Mineralium Deposita (2021) 56:1–10
https://doi.org/10.1007/s00126-020-01027-y

ARTICLE

Introduction to the special issue on the Flatreef PGE-Ni-Cu deposit, northern limb of the Bushveld Igneous Complex

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Received: 19 June 2020 / Accepted: 4 November 2020 / Published online: 2 December 2020

Abstract

More than 30 years ago, Cox and Singer (1986) suggested that magmatic platinum-group element (PGE)-Ni-Cu deposits are amongst the best understood of ore deposits, yet the origin of PGE mineralization in the Bushveld Igneous Complex (BIC) remains controversial after a century of study. In the northern limb of the BIC, the unravelling of ore formation proved particularly difficult due to relatively poor outcrop, which is typically affected by contamination of the intruding magmas with the host rocks and expressed in the form of abundant xenoliths, footwall rafts and disturbance of magmatic stratigraphy. In this thematic issue, we present contributions on the Flatreef, a recently discovered world-class PGE-Ni-Cu deposit constituting a downdip extension of the mineralized unit of the Platreef of the northern limb. Two deep shafts are currently being sunk, making the Flatreef one of the most significant new mine development on the Bushveld in several decades.

Stratigraphy of the Bushveld northern limb and definitions of the Platreef and Flatreef

The detailed stratigraphic relationship between the Platreef and the Flatreef and potential stratigraphic correlations between both horizons with the Upper Critical Zone (UCZ) in the western and eastern limbs of the Bushveld Complex have been debated for years. One reason for this is the lack of consistent definitions for the terms Platreef and Flatreef. In the following section, we first review the current use of both terms in the context of the broader stratigraphic framework of the Bushveld northern limb and then propose updated definitions.

After nearly 100 years of study, it is now widely recognized that in the northern limb (Figs. 1, 2) all major stratigraphic zones constituting the Rustenburg Layered Suite (RLS) have different thicknesses, chemical composition and mineralogy than equivalent units in the remainder of the Bushveld Igneous Complex.

In the western and eastern Bushveld limbs, the Marginal Zone comprises a compositionally and texturally diverse suite of intrusives (gabbronorite, norite, pyroxenite, harzburgite) forming either sills in the floor or a contact layer at the base of the main Bushveld layered body (Sharpe 1981; Cawthorn et al. 1981). The Marginal Zone has been suggested to be relatively poorly developed within the northern limb (Kinnaird et al. 2005; Grobler et al. 2019). However, this may be partly due to terminology. Firstly, noritic and pyroxenitic sills that likely represent the Marginal Zone have in the past been included within the Platreef. Secondly, ultramafic sills enclosed in sedimentary and granitic floor rocks have been grouped into the Lower Zone. Thus, the lowermost parts of the Platreef (or the so-called Lower Platreef; Manyeruke et al. 2005; Kinnaird et al. 2005; Ihlenfeld and Keays 2011) that are bordered by sedimentary rocks in their floor and roof could instead be considered to be part of the Marginal Zone. Recent work by Yudovskaya et al. (this volume) shows that mafic sills underlying the Lower Zone are widespread in the northern limb, and their relics are recognized as the so-called brown norite and recrystallized norite, respectively. However, the temporal relationships for specific sills remain unconstrained.

Editorial handling: G. Beaudoin

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The Lower Zone (LZ) is developed along most of the strike of the northern limb and cannot be readily correlated with the LZ elsewhere as it contains massive chromitites and PGE-mineralized zones. Its thickness has likely been influenced by floor topography and tectonism. The zone reaches 1700 m on the farm Grasvally (Hulbert and von Grunewaldt 1982) and over 800 m on Turfspruit (Yudovskaya et al. 2013). At most localities, the Lower Zone (rather than the Platreef) composes the basal cumulate unit of significant thickness in the northern limb, and it is separated from the overlying Platreef by sedimentary inlayers or rafts up to 300-m thick (Hulbert and von Gruenewaldt 1982; Maier et al. 2008; Yudovskaya et al. 2013). Where in direct contact with the Platreef, the upper boundary of the LZ is defined as the top of the uppermost thick plagioclase-poor harzburgite, as has been suggested for the western limb (Teigler and Eales 1996).

