# SERIES

# Igneous Rock Associations 23. The Bushveld Complex, South Africa: New Insights and Paradigms

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## SUMMARY

The Bushveld Complex has continued to serve as the basis for study into the fundamental nature of petrological processes for layered intrusion formation and for oxide and sulphide-hosted Platinum Group Element (PGE)–Cu–Ni ore deposits. These studies have included discoveries in terms of the physical extent of Bushveld magmatism, both laterally and internally. Lateral variations in the mafic to ultramafic Rustenburg Layered Suite of the Northern Lobe of the complex have also revealed petrologically distinctive Upper Critical Zone equivalent rocks (the so-called Flatreef) with enhanced contamination and mineralization traits that reflect a transition between Eastern and Western Lobe equivalent stratigraphy and Platreef-style complexity. Traditional magma mixing models have been re-examined in light of radiogenic isotopic evidence for crustal involvement early in the chromite precipitation or formation process, combined with evidence for associated heterogeneous fluid contents, cryptic layering profiles, and textural evidence. A wide variety of alternative ore-genesis models have been proposed as a consequence. The fundamental mechanics of magma chamber processes and the existence of the magma chamber as an entity have been called into question through various lines of evidence which have promoted the concept of progressive emplacement of the complex as a stack of not-necessarily-quite-sequentially intruded sills (with or without significant quantities of transported phenocrysts), emplaced into variably crystallized and compacted crystal-liquid mush mixtures, modified by compaction-driven late magmatic fluid (silicate and aqueous) activity. Alternatively, petrological and geochemical observations have been used to discount these interpretations in favour of more conventional cooling and gravity-driven accumulation of silicate and ore minerals in a large, liquid-dominated system.

## RÉSUMÉ

Le complexe de Bushveld a demeuré à la base d'études sur la nature fondamentale des processus pétrologiques de formation d'intrusions litées et des gîtes des éléments du groupe platine (ÉGP)-Cu-Ni hébergés dans les oxydes et les sulfures. Ces études ont comporté des découvertes sur l'étendue physique, à la fois latérale et interne, du magmatisme de Bushveld. Les variations latérales de la suite stratifiée et mafique à ultramafique Rustenburg du lobe nord du complexe ont également révélé des roches équivalentes pétrologiquement distinctes de la zone critique supérieure (le communément désigné Flatreef) avec des traits de contamination et de minéralisation accrus qui reflètent une transition entre la stratigraphie équivalente des lobes est et ouest et la complexité de type Platreef. Les modèles traditionnels de mélanges magmatiques ont été réexaminés à la lumière de preuves isotopiques radiogéniques indiquant une implication de la croûte au début du processus de précipitation ou de formation de la chromite, combinées à des preuves de contenu fluide hétérogène associé, de profils de litage cryptique et de preuves texturales. Ainsi, une grande variété de modèles alternatifs de genèse de minerai a été proposée. La mécanique fondamentale des processus de la chambre magmatique et l'existence de la chambre magmatique en tant qu'entité ont été remises en question au moyen de divers éléments de preuve qui ont mis en avant le concept de mise en place progressive du complexe sous forme d'un empilement non-nécessairement séquentiel de sills injectés (avec ou sans quantités significatives de phénocristaux transportés) mis en place dans des mélanges de bouillie cristaux/liquide à cristallisation et compaction variable, modifiés par une activité tardive de fluide

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magmatique (silicaté et aqueux) induite par la compaction. Alternativement, des observations pétrologiques et géochimiques ont été utilisées pour écarter ces interprétations en faveur d'un processus plus conventionnel de refroidissement et d'accumulation de minérais silicatés et minéralisés induite par la gravité dans un vaste système à dominance liquide.

*Traduit par la Traductrice*

## INTRODUCTION

The Bushveld Complex (or Bushveld Igneous Complex, BIC), hosted in northeastern South Africa, represents the world's largest known layered mafic intrusive complex, and the largest magmatic ore resource (Lee 1996; Viljoen 2016), containing significant proportions of the Earth's known extractable ores of Platinum Group Elements (PGE), Cr, and V, along with other subsidiary magmatic and contact metamorphic (andalusite, specifically) ores. The Bushveld has been the subject of geological study since 1872, evidently having engendered on the order of 200 publications by the 1930s (Eales 2014), on the order of a thousand by the 1970s (see Cawthorn 2015; p. 521), and thousands since then (nearly 3000 publications since 1994 contain 'Bushveld Complex' in their titles, based on a quick online search, including about 500 in just the past four years). This review does not, therefore, purport to represent an overview of the existing knowledge on the Complex, which is in a constant state of flux and has been usefully summarized in the relatively recent past by authors including von Gruenewaldt et al. (1985), Eales and Cawthorn (1996), Cawthorn (2015), and Viljoen (2016), for example. A particularly useful review of the key aspects of genetic models for mineralization and relevant igneous processes was published by Maier et al. (2013), and an introductory level, less technical overview has also been provided recently by Eales (2014). The reader seeking supplementary accounts of the detailed characteristics of the Complex is also directed to works such as these.

The Bushveld Complex includes, in approximate order of emplacement, the bimodal volcanic rocks of the Rooiberg Group (Hatton and Schweitzer 1995), the ultramafic to mafic rocks of the Rustenburg Layered Suite (RLS), and the granitic intrusive rocks of the Lebowa Granite Suite (see Eales and Cawthorn 1996, and references therein). For the purposes of this review, the term Bushveld Complex is being used here with specific reference to the rocks of the Rustenburg Layered Suite, unless otherwise noted. In spite of the plethora of research on the Bushveld Complex over its history, a wide range of extremely fundamental questions remain unresolved and under active investigation over the last decade or two. Many of these questions have arisen as a consequence of improvements in analytical resolution or access to previously inaccessible types of data, while others have arisen as a consequence of detailed mapping and the extrapolation and development of new ideas. Unresolved questions include such basic elements as the original extent of the vertical and lateral stratigraphy of the BIC, the nature of the parent magmas, the basic manner of emplacement of the constituents of the complex, the triggering and concentrating mechanisms for the Cr–Fe oxide, PGE-sulphide, and Fe–Ti–V oxide ores, each of which have their own set of models, and the fundamental tectonic justification for the existence of the BIC. In this review the concepts relating to the Bushveld Complex have been presented in the following categories, in which there have been significant developments which have helped to resolve long-standing issues, or more often, to introduce new concepts which undermine traditional paradigms in igneous petrology and magmatic ore petrogenesis:

- the basic stratigraphy of the BIC
- ore deposit models applied to the BIC
- the nature of the parent magma to metalliferous rocks
- constraints on contamination of BIC magmas
- emplacement processes for BIC rocks

A simplified geological map and stratigraphic column are provided as Figures 1 and 2, respectively. The Critical Zone, overlying the Lower Zone, features the presence of discrete horizons of chromitite, associated with rhythmic modal layering in the Upper Critical Zone, which is distinguished from the Lower Critical Zone by the presence of cumulate (primocryst) plagioclase in the former. The chromitite layers range from cm- to metre-scale thicknesses, and provide economic quantities of chrome ores. The chromitite layers are hosted within harzburgite and pyroxenite in the Lower Critical Zone, supplemented and/or replaced by (increasingly poikilitic upwards) leuconorite to anorthositic and noritic layers in the Upper Critical Zone. Most of the chromitite horizons are enriched in PGE relative to the silicate rocks, and the PGE are largely present as platinum-group minerals (e.g. Kinloch 1982; Junge et al. 2016), although disseminated sulphide minerals and PGE are not strictly restricted to the oxide horizons. The chromitite layers are designated as LG (Lower Group) chromitite, numbered from 1–7 upwards, then MG (Middle Group), within which sequence the Upper Critical Zone commences, and finally the UG (Upper Group) chromitite layers, which include the distinctively bifurcated and multi-layered UG-1, the PGE-rich UG-2, and capped by the PGE-rich Merensky Reef. The Merensky Reef is itself overlain by a PGE-poor lithological sequence which otherwise virtually replicates the Merensky sequence, which is hence known as the Bastard unit. Overlying this is the Main Zone, featuring the appearance of primocryst clinopyroxenes (both pigeonite, now inverted, and augite). Near the top of the Main Zone is the so-called Pyroxenite Marker (which varies lithologically around the complex). The Main Zone is overlain by the Upper Zone, which features an increasingly ferrogabbroic sequence interrupted by a suite of Fe-Ti oxide layers (at least 21 of them) dominated by magnetite with subsidiary ilmenite and ulvospinel, and economic grades of vanadium, decreasing in grade upwards through the sequence. The top of the Main Zone features apatite-rich dioritic rocks, grading into what has been proposed as the Roof Zone granophyric rocks (Cawthorn 2013), which represent the interactive zone between Bushveld differentiates and the Rooiberg volcanic rocks (Hatton and Schweitzer 1995), which serve as the roof to the BIC.

