



Litho- and chemostratigraphy of the Flatreef PGE deposit, northern Bushveld Complex

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Abstract

The Flatreef is a world-class platinum-group element (PGE) deposit recently discovered down-dip from existing mining and exploration operations on the northern limb of the Bushveld Complex. Current indicated resources stand at 42 Moz PGE (346 Mt with 3.8 g/t Pt+Pd+Rh+Au, 0.32% Ni and 0.16% Cu) which, in the case of Pt, is equivalent to ~10 years global annual production, making it one of the largest PGE deposits on earth. The grade and thickness of the Flatreef mineralised interval is highly unusual, with some drill core intersections containing up to 4.5 g/t Pt+Pd+Rh+Au over 90 m in drill core. Here, we document the down-dip and along-strike litho- and chemostratigraphy of the Flatreef and its footwall and hanging wall rocks, based on a diamond drill core database totalling >720 km. At the base of the sequence intersected in the drill cores are up to 700-m-thick sills of ultramafic rocks (dunite, harzburgite, pyroxenite) emplaced into pelitic, dolomitic, and locally quartzitic and evaporitic rocks belonging to the Deutschland Formation of the Transvaal Supergroup. Next is an approximately 100–200-m sequence of low-grade-sulphide-mineralised, layered mafic-ultramafic rocks containing abundant sedimentary xenoliths and, in places, several chromite seams or stringers. This is overlain by a ~100-m-thick sequence of well-mineralised mafic-ultramafic rocks (the Flatreef *sensu strictu*), overlain by a laterally persistent mottled compositional analogies at the base of >1 km of homogenous Main Zone gabbronorite. Based on stratigraphic, lithological and compositional analogies to the layered rocks in the eastern and western Bushveld Complex, we correlate the Flatreef and its chromite bearing footwall rocks with the Upper Critical Zone, notably the interval between the UG2 chromitite and the Bastard Reef as found elsewhere in the Bushveld Complex. This includes recognition of a Merensky Reef correlative. The ultramafic rocks below the main chromitite seam (UG2 correlative) in the Flatreef footwall are correlated with the Lower Critical and Lower zones. However, compared to the western and eastern Bushveld limbs, the studied sequence is strongly enriched in sulphide and PGE, many of the rocks show elevated CaO, K₂O, Rb and Zr contents, and lateral continuity of layers between drill cores is less pronounced than elsewhere in the Bushveld, whereas ultramafic units are locally considerably thickened. These compositional and lithological traits are interpreted to result from a range of processes which include contamination with calcsilicate and hornfels, intrusion of granitic magmas, and the influence of multiple structural events such as pre- to syn-emplacement regional-scale open folding and growth faults. Evidence for the existence of potholes also exists. In the shallow, up-dip portions of the project area, the entire magmatic sequence below the Main Zone becomes increasingly contaminated to the extent that individual units are somewhat more difficult to correlate between drill cores. This package represents the Flatreef as exposed in outcrop and shallow bore holes across much of the northern limb of the Bushveld Complex. The new data presented here thus indicate that the Flatreef is a relatively more contaminated up-dip extension of parts of the Critical and Lower zones.

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Introduction

The Bushveld Complex of South Africa is the world's largest layered intrusion and hosts the bulk of global PGE resources (~75%, Mudd 2012). The PGEs are currently mined in two types of deposits. Relatively narrow stratiform, but laterally extensive reefs (~1 m thick, 5–8 ppm PGE, >100 km strike) occur some 2 km above the base of the western and eastern Bushveld Complex (WBC and EBC, respectively, Fig. 1a). Type examples

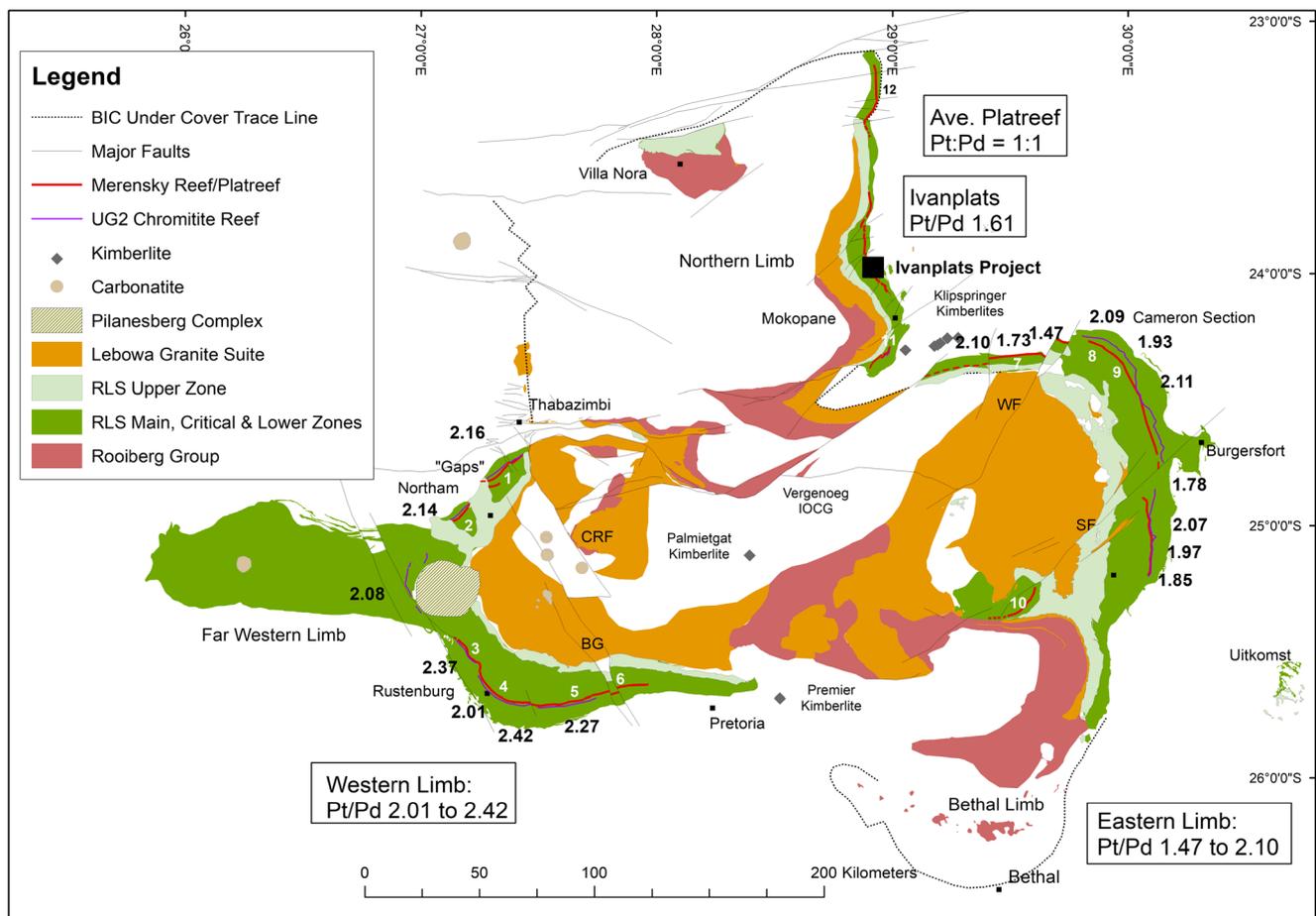


Fig. 1 a Simplified geological map of the Bushveld Complex showing localities mentioned in the text. Also shown are Pt/Pd ratios calculated from various company online resource statements for the Merensky Reef across various sectors of the Bushveld Complex. TML Thabazimbi Murchison lineament, CRF Crocodile River fault, BG Brits graben, SF Steelpoort fault, WF Wonderkop fault. 1, Amandelbult section with Tumela, Dishaba and Northam platinum mines; 2, Union platinum mine; 3, Impala platinum mines; 4, Rustenburg platinum mine; 5,

Western platinum and Karee mines; 6, Crocodile River mine; 7, Limpopo platinum mine; 8, Atok platinum mine; 9, Maandagshoek section with Modikwa platinum mine; 10, Mineral Range and Sheba's Ridge deposit; 11, Rooipoort, Moorddrift, and Grasvally farms; 12, Nonnenwerth. **b** Geological map of northern limb of the Bushveld Complex, with localities mentioned in text (modified after Ashwal et al. 2005). **c** Geological map of the Turfspruit farm displaying the position of Shaft #1, important drill holes and section lines discussed in text

are the Merensky Reef and UG2 chromitite. These reefs are largely mined underground and have been exploited for much of the last 100 years, but they have become economically marginal in the last decade, in the wake of increasing production costs. The second deposit type being exploited in recent years is thicker with lithologically and compositionally more heterogeneous zones of mineralisation (typically > 10 m thick, with up to 3–4 ppm PGE). Economically viable mineralised zones are located near the basal contact of the northern limb of the complex (Fig. 1a, b), normally referred to as “Platreef” (Van der Merwe 1976). This has been mined in large open pits at Anglo Platinum's Mokgalakwena mine since 1990 and is more profitable, mainly because the mineralised zone is wider, production costs are lower and working conditions are safer.

Since the discovery of the two different types of deposits by Hans Merensky and his associates in the 1920s (Merensky 1926; Wagner 1929), debate has continued about the stratigraphic correlation between the Platreef and the Merensky reef of the WBC and EBC (e.g., Maier et al. 2008; McDonald and Holwell 2011, and references therein). This is an important question for the exploration and mining industry because an understanding of the stratigraphy of a deposit is critical in generating greenfields and brownfield targets. In the present paper, we aim to resolve this question by documenting the litho- and chemostratigraphy of the Flatreef PGE deposit, a down-dip extension of the Platreef, recently discovered by Ivanhoe Mines on the farm Turfspruit. Based on the inspection and analysis of more than 720 km of diamond drill core intersections of

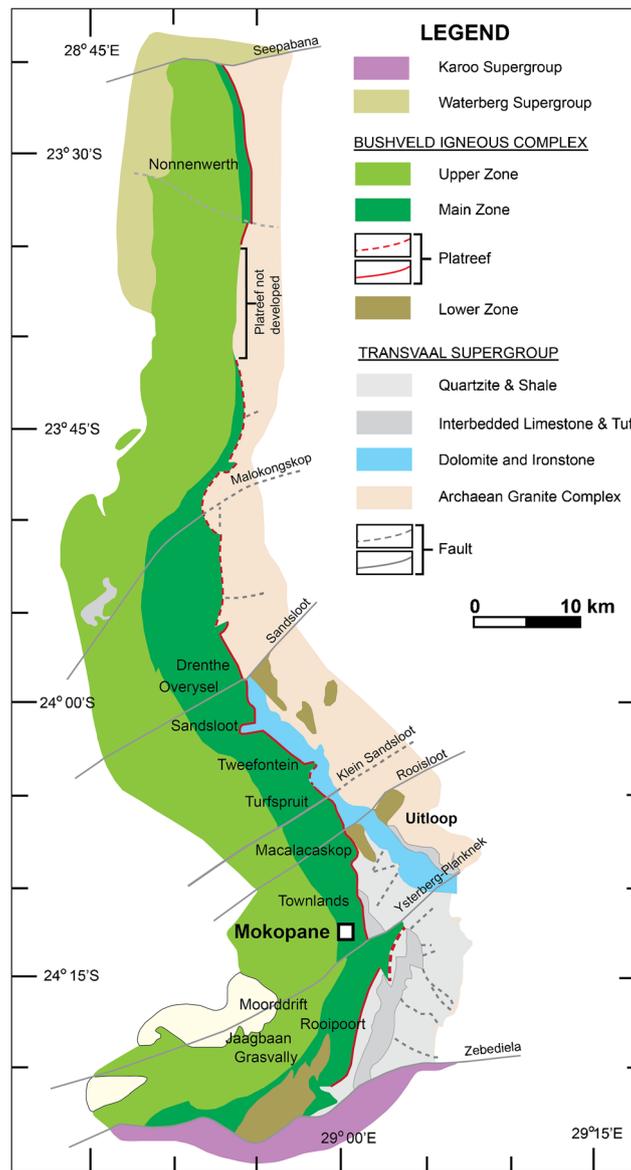


Fig. 1 (continued)

the Bushveld rocks, we show that the Flatreef sequence contains strong similarities to the Upper Critical Zone in the WBC and EBC and go on to suggest that these stratigraphic sequences can be correlated.

Stratigraphy of the mafic-ultramafic rocks of the western and eastern limbs of the Bushveld Complex

The mafic-ultramafic rocks of the Bushveld Complex are collectively grouped into the Rustenburg Layered Suite (RLS) which, in the well-characterised western and eastern limbs, is sub-divided into five stratigraphic zones, including the Marginal

Zone, Lower Zone (LZ), Critical Zone (CZ), Main Zone (MZ) and Upper Zone (UZ) (Hall 1932). In the WBC and EBC, these zones form a contiguous, 6–8-km-thick package of rocks.

At the base is the Marginal Zone, consisting of up to several hundreds of metres of quenched to fine-grained norite and gabbro-norite (Sharpe 1981).

The LZ consists predominantly of interlayered harzburgite, dunite and orthopyroxenite. Plagioclase is rarely present as a cumulate phase (Cameron 1978; Teigler and Eales 1996). Chromite makes up < 1 modal % in most LZ rocks, irrespective of lithology. The LZ shows pronounced lateral variation in thickness and lithology. It may reach a thickness of > 1 km in certain trough structures, but it is thinner or absent above swells between the troughs.

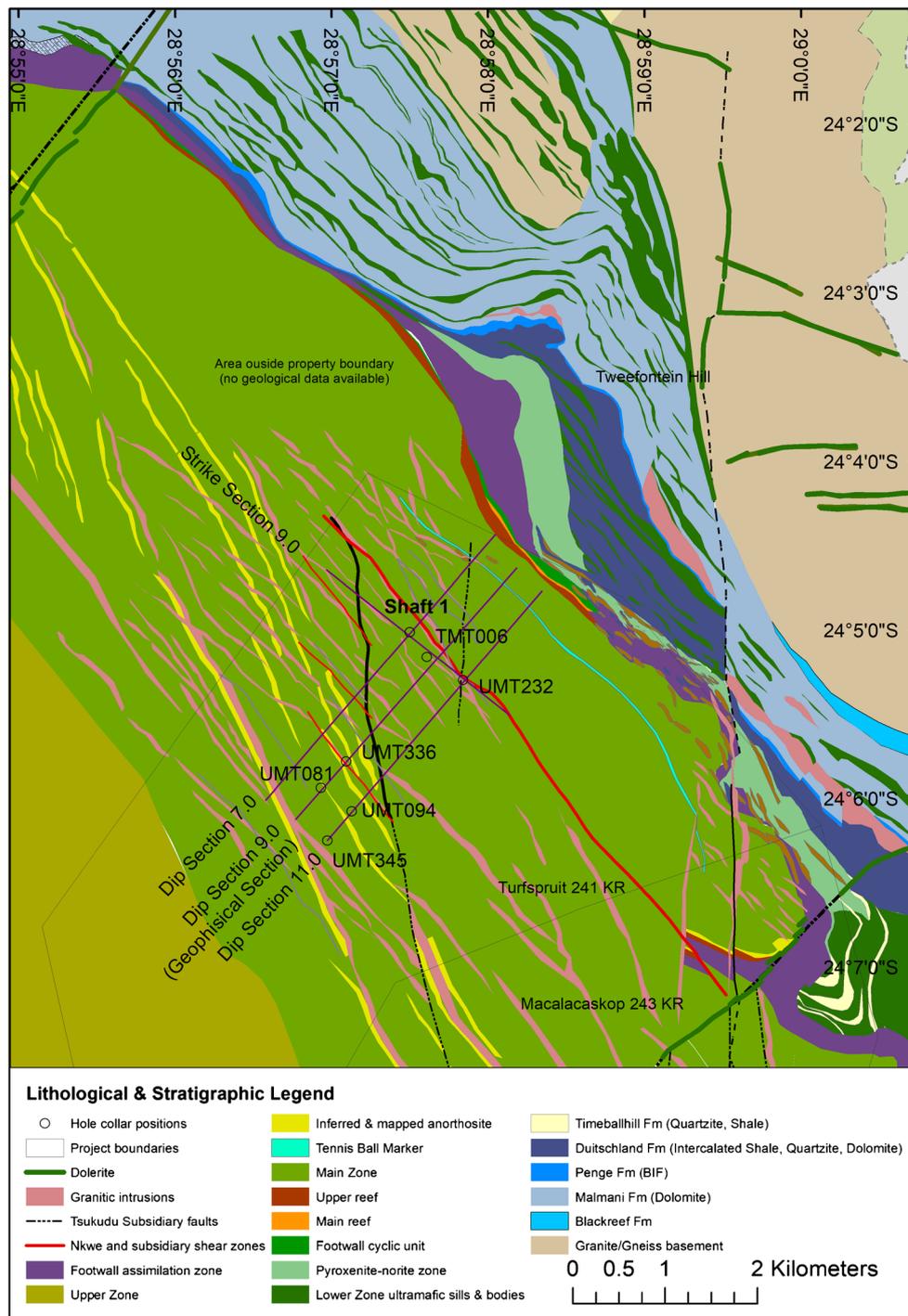


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The Critical Zone is subdivided into a lower and an upper portion. The 700–800-m-thick Lower Critical Zone (LCZ) consists predominantly of orthopyroxenite. There are nine major chromitite seams (Lower Group/LG seams 1–7 and Middle Group/MG seams 1–2). The seams have been correlated, albeit at highly variable thickness, across much of the WBC and EBC (Cousins and Feringa 1964; Teigler and Eales

1996). The base of the LCZ has been placed either at the level where there is a significant increase in intercumulus plagioclase (from 2 to 6%: Cameron 1978), or ~200 m lower, at the top of the main olivine-rich interval (Teigler and Eales 1996).