In the western and eastern limbs, the Critical Zone hosts the 13 main chromitite seams of the Bushveld Complex (lower group, middle group and upper group) and the main PGE reefs (UG2 and Merensky Reef). In those limbs, the Critical Zone is approximately 1000-m thick and subdivided into a lower portion (LCZ) consisting mainly of pyroxenite and harzburgite (Cameron 1978; Teigler and Eales 1996) and an upper portion (UCZ) featuring repetitive cyclic units of cumulates that are progressively more evolved with height, i.e. in the ideal case chromitite-harzburgite-pyroxenite-norite-anorthosite (Eales et al. 1988). In the northern limb, the LCZ appears to be absent, whereas the UCZ that is now normally equated with the Platreef is much more contaminated and sulfide enriched than elsewhere, and somewhat depleted in chromite.

It is instructive to consider the evolving meaning of the term Platreef. Hans Merensky, the discoverer of the Bushveld PGE reefs in 1925, believed that the stratiform PGE orebody of the northern limb represents a thickened lateral equivalent of the Merensky Reef as exposed in the western and eastern Bushveld (Wagner 1929; Cawthorn 2015). In contrast, van der Merwe (1976) considered the mineralized interval, for which he coined the term Platreef, to constitute the base of the Main Zone, despite equating the Platreef with the "Platinum Horizon" of Wagner (1929). With increasing geological knowledge due to extensive exploration, mining and research activities, particularly since the opening of Mogalakwena mine in 1990, it became clear that the Platreef may contain multiple concordant and discordant sills and corresponds to a zone rather than a layer. Thus, in the recent literature, the term Platreef has been used to denote either the whole stratigraphic interval between the LZ and the Main Zone in the northern limb (Kinnaird and McDonald 2005; McDonald and Holwell 2011) or only the mineralized portion thereof (van der Merwe 1976, 1978; Viljoen and Schurmann 1998).

One of the earliest definitions of the Platreef was provided by Gain and Mostert (1982; p. 1396) who described the Platreef as "composed of a complex sequence of medium- to coarse-grained pyroxenites, melanorites, and norites, in places pegmatoidal and serpentinized, containing metasedimentary xenoliths of the floor rocks". Using the data accumulated since the 1990s, Kinnaird and McDonald (2005; p. 196) defined the Platreef as "Mafic units enriched in Ni-Cu-PGE that occur between the Archaean granite-gneiss basement or the Transvaal Supergroup and the gabbronorites of the Main Zone, north of the Planknek Fault". This definition essentially interprets the Platreef as the correlative of the entire UCZ, but it excludes the Ni-Cu-PGE mineralization south of the Planknek–Ysterberg Fault (termed the GNPA member by Hulbert and von Gruenewaldt 1982), based on the fact that the stratigraphy in this area is more correlatable with the Bushveld eastern and western limbs, including a massive chromitite regarded as the UG2 equivalent (Hulbert and Von Gruenewaldt 1982; Maier et al. 2008; Smith et al. 2014; Kinnaird and Nex 2015). Given the presence of the UG2-like chromitite on Turfspruit (Grobler et al. 2019; Langa et al. 2020) and Akanani (Yudovskaya et al. 2011), this argument is not applicable anymore, and, therefore, the GNPA member south of the Planknek Fault should be accepted as a southern facies of the Platreef and a stratigraphic equivalent of the Upper Critical Zone (Kinnaird and McDonald 2018).

The definition by Kinnaird and McDonald (2005) also so did not include the mineralization occurring in the northern portion of the northern Bushveld limb, notably at the Aurora project on the farms Altona, Kransplaats, La Pucella, Luge, Nonnenwerth, Non Plus Ultra and Schaffhausen. This area is regarded as the northern facies of the Platreef by Manyeruke (2007) and Maier et al. (2008), whereas McDonald et al. (2017) and McFall et al. (2019) argue that because the geochemical and mineral characteristics are consistent with Main Zone compositions, this mineralization should not be included in the Platreef.