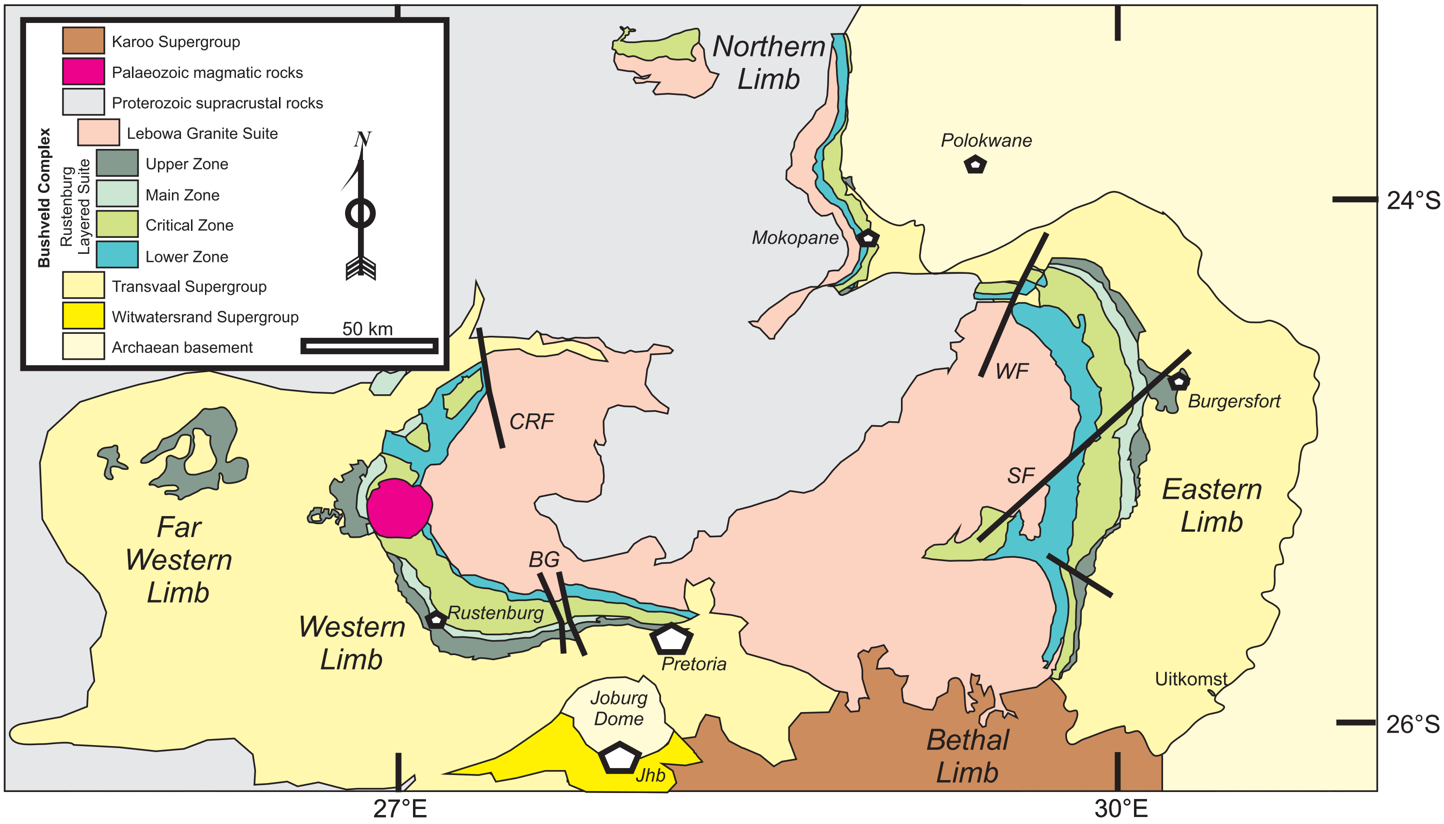

**Figure 1.** Simplified geological map of the Bushveld Complex and geographically associated rocks. Jhb = Johannesburg. Adapted from Johnson and Wolmarans (2008). Positions of crustal lineaments and/or faults (solid lines transecting the Rustenburg Layered Suite -RLS) after Cawthorn (2006) and Maier et al. (2013). BG = Brits Graben; CRF = Crocodile River Fault; SF = Steelpoort Fault; WF = Wonderkop Fault; Joburg Dome = Johannesburg Dome.

## EXTENT OF BUSHVELD MAFIC MAGMATISM

The total thickness of the sequence in the Eastern Limb is ca. 8100 m, as compared to around 7220 m in the Western Limb (Eales and Cawthorn 1996). A distinguishing feature of the suite is the remarkable lateral continuity of the modal layering, particularly of the oxide layers, which can be traced and correlated for tens to hundreds of kilometres across the complex with relatively little systematic change in character over large lateral distances. Any genetic model for their formation is constrained by this trait. Only the eastern and western limbs feature these thicknesses of relatively complete lithological sections through the complex. The Bethal Limb appears to reflect mostly Upper Zone rocks, while the Far Western Limb features Lower Zone equivalents. The Northern Limb was mapped (van der Merwe 1978) as featuring Upper and Main Zone lithologies only, with Lower Zone equivalents present as discrete bodies hosted within the footwall, and until relatively recently, it was understood that Critical Zone magmas and the resultant rhythmically layered sequences and laterally continuous chromitite layers were not present there (Kruger 2005).

Recent drilling in the northeastern part of the Eastern Limb (the so-called Clapham Section) has revealed a new and significant magmatic sequence below the Lower and Marginal Zones (i.e. the putative base of the Bushveld sequence), such that an additional 750 m or so of primitive ultramafic rocks has been identified, summarized in Figure 3. This sequence, which is similar to the Lower Zone in terms of lithological assemblages, has been named the Basal Ultramafic Succession (BUS) by Wilson (2015), who distinguished it from the overlying Lower Zone, from which it is separated by the Marginal Zone rocks. This sequence also features a ca. 1 m thick contact chilled zone against the floor quartzite, as well as additional chilled units, spinifex-textured and harrisitic-textured rocks in the lowermost 100 metres. Wilson (2015) has proposed that this represents the earliest and most primitive Bushveld material to be injected into the upper crust. It remains to be seen how extensive and/or representative this unit may prove to be. Sharpe and Hulbert (1985) reported chilled ultramafic sill textures from the eastern lobe, but it is perhaps noteworthy that recent work in the Northern Limb has also shown extensive thicknesses of putative Lower Zone ultramafic rocks typically lying below (rather than above, although this is also described) the Marginal Zone norite and feldspathic pyroxenite (Yudovskaya et al. 2013b). In addition, Maier et al. (2016) have reported spinifex-textured komatiitic marginal chilled rocks from the western Bushveld.

### Other Bushveld-type Magmatism

In addition to these main constituents of the BIC, compositional equivalents have been identified farther to the west and to the east. To the west, in Botswana, the Molopo Farms Complex constitutes an additional 30% of the surface area of the

