rocks to the south and the north where it is also the basal zone in the northern lobe

The position of the boundary between the Main Zone and the Upper Zone remains also controversial. Based on a reversal in Sr isotopic ratio and in the trend of iron enrichment (Von Gruenewaldt, 1973; Klemm et al., 1985), Kruger (1990) placed the boundary at the level of the Pyroxenite Marker, a prominent layer some 2.5 km above the base of the Main Zone. The more commonly used subdivision is that of Wager and Brown (1968) who defined the base of the Upper Zone by the first occurrence of cumulus magnetite, some 660 m above the Pyroxenite Marker. The Upper Zone is a 2-3 km thick, well layered unit that consists of gabbronorite, gabbro, anorthosite, and quartz-bearing ferrodiorite. There are 24 layers of massive magnetite, up to 7 m thick that host the bulk of the world's V resources. Near the top of the Upper Zone occur highly differentiated rocks enriched in K-feldspar and quartz that may be termed granodiorite (Von Gruenewaldt, 1973).

2.1.2 Parental magmas

Based on the composition of the chilled marginal rocks, the Bushveld Complex is thought to have resulted from the intrusion into the Bushveld chamber of two or more chemically distinct parental magmas producing the layered succession of mafic rocks (Sharpe, 1981, 1985; Harmer and Sharpe, 1985). These are a high-Mg basaltic andesite (B1 of Sharpe, 1981; magnesian basaltic suite of Davies and Tredoux, 1985) and a tholeiitic basalt (B2/B3 of Davies and Tredoux, 1985). The Lower Zone is thought to have formed from the high-Mg andesite. Periodic mixing of the tholeiite and high-Mg andesite is considered to be responsible for the formation of the chromitite layers (Sharpe and Irvine, 1983; Hatton and von Gruenewaldt, 1987), the Merensky Reef (Kruger and Marsh, 1982, 1985; Naldrett et al., 1986; Hatton, 1989) and the liquation of immiscible sulphide melt (Naldrett and von Gruenewaldt, 1989). The Main Zone formed predominately from the tholeiitic basalt.

2.1.3 PGE-mineralization

The PGE-mineralization in the Rustenburg Layered Suite occurs in the form of:

a) stratiform sulphide-bearing layers including the Merensky Reef (Lee, 1983; Naldrett et al., 1986; Barnes and Maier, 2002), Platreef (Gain and Mostert, 1982; Van der Merwe, 1976), Bastard Reef (Lee, 1983), Pseudoreef and Tarentaal layers (Naldrett et al., 1986), and the footwall of the Main Magnetite Layer (Von Gruenewaldt, 1976).

b) chromitites (Gain, 1985; Von Gruenewaldt et al., 1986; Hiemstra, 1986; Lee and Parry, 1988; Teigler, 1990 a, b; Scoon and Teigler, 1994) and

c) discordant PGE-enriched pipes of mafic-ultramafic pegmatite and magnesian dunite in the Critical Zone of the eastern Bushveld Complex, at Mooihoek, Onverwacht and Driekop (Scoon and Mitchell, 1994)

For stratiform sulphides-bearing layers, two main genetic models are generally considered. Most workers believe that the PGE were concentrated by a sulphide liquid that segregated from the silicate magma after sulphide saturation was achieved. In the past, it was widely believed that sulphide saturation could be triggered by mixing of compositionally contrasting magmas, one being primitive, the other being more evolved (Naldrett and von Gruenewaldt, 1989; Irvine and Sharpe, 1986; Li et al., 2001a). Cawthorn (2002) suggested that this model is incorrect and that magma mixing cannot trigger sulphide supersaturation. However, Li & Ripley (2005) presented new data that support the original model. They argue that attainment of sulphide saturation after magma mixing is strongly dependent on the sulphur concentrations of the end-member magmas, mixing proportions, as well as pressure and temperature.

