ARTICLE

Iain McDonald · David A. Holwell
Paul E. B. Armitage

Geochemistry and mineralogy of the Platreef and "Critical Zone" of the northern lobe of the Bushveld Complex, South Africa: implications for Bushveld stratigraphy and the development of PGE mineralisation

Abstract The northern lobe of the Bushveld Complex is currently a highly active area for platinum-group element (PGE) exploration. This lobe hosts the Platreef, a 10–300-m thick package of PGE-rich pyroxenites and gabbros, that crops out along the base of the lobe to the north of Mokopane (formerly Potgietersrus) and is amenable to large-scale open pit mining along some portions of its strike. An early account of the geology of the deposit was produced by Percy Wagner where he suggested that the Platreef was an equivalent PGE-rich layer to the Merensky Reef that had already been traced throughout the eastern and western lobes of the Bushveld Complex. Wagner's opinion remains widely held and is central to current orthodoxy on the stratigraphy of the northern lobe. This correlates the Platreef and an associated cumulate sequence that includes a chromitite layer—known as the Grasvally norite-pyroxenite-anorthosite (GNPA) member—directly with the sequence between the UG2 chromitite and the Merensky Reef as it is developed in the Upper Critical Zone of the eastern and western Bushveld. Implicit in this view of the magmatic stratigraphy is that similar Critical Zone magma was present in all three lobes prior to the development of the Merensky Reef and the Platreef. However, when this assumed correlation is examined in detail, it is obvious that there are significant differences in lithologies, mineral textures and chemistries (Mg# of orthopyroxene and olivine) and the geochemistry of both rare earth elements (REE) and PGE between the two sequences. This suggests that the prevailing interpretation of the stratigraphy of the northern lobe is not correct. The "Critical Zone" of the northern lobe cannot be correlated with the Critical Zone in the rest of the complex and the simplest explanation is that the GNPA-Platreef sequence formed from a separate magma, or mixture of magmas. Chilled margins of the GNPA member match the estimated initial composition of tholeiitic (Main Zone-type) magma rather than a Critical Zone magma composition. Where the GNPA member is developed over the ultramafic Lower Zone, hybrid rocks preserve evidence for mixing between new tholeiitic magma and existing ultramafic liquid. This style of interaction and the resulting rock sequences are unique to the northern lobe. The GNPA member contains at least seven sulphide-rich horizons with elevated PGE concentrations. Some of these are hosted by pyroxenites with similar mineralogy, crystallisation sequences and Pd-rich PGE signatures to the Platreef. Chill zones are preserved in the lowest Main Zone rocks above the GNPA member and the Platreef and this suggests that both units were terminated by a new influx of Main Zone magma. This opens the possibility that the Platreef and GNPA member merge laterally into one another and that both formed in a series of mixing/quenching events involving tholeiitic and ultramafic magmas, prior to the main influx of tholeiitic magma that formed the Main Zone.

Keywords Bushveld Complex · Platreef · Merensky Reef · Stratigraphy · Platinum-group elements

I. McDonald (✉) · D. A. Holwell
Department of Earth, Ocean and Planetary Sciences,
Cardiff University, P.O. Box 914, Cardiff,
CF10 3YE, UK
E-mail: iain@earth.cf.ac.uk
E-mail: holwellda@Cardiff.ac.uk

P. E. B. Armitage
Department of Earth and Environmental Sciences,
University of Greenwich, Chatham Maritime,
Kent, ME4 4TB, UK

Introduction

The Bushveld Complex of South Africa is the largest repository of platinum-group elements (PGE) in the

world (Lee 1996; Cawthorn 1999a). All PGE mining activities in the eastern and western lobes of the Bushveld Complex currently take place from tabular horizons within the layered sequence associated with sulphides or chromitite where the PGE are concentrated. The most important of these are the Merensky Reef and the UG2 chromitite layer. The stratigraphy and the positions of the PGE horizons in the eastern and western lobes of the complex are broadly the same (Lee 1996; Cawthorn and Lee 1998; Barnes and Maier 2002a). This, as well as other geophysical evidence, led Cawthorn and Webb (2001) to infer that the eastern and western lobes were connected throughout much of the evolution of the Bushveld Complex, that similar magmas were present in both lobes and that mineralisation processes operated concurrently in both lobes to produce stratiform PGE deposits such as the Merensky Reef and the UG2 chromitite.

While PGE mining and exploration in the eastern and western lobes of the Bushveld Complex to date have produced sufficient data to bring genetic understanding of the Merensky Reef and UG2 chromitite mineralisation to a mature stage, the same cannot be said of the PGE mineralisation in the northern (Potgietersrus) lobe of the complex. In this sector, PGE are associated with a basal unit called the Platreef that rests directly on the early Proterozoic sediments and Archaean granite that form the floor of the complex (Fig. 1). The Platreef is a contaminated, frequently xenolith-rich, unit that is geologically more complex than any of the PGE reefs in the eastern and western lobes, but which is also thicker and carries sufficiently consistent grade to allow large-scale open pit mining along some areas of its strike (Viljoen and Schürmann 1998; Bye 2001; Kinnaird and Nex 2003). Anglo Platinum, currently operates one open pit mine on the farm Sandsloot 236KR, is developing a second on the farm Zwartfontein 818LR, and has plans for others at staged intervals over the next 30 years (Bye 2001). The potential for more high-tonnage and low-cost open pits in this sector have led other companies to explore on the Platreef adjacent to Anglo Platinum's licence area and the northern lobe is currently the most active exploration centre on the Bushveld Complex.

The Platreef was discovered not long after the discovery of the Merensky Reef in the eastern Bushveld in 1924 and was systematically explored and mined until 1930, when the platinum price collapsed during the Great Depression (Buchanan et al. 1981). The most comprehensive early account of the geology of the deposit is given by Wagner (1929) who recognised and documented key features of the Platreef, most notably: (a) the great thickness of the mineralised layer(s); (b) the position of the mineralised pyroxenite ("bronzitite") at the base of the igneous sequence in contact with the metamorphosed sediments and granite; (c) the ratio of Pt:Pd at unity or lower; and (d) the presence of PGE mineralisation in metamorphosed and metasomatised footwall, often at considerable distance from the igneous rocks.

Wagner (1929) observed a "feldspathic bronzitite" and a "pseudoporphyritic poikilitic diallage norite" at many sites along the Platreef and termed these as "Merensky Reef" because of a similar appearance to the rocks of Merensky Reef that were already known in the eastern and western lobes of the Bushveld Complex. Wagner (1929) took this further and evidently believed that not only were the Platreef and the Merensky Reef similar, but that they represented the same layer:

"The Main Potgietersrust or Merensky Platinum Horizon...is the main platinum horizon of the Potgietersrust fields. This is taken to be the equivalent of the Merensky Horizon of the Lydenburg and Rustenburg districts." (p.167).

In discussing the wider genetic aspects of the mineralisation, Wagner (1929)

"...maintains that in endeavouring to arrive at the correct solution of the problem, the platinum deposits of the Potgietersrust district must be viewed in their entirety. In other words, the Zwartfontein deposits must be viewed in their relation to the Merensky Horizon as developed to the north and south of them and in the Rustenburg and Lydenburg districts." (p.182).

Wagner's suggestion that there was a direct correlation between the Platreef of the northern lobe and the Merensky Reef elsewhere in the Bushveld Complex is of great importance because it has been accepted uncritically in most subsequent work on the Platreef (e.g. Buchanan et al. 1981; Kinloch 1982; Buchanan and Rouse 1984; White 1994; Vermaak 1995; Viljoen and Schürmann 1998). More fundamentally, the assumed link between the two units is one of the foundations of the prevailing view of the stratigraphy of the northern lobe and its relationship with the rest of the complex.

The northern lobe

The stratigraphy of the northern lobe and the widely accepted view of its relationship with the rest of the Bushveld Complex are summarised in Figs. 2, 3. The northern lobe is divided into four principal zones but detailed elements of the stratigraphy are different from the eastern and western lobes. Lower Zone (LZ) rocks comprise >1,600 m of pyroxenites and harzburgites with chromitite layers, consisting of at least 37 different cyclic units (Hulbert 1983; Hulbert and Von Gruenewaldt 1985). The LZ is best developed to the south of Mokopane on the farms Grasvally 293KR and Zoetveld 294KR (Hulbert and Von Gruenewaldt 1986) but also occurs as small satellite bodies north of the town (Fig. 1). The mafic rocks
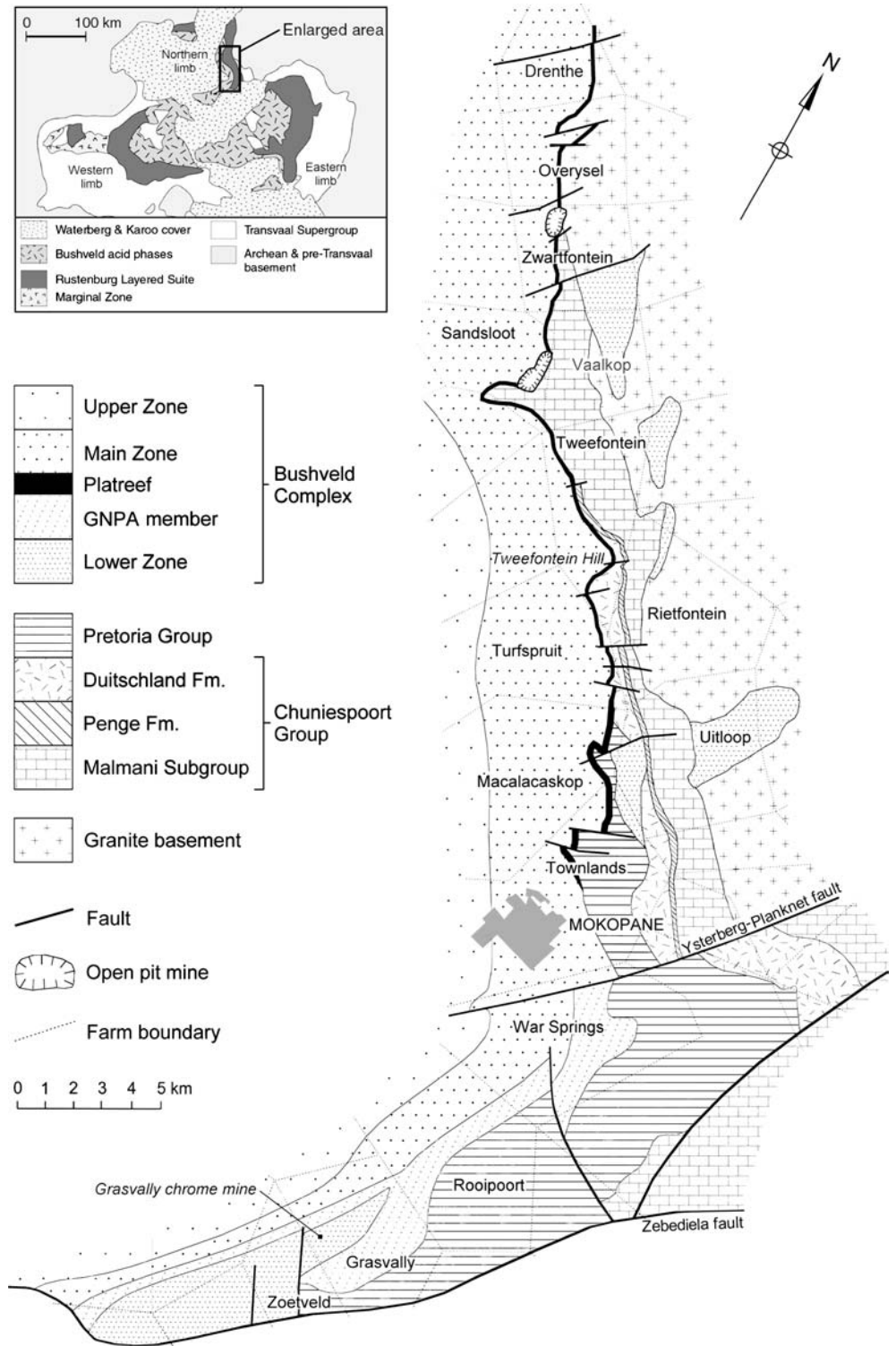
of the LZ here have higher Mg# ((Mg/(Mg + Fe)) values
in olivine and orthopyroxene and contain chromitites
with higher Cr_2O_3 than similar LZ-type rocks in the rest
of the Bushveld Complex. In addition, a sulphide horizon
with PGE occurs in the Volspruit Subzone (Fig. 2),
whereas the LZ in the rest of the complex contains no

stratiform PGE mineralisation (Hulbert and Von Gru-
enewaldt 1982; Hulbert 1983). Van der Merwe (1976,
1998) considers these as unique features of the northern
lobe, distinctive from the rest of the complex.

A thin sequence of rocks known as the Grasvally
norite-pyroxenite-anorthosite (GNPA) member is

Fig. 2 Stratigraphy of the northern lobe showing the major chromitite, magnetite and Ni-Cu-PGE deposits (after Von Gruenewaldt et al. 1989)
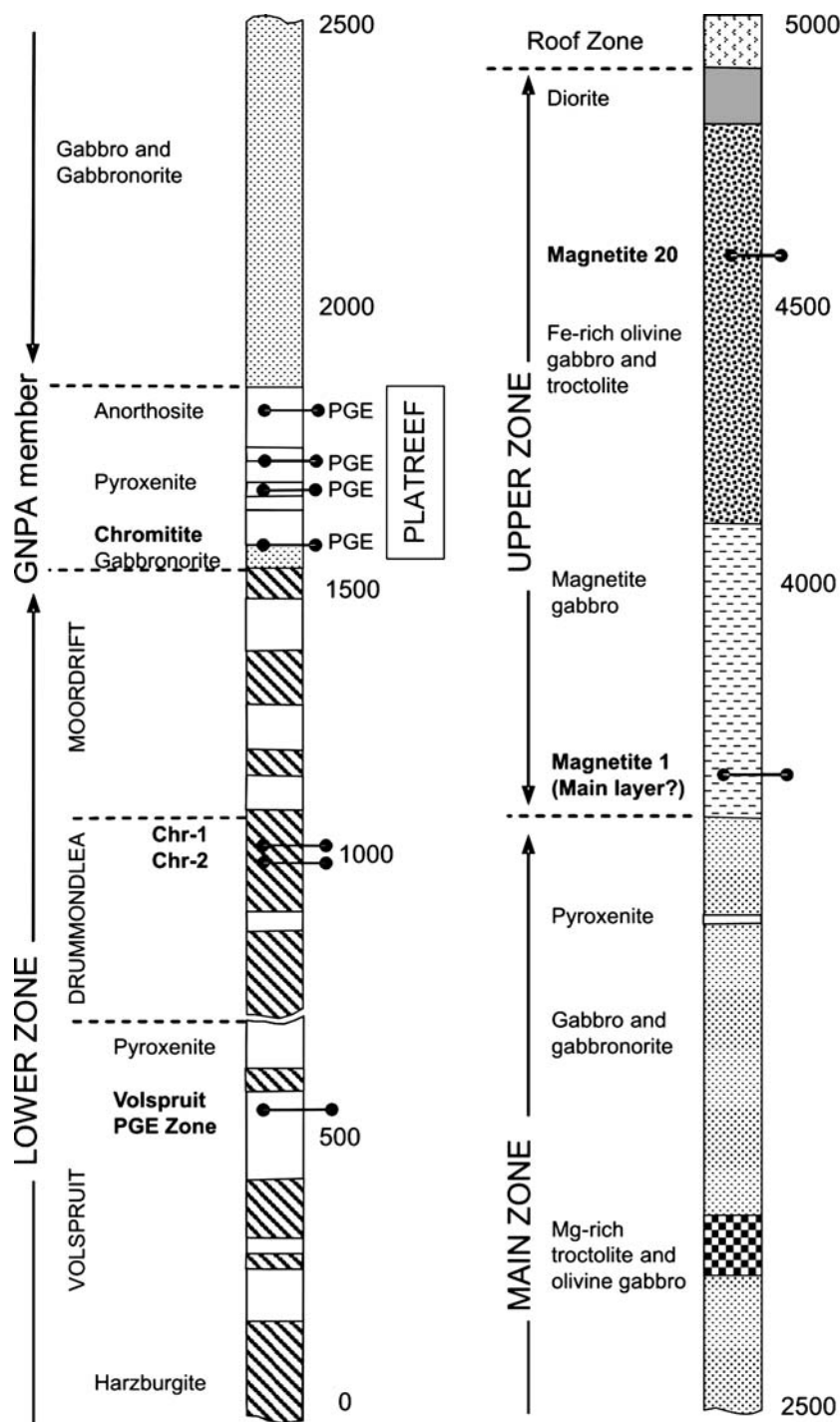
developed over LZ rocks and sediments of the Pretoria Group south of Mokopane (Hulbert 1983; Hulbert and Von Gruenewaldt 1985, 1986; Fig. 1). This sequence contains layered norites, gabbronorites and anorthosites along with a chromitite layer and is termed as the "Critical Zone" in all the current literature on the northern lobe. Hulbert (1983) termed the chromitite layer in the GNPA member the "UG2-like" chromitite and it has been correlated directly with the UG2

chromitite by some authors (e.g. Van der Merwe 1998). The top of the GNPA member is xenolith-rich and hosts PGE mineralisation. The occurrence of both xenoliths and PGE has led to suggestions that the upper part of the GNPA member may correlate with the Platreef north of Mokopane (Von Gruenewaldt et al. 1989).