Maier et al. (2008) suggested that all mineralized rocks at the base of the northern limb should be termed "Platreef" arguing that this definition provides a clear exploration guideline that can be applied in the field, without the need of geochronology or geochemistry. However, this definition does not help distinguish between contact-style and internal reef-style PGE mineralization that may occur at the basal and

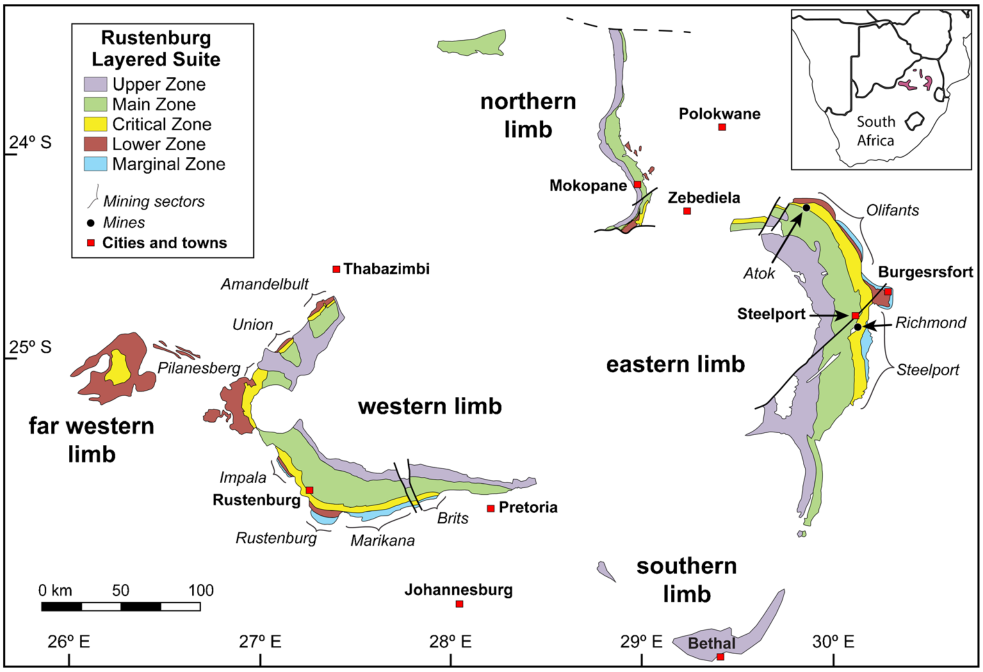

Fig. 1 Geological map of the Rustenburg Layered Suite of the Bushveld Igneous Complex (after Mungall et al. 2016) showing locations mentioned in this issue and other relevant locations

in the top parts of the Platreef, respectively, as seen in the Flatreef sequence on Turfspruit (Grobler et al. 2019). In other areas of the northern limb, these two types of mineralization are superimposed and may form a thick high-grade orebody, as seen on Sandsloot where high-grade ores occur both in intrusive and metasedimentary rocks (McDonald and Holwell 2011; Klemd et al. 2016; Mwenze et al. 2019).

Other problems with the definitions by Kinnaird and McDonald (2005) and Maier et al. (2008) are as follows: (i) both encompass the PGE mineralization in the Lower Zone, e.g. on Grasvally, Turfspruit and Uitloop, with other areas remaining poorly explored; (ii) so far, the known stratigraphy of the Platreef does not include undisputable Lower Critical Zone rocks, unless the Akanani deeper sections could be considered to represent this (Mitchell and Scoon 2012; Scoon et al. 2020). However, the presence of LCZ in the deep western portions of the northern limb cannot be excluded, and any definition of the Platreef (and Flatreef) should be flexible enough to allow a potential inclusion of LCZ in the future; (iii) both definitions do not include the thick unmineralized or poorly mineralized portions of the Platreef that can be a predominant constituent of the sequence.