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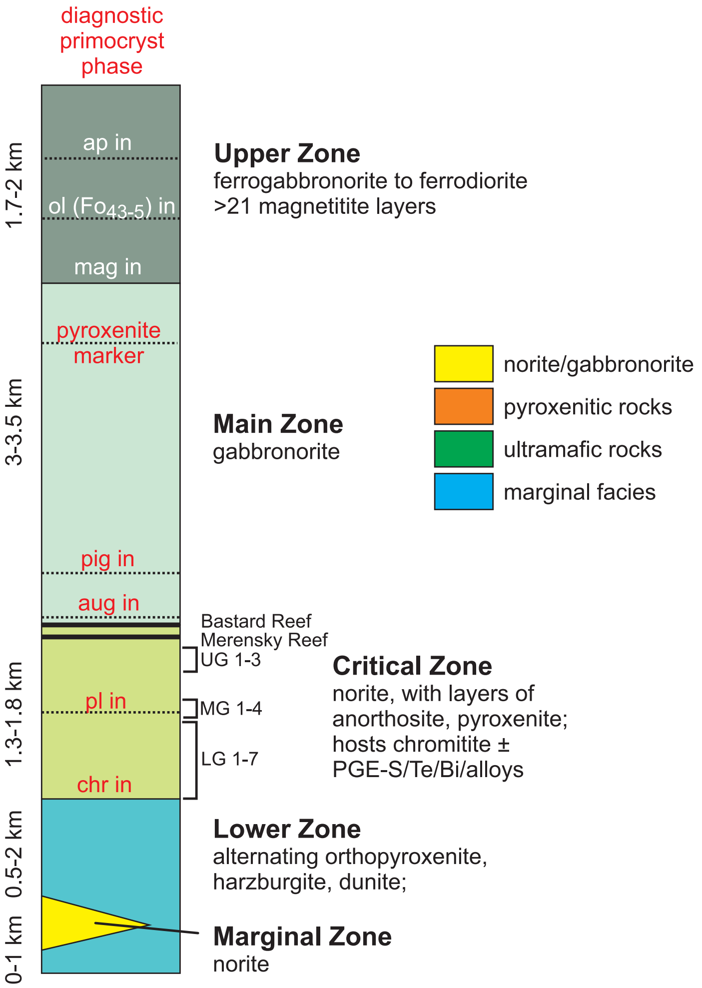

**Figure 2.** Simplified stratigraphy of the Bushveld Complex, showing the main lithostratigraphic zones and their associated ore horizons, modified after Eales and Cawthorn (1996), Cawthorn (2006) and Wilson (2012).
The thickness of individual zones and/or subzones varies across and within lobes; the typical ranges are shown here.
*ap = apatite; ol = olivine; mag = magnetite; pig = pigeonite; aug = augite; pl = plagioclase feldspar; chr = chromite.*
The two main cumulus minerals whose disappearances are noteworthy are chromite, which ceases at the top of the Critical Zone, and olivine. Olivine's occurrence is intermittent in the Lower Zone and Lower Critical Zone, and then it reappears intermittently in association with specific mineralized reefs higher in the Critical Zone, in somewhat anomalous circumstances. It should not, therefore, be treated as a persistent cumulus/cotectic mineral over this whole interval.

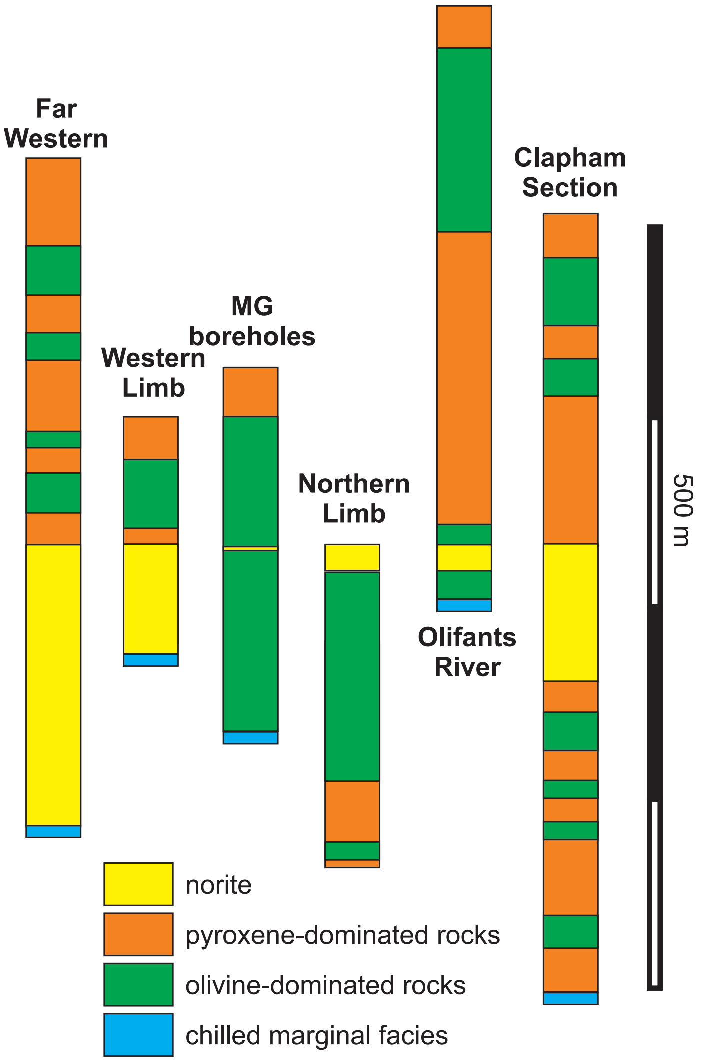

**Figure 3.** The stratigraphy of the Lower and Marginal Zones of the Bushveld Complex, in simplified sections from west to east, using the Shelter Norite of the so-called Marginal Zone as the index horizon. Modified after Wilson (2012).

Bushveld, albeit occurring entirely in the subsurface and consequently relatively poorly studied. A poorly-constrained Rb-Sr age published in prospecting reports suggests that the intrusion is contemporaneous with the BIC (usefully summarized in Kaavera et al. 2018). Prendergast (2012) suggested that the Molopo Farms Complex was derived from magmatic equivalents to the ultramafic Bushveld Lower Zone, and hence is not a strong prospect for either Critical Zone nor Platreef-style (Northern Limb) sulphide mineralization. However, Kaavera et al. (2018) suggested that rocks consistent with the putative parental magmas to Bushveld rocks of the Lower and Main (but not the Critical) Zones are all identifiable within the Molopo Farms stratigraphy, such that rather than the Molopo Farms being a residual Lower Zone equivalent only (Figure 4), it is rather a more complete Bushveld magmatic equivalent but with a distinct (more rapid) crystallization history.

Gauert (2001) suggested that the Uitkomst was a conduit or feeder to a now-eroded (or otherwise undiscovered) Bushveld-like body to the east, rather than having fed the Bushveld Complex proper to the northwest (Figure 5), consistent with geometric factors (the sill is tilted upwards to the southeast), but mainly based on geochemical criteria such as timing of contamination, cumulate extraction and sulphur saturation. Eales and Cawthorn (1996) reported several other small but less well studied Bushveld-equivalent bodies hosted in footwall rocks within about 50 km of the known sections, in various directions.

### Geophysical Evidence for Interconnectivity of Lobes

One of the long-standing fundamental aspects relating to the mafic magmatism (the RLS) in the Bushveld is whether the exposed lobes are in fact interconnected at depth. The review

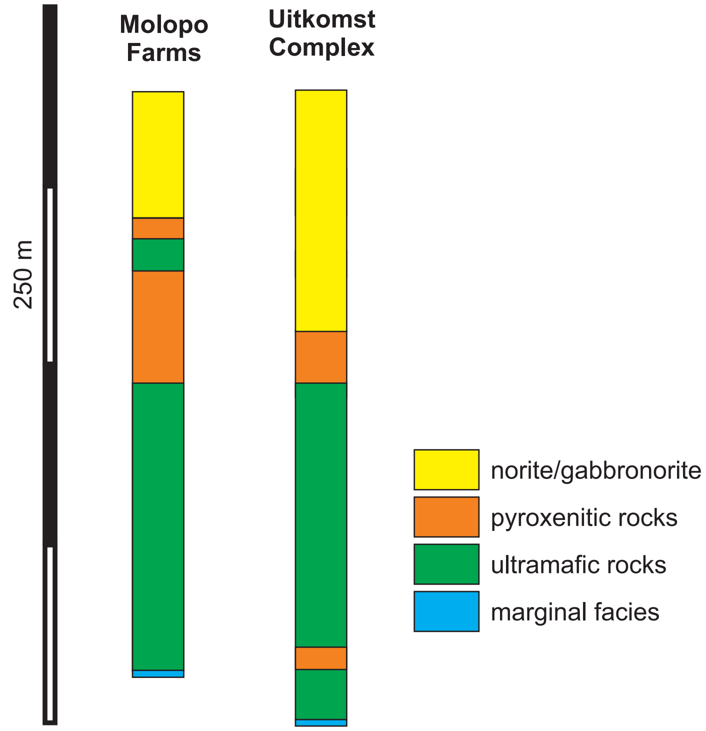

**Figure 4.** Simplified stratigraphic sections of the Molopo Farms and Uitkomst complexes, coeval intrusive complexes with Bushveld-like magma compositions. See text for additional information. Molopo stratigraphy modified after Kaavera et al. (2018) and Uitkomst after Maier et al. (2018).

by Cole et al. (2014) usefully summarized the history of interpretation of the geophysical evidence over the past 60 years, wherein Cousins (1959) interpreted the RLS as representing two entirely independent intrusive bodies, apparently flying in the face of the geological interpretations offered over the first half of the 1900s in which the complex was depicted as a laterally continuous, inwards-dipping lithological package. The subsequent geophysical interpretation by Meyer and de Beer (1987) incorporated the geological criteria but also determined that there were insufficient grounds to justify the presence of a buried mass of mafic to ultramafic rocks in the interior of the complex.