The base of the 500-m-thick Upper Critical Zone (UCZ) is defined by the first occurrence of anorthosite, forming a laterally continuous, 1–3-m-thick layer. Further anorthosite layers

occur in the upper portion of the UCZ, but the main lithologies are orthopyroxenite (~70 %) and norite (~25 %) (Teigler and Eales 1996). Olivine-bearing rocks (harzburgite and troctolite) make up < 1 % of the UCZ and are largely confined to the northwestern Bushveld (Viljoen et al. 1986a, b; Eales et al. 1988; Maier and Eales 1997) where they form part of the Merensky and Pseudo Reefs, consisting of decimeter- to meter-wide coarse-grained to pegmatoidal orthocumulate layers. In addition to abundant disseminated chromite, the UCZ contains four to five major chromitite seams, including Middle Group (MG) seams 3 and 4 and Upper Group (UG) seams 1 to 3, as well as dozens of minor seams and stringers including those bracketing the Merensky Reef pegmatoid.

Particularly typical of the UCZ are so-called cyclic units (Cameron 1982; Eales et al. 1986, 1988, 1990). These tend to be characterised by basal chromitite, overlain by harzburgite and/or pyroxenite, norite and then anorthosite. The thicknesses of the units range between a few centimetres to several 100 metres (Eales et al. 1990). Platinum-group element mineralization may be concentrated in the basal ultramafic portions of many cyclic units, particularly in the economically important Merensky Reef and UG2 chromitite, as well as the sub-economic Pseudo Reef and Bastard Reef.

The bulk of the MZ consists of relatively massive norite and gabbro-norite with typically 10–30% orthopyroxene, 10–20 % clinopyroxene, and about 50% plagioclase. Intervals that show distinct layering on a hand specimen- or outcrop-scale are rare.

The approximately 1–2-km-thick UZ consists of cyclic units of magnetitite, gabbro-norite, anorthosite and, in the uppermost portions of the sequence, ferrodiorite (Molyneux 1970; Von Gruenewaldt 1970). Up to 26 magnetite layers are known from the eastern and western limbs (Cawthorn and Molyneux 1986; Tegner et al. 2006), measuring between a few centimetres to > 10 m in thickness (magnetite layer 21).

Regional geology of the northern limb of the Bushveld Complex

The northern limb of the Bushveld Complex is separated from the remainder of the complex by a craton-wide linear structure called the Thabazimbi–Murchison Lineament (TML, Fig. 1a). In the area around Mokopane, the near-surface expressions of the lineament are the Zebediela and Ysterberg–Planknek Faults (Fig. 1b). These faults compartmentalize the northern limb and disrupt the magmatic stratigraphy (Van der Merwe 1976). It has been proposed that the TML exercised some control over the structure of the magma chamber and the mode of magma injection, possibly acting as a feeder (Kinnaird et al. 2005).

The geology of the northern limb has been described in numerous publications (see summaries in Wagner 1929; Van der Merwe 1976; Maier et al. 2008; McDonald and Holwell 2011; Kinnaird and Nex 2015). In contrast to the western and eastern

limbs of the complex where the layered mafic-ultramafic rocks largely intruded into, or on top of, the Magaliesberg quartzite, in the northern limb the complex has been regionally transgressive relative to the floor rocks. Thus, in the southernmost sector of the northern limb, i.e. to the south of the Planknek–Ysterberg fault, the Rustenburg Layered Suite (RLS) overlies the Magaliesberg quartzite, whereas towards the north, the RLS progressively transgresses through the entire Transvaal Supergroup until, from the farm Drenthe northwards, it overlies the Archean basement (Fig. 1b). Concurrent to these regional transgressive relationships the igneous sequence undergoes significant lithological change; south of the Ysterberg–Planknek fault, on the farm Grasvally, the available evidence suggests that the RLS forms a compact, > 3.2-km-thick sequence, consisting of LZ, UCZ, MZ and UZ (Hulbert 1983). A succession of intercalated gabbro-norite-pyroxenite and anorthosite units occurring at the stratigraphic level of the Platreef/UCZ was termed the GNPA (gabbro-norite, pyroxenite, anorthosite) member by Hulbert (1983), Maier et al. (2008) and Smith et al. (2014). The LCZ and the lower portions of the UCZ (including the UG1 chromitite) appear not to be developed on Grasvally and, to date, have also not been recognised further to the north. On the farm Rooipoort, immediately to the north of Grasvally, the LZ is no longer directly overlain by the UCZ, but separated from the latter by a zone of microgabbro and metasedimentary rocks several tens of metres thick (Maier et al. 2008). Further towards the north, rocks correlated with the LZ form numerous sill-like bodies within the sedimentary floor rocks (Van der Merwe 1976; Yudovskaya et al. 2013).

Of key interest for the present study are the compositional changes affecting the rock sequence at the stratigraphic level of the Platreef along strike and down-dip in the northern limb. The earliest workers proposed that the mineralised rocks geographically located to the north of the TML are stratigraphic equivalents of the UCZ (Wagner 1929; Merensky 1926). Evidence supporting this interpretation is the presence of PGE-rich sulphide mineralisation within pyroxenitic and noritic-anorthositic rocks of broadly similar composition as the Merensky Reef, stratigraphically located below the Main Zone. Van der Merwe (1976) concurred with this interpretation, but since he could not establish a clear stratigraphic subdivision for the UCZ in this area he coined the term Platreef for the mineralised sequence in the Northern limb. However, the stratigraphic correlation to the UCZ elsewhere in the BIC has remained controversial, partly because the outcropping mineralised rocks in the northern limb are more contaminated and altered than the UCZ in the remainder of the Bushveld Complex, and they show more variation in thickness and composition along strike (Gain and Mostert 1982; Barton et al. 1986; Cawthorn et al. 1985; White 1994; Armitage et al. 2002; Manyeruke et al. 2005; Kinnaird et al. 2005; McDonald et al. 2005; Maier et al. 2008; McDonald and Holwell 2011; Smith et al. 2014; Kinnaird and Nex 2015).

Throughout much of the northern limb, the Platreef is overlain by up to 2 km of relatively homogenous gabbro-norite, generally accepted to be a correlative of the Main Zone in the WBC and EBC (Wagner 1929; van der Merwe 1976; Ashwal et al. 2005). In places, the lower portion of the MZ appears to pinch out, such as on Nonnenwerth and the Aurora project. In the far north, the basement is overlain by rocks with the chemical signature of the central to upper MZ (Manyeruke 2007; Maier et al. 2008; McDonald et al. 2016). Within the latter, there is a thick, mineralised troctolitic-harzburgitic interval that does not have a stratigraphic analogue in the remainder of the Bushveld (van der Merwe 1978). Overlying the Main Zone is the UZ which hosts more than 20 massive magnetite layers (van der Merwe 1978; Ashwal et al. 2005), analogous to the remainder of the Bushveld Complex. The roof rocks are mostly granites. Notably, in the Waterberg project, to the north of the Aurora project, the RLS significantly decreases in thickness, with the UZ locally pinching out or being unconformably overlain by the Waterberg red beds (Huthmann et al. 2016; Kinnaird et al. 2017).

Geology of the farm Turfspruit and discovery of the Flatreef

On the farm Turfspruit, located some 15 km to the north of Mokopane (Fig. 1b, c), the basal part of the RLS intruded shallow-marine to shelf-deposited clastic sediments of the Deutschland Formation, stratigraphically situated at the base of the Pretoria Group of the Transvaal Supergroup (Bekker 2001). Geophysical and drill core data indicate numerous sills of interpreted LZ and Platreef/CZ (Fig. 1c). The base of the contiguous RLS appears to be situated close to the unconformity of the Deutschland Formation with the platform carbonates of the Chuniespoort Group (Bekker 2001), but some LZ bodies (Uitloop) occur near the base of the Transvaal Supergroup (Yudovskaya et al. 2013). To the north of Turfspruit, the RLS transgresses the contact between the Chuniespoort and Pretoria Groups, stoping into banded ironstones of the Penge Formation and dolomites of the Malmani Subgroup that is situated towards the base of the Transvaal Supergroup.

The Deutschland Formation attains a maximum thickness of approximately 1000 to 1200 m and is sub-divided into two by a clear sequence boundary. Below this boundary, the formation is characterised by a basal conglomerate and diamictite unit overlain by thick carbonaceous shale and interbedded carbonates that formed in a deep-water environment (Bekker 2001). The sequence boundary reflects the change from shallow-marine to shelf-clastic sediments and is marked by a conglomerate at the base of a quartzite unit which is upward fining into shales that form the base of two shale-carbonate cycles. The carbonates are limestone and dolomite, with

dolomite dominating higher in the formation (Eriksson et al. 2001; Bekker 2001).

Surface exposure of the Platreef on Turfspruit is limited, but good outcrop of the igneous rocks and the sedimentary footwall is available in the Dithokeng stream section situated north of Tweefontein hill. Based on drill core data from the farm Tweefontein 238 KR, Kinnaird et al. (2005) showed that the sedimentary rocks contain sills of Platreef. In total, the Platreef is approximately 400 m thick at this locality and consists of medium-grained melanorite containing numerous centimetre- to metre-sized xenoliths of hornfels and calcsilicate. The contact to the MZ is marked by a definitive mottled anorthosite of variable thickness.

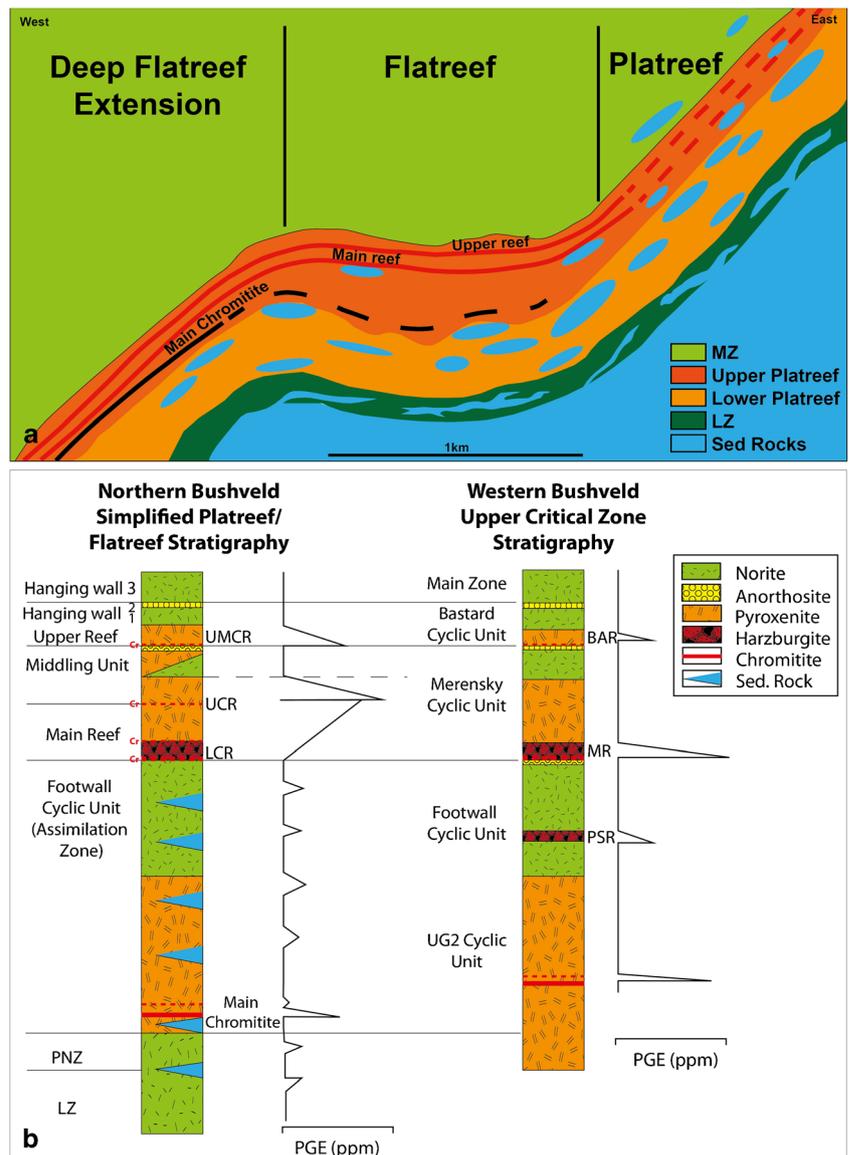
In 1998, Ivanplats, the local subsidiary of Ivanhoe Mines Ltd, acquired a prospecting licence for the Turfspruit and Macalacaskop farms. The initial exploration focus was on the delineation of mineralization that could support open-pit mining to a depth of 400 m below surface. In 2007, Ivanplats commenced a deep drilling program to investigate the continuity and grade in an area targeted as having underground mining potential. This led to the discovery that, at a depth of around 600 m, the dip of layering flattens temporarily (for about 1–2 km in the dip-direction) from $\sim 40^\circ$ to the sub-horizontal. This sub-horizontal section is characterised by thickened mineralised layered units termed the “Flatreef” (Kekana 2014). In the western most portions of Turfspruit, the layering resumes its normal $\sim 40^\circ$ westerly dip (Fig. 2a). Grobler et al. (2012) introduced the Turfspruit Cyclic Unit (TCU) and proposed correlations to UCZ equivalents as found elsewhere in the BIC. In turn, Yudovskaya et al. (2017) recognised an Upper and a Main reef and presented geochemical and mineralogical evidence for correlation of the latter with the Merensky Reef. Drilling has to date traced the mineralised layers to a depth of ~ 1.8 km, some 3–4 km west of the surface outcrop of the Platreef.

The Flatreef discovery is significant as it displays well mineralised, thickened layered magmatic strata lending itself to bulk underground mining, a first with regards to PGE mining in South Africa. The most recently declared mineral resource figures for the Flatreef and its downdip extension are 42 Moz 4E (346 Mt with 3.8 g/t Pt+Pd+Rh+Au, 0.32% Ni and 0.16% Cu) (<https://www.ivanhoemines.com>). The Pt content is equivalent to > 10 years of the current global annual production, making it one of the largest PGE deposits on earth.

Samples and methods

On the Ivanplats exploration properties, a total of 724,000 m were drilled, of which 529 600 m were focussed on evaluation of the Flatreef underground deposit (UMT and TMT drill cores). More than 251,000 samples were assayed for the six major elements of economic interest (Pt, Pd, Rh, Au, Cu, Ni)

Fig. 2 **a** Schematic plot showing relationship between Platreef, Flatreef and downdip extension of mineralised sequence on the farm Turfspruit, and position of main mineralised zones. Sedimentary blocks are remnants of metamorphosed xenoliths partially melted and assimilated by intruding Bushveld magma. **b** Comparison of stratigraphy of Platreef/Flatreef with UCZ in western Bushveld Complex



as well as S and Cr. Ivanplats followed a 100-m exploration grid (infilled to 50-m spacing in some instances) to declare an *indicated resource* for the underground deposit. The holes were all near-vertical at their collars, but with depth, the holes tend to incline less steeply. The average drillhole length is 1047 m, minimum drillhole length is 413 m and the maximum drillhole length is 1973 m. Final core logging and interpretation was performed along dip-section lines as logging of individual drill holes in isolation proved to be inadequate for stratigraphic interpretation. Final section logging was done in conjunction with simultaneous data capturing and geological modelling in *Leapfrog®* software. For the underground resource drilling program of the Flatreef deposit, assay sampling was initiated 5 m above the Flatreef (in the Main Zone). Samples were taken continuously through the Flatreef and extended, for most drillholes, 20 m into the igneous or

sedimentary footwall rocks. All drill cores within the Flatreef were sampled for assaying. The nominal sample length is 1 m, with a maximum of 1.25 m and a minimum of 0.3 m. Sample lengths were constrained by lithological contacts.

Sample analysis is described in detail within the Platreef 2017 Feasibility Study (Peters et al. 2017) which conforms to an Independent NI 43-101 Technical Report using Canadian National Instrument 43-101 Standards of Disclosure for Minerals Projects (NI 43-101). Ultra Trace (Bureau Veritas Minerals) is the main commercial laboratory used to analyse exploration samples. The laboratory used a multi-acid digestion process followed by inductively coupled plasma-optical emission spectroscopy (ICP-OES) to determine total Ni, Cu, Cr and sulphur. Some samples were also assayed for sulphur using a LECO furnace (controlled combustion of sample pulp

with infrared reading of SO₂ gas); the LECO and ICP sulphur results show close agreement. Lead collector fire assays with an ICP-MS finish were used to determine Pt, Pd and Au. Samples submitted for Rh analysis were assayed by fire assay using lead collection and palladium collection followed by inductively coupled plasma-mass spectrometry (ICP-MS).

A number of samples were analysed by Set Point laboratories (Torre Industries) who utilized the following assay methods: fire assay lead collection followed by ICP-MS for Au, Pt and Pd; total acid digestion followed by ICP-OES for Cu and Ni; bulk rock S by Leco carbon-sulfur analyzer; fire assay Pd collection followed by ICP-MS for Au, Pt and Rh; NiS collection for Au, Pt, Pd, Rh, Ir, Ru and Os.

An extensive set of certified reference materials (CRMs) and blanks were analysed with the exploration samples. These included reference materials from the laboratories as well as an extensive suite of as many as nine different CRMs from African Mineral Standards (AMIS, Johannesburg). The average BVM results are accurate to within 5% of the certified value for the main elements of interest (Ni, Pt, Pd, Au, Cu and S). Detailed sampling- and QA&QC information is available in Peters et al. (2017) and other previously released company reports available on www.sedar.com.

In order to further constrain the stratigraphy of the Flatreef and its host rocks, we have generated whole-rock chemical data for 18 drill cores across the project area. Amongst these drill cores are intersections of the mineralised sequence which include samples from the lowermost units of the Main Zone continuing into the immediate footwall of the Flatreef (e.g. UMT 232, TMT 006-D2), but also drill core samples of the entire stratigraphy from the Main Zone into the Lower Zone (UMT 336, 345, 81, 94) (Fig. 1b). Samples were taken from pulps collected from the 1-m-length PGE+Ni+Cu exploration samples submitted to Bureau Veritas Minerals during the exploration phase. Major and trace element analyses were conducted by XRF. Base metal and precious metal analyses were undertaken by multi-acid digestion followed by ICP-MS and OES. Most assays were performed by BVM, with a limited number analysed by Setpoint Laboratories.