Van der Merwe (1976) placed the Platreef ("Platinum Horizon" of Wagner 1929 and Willemse 1969) at the base of the Main Zone (MZ). This correlation is not

universally accepted and other authors (e.g. Von Gruenewaldt et al. 1989; White 1994) believe the Platreef to be a part of the Upper Critical Zone (UCZ). The Platreef can be traced for over 30 km along strike north of Mokopane and is generally developed between norites and gabbronorites ascribed to the MZ and the floor of the complex. As the Platreef strikes north, it transgresses sedimentary rocks of the Transvaal Sequence, and eventually rests on Archaean granite (Fig. 1). The rest of the MZ comprises 2,200 m of gabbros and gabbronorites. The only reliable markers in this part of the sequence are four prominent pyroxenites developed 300 m above the Platreef and a 100–200-m thick troctolite that is found 1,100 m above the Platreef. These layers have no equivalents in the rest of the Bushveld Complex. Van der Merwe (1976) suggested that a pyroxenite corresponding to the Pyroxenite Marker is developed 2,000 m above the Platreef, but Harris et al. (2004) have discounted this correlation. The pyroxenite unit also appears to be absent in the south of Mokopane and is missing from the stratigraphic compilations by Hulbert (1983) and Von Gruenewaldt et al. (1989).

The Upper Zone is approximately 1,400 m thick and comprises a sequence of magnetite gabbros, anorthosites and olivine diorites, along with a number of magnetite layers. As indicated in Fig. 3, one of these may be correlated on the basis of thickness and vanadium content with the Main Magnetite layer developed elsewhere in the Bushveld Complex (Van der Merwe 1976; Von Gruenewaldt et al. 1989).

The question of how the Platreef and other cumulates that have been ascribed to the "Critical Zone" in the northern lobe actually relate to the stratigraphy of the rest of the Bushveld Complex has important implications for the timing and genesis of the Platreef mineralisation. If it is not equivalent to the Merensky Reef and formed in a separate event, then genetic models constructed for the Platreef on the basis of what is known about the Merensky Reef or which link the two horizons in time may be inappropriate. The purpose of this paper is to critically review the geology of the Platreef and Merensky Reef, using existing knowledge and new geochemical and mineralogical data, with the aim of establishing the validity of the assumed link between the two units.

Samples

Samples of Platreef used in this study were collected from faces 135/014 and 138/014 in the southwest corner (SW1 and SW2 series) and faces 132/038 and 141/011 along the north wall (N1 and N3 series) of the southern central pit at Anglo Platinum's Sandsloot open pit mine (Fig. 4). The footwall is composed primarily of siliceous dolomite and calc-silicate. Close to the contact, these rocks are transformed into a mixture of massive diopside clinopyroxenites, locally rich in metamorphic olivine (commonly referred to as "parapyroxenites"), that have
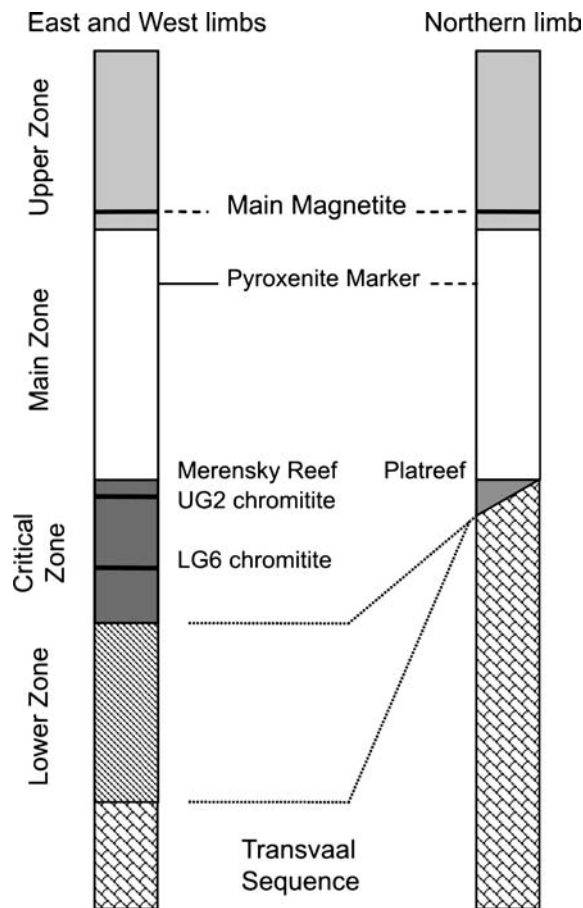

Fig. 3 Currently accepted stratigraphic relationships between the eastern and western limbs and the northern limb of the Bushveld Complex (after White 1994; and Cawthorn and Lee 1998)

suffered variable serpentinisation (Armitage et al. 2002). Additional samples of footwall were collected from faces that connect to the three reef sections along the south and east walls of the pit. These samples are labelled as the S series and the E series, respectively. Sample DH-G is a grab sample collected from the same area as Face 132/038 and is included with the N1 series for comparison.

Analytical methods

The initial preparation of samples was as described by Armitage et al. (2002). Detailed mineralogical examinations and the analysis of silicates were carried out at Cardiff University using a Cambridge Instruments LEO S360 scanning electron microscope coupled to an Oxford Instruments INCA energy dispersive X-ray analysis system. Additional analyses were also carried out at the Natural History Museum using a JEOL 5900LV (SEM) with attached Oxford instruments EDX INCA system. Typical analytical conditions and procedures are described in Hutchinson (2001). Bulk analysis for major

element and trace elements was carried out using a JY Horiba Ultima 2 inductively coupled plasma optical emission spectrometer (ICP-OES) and Thermo X7 series inductively coupled plasma mass spectrometer (ICP-MS). Samples were first ignited at 900°C to determine loss on ignition and then fused with Li metaborate on a Claisse Fluxy automated fusion system to produce a melt that could be dissolved in 2% HNO_3 for analysis. Full details of the ICP analysis procedures and the instrumental parameters are given in McDonald et al. (2005). Geochemical data for Platreef, hanging wall and footwall samples are given in Tables 1, 2, 3. A complete set of silicate mineral data, comprising over 200 analyses, is available from the first author on request.

Petrography of the Platreef at Sandsloot

White (1994) recognised three principal rock types within the Platreef that he termed as A reef, B reef and C reef. The A reef is a pegmatoidal feldspathic pyroxenite at the base of the sequence that carries sporadic base metal sulphide mineralisation. Above this is the B reef, the principal PGE carrier, which is a coarse grained pyroxenite with 50–90% orthopyroxene, common base metal sulphides and very sporadic chromitite. At the top of the sequence is the C reef, which is a fine-grained feldspathic pyroxenite that may contain up to 70% clinopyroxene. Despite the fact that they are essentially mining terms designed to categorise Platreef facies on a broad scale, these have become entrenched in the recent literature (Lee 1996; Viljoen and Schürmann 1998; Cawthorn and Lee 1998; Barnes and Maier 2002a; Cawthorn et al. 2002a) leading to the dangerous misconception that the A–B–C sequence represents "typical" Platreef.

Sections of the Platreef have been described in several papers prior to the A–B–C terminology being introduced, and reveal how, without any preconceived subdivisions, the terminology is simply not applicable in many parts of the Platreef. On the farm Drenthe 788LR, Gain and Mostert (1982) describe a basal feldspathic pyroxenite overlain by norites and melanorites, capped by a feldspathic pyroxenite. This sequence of pyroxenite-norite-pyroxenite is inconsistent with the A, B and C-reefs, as the inferred 'B-reef' is noritic and contains cumulus plagioclase. In the adjacent farm to the south, Overysel 815LR, Cawthorn et al. (1985) describe the Platreef as often having a thin medium-grained norite at the base which grades upwards into a coarse pyroxenite with inhomogenous mineralogy, overlain by gabbro and norite.

More recent work has also revealed limitations with the "A–B–C" terminology (Armitage et al. 2002; Kinnaird et al 2005). The definitions of the reef types do not conform to the recognised IUGS classifications, are not sufficient to allow unambiguous distinctions between different units, and encourage pigeonholing rather than proper description of potentially new rock types. For example, in the faces mapped by Armitage et al. (2002) at Sandsloot, rocks corresponding to the A and C reef types were conspicuously absent. That study and new data presented here reveal other lithologies that form components of the Platreef at Sandsloot and do not fit into the previous terminology at all. For these reasons we avoid it and classify our samples according to the established IUGS guidelines.

Maps of face 132/038 (N1), and faces 138/014 (SW1) and 141/021 (SW2) are shown in Figs. 4, 5, 6. Sample points and numbers for all of the samples collected for petrography and/or geochemical analysis are indicated on each map. The upper portion of Platreef in face 132/038 has been described previously (as face 132/035) in Armitage et al. (2002); it has a true thickness of 12–15 m and is dominated by coarse grained pyroxene-rich gabbro-gabbronorite that grades locally into pyroxenite and websterite. Cumulus orthopyroxene is ubiquitous and is accompanied by cumulus or intercumulus
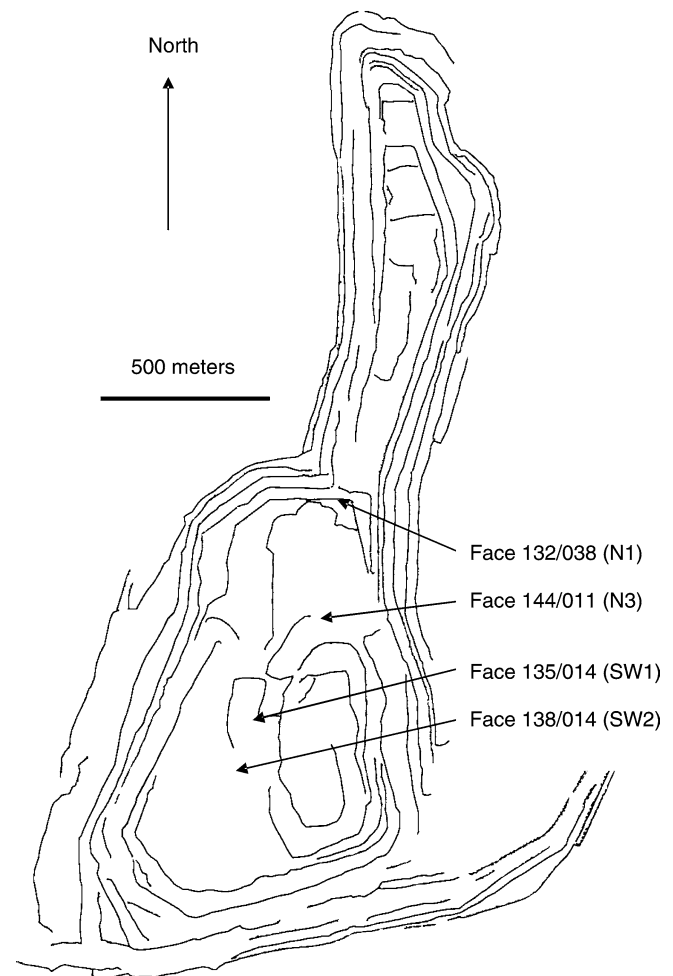

Fig. 4 Wireframe plan view of the Sandsloot open pit in July 2000 showing the locations of the faces mapped and sampled in this study. *Solid lines* represent the bench tops and the deepest area of the pit (south central area) is approximately 190 m below the level of the outer wall
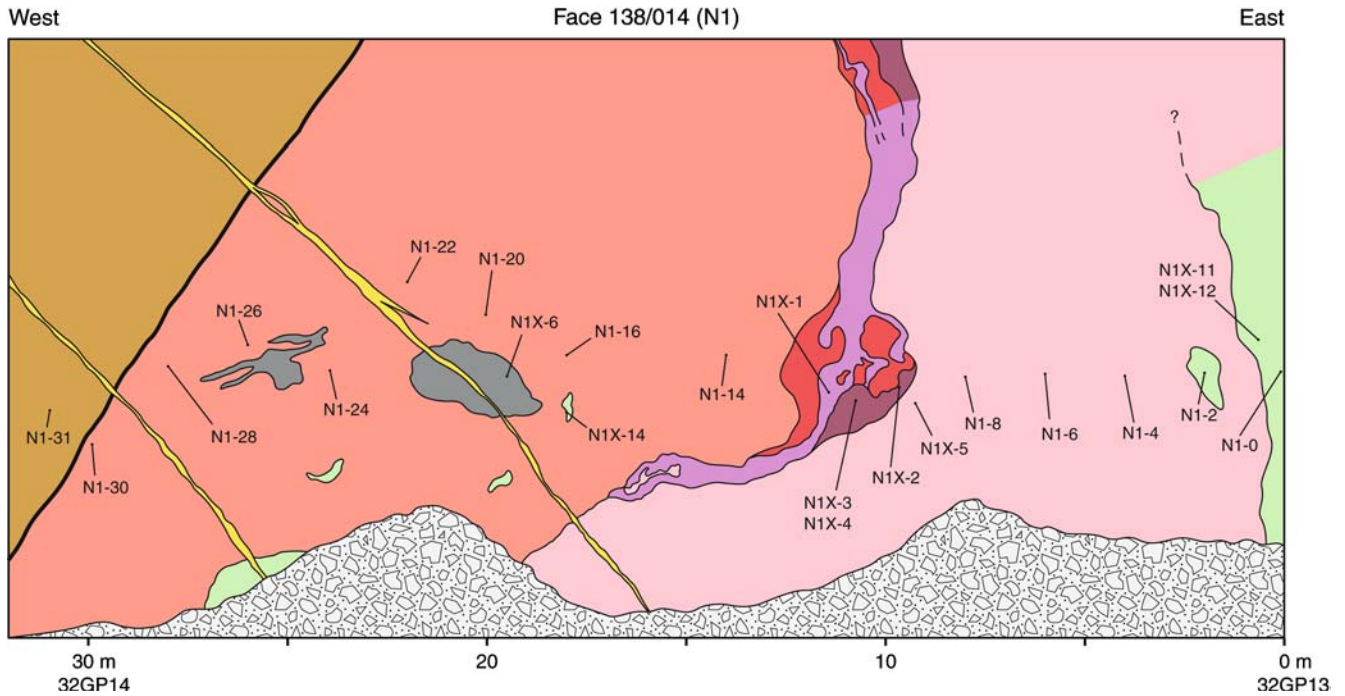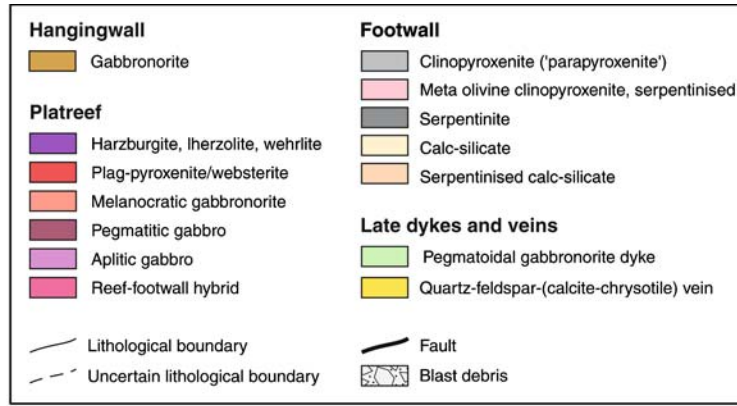
Fig. 5 Dip parallel section through the Platreef on face 132/035 (N1). This shows the major lithologies and the positions of samples taken for petrographic/geochemical analysis. 32GP13 and 32GP14 are the positions of mine survey geopoints

clinopyroxene, and intercumulus plagioclase that may occur as large oikocrysts. Sulphides and PGM are generally restricted to interstitial sites between the cumulate pyroxenes. Chromite, ilmenite, rutile, armalcolite, perovskite, phlogopite and zircon are present as accessories. A pegmatoidal zone of aplitic gabbro and fragmented pyroxenite occurs along the footwall contact where the reef thickens but is absent from thinner reef lower down the face. The contact with the hanging wall in this face is tectonised, and comprises a serpentinised brittle-ductile shear zone up to 20 cm thick (Fig. 3). The hanging wall is a medium-coarse grained norite with cumulus plagioclase and intercumulus pyroxene (sample N1-31). The Platreef in face 144/011 (N3) appears similar to face N1 and the top contact of the reef was photographed and sampled. Here, instead of a tectonite, there is a planar magmatic contact between the top of

the Platreef and the hanging wall gabbros. The contact is marked by a 10–15 cm thick leuconorite with cumulus plagioclase and orthopyroxene oikocrysts, overlain by a 5 cm thick layer of fine-grained gabbronorite (Fig. 6). The leuconorite and gabbronorite are samples N3X4B and N3X4A in Table 1.