More recently, Webb et al. (2004) and a series of follow-up studies have established a relatively good fit between modelled and observed gravity field measurements across the complex (Fig. 6) by incorporating revised data and interpretations of the thickness and density of the crust, particularly those of Nguuri et al. (2001), Nair et al. (2006) and Kgaswane et al. (2012), and the density of the mantle, across the section. Cole et al. (2014) demonstrated that as a consequence, the BIC is best modelled as a set of interconnected lobes, as opposed to separate inwards-dipping sheets. This interpretation is consistent with the findings of unspecified drilling reported in Eales and Cawthorn (1996), which has revealed Lower Zone-equivalent rocks at depth beneath granite and sedimentary rocks in the interior of the complex, and with the identification of Bushveld-type Critical Zone-like rocks as xenoliths found in the Palmietgtat kimberlite pipe (Webb et al. 2011), which has intruded the interior of the complex.

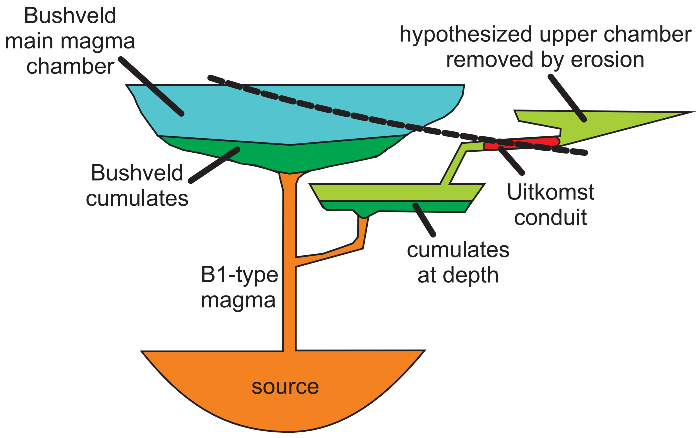

**Figure 5.** Simplified model of the genetic relationship between the Bushveld and the Uitkomst complexes. The dashed line indicates the current erosional level. Modified after Gauert (2001); see text for discussion.

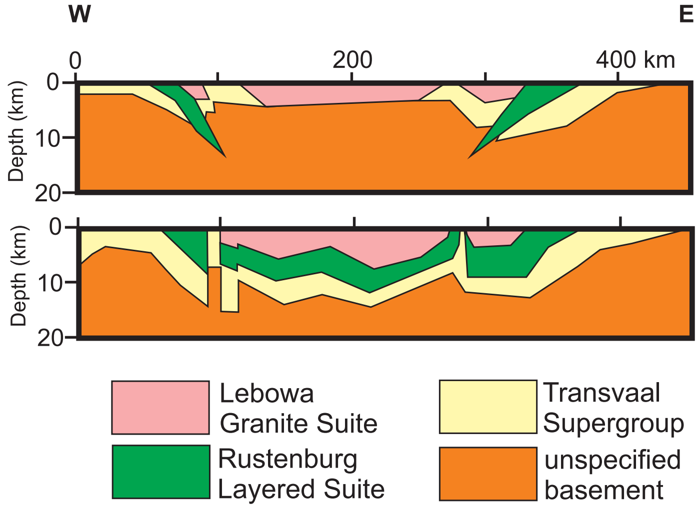

**Figure 6.** Geophysical models for the Bushveld Complex, contrasting the old, dipping but separate lobes model above, and the recent, revised contiguous stratigraphy model below. See text for discussion. Modified after Webb et al. (2011).

Although Cawthorn (2015) indicated concerns with some of the evidence for specific prospective feeders, there appear to be no real issues with the concept of multiple injection or intrusion sites. The implication is then that magma derived from a common, deeper source was injected into the shallow crystal-liquid pile that was the nascent RLS, and experienced similar (nearly identical) circumstances across the entire breadth of the intrusion in order to generate broadly correlative suites of oxide (chromitite or magnetitite) layers and associated sulphide minerals in a broadly similarly well-correlated lithologic sequence of silicate rocks. Therefore, any process proposed as an explanation for the associated oxide and sulphide layers must take into account the lateral continuity required for such a process. This will be referred to more specifically in the section relating to oxide reef petrogenesis below.

## ORE DEPOSIT MODELS

Although not an issue necessarily specific to the Bushveld Complex, the association of disseminated sulphide minerals with the oxide reefs (both chromitite and magnetitite types) is well established (e.g. Lee 1996; Naldrett 2004; Naldrett et al. 2009) and as a consequence underpins many of the genetic models for these horizons. The crustal contamination model originally proposed by Irvine (1975) as a mechanism for inducing the *in situ* formation of chromitite layers in mafic to ultramafic intrusions has been seen as particularly appealing, since crustal contamination is widely applied as a trigger for sulphur saturation and the formation of sulphide liquids in layered intrusions (e.g. Li and Naldrett 1993; Naldrett 2004). The apparent congruence of these models with the physical evidence for crustal contributions associated with the oxide (specifically the chromitite) layers has contributed to the appeal of the crustal contamination model.

The variant of the model proposed by Campbell and Turner (1986) involves upwards-pluming of the incoming magma and subsequent turbulent interaction with granitoid roof rocks to create a hybrid magma from which chromite precipitated and was subsequently deposited elsewhere. Evidence includes the association of more radiogenic Sr and Nd with chromitite horizons (e.g. Kruger 1994; Kinnaird et al. 2002), although the precise nature of the spatial relationship between isotopic enrichments and chromitite is inconsistent. The most comprehensive study published so far is that by Kinnaird et al. (2002) in which transects were taken across a variety of chromitite layers in the eastern and western lobes, and including Lower and Upper Critical Zone rocks. Data from selected chromitite layers are shown in Figure 7, selected based on examples where there were relatively tight sampling intervals from footwall, chromitite reef, and hangingwall rocks.

## NATURE OF PARENT MAGMA AND METAL BUDGET IMPLICATIONS

### Chilled Margins and Feeder Dykes

It has been established that the Marginal Zone norite does not represent a chilled marginal facies (Cawthorn et al. 1981), as had been proposed by Wager and Brown (1968), and its origins and relationship to the rest of the BIC rocks remain somewhat enigmatic. Eales and Cawthorn (1996) suggested that these rocks might in fact be intrusive sills. Cawthorn (2015) provided a useful analysis of the norite with regard to Wager and Brown's proposed context. In Figure 8, evidence of local modal mineralogical variation exhibited in Marginal Zone noritic rocks indicate that these rocks have experienced post-emplacement petrological evolution inconsistent with a primary chilled margin. It may be worth observing that apparently stratigraphically anomalous, near-basal, geochemically and isotopically evolved rock layers also occur elsewhere in layered intrusions, such as the microgabbroic unit near the base of the Panzhihua magnetiferous ferrogabbroic intrusion (Howarth and Prevec 2013), which is also characterized by thick oxide ore horizons.

Mapping of sills and dykes in the footwall rocks of the complex in the 1980s allowed for the identification of various suites of broadly basaltic affinity, some of which were identified as prospective feeder dykes to various parts of the Bushveld (Sharpe 1981; Cawthorn et al. 1981; Sharpe and Hulbert 1985). Of particular interest were those proposed to be responsible for the Cr- and PGE-mineralized Critical Zone rocks, which are known as the B1 dykes (parental to the Cr-rich Lower Zone and Lower Critical Zone) and the B2 dykes (parental to the PGE-rich Upper Critical Zone) of Sharpe (1981). Other dykes and/or melt compositions have been proposed for the overlying Main (B3 dykes) and Upper Zones, summarized by Eales and Cawthorn (1996). These dyke compositions continue to be widely applied as reference compositions for Bushveld parent magmas (e.g. Arndt 2005; Maier et al. 2018), but the inferred crystallization sequence and metal budgets in particular remain problematic with the use of tholeiitic compositions. Specifically, the B2 composition, postulated as the parent for the PGE- and chromitite-bearing Upper Critical Zone rocks, is poor in Ni and PGE, and rich in Cu and in high field strength elements such as REE and Y, relative to B1 and B3 compositions (Barnes et al. 2010), and relative to its Cr-budgetary requirements (see below).