Lithostratigraphy

Introduction

The establishment of a stratigraphic system is essential, in near-mine and regional exploration for PGE reefs, but has proven challenging on Turfspruit (and elsewhere on the northern limb) because of the following factors: (i) limited outcrop; (ii) the near surface sequence is locally strongly contaminated with sedimentary floor rocks, resulting in the presence of abundant xenoliths and strong alteration of some lithologies; and (iii) individual layers show considerable thickness

variation between drill cores. Thus, the only units that can be confidently placed into an existing stratigraphic system are the Main Zone (Kinnaird et al. 2005) and the Lower Zone (Yudovskaya et al. 2013). In the following sections, we present a detailed description of the Flatreef and its hostrocks, with the aim to provide a lithostratigraphic framework for the sequence in the northern limb which is correlated with Bushveld rocks found elsewhere.

Main Zone

Because the Main Zone is the lithologically least variable unit of the studied sequence, with several marker layers traceable along the entire strike length and dip-extent of the project area, it serves as a useful frame of reference and will be described first. Up to 1450 m (apparent thickness) of Main Zone rocks are exposed in individual drill cores at Turfspruit, permitting a comprehensive study of this interval.

In most drill cores, the Main Zone consists largely of gabbronorite, coded Hanging Wall 3 (HW3) in Fig. 2b, that is massive on a scale of tens of metres. Three units have been informally assigned to ‘marker horizon’ status by Ivanhoe geologists: (i) the ‘Tennis Ball Marker’ (TBM) is situated approximately 280 m above the base of the MZ. The TBM is named after up to 5-cm-wide melanorite-pyroxenite spheres within gabbronorite (Online resource 1a, b). Notably, a similarly named horizon in the EBC occurs in the upper MZ (von Gruenewaldt 1966) and is thus not a stratigraphic correlative of the layer described here. (ii) The ‘Basal Melagabbronorite’ (BMGN) is a 30-m-thick melanocratic gabbronorite layer situated 30 m below the downwards. It generally displays a gradational top contact grading from mesocratic gabbronorite to melanocratic gabbronorite. A “middling” gabbronorite is occasionally developed. The basal contact is either sharp, or gradational into finely layered leuco-gabbronorite below. (iii) Between the TBM and the BMGN is the Ping Pong Marker (PPM), another, fairly continuous layer within the MZ. The PPM is, on average, around 5 m thick and consists of a horizon of erratically dispersed centimetre-scale anorthositic spheres, globules or blebs, within a gabbronorite horizon (Online resource 1c). The PPM can be traced within the eastern and southeastern parts of the property, but has also been recorded (with slightly less continuity) within the central and down-dip western parts of the property. Interestingly, the marker units show a gentle westerly dip of 25°–35°, whereas the Flatreef dip is subhorizontal to 35°–45° to the west.

Certain intervals of more pronounced layering of gabbronorite, melagabbronorite and mottled anorthosite within the MZ may display well-developed cyclic units resembling those in the UCZ. Features observed include reversed grading to progressively more mafic rocks (e.g. at 300–302 m in drill core UMT263) and thin melanocratic layers above a thicker melanocratic unit (UMT336 ~ 755 m). In some cases, the base

of cyclic units is relatively fine grained (UMT081 951 m), possibly reflecting intraplutonic quenching. Anorthosite layers are relatively rare. They usually measure from a few centimetres to a few metres in thickness and typically contain mottles (oikocrysts) of anhedral pyroxene that may become progressively elongated towards the contacts of the layers (e.g. UMT81, 260 m; UMT421, 105 m). Autoliths or xenoliths of ultramafic rocks and of anorthosite are observed in several drill cores, whereas calcsilicate and hornfels xenoliths are rare. In places, cm-dm wide veins of ultramafic rock enriched in coarse-grained pyroxene have been observed (UMT345, 935.5 m).

Flatreef

The Flatreef is the down-dip extension of the Platreef, forming a laterally continuous, sub-horizontal sequence of PGE-mineralised magmatic cyclical units of interlayered chromitite-pyroxenite-norite-anorthosite, several tens to locally > 100 m in thickness, found along the base of the Main zone of the Northern Limb (Fig. 2b).

The uppermost unit of the Flatreef is a laterally highly continuous mottled anorthosite, termed Hanging wall unit 2 (HW2) (Fig. 2b, thickness 0.3–30 m, averaging 4.2 m). The anorthosite may contain autoliths of ultramafic rocks (e.g. in drill core UMT390 at 640.1 m). In several drill cores, the mottles near the base of the layer (and sometimes along its top contact) are highly elongated (Fig. 3a), whereas the host pyroxenite/norite is undeformed (UMT081, 411 and 402). Below the anorthosite are typically 0–20 m of interlayered mela- and leucogabbronorite (HW1, Fig. 2b), but in some drill cores, the transition zone between the Main Zone and the Flatreef (i.e. HW1 and HW2) can comprise up to 60 m of interlayered pyroxenite, norite, mottled anorthosite and gabbro, with sporadic low-grade sulphide mineralisation occurring in both anorthosite and pyroxenite (e.g. UMT314, 336). The pyroxenite layers/lenses are commonly altered near their bottom and top contacts.

Below the layered mafic-ultramafic interval of HW1 is a 5–10-m-thick pyroxenite that is commonly mineralised within its basal 2–5 m, with a thin (0–2 mm), poorly developed, basal chrome stringer (Fig. 3b–d). The mineralised rocks have been grouped as the ‘Upper Reef’ by Yudovskaya et al. (2017) (Fig. 2b).

In many drill cores, notably in the relatively deep western and south-central portions of the property, the Upper Reef is underlain by a 14–100-m interval of interlayered pyroxenite-norite-anorthosite (Fig. 3e), locally containing up to several 100 ppb PGE in pyroxenite. In the relatively shallow central and eastern portions of the property, the layered feldspathic interval is rarely present, such that the Upper Reef directly overlies typically unmineralised medium grained feldspathic orthopyroxenite. Both the interlayered pyroxenite-norite-

anorthosite and the feldspathic orthopyroxenite are grouped into the Middling unit (Fig. 2b).

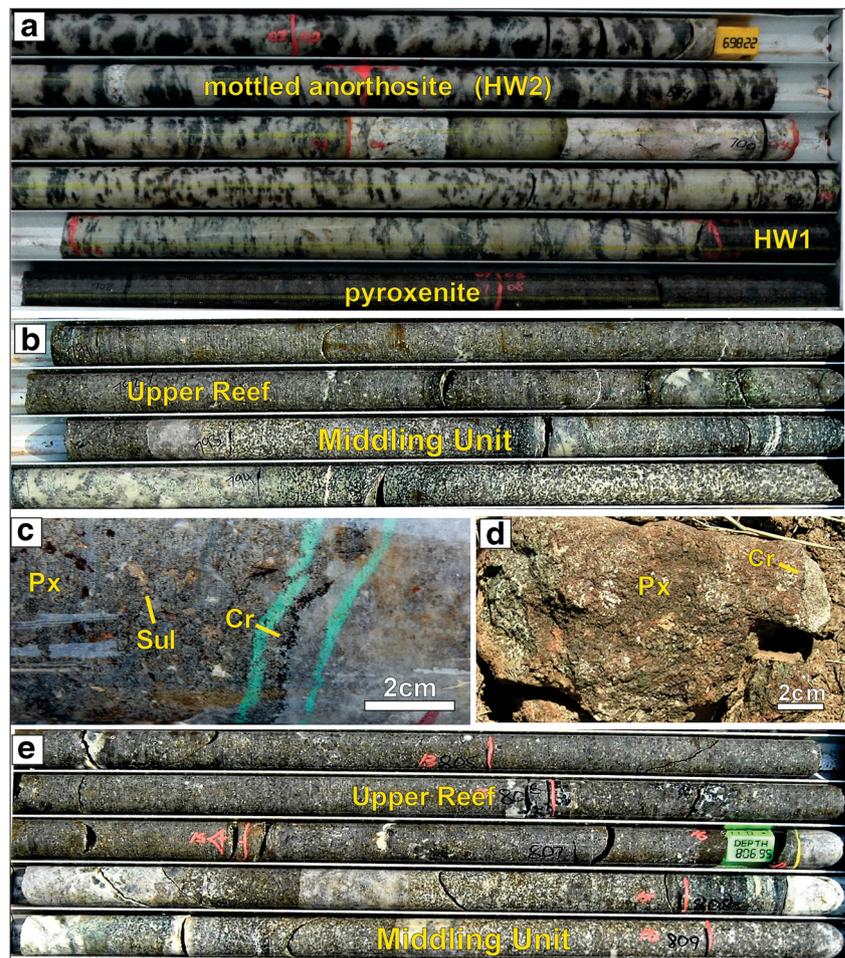
At the base of the medium-grained Middling unit is typically a 2.5–10 m sulphide mineralised orthopyroxenite with a sporadically developed upper-, and a more persistently developed basal chromitite stringer (Figs. 2b and 4a–e). The mineralised pyroxenite can reach a grade of > 10 ppm PGE as was found in drill core TMT006, the richest intersection in the Flatreef. It is underlain by a pegmatoidal ultramafic layer that consists of orthopyroxenite and/or harzburgite (Fig. 4a–c). Where both lithologies are present, orthopyroxenite typically forms the upper portion of the pegmatoidal layer, and poikilitic harzburgite the lower portion (Fig. 4a, b). PGE grades are only slightly lower than in the overlying medium-grained pyroxenite, but progressively decrease with depth. The base of the pegmatoidal interval is commonly defined by a further Cr stringer (Fig. 4f–h). The pegmatoidal interval attains an average thickness across the project area of around 15 m, but can reach thicknesses of over 60 m in some areas (Peters et al. 2016). The combined mineralised interval of medium grained orthopyroxenite, pegmatoidal orthopyroxenite and poikilitic harzburgite has previously been grouped into the Main Reef by Yudovskaya et al. (2017) (Fig. 2b).

Footwall cyclic unit (FCU)

The footwall to the Main Reef is variable, depending on locality and depth below surface within the project area. Where the unit has been intersected in the deep drill cores on western and southwestern Turfspruit it consists of a 45–100-m-thick sequence of cm-dm scale layers and lenses of alternating pyroxenite-norite-anorthosite sub-units (Fig. 5a). Occasional mechanically disturbed sub-angular fragments of pyroxenite-norite-anorthosite and sediment have been noted (Fig. 5e). This stratigraphic unit has previously been termed ‘Norite Cycles’ (Kinnaird et al. 2005; Grobler et al. 2012) but is termed Footwall Cyclic Unit here. Many of the contacts between pyroxenite and anorthosite within this unit show thin (mm-thick) chromitite stringers (Fig. 5b–d). The stringers may follow both the bottom and the top contacts of the pyroxenite lenses or layers. Many of the pyroxenite layers contain disseminated sulphides, mostly near their base, but occasionally concentrated in their centre (Fig. 5d).

In contrast to the magmatic cyclic encountered in the deep western sector of the project area, the Footwall Unit below the central portion of the project area hosting the Flatreef is lithologically highly variable and consists of varied-textured (commonly pegmatoidal) pyroxenite-norite-gabbronorite containing abundant sedimentary xenoliths. Magmatic cyclicity of the Footwall Unit in this sector has only been partially preserved. The modification of magmatic rocks and absence of clear magmatic contacts rendered the identification of magmatic

Fig. 3 **a** Mottled anorthosite of HW2 showing progressively more pronounced elongation of mottles near base, and sharp contact with footwall pyroxenite, UMT411, 696–702 m. **b** Base of Upper Reef. Note interlayering of anorthosite and norite in footwall. UMT231, 790–796 m. **c** Chromitite stringer at base of Upper Reef, drill core UMT231, 793 m. (Sul sulphide, Cr chromitite stringer, Px pyroxenite). **d** Bastard Reef on farm Driekop, EBC. **e** Upper Reef pyroxenite with underlying Middling units of anorthosite and norite. UMT232, 803–810 m. Width of NQ drillcore in a–h = 4.8 cm.



stratigraphic boundaries complicated and the term ‘Footwall Assimilation Zone’ (FAZ) (Fig. 2b) is used to collectively identify these units. Detailed observations across the entire study area have shown magma-sediment assimilation processes to be highly variable in extent and intensity. Zones of assimilation can include most stratigraphic units, such as in the eastern, near-surface extent of the Platreef where the FAZ includes the Upper Reef, Middling Unit and Main Reef, as well as, locally, the lower units of the Main Zone. Further down-dip, in the Flatreef, the sediment assimilation processes are less pronounced and are limited to the strata below the Main Reef. In the western portion of the study area footwall assimilation is limited to units below the FCU.

Lithological variants in the FAZ include (1) norite with shale-hornfels xenoliths, (2) para-pyroxenite/paraharzburgite (described below) with abundant xenoliths and large bodies up to > 100 m in width and thickness of undigested, but intensely metamorphosed, dolomitic (now calc-silicate) and alumino-silicate (now hornfels) sedimentary rocks of the Deutschland Formation (Fig. 6a–c). The latter rocks may form continuous layers at this stratigraphic level, several tens to hundreds of metres in any dimension,

and they preserve bedding planes that broadly conform to the regional dip suggesting that they represent in situ relicts of the floor rocks to the RLS. Interaction between the Bushveld magma and the sedimentary rocks resulted in pervasive modification of the igneous rocks, including the formation of hybrid cumulates. This interval of pronounced interaction can be well mineralised, e.g. in the lower part of drill core TMT006.

Detailed and our own observations petrological examination by Sluzhenikin et al. (2014) indicated that the main contaminants in the Flatreef are dolomite/limestone, argillite/shale (locally enriched in anhydrite or graphite) and quartzite (the latter notably in the southern sector of the project). The nature of the contacts between the sedimentary and intrusive rocks varies from sharp to transitional. Intercalated zones of sedimentary rocks and magmatic units persist over centimetres to hundreds of metres. The degree of metamorphism, metasomatism and/or melting of the assimilated sedimentary clasts varies according to the sedimentary rock type and the magmatic unit that intruded into the sediment. Thus, argillite xenoliths are typically thermally metamorphosed to hercynite + cordierite ± plagioclase ± hypersthene hornfels

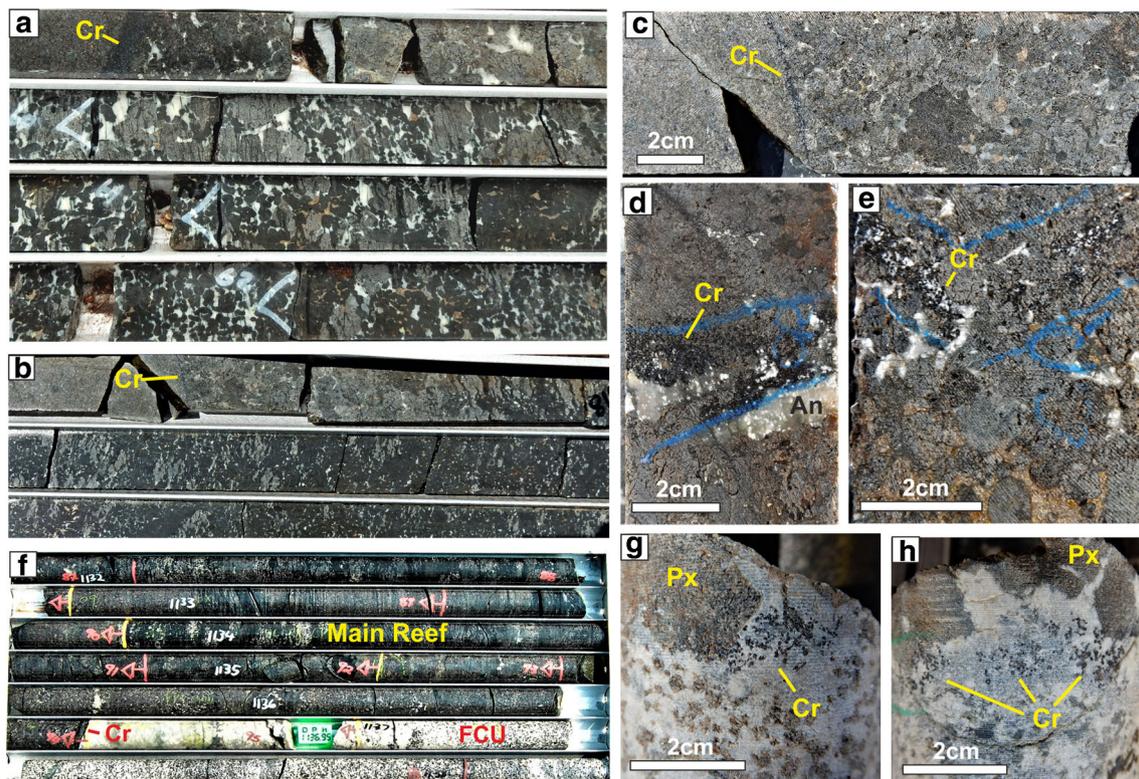


Fig. 4 Lithologies of the Main Reef. **a–c** Contact between Main Reef upper medium-grained pyroxenite and pegmatoid, defined by a Cr stringer; **a** UMT402, 793 m; **b, c** UMT448, 811 m. **d, e** Cr stringers at top of Main Reef, **d** UMT336D1, 1063.1 m, **e** UMT336D1, 1137.2 m. **f–**

h Cr stringers at contact between Main Reef and Footwall cyclic unit, **f** UMT336, 1131 m, **g, h** UMT336D1, 1066.4 m. Width of NQ drillcore is 4.8 cm (Cr chromitite stringer, Px pyroxenite).

and may have been partially or completely molten (Fig. 6b). They tend to be associated with plagioclase-bearing pyroxenite and norite units; the elevated feldspar and mica content in these units is attributed to the incorporation of partial melts and fluids derived from the clasts.