An alternative model (Boudreau et al. 1986) proposes that PGE in the basal portions of the intrusion partition into percolating late-magmatic fluids and are reprecipitated in sulphide-bearing layers at higher stratigraphic levels, but this model has been criticized by several authors, based mainly on the occurrence of PGE-enriched rocks throughout much of the Lower and Critical Zones of the Complex. Further, in terms of this model, the thickness of the silicate rocks underlying a mineralized layer ought to have had an influence on the grade of the PGE-mineralization in the layers. In reality, the grade of the reefs remains relatively constant along strike. Yet, the Merensky Reef is underlain by ~ 400 m of unmineralized pyroxenite, norites and anorthosite in the Winnaarshoek area, but by 60 - 120 m of unmineralized rocks at Impala mine in the Rustenburg area (www.implats.co.za).

Mineralization in the Merensky Reef is hosted by up to 3% base metal sulphides (pyrrhotite, pentlandite, pyrite, cubanite and rare sulpharsenides, galena and sphalerite) and accessory PGE-minerals interstitial to the silicates. The Precious metals of the Merensky Reef typically average 5-7g/t over hundreds of kilometers of strike, mainly within the eastern and western lobes of the Complex (Barnes and Maier 2002a, b; Cawthorn *et al*., 2002) and are in the proportions of 4.82 ppm Pt, 2.04 ppm Pd, 0.66 pp Ru, 0.24 ppm Rh, 0.08 ppm Ir, 0.26 ppm Au, and the Cu:Ni ratio is 0.61 (Lee, 1996). Interestingly, the extent and relative amount of PGE and base metal sulphides appears to be a function of reef thickness with the highest grades occurring where the reef is thin. This remarkably constant grade of the reef over extensive strike distances is not mirrored by the composition of the actual platinum group mineralogy which is extremely variable even from mine to mine (Cawthorn et al., 2002b).

For S-poor chromitites, some workers have proposed that the PGE were initially concentrated by sulphides, but that much of the sulphur was subsequently lost during late magmatic processes, with the PGE remaining behind (e.g. Naldrett and Lehmann, 1988; von Gruenewaldt et al., 1989; Boudreau, 1998). Other authors have considered whether PGM can precipitate directly from the silicate magma, or were transported by the magma from the mantle source (Keays and Campbell, 1981; Barnes and Naldrett, 1987). The PGM could act as nuclei for crystallizing chromite or olivine. The weakness of this model is that it requires the magma to become saturated with PGM although it contains very low levels of these elements (10-20 ppb) (Mathez and Peach, 1997). As a possible alternative, Tredoux et al., 1995, proposed that PGE-ions in the melt tend to form clusters. When the clusters are destabilised in response to crystallisation of chromite or magnetite, PGM could crystallise directly from the magma. A criticism to this model is that most of the mineralized layers contain cumulus sulphide. It would not be possible to crystallize PGM from a magma that is at the same time segregating sulphide liquid. Thus, if the PGE are collected by PGM the sulphides must have been added to the rock after the formation of the PGM.

The UG2 chromitite has 60-90% chromite with an average Cr/Fe ratio between 1.26-1.4 and 43.5% Cr_2O_3. The PGE are interstitial to the chromite grains with the exception of laurite which is commonly found enclosed by chromite. PGE contents are up to 10 ppm PGE+Au (3.6 ppm Pt, 3.81 ppm Pd, 0.3 ppm Rh). Base metal sulphides are accessory and Cu and Ni are low, generally less than 0.05% (Lee, 1996). The PGE distribution frequently displays two peaks (Hiemstra, 1985).

The PGE-mineralized discordant pipes consist of Fe-rich clinopyroxenite, Mg-dunite and hortonolite dunite (Wagner, 1929). The pipes contain a very unusual PGE-assemblage, dominated by Pt, suggesting that the mineralization is not of primary magmatic origin. Stumpfl (1993) has suggested that the PGE are the result of hydrothermal remobilisation from cumulates that host the pipes. The origin of the pipes remains unresolved. They may possibly represent ultramafic density flows crystallised from late magma injections (Viljoen and Schürmann, 1998).