Attempts to model the crystallization sequence of a magma of B2 composition, such as using the modelling program PELE of Boudreau (1999) at upper crustal pressures (1–5 kbar) and oxygen fugacities around QFM suggest that orthopyroxene will not occur initially on the liquidus (Barnes et al. 2010), which is inconsistent with the dominantly noritic modes of the Critical Zone rocks, featuring prominently primocrystic (cumulus-textured) orthopyroxene. One possible solution noted by Barnes and Maier (2002) was to model a hybrid magma composition, wherein a 60:40 mixture of B1 and B2 compositions, respectively, could generate the requisite mineral assemblage, consistent with the suggestion of Sharpe and Irvine (1983) in which crystallization sequences appropriate to the Upper Critical Zone were derived through mixing of A (anorthositic) and U (ultramafic, boninitic) magma compositions. Similarly, Li et al. (2005) suggested an equal mixture of the residual liquid from 44% crystallized B1 melt with a B3 (proposed Main Zone parent) liquid to account for the compositions found in the Merensky Reef. It has even been suggested that the B2 composition could in fact represent residual magma (Cawthorn 2007) from which the Critical Zone rocks had already been extracted, rather than a putative parental magma composition, which would be more consistent with the observed depletion in Cr and PGE, as well as the relatively evolved Cu, PGE, and Mg#. This residual magma, if it was indeed such, could not itself have subsequently crystallized as the olivine-free Main Zone, nor from the largely olivine-free Upper Critical Zone, however, as it contains olivine on the liquidus.

In addition to tholeiitic basaltic and boninite-like (Barnes 1989) parental magma compositions having been proposed, contaminated ultramafic parent magmas have been suggested (Sharpe and Irvine 1983; Eales and Costin 2012; Maier et al.

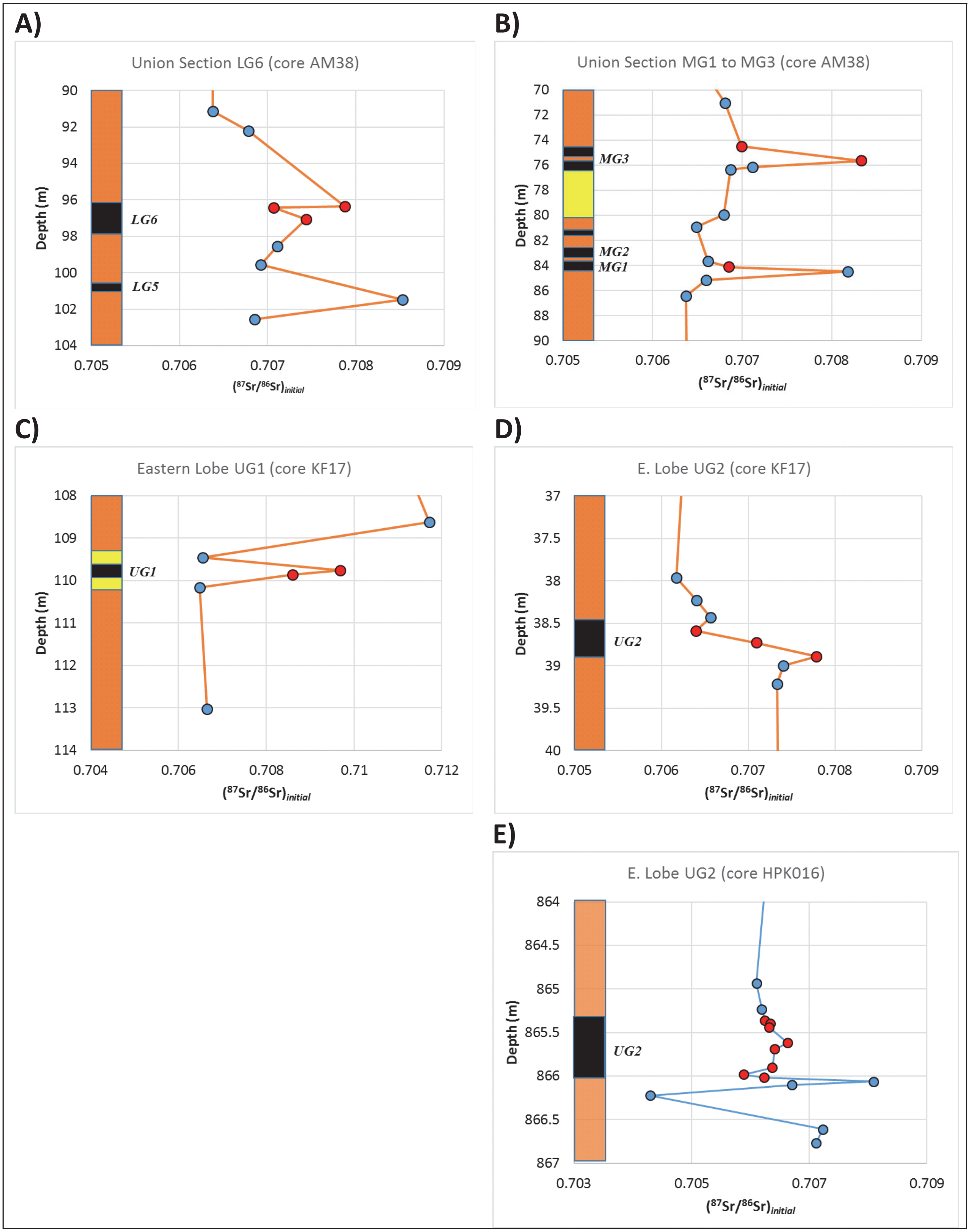

**Figure 7.** Variations in initial $^{87}$Sr/$^{86}$Sr ratio across various chromitite seams, after Kinnaird et al. (2002) (A–D) and Schannor et al. (2018) (E). Lithological sections along the y-axis include pyroxenite (orange), anorthosite (yellow), and chromitite (black). Data points in red indicate chromitite seams (analyzed as plagioclase mineral separates).

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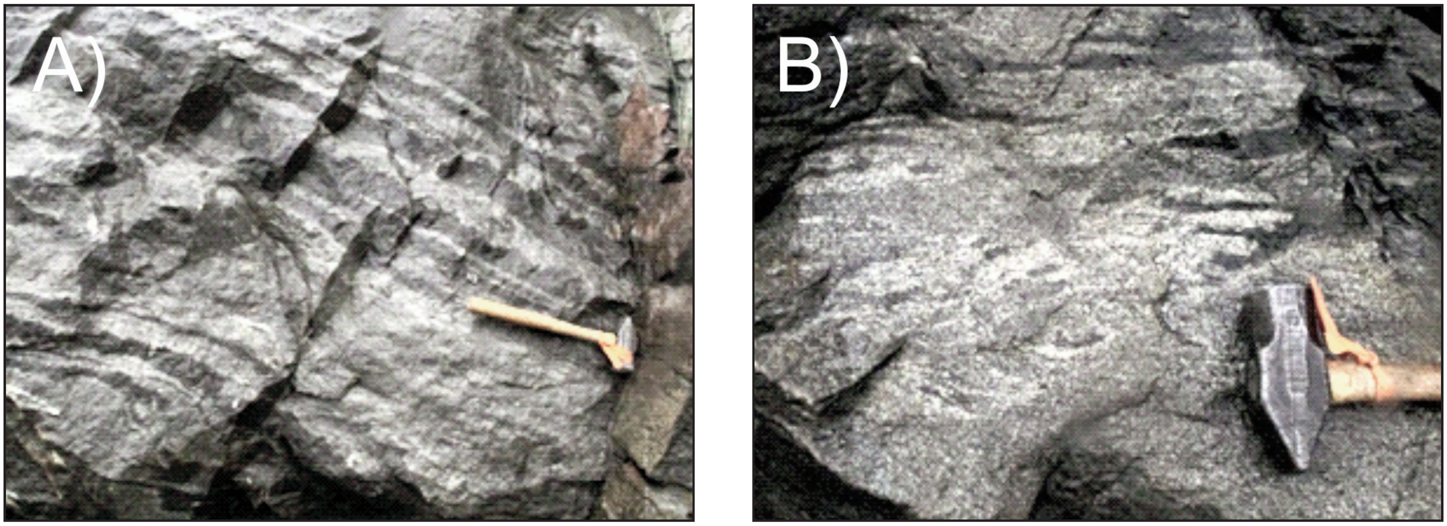

**Figure 8.** Local modal variation exhibited in the so-called Marginal Zone norite adjacent to the footwall contact, from the Eastern Lobe of the Bushveld, illustrating evidence for mineral fractionation processes. Geological hammer is approximately 35 cm long. A) shows distinct modal layering of pyroxenitic and noritic layers, and local plagioclase-rich segregations. In B), disrupted modal layering is suggestive of a dynamic magmatic environment prior to complete solidification.