Scoon et al. (2020) suggested to use the term “Platreef Unit” for the entire sequence correlative of the Critical Zone (Mitchell and Scoon 2012), whereas the term “Platreef” should be reserved for the mineralized part or an orebody within the sequence. To our mind this approach represents a useful compromise. We thus propose the following new definition: The Platreef Unit of the Bushveld northern limb is a complex sequence composed of coalescing magmatic units, some of which representing sills, with enclosed metasedimentary inlayers that represents a contaminated analogue of the chromite-bearing Upper Critical Zone of the western and eastern Bushveld and is overlain by chromite-free Main Zone rocks. It is pervasively, yet irregularly PGE mineralized, with economic PGE deposits defined as Platreef deposits. The top contact with the Main Zone is a key characteristic to distinguish the Platreef Unit from mafic-ultramafic marginal sills and satellite bodies crystallized from Critical Zone magmas but emplaced completely into

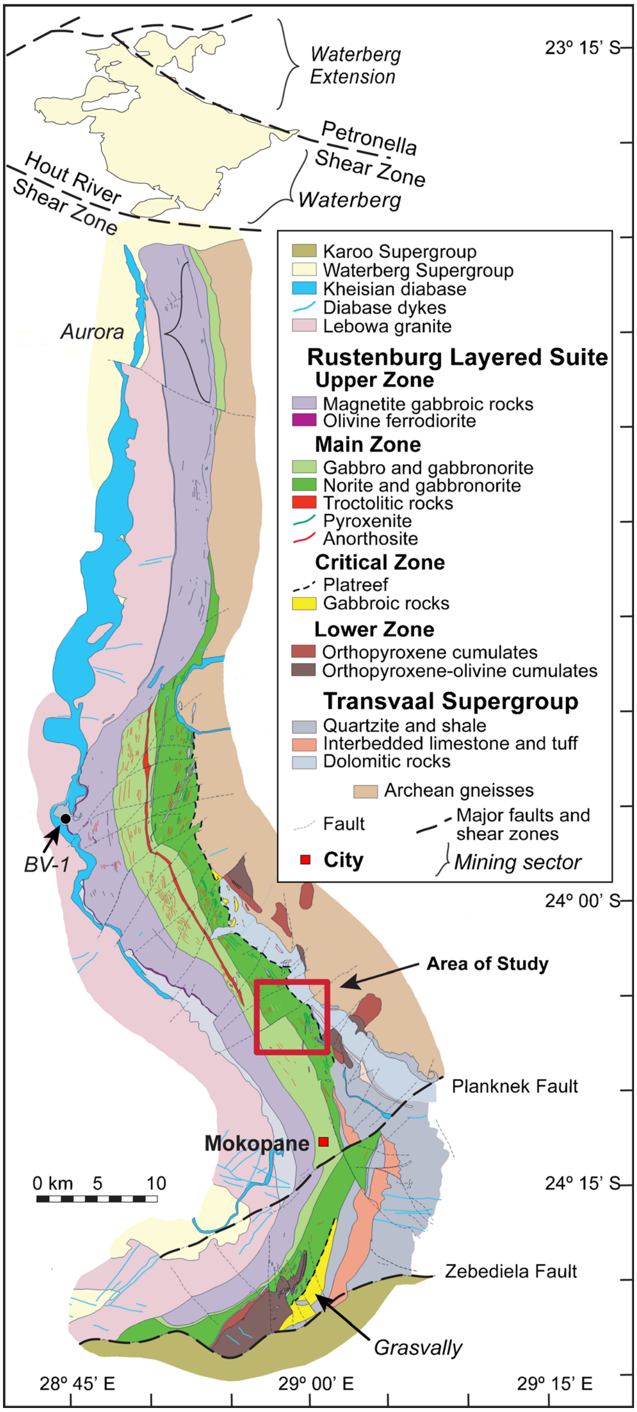

Fig. 2 Geological map of the northern limb after (after Ashwal et al. 2005) and the Waterberg extension (after Yudovskaya et al. 2018) showing the area of study in this issue and several other relevant locations

sedimentary wallrocks and not having the Main Zone roof. The Flatreef Unit represents the deep western facies of the Platreef Unit (or the Critical Zone as a synonym, Grobler et al. 2019), characterized by a change in dip, decreasing amount of contamination and less disturbance of magmatic stratigraphy (Fig. 3). The Flatreef includes several lower-rank units and sub-units, with some of the uppermost ones representing the thick facies PGE reef correlatives of the Merensky and Bastard reefs. This facies concept has proven to be a useful tool to correlate layers in the western and eastern limbs (Eales et al. 1988, Viljoen 1999; Maier and Teigler 1995, Maier and Eales 1997) and it should be further developed for the northern limb with particular attention being paid to regional markers aiming to see similarities rather than differences which are often of a secondary character.