Platreef in the southwest corner of the pit shows important mineralogical and textural differences from the reef exposed to the north. Towards the top contact, Fe-rich olivine is widespread and occurs as a late-stage mineral. It replaces orthopyroxene through many metres of the reef. Plagioclase may also be replaced by Fe-rich clinopyroxene leading to the development of Fe-rich wehrlites, olivine lherzolites and harzburgites and an overall darkening of the rock. These rock types have been noted to the south where the Platreef rests on banded ironstone (Buchanan et al. 1981; Buchanan and

Fig. 6 Leuconorite and fine-grained gabbronorite at the hanging wall contact in face 141/011 (N3). The pen on the right is 12-cm long
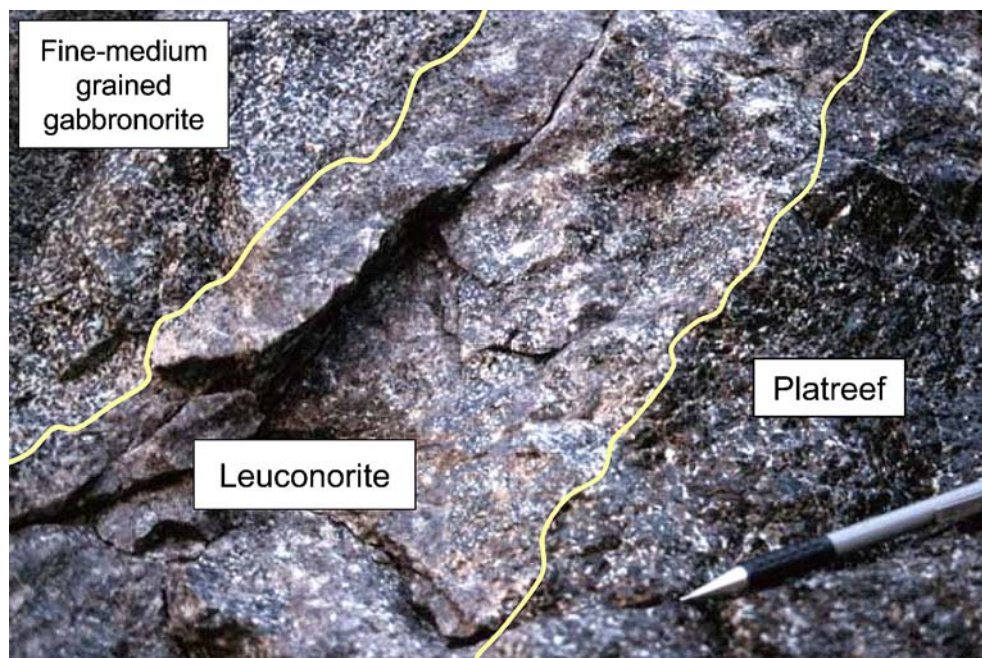
Rouse 1984), but have not been described elsewhere. The Fe enrichment and reaction textures observed here are similar to those found in Fe-rich pipes and pegmatoids elsewhere in the complex (Schiffries 1982; Viljoen and Scoon 1985) and may result from reaction between Platreef pyroxenites and gabbros and a late-stage Fe-rich melt or fluid. For the ease of discussion, this type of Fe-rich (ultramafic) Platreef is hereafter referred to as "replaced reef".

Face 135/014 (SW1) shows Platreef cutting the foot-wall lithologies at a high angle. A serpentinised mixed rock comprising relict metamorphic clinopyroxenite (with or without olivine) and pyroxenites and websterites with igneous textures, (termed as "footwall-reef hybrid") forms the base of the Platreef. The primary Platreef is heavily replaced and mixtures of orthopyroxenites, websterites, gabbronorites and wehrlites are common. The rocks become more pematoidal and olivine-rich upwards, grading into Fe-rich olivine lherzolite close to the hanging wall contact (Fig. 7). The hanging wall for a few metres above the contact is fine-grained gabbronorite with cumulus plagioclase (sample SW1-47).

Face 138/014 (SW2) also shows Platreef cutting the footwall calc-silicates at a high angle to the remnant layering and is similar in some respects to Face 135/014. Olivine in the footwall is heavily serpentinised and these rocks contain an extensive fracture network filled with magnetite and ilmenite. A thick zone of serpentinised hybrid rocks is present at the base of the reef and wehrlite occurs close to the hybrid rocks. This merges upwards into gabbronorite and pyroxenite that become very Fe-rich, but without much development of olivine, close to the hanging wall. A 15-cm wide dark xenolith of websterite (sample SW2-83) that carries high levels of Cr

and some PGE grade is present a few metres above the contact in the hanging wall gabbronorite (Fig. 8; Table 3).

Geochemical trends associated with the Platreef at Sandsloot

Harris and Chaumba (2001) noted that the igneous Platreef was richer in Cr, Co and Fe than the footwall or the hanging wall lithologies, which is replicated here (Tables 1, 2, 3). The footwall clinopyroxenites and serpentinites contain less Si and Fe than the reef but more Ca and Mn. Similarly, the hanging wall norites and gabbronorites typically contain more Si, Al, Na, K, Rb, Sr and Ba than the reef or the footwall. Harris and Chaumba (2001) noted an upward trend of Fe enrichment in their reef samples and in the N1 face, where there is the least evidence of replacement; we find a similar gradual increase in Fe towards the top of the reef. In replaced reef (e.g. face SW1), the Fe enrichment is dramatic and these areas are also enriched in Ti, Mn, Hf and Nb (and sometimes U and Th) relative to primary reef. The plagioclase-rich hanging wall rocks and the cross-cutting pegmatoidal gabbronorite dyke in the N1 face are also characterised by a consistently positive Eu anomaly (Eu/Eu* >1.0), while the opposite is generally true of the reef and the footwall. As might be expected, footwall-reef hybrid rocks show concentrations of Si, Mg, Ca, Fe, Co and Cr that are intermediate between reef and footwall (Tables 2 and 3) but nevertheless the Cr concentration is a useful indicator for primary reef, hybrid zones and footwall where the lithological relations are ambiguous.

Table 1 Geochemical data for faces N1 and N3

	E195	E205	E227	N1-02	N1-2	N1-4	N1-6a	N1-6b	N1-14	N1-X6	N1-22	N1-24	N1-26	N1-30	N1-31	DH-G	N3X4A	N3X4B
Unit	FW	FW	DYKE	DYKE	DYKE	FW	FW	FW	PR	XN	PR	PR	PR	PR	HW	PR	HW	HW
Rock Type	SPT	PPX	GBNRT	GBNRT	GBNRT	CS-PPX	PPX	SPT vein	Fel PX	SPT	Fel PX	GBNRT	GBNRT	GBNRT	NRT	WBST	GBNRT	LCNRT
SiO_2 (wt%)	39.55	46.26	49.40	50.44	48.77	39.61	43.22	37.08	52.55	33.92	49.18	51.86	50.59	51.25	51.87	50.39	51.81	50.85
TiO_2	0.09	0.26	0.33	0.17	0.18	0.12	0.26	0.07	0.19	0.20	0.20	0.16	0.17	0.14	0.16	0.19	0.20	0.09
Al_2O_3	2.77	3.22	16.52	14.81	16.85	12.87	11.31	8.46	6.42	10.88	4.28	5.19	5.70	4.17	22.63	5.79	17.48	26.64
Fe_2O_3	6.34	9.12	8.00	7.17	8.43	10.52	7.21	14.44	11.52	8.36	15.07	13.96	13.26	13.93	5.56	12.82	9.75	1.95
MnO	0.22	0.57	0.15	0.13	0.14	0.35	0.52	0.42	0.21	0.73	0.26	0.23	0.26	0.23	0.10	0.22	0.14	0.04
MgO	34.39	21.25	8.05	10.58	9.61	17.59	14.09	28.04	22.14	34.18	22.88	23.23	21.19	22.53	5.38	19.74	6.48	1.61
CaO	2.36	15.51	10.73	9.60	10.00	11.76	18.95	1.78	5.20	0.32	4.57	4.18	5.41	4.03	11.52	8.83	11.17	13.08
Na_2O	0.01	0.21	2.79	3.76	1.91	0.22	0.05	0.02	0.50	0.02	0.58	0.46	0.91	0.66	2.77	0.26	1.79	3.35
K_2O	0.01	0.15	1.99	0.72	1.20	0.50	0.05	0.09	0.24	0.03	0.20	0.14	0.07	0.05	0.52	0.01	1.30	0.79
P_2O_5	0.01	0.03	0.04	0.05	0.02	0.03	0.02	0.02	0.03	0.01	0.03	0.03	0.04	0.03	0.02	0.03	0.00	0.00
LOI	12.98	3.38	2.98	2.84	1.17	5.58	5.64	11.14	0.41	11.90	1.20	0.76	0.56	1.75	1.33	0.87	1.14	0.90
Total	98.73	99.95	100.99	100.26	98.27	99.14	101.30	101.55	99.42	100.55	98.46	100.21	98.16	98.76	101.85	99.13	101.25	99.30
Sc (ppm)	8.12	33.8	18.6	18.4	15.8	15.34	26.8	8.2	28.2	24.7	30.8	13.3	29.7	28.3	30.9	27.8	30.8	5.7
V	44.5	153.2	126.9	128.0	93.4	81.5	133.2	51.0	171.1	51.6	168.5	120.3	130.4	125.1	123.1	135.5	190.9	60.9
Cr	14.4	37.3	485.0	279.9	610.9	198.5	331.9	111.5	1817.4	144.1	1734	1916	1688	3021	462.9	1741	424.0	285.8
Co	42.0	20.4	68.3	44.8	43.9	41.1	55.9	83.1	88.0	35.8	158.1	112.8	110.0	121.4	53.3	98.1	40.9	14.7
Ni	389.8	62.6	289.5	165.1	716.0	253.6	408.1	152.1	1292	93.6	2818	4020	2597	3206	160.4	1736	346.2	56.9
Cu	115.2	69.3	148.7	11.6	310.6	139.3	133.1	227.3	210.1	93.6	1549	1577	885	834.7	74.5	610.1	120.6	79.0
Ga	5.2	5.8	13.5	12.26	14.4	10.7	10.99	15.14	6.71	18.62	5.9	6.3	6.76	4.86	22.9	6.72	18.2	24.64
Rb	0.0	16.2	107.2	36.32	59.7	34.0	1.79	6.24	3.50	1.02	7.2	8.2	1.08	2.74	28.9	2.10	49.9	20.70
Sr	7.7	14.1	280.3	236.0	238.6	164.7	66.3	16.3	101.9	9.5	37.8	54.4	55.4	35.0	332.6	16.9	332.8	385.5
Y	3.2	10.1	7.1	7.1	4.3	3.8	10.2	1.6	5.5	4.4	6.0	5.1	6.5	3.2	5.7	5.7	7.4	2.21
Zr	3.6	24.3	26.0	38.2	32.3	14.0	40.3	16.6	25.7	35.4	11.5	10.0	49.8	10.5	8.8	17.6	11.5	4.31
Nb	0.21	0.73	2.40	0.82	0.83	0.80	3.08	2.66	2.94	2.78	0.48	0.44	0.30	0.26	0.65	0.47	0.4	0.15
Ba	n.d.	8.4	186.3	211.7	217.7	108.9	26.1	16.1	80.0	8.5	23.1	28.3	40.6	35.2	111.2	19.1	149.6	151.1
La	1.50	4.02	6.51	4.16	2.47	3.59	4.21	1.33	2.89	1.28	2.51	1.84	2.17	1.74	4.96	2.97	2.59	4.75
Ce	1.89	9.06	9.45	7.21	5.58	5.86	9.67	2.29	5.73	2.89	5.63	4.88	4.76	2.57	8.33	5.15	5.14	8.33
Pr	0.24	1.32	1.22	0.83	0.68	0.73	1.31	0.26	0.72	0.41	0.73	0.63	0.53	0.27	0.99	0.62	0.66	0.90
Nd	0.92	5.39	4.67	3.74	2.43	2.70	5.56	0.95	2.90	1.84	2.81	2.40	2.41	1.31	3.47	2.96	2.54	3.06
Sm	0.17	1.26	1.06	0.92	0.49	0.55	1.34	0.19	0.61	0.47	0.59	0.51	0.54	0.28	0.62	0.70	0.60	0.46
Eu	0.06	0.27	0.51	0.40	0.49	0.33	0.54	0.11	0.21	0.10	0.16	0.19	0.15	0.09	0.62	0.20	0.34	0.71
Gd	0.24	1.35	1.07	0.94	0.54	0.56	1.50	0.18	0.67	0.51	0.66	0.59	0.59	0.34	0.64	0.86	0.68	0.43
Tb	0.04	0.23	0.18	0.16	0.09	0.09	0.26	0.04	0.13	0.10	0.12	0.10	0.10	0.06	0.11	0.14	0.12	0.06
Dy	0.37	1.51	1.15	1.05	0.61	0.58	1.61	0.23	0.83	0.65	0.81	0.71	0.71	0.47	0.71	1.09	0.87	0.39
Ho	0.09	0.28	0.22	0.21	0.13	0.11	0.33	0.05	0.18	0.14	0.17	0.15	0.14	0.09	0.14	0.24	0.18	0.07
Er	0.35	0.90	0.73	0.65	0.44	0.38	0.86	0.14	0.50	0.39	0.61	0.57	0.48	0.33	0.47	0.76	0.64	0.21
Tm	0.06	0.13	0.11	0.09	0.07	0.06	0.13	0.02	0.08	0.07	0.10	0.09	0.08	0.06	0.07	0.12	0.10	0.03
Yb	0.48	0.81	0.70	0.68	0.46	0.36	0.94	0.20	0.65	0.86	0.68	0.58	0.56	0.43	0.48	0.92	0.69	0.17
Lu	0.09	0.14	0.12	0.10	0.08	0.06	0.19	0.08	0.15	0.21	0.11	0.10	0.07	0.05	0.08	0.14	0.11	0.03
Hf	0.09	0.67	0.67	0.73	0.64	0.36	1.20	0.42	0.60	1.08	0.29	0.22	0.14	0.17	0.20	0.43	0.25	0.09
Ta	0.02	0.07	0.18	0.08	0.07	0.05	0.23	0.18	0.21	0.21	0.06	0.05	0.05	0.03	0.04	0.05	0.01	0.01
Th	0.45	1.08	1.52	0.64	0.57	0.67	1.19	0.37	1.11	0.86	0.95	0.54	0.49	0.34	0.51	0.62	0.39	0.26
U	0.85	0.20	0.37	0.18	0.09	0.11	0.30	0.12	0.29	0.26	0.11	0.13	0.11	0.06	0.06	0.12	0.01	0.02
Eu/Eu*	0.90	0.64	1.45	1.29	2.86	1.81	1.16	1.79	1.02	0.62	0.78	1.05	0.78	0.93	2.97	0.79	1.63	4.78
La/LuN	1.77	3.03	5.85	4.12	3.39	6.66	2.34	1.82	2.01	1.03	2.42	1.98	3.16	3.35	6.48	2.16	2.42	19.42
PGE grade	n/a	n/a	n/a	v. low	n/a	low	n/a	n/a	n/a	n/a	inter	inter	high	high	v. low	inter	inter	v. low
Pt/Pd	n/a	n/a	n/a	0.75	n/a	0.90	n/a	n/a	n/a	n/a	1.04	0.98	1.94	0.93	1.36	1.03	0.91	0.87

Rare earth element values in chondrite used for normalisation come from Taylor and McLennan (1985)

PGE grade bands based on total Rh + Pt + Pd + Au: < 0.1 ppm = very low; 0.1–2.0 ppm = low; 2.0–6.0 = intermediate; 6.0–10.0 = high; > 10.0 = very high

Major units: *FW* footwall; *DYKE* cross-cutting pegmatoidal dykes; *XN* xenoliths; *HW* hanging wall