2016) in order to provide the combination of contaminated but metalliferous characteristics that appear to be required to explain the metal budgets and bulk compositions, particularly in light of the additional volumes of ultramafic material recently revealed (Wilson 2015). In Table 1 below, the major element compositions of the B1 and B2 dykes are compared with prospective ultramafic compositions that have been proposed.

## Metal Budget Constraints

The capability of these magmas to provide sufficient metals, specifically chromium, to meet the requirements of the observed chromium budget of the Lower and Critical Zones of the complex can be simplistically tested. Eales (2000) undertook to estimate the chromium budget of the Western Lobe of the complex, summarized here in Table 2, for which his wt.% $Cr_2O_3$ data have been converted to Cr (ppm) for ease of reference. Note that Cawthorn (2015; p. 550) discussed the potential oversimplification of Eales' approach to this calculation, but in the absence of alternative estimates, these remain the most useful reference data available to date.

Furthermore, assuming that all Cr was introduced into the Bushveld Complex within Cr-undersaturated parental magmas (i.e. excluding the possibility of transported xenocrystic or phenocrystic chromite grains), the amount of parent magma required to accommodate each of the various zones of the Rustenburg Layered Suite can also be estimated, as displayed in Table 3 (A, B). These calculations indicate that a B2 magma composition would require on the order of 40 km thickness of material to produce the amount of Cr currently observed in the Critical Zone of the Bushveld alone, in stark contrast to the 1.3–1.8 km of Critical Zone currently known (Eales and Cawthorn 1996), or even the 7–9 km total thickness of the complex, if one were to postulate that the metals were extracted from the magma in its entirety (i.e. that one parent magma, albeit with a complex multistage contamination and upper

**Table 1.** Compositions of proposed parent magmas for the lower, ultramafic to mafic units of the Bushveld Complex.

| Element (wt %) | B1 | B2 | footwall peridotite | contaminated komatiite | B1 chill margin |
|---|---|---|---|---|---|
| $SiO_2$ | 55.74 | 50.79 | 47.35 | 51.89 | 56.09 |
| $TiO_2$ | 0.34 | 0.76 | 0.16 | 0.4 | 0.28 |
| $Al_2O_3$ | 11.82 | 15.7 | 6.12 | 9.5 | 11.31 |
| $Fe_2O_3$* | 10.5 | 12.54 | 10.11 | | |
| FeO | | | | 9.43 | 7.79 |
| $Fe_2O_3$ | | | | 1.25 | 1.53 |
| MnO | 0.18 | 0.19 | 0.15 | 0.27 | 0.17 |
| MgO | 11.85 | 6.91 | 27.85 | 18.28 | 13.58 |
| CaO | 6.5 | 10.7 | 3.57 | 7.67 | 6.34 |
| $Na_2O$ | 1.63 | 1.94 | 0.63 | 0.33 | 1.43 |
| $K_2O$ | 0.98 | 0.25 | 0.43 | 0.67 | 1.05 |
| $P_2O_5$ | 0.08 | 0.16 | 0.04 | 0.09 | 0.07 |
| Cr (ppm) | 965 | 201 | 5722 | 1386 | 1576 |

B1, B2 and ultramafic footwall sills from Barnes et al. (2010)
Contaminated komatiite from Maier et al. (2016)
B1 chill from Wilson (2012)
$Fe_2O_3$* = total Fe as $Fe_2O_3$.

**Table 2.** Calculated chromium budgets for the Lower and Critical Zones of the Bushveld (after Eales 2000).

| Stratigraphic Interval | thickness (m) | average %$Cr_2O_3$ | Cr (ppm) |
|---|---|---|---|
| Upper Zone | 1900 | <0.01 | <68 |
| Upper Main Zone | 205 | 0.03 | 205 |
| Lower Main Zone | 2205 | 0.02 | 137 |
| | | | |
| Upper Critical Zone | 475 | 0.88 | 6021 |
| Lower Critical Zone | 785 | 1.71 | 11700 |

**Table 3A.** Calculated thicknesses of ore-hosting units assuming all chromium was dissolved in the designated parent magma (based on Cr values and unit thicknesses of Eales (2000)).

| | | | | | *parental magma candidate* | |
|---|---|---|---|---|---|---|
| **Element** | | **B1** | **B2** | **footwall peridotite** | **contaminated komatiite** | **B1 chill margin** |
| Cr (ppm) | | 965 | 201 | 5722 | 1386 | 1576 |
| **Unit** | **Thickness (m)** | **Amount of parent (m) required for the observed Cr contents** | | | | |
| CZ | 1,260 | 12,459 | 59,816 | 2,101 | 8,675 | 7,629 |
| CZ + LZ | 2,080 | 16,940 | 81,327 | 2,857 | 11,794 | 10,372 |
| LCZ + LZ | 1,605 | 13,946 | 66,955 | 2,352 | 9,710 | 8,539 |

CZ = Critical Zone, LZ = Lower Zone, and LCZ = Lower Critical Zone. Sources as in Tables 1 and 2.

**Table 3B.** Calculation of parent magma volume required to account for Cr budget (from Table 3A) represented as proportions of the actual reported unit thickness.

| **Unit** | **Thickness (m)** | **Amount of parent, as a factor of unit thickness, required for the observed Cr contents** | | | | |
|---|---|---|---|---|---|---|
| CZ | 1,260 | 9.9 | 47.5 | 1.7 | 6.9 | 6.1 |
| CZ + LZ | 2,080 | 8.1 | 39.1 | 1.4 | 5.7 | 5.0 |
| LCZ + LZ | 1,605 | 8.7 | 41.7 | 1.5 | 6.0 | 5.3 |
| | proposed parent: | **B1** | **B2** | **footwall peridotite** | **contaminated komatiite** | **B1 chill margin** |

crustal emplacement history, perhaps largely taking place in sub-crustal settings, was serving as the source for the Rustenburg Layered Suite). Conversely, the B1 magma would only require 8–10 km thickness to produce the required amount of Cr for the whole complex, hosted within the basal 2–3 km, and within the order of magnitude of the total magmatic resource available. Even the postulated ultramafic compositions would require more magma than is currently represented in the existing stratigraphy, but the required volumes are within a factor of six of the observed Cr requirements. The calculated parent magma thicknesses required can also, or alternatively, be expressed as a factor of the measured unit thickness, for ease of analysis, as is shown here in Table 3B. The same budget concerns apply to the PGE, Cu and Ni, as noted by Barnes et al. (2004), for example.

## EMPLACEMENT MODELS

### The Conduit Model

The conduit model means in effect that no proposed parent magma can easily account for the Cr budget of the Critical Zone entirely transported as dissolved Cr within the incoming magma (i.e. there is no proposed parent magma for which a factor of 1 (or less) times the observed unit thickness can be derived). There are two obvious solutions to this apparent dilemma. One would involve the application of the so-called conduit model, wherein the Bushveld Complex as it is currently preserved would be seen as a cumulate-dominated system through which large volumes of magma had passed (i.e. continental flood basalt), to be extruded or emplaced elsewhere leaving behind a disproportionate volume of residual solids, including cumulate-textured ultramafic rocks and early dense metals (such as chromite and sulphide-hosted ores). The ore deposits and host rocks at Noril'sk (e.g. Naldrett et al. 1995; Arndt 2005), Voisey's Bay (e.g. Li and Naldrett 1999) and Duluth (e.g. Ripley 2014) are generally envisioned as classic examples of this deposit type, as is the Bushveld-affiliated Uitkomst Complex, as has already been described. Cawthorn and Walraven (1998) proposed that on the order of 1.5 km of magma was 'missing' from the complex on the basis of incompatible element budgets (K, Zr), and even larger volumes of Critical Zone magma must be missing in order to meet PGE budgetary requirements predicated on models involving vertical settling of metals from above the most PGE-rich deposits at the top of the Critical Zone (e.g. Cawthorn 2006), namely those of the UG2 and Merensky Reef lithological suites. Cawthorn (2015) noted that given that Critical Zone mineral compositions have been correlated to less than 20% crystallization of the parent magma, this would require five times more magma volume (i.e. five times the existing Critical Zone thickness as residual liquid) to be accounted for. (This deduction excludes the possibility that the residual magma went on to crystallize as any other observed part of the Bushveld Complex.) Li et al. (2005) suggested nearly 50% crystallization of B1 magma to get to the top of the Critical Zone, so with losses for trapped liquid in those cumulates, the 'missing liquid' in this context could conceivably be reduced to a factor of two or less, based on mineral compositional criteria. However, even taking into account large errors due to regional variations in the estimations of metal budgets, unit thicknesses, degree of fractionation, it is clear that the units that currently host the ore deposits cannot have deposited those ores as closed systems. This missing magma would have to have been either erupted or intruded elsewhere laterally (or both); there is currently no evidence of the former, but numerous Bushveld-equivalent laterally-intruded bodies exist, as outlined earlier, albeit none so far identified with Critical or Main Zone geochemical affinities. In addition, the possibly partly coeval lavas (Hatton and Schweitzer 1995) of the Dullstroom Formation of the Rooiberg Group, and the extensive Rooiberg felsites (e.g. Twist and French 1983), as well as the extensive Lebowa Granite Suite (Walraven and Hattingh 1993) cannot be entirely dismissed as potential comagmatic components, in part, at least (Hatton and Sharpe 1989), although these are most likely dominantly crustal partial melts (Hatton 1995; Hatton and Schweitzer 1995) rather than differentiates of basaltic composition source rocks or magmas.