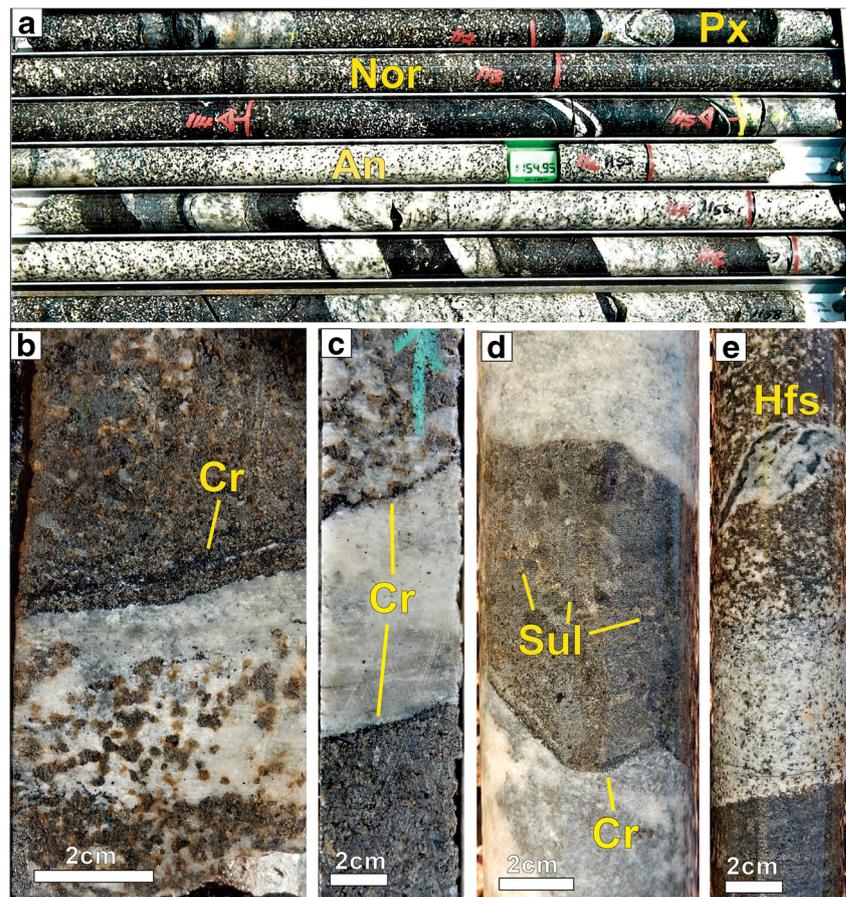
Dolomite and limestone xenoliths have been metamorphosed and melted retrograde to calc-silicate and marble, with associated metasomatic and mineral replacement processes leading to the formation of localised skarn assemblages (Fig. 6a, c).

Skarns can be developed along sedimentary bedding planes within dolomitic limestone and/or limestone and along contacts between carbonaceous xenoliths and the igneous rocks. Magnesian skarn assemblages are restricted to the contact aureoles of dolomite/limestone xenoliths. Magnesian minerals include metamorphic olivine (monticellite) and clinopyroxene (fassaite) with retrograde alteration of periclase to brucite and other alteration products (talc and serpentine) (Sluzhenikin et al. 2014). Magmatic units underwent modification due to the introduction of magnesian components at high temperatures into the magma during the assimilation process. This gave rise to the formation of so-called para-pyroxenite (clinopyroxene dominant) and para-harzburgite (serpentinised olivine dominant) rock types (Gain and Mostert 1982; White 1994; Buchanan et al. 1981).

Main chromitite seam and associated rocks

Below the norite cycles of the Footwall Cyclic Unit, notably within the central to western reaches of the farm Turfspruit, occurs a thick, laterally extensive pyroxenite unit containing intervals of massive or semi-massive chromitite (Figs. 2b and 7). Where the chromitite is massive pyroxenite (Fig. 7a, b), as is frequently the case towards the lower contact of the unit, it forms a seam that measures, on average, about 1 m in thickness. In several drill cores from the deeper western intersections, the immediate hangingwall of the seam contains up to three thin chromitite stringers (e.g. in UTM336 and UTM345; Nodder 2015). The main chromitite seam may display a mottled texture (Fig. 7c) and contain schlieren and small sub-rounded fragments of chromitite (Fig. 7d), as well as traces of plagioclase and calcite, whereas the ultramafic silicate rocks of the immediate hanging wall and footwall are essentially seam barren of plagioclase. In one drill core (UMT081), the chromitite has a narrow (1–2 cm) apophyse extending into its roof rocks. Occasionally, the footwall to the chromitite tends to be pegmatoidal pyroxenite/harzburgite (UMT081, UMT336). Nodder (2015) described the petrography, mineral and whole-rock chemistry of the chromite-rich horizon found at this stratigraphic level in drillhole UMT336 and its deflection (UMT336D1).

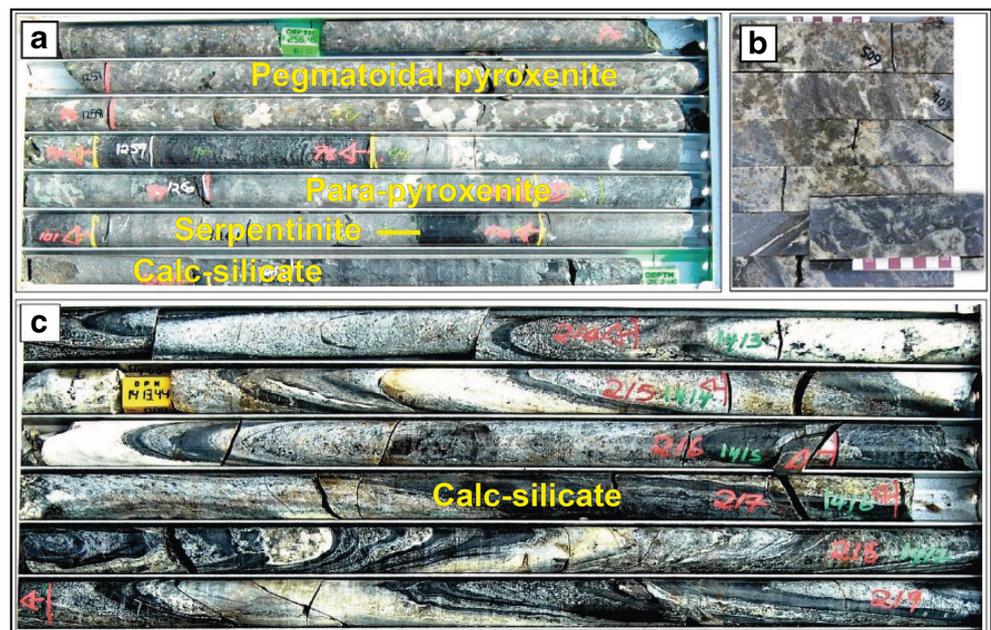
Fig. 5 The Footwall Cyclic Unit (Norite Cycles) on Turfspruit. **a** Drill core UMT336, 1151–1157 m. **b** UMT345, 1485.8 m. **c** UMT345, 1486 m. **d** UMT336, 1165.8 m. **e** UMT336, 1156.5 m. Width of NQ drillcore is 4.8 cm (Sul sulphide, Cr chromitite stringer, An anorthosite, Nor norite, Px pyroxenite, Hfs hornfels).



Selected chromitite-rich intersections from the Turfspruit project are presented in Table 1. The thickness of the seam ranges from 0.47 to 2.52 m, and chromitite content from 6.0 to 17.5 wt% Cr. PGE contents range from 2 to 6 ppm. The Pt/Pd

ratios are relatively high, e.g. at ~ 3.8 in UMT345D1 and ~ 2 in UMT081. Furthermore, in all analysed drill cores, the seam has relatively high Rh contents (Table 1). Sulfur contents reach 0.85 wt% and Cu up to 0.17 wt%.

Fig. 6 **a** Interaction between the Flatreef and sedimentary floor rocks, UMT334 at 1256–1264 m. **b** Extent and intensity of melting processes evident in drill core within some areas of hornfels-magma interaction. Note how re-release of feldspar into the mafic/ultramafic magma resulted in noritic units derived from original pyroxenite-dominant units. **c** Calc-silicate layer in UMT094, 1412.24–1418.88 m. Width of NQ drillcore is 4.8 cm



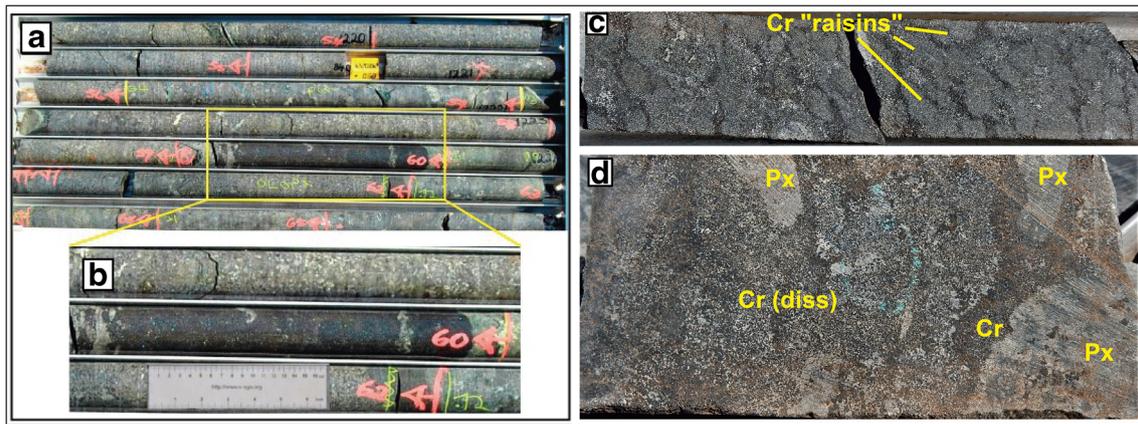


Fig. 7 **a, b** The main chromitite in UMT383, 1223.32 to 1223.79 m (modified from Parker et al. 2013). **c, d** The main chromitite in UMT336D1, 1211.95–1212.8 m. Width of NQ drillcore is 4.8 cm

Pyroxenite-Norite Zone (PNZ)

In the deep western portion of Turfspruit and in portions of the Flatreef the main chromitite seam and its immediate harzburgitic floor rocks are underlain by the Pyroxenite-Norite Zone (PNZ, Fig. 2b), typically represented by poorly differentiated, fine to medium grained pyroxenite/norite containing abundant hornfels xenoliths (Fig. 8a). The unit can be up to 570 m thick and was identified in all bore holes that have been drilled to sufficient depth (e.g. UMT345, 81, 336). The rocks are mostly fine- to medium-grained and show a distinct fabric of elongated orthopyroxene and plagioclase. Important to note is the fact that poorly developed bands, stringers and disseminated zones of chromitite have been identified within the upper part of the PNZ in areas of low sediment contamination (e.g. UMT377).

In the central and eastern portions of Turfspruit, the PNZ occurs as thick sill-like bodies within sedimentary floor rocks to the main chromitite seam.

Lower Zone

The presence of Lower Zone lithologies on Turfspruit has been confirmed through surface mapping,

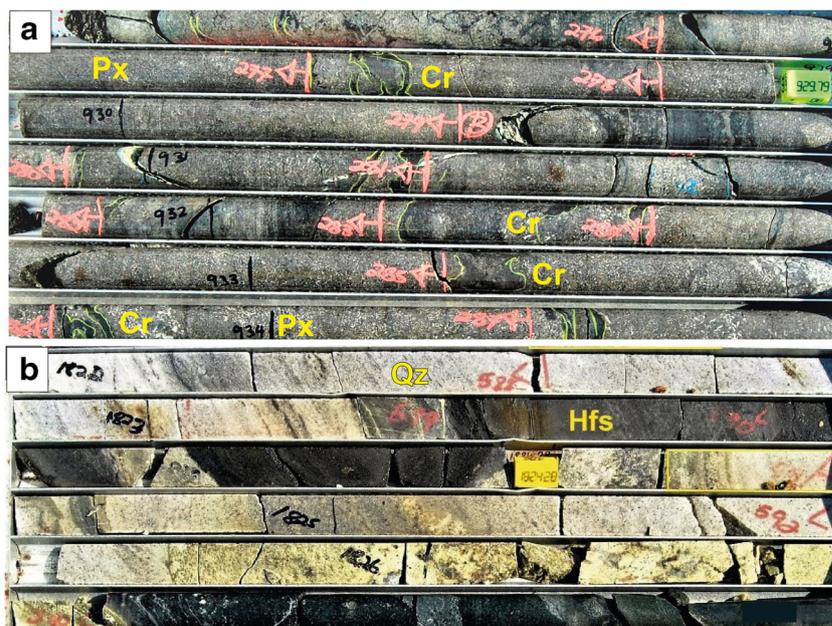
geophysical surveys and drilling. This includes work performed on three drill cores from the central sector of the project area (UMT006, UMT009 and UMT0011) by Yudovskaya et al. (2013). The thickness of the LZ is > 770 m, as evidenced in UMT006, drilled to a depth of 1973 m. The sequence predominantly consists of pyroxenite, dunite and harzburgite that tend to form cyclic units with varying thicknesses and transitional contacts. Dunite consists of equigranular unaltered olivine with minor amounts of cumulus chromite. Harzburgite occurs as distinct equigranular and poikilitic varieties. In both cases, the olivine grains tend to be strongly altered to serpentine. The pyroxenites show elongated orthopyroxene grains as well as minor interstitial plagioclase (<2 vol %) and clinopyroxene. Noritic units occur in a number of drill cores, notably in UMT336 where they underlie the LZ. The rocks are mostly fine- to medium-grained and show a distinct fabric of elongated orthopyroxene and plagioclase. It remains unclear whether these represent equivalents of the Marginal Zone of the Bushveld Complex.

The presence of inter-fingering LZ sills was confirmed during regional mapping, and by interpretation of the regional and project-area magnetic data. The sills

Table 1 Selected chromitite-rich intersections from the Turfspruit project

Hole ID	From	To	Width	3PGE	4PGE	Pt (g/t)	Pd (g/t)	Rh (g/t)	Au (g/t)	Cr (%)	Ni (%)	Cu (%)	S (%)	Pt/Pd ratio
UMT081	1421.54	1422.92	1.38	5.01	5.34	2.84	2.02	0.34	0.15	11.39	0.31	0.17	0.59	2.04
UMT335	1716.61	1719.13	2.52	2.35	1.92	1.11	1.17	0.14	0.07	5.96	0.26	0.16	0.85	2.94
UMT336	1212.27	1213.00	0.73	2.01	2.21	0.84	1.12	0.20	0.05	17.51	0.19	0.10	0.61	2.08
UMT345	1519.95	1521.17	1.22	2.86	3.08	1.73	1.05	0.22	0.07	14.42	0.24	0.15	0.54	2.56
UMT345D1	1516.34	1517.16	0.82	5.79	6.09	3.46	2.16	0.30	0.16	7.70	0.28	0.15	0.69	3.83
UMT336	1584.85	1586.88	2.03	1.49	0.00	0.56	0.86	ND	0.07	7.55	0.24	0.14	0.85	1.93
UMT383	1223.32	1223.79	0.47	2.97	3.16	1.62	1.27	0.19	0.08	17.10	0.23	0.09	0.29	2.71

Fig. 8 **a** Rocks of the PNZ in UTM377 (929–934.6 m). Fine- to medium-grained pyroxenite with granular to elongated pyroxene and feldspar defining a laminated igneous texture. **b** UMT081 (1822–1827.5 m) interbedded quartzite and hornfels shale. Width of NQ drillcore is 4.8 cm (Cr chromitite stringer/seam, Px pyroxenite, Qz quartzite, Hfs hornfels shale)



appear to have contrasting thicknesses along dip and strike. The presence of large, stratified LZ bodies along the basal contact of the Transvaal Supergroup with the granite basement suggests fault block control on emplacement. Furthermore, work done by Ivanhoe geologists has shown that these bodies are most likely connected through sills intersected in Turfspruit drill core at depth below the Flatreef.

Chemostratigraphy of selected drill cores

In order to further illustrate the lithostratigraphic variability in the project area, we show whole-rock data for two representative drill cores intersecting the Flatreef (Fig. 9), and for one drill core intersecting the interval from the base of the Main Zone across the Flatreef and the underlying PNZ, in the deep, western portion of the property (Fig. 10).

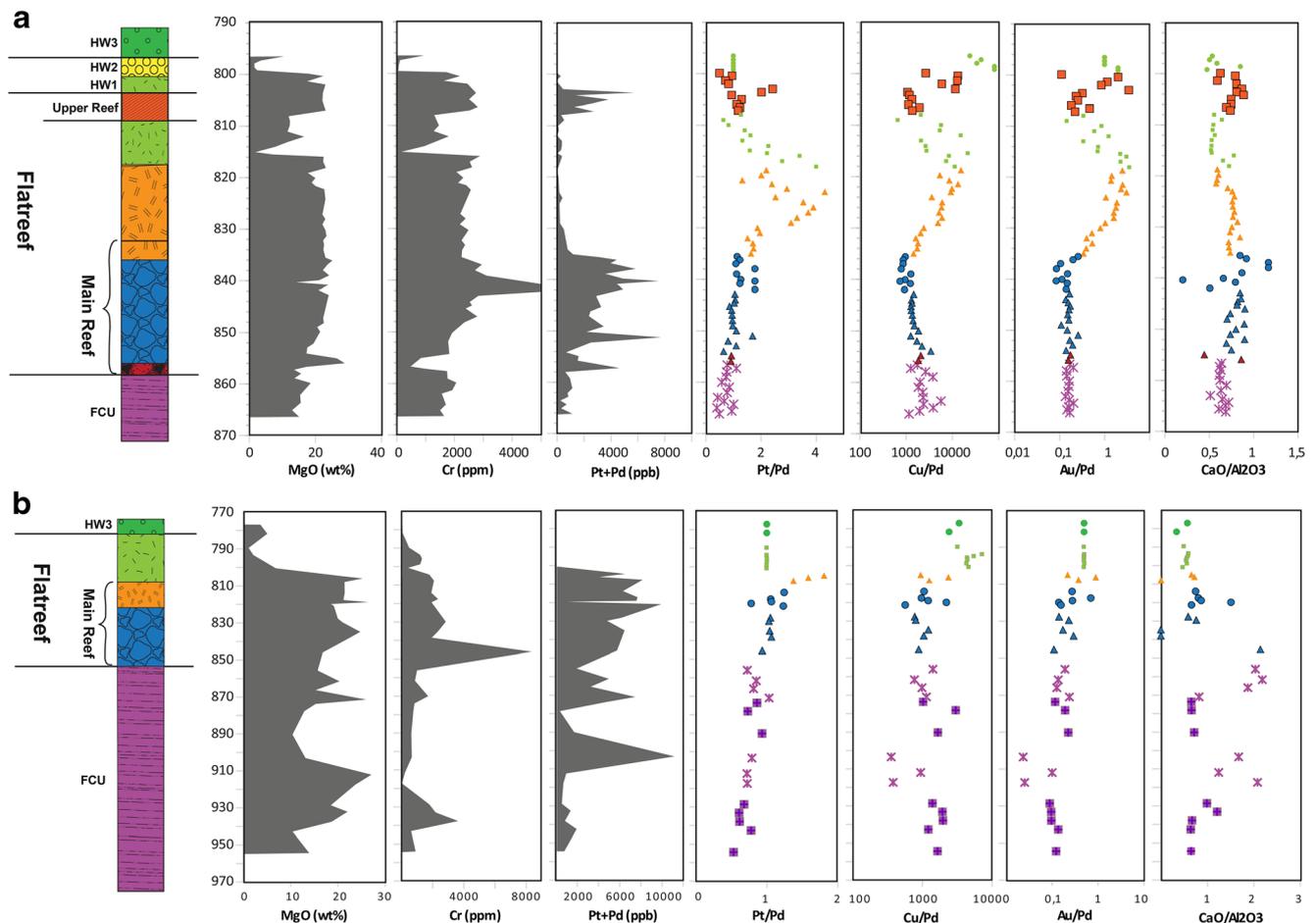
Drill core UMT232 (Fig. 9a) is typical of the central, sub-horizontal sector of the project area (i.e. the Flatreef *sensu strictu*) (Fig. 1c). Here, the Main Zone (HW3) is underlain, from top to bottom, by mottled anorthosite (HW2), interlayered norite and pyroxenite (HW1), followed by pyroxenite which is mineralised in its basal 2–5 m, and a thin basal chromitite, the latter two lithologies constituting the Upper Reef.