Rock types: *SPN* serpentinite; *PPX* para(clino)pyroxenite; *CS* calc-silicate; *GBNRT* gabbornorite; *PX* pyroxenite; *NRT* norite; *WBST* websterite; *LCNRT* leuconorite
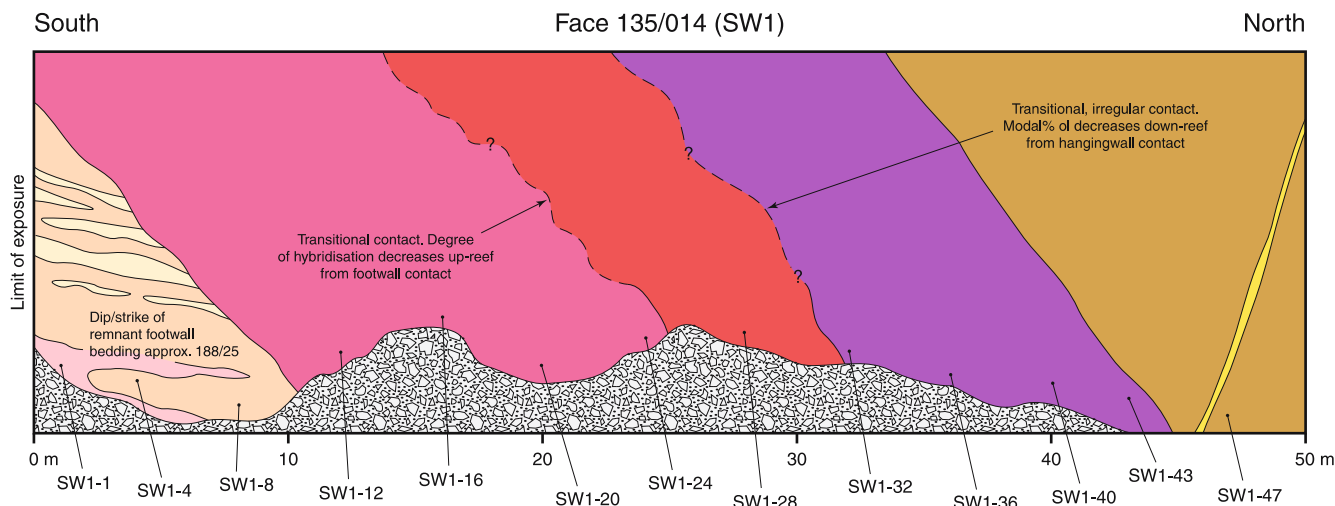
Fig. 7 Slightly oblique section through the Platreef on face 135/014 (SW1). This shows the major lithologies with contacts extrapolated/inferred at height and the positions of samples taken for petrographic/geochemical analysis. The key is as in Fig. 5

Links between the Platreef and the Merensky Reef

Stratigraphic context

The modern consensus stems from Willemse (1969) and van der Merwe (1976) who followed Wagner (1929) and correlated the Platreef with the Merensky Reef. This interpretation is primarily based on the nature of the rocks immediately above the Platreef. The hanging wall norites and gabbros are visually similar and have similar orthopyroxene compositions to MZ rocks elsewhere in the Bushveld Complex. Von Gruenewaldt et al. (1989) suggested that the Platreef might be correlated with the upper part of the GNPA member (shown in detail in Fig. 9). Evidence cited in support of this includes: the layering of some units and the presence of cumulus chromite and development of a chromitite layer. These are the characteristic features of the UCZ in the eastern and western Bushveld and the MZ is notable for the absence of both. The terms "Critical Zone" and "Main Zone" when applied to the northern lobe effectively refer

to whether the rocks are located above or below the Platreef. The veracity of this assumption will be tested below.

Petrographic similarities between the Platreef and the Merensky Reef

Both units are dominated by cumulus orthopyroxene, with subordinate amounts of plagioclase and clinopyroxene, and carry an assemblage of interstitial sulphides and elevated concentrations of PGE. Buchanan et al. (1981) suggested that pyroxene compositions in the Platreef were the same as in the Merensky Reef (see below for discussion). In places, both units develop pegmatoidal facies. Chromite in the form of one or two chromitite layers is a ubiquitous feature of the Merensky Reef and the highest PGE grades are generally associated with one or both chromitites (Lee 1996; Kinnaird et al. 2002). Chromite occurs as isolated crystals, or as rare pods/schlieren, in the Platreef (Viljoen and
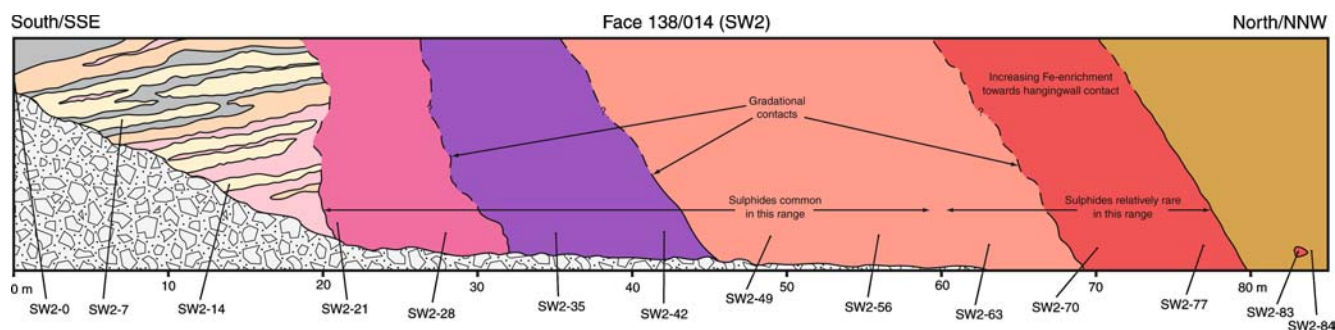

Fig. 8 Oblique section through the Platreef on face 138/014 (SW2). This shows the major lithologies with contacts extrapolated/inferred at height and the positions of samples taken for petrographic/geochemical analysis. The key is as in Fig. 5

Table 2 Geochemical data for face SW1

	SW1-1	SW1-4	SW1-8	SW1-20	SW1-24	SW1-28	SW1-32	SW1-36	SW1-40	SW1-43	SW1-47B	SW1-47A
Unit	FW	FW	FW	HYB	HYB	PR	RR	PR	RR	RR	HW	HW
Rock Type	PPX	CS	CS	n/a	n/a	WBST	LHRZ	PX	HZBG	LHRZ	GBNRT	GBNRT
SiO2 (wt%)	43.51	40.24	40.94	44.38	42.66	45.16	44.84	46.55	48.11	44.21	51.44	49.44
TiO2	0.42	0.29	0.09	0.62	0.15	0.14	0.18	0.14	0.21	0.23	0.19	0.16
Al2O3	6.08	3.32	2.48	5.47	6.27	3.61	3.44	3.70	2.56	3.29	16.48	16.30
Fe2O3	8.03	3.89	7.38	13.49	12.86	13.28	19.36	13.43	17.85	22.08	8.83	9.04
MnO	0.35	0.68	0.73	0.31	0.29	0.24	0.33	0.22	0.32	0.38	0.19	0.15
MgO	14.79	29.81	27.00	10.62	18.43	20.63	22.58	23.27	23.46	21.76	6.93	8.55
CaO	23.83	9.61	11.52	24.30	16.05	12.36	6.31	8.99	4.75	6.48	12.06	11.75
Na2O	0.19	0.03	0.01	0.19	0.29	0.67	0.37	0.33	0.10	0.33	2.43	2.52
K2O	0.02	0.00	0.01	0.02	0.46	0.13	0.15	0.13	0.19	0.23	0.41	0.43
P2O5	0.03	0.00	0.01	0.03	0.02	0.03	0.05	0.02	0.03	0.04	0.01	0.02
LOI	0.83	10.85	8.28	0.27	4.00	3.09	1.06	1.57	0.52	0.57	1.34	2.27
Total	98.09	98.73	98.45	99.69	101.48	99.33	98.66	98.35	98.12	99.59	100.32	100.65
Sc (ppm)	28.0	5.57	4.90	46.12	26.9	34.8	24.3	30.0	25.8	31.0	37.8	28.1
V	159.2	46.1	47.4	333.4	117.7	129.2	126.5	126.3	145.4	187.9	200.0	152.2
Cr	41.5	27.7	48.3	835.0	601.8	3065	3042	3061	3104	2304	292.0	551.5
Co	37.8	11.3	56.4	71.0	92.9	123.3	116.4	134.9	131.3	136.9	48.3	59.1
Ni	1683	189.7	3732	928.3	2286	2156	2769	3921	2804	3390	406.9	376.1
Cu	1448	87.1	2097	675.5	839.0	828.7	764.5	1477	1156	1329	170.5	186.6
Ga	7.6	6.3	4.3	10.2	6.5	4.88	5.50	4.5	5.2	5.6	18.1	15.7
Rb	1.9	−0.1	0.1	3.7	26.3	6.32	5.72	7.3	15.4	11.9	7.3	11.9
Sr	25.5	7.6	7.2	25.6	31.3	47.1	85.5	60.9	34.4	66.1	282.2	233.9
Y	18.2	29.6	14.9	12.3	6.6	6.7	7.9	5.3	6.5	10.3	11.7	8.2
Zr	67.5	7.8	3.0	58.2	12.6	15.7	19.5	10.3	14.0	15.5	5.1	7.0
Nb	1.36	2.08	0.52	1.51	0.61	0.54	0.98	0.49	0.78	0.62	0.03	0.15
Ba	2.1	n.d.	n.d.	1.8	37.7	54.0	85.6	44.2	37.3	52.1	76.6	71.6
La	5.53	6.27	1.93	3.91	1.82	1.90	3.24	1.69	1.82	2.52	1.80	2.04
Ce	15.56	17.57	5.40	9.40	4.61	4.47	6.94	3.46	4.54	6.35	4.03	4.53
Pr	2.26	2.26	0.75	1.43	0.67	0.59	0.87	0.50	0.64	0.97	0.60	0.64
Nd	9.29	8.51	3.10	6.16	2.91	3.06	4.07	2.22	2.67	4.23	2.68	2.75
Sm	2.27	2.11	0.81	1.69	0.74	0.81	0.98	0.56	0.62	1.11	0.75	0.73
Eu	0.61	0.46	0.21	0.42	0.23	0.21	0.28	0.18	0.17	0.29	0.39	0.45
Gd	2.49	2.64	1.19	1.80	0.88	0.96	1.04	0.70	0.72	1.27	0.95	0.86
Tb	0.42	0.54	0.24	0.30	0.16	0.16	0.19	0.11	0.13	0.21	0.18	0.16
Dy	2.64	3.68	1.74	1.86	1.02	1.09	1.23	0.81	0.94	1.48	1.23	1.07
Ho	0.48	0.73	0.37	0.34	0.19	0.22	0.25	0.15	0.19	0.28	0.24	0.21
Er	1.60	2.68	1.44	1.11	0.65	0.64	0.73	0.54	0.68	0.99	0.86	0.72
Tm	0.24	0.43	0.25	0.17	0.09	0.09	0.13	0.08	0.11	0.15	0.14	0.11
Yb	1.45	2.80	1.70	1.11	0.59	0.65	0.80	0.51	0.74	0.99	0.91	0.73
Lu	0.22	0.44	0.27	0.19	0.09	0.08	0.13	0.08	0.13	0.16	0.15	0.11
Hf	1.93	0.27	0.09	1.70	0.32	0.35	0.38	0.26	0.35	0.37	0.21	0.20
Ta	0.12	0.64	0.06	0.09	0.04	0.04	0.09	0.04	0.07	0.05	0.01	0.01
Th	1.63	11.93	1.32	1.45	0.52	0.58	0.86	0.51	0.76	0.71	0.29	0.29
U	0.86	0.95	0.11	0.41	0.10	0.11	0.26	0.04	0.15	0.12	0.00	0.01
Eu/Eu*	0.78	0.60	0.65	0.73	0.85	0.72	0.84	0.86	0.76	0.75	1.40	1.74
La/LuN	2.57	1.48	0.74	2.11	2.08	2.40	2.57	2.13	1.44	1.66	1.28	1.87
PGE grade	v. high	low	v. high	inter	inter	high	inter	high	inter	v. high	low	low
Pt/Pd	0.86	0.65	0.99	0.88	0.67	1.28	0.81	0.74	0.55	0.70	0.95	0.97

Rare earth element values in chondrite used for normalisation come from Taylor and McLennan (1985)

PGE grade bands based on total Rh + Pt + Pd + Au: < 0.1 ppm = very low; 0.1–2.0 ppm = low; 2.0–6.0 = intermediate; 6.0–10.0 = high; > 10.0 = very high

Major units: *FW* footwall; *DYKE* cross-cutting pegmatoidal dykes; *HYB* footwall hybrid; *PR* primary reef; *RR* replaced reef; *HW* hanging wall

Rock types: *PPX* para(clino)pyroxenite; *CS* calc-silicate; *GBNRT* gabbornorite; *PX* orthopyroxenite; *LHRZ* lherzolite; *HZBG* harzburgite

Schürmann 1998; Armitage et al. 2002), but is most commonly an accessory component. A more widespread chromitite (inferred from the presence of chromite at the same level in many drillcores) is apparently developed in the Platreef to the south of Sandsloot on the farm Tweefontein 238KR. PGE grades are highest in the pyroxenite immediately beneath the chromitite and Viljoen and Schürmann (1998) suggest that at this locality the Platreef bears the greatest similarity to normal Merensky Reef.

Strontium and osmium isotopes

Cawthorn et al. (1985) found a wide range of $^{87}Sr/^{86}Sr$ initial ratios in Platreef whole rock samples that they

Table 3 Geochemical data for face SW2

	S2-6	S2-12	S2-18	SW2-14	SW2-28	SW2-35	SW2-49	SW2-77	SW2-83
Unit	FW	FW	FW	FW	HYB	RR	PR	RR	XN
Rock Type	SPPX	SPPX	CS	SPPX	n/a	WHRL	GBNRT	PX	WBST
SiO2 (wt%)	40.71	31.57	26.73	34.12	46.60	46.40	48.49	50.03	52.78
TiO2	0.12	0.11	0.34	0.29	0.19	0.21	0.21	0.37	0.17
Al2O3	3.69	11.32	8.27	17.65	5.37	5.26	5.44	4.35	3.42
Fe2O3	11.02	8.79	11.85	7.66	8.83	15.53	16.48	16.95	10.23
MnO	0.54	0.26	0.31	0.26	0.40	0.33	0.29	0.34	0.23
MgO	27.08	20.30	21.95	13.22	23.53	20.27	18.63	16.33	22.59
CaO	7.50	15.98	18.17	20.09	13.09	11.07	8.73	9.65	8.64
Na2O	0.06	0.02	0.10	0.14	0.13	0.44	0.84	0.69	0.37
K2O	0.06	0.00	0.02	0.08	0.03	0.17	0.25	0.05	0.23
P2O5	0.03	0.04	0.03	0.02	0.02	0.03	0.06	0.02	0.02
LOI	8.05	10.12	11.68	5.41	2.98	1.02	0.86	0.57	0.93
Total	98.85	98.52	99.45	98.93	101.17	100.73	100.28	99.34	99.61
Sc (ppm)	11.5	3.1	4.8	16.0	20.6	32.3	28.8	48.3	37.4
V	55.7	8.1	28.8	76.6	76.0	137.1	132.9	261.0	157.2
Cr	64.5	20.5	35.9	215.3	777.1	2467	2406	1568	3435
Co	47.2	34.9	8.4	35.0	52.8	122.3	112.9	84.6	80.6
Ni	860.0	764.5	113.2	408.4	1451	3231	2779	559.1	1034
Cu	130.4	201.4	330.3	18.8	372.5	867.8	1395	139.1	198.2
Ga	4.46	21.09	8.77	20.67	6.36	6.75	7.16	7.16	5.2
Rb	2.24	0.06	2.21	1.86	2.01	3.08	13.74	1.34	9.7
Sr	10.8	5.0	3.3	28.7	74.4	101.4	106.9	44.9	38.1
Y	4.8	12.8	10.4	8.0	7.6	9.3	7.7	18.2	6.6
Zr	18.3	15.3	13.2	49.0	31.7	28.0	23.1	46.2	9.9
Nb	0.31	0.23	0.00	3.18	2.75	2.87	1.01	3.61	0.39
Ba	33.3	15.1	15.1	39.7	75.4	84.1	105.2	23.4	33.7
La	2.71	3.64	0.18	3.29	2.17	2.69	3.84	4.27	1.43
Ce	5.76	9.00	0.29	8.17	5.12	6.33	7.82	10.92	3.71
Pr	0.76	1.32	0.04	1.18	0.76	0.94	0.87	1.67	0.55
Nd	3.82	6.80	0.52	4.98	3.41	4.15	4.03	7.66	2.33
Sm	1.00	1.63	0.30	1.15	0.90	1.10	0.93	2.06	0.55
Eu	0.23	0.37	0.08	0.31	0.29	0.35	0.26	0.60	0.18
Gd	1.07	1.69	0.71	1.21	1.02	1.29	1.05	2.36	0.68
Tb	0.17	0.29	0.16	0.21	0.19	0.24	0.18	0.44	0.12
Dy	1.17	1.78	1.24	1.30	1.18	1.47	1.25	2.79	0.86
Ho	0.23	0.36	0.28	0.27	0.26	0.31	0.25	0.60	0.17
Er	0.68	1.02	0.92	0.68	0.65	0.82	0.78	1.62	0.62
Tm	0.10	0.16	0.17	0.10	0.09	0.12	0.12	0.24	0.09
Yb	0.68	1.03	1.13	0.72	0.71	0.91	0.87	1.83	0.61
Lu	0.09	0.16	0.19	0.15	0.14	0.17	0.13	0.33	0.10
Hf	0.36	0.23	0.31	1.60	0.95	0.75	0.55	1.22	0.27
Ta	0.05	0.02	0.01	0.22	0.19	0.20	0.08	0.26	0.03
Th	0.53	0.37	0.19	0.83	0.58	0.75	1.27	1.39	0.49
U	0.19	0.04	0.02	0.22	0.17	0.21	0.39	0.50	0.05
Eu/Eu*	0.66	0.67	0.51	0.79	0.91	0.89	0.80	0.83	0.91
La/LuN	3.00	2.43	0.10	2.32	1.58	1.63	3.10	1.33	1.52
PGE grade	v. low	low	v. low	n/a	n/a	n/a	high	n/a	low
Pt/Pd	2.76	0.55	2.81	n/a	n/a	n/a	1.48	n/a	1.65

Rare earth element values in chondrite used for normalisation come from Taylor and McLennan (1985)

PGE grade bands based on total Rh + Pt + Pd + Au: < 0.1 ppm = very low; 0.1–2.0 ppm = low; 2.0–6.0 = intermediate; 6.0–10.0 = high; > 10.0 = very high.