### Transported Metals and Slurries

The alternative to a conduit model is the proposition that the metals were introduced to the stratigraphy as transported load, at least in part, but potentially in large part, if the budget calculations above are to be believed, and depending on the parent magma composition proposed. Eales (2000) has suggested that very fine-grained primary chromite, as well as olivine and orthopyroxene, may have been sourced from a more ultramafic subchamber "at depth", from which the solid material could have been transported as a mush or slurry and then redeposited within the upper Bushveld as periodic injections, mixing with the resident residual liquids (Eales 2000; p. 148). He proposed that the chromite could then have been concentrated during deposition by processes including convective scavenging (Rice and von Gruenewaldt 1995), to which the hydraulic sorting process proposed by Maier et al. (2013), may be added, and then subsequently annealed and further concentrated by late magmatic or subsolidus recrystallization and ripening to achieve their current grain size and distribution (Hulbert and von Gruenewaldt 1985). Peridotitic bodies hosted in the footwall (which are otherwise viewed as Lower Zone-like overflows; Sharpe and Hulbert 1985) are presented as possible manifestations of such an injection process.

Some of the main concerns with sourcing either individual lithological or modal layers or packages of rock (i.e. a modally layered cycle or suite) from laterally injected slurries into an existing crystal–liquid mush pile include the ability to transport such layers laterally with great continuity in style and mineralogy and metal grade for tens to hundreds of kilometres, the ability to maintain a suspended load over great distances and then very efficiently sort it, largely by density, upon the cessation of lateral transport, and the presence of vertical cryptic and whole-rock chemical fractionation trends within lithostratigraphic units, which would seem to mitigate against the dumping of a transported crystal mass. Essentially the 'need' for the introduction of metals as transported phenocrysts (fundamentally the metal and cumulate budget imbalance) has led to the motivation for a lateral slurry model, which has then been supported by various petrological lines of evidence, but the mechanical process of emplacement remains the biggest hurdle. Note that while a process of emplacing a slurry created by gravitational collapse and slumping laterally across the transient magma chamber floor, as proposed for the Skaergaard by Wager and Brown (1969) and invoked for the Bushveld by Maier et al. (2013) may involve less resistance from the resident magma-crystal mixture than a forcible lateral intrusion into a semi-solid cumulate pile, the fundamental process controls are similar. If the cumulate pile is entirely solid, it requires other considerations. Cawthorn (2015) devoted about seven pages to critically addressing the concept of laterally-introduced slurries, and his topics include the apparent absence of high-pressure mineral compositions (such as aluminum-rich pyroxene or chromite, which would apply to mantle-derived crystals, less dramatically to crystals forming in crustal plumbing systems, and not at all to wall-collapse-derived slurries), and the isotopic discrepancies between the chromitite layers and their overlying silicate units (as shown in Fig. 7 above) which suggest that they are not obviously cogenetic, among others.

The need to justify metal budgets through injection of phenocryst-rich sills has led to the consideration of the concept of layered intrusions as stacks of sills, emplaced at intervals, and introduced loosely but not precisely sequentially from bottom to top. This concept has been partially laid at the door of Bruce Marsh for his assertions that cumulate layering can only be a product of dumping of transported crystal loads, and not the products of in situ differentiation and fractionation processes (e.g. Marsh 1996, 2006 and 2013), concepts which owe much to studies of crystallizing lava lakes and Antarctic sills, cited in Marsh's work. His models, in contrast to the application of some of these ideas to the Bushveld, are entirely independent of the concepts relating to metal budget imbalances. The concepts attributed to Marsh have been addressed directly (e.g. Latypov 2009; Latypov et al. 2015), and in recent years the discussion has moved specifically to the rocks of the Bushveld Complex, although not so much into the literature in terms of testing models as yet. Assessing the ongoing debate about the validity or relevance of the in situ evolution versus transported phenocrysts concepts to the origins of layered intrusions is beyond the scope of this review, but its application to Bushveld rocks is unavoidable and represents a significant component of the current research discussion. Among other things, there have been petrologically and geochemically-motivated arguments made in support of intrusive origins to either the chromite and PGE-bearing units (e.g. Scoon and Teigler 1994; Naldrett et al. 2012) or the overlying gabbronorite units (e.g. Roelofse and Ashwal 2012), and efforts have been made to assess the mechanical and thermal/temporal restrictions on emplacing the complex as a series of smaller sills, versus fewer larger ones (e.g. Cawthorn 2012). Latypov et al. (2017) also noted that chromitite-bearing units are commonly transected by their overlying hangingwall units in the form of apparently syn-magmatic erosive pothole structures, for example, which would preclude the inversion of the emplacement sequence. For more details on this, a subsequent discussion and reply to this paper has followed thereafter (Scoon and Mitchell 2018; Laytpov et al. 2018a).

In particular, recent precise U–Pb zircon geochronological results (e.g. Mungall et al. 2016) have indicated, controversially, that the zircon closure temperatures reflect non-sequential emplacement of mafic and ultramafic components within the Critical and Lower Main Zones, summarized in Figure 9. At face value (i.e. interpreted as straightforward magmatic crystallization ages corresponding to emplacement), this would appear to require the intrusion of mafic to ultramafic sills into existing semi-solid or arguably solidified mush or hot rock (respectively) sequences of mafic material. The analysis of precisely what cooling conditions are being recorded by the zircon ages, the ability to reproduce these age relationships from different sections of the Bushveld sequence (i.e. both laterally and perhaps vertically), and what mechanical conditions could facilitate such age relationships, have yet to be established. It has been suggested, for example, that late magmatic volatile activity may have had a disproportionate influence on prolonging the cooling of zircon hosted within the lower units of the Critical Zone, as contrasted to zircon near the top of it (Yudovskaya et al. 2013a), based on Ti geothermometric and trace element abundance data in zircon cores and rims, which could influence the interpretation of the newer zircon geochronological evidence.

The volumes or thicknesses of individual pulses within the Bushveld have been speculated upon by various authors, largely model-dependent, such as based on geochemical or radiogenic isotopic characteristics, rather than petrologically dictated in any rigorous mechanically or compositionally modelled way. In Figure 10, some of the proposed dimensions of magma influxes are presented based on Bushveld Critical Zone rocks, where rhythmically layered repetitive suites or cycles have been most prominently described.

The nature of the apparent cyclic rhythmically layered units has been called into question in recent years as well. The fundamental cyclic lithological unit of the Upper Critical Zone may be described as a sequence consistent with density stratification, with an oxide (chromite)-rich base (typically chromitite), overlain by pyroxenite, grading upwards into leuconorite or anorthosite, commonly with a very thin layer of pure anorthosite underlying the next cycle. Each of these cycles occurs on a scale of metres to tens of metres, with varying thicknesses of relatively homogeneous norite separating them. This is highly oversimplified in terms of actual Bushveld stratigraphy, but probably acceptable. Figure 11 illustrates various representative sections across the Merensky Reef from the western and eastern lobes of the Bushveld, demonstrating the inconsistent relationships between the pyroxenite, the chromitite, the pegmatoid units, and the PGE.