The interval between the Upper and Main Reef is represented by pyroxenite-norite-anorthosite cyclic units (Middling 2) which may be absent in places, unmineralised feldspathic orthopyroxenite (Middling 1), and then the Main Reef. The latter consists of well-mineralised medium grained pyroxenite, a basal Cr stringer, and strongly mineralised coarse-grained pegmatoidal orthopyroxenite

and poikilitic harzburgite. The medium-grained pyroxenite tends to show an upward decrease in grade, whereas the pegmatoidal and pyroxenite normally shows a downward decrease in metal grade, Pt/Pd. Notably, within the hanging wall rocks to the Main Reef, Pt/Pd and Au/Pd first increase with height before decreasing in the immediate footwall of the Upper Reef, resulting in a characteristic bulge seen in the graph curves of most drill cores. Cu/Pd is relatively low in the mineralised rocks, but higher than 5000 in the poorly mineralised intervening gabbro-noritic rocks. CaO/Al₂O₃ in the Main Reef and its footwall rocks is mostly between 0.5 and 1, similar to mineralised pyroxenites in the western Bushveld (Maier and Eales 1994), reflecting relatively low clinopyroxene contents.

Drill core TMT006 (Fig. 9b) was drilled through the central portion of the property (Fig. 1c). The hole intersected the most richly mineralised interval of the property averaging 4.5 ppm PGE over 90 m (Ivanhoe Mines, Public announcement, Nov. 2013). PGE grades, Pt/Pd and Au/Pd decrease with depth within and below the Main Reef, but the FCU, which in this area is characterised by intense shale–hornfels assimilation, shows several high-grade zones with > 5 ppm PGE. In the mineralised rocks, Cu/Pd is lower than in primitive mantle (~ 7000) but much of increases to mantle levels above the Main Reef. Throughout the reefs and their footwall rocks, CaO/Al₂O₃ is markedly higher than in drill core UTM232, and there is ample evidence of shale/hornfels and calc silicate assimilation and modification of magmatic textures, suggesting enhanced contamination with sedimentary rocks.

Drill core UMT345 was collared in the western portion of the property (Fig. 1c). As in the other holes, the PGE grade and Pt/Pd decrease with depth (Fig. 10). Notably, within the entire 160 m intersected below the Main Zone, few samples



Figs 9 **a** Geochemical stratigraphy of drill core UTM232, located in the central portion of the Flatreef. The drill core intersected the Main Zone, Upper and Main Reef, and contaminated footwall rocks. **b** Drill core

TMT006, intersecting Main Zone, Main Reef and Footwall Cyclic Unit. See text for further discussion

have < 200 ppb Pt+Pd, and the total Pt+Pd content of the interval normalised to 1 m is a phenomenal 150 ppm. The mineralisation in the PNZ is of relatively low grade (< 20 ppm Pt+Pd in sulphide as opposed to around 200 ppm in the Upper and Main reefs) and high Cu/Ni 0.7–1 (as opposed to around 0.5 in the Upper and Main reefs).

Discussion

The need for a stratigraphic system for the Platreef

Ever since the discovery, in the northern limb, of the mineralised Platreef, its position within the stratigraphy of the Bushveld Complex has remained contentious. Early workers proposed that the Platreef is the stratigraphic correlative of the Merensky Reef, as exposed in the EBC and WBC, albeit substantially modified through contamination with the floor rocks (Merensky 1926; Wagner 1929). Many subsequent researchers (McDonald and Holwell 2011, and references therein) have rejected this model, because of contrasting

whole rock and mineral compositions, sulphide and noble metal budget, and PGM assemblage between the Platreef and the Merensky Reef. Some authors instead proposed that the Platreef was sourced from a distinct staging magma chamber, whereas Naldrett et al. (2008) suggested that the Platreef crystallised from residual Upper Critical Zone magma migrating towards the relatively shallow periphery of the Bushveld lopolith.

The ongoing controversy is largely due to the lack of a coherent stratigraphic framework in the northern limb, which in turn is the result of relatively poor exposure, lack of geological information at depth, and extensive contamination of the magmatic strata. Thus, whereas the key mineralised intervals of the WBC and EBC have been well characterised in numerous mining operations, comparable exposure of the Platreef is confined to Mokgalakwena open pit mine. Only locally do floor updomings and anticlines bring reefs that are located somewhat more distal to the margins of the intrusion to the sub-surface where they were intersected in drill cores. For example, on the farm Rooipoort in the southern segment of the northern limb, PGE and Cr rich intervals interpreted to

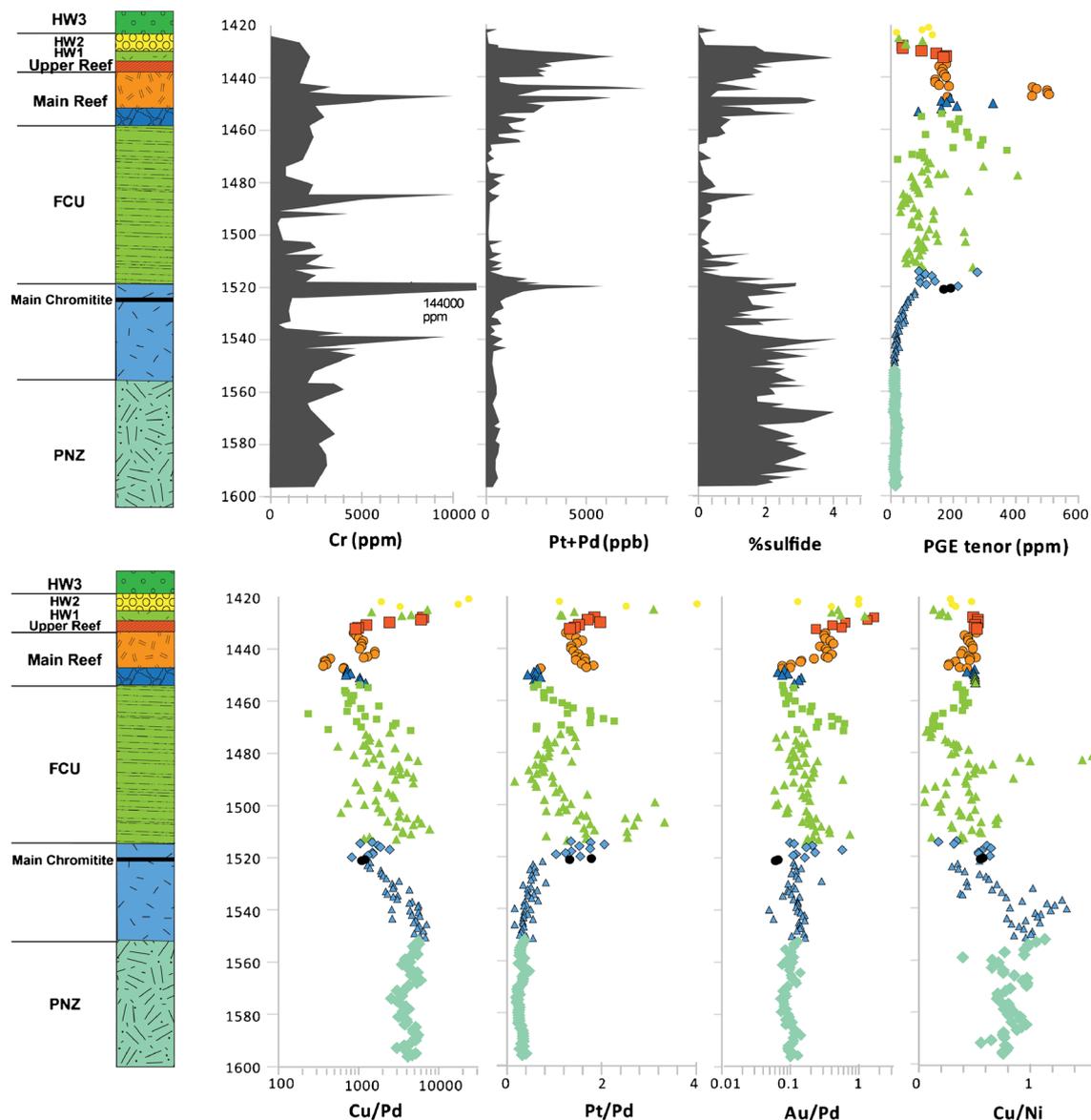


Fig. 10 Compositional data for drill core UTM345. Note high Pt/Pd ratios for Upper and Main Reefs and Main chromitite layer

represent Merensky Reef correlatives were intersected by Caledonia Mining (de Klerk 2005; Maier et al. 2008). On the nearby farm Jaagbaan, drilling by JCI in the 1970s intersected what were interpreted Merensky Reef and UG2 analogues at a depth of 550–715 m. Here, the Merensky Reef equivalent consists of a 20-m interval of elevated PGE contents, with an average grade of 0.84 ppm Pt+Pd+Au, and a 3.7-m high-grade interval having an average grade of approximately 3 ppm. The UG2 was intersected approximately 150 m below the Merensky Reef, as a disseminated chromitite with a true width of 43 cm containing ~1 ppm PGE. Somewhat similar intersections were drilled in the 1980s on the neighbouring farm Moorddrift by Gold Fields Ltd (Botha 1985). These data sets were interpreted by Maier et al. (2008) to reflect the transition of the Platreef into relatively narrow Merensky and UG2 reefs at depth (but see Smith et al. 2014

for a contrasting interpretation). A further potential example of this transition is exposed on the farm Zwartfontein (Akanani project), down-dip of Mokgalakwena mine, where Mitchell and Scoon (2012) proposed the presence of UCZ analogues, including the Merensky Reef and the Pseudo reefs. The drillhole intersections of the Flatreef, notably those in the down-dip western deep portion of the Turfspruit property, offer a rare opportunity to test this model and thereby generate improved brownfields and greenfields exploration targets.

Stratigraphic correlation of the interval between the Main Zone and the base of the Upper Reef

One of the most reliable stratigraphic marker horizons in the Turfspruit project area is the mottled anorthosite at the base of

the Main Zone. Mottled anorthosite of similar appearance, but mostly enhanced thickness, also occurs in the WBC (and EBC) where it has been termed the Giant Mottled Anorthosite (GMA), constituting the uppermost layer of the Bastard Unit, named so due to its similar appearance (yet lower grade) as the Merensky Reef (Fig. 2b). The most comprehensive study of the Bastard Unit was undertaken by De Klerk (2005), working at Union Section in the WBC where the unit consists of a basal pyroxenite (typically 3–5 m), overlain by melanorite (5–10 m), leuconorite (2–3 m), and then the 0–50-m-thick GMA. PGE mineralisation occurs over a width of a few decimetres at the base of the Bastard pyroxenite, notably associated with a thin (1–5 mm) basal chromitite that overlies another mottled anorthosite of the underlying Merensky Unit (Fig. 3d) (Maier and Barnes 2008; Naldrett et al. 2009).

On Turfspruit, as in the WBC, the GMA is underlain by melano- to leucogabbronorite and pyroxenite (HW1 and 2, respectively), but these lithologies are distinctly more interlayered than in the WBC. Sulphide mineralisation commonly occurs near the base of the lowermost pyroxenite (i.e. the Upper Reef) (Fig. 2b), and there is also a thin, poorly developed basal chromitite stringer. Based on the similarity in lithologies and stratigraphic position relative to the MZ, we define the interlayered noritic-pyroxenitic interval as the Bastard Cyclic Unit (BCU), and the mineralised pyroxenite and basal chromitite stringer as the Bastard Reef (BAR in Fig. 11). This interpretation is consistent with the whole-rock data obtained from several recent MSc studies performed on Turfspruit drill core (Smart 2013; Nodder 2015; Marquis 2015; Vekić 2017). Amongst the drill cores examined for this study, the BCU is best exposed in UMT231, 232, and 402 (Fig. 1c). The main difference to the WBC is that on Turfspruit, the Bastard Reef can be much thicker, giving rise to higher sulphide and PGE contents (typically 1–3 ppm, locally 10 ppm over 6 m, e.g. in TMT006-D1). However, in other areas on Turfspruit, the Bastard Reef shows erratic mineralisation with variable thickness, similar to elsewhere in the Bushveld Complex.

Stratigraphic correlation of the interval between the Upper Reef and Main Reef

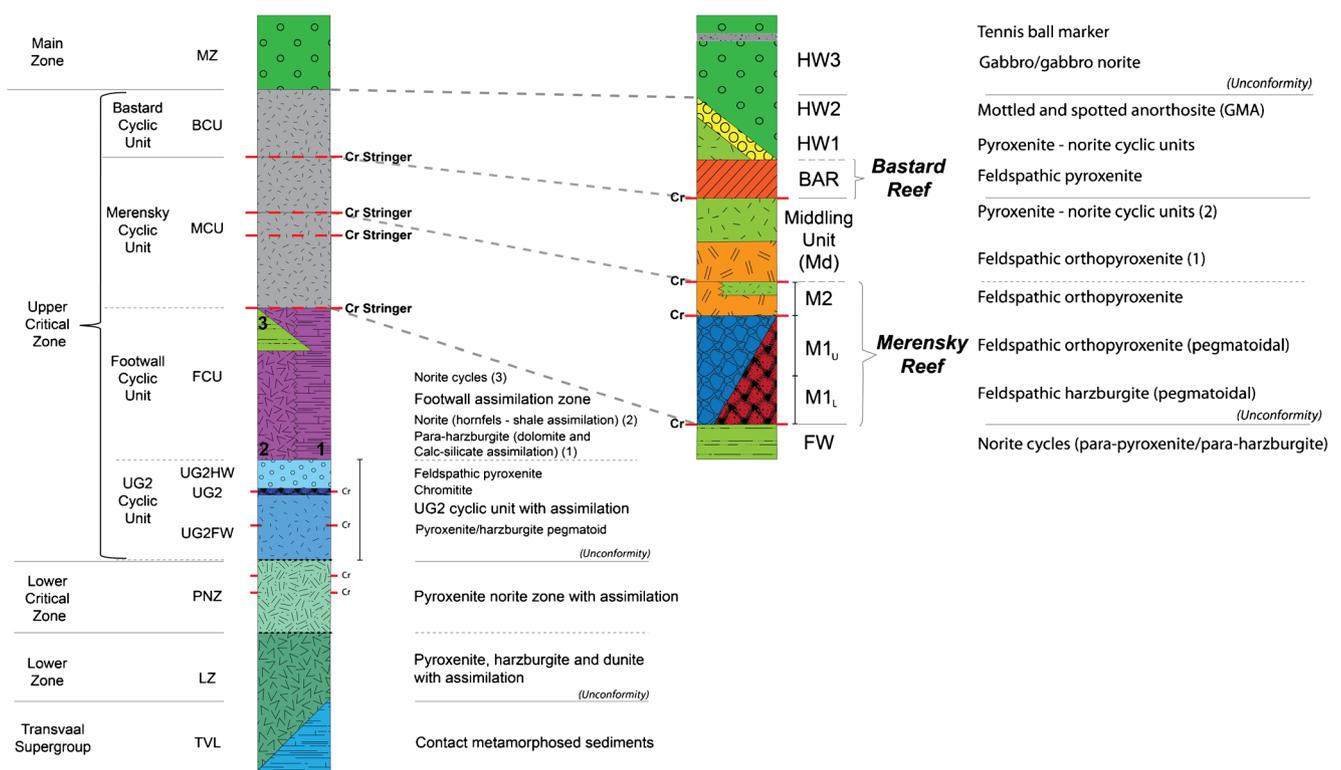
In the WBC, the BCU is underlain by a 20–25 m cyclic unit consisting, from top to base, of 2–5 m of mottled anorthosite, 5 m of leuconorite, 5–15 m of melanorite and 3–15 m of pyroxenite, at the base of which is the Merensky Reef. The latter is a 0.6–4-m-thick, lithologically complex interval that shows considerable lateral variation, with its thickness depending on the degree of potholing (Table 2). At Union section, the Merensky Reef consists of orthopyroxenite at the top, underlain by a pegmatoidal harzburgite layer that is bracketed by Cr stringers at its upper and basal contact (Viljoen et al. 1986a; de Klerk 1992). At Northam mine, the pegmatoid is zoned, with orthopyroxenite at the top and harzburgite at the

base (Roberts et al. 2007). At the Impala and Rustenburg mines, the pegmatoid is thin or missing, and generally less olivine-rich than in the northwestern Bushveld (Leeb-du Toit 1986; Viljoen and Hieber 1986; Barnes and Maier 2002a). The grade of the reef in the WBC is generally 5–8 ppm PGE (4E) over a width of approximately 1 m.