The base of the 3-km-thick Main Zone (MZ) is usually delineated by a sharp contact to distinctive layers of mottled (poikilitic) anorthosite which form the uppermost unit of the UCZ. In the centre of the MZ is the troctolite unit, which does not appear in the Main Zone elsewhere in the Bushveld Complex (van der Merwe 1976; Kennedy 2019). In contrast, the Pyroxenite Marker (PM), which marks a pronounced isotopic and trace element shift at the top of the Main Zone in the eastern and western Bushveld, was thought to be absent in the northern limb (Ashwal et al. 2005; Tanner et al. 2019). However, Maier and Barnes et al. (2010) correlate PGE rich layers on Moorddrift with the PM, and Cawthorn (2020) suggested that a lateral equivalent of the PM does exist in the Bellevue drill core and reflects an addition of a relatively unevolved magma (Fig. 2).

The Upper Zone (UZ) in the northern limb is < 1.2-km thick (Ashwal et al. 2005) and contains ~ 32 discrete magnetitite layers which can be traced along the strike of the northern limb and within the Villa Nora fragment to the northwest. Ashwal et al. (2005) suggested that the boundary between the Upper and Main Zones should be identified by a sharp increase in magnetic susceptibility that is caused by the presence of significant modal magnetite. This approach was adopted during the Waterberg project exploration to postulate the presence of UZ (with PGE mineralization at

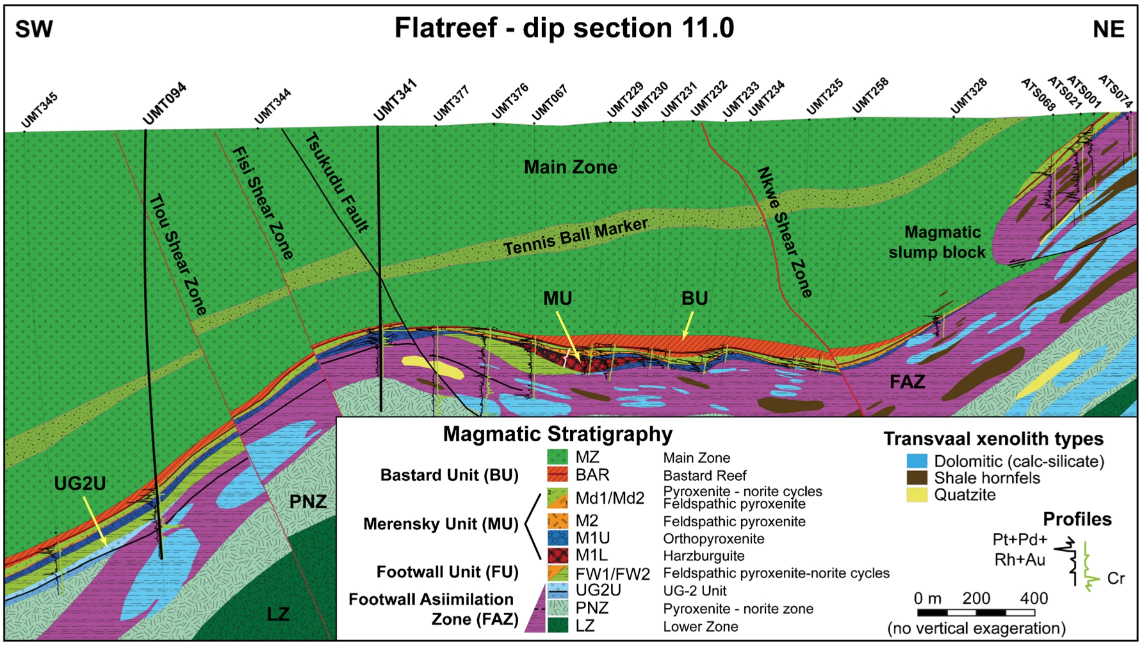

Fig. 3 Representative cross section through the Platreef in the Turfspruit area showing the change in dip that defines the Flatreef (after Grobler et al. 2019). Two of the drillholes used in contributions to this issue are in bold

its base) in the uppermost portion of the exposed stratigraphy (Kinnaird et al. 2017, and Huthmann et al. 2018).