Major units: *FW* footwall; *DYKE* cross-cutting pegmatoidal dykes; *HYB* footwall hybrid; *PR* primary reef; *RR* replaced reef; *HW* hanging wall

Rock types: *SPPX* serpentinised para(clino)pyroxenite; *CS* calc-silicate; *GBNRT* gabbornorite; *PX* pyroxenite; *WBST* websterite; *WHRL* wehrlite

ascribed to the effects of contamination by local granite footwall. In a follow-up study, Barton et al. (1986) determined [87]Sr/[86]Sr initial ratios in orthopyroxene and plagioclase mineral separates and found that most of the radiogenic Sr was hosted by plagioclase and other intercumulus minerals. The lowest [87]Sr/[86]Sr initial ratio found in orthopyroxene separated from the Platreef was 0.7079, outside the normal UCZ range of 0.7055–0.7065, but within the range of initial ratios determined for the Merensky Reef (e.g. Kruger 1994).

Chaumba et al. (1998) reported initial [187]Os/[188]Os ratios for the Platreef that ranged from 0.10974 to 0.20292. The Platreef range encompasses the range of initial ratios found in the Merensky Reef (Os minerals

with $^{187}Os/^{188}Os_i$ ~0.94, and laurite with $^{187}Os/^{188}Os_i$ 0.142–0.151; Hart and Kinloch 1989; McCandless and Ruiz 1991). Chaumba et al. (1998) interpret this as indicating that Os in the Merensky Reef and the Platreef came form the same source. On close inspection though, the comparison is less robust than it first appears. Chaumba et al. (1998) only presented the range of initial ratios they found. No information was given on what samples were analysed, their positions within or outside the igneous reef, or which initial ratios came from samples with the most Os. Until more information is available, these Os data are open to multiple interpretations and cannot be used to argue strongly for a link between the Merensky Reef and Platreef.

Differences between the Platreef and the Merensky Reef

There are other lines of evidence that would seem to contradict the stratigraphic link implied in Fig. 3. These are outlined below:

Mineralogy of the "Critical Zone" of the northern lobe

Hulbert (1983) divided the GNPA member into two sub-zones (Fig. 9). The lower sub-zone contains orthopyroxene-clinopyroxene, orthopyroxene-clinopyroxene-chromite and orthopyroxene cumulates with subordinate plagioclase-rich units. The upper sub-zone is dominated by plagioclase cumulates with minor norites. Clinopyroxene is ubiquitous at between 5 and 25 modal%, even where chromite is present, and clinopyroxene is sometimes a cumulus mineral with chromite (Hulbert and Von Gruenewaldt 1985). Clinopyroxene is less abundant in the UCZ elsewhere in the complex (typically < 10 modal%; Cameron 1982; Maier and Barnes 1998) and is never present in a cumulus association with chromite. Unusual orthopyroxene-clinopyroxene-chromite cumulates (at −85 and + 10 m; Fig. 9) are only developed where the GNPA member rests on LZ cumulates and are unknown from elsewhere in the complex (Hulbert and Von Gruenewaldt 1985). Chromite in the GNPA member has TiO_2 contents (1.77–3.08 wt%; Hulbert 1983) that are generally higher than UCZ stratiform chromites outside of Fe-rich replacement pegmatoids (e.g. Stumpfl and Rucklidge 1982) and the Ti enrichment increases with stratigraphic height in the GNPA sequence.

Rocks of the upper sub-zone of the GNPA member are also unusual because the basal layers of all of the cyclic units recognised by Hulbert (1983) are plagioclase-only cumulates. The crystallisation order for this part of the sequence appears to be governed by the liquidus order plagioclase-orthopyroxene-clinopyroxene (Hulbert 1983). A few cyclic units with basal plagioclase-rich units are known from the UCZ in the eastern and western Bushveld but even in these, plagioclase is invariably joined by orthopyroxene or chromite as the cumulus phase (Cameron 1982).

Considering only those cumulates containing > 50% orthopyroxene (in order to minimise the effects of reaction with trapped liquid; cf Cawthorn 1996, 2002), the compositions of cumulus orthopyroxene in the GNPA member range between $Mg\#_{75-78}$(Hulbert 1983; Fig. 9). These pyroxenes are systematically more Fe-rich than those in similar UCZ cumulates elsewhere in the Bushveld Complex ($Mg\#_{78-84}$; Cameron 1982; Naldrett et al. 1986; Eales et al. 1993; Maier and Eales 1994; Cawthorn 2002). The available data show that the cumulus plagioclase compositions in the GNPA member are An_{68-78}(Hulbert 1983). This range overlaps with the lower part of the range of UCZ plagioclase compositions observed in the rest of the complex (An_{68-85}; Cameron 1982; Naldrett et al. 1986; Kruger and Marsh 1985; Maier and Eales 1994), but not with the upper part of the range.

Mineralogy of the Platreef and the Merensky Reef

The primary Platreef records differences in mineral textures from those commonly found in the Merensky Reef. In the Mernesky Reef, the liquidus order is orthopyroxene-plagioclase-clinopyroxene (e.g. Cawthorn 2002). In the mafic units of the Platreef, clinopyroxene either follows orthopyroxene or crystallises concurrently with it, and generally precedes plagioclase, which is usually intercumulus. Contamination of the Platreef with dolomite at Sandsloot may promote clinopyroxene crystallisation (e.g. Harris and Chaumba 2001) but it is important to note that the same crystallisation order also occurs where the footwall comprises rocks other than dolomite. For example, orthopyroxene-clinopyroxene-chromite cumulates occur in the Platreef on Overysel 815LR, where the footwall is granite (Hulbert 1983; D Holwell unpublished data). In this sense, the Platreef shows greater similarity with the orthopyroxene-clinopyroxene cumulates of the GNPA member (which are floored by harzburgites or quartzites) than the Merensky Reef. Chromite also shows important petrographic differences. Chromite is consistently the earliest phase in the Merensky Reef, forming layers and inclusions in pyroxenes, but it is most commonly post-cumulus in the Platreef.

Olivine is an important component of the Merensky Reef in some sectors of the Bushveld Complex. In the western lobe around the Union and Rustenburg sections, olivine (Fo_{79-80}) is common and the reef may be developed as a pegmatoidal harzburgite (Vermaak and Hendriks 1976; Kruger and Marsh 1985; Maier and Eales 1994) but in other areas of the complex, olivine is absent from the Merensky Reef. Primary olivine in the Platreef is more problematic. Van der Merwe (1976; Fig. 3 and p.1341) alludes to olivine (Fo_{84}) in a harzburgite or lherzolite at the base of the Platreef but the locality is not described. High-Mg metamorphic olivine
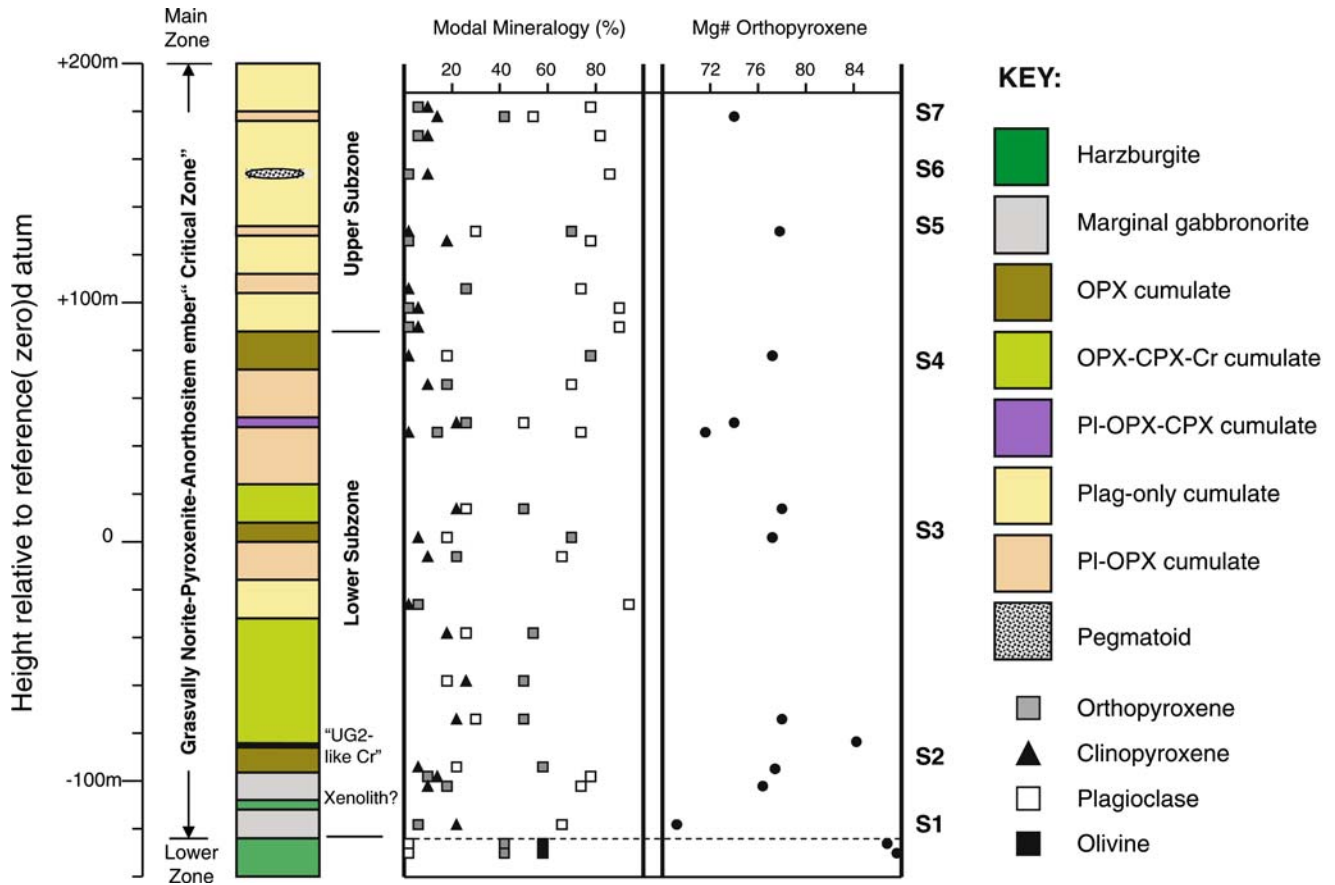
Fig. 9 Summary of the cumulate sequence in the Grasvally Norite-Pyroxenite-Anorthosite member (adapted from Hulbert 1983). Modal mineralogy comprises percentages of olivine (*black square*); orthopyroxene (*grey square*); clinopyroxene (*black triangle*); and plagioclase (*white square*). Layers indicated with S1–S7 contain sulphide mineralisation with PGE. The high Mg# of orthopyroxene in association with chromite in the "UG2-like chromitite" is not primary, but the result of reaction (Fe loss) between the pyroxene and spinel (Hulbert 1983)

(Fo$_{82–85}$) occurs in the footwall at Sandsloot (Harris and Chaumba 2001; this work) but Kinnaird et al. (2005) also report the presence of igneous harzburgites with magnesian olivine at the base of the Platreef on the farm Macalacaskop 243KR. These rocks may belong to satellite intrusions of the LZ (see Discussion below). Buchanan and Rouse (1984) found Fe-rich olivine (Fo$_{71}$) in a basal "peridotitic" Platreef facies on the farm Turfspruit 241KR which they ascribed to the assimilation of banded ironstones into the reef. Similarly Fe-rich olivine (Fo$_{64–72}$) occurs in replaced reef at Sandsloot. Buchanan et al. (1981) analysed apparently igneous olivine (Fo$_{75–76}$) and this is currently the best (and only) estimate of the composition of primary Platreef olivine.

The most common mineral in the Platreef is orthopyroxene and this allows the most systematic comparison between different localities. Buchanan et al. (1981) studied orthopyroxenes on the farm Tweefontein 238KR where the reef is contaminated by banded ironstone and dolomite. They found pyroxenes with Mg#$_{74–78}$ in primary reef but more Fe-rich pyroxenes (Mg#$_{36–42}$) in contaminated units. Orthopyroxenes in the Platreef on Drenthe 788LR and Overysel 815LR, where the reef is contaminated by granite, gneiss and dolomite (Fig. 1), show a range of compositions with a similar upper limit (Mg#$_{65–77}$; Gain and Mostert 1982; Cawthorn et al. 1985).

Pyroxene compositions in the Platreef at Sandsloot are complicated by the presence of a reactive footwall that is rich in both Ca and Mg. Our data show a range of orthopyroxene compositions with a main population between Mg#$_{76–80}$ (Fig. 10) in samples of primary reef. The main population is similar to results obtained by Harris and Chaumba (2001), but smaller sub-populations with Mg#$_{81–83}$ and Mg#$_{64–74}$ exist. The high Mg# population come from a gabbro (N1-26) associated with ragged serpentinite xenoliths (Fig. 4) and from a gabbro (SW2-49) in the southwest corner that has been partially altered to a mixture of tremolite, actinolite, chlorite and sericite. Analyses from N1-26 and SW2-49 are shown as "contaminated reef" and "altered reef", respectively in Fig. 10. In both cases, the Ca contents of clinopyroxenes are higher than expected for igneous pyroxenes (Wo$_{45–48}$; Fig. 10) and the pyroxene compositions in these samples appear to be affected by local enrichment in Ca and Mg.