Eales et al. (1986, 1988) referred to the entire 20–25 m sequence, described above, as the Merensky Cyclic Unit (MCU) and interpreted it to have crystallised from a single magma pulse replenishing the chamber. In contrast, Cawthorn et al. (2002) suggested that the Merensky Reef formed from two magma influxes. The first influx precipitated the pegmatoidal harzburgite/pyroxenite and its basal chromitite that are collectively referred to (by Cawthorn et al. (2002)) as the pre-Merensky unit, whereas the second influx precipitated the overlying Cr stringer, medium grained pyroxenite, norite and anorthosite and was named the MCU by Cawthorn et al. (2002). The PGE mineralisation is generally concentrated in close proximity to the Cr stringers and may be much reduced in the intervening silicate rocks, except in those cases where the pre-Merensky unit measures less than ~50 cm, in which case a single mineralised interval of 1–2 m in thickness is developed (Viring and Cowell 1999). In the southeastern segment of the WBC, the pre-Merensky unit is up to 10 m thick (Viljoen 1999) and with two PGE peaks that are separated by barren pyroxenite. In the EBC, the pre-Merensky unit consists of 1–3 m of medium-grained pyroxenite that only locally attains a pegmatoidal texture (Mitchell and Scoon 2007).

The stratigraphy of the Turfspruit sequence below the Upper Reef/BCU shows many similarities to the MCU in the WBC and EBC. This is particularly so in the deep, western portions of the project area where the Upper Reef/Bastard Reef is underlain by the ‘Middling Unit (Md)’, a 14–100 m interval of interlayered pyroxenite-norite-anorthosite (Fig. 11). Barren pyroxenite at the base of the Middling Unit is typically underlain by mineralised medium-grained pyroxenite of the Main Reef that has a basal chromitite stringer (Fig. 4a–e). The mineralised pyroxenite-chromitite package is typically around 2.5 m thick, but it can exceptionally reach a thickness in excess of 10 m, with a grade of > 10 ppm PGE (TMT006). In the present work, it is correlated with the upper portion of the Merensky Reef (i.e. the MCU of Cawthorn et al. 2002), and referred to as ‘M2’ (Fig. 11). The underlying pegmatoidal interval is correlated with the lower portion of the Merensky Reef in the WBC (the pre-Merensky cyclic unit in the terminology of Cawthorn et al. 2002). The layer is termed M1 in our stratigraphic system, with the orthopyroxenite being ‘M1 Upper’ and the harzburgite ‘M1 Lower’ (Figs. 4 and 11).

The proposed stratigraphic correlation between the Merensky Reef of the EBC and WBC and the M1-M2 unit of the Flatreef is supported by consistent overlap in age of the Platreef (2056.2 ± 4.4 Ma, U-Pb on zircon in chromite; Yudovskaya et al. 2013) with that of the



Not to scale

Fig. 11 Stratigraphic sub-division of the Flatreef on Turfspruit. Note position of the Bastard, Merensky and UG2 cyclic units identified on Turfspruit. The magmatic footwall rocks below the Flatreef exhibit textures of increased assimilation and melting of sedimentary xenoliths/autoliths

Merensky Reef in the eastern (2056.88 ± 0.41 Ma) and western limb (2057.04 ± 0.55 Ma) (Scoates and Wall 2015; Scoates and Friedman 2008).

Stratigraphic correlation of the chromite-rich rocks in the footwall to the Flatreef

In the WBC and EBC, the Merensky Reef is underlain by a 80–250-m-thick interval of strongly layered ultramafic-mafic

rocks floored by the uppermost massive chromitite seam of the Upper Critical Zone, namely the UG2 (Gain 1985; Leeb-du Toit 1986; Viljoen et al. 1986a, b; Eales et al. 1986, 1988, 1990). Most of these studies grouped the rocks between the Merensky Reef and the UG2 hanging-wall pyroxenite into the Footwall Cyclic Unit, whereas the underlying pyroxenite, the UG2 chromitite, and pyroxenite/harzburgite below the UG2 chromitite are grouped into the UG2 Cyclic Unit. Lateral variation within this sequence is more pronounced than in the

Table 2 Comparison of thickness of Merensky and Bastard cyclic units in western and eastern Bushveld Complex and at Turfspruit project area (present study, in italics)

Area	MCU—thickness (m)	BCU—thickness (m)	Reference
Amandelbult Section	16	32	Viljoen et al. (1986a)
Rustenburg Section	10	100	Viljoen and Hieber (1986)
Northam Mine	23	61	Viring and Cowell (1999)
Impala Platinum Mine	11	110	Leeb-du Toit (1986)
Union Section	32	35	Viljoen et al. (1986b)
Atok Platinum Mine	27	55	Mossom (1986)
North-eastern Bushveld	18	59	Lea (1996)
<i>Turfspruit 241KR</i>	25	32	<i>Av. thickness this study (439 holes)</i>
Average excl Turfspruit	20	65	
Average incl Turfspruit	20	61	

Merensky and Bastard units, and considered to be controlled by potholing and proximity to a postulated magma feeder zone at Union Section (Eales et al. 1988). Thus, in the north-western Bushveld, located proximal to the feeder, several layers of harzburgite (the so-called Pseudo reefs) may occur in this interval, and feldspathic units are either thinned or not developed. The Pseudoreefs wedge out with increasing distance from the feeder, while the thickness of the feldspathic layers increases and the compositions of pyroxene and plagioclase become more evolved (Maier and Eales 1994, 1997).

Within the deep drill core intersections of the western and southwestern portions of Turfspruit, the MCU is underlain by the Norite cycles of Kinnaird et al. (2005) which we correlate with the FCU of the WBC and EBC, based on lithological similarities and stratigraphic position (Figs. 2b and 11). However, on Turfspruit, layers are more numerous than in the WBC and may contain small hornfels/calc-silicate xenoliths (e.g. in UMT336). Pyroxenite lenses may be bracketed by chromitite stringers, somewhat analogous to the boulders of the Boulder Bed in the WBC that have been interpreted to represent a dismembered pyroxenite layer (Jones 1976; Maier and Barnes 2003). However, the pyroxenite lenses in the Flatreef are enriched in disseminated sulphides compared to most of the pyroxenitic layers, lenses and boulders in the WBC (Fig. 5d).

The FAZ in the central to eastern portions of Turfspruit is interpreted to have crystallised from a Ca-contaminated magma, with the pegmatoidal texture resulting from the introduction of volatiles and partial melts derived from devolatilisation and melting of sedimentary xenoliths. The FAZ (Fig. 11) has been identified throughout the northern limb and is characterised as a zone where the sediment and magma interaction has obliterated, or prevented, the formation of identifiable magmatic strata. The assimilation effects are not confined to certain magmatic units, but straddle and transgress the magmatic stratigraphy. This is especially project evident within the upper, near-surface reaches of the Turfspruit area where the assimilation effects transgress into the lower reaches of the Main Zone.

The thickest of the chromitite seams below the FCU is here correlated with the UG2 (Fig. 7), based on its stratigraphic position as well as similar thickness (about 1 m) and the presence of thin leader seams (Nodder 2015, Leeb du Toit 1986; Viljoen and Hieber 1986; Viljoen et al. 1986a, b). Analogous to the UG2 at, e.g. Impala mine in the WBC (Maier and Barnes 2008), the hanging wall is a feldspathic pyroxenite and the footwall to the chromitite may be a pegmatoidal pyroxenite or harzburgite (UTM081, UMT336). PGE contents are lower (2–6 ppm) than in the WBC and EBC where the seam contains 5–8 ppm PGE, but the Pt/Pd ratio is broadly similar, mostly at above unity. Furthermore, in all analysed drill cores the Cr seam has a relatively high Rh content, similar to the UG2 chromitite

elsewhere (Mossom 1986). Sulfur and Cu contents are higher than in most UG2 intersections of the WBC, but resemble those at Lebowa platinum mine (von Gruenewaldt et al. 1990). Mineral and whole rock compositions of the Cr-rich interval are difficult to compare to the WBC and EBC because the Turfspruit sequence shows considerable interaction with the sedimentary floor rocks.

Stratigraphic correlation of the ultramafic rocks below the Main/UG2 chromitite

The ultramafic rocks below the main chromitite/UG2 comprise the putative PNZ and LZ. Based on field relationships and in view of the lack of evolved rocks that may represent residual liquids, we infer that the PNZ was emplaced in the form of sills of pyroxene-rich crystal slurries. However, direct correlation of the PNZ with intervals of the WBC and EBC remains tenuous. A laterally persistent sequence of chromitite layers, as in the footwall of the UG2 in the WBC and EBC, could not be identified at Turfspruit, but certain drill cores show several dm-thick, disseminated to massive chromitite seams with planar to irregular contacts (Fig. 8). Dip sections of block model PGE and base metal grades display a layered sequence of mineralised rocks below the Flatreef (Fig. 12). Based on stratigraphic position and lithological analogies, we thus interpret the PNZ as the stratigraphic correlative of the LCZ.

Below the PNZ occur interlayered pyroxenite-harzburgite-dunite sills that have previously been interpreted to represent the Lower Zone (Van der Merwe 1976; Yudovskaya et al. 2013), based on lithological and compositional similarities to LZ rocks in the EBC and WBC where the zone forms a 500–1500 m sequence of predominantly orthopyroxenite, harzburgite and dunite (Karykowski and Maier 2017; Teigler and Eales 1996; Wilson 2012, 2015). The classical definitions of the boundary between LZ and LCZ established at Cameron Section and Union Section cannot be applied to Turfspruit, or indeed many other Bushveld localities as the Lower Zone shows significant lithological variation within and between limbs. For example, in the WBC, the zone is predominantly ultramafic in the northwest and southwest, but transitions into noritic rocks to the east of the Brits graben (Teigler 1990; Teigler et al. 1992; Teigler and Eales 1996). Similarly, whereas the LZ is normally barren of massive chromitite seams in the EBC and WBC, in the southern portion of the northern limb, on the farm Grasvally, several Cr seams were intersected during drilling, displaying less evolved compositions than CZ chromitite seams elsewhere (Hulbert and von Gruenewaldt 1985). Finally, whereas the LZ and CZ form a contiguous package in much of the WBC and EBC, to the NW of Pretoria the LZ is separated from the CZ by intervals of hornfels and quartzite (Maier and Bowen 1996), reminiscent of the

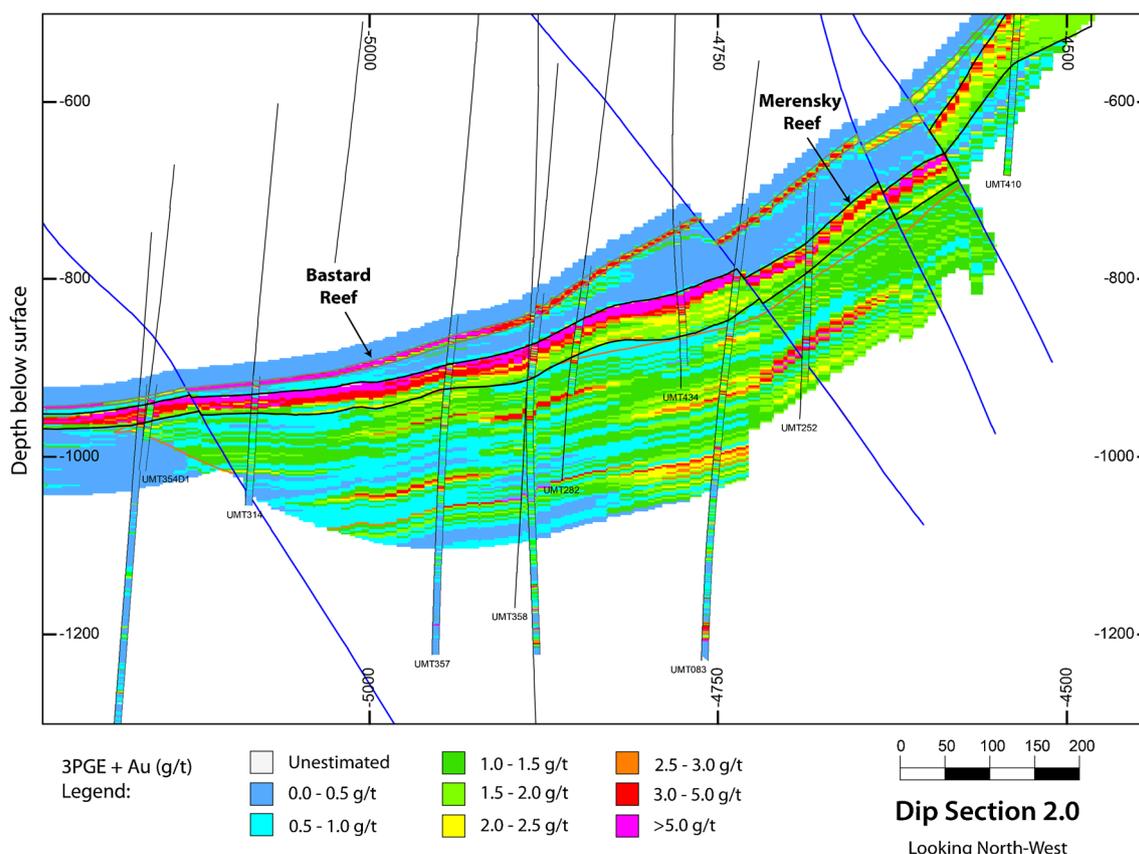


Fig. 12 Dip section 2 showing 3E+Au Block grades (50-m drillhole projection) looking north-west. Note stratiform nature of Bastard and Merensky reef equivalents directly below Main Zone gabbro-norite hangingwall and layered nature of mineralisation below into footwall disrupted by sediment rafts. Both the drillholes and block model were first transformed to a set maximum elevation of 1000 m, hung from the top contact of the modelled zone. This allowed for estimation in ‘unfolded’ space. The search parameters were set isotropic (250 m by 250 m) in

easting and northing, with a restricted search of 10 m vertically. Blocks (10 mE by 10 mN by 2 mRL) were estimated using a minimum of 4 samples and a maximum of 15 samples. A maximum of three samples were allowed from an individual drillhole, ensuring blocks could only be estimated if samples were available from at least two drillholes. Grades were estimated using inverse distance to the third power. Following estimation, blocks were restored to their correct elevation (Peters et al. 2017)

situation in the northern limb, e.g. on Rooipoort (Maier et al. 2008) and parts of Turfspruit (Yudovskaya et al. 2013).

Summary of stratigraphic model

Based on detailed observations and interpretation of the available geochemical data from the project area and the remainder of the Bushveld Complex we propose a new stratigraphic sub-division for the layered sequence on Turfspruit (Fig. 11) (Grobler et al. 2017). At the top of the sequence is the Main Zone, forming a laterally persistent unit across much of the northern limb. The MZ is underlain by a 100–200 m mineralised zone that onlaps to the sedimentary floor in the shallow eastern portion of the project area, but is located several 100 m above the floor in the deeper, central to southwestern portions of the property. In the former case the rocks are strongly contaminated, forming the Platreef. In the latter case, the sequence is relatively little contaminated and layering is

laterally relatively persistent. This is the Flatreef and its downdip extensions (Fig. 13), and within it the Bastard, Merensky, Footwall and UG2 units may form classical cyclic units consisting, from the base upward, of chromitite, pyroxenite, norite and anorthosite. In places, notably the antiformal feature to the west of the Flatreef (Fig. 13), the feldspathic components of units may be missing.

Some additional terms have been introduced for the benefit of the mining operation. Thus, the uneconomic rock units above the Bastard Reef (but belonging to the Bastard Cyclic Unit) are grouped into Hanging wall (HW) units 1–2, whereas MZ gabbro-norite is HW unit 3. Unmineralised rocks above the Merensky Reef are grouped into Middling units 1–2, and rocks below the Merensky Reef are grouped into Footwall units 1 to 3 (Fig. 11), with FW3 representing the well-developed magmatic footwall cyclic units while FW 2 and 1 represent their hornfels- and calc-silicate-contaminated equivalents, respectively.

Lateral correlation of lithological units on Turfspruit

The extensive database of > 720 km of diamond drill core proved to be critical in the detailed correlation of lithological units across a large extent of the project area, along strike and downdip. The dip section in Figure 13 illustrates that in the Flatreef and its hostrocks, lateral continuity of layers between drill cores tends to be less prominent than in the WBC. This could be due to several reasons: (i) contamination of the magma with sedimentary footwall rocks, reflected in relative enrichment of the Flatreef in CaO, K₂O, Rb and Zr, and depletion in Al₂O₃. (ii) Infiltration and intrusion of mafic cumulates by granitic melts and fluids. (iii) Pinching-out of feldspathic

intervals and local thickening of ultramafic units, possibly in response to potholing or syn-magmatic updoming or infill of fold structures of the floor rocks.