2.2 General geology of the Platreef

The Platreef is a zone of mineralization developed mostly at or near the base of the northern limb of the Bushveld Complex (Fig. 2.3). It consists of a thick (up to 400 m; Kinnaird et al., 2005) package of texturally heterogeneous pyroxenite, norite and gabbronorite, containing numerous xenoliths of dolomite, calc-silicate, shale (graphitic in part), quartzite and Fe-formation derived from the floor rocks. The xenoliths range from several cm to 100s of metres in diameter. The Platreef rests on the Lower Zone in the southern part of the northern lobe (on the farms Grassvally and Rooipoort; Hulbert, 1983; Maier et al., 2007), on Transvaal Supergroup rocks between Rooipoort and Zwartfontein and on Achaean granite gneiss between Overysel and the northern edge of the lobe (Fig. 2.3). An up to 2000 m package of gabbro, magnetite gabbro and diorite belonging to the Main and Upper Zones of the Rustenburg Layered Suite

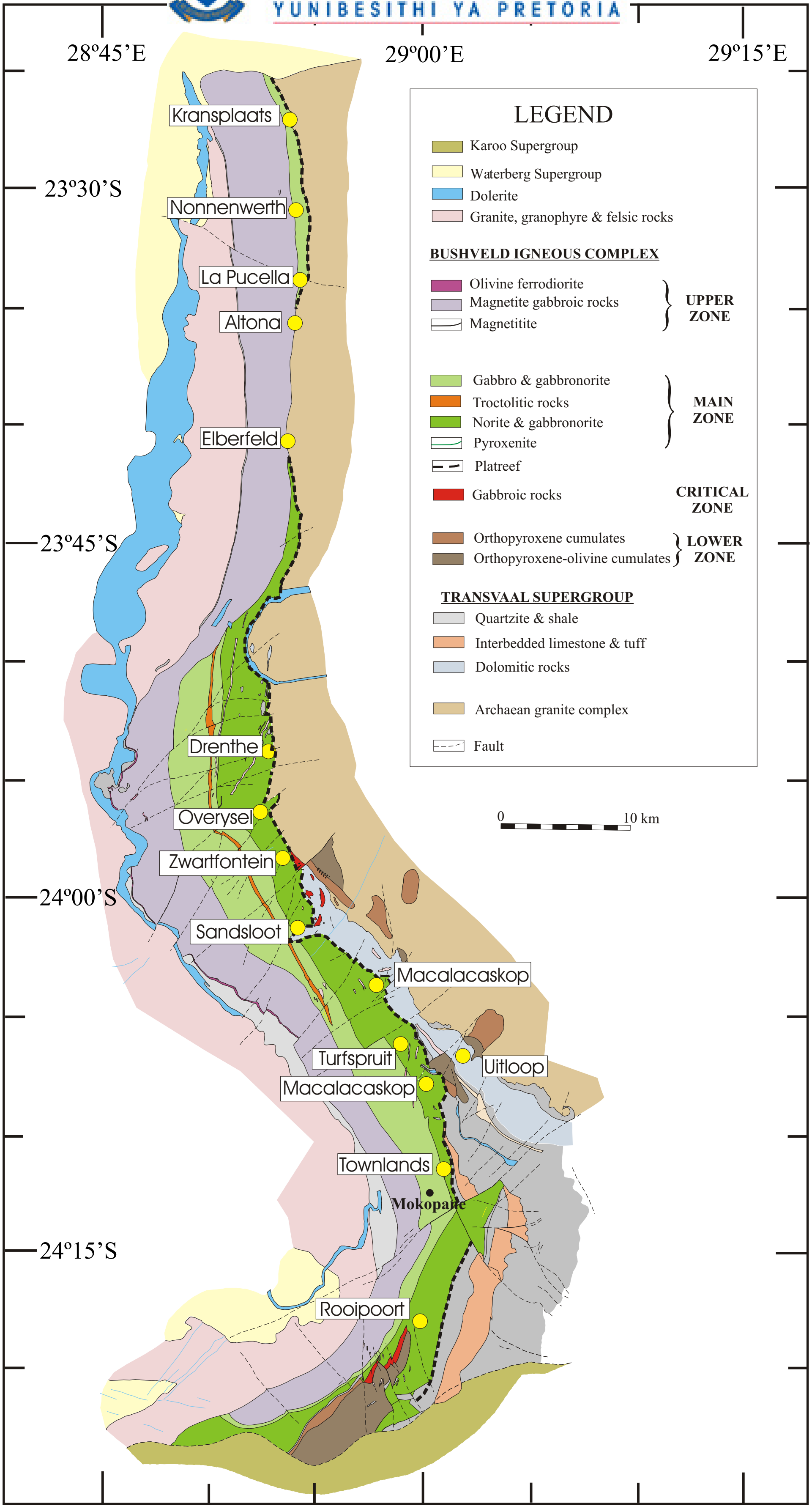

Fig. 2.3: Geological map of the Northern limb of the Bushveld Complex. (modified after Ashwal, et al., 2005).

overlies the Platreef. Between the farms Elberfeld and Altona, a ca. 10-km sector to the south of Nonnenwerth, the Main Zone and the Platreef are apparently not developed. In this area the Upper Zone has transgressed through the Main Zone and directly overlies the Archean basement which forms the floor of the intrusion (Fig. 2.3). The absence of sulfide mineralization in this area is indicated by a stream sediment survey conducted by the Geological Survey of South Africa. The survey failed to identify a pronounced positive Cu anomaly that is typical of the base of the remainder of the northern lobe. The implication here is that where Upper Critical Zone rocks overlie floor rocks, no basal contact-style PGE mineralization is developed, possibly because the parental magma to the Upper Critical Zone is too depleted in PGE to form a reef (Barnes *et al*, 2004).