Fig. 10 a Compositions of pyroxenes from different types of Platreef at Sandsloot Mine. *Shaded area* shows the range of typical Merensky Reef pyroxenes (Buchanan et al. 1981; Cawthorn et al. 1985). Note the high En and Wo contents of pyroxenes from contaminated reef where enrichment of Ca and Mg has taken place (see text for more information). **b** Compositions of pyroxenes from the GNPA member, GNPA member chilled magmas and chilled MZ at Grasvally (data from Hulbert 1983)
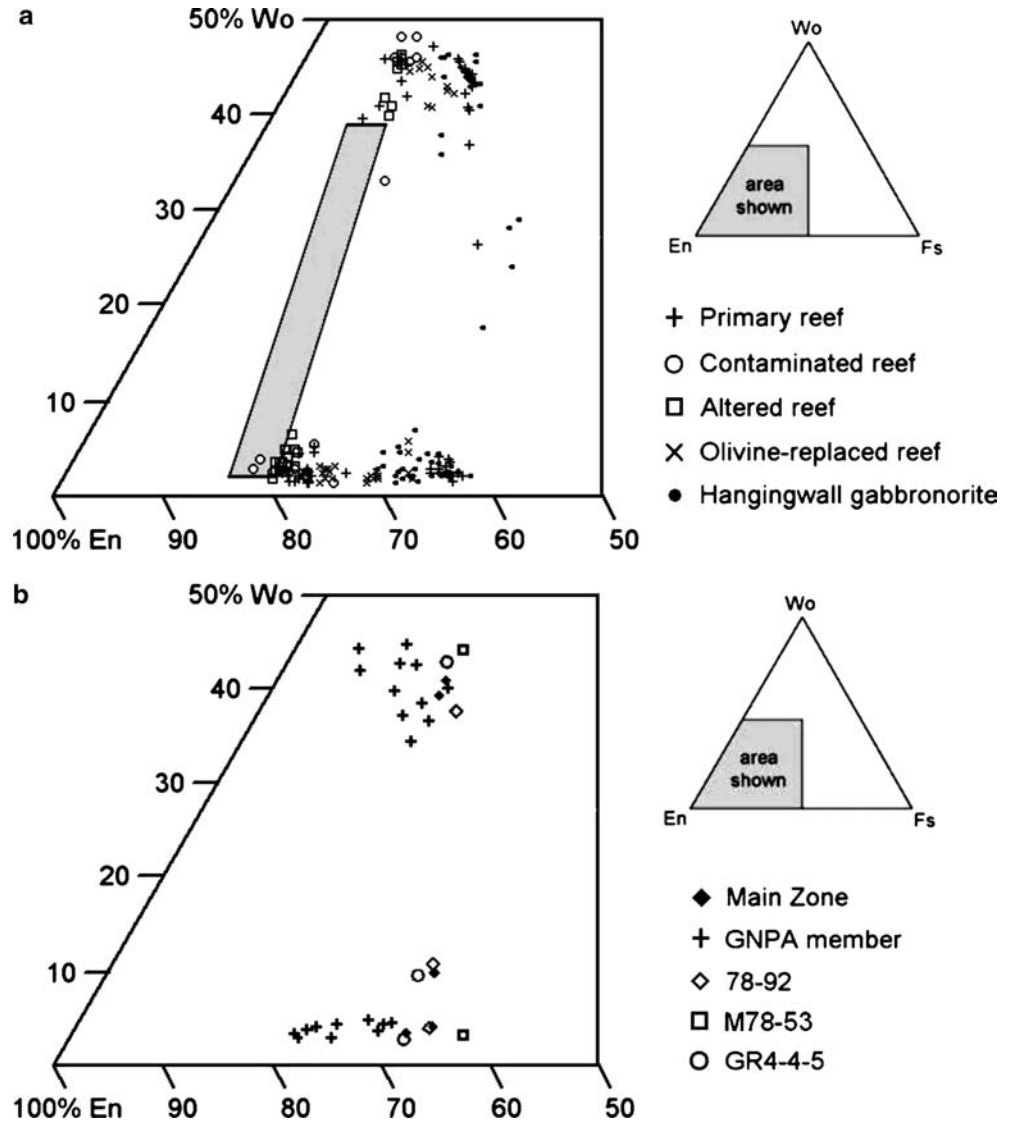
The low Mg# population in our dataset comes from samples of replaced reef, located close to the top of the reef in southwest corner of the pit. Fe-rich olivine is common as a replacement for orthopyroxene in many of these rocks and this strongly suggests that the Fe-rich pyroxene composition is not primary. Orthopyroxene in a coarse-grained pyroxenite (SW2-77) at the top of the reef is as Fe-rich as the hanging wall gabbronorite (Mg#$_{64-66}$; Fig. 10), but the rock has cumulus orthopyroxene and lacks obvious textural evidence for replacement. It may represent differentiated Platreef that crystallised from a residual melt or which underwent some kind of reaction with the hangingwall liquid.

Based on all the data summarised above, if one accepts Mg#$_{80}$ and Mg#$_{76}$ as the upper compositional limits of orthopyroxene and olivine in primary Platreef, then the pyroxene composition is consistent with the GNPA member (Fig. 10). However, the Platreef silicates appear systematically more Fe-rich than their equivalents in the Merensky Reef (Mg#$_{78-84}$ for orthopyroxene and Mg#$_{79-80}$ for olivine; Buchanan et al. 1981; Kruger and Marsh 1985; Naldrett et al. 1986; Holwell 2002; Scoon and Mitchell 2002).

Rare earth element geochemistry

Rare earth element data for reef, hanging wall and footwall lithologies at Sandsloot are given in Tables 1, 2, 3. The footwall rocks have a characteristic and sometimes quite pronounced negative Eu anomaly when normalised to chondrite (Eu/Eu* 0.48–0.80) and show a range of LREE:HREE fractionation. La/Lu$_N$ in the footwall varies between 0.09 and 5.89, but most samples fall within the range 1.2–4.0, which overlaps with the narrow range (1.3–3.3) observed in the reef rocks. Small negative Eu anomalies (Eu/Eu* 0.72–0.93) are observed in most of the reef samples, with the exception of some

more plagioclase-rich reef gabbronorites from the north wall (e.g. N1-14 and N1-24), where there are very small positive anomalies (Eu/Eu* 1.02–1.05).

These observations are in marked contrast to the melanorites in the Merensky Reef at Union Section studied by Barnes and Maier (2002b). These rocks show a much broader range of La/Lu$_N$ ratios (2.8–5.7) and a more pronounced negative Eu anomaly (Eu/Eu* = 0.42–0.80) when compared with the Platreef. Other pyroxenites in the UCZ between the MG4 chromitite and the Bastard Reef show La/Lu$_N$ ratios (1.8–5.8), commonly above Platreef values. These pyroxenites also show more pronounced positive and negative Eu anomalies (Eu/Eu* 0.6–1.4; Maier and Barnes 1998). The Platreef would appear to have formed from a less LREE-enriched magma that had experienced less plagioclase fractionation than the magma that formed the Merensky Reef.

PGE mineralogy

The PGE in the Platreef and the Merensky Reef are carried by common groups of PGM. Kinloch (1982) recognised eight major categories of PGM and found all of these in the Platreef and in the different regional facies of Merensky Reef. Regional PGM variation in the Merensky Reef was ascribed to proximity to magmatic feeders and other local factors such as potholes and occurence of replacement pegmatoids (Kinloch 1982; Kinloch and Peyerl 1990). The Platreef also shows local variation in PGM assemblages (Viljoen and Schürmann 1998) but these changes seem to correlate with changes in the footwall lithology that interacted with the Platreef magma. For example, Kinloch (1982) found a high proportion of Pt sulphides in boreholes that intersected the Platreef on the northern portion of the farm Zwartfontein 818LR and the farm Overysel 815LR, where the footwall is mostly granite. Boreholes on the southern portion of Zwartfontein and samples from the Sandsloot open pit, where the footwall is primarily dolomite, show almost no Pt or Pd sulphides and the assemblage is dominated by Pt and Pd tellurides and alloys (Kinloch 1982; Armitage et al. 2002).

PGE Geochemistry

One of the most striking differences between the PGE deposits of the northern lobe and the rest of the Bushveld Complex is to be found in their noble metal budgets; a feature first noted by Wagner (1929). Davies and Tredoux (1985) were the first to observe that the chondrite normalised PGE pattern of the Merensky Reef was almost parallel to the pattern of high-Mg basaltic sills thought to represent the parental (B1) magma of the Lower Zone and possibly the Critical Zone (Sharpe 1981; Harmer and Sharpe 1985). This similarity has led various authors to infer that the formation of the

Merensky Reef transposed the PGE signature of the magma largely unchanged into the sulphide-bearing reef (Davies and Tredoux 1985; Tredoux et al. 1995; Cawthorn 1999b; Ballhaus and Sylvester 2000). Similar normalised patterns are found from other sulphide-bearing reefs (Pseudoreef, Boulder Bed, Tarentaal and Bastard) in the UCZ of the eastern and western Bushveld (Maier and Barnes 1999) and, like the Merensky Reef, these layers provide a snapshot of the PGE chemistry of the magma that formed the reef. One might therefore expect that the PGE signatures of sulphide-bearing reefs in the UCZ of the eastern and western Bushveld and the GNPA member and the Platreef of the northern lobe should be broadly similar, if these layers formed from a common magma—as the currently accepted stratigraphy implies.

The Merensky Reef PGE data compiled by Kinnaird et al. (2002) and Cawthorn et al. (2002b) show variation in the Pt/Pd ratio between different mining areas, from 1.8 to 2.9. This highlights the fact that UCZ cumulates in general through the eastern and western Bushveld are systematically richer in Pt than in Pd, i.e. Pt/Pd is > 2.0 (with isolated values up to 24), for most of the sequence regardless of whether the rocks contain sulphide or not. The reasons for this striking Pt enrichment are not well understood and cannot be explained by silicate-sulphide or sulphide-sulphide liquid fractionation (Maier and Barnes 1999) and there are no matching Pd-rich cumulates in the MZ or UZ to satisfy the mass balance (Barnes and Maier 2002c). The excess platinum seems to
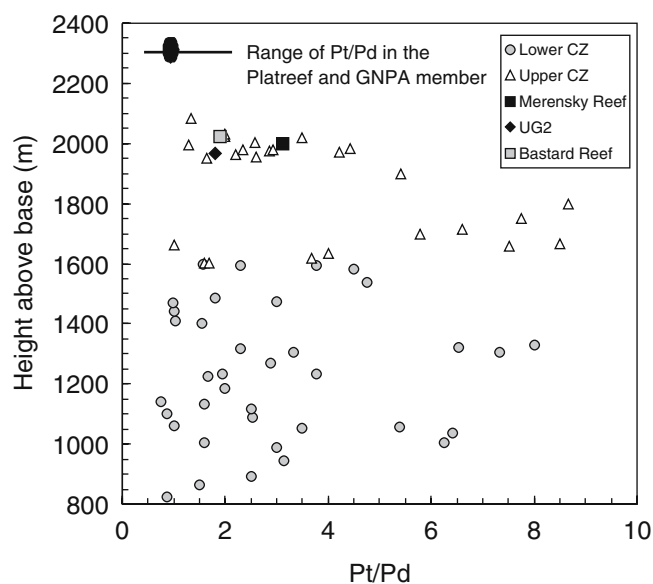

Fig. 11 Variation in Pt/Pd ratios through the Critical Zone in the western lobe (Maier and Barnes 1999) compared with the range (represented by the *bar*) and the mean (represented by the *ellipse*) for the "Critical Zone" and Platreef of the northern lobe (Von Greunewaldt et al. 1989; this work). Very high Pt/Pd ratios in some Critical Zone rocks that are off scale are not shown in the diagram. Note the generally lower Pt/Pd ratios in the northern lobe compared with the Critical Zone elsewhere in the complex

be a fundamental compositional feature of the magma(s) that fed the UCZ.

Platinum group element ratios for the Platreef and the sulphide-rich reef of the GNPA member are compared with those in sulphide reefs of the UCZ in Table 4. These comparisons indicate that all the sulphide-bearing reefs in the northern lobe are different from those found in the UCZ. The Platreef and all of the sulphide reefs in the GNPA member show greater fractionation of low-temperature PGE (Pt and Pd) from high-temperature PGE (Ir and Ru) and all of them are Pd-rich compared with reefs between the UG2 and the Merensky Reef in the eastern and western lobes. It is important to note that this comparison does not take account of PGE in the footwall. High-grade zones in the footwall at Sandsloot often show even lower Pt/Pd ratios than the main reef (Tables 1, 2, 2), suggesting that there may have been preferential mobilisation of Pd over Pt into the footwall from the proto-reef. The outcome of this would be to raise the apparent Pt/Pd ratio of the Platreef, i.e. the original Pt/Pd ratio of the Platreef before it preferentially lost Pd to the footwall could have been even lower and further removed from UCZ values than it appears currently.

An important primary observation from the northern lobe is that the GNPA member and the Platreef (and silicate rocks with total PGE contents as low as 10 ppb; Tables 1, 2, 3) show lower and more restricted Pt/Pd ratios than the UCZ, where Pt/Pd ratios may exceed those in the northern lobe until well above the level of the Bastard Reef (Fig. 11). Whatever the reason for the striking Pt enrichment in the eastern and western lobes during formation of the UCZ, it is not repeated in any of the sulphide-bearing reefs of the GNPA member, or in the Platreef!

Discussion

Implicit in current models for the evolution of the northern lobe is the idea that UCZ magma entered the northern lobe and formed a sequence of layered cumulates represented by the GNPA member prior to the development of the Platreef (e.g. Van der Merwe 1976, 1998; Von Gruenewaldt et al. 1989). The GNPA member was subsequently covered by mixed UCZ-MZ magma that spread out to the north, interacted with the footwall rocks, and formed the Platreef. If the Platreef is correlated with the Merensky Reef, then introduction of this magma into the northern lobe may be assumed to be coincident with the massive injection of MZ magma that led to the formation of the Merensky Reef and the MZ sequence elsewhere in the complex (e.g. Kruger 2003).

In most tholeiitic magmas, chromite crystallisation terminates before clinopyroxene attains cumulus status due to a reaction relationship between spinel and pyroxene but this reaction is sensitive to oxygen fugacity. The lack of reaction between chromite and clinopyroxene in the orthopyroxene-clinopyroxene-chromite cumulates of the GNPA member led Hulbert (1983) to conclude that the GNPA member magma had an unusually high fO_2 that provided enough ferric iron to stabilise chromite. If this is correct, it follows that the Fe-rich nature of the pyroxenes in the GNPA member cannot be ascribed to fO_2 as, if the GNPA member started with the same composition as the UCZ, a higher

Table 4 Platinum group elements ratios of Upper Critical Zone sulphide-rich reefs and parental magmas (see text for further details)

	Pt/Pd	Pt/Ir	Pd/Ir	Pd/Rh	Source
Eastern and western lobes					
Bastard Reef	3.03	41.8	13.8	3.45	1
Merensky Reef (eastern lobe)	1.57	41.1	26.2	12.9	1
Merensky Reef (western lobe)	1.94	41.9	21.6	8.46	1
Boulder Bed	3.04	32.6	10.7	4.97	2
Tarentaal	4.43	105.6	23.8	5.41	2
Pseudoreef	2.35	37.2	15.9	3.52	1
Northern lobe					
Lower Platreef (Drenthe)	0.81	76	93	18	3, 8
Upper Platreef (Drenthe)	0.65	89	139	58	3, 8
Platreef (Sandsloot)	0.95	96	63	15	4
S7 Norite (top of GNPA member)	0.29	65	230	31	3
S6 Pegmatitic gabbronorite	0.99	41	41	19	3
S4 Ni-rich leuconorite	0.41	30	73	20	3
S2 Footwall (UG2-like chromitite)	0.43	63	130	19	3
S1 Basal gabbronorite	0.39	54	140	21	3
Pyroxenite (Unit 36 Lower Zone)	0.34	n/a	n/a	n/a	5, 6
UpperVolspruit (Unit 11 Lower Zone)	0.72	34	47	6.8	3, 7
Parental magmas					
B1 (Lower/Critical Zone)	1.64	56.2	34.3	10	1
B3 (Main Zone)	1.55	77.8	50	15	1

Data sources: (1) Barnes and Maier 2002a; (2) Naldrett et al. 1986; (3) recalculated from Von Greunewaldt et al. 1989; (4) this work; (5) Hulbert 1983; (6) van der Merwe 1998; (7) R.M. Harmer (personal communication); (8) A.J. Naldrett (personal communication). S1 to S7 refer to sulphide reefs in Fig. 8

fO_2 would be expected to generate more Mg-rich silicates. The lower Mg/Fe ratios observed in the GNPA member are therefore most probably a consequence of a starting magma composition that was more Fe-rich than the UCZ magma.

We have shown above that, apart from the visually similar appearance and the presence of high PGE concentrations, evidence linking the Platreef with the Merensky Reef is not strong. Significant mineralogical and geochemical differences exist between the Platreef and the GNPA member of the northern lobe and the Merensky Reef and the UCZ in the rest of the Bushveld Complex. In contrast, the greater similarities in terms of pyroxene compositions (Fig. 10), crystallisation sequences and PGE signatures between the Platreef and the GNPA member are more consistent with a model whereby these units formed from the similar or related magmas.

The simplest explanation for this apparent paradox is that the Merensky Reef and the Platreef (along with any related pre-reef cumulates) formed from separate magmas with different Mg/Fe ratios and PGE budgets. On the basis of a higher modal clinopyroxene content, the lower Mg# of orthopyroxene and the PGE ratios, the northern lobe rocks formed from a magma that was poorer in Mg, richer in Ca and Fe, was more highly PGE fractionated (greater Pt/Ir and Pd/Ir ratios) and was Pd rather than Pt-dominant relative to the magma(s) that formed the UCZ and Merensky Reef in the eastern and western lobes.

The obvious question is what was this northern lobe magma? The B1 magma of Sharpe (1981), believed to be parental to the Lower and Critical Zones in the eastern and western lobes, is a high Mg basaltic andesite that produces a crystallisation sequence olivine; olivine-orthopyroxene, orthopyroxene, orthopyroxene-plagioclase that is observed in the Lower and Critical Zones (Barnes and Maier 2002a). In contrast, the B3 (tholeiitic) magma believed to be parental to the MZ crystallises plagioclase-orthopyroxene, and then plagioclase plus both pyroxenes (Harmer and Sharpe 1985; Barnes and Maier 2002a). Neither of these magmas on their own can generate the observed crystallisation sequences for the GNPA member or the Platreef.

In order to account for the different PGE ratios, Cawthorn et al. (2002a) proposed that UCZ-type magma similar to that formed the UG2 chromitite in the eastern lobe (which has a Pt/Pd ratio close to unity) could have either flowed northwards or been present in the northern lobe prior to the formation of the Platreef. Cawthorn et al. (2002a) suggest that this magma did not form any chromitite layers and retained its PGE signature until the event that formed the Platreef. This is not supported by the available evidence as the GNPA member contains a chromitite layer as well as thick pyroxenite cumulates with disseminated chromite. The model also fails to explain the Fe-rich nature of the orthopyroxenes, the abundance of clinopyroxene in the GNPA member and why and all the reefs actually have

Pt/Pd ratios lower than unity. In any case, the magma in the eastern lobe became Pt-dominant again at the level of the Merensky Reef. No evidence for this is found in the northern lobe.