Considering potholing, it is conceivable that this was more prominent than in the WBC as devolatilisation of the dolomites likely released abundant gas CO₂, possibly generating bubbles that lowered the viscosity of crystal mushes (Leshner and Spera 2015) thereby enhancing the efficiency of hydrodynamic erosion of footwall cumulates. Direct evidence, such as CO₂ or CH₄ rich fluid inclusions, is presently lacking. However, the lower Flatreef units sporadically contain abundant graphite (locally forming dm-wide massive graphite intersections in drill core) and carbonate, which we interpret to result from reaction

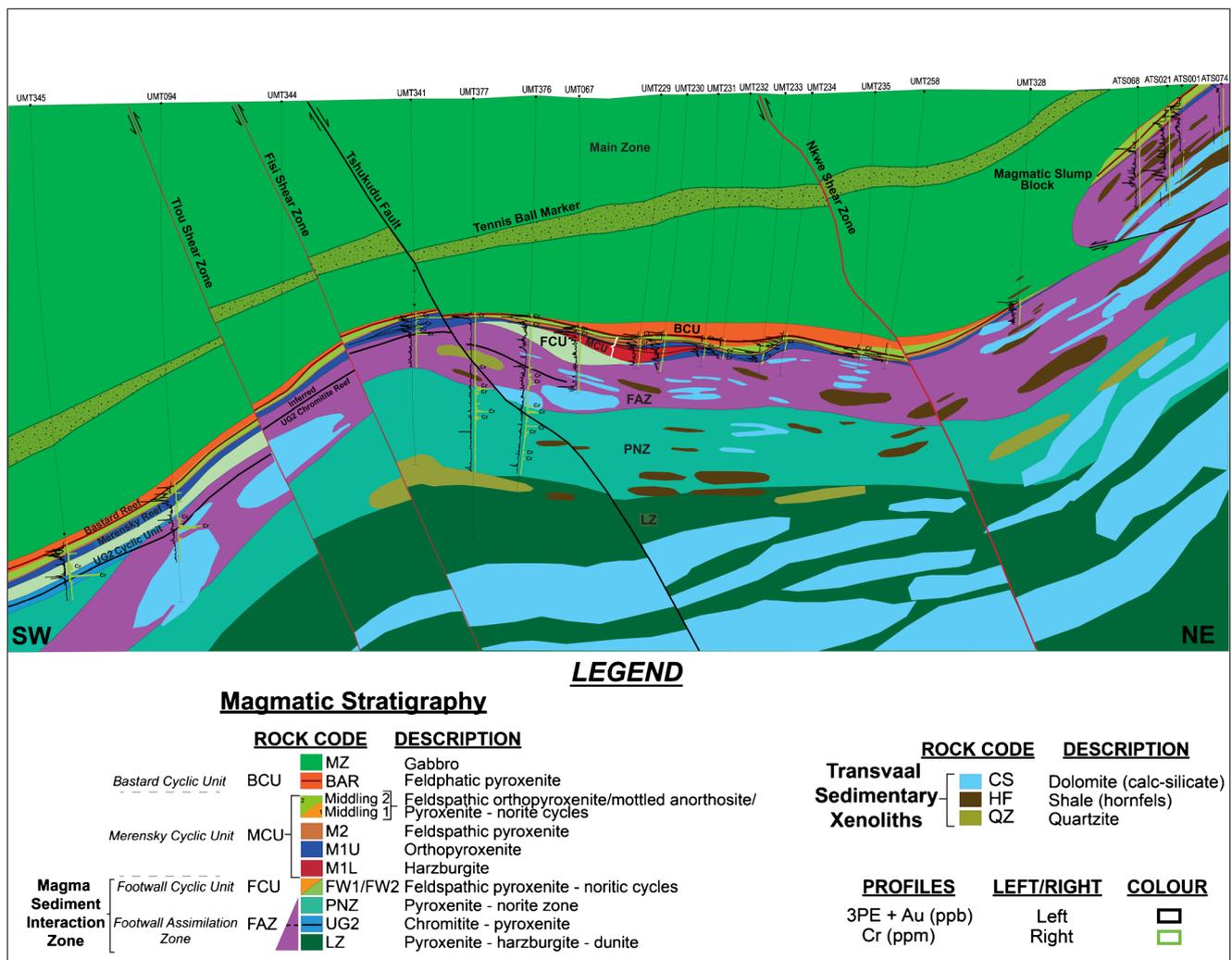


Fig. 13 West to east dip section (section 11.0) across the Flatreef portion of Turfspruit. The section is compiled from drill core, assay data and the 3D geological model. Section clipping distance is set at a maximum of 50 m. The UG2 chromitite is shown below the Flatreef within the footwall zone only in instances where the layer was confirmed from assay data (elevated chrome and PGE values). The position, orientation and dimensions of dolomitic and shale xenoliths within the PNZ and LZ

have been inferred and interpreted from findings made in high density near surface and outcrop mapping and drilling. Xenoliths below the drill limit at depth have been inferred from geophysical data (gravity inversion model and 3D seismic surveys) and modelled in Leapfrog software. Geological structures indicated on the section are as characterised from geophysical data and drill core intercepts

of carbonic fluids with the crystal mushes. Devolatilisation may also have potentially triggered low-angle (detachment) faulting within the dolomite, generating pull-apart structures such as those documented by Maier et al. (2016) at Maandagshoek, EBC. Due to paucity of outcrop, we could not yet identify large potholes at Turfspruit, but cm-sized potholes are abundant in drill core and in Shaft #1 exposures (Online resource 2). Synmagmatic doming of the floor rocks to the Bushveld is equally to be expected, in view of the abundant Bushveld aged sills below the complex (Sharpe 1981; Button and Cawthorn 2015) that likely caused localised partial melting of the sedimentary rocks. Examples of such domes have been documented by Sharpe and Chadwick (1982), Uken and Watkeys (1997) and Scoon (2002). This could have caused compartmentalisation of the chamber at an early stage, controlling the thickness of cumulate layers.

From PGE distribution profiles compiled across the entire project area, it became evident that the thickness of the MCU, as reflected by the distance between the base of M1 and BAR, shows considerable down-dip and along-strike variation (Figs. 13 and 14). The Flatreef is representative of the area where the

mineralised sequence both flattens and becomes markedly thicker (Fig. 13, Online resource 3). Thinning of the lithological units to the west, across an antiform, brings the Bastard mineralisation closer to the Merensky Reef (UMT276) (Fig. 14). Furthermore, an inverse relationship exists between the thickness of the Bastard Reef and that of its layered hanging wall sequence, and between the latter and the thickness of the GMA. Thus, where the Bastard Reef is thick, its hanging wall is thin and the GMA is thick. Other notable observations are that the distribution of the harzburgitic M1L seems to be spatially controlled by the presence of calc-silicate rafts in its footwall, and that the UG2 Unit is best developed in the relatively deep intersections in the southwest of the property.

The profiles in Fig. 13 and in Online resource 3 and 4 further illustrate (i) the sill-like nature of the LZ and the PNZ/LCZ, intruded below a regionally extensive raft of metamorphosed shale and dolomite, (ii) the presence of the Tennis Ball Marker horizon in the MZ that does not appear to follow the Flatreef upper contact, and (iii) the development of a major structure in the up-dip extension of the Flatreef, causing duplication of the Critical Zone strata and trapping of MZ gabbro-norite between

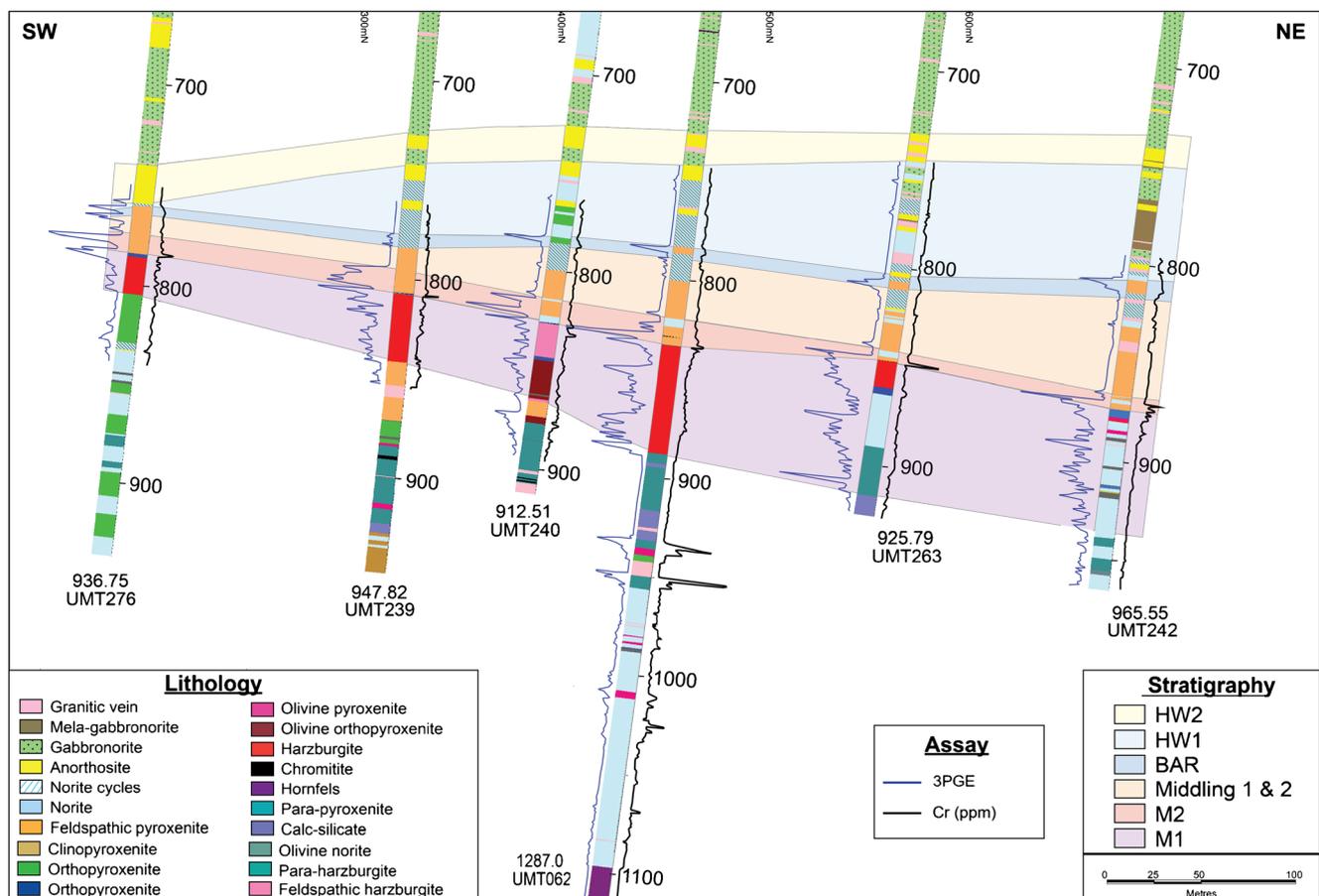


Fig. 14 Portion of dip section 11 illustrating thickness variation of the Merensky Cyclic Unit and the M1-BAR interval. West is at left of diagram, i.e. in this specific portion of the property representing the western

segment of the Flatreef, the reefs are dipping gently towards the east as they approach the hinge of an antiform (see also Fig. 13). Assay values for PGE's are plotted to the left and Cr to the right of each downhole trace

the base of a faulted block and the Critical Zone strata extending underneath it. This is somewhat analogous to the Main Zone intrusions into sheared and faulted Platreef, mapped in the Zwartfontein pit by Holwell and Jordaan (2006). Further updip (towards the east) a reef loss correspondent to the projected movement of the faulted block is evident. The upper reef interval of this package is now called the Bikkuri Reef (Bikkuri is Japanese for ‘surprise’) (Parker et al. 2012). In most cases, it consists of relatively thin Bastard Reef and Merensky Reef directly in contact with highly contaminated calc-silicate foot-wall rock. The Bikkuri Reef is largely devoid of harzburgitic lithologies. Pegmatoidal pyroxenite is also not well developed and the associated mineralisation is generally disrupted and of lower-grade. The basal contact between the calcsilicate footwall of the Bikkuri Reef and the underlying Main Zone wedge shows evidence of structural movement, but chilled contact rocks and intrusive relationships are also observed. Thermal erosion and ductile deformation features are characteristic of the upper frontal portion of the slumped block, as are disturbed strata of the Main Zone, which suggests a ductile environment, and syn-magmatic formation of this feature. These observations suggest that the Bikkuri reef formed through detachment of a semi-consolidated cumulate pile along a low-angle fault located within, or above, devolatilising dolomite. The entire package slumped into the semi-consolidated Main Zone crystal mush,

possibly during loading and sagging of the Bushveld magma triggered by Main Zone emplacement (cf Maier et al. 2013). The semi-consolidated state of the magma appears to mostly have obliterated evidence of movement on the contact surfaces. In areas where ‘reef loss’ occurred due to the slumping, only low-grade mineralisation is recognised within highly contaminated FAZ rocks (Fig. 15 and Online resource 5). Although these observations indicate distinct time lapses to have occurred during the emplacement of the LZ, LCZ, UZ and MZ they also suggest that these lapses were of relatively short duration.

The above observations may be of considerable importance in unravelling the magmatic processes that formed the RLS. Mungall et al (2016) proposed an out-of-sequence emplacement for the mafic-ultramafic layers as sills. The RLS exposed on Turfspruit may form a unique opportunity to test this hypothesis.

Conclusions

The Flatreef on the farm Turfspruit, northern limb of the Bushveld Complex, represents the sub-horizontally dipping, down-dip extension of the Platreef. In the present contribution, we present a detailed stratigraphic framework for the Flatreef that may be used to correlate marker units between different areas across the northern limb of the Bushveld Complex. The available data constitutes

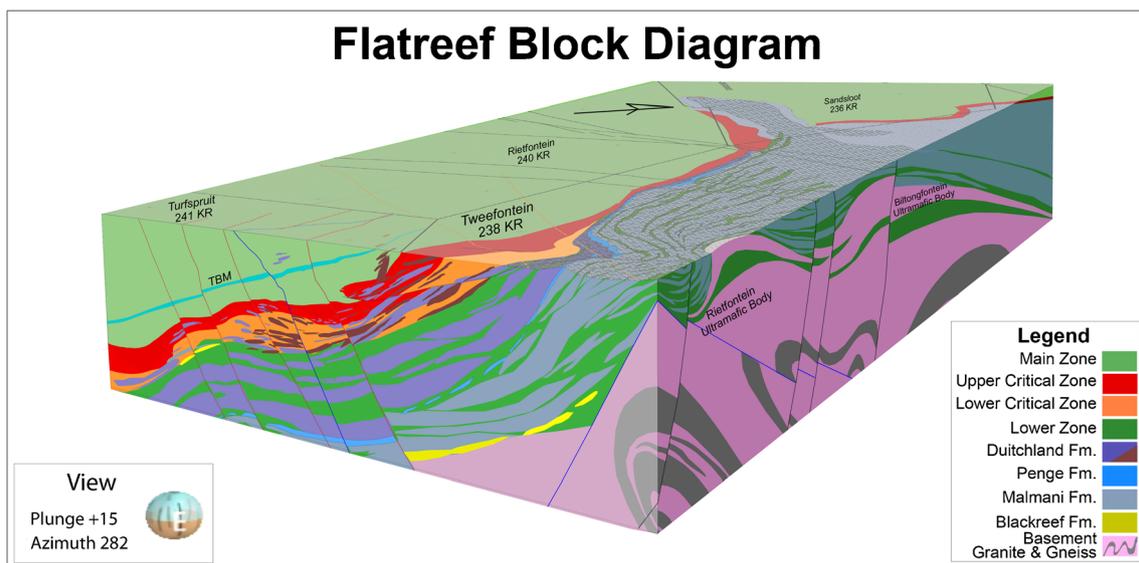


Fig. 15 3D block diagram of the Bushveld northern limb in the Turfspruit area and surrounds, looking towards the north-west. The diagram is a compilation of Flatreef dip sections (e.g. section 11 in this paper), detailed project scale surface geological mapping and published regional scale mapping from the Council of Geoscience (1:250,000 scale geological map). The block covers a down-dip distance of 9 km from the floor to the Bushveld (in the southeast) to the deep down-dip extension of the Platreef/Flatreef (in the southwest), and 13 km along strike (southeast to northwest). Section depth is to approximately 3 km below surface. The diagram shows the intensely folded greenstone amphibolites and schists intruded by later Proterozoic granites along the

eastern section. Folding becomes less pronounced higher up the succession towards the Transvaal Supergroup sediments, which forms the floor to the Bushveld intrusion in the area. The Transvaal sediments show open folding, controlling to some extent the emplacement and distribution of Bushveld strata. Folding and possible doming (an example of this is the dolomite ‘tongue’ at Sandsloot in the north) of the sediments was active during emplacement of the Bushveld magmas. Faulting originated from the basement and was re-activated during and after emplacement. These faults acted as growth faults, further controlling the distribution of Bushveld strata. The effect of structural control on magma distribution diminishes with progressive emplacement

strong evidence for the stratiform nature of mineralised horizons and highlights the marked similarities to the UCZ found elsewhere in the Bushveld. This includes the positive identification of Bastard Reef, Merensky Reef and UG2 chromitite equivalents in the Flatreef deposit. Moreover, whereas these reefs directly overlie sedimentary and granitic floor rocks in the shallow portions of the property and, consequently, are strongly contaminated (constituting the Platreef), in the deeper, southwestern portions of the project area, they are underlain by thick units of ultramafic intrusives, correlated with the LZ and LCZ.

The Bastard, Merensky and UG2 mineralised zones can now be traced from the Flatreef into the shallow updip parts of the Platreef where increased magma–sediment interaction previously made recognition of the magmatic stratigraphy tentative. These observations show that the broad zone of erratically mineralised “Platreef” found at the base of the northern limb includes a large portion of the CZ stratigraphy. In particular, it explains the failure of previous attempts of direct correlation with the Merensky Reef.