The Platreef displays varying styles of mineralization in different sectors of the northern lobe. The PGE may be concentrated near the base of the layer e.g., at Tweefontein, near the top e.g., at Drenthe, or the PGE may be evenly distributed throughout the Platreef e.g., at Overysel (Kinnaird, 2005). Sulphide mineralization (up to 20%) may occur in the form of disseminated, net-textured, sub-massive or massive chalcopyrite, pentlandite and pyrrhotite, with minor galena and sphalerite with overall grades of 0.1-0.6% Cu and Ni. The mineralization may occur in norite, gabbronorite, anorthosite and pyroxenite. PGE grades are low and mostly <1–2 ppm, but higher grades are have been recorded in individual samples throughout the northern limb and, in particular, at Sandsloot and surrounding farms where average grades are ca. 4 ppm over 10 m (Vermaak 1995; Armitage et al., 2002). The PGE’s occur as PtFe, Pt_3Sn and variable Pd or Pt-tellurides, bismuthides, arsenides, antimonides, bismuthoantimonides and complex bismuthotellurides (Hutchinson and Kinnaird, 2005; Holwell *et al*., 2006). Pt:Pd ratio is ~1. PGM are rarely included in the sulphides. They occur as micron-sized satellite grains around interstitial sulphides and are common in serpentinised zones.

The correlation of the Platreef with the cumulate succession elsewhere in the Bushveld Complex remains unclear. In most of the northern lobe, the Platreef is overlain by the Main Zone and underlain by the sedimentary floor rocks. Together with the occassionally pegmatoidal textures of the Platreef, this has led several authors to correlate the Platreef with the Merensky Reef (Wagner, 1929; White, 1994). However, significant differences exist between the Platreef and the Merensky Reef as exposed in the western and eastern lobes of the Complex (e.g. Van der Merwe, 1976; Buchanan et al., 1981; Eales & Cawthorn, 1996). Firstly, the Merensky Reef tends to occur within the layered sequence, in many instances some 2 km above the floor of the Bushveld Complex, whereas in most cases the Platreef directly overlies the floor of the Complex or is separated from the later by a few 10's of meters (Fig. 2.4). Secondly, the mineralized interval is much thicker in the Platreef than in the Merensky reef (up to 400 m versus ca 1 m). Thirdly, there are important mineral- and whole rock compositional differences between the two layers, namely a relatively higher crustal component and lower metal tenors (e.g. Buchanan et al. 1981) in many Platreef intersections relative to the Merensky Reef (Barnes and Maier, 2002). The Platreef is also characterized by relative lower Pt/Pd ratios.