The Waterberg project is of particular note because, in addition to the Flatreef, it represents a further example of a recent discovery of significant new PGE deposits in the Bushveld. In the Waterberg project, the RLS includes an ultramafic portion with a composition very similar to that of the uncontaminated ultramafic part of the Platreef (e.g. on Turfspruit, Yudovskaya et al. 2017; Grobler et al. 2019) and a gabbroic to troctolitic portion that has a homogeneous Sr isotope composition reminiscent of the UZ showing progressively more UZ-like chemical characteristics upwards, such as increased disseminated magnetite contents (Kinnaird et al. 2017; Huthmann et al. 2017). The possible PGE fertility of the UZ magmas has previously been hypothesized by von Gruenewaldt (1976). However, the UZ of the Waterberg project area lacks massive magnetite which led Kinnaird et al. (2017) to suggest that the RLS segment north of the Hout River Shear Zone (HRSZ) was developed as a separate magmatic basin fed from a distinct crustal sub-chamber at the rifted edge of the craton.

Both the ultramafic and the gabbroic-troctolitic portions contain intervals of high-grade, low-sulfide PGE mineralization, referred to as F zone (in the ultramafic rocks) and T zone (in gabbroic rocks) (McCreesh et al. 2018). Preliminary data suggest that these two contrasting styles of mineralization are also recognizable immediately south across the HRSZ on the farm Harriet's Wish (van Scheltema 2019). The T zone can be potentially correlated with Main Zone-hosted troctolite marker mineralization (van der Merwe 1976, 1978) studied on the farm Vogelstruisfontein (Kennedy 2019) and mineralized melagabbro and pyroxenite layers on Moorddrift, 20 km to the S of Mokopane (Maier and Barnes 2010).

Brief overview of petrogenetic models for the Bushveld PGE reefs

A common thread of most of the previously published petrogenetic models for the Bushveld PGE reefs is the assumption that the PGE were originally concentrated by magmatic sulfides. However, the trigger for sulfide melt saturation and segregation remains debated. Two main models can be distinguished: Advocates of Model 1 suggest that sulfide melt saturation occurred within the Bushveld magma chamber. Proposed triggers for sulfide melt saturation include the following:

i. Chromite crystallization resulting in a decrease in Fe content of the magma (Vermaak 1976). However, the amount of chromite in the known exposures of the Merensky Reef, Platreef and Flatreef is relatively small (usually < 1–2%), and it is unclear whether the resulting decrease in Fe content is sufficient to trigger sulfide saturation.

ii. Mixing of relatively light replenishing magma with denser resident magma (Campbell et al. 1983; Naldrett and von Gruenewaldt 1989). The sulfide melt segregated through, and equilibrated with, a large body of silicate melt, thereby achieving large R factors (mass ratio of silicate melt to sulfide melt) and high metal tenors. However, Li and Ripley (2005) showed that magma mixing can trigger sulfide melt saturation only if both mixing end members are nearly sulfide saturated, yet the available data from the presumed parent magmas of the Bushveld Complex suggest that the magmas were strongly S undersaturated (Barnes et al. 2010).

iii. Fractionation of the magma in the chamber leading to saturation in a sulfide liquid and accumulation of the sulfide liquid at the top of the cumulate pile (Barnes et al. 2010). However, as the cotectic ratio of sulfides forming from Bushveld magmas is likely < 1% (Cawthorn 2005), a further step is required to concentrate the sulfides to levels observed in the reefs (commonly 2–4%; Barnes and Maier 2002, McDonald and Holwell 2011).