Development of the GNPA member

The answer to the question may lie with a marginal member defined by Hulbert (1983) that is developed at the base of the GNPA member where it rests on LZ ultramafic cumulates and Pretoria Group sediments. He suggested that these unusual pigeonite gabbronorites were chilled "Critical Zone" magma or hybrids of chilled magma with LZ or sedimentary footwall melts. Hulbert (1983) suggested that a sample (M78-53) found in the marginal zone above the Pretoria Group might represent the closest match to the initial "Critical Zone" magma composition. Another fine-grained pigeonite gabbronorite (GR4-4-5) developed above LZ cumulates has similar characteristics. The bulk chemistries of these two rocks are compared with estimated compositions of the parental magmas for the Critical and Main Zones in Table 5 and their pyroxene compositions are compared with GNPA member and MZ compositions in Fig. 10. It is clear that both M78-53 and GR4-4-5 lie closer to the model MZ magma than CZ magma.

If this is correct and these rocks represent chilled tholeiitic (MZ) magma, then it offers a possible explanation for the unique orthopyroxene-clinopyroxene-chromite cumulates and the lack of mineralogical or geochemical similarity between the GNPA member and the UCZ in the rest of the complex. Where the marginal member rests on the LZ, Hulbert (1983) cited the fine grain size, the abundance of pigeonite and rapid reversal in orthopyroxene compositions—from Mg#$_{84}$ in the last LZ harzburgite to Mg#$_{67-71}$ just above the contact (Fig. 9)—as evidence for undercooling and crystallisation of new liquid to form the marginal gabbronorites.

Hulbert (1983) observed at least five cyclic sub-units within the marginal member, each with a fine-grained basal gabbronorite. Skeletal plagioclase crystals with trapped melt and orthopyroxenes with Mg#'s close to the bulk Mg# of the rock (e.g. M78–53) suggest rapid supercooling, which becomes less effective upwards. Each sub-unit shows upward increases in the Mg# of orthopyroxene and in the absolute concentrations of Ni, Cu and PGE, which are most enriched in coarser (sometimes pegmatitic) zones above the fine-grained base of each sub-unit. Hulbert (1983) suggested that the marginal member was emplaced as a series of thin pulses of colder, denser liquid at the base of the magma chamber. Model crystallisation of liquids with M78-53 or GR4-4-5 compositions at 1,500 bars in the PELE programme (Boudreau 1999) produces liquidus temperatures of 1210–1230°C and crystallisation sequences of plagioclase, plagioclase-orthopyroxene, then plagioclase as well as both pyroxenes, which mirror the observed textures. The idealised section given by Hulbert

Table 5 Comparison of fine-grained gabbronorite chills with estimated Critical and Main Zone magma compositions.

Sample Position	GR4-4-5 LZ-GNPA	78-53 Pret-GNPA	B1 (LZ/CZ)	B3 (MZ)	Crit Zone	Main Zone	78-92 GNPA-MZ	N3X4A Plat-MZ	SW1-47B Plat-MZ	SW1-47A Plat-MZ
SiO_2 (wt%)	52.11	49.97	53.17	50.70	55.87	50.48	53.61	51.81	51.44	49.44
TiO_2	0.10	0.62	0.36	0.41	0.37	0.71	0.34	0.20	0.19	0.16
Al_2O_3	17.31	15.67	11.36	16.03	12.55	15.79	17.36	17.48	16.48	16.30
FeO	5.34	8.82	10.72*	9.14*	9.15*	11.61*	5.13	n/a	n/a	n/a
Fe_2O_3	1.60	2.12	n/a	n/a	n/a	n/a	1.84	9.75*	8.83*	9.04*
MnO	0.15	0.19	0.20	0.17	0.21	0.18	0.13	0.14	0.19	0.15
MgO	8.86	7.77	14.93	9.21	12.65	7.26	7.42	6.48	6.93	8.55
CaO	11.66	10.91	7.47	11.14	7.29	10.86	11.58	11.17	12.06	11.75
Na_2O	2.15	2.15	1.57	2.52	1.53	2.20	2.38	1.79	2.43	2.52
K_2O	0.67	0.58	0.17	0.23	0.77	0.16	0.58	1.30	0.41	0.43
P_2O_5	0.02	0.10	0.07	0.08	0.10	0.16	0.04	0.01	0.01	0.02
Sc (ppm)	n/a	n/a	n/a	n/a	41	35	n/a	31	38	28
V	90	232	n/a	n/a	179	182	119	191	200	152
Cr	390	396	1240	205	939	335	317	424	292	551
Co	80	88	n/a	n/a	73	53	66	41	48	59
Ni	184	184	337	162	329	128	128	346	407	376
Cu	75	120	n/a	n/a	58	62	23	121	170	187
Rb	30	20	4	7	27	3	13	50	7	12
Sr	385	353	183	324	170	340	275	333	282	234
Y	7	19	15	n/a	n/a	n/a	13	7	12	8
Zr	6	30	47	20	80	60	39	12	5	7
Source	1	1	2	2	3	3	1	4	4	4

Position key: *LZ* Lower Zone; *MZ* Main Zone; *Plat* Platreef; *Pret* Pretoria Group; *GNPA* GNPA member
Sources: (1) Hulbert 1983; (2) Sharpe 1981; (3) Barnes and Maier 2002b; (4) this work
* indicates total Fe as FeO or Fe_2O_3 as appropriate

and Von Gruenewaldt (1986) shows the marginal member developed across the LZ cumulates and over the adjacent Pretoria Group quartzites. In this situation, heat loss would have taken place primarily against the quartzites and a thermal gradient extended laterally from this zone into the liquid overlying the LZ cumulates. General coarsening of units upwards from the contact suggests more effective thermal insulation as the member thickened (Hulbert 1983).

Hulbert (1983) noted that pyroxenes in the marginal member overlying the LZ cumulates were more Mg-rich than those developed in the gabbronorites against the Pretoria Group and that abundant sulphides, high PGE and Cr concentrations were also restricted to the marginal member above the LZ. He argued that these features could only be accounted for by adding some residual LZ melt to the new liquid as the marginal member developed. This may also provide a mechanism to generate the unusual orthopyroxene-clinopyroxene-chromite cumulates associated with the "UG2-like" chromitite (Fig. 9). In addition to the unusual crystallisation order, these units are very rich in Cr (2,500–28,500 ppm) and it is hard to see how to generate them from liquids similar to M78-53 (with <400 ppm Cr) alone. We suggest that mixing the new tholeiitic liquid with an existing volume of overlying resident LZ-type magma crystallising olivine, orthopyroxene ($Mg\#_{84-88}$) and chromite could produce a hybrid magma that crystallises orthopyroxene and chromite, followed by orthopyroxene, chromite and clinopyroxene, which mirrors the observed sequence in the lower part of the GNPA member (Fig. 9). Densities calculated in PELE for melts of M78-53 and GR4-4-5 at 1,500 bars are 2.71

and 2.65 $g.cm^{-3}$, respectively, and may be sufficiently high to displace a hotter (>1,270°C) LZ-type liquid upwards in the manner suggested by Tegner et al. (1993). Undercooling of the resident LZ-type liquid by repeated injections of colder liquid at the base, coupled with gradual heating of the new liquid as thermal insulation of the thickening marginal member becomes more efficient would lower the temperature gradient and the density contrast to the point where the mafic and tholeiitic liquids might mix.

A second cycle with basal orthopyroxenite and orthopyroxene-clinopyroxene-chromite cumulates occurs higher in the sequence at the zero reference, and a third one at +75 metres is overlain by anorthosite (Fig. 9). These orthopyroxene-rich cumulates are additionally important because they carry sulphides and associated Pd-rich PGE mineralisation. Decreasing volumes of orthopyroxene-clinopyroxene-chromite cumulates and the trend of Ti enrichment in chromite developed with height probably reflect diminishing volumes of mafic magma available for mixing as the chamber becomes swamped with tholeiitic magma. Peck and Keays (1990) have independently proposed a similar process, involving injection of small volumes of gabbroic liquid into a larger volume of ultramafic magma, to explain the development of thin layers of chromite gabbronorite in harzburgites of the Heazlewood River Complex.

We suggest that the explanation for why the orthopyroxene-clinopyroxene-chromite cumulates are unique to the northern lobe is because these two magma types do not mix together in this manner elsewhere in the Bushveld Complex. The process outlined here is similar in some respects to the mixing of ultramafic (U-type) and

tholeiitic (T-type) magmas proposed by Irvine and Sharpe (1986) for the origin of stratiform chromitite and PGE reefs, including the Merensky Reef. The principal difference lies in the nature of the U-type magma and the degree of interaction. The Critical Zone in the eastern and western lobes preserves chemical and isotopic signatures inherited from the LZ and the new, distinctively Pt-rich, magma(s) which hybridised with it during the formation of the UCZ. The base of the UCZ marks the change from olivine-orthopyroxene cumulates to a chromite-orthopyroxene-plagioclase liquidus order, which persists throughout the UCZ, until the introduction of MZ magma coincident with the formation of the Merensky Reef (Kruger 1994), where the last cumulus chromite appears. Mass balance modelling by Barnes and Maier (2002b) suggests that the Merensky event involved ~40% tholeiitic magma mixed with ~60% UCZ-type magma crystallising orthopyroxene and plagioclase.

In the northern lobe, we suggest that there was no distinctive Pt-rich magma and no intermediate stage where the liquidus order shifted from olivine-orthopyroxene to chromite-orthopyroxene-plagioclase. The GNPA member formed by a series of rapid and dramatic interactions between progressively larger volumes of new tholeiitic liquid and a resident LZ-type liquid. In addition, we suggest that the tholeiitic and mafic liquids are derived from different sources with different isotopic signatures (see below) and within a few mixing/quenching interactions following the first introduction of the tholeiitic liquid, the reservoir of mafic liquid was exhausted or it ceased to be supplied to the chamber. Magmatic evolution beyond that point is controlled by the chemistry of the dominant tholeiitic liquid which later formed the MZ of the northern lobe.

Further support for the involvement of tholeiitic magma comes from the rocks at the top contact of the GNPA member. Above a prominent mottled anorthosite which caps the member, Hulbert (1983) found a 1–2-m thick layer of medium-grained gabbronorite (sample 78–92) with distinctive radiating clusters of acicular plagioclase and inverted pigeonite. He interpreted this as an influx of new MZ magma which supercooled and chilled against the GNPA cumulates. The composition of 78–92 is close to the chilled rocks at the base of the GNPA member (Table 5). This can only be explained if MZ-type magma was involved prior to, during, and after the formation of the GNPA member.

This interpretation apparently contradicts the view that there was major hiatus between the emplacement of the magmas of the LZ and the MZ (Van der Merwe 1978). Field evidence cited to support this is based on apparently transgressive relationships established between LZ intrusives and the Platreef north of Mokopane that are not in dispute, plus the assignment of the GNPA member to a pre-Platreef UCZ, which is disputed. Fundamentally, van der Merwe's model rests on two assumptions; first, that the LZ was fully crystallised (not just the satellite intrusions where the transgressive relationships occur) and second, that the

Platreef and the GNPA member are unrelated to the LZ. The evidence presented above suggests that mafic liquid remained in the Grasvally magma chamber up to the development of the GNPA member and it is possible that supply of magma into the northern satellite chambers ceased while mafic magma continued to enter the Grasvally chamber. The role of LZ magma in the formation of the Platreef is discussed in the next section.

Links between the GNPA member and the Platreef

The exact relationship between the Platreef and the LZ and the GNPA member to the north of the Grasvally area is poorly known and will only be revealed as further exploration takes place on farms between Grasvally and Mokopane. Hammerbeck and Schürmann (1998) indicate that the ''Critical Zone'' wedges out to the south of Mokopane but Von Gruenewaldt et al. (1989) equated xenolith-rich portions of the GNPA member with the Platreef and implied that one might merge laterally into the other; a proposal supported by the data presented here. Kinnaird et al. (2005) report that north of Mokopane, LZ rocks may occur below the Platreef but the LZ appears to wedge out on the farm Macalacaskop 243KR and the Platreef rests directly on metasedimetary footwall from Macalacaskop northwards to Zwartfontein. Indeed it seems more than a coincidence that the modal mineralogy of the GNPA member orthopyroxene and orthopyroxene-clinopyroxene cumulates (55–60% opx, 15–25% plag, 20–25% cpx), the crystallisation order, orthopyroxene compositions ($Mg\#_{70–78}$; Fig. 10) and Pd-dominant PGE mineralisation are similar to the Platreef at Sandsloot at many of the localities described above. Orthopyroxene-clinopyroxene-chromite cumulates, apparently similar to those that occur in the GNPA member, occur in the Platreef on the farm Overysel 815LR (Hulbert 1983).

It is also possible that the contacts between the GNPA member and the Platreef with the base of the MZ may correlate along strike. At Sandsloot, the unsheared contact with the hanging wall MZ gabbros is marked by leuconorite (''mottled anorthosite'') and a fine to medium-grained gabbronorite (Fig. 6). This unit contains traces of inverted pigeonite, PGE grade up to 2.0 g/t, and a PGM assemblage containing laurite (RuS_2) and Pd-bearing pentlandite that is very different from that in the Platreef (Holwell et al. 2004). On Turfspruit 241KR, Kinnaird et al. (2005) observed that the upper contact of the Platreef with the MZ is marked by a prominent mottled anorthosite and on Drenthe 788LR, inverted pigeonite is also found in the MZ immediately above the Platreef (Gain and Mostert 1982). These associations are remarkably similar to the rocks at the contact between the MZ and GNPA member at Grasvally (Hulbert 1983). The chemistry of fine-grained gabbronorites from just above the Platreef are compared with a MZ chill against the GNPA cumulates (78–92) in Table 5. These

rocks are separated by $\sim$40 km (Fig. 1) but the match between their major and trace element signatures is striking and suggests that chilled MZ magma may terminate both the GNPA member and the Platreef. The presence of PGE in the MZ basal chill zone further suggests that the quenching of MZ magma may be an important trigger for the development of PGE-rich zones around rafts of disaggregated country rock in the MZ (e.g. on Drenthe 788LR and other farms).

In the light of the above, the finding by Barton et al. (1986) that orthopyroxene separated from the Platreef has an $^{87}Sr/^{86}Sr$ initial ratio of 0.7079 may be highly significant. Barton et al. (1986) suggested that even this should be considered an upper limit because of the possibility that the pyroxene separates contained traces of plagioclase with elevated $^{87}Sr/^{86}Sr$ initial ratios influenced by late-stage melts or fluids derived from the footwall. The MZ magma in the northern lobe shows $^{87}Sr/^{86}Sr$ initial ratios in the range 0.708–0.710 (Barton et al. 1986). Data for the Lower LZ in the northern lobe is lacking but if one assumes that this magma had a similar initial ratio to LZ rocks in the western Bushveld (0.705–0.707; Kruger 1994), then the lowest initial ratio of 0.7079 found by Barton et al. (1986) in the Platreef is consistent with a mixture of MZ-type and LZ-type magmas. In the absence of further geochemical data, particularly REE and isotopes from the GNPA member and elsewhere on the Platreef, the proposed link between the two must be considered possible, but unproven, at this stage. Nevertheless, the similarity is intriguing and underlines the need for further research into these rocks.

Implications for connectivity between the northern lobe and the rest of the Bushveld Complex

Cawthorn and Webb (2001) concluded that the eastern and western lobes were linked throughout the development of the Critical, Main and Upper Zones but that links with other lobes, including the northern lobe, were less certain and had to remain speculative. Kruger (1999, 2003), following the conventional stratigraphy, considered the northern lobe to have been linked with the eastern and western lobes during UCZ and MZ times. In his model, a mixed MZ and UCZ magma flows north across the chamber, overtops the Thabazimbi-Murchison Lineament (locally manifested as the Zebediela and Ysterberg-Planknek Faults; Fig. 1) and flows into the northern lobe, generating the Platreef along the base. LZ-type magma plays no role in forming the Platreef.

This work has shown that the conventional stratigraphic interpretation shown in Fig. 3 is untenable. The "Critical Zone" of the northern lobe, incorporating the "UG2-like" chromitite and Platreef cannot be correlated with the UG2-Merensky Reef package in the rest of the complex. The UCZ-type magma with its high Mg/Fe ratios, chromite-orthopyroxene-plagioclase-clinopyroxene crystallisation sequence and distinctive Pt enrichment did not play a role in the development of the

GNPA member or the Platreef. The orthopyroxene-clinopyroxene-chromite cumulates of the GNPA member and the Pd-dominant PGE mineralisation contained in it and the Platreef are unique to the northern lobe of the complex. Their origin requires different magmatic components.