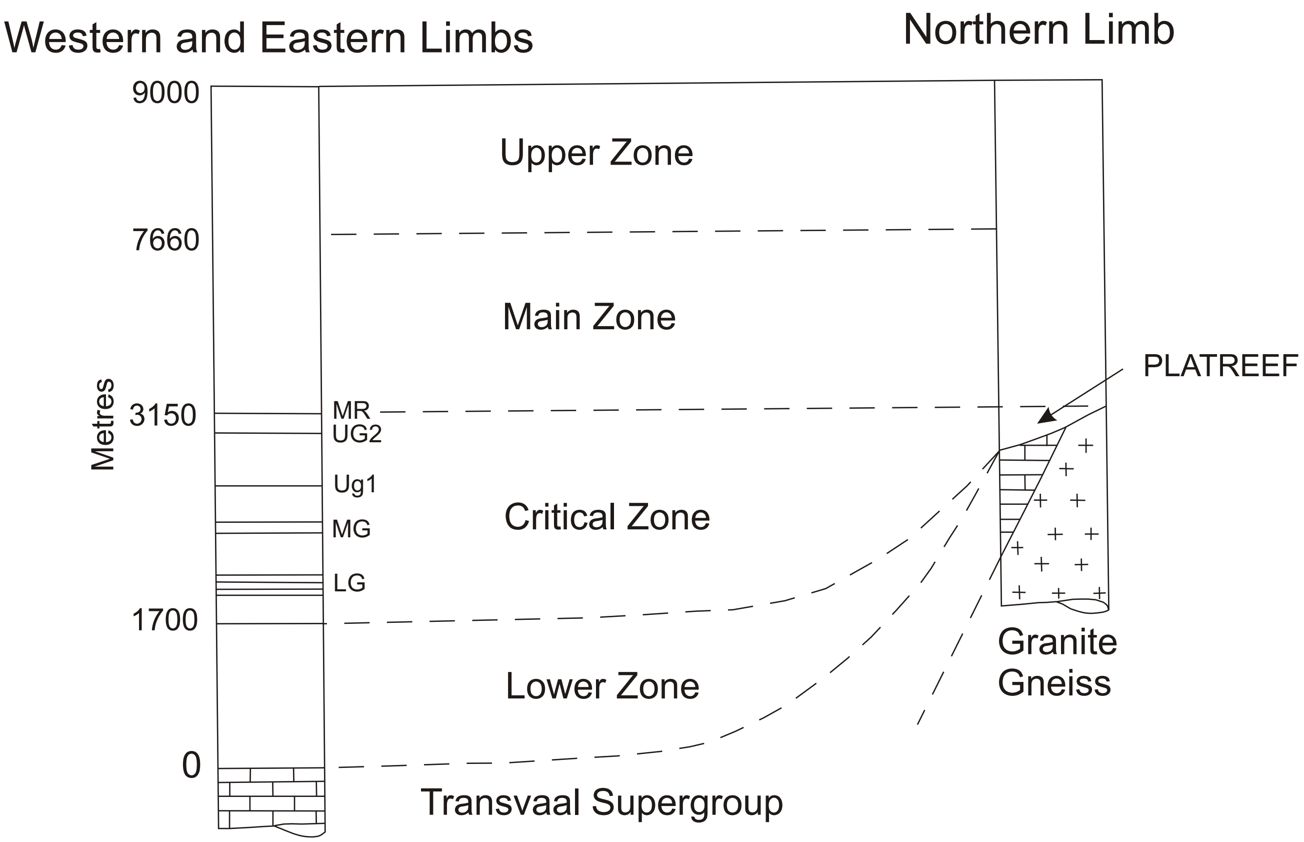

Fig. 2.4: Schematic section through the Rustenburg Layered Suite in different limbs of the Bushveld Complex (from Cawthorn *et al.*, 2002). Lateral correlation after Buchanan *et al*. (1981).