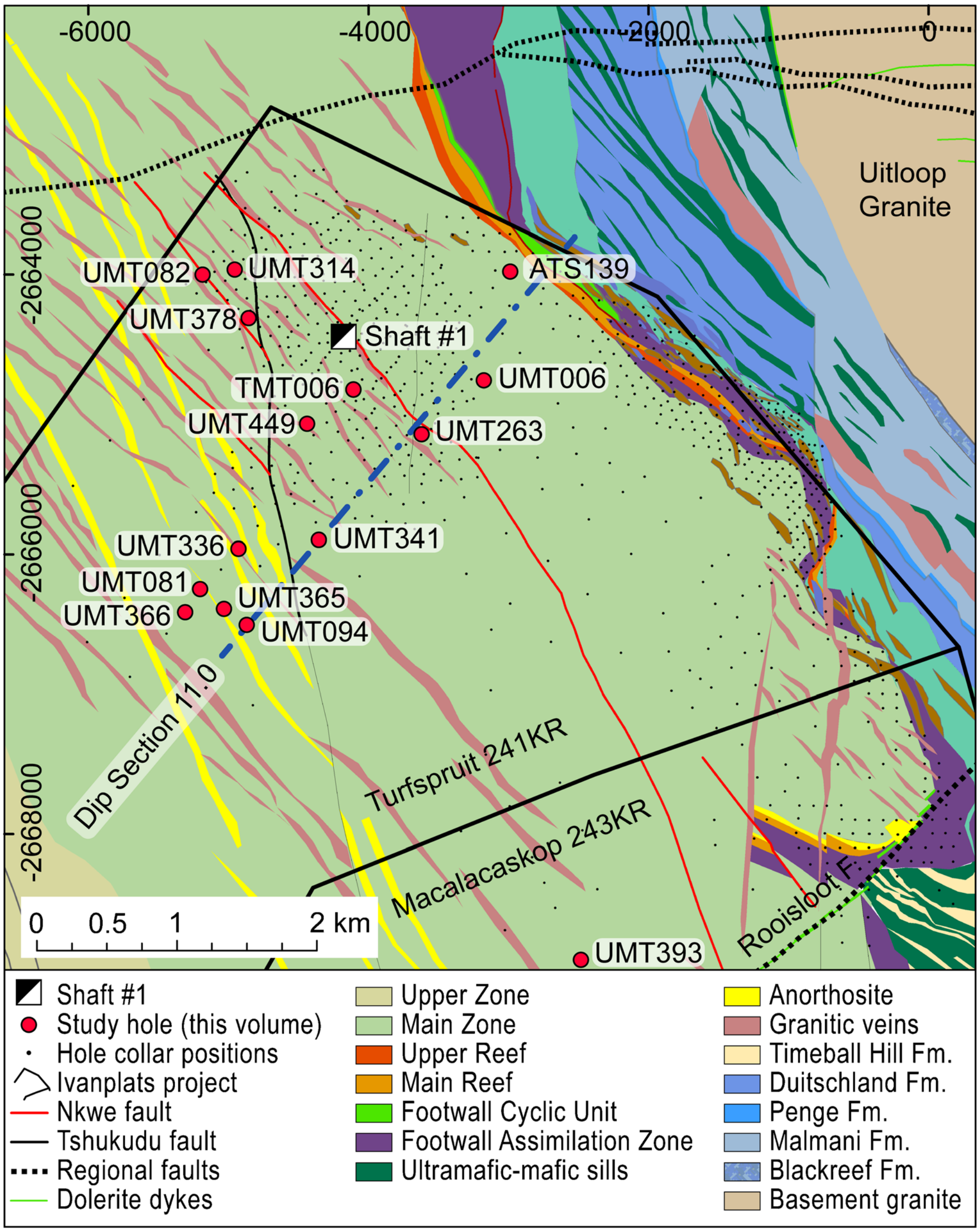

Fig. 4 Detailed geological map of the area of study showing the location of the drillholes documented in this issue. The location of Shaft #1 and the boundaries of the Turfspruit and Macalacaskop farms are also shown

iv. To address this problem, Maier et al. (2013) proposed a hydrodynamic model in which sulfides were concentrated by phase sorting and kinetic sieving, in response to seismically induced slumping and fluidization of crystal slurries during filling of the magma chamber. The model was experimentally tested by Forien et al. (2015) using circular beads as crystal analogues, but it remains to be examined whether lath-like particles that constitute a closer analogue to plagioclase and pyroxene crystals would behave differently.

v. Nucleation of sulfides at the crystallisation front near the top of the cumulate pile and collection of PGE from magma flowing past the sulfide (Latypov et al. 2017). Similar challenges as for trigger mechanism (ii) apply, i.e. known Bushveld magmas are strongly sulfide undersaturated.

vi. Mobilization and concentration of early formed cumulus sulfide and PGE by late magmatic fluids (Boudreau and McCallum 1992). However, the available evidence suggests that some of the PGE concentrated in the reefs (notably Ir, Ru, Rh) are highly immobile under normal magmatic conditions.