We interpret the available evidence to suggest that the GNPA member and the Platreef may represent a transitional period where the earliest tholeiitic MZ-type magmas interacted with pre-existing mafic LZ-type magmas. It should perhaps be renamed the Transitional Zone of the northern lobe. The questions of when these two major magma types were introduced into the northern lobe, how their introduction relates to emplacement of magmas in the eastern and western lobes, and how their interaction might have generated the mass of PGE present in the GNPA member and the Platreef all remain unclear at this time and need further research.

In our view, the Merensky Reef and the Platreef formed from compositionally different magmas with different lineages and there is no genetic link between them. The possibility remains that introduction of tholeiitic magma into the northern lobe took place at the same time as into the eastern and western lobes but this cannot be proved unequivocally and a reliable time line cannot be drawn between the Merensky Reef and the Platreef. The "Critical Zone" of the northern lobe is not the Critical Zone as known from the rest of the Bushveld Complex. The former term is confusing and should be discontinued. There may be a reliable link between lobes in the Upper Zone at the level of the Main Magnetite (Fig. 3), but it remains to be established how closely the stratigraphy of the MZ of the northern lobe matches that seen in the rest of the complex. The northern lobe may have been completely separated from the rest of the complex until intrusion of the Upper Zone. The stratigraphy of the northern lobe must be evaluated on its own merits, without premature attempts to fit it into that established elsewhere.

Conclusions

This work has shown that the Platreef and the GNPA member, long thought to correlate with the Merensky Reef and the UCZ elsewhere in the complex, formed from a different magma than that which generated the UCZ in the eastern and western lobes of the complex. The Platreef and the GNPA member show pyroxene compositions that are systematically more Fe-rich and PGE signatures that are more fractionated and more Pd-rich than the Merensky Reef and other reefs of the UCZ. This work demonstrates that UCZ magma, with its characteristic and economically significant Pt enrichment, was not involved in the generation of the Platreef and that there is no compelling evidence linking the formation of the Platreef either genetically or temporally with the Merensky Reef.

Chilled MZ-type magma is preserved at the base and the top of the GNPA member and this unit is suggested to have formed from the mixing of existing LZ-type magma and new tholeiitic MZ-type magma that first intruded along the floor of the Grasvally chamber. Mixing/quenching events produced a series of orthopyroxenites that grade upwards into orthopyroxene-clinopyroxene-chromite cumulates that are unique to this area of the complex. The basal orthopyroxenites are invariably associated with the presence of sulphide and elevated base metal and PGE values. The GNPA member rocks show similarities in terms of mineral chemistries, modal mineralogy, crystallisation sequences, and PGE ratios with Platreef rocks and a compositionally similar MZ liquid is chilled against the top of both the GNPA member and the Platreef. These similarities open up the possibility that the Platreef and GNPA member merge laterally into one another and that both result from interactions between MZ and LZ-type magmas.

On a final note, although we have demonstrated that Wagner's original link between the Platreef and the Merensky Reef may be incorrect, it would be unjust to be overly critical of him. The visual similarity between the two reefs is striking and this, coupled with the apparently unlikely possibility that there could be another fantastically rich platinum horizon in addition to the Merensky Reef, must have played a part in forming his opinion. The fact that the assumed link has remained unchallenged for so long is surely a measure of the immense respect that Wagner's pioneering work still commands 75 years after his death.

References

Armitage PEB, McDonald I, Edwards SJ, Manby GM (2002) Platinum-group element mineralisation in the Platreef and calc-silicate footwall at Sandsloot, Potgietersrus district, South Africa. Appl Earth Science (Trans Inst Min Metall B) 111:B36–B45

Ballhaus C, Sylvester P (2000) Noble metal enrichment processes in the Merensky Reef, Bushveld Complex. J Petrol 41:545–561

Barnes SJ, Maier WD (2002a) Platinum-group element distributions in the Rustenburg Layered Suite of the Bushveld Complex, South Africa. In: Cabri L (ed) The geology, geochemistry, mineralogy and mineral benefication of the platinum-group elements. Can Inst Min Metall Special Volume 54:431–458

Barnes SJ, Maier WD (2002b) Platinum-group elements and microstructures of normal Merensky Reef from Impala Platinum Mine, Bushveld Complex. J Petrol 43:103–128

Barnes SJ, Maier WD (2002c) Plaitnum-group elements in the Upper Zone of the Rustenburg Layered Suite of the Bushveld Complex: preliminary results from the Bellevue Borehole. In: 9th international platinum symposium, Billings, Montana, (abstract)

Barton JM, Cawthorn RG, White J (1986) The role of contamination in the evolution of the Platreef of the Bushveld Complex. Econ Geol 81: 1096–1104

Boudreau AE (1999) PELE—A version of the MELTS software program for the PC platform. Comput Geosci 25:21–203

Buchanan DL, Rouse JE (1984) Role of contamination in the precipitation of sulphides in the Platreef of the Bushveld Complex. In: Buchanan DL, Jones MJ (eds) Sulphide deposits in mafic and ultramafic rocks. Inst Min Metall, Lond, pp 141–146

Buchanan DL, Nolan J, Suddaby P, Rouse JE, Viljoen MJ, Davenport JWJ (1981) The genesis of sulfide mineralisation in a portion of the Potgietersrus lobe of the Bushveld Complex. Econ Geol 76:568–579

Bye AR (2001) Mining the Platreef. Appl Earth Science (Trans Inst Min Metall B) 110:B209–B210

Cameron EN (1982) The upper critical zone of the Eastern Bushveld Complex – precursor of the Merensky Reef. Econ Geol 77:1307–1327

Cawthorn RG (1996) Re-evaluation of magma compositions and processes in the uppermost Critical Zone of the Bushveld Complex. Min Mag 60: 131–148

Cawthorn RG (1999a) The platinum and palladium resources of the Bushveld Complex. S Afr J Sci 95:481–489

Cawthorn RG (1999b) Platinum-group element mineralisation in the Bushveld Complex – a critical reassessment of geochemical models. S Afr J Geol 102:268–281

Cawthorn RG (2002) Delayed accumulation of plagioclase in the Bushveld Complex. Min Mag 66:881–893

Cawthorn RG, Lee CA (1998) Field excursion guide to the Bushveld Complex. In: 8th international platinum symposium. Geol Soc South Africa and S African Inst Min Metall, p 113

Cawthorn RG, Webb SJ (2001) Connectivity between the western and eastern lobes of the Bushveld Complex. Tectonophysics 330:195–209

Cawthorn RG, Barton JM Jr, Viljoen MJ (1985) Interaction of floor rocks with the Platreef on Overysel, Potgietersrus, northern Transvaal. Econ Geol 80:988–1006

Cawthorn RG, Merkle RK, Viljoen M (2002a) Platinum-group element deposits in the Bushveld Complex, South Africa. In: Cabri L (ed) The geology, geochemistry, mineralogy and mineral benefication of the platinum-group elements. Can Inst Min Metall 54:389–429

Cawthorn RG, Lee CA, Schouwstra RP, Mellowship P (2002b) Relationship between PGE and PGM in the Bushveld Complex. Can Mineral 40:311–328

Chaumba JB, Harris C, Tredoux M, Reisberg L, Arndt NT (1998) Oxygen, strontium and osmium isotope geochemistry of the Platreef of the northern lobe of the Bushveld Complex, South Africa. In: 8th international platinum symposium, S African Inst Min Metall Symposium Series S18:71–72

Davies G, Tredoux M (1985) The platinum-group element and gold contents of marginal rocks and sills of the Bushveld Complex. Econ Geol 80: 838–848

Eales HV, Botha WJ, Hattingh PJ, de Klerk WJ, Maier WD, Odgers ART (1993) The mafic rocks of the Bushveld Complex. J Afr Earth Sci 16: 121–142

Gain SB, Mostert AB (1982) The geological setting of the platinoid and base metal sulphide mineralisation in the Platreef of the Bushveld Complex on Drenthe, north of Potgietersrus. Econ Geol 77:1395–1404

Hammerbeck ECI, Schürmann LW (1998) Nickel. In: Wilson MGC, Anhaeusser CR (eds) The Mineral Resources of South Africa. Coun Geosci Handbook 16:471–482

Harmer RE, Sharpe MR (1985) Field relations and strontium isotope systematics of the marginal rocks of the Eastern Bushveld Complex. Econ Geol 80:813–837

Harris C, Chaumba JB (2001) Crustal contamination and fluid-rock interaction during the formation of the Platreef, northern lobe of the Bushveld Complex, South Africa. J Petrol 42:1321–1347

Harris C, Pronost JM, Ashwal LD, Cawthorn RG (2004) Oxygen and hydrogen isotope stratigraphy of the Rustenburg Layered Suite, Bushveld Complex: constraints on crustal contamination. J Petrol 46:579–601

Hart SR, Kinloch ED (1989) Osmium isotope systematics in Witwatersrand and Bushveld ore deposits. Econ Geol 84:1651–1655

Holwell DA (2002) Base-metal sulphide geochemistry of the Merensky Reef, Bushveld Complex. MSc dissertation, Camborne School of Mines, (unpublished)

Holwell DA, McDonald I, Armitage PEB (2004) Platinum-group mineral assemblages in the Platreef at Sandsloot Mine, Limpopo Province, South Africa. Geoscience Africa, University of the Witwatersrand, 12–16 July 2004 (abstract)

Hulbert LJ (1983) A petrographical investigation of the Rustenburg Layered Suite and associated mineralisation south of Potgietersrus. DSc dissertation, University of Pretoria, (unpublished)

Hulbert LJ, Von Gruenewaldt G (1982) Nickel, copper and platinum mineralisation in the Lower Zone of the Bushveld Complex, south of Potgietersrus. Econ Geol 77:1296–1306

Hulbert LJ, Von Gruenewaldt G (1985) Textural and compositional features of chromite in the lower and critical zones of the Bushveld Complex south of Potgietersrus. Econ Geol 80:872–895

Hulbert LJ, 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: Anhauesser CR, Maske S (eds) Mineral Deposits of Southern Africa. Geol Soc South Africa, Johannesburg, 2:1237–1249

Hutchinson D (2001) The origin and distribution of platinum-group mineralisation in the oceanic upper mantle: a comparison of samples from the Lizard and Troodos ophiolite complexes and dredge samples from the Tonga trench. PhD thesis, Cardiff University, (unpublished)

Irvine TN, Sharpe MR (1986) Magma mixing and the origin of stratiform oxide ore zones in the Bushveld and Stillwater complexes. In: Gallagher MJ, Ixer RA, Neary CR, Prichard HM (eds) Metallogeny of Basic and Ultrabasic rocks. Inst Min Metall, Lond, pp 183–198

Kinloch ED (1982) Regional trends in the platinum-group mineralogy of the critical zone of the Bushveld Complex, South Africa. Econ Geol 77: 1328–1347

Kinloch ED, Peyerl W (1990) Platinum-group minerals in various rock types of the Merensky Reef, genetic implications. Econ Geol 85:537–555

Kinnaird JA, Nex PAM (2003) Mechanisms of marginal mineralisation in the Bushveld Complex. Appl Earth Science (Trans Inst Min Metall B) 112: B206–B208

Kinnaird JA, Kruger FJ, Nex PAM, Cawthorn RG (2002) Chromitite formation – a key to understanding processes of platinum enrichment. Appl Earth Science (Trans Inst Min Metall B) 111:B23–B35

Kinnaird JA, Hutchinson D, Schürmann L, Nex PAM, de Lange R (2005) Petrology and mineralisation of the southern Platreef: northern limb of the Bushveld Complex, South Africa. Mineral Deposita (this volume)

Kruger FJ (1994) The Sr-isotopic stratigraphy of the western Bushveld Complex. S Afr J Geol 97:393–398

Kruger FJ (1999) The Bushveld Complex unconformity related ore deposits: an isotopic perspective. In: Stanley CJ et al (eds) Mineral deposits: processes to processing. Balkema, Rotterdam, pp 737–738

Kruger FJ (2003) Filling the Bushveld Complex magma chamber: intra-chamber magma dynamics and the generation of giant chromite and PGE deposits. Appl Earth Science (Trans Inst Min Metall B) 112: B208–B209

Kruger FJ, Marsh JS (1985) The mineralogy, petrology and origin of the Merensky Cyclic Unit in the Western Bushveld Complex. Econ Geol 80: 958–974

Lee CA (1996) A review of mineralisation in the Bushveld Complex and some other layered intrusions. In: Cawthorn RG (ed) Layered intrusions. Elsevier, Amsterdam, pp 103–146

Maier WD, Barnes SJ (1998) Concentrations of rare earth elements in silicate rocks of the Lower, Critical and Main Zones of the Bushveld Complex. Chem Geol 150:85–103

Maier WD, Barnes SJ (1999) Platinum-group elements in silicate rocks of the Lower, Critical and Main Zones at Union Section, Western Bushveld Complex. J Petrol 40:1647–1671

Maier WD, Eales HV (1994) A facies model for the interval between the UG2 chromitite and Merensky Reef, western Bushveld Complex. Appl Earth Science (Trans Inst Min Metall B) 103:B22–B30

McCandless TE, Ruiz J (1991) Osmium isotopes and crustal sources for platinum-group mineralisation in the Bushveld Complex, South Africa. Geology 19:1225–1228

McDonald I, Irvine GJ, de Vos E, Gale AS, Reimold WU (2005) Geochemical search for impact signatures in possible impact-generated units associated with the Jurassic-Cretaceous boundary in southern England and northern France. In: Cockell C, Gilmour I, Koeberl C (eds) Biological Processes Associated with Impacts. Spinger, Berlin, Heidelberg, New York pp 101–131

van der Merwe MJ (1976) The layered sequence of the Potgietersrus lobe of the Bushveld Complex. Econ Geol 71:1337–1351

van der Merwe MJ (1998) Platiniferous horizons of the Potgietersrus lobe of the Bushveld Complex. In: 8th internaional platinum symposium. S Afr Inst Min Metall Symposium Series S18:407–409

Naldrett AJ, Gasparrini EC, Barnes SJ, von Gruenewaldt G, Sharpe MR (1986) The Upper Critical Zone of the Bushveld Complex and a model for the origin of Merensky-type ores. Econ Geol 81:1105–1118

Peck DC, and Keays RR (1990) Geology, geochemistry and origin of platinum-group element-chromite occurrences in the Heazlewood River Complex, Tasmania. Econ Geol 85:765–793

Schiffries CM (1982) The petrogenesis of a platiniferous dunite pipe in the Bushveld Complex: infiltration metasomatism by a chloride solution. Econ Geol 77:1439–1453

Scoon R, Mitchell AA (2002) The Merensky Reef at Winnaarshoek, Eastern Bushveld Complex: insights from a wide reef facies. In: Boudreau A (ed) 9th international platinum symposium, extd abstracts, Billings, Montana, pp 401–404

Sharpe MR (1981) The chronology of magma influxes to the eastern compartment of the Bushveld Complex as exemplified by its marginal border groups. J Geol Soc Lond 138:307–326

Stumpfl EF, Rucklidge JC (1982) The platiniferous pipes of the Eastern Bushveld. Econ Geol 77:1419–1431

Taylor SR, McLennan SM (1985) The continental crust: its composition and evolution. Blackwell, Oxford

Tegner C, Wilson JR, Brooks CK (1993) Intraplutonic quench zones in the Kap Edvard Holm layered gabbro complex, East Greenland. J Petrol 34: 681–710

Tredoux M, Lindsay NM, Davies G, McDonald I (1995) The fractionation of the platinum-group elements in magmatic systems with the suggestion of a novel causal mechanism. S Afr J Geol 98:157–167

Vermaak CF (1995) The Platinum-Group Metals—A Global Perspective. Mintek, Randburg

Vermaak CF, Hendriks LP (1976) A review of the mineralogy of the Merensky Reef, with specific reference to new data on the precious metal mineralogy. Econ Geol 71:1244–1268

Viljoen MJ, Schürmann LW (1998) Platinum-group metals. In: Wilson MGC, Anhaeusser CR (eds) The mineral resources of South Africa. Coun Geosci Handbook 16:532–568

Viljoen MJ, Scoon RN (1985) The distribution and main geologic features of discordant bodies of iron-rich ultramafic pegmatite in the Bushveld Complex. Econ Geol 80:1109–1128

Von Gruenewaldt G, Hulbert LJ, Naldrett AJ (1989) Contrasting platinum-group element concentrations in cumulates of the Bushveld Complex. Mineral Deposita 24:219–229

Wagner PA (1929) The platinum deposits and mines of South Africa. Oliver and Boyd, Edinburgh

White JA (1994) The Potgietersrus prospect – geology and exploration history. In: Anhausser CR (ed) Proceedings XVth CMMI Congress. S Afr Inst Min Metall, Johannesburg, vol. 3, pp 173–181

Willemse J (1969) The geology of the Bushveld Complex: the largest repository of magmatic ore deposits in the world. Econ Geol Monograph 4: 1–22