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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. *Trans Inst Min Metall* 111:B36–B45
- Ashwal LD, Webb SJ, Knoper MW (2005) Magmatic stratigraphy in the Bushveld northern limb: continuous geophysical and mineralogical data from the 2950m Bellevue drillcore. *S Afr J Geol* 108:199–232
- Barnes S-J, Maier WD (2002) Platinum-group elements and microstructures of normal Merensky Reef from Impala Platinum Mines, Bushveld Complex. *J Petrol* 43:103–128
- 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
- Bekker A (2001) Chemostratigraphy of the Early Paleoproterozoic Carbonate successions (Kaapvaal and Wyoming Cratons). PhD Thesis, Virginia Tech. 39pp
- Botha MJ (1985) Geology of the Rustenburg Layered Suite and associated mineralization on the farms Moorddriif 289KR, Jaagbaan 291KR and Grasvally 293KR, south of Potgietersrus. Gold Fields of South Africa Ltd., Internal Report, pp. 43
- Buchanan DL, Nolan J, Suddaby P, Rouse JE, Viljoen MJ, Davenport JWJ (1981) The genesis of sulphide mineralisation in a portion of the Potgietersrus limb of the Bushveld Complex. *Econ Geol* 76:568–579
- Button A, Cawthorn RG (2015) Distribution of mafic sills in the Transvaal Supergroup, northeastern South Africa. *J Geol Soc* 172(3):357–367
- Cameron EN (1978) The lower zone of the eastern Bushveld Complex in the Olifants River trough. *J Petrol* 19:437–462
- Cameron EN (1982) The Upper Critical Zone of the Eastern Bushveld Complex—Precursor of the Merensky Reef. *Econ Geol* 77:1307–1327
- Cawthorn RG, Molyneux T (1986) Vanadiferous magnetite deposits of the Bushveld Complex. *Miner Depos Southern Afr* 2:1251–1266
- 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 R KW, Viljoen MJ (2002) Platinum-group element deposits in the Bushveld Complex, South Africa. In: Cabri LJ (ed) *The geology, geochemistry, mineralogy and mineral beneficiation of platinum-group elements*. *Can Inst Min Metall Spec* 54:389–429
- Cousins CA, Feringa G (1964) The chromite deposits of the western belt of the Bushveld Complex. In: Houghton SH (ed) *The geology of some ore deposits in Southern Africa, vol. 2*. Geological Society of South Africa, Johannesburg, pp 183–202
- De Klerk WJ (1992) Petrogenesis of the Upper Critical Zone of the Western Bushveld Complex with emphasis on the UG1 footwall and Bastard Units. Ph.D. thesis, Rhodes University, Grahamstown: 294
- De Klerk WJ (2005) Bushveld stratigraphy of Rooipoort, Potgietersrus limb. Workshop on Platinum exploration and exploitation in Africa, October 2005, Johannesburg
- Eales HV, Marsh JS, Mitchell AA, De Klerk WJ, Kruger FJ, Field M (1986) Some geochemical constraints upon models for the crystallization of the Upper Critical Zone–Main Zone interval, northwestern Bushveld Complex. *Mineral Mag* 50:567–582
- Eales HV, Field M, de Klerk WJ, Scoon RN (1988) Regional trends of chemical variation and thermal erosion in the Upper Critical Zone, western Bushveld Complex. *Mineral Mag* 52:63–79
- Eales HV, De Klerk WJ, Teigler B (1990) Evidence for magma mixing processes within the critical and lower zones of the northwestern Bushveld Complex, South Africa. *Chem Geol* 88:261–278
- Eriksson PG, Altermann W, Catuneanu O, Van der Merwe R, Bumby AJ (2001) Major influences on the evolution of the 2.67–2.1 Ga Transvaal basin, Kaapvaal craton. *Sediment Geol* 141:205–231
- Gain SB (1985) The geologic setting of the platinumiferous UG2 chromitite layer on the Maandagshoek, eastern bushveld complex. *Econ Geol* 80:925–943
- Gain SB, Mostert AB (1982) The geological setting of the platinumoid and base metal sulphide mineralisation in the Platreef of the Bushveld Complex on Drenthe, north of Potgietersrus. *Econ Geol* 77:1395–1404
- Grobler DF, Nielsen SA, Broughton D (2012) Upper Critical Zone (Merensky Reef-UG2) correlates within the Platreef on the Turfspruit 241KR, Northern Limb, Bushveld Complex: 5th Platreef Workshop Mokopane, 9th – 11th November 2012

- Grobler DF, Brits JAN, Crossingham A, Maier WD (2017) Litho- and chemostratigraphy of the 42 Moz Flatreef PGE Deposit, northern Bushveld Complex. Keynote presentation. Proceeding of the 14th SGA Biennial Meeting, 20–23 August 2017, Québec City, Canada: pages 43–46
- Hall AL (1932) The Bushveld Igneous Complex in the central Transvaal. *Geol Soc S Afr Memir* 28:544
- Holwell DA, Jordaan A (2006) Three-dimensional mapping of the Platreef at the Zwartfontein South mine: implications for the timing of magmatic events in the northern limb of the Bushveld Complex South Africa. *Appl Earth Sci (Trans Inst Min Metall)* 115:41–48
- Hulbert LJ (1983) A petrographical investigation of the Rustenburg Layered Suite and associated mineralization south of Potgietersrus. DSc dissertation (unpublished), University of Pretoria, p. 511
- 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
- Huthmann FM, Yudovskaya MA, Frei D, Kinnaird JA (2016) Geochronological evidence for an extension of the Northern Limb of the Bushveld Complex, Limpopo Province, South Africa. *Precambrian Res* 280:61–75
- Jones JP (1976) Pegmatoidal nodules in the layered rocks of the Bafokeng leasehold area. *Trans Geol Soc S Afr* 79:312–320
- Karykowski BT, Maier WD (2017) Microtextural characterisation of the Lower Zone in the western limb of the Bushveld Complex, South Africa: evidence for extensive melt migration within a sill complex. *Contributions to Mineralogy and Petrology* 172(8):6
- Kekana SM (2014) An investigation of mineralisation controls in the upper section of the Platreef in the southern sector, on Turfspruit, Northern Limb, Bushveld Complex, South Africa. MSc thesis, University of the Witwatersrand, pp. 128
- Kinnaird JA, Nex P (2015) An overview of the Platreef. In: Hammond NQ, Hatton C (eds) *Platinum-group element (PGE) mineralisation and resources of the Bushveld Complex*, Council for Geoscience, Pretoria, South Africa, pp 293–341
- Kinnaird JA, Hutchinson D, Schurmann L, Nex PAM, de Lange R (2005) Petrology and mineralization of the southern Platreef: northern limb of the Bushveld Complex, South Africa. *Mineral Deposita* 40:576–597
- Kinnaird JA, Yudovskaya M, McCreech M, Huthmann F, Botha TJ (2017) The Waterberg platinum group element deposit: atypical mineralization in mafic-ultramafic rocks of the Bushveld Complex, South Africa. *Econ Geol* 112:1367–1394
- Lea SD (1996) The geology of the Upper Critical Zone, northeastern Bushveld Complex. *S Afr J Geol* 99(3):263–283
- Leeb-Du Toit A (1986) The Impala Platinum Mines. In *mineral deposits of Southern Africa*, Vol. I & II. *Geol Soc S Afr* 1091–1106
- Leshner CE, Spera FJ (2015) Thermodynamic and transport properties of silicate melts and magma. 113e141. In: Sigurdsson H, Houghton B, McNutt S, Rymer H, Stix J (eds) *The encyclopedia of volcanoes*. Academic Press, pp 113–141
- Maier WD, Barnes S-J (2003) Platinum-group elements in the Boulder Bed, western Bushveld Complex, South Africa. *Mineral Deposita* 38:370–380
- Maier WD, Barnes S-J (2008) Platinum-group elements in the UG1 and UG2 chromitites and the Bastard reef at Impala platinum mine, western Bushveld Complex. *S Afr J Geol* 111:159–176
- Maier WD, Bowen MP (1996) The UG2 - Merensky Reef interval of the Bushveld Complex northwest of Pretoria. *Mineral Deposita* 31:386–393
- Maier WD, Eales HV (1994) A facies model for the interval between UG2 - Merensky Reef, Western Bushveld Complex. *Trans Inst Min Metall* 103:B65–B72
- Maier WD, Eales HV (1997) Correlation within the UG2-Merensky Reef interval of the Western Bushveld Complex, based on geochemical, mineralogical and petrological data. *Bulletin* 20. Council for Geoscience, pp. 56
- Maier WD, de Klerk L, Blaine J, Manyeruke T, Barnes S-J, Stevens MVA, Mavrogenes JA (2008) Petrogenesis of contact-style PGE mineralisation in the northern limb of the Bushveld Complex: comparison of data from the farms Rooipoort, Townlands, Drenthe and Nonnenwerth. *Mineral Deposita* 43:255–280
- Maier WD, Barnes S-J, Groves DI (2013) The Bushveld Complex, South Africa: formation of platinum-palladium, chrome and vanadium-rich layers via hydrodynamic sorting of a mobilized cumulate slurry in a large, relatively slowly cooling, subsiding magma chamber. *Mineral Deposita* 48:1–56
- Maier WD, Karykowski BT, Yang SH (2016) Formation of transgressive anorthosite seams in the Bushveld Complex via tectonically induced mobilisation of plagioclase-rich crystal mushes. *Geosci Front* 7(6): 875–889
- Manyeruke TD (2007) Geochemical variation of the Platreef in the northern limb of the Bushveld Complex: implications for the origin of the PGE mineralization. PhD thesis, University of Pretoria, pp. 248
- Manyeruke TD, Maier WD, Barnes S-J (2005) Major and trace element geochemistry of the Platreef on the farm Townlands, northern Bushveld Complex. *S Afr J Geol* 108:381–396
- Marquis E (2015) Petrogenesis of the Harzburgitic to troctolitic units in the Turfspruit Cyclic Unit, Northern Bushveld Complex, South Africa. MSc Geology Thesis. Cardiff University, pp. 255
- McDonald I, Holwell DA (2011) Geology of the northern Bushveld Complex and the setting and genesis of the Platreef Ni–Cu–PGE deposit. In Li C, Ripley EM (eds) *Magmatic Ni–Cu and PGE deposits: geology, geochemistry, and genesis*. *Rev Econ Geol* 17:297–327
- McDonald I, Holwell DA, Armitage PEB (2005) 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 mineralization. *Mineral Deposita* 40:526–549
- McDonald I, Harmer RE, Holwell DA, Huges HSR, Boyce AJ (2016) Cu–Ni–PGE mineralisation at the Aurora project and potential for a new PGE province in the northern Bushveld Main Zone. *Ore Geol Rev* 80:1135–1159
- Merensky H (1926) Die neuentdeckten Platinfelder im mittleren Transvaal, und ihre wirtschaftliche Bedeutung. *Berl Z Der Deut Geol Ges* 78:296–314
- Mitchell AA, Scoon RN (2007) The Merensky Reef at Winnaarshoek, eastern Bushveld Complex: a primary magmatic hypothesis based on a wide reef facies. *Econ Geol* 102:971–1009
- Mitchell AA, Scoon RN (2012) The Platreef of the Bushveld Complex, South Africa: a new hypothesis of multiple, non-sequential magma replenishment based on observations at the Akanani Project, northwest of Mokopane. *S Afr J Geol* 115:535–550
- Molyneux TG (1970) The geology of the area in the vicinity of Magnet Heights, eastern Transvaal, with special reference to the magmatic iron ore. *Geol Soc S Afr Spec Publ* 1:228–241
- Mossom RJ (1986) The Atok Platinum Mine. In *Mineral deposits of Southern Africa*, Vol. I & II. *Geol Soc S Afr* 1143–1154
- Mudd GM (2012) Key trends in the resource sustainability of platinum group elements. *Ore Geol Rev* 46:106–117
- Mungall JE, Kamo SL, McQuade S (2016) U–Pb geochronology documents out-of-sequence emplacement of ultramafic layers in the Bushveld Igneous Complex of South Africa. *Nat Commun* 7:13385
- Naldrett T, Kinnaird JA, Wilson A, Chunnnett G (2008) Concentration of PGE in the Earth’s crust with special reference to the Bushveld Complex. *Earth Sci Front* 15(5):264–297
- Naldrett AJ, Wilson A, Kinnaird JA, Chunnnett G (2009) PGE tenor and metal ratios within and below the Merensky Reef, Bushveld Complex: implications for its genesis. *J Petrol* 50(4):625–659
- Nodder SN (2015) Correlating the Bushveld’s northern limb with the western and eastern limbs: a geochemical and petrological study. MSc Geology Thesis. Cardiff University, pp. 257

- Parker HM, Kuhl T, David D (2012) NI43–101 Technical report on mineral resources, Platreef Project, Limpopo province, Republic of South Africa: report for Ivanplats Pty Ltd published on www.sedar.com
- Parker HM, Kuhl T, Valenta M (2013) NI 43-101 technical report on updated mineral resource estimate, platreef project, Limpopo Province, Republic of South Africa: report for Ivanplats Ltd published on www.sedar.com
- Peters BF, Parker HM, Kuhl T, Joughin W, Lawson M, Coetzee V, Smith G (2016) Platreef Project. Platreef 2016 Resource Technical Report. NI 43–101 published on www.sedar.com. Effective date 22 April 2016, pp. 509
- Peters BF, Parker HM, Joughin W, Treen J, Coetzee V, Marais F (2017) Platreef Project. Platreef 2017 Feasibility Study, published on www.sedar.com, pp. 633
- Roberts MD, Reid DL, Miller JA, Basson IJ, Roberts M, Smith D (2007) The Merensky Cyclic Unit and its impact on footwall cumulates below Normal and Regional Pothole reef types in the Western Bushveld Complex. *Mineral Deposita* 42:271–292
- Scoates JS, Friedman RM (2008) Precise age of the platiniferous Merensky Reef, Bushveld Complex, South Africa, by the U-Pb zircon chemical abrasion ID-TIMS technique. *Econ Geol* 103(3):465–471
- Scoates JS, Wall CJ (2015) Geochronology of layered intrusions. In: Charlier B et al (eds) Layered intrusions. Springer Science, Amsterdam, Netherlands, pp 3–74
- Scoon RN (2002) A new occurrence of Merensky Reef on the flanks of the Zaaikloof dome, northeastern Bushveld Complex: relationship between diapirism and magma replenishment. *Econ Geol* 97(5):1037–1049
- Sharpe MR (1981) The chronology of magma influxes to the eastern compartment of the Bushveld Complex, as exemplified by its marginal border group. *J Geol Soc Lond* 138:307–326
- Sharpe MR, Chadwick B (1982) Structures in Transvaal Sequence rocks within and adjacent to the eastern Bushveld Complex. *Trans Geol Soc S Afr* 85:29–41
- Sluzhenikin S, Yudovskaya M, Grobler DF, Brits JAN, Costin G (2014). Contact metamorphic and contact metasomatic rocks in the Platreef footwall on Turfspruit (preliminary data) Abstract 6th Platreef Workshop, 8-10th May 2015, Mokopane, South Africa
- Smart GD (2013) PGE in the Platreef: a petrological and geochemical study of the Turfspruit Cyclic Unit on the Turfspruit farm prospect. MEdSci Geology Thesis. Cardiff University, pp. 163
- Smith JW, Holwell DA, McDonald I (2014) Precious and base metal geochemistry and mineralogy of the Grasvalley Norite–Pyroxenite–Anorthosite (GNPA) member, northern Bushveld Complex, South Africa: implications for a multistage emplacement. *Mineral Deposita* 49:667–692
- Tegner C, Cawthorn RG, Kruger FJ (2006) Cyclicity in the Main and Upper Zones of the Bushveld complex, South Africa: crystallization from a zoned magma sheet. *J Petrol* 47(11):2257–2279
- Teigler B (1990) Mineralogy, petrology and geochemistry of the Lower and Lower Critical Zones, northwestern Bushveld Complex. Ph.D. thesis, Rhodes University, Grahamstown, pp. 247
- Teigler B, Eales HV (1996) The Lower and Critical Zones of the Western Limb of the Bushveld Complex as intersected by the Nooitgedacht boreholes. *Bull Counc Geosci* 111:126
- Teigler B, Eales HV, Scoon RN (1992) The cumulate succession in the critical zone of the Rustenburg layered suite at Brits, western Bushveld Complex. *S Afr J Geol* 95:17–28
- Uken R, Watkeys MK (1997) Diapirism initiated by the Bushveld Complex, South Africa. *Geology* 25:723–726
- Van der Merwe MJ (1976) The layered sequence of the Potgietersrus limb of the Bushveld Complex. *Econ Geol* 71:1337–1351
- Van Der Merwe MJ (1978) The geology of the basic and ultramafic rocks of the Potgietersrus limb of the Bushveld Complex, pp. 1–29
- Vekić N (2017) Petrogenetical and geochemical comparison of the Ni-Cu-PGE-Au mineralisation of the Platreef with the Merensky Reef and the Bastard Reef, Bushveld Complex, South Africa. MSc Thesis, Technische Universität Bergakademie Freiberg, pp. 212
- Viljoen MJ (1999) The nature and origin of the Merensky Reef of the western Bushveld Complex based on geological facies and geophysical data. *S Afr J Geol* 102:221–239
- Viljoen MJ, Hieber R (1986) The Rustenburg Section of Rustenburg Platinum Mines Limited, with reference to the Merensky Reef. In *Mineral Deposits of Southern Africa, Vol. I & II*. *Geol Soc S Afr* 1107–1134
- Viljoen MJ, Theron J, Underwood B, Walters BM, Weaver J, Peyerl W (1986a) The Amandelbult Section of the Rustenburg Platinum Mines Ltd, with Reference to the Merensky Reef: In *Mineral Deposits of Southern Africa, Vol. I & II*. *Geol Soc S Afr* 1041–1160
- Viljoen MJ, De Klerk WJ, Coetze, Hatch NP, Kinloch E, Peyerl W (1986b) The Union Section of Rustenburg Platinum Mines Ltd, with Reference to the Merensky Reef: In *Mineral Deposits of Southern Africa, Vol. I & II*. *Geol Soc S Afr* 1061–1090
- Viring RG, Cowell MW (1999) The Merensky Reef on Northam Platinum Limited. *S Afr J Geol* 102:192–208
- Von Gruenewaldt G 1966 The geology of the Bushveld Igneous Complex east of the Kruis river cobalt occurrence, north of Middelburg, Transvaal. MSc Thesis, Pretoria University, Unpublished. p. 104
- Von Gruenewaldt G (1970) A petrographic and mineralogical investigation of the rocks of the Bushveld Igneous Complex in the Tauteshoogte-Roosenekal area of the Eastern Transvaal. DSc Thesis, University of Pretoria, p. 228
- Von Gruenewaldt G, Dicks G, de Wet J, Horsch H (1990) PGE mineralization in the western sector of the Eastern Bushveld Complex. *Mineral Petrol* 42:71–95
- Wagner PA (1929) The platinum deposits and mines of South Africa. Oliver and Boyd, Edinburgh
- White JA (1994) The Potgietersrus project geology and exploration history: Proceedings, 15th CMMI Congress. *South Afr Inst Min Metall*:173–182
- Wilson AH (2012) A chill sequence to the Bushveld Complex: insight into the first stage of emplacement and implications for the parental magmas. *J Petrol* 53:1123–1168
- Wilson AH (2015) The earliest stages of emplacement of the eastern Bushveld Complex: development of the lower zone, marginal zone and basal ultramafic sequence. *J Petrol* 56:347–388
- Yudovskaya MA, Kinnaird JA, Sobolev AV, Kuzmin DV, McDonald I, Wilson AH (2013) Petrogenesis of the lower zone olivine-rich cumulates beneath the Platreef and their correlation with recognized occurrences in the Bushveld Complex. *Econ Geol* 108:1923–1952
- Yudovskaya MA, Kinnaird JA, Grobler DF, Costin G, Abramova VD, Dunnett T, Barnes S-J (2017) Zonation of Merensky style platinum mineralization in Turfspruit thick reef facies (northern limb of the Bushveld Complex). *Econ Geol* 112(6):1333–1365