The proponents of Model 2 argue that sulfide saturation was reached in a staging chamber below the main Bushveld chamber, triggered by contamination and/or fractionation. The sulfides were entrained and partially resorbed during continued magma ascent, resulting in sulfide and PGE rich magmas being emplaced into the Bushveld chamber, followed by segregation of the sulfides to form the reefs (Lee and Butcher 1990; Mitchell and Scoon 2007; Naldrett et al. 2009; Latypov et al. 2017). The model has been particularly popular for the Platreef (Lee 1996; McDonald and Holwell 2007; Holwell et al. 2011) because the total amount of PGE in the Platreef would require a complementary magma column of up to 10 km of overlying PGE depleted magma (at least in a simplistic 2D model). However, cumulates and residual liquids may have migrated towards the interior or the periphery of the chamber. Another problem with Model 2, as with some of the proposed mechanisms listed under Model 1 above, is that there is presently no evidence for PGE or sulfide-rich parent magmas to the Bushveld Complex although numerous fine-grained sills and several chilled margins have been studied (Davies and Tredoux 1985; Barnes et al. 2010; Wilson et al. 2015; Maier et al. 2016). However, the available data are all from the western and eastern Bushveld, and thus more work is required to study the marginal suite in the northern limb.

Contributions in this thematic issue

In the papers within this thematic issue, we present a large amount of new data for the Flatreef based on the study of the extensive drill core archive of Ivanplats. The locations of the drillholes used in the studies in this issue are shown in Figure 4. Most of the papers are based on research presented first at the northern limb session during the 13th International Platinum Symposium held in Limpopo, South Africa, in June–July 2018. The efforts of the organizing committee in carrying out field excursions and coreyard visits are gratefully acknowledged.

Maier et al. (2020) focus on the petrogenesis of the most highly mineralized portion of the Flatreef, namely, the interval between the MZ and the base of the Merensky Reef. Based on a detailed examination of four drill cores, they propose that the combination of several favourable processes, including country rock assimilation as well as hydrodynamic and hydromagmatic processes, resulted in exceptionally thick mineralized intervals (e.g. 22m at >8 ppm in UMT378).

Langa et al. (2020) compare the UG2 chromitite in the Flatreef with a UG2 reference suite from the western Bushveld using a range of techniques including petrography, electron probe microanalysis, laser ablation-inductively coupled plasma-mass spectrometry and Mössbauer spectroscopy. They conclude that whereas semi-massive and disseminated chromitite may have a variable composition due to equilibration with trapped silicate melt, the massive portions of the seams have overlapping compositions.

Yudovskaya et al. (2020) conducted a detailed petrographic and compositional study of the interaction between the intruding Lower Zone magmas and the anhydrite-rich country rocks in drill core UMT336. The study shows that contact metamorphism and partial melting may result in the formation of hybrid rocks with Sr isotope characteristics similar to those of the pristine magmatic counterparts.

The papers by Mayer et al. (2020) and Beukes et al. (2020) present the first Sr isotopic profiles of the Flatreef on the farms Turfspruit (Mayer et al.) and Macalacaskop (Beukes et al.). Both studies document a similar Sr isotopic stratigraphy and range in initial Sr isotope ratio as previously documented in the Merensky Reef interval of the western Bushveld by Kruger and Marsh (1985).

Keir-Sage et al. (2020) present a detailed S isotopic profile of the Flatreef as intersected in deep drill core

UTM94. The authors show that the lower portion of the Flatreef has $\delta^{34}S$ values up to + 8‰ suggesting strong contamination by the country rocks, whereas the upper portions, including the proposed correlatives of the Merensky and Bastard reefs, have $\delta^{34}S$ values of + 2 to + 4‰ overlapping with the uppermost Critical Zone of the western Bushveld.

In summary, papers in this thematic issue provide support for correlation between the Flatreef of the northern limb and the uppermost Critical Zone in the remainder of the Bushveld Complex while also documenting strong contamination of the Flatreef rocks by the country rocks.

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