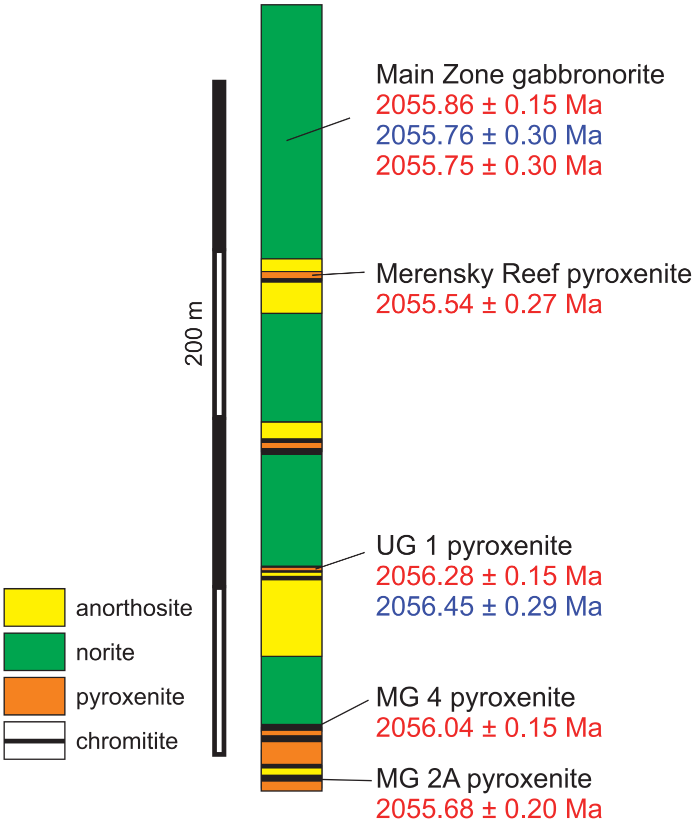

**Figure 9.** Simplified stratigraphy and summary of the U–Pb geochronological results of Mungall et al. (2016). Ages in red are from zircon separates, ages in blue are from baddeleyite grains.

The broad modal sequence exhibited is thus generally consistent with traditional crystallization models wherein the relatively early crystallized, first on the liquidus minerals also tend to be the dense ones, so sequences that are sequentially chromite-, orthopyroxene-, and plagioclase-dominated are consistent with both equilibrium crystallization (in principle, if not necessarily in terms of mineral proportions) and with density sorting. This is convenient from the perspective of traditional primary magmatic models for igneous layering (e.g. Naslund and McBirney 1996), and remains the prevalent model for the Bushveld rocks (e.g. Naldrett et al. 2012). However, alternatives to the cyclic rhythmic modal layering model have been proposed for Upper Critical Zone chromitite units in recent years. For example, it has been suggested at various times that the anorthositic 'tops' to rhythmic cycles have been induced by the introduction of hot, dense rocks above them, rather than representing plagioclase-rich 'floats' or crystallization from residual liquids expelled from the underlying cumulates. For example, Nicholson and Mathez (1991) noted that the thickness of the anorthositic footwall was positively correlated with the thickness of the overlying chromitite, specifically for the Merensky Reef near Rustenburg (as shown in figure 12A), and inferred a causal link. Mungall et al. (2016) successfully modelled the major element compositions of the footwall anorthosite units as residues of partially melted footwall norite (Fig. 12B), induced by emplacement of ultramafic sills above them, which themselves become the hosts to the mineralized reefs. These models are consistent with the suggestion of Latypov et al. (2016) that the chromitite reefs are, in part, formed from Cr extracted from their footwalls as a consequence of partial melting, a variant on the model that was proposed by Nicholson and Mathez (1991) involving scavenging of chromium from the cumulate pile underlying the reefs by partial remelting induced by compaction-driven interstitial hydrous fluid migration upwards, but which they later rejected

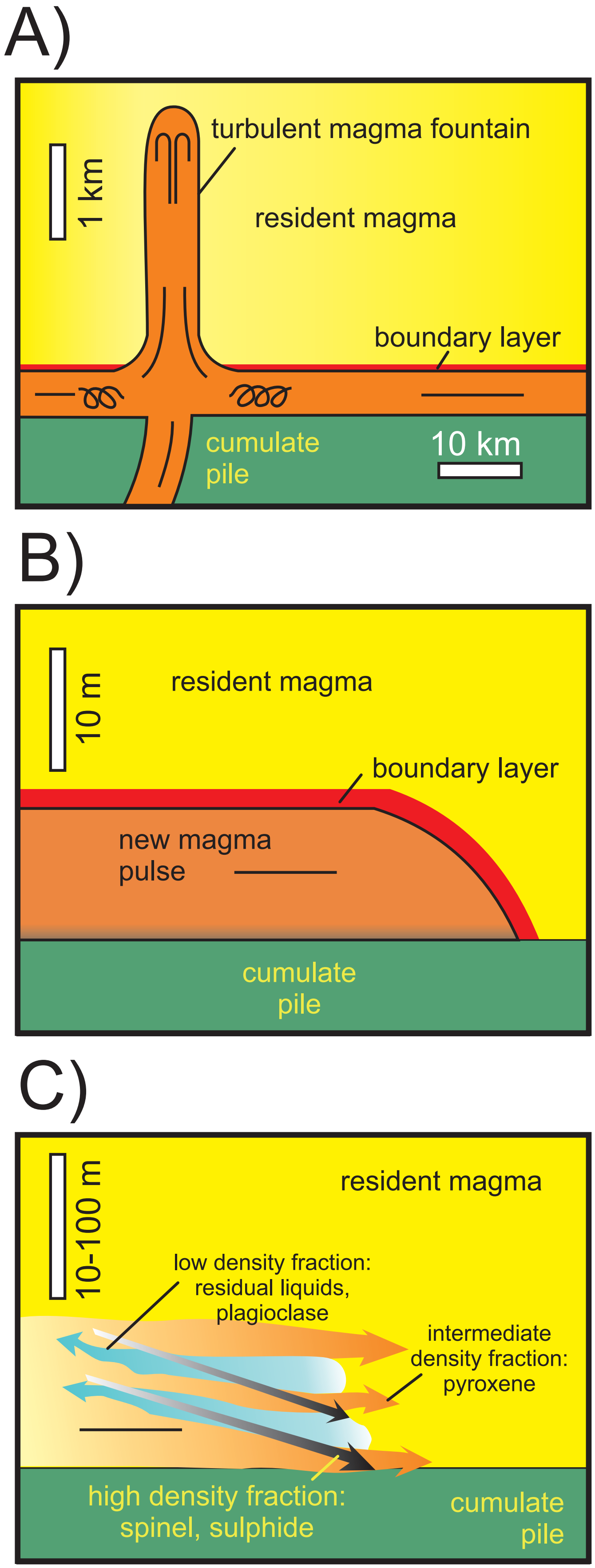

**Figure 10.** Schematic illustrations of proposed mechanisms for chromite+PGE sulphide-bearing reefs of the Bushveld Complex, with specific application to the Merensky Reef. In each diagram, the transient magma chamber floor is represented as the top of the cumulate pile. Note that the 'resident magma' above would also likely be a crystal-liquid suspension (e.g. Marsh 1996). Boundary layer zones occurring along the interfaces of new magma pulses and resident magmas represent sites of diffusive interaction and progressive compositional change. Black arrows indicate principal motion directions.
In A), Scoon and Teigler (1994) proposed magma introduction as a prominent fountain, followed by lateral settling of the hybrid magma across the floor, with the scale of the lateral flow being on the order of 0.5 km or more. The new magma is represented as turbulent throughout, as well as interacting with resident magma at the plume and along the boundary layer interface. The resident magma composition, and subsequently that of the magma flow, also changes with proximity to the influx plume. These ideas appear have been refined (Mitchell and Scoon 2007) to correspond with influxes with flow thicknesses on the order of metres, dominated by the pyroxenitic component, although this is not explicitly stated as such.
In B), Naldrett et al. (2009) proposed a comparable model in terms of flow geometry and boundary layer localized diffusion and mixing, omitting the magma fountain and the proximal/distal elements from their model, although they elsewhere espoused the concept of magma pluming and roof interaction to facilitate crustal contamination and resultant sulphide and spinel precipitation, which settle according to density to the flow base.
In C), Maier et al. (2013) proposed a variant wherein components are separated by hydrodynamic sorting (i.e. based on density and shape) during lateral flow, with flow scales on the order of tens to hundreds of metres. Experimental studies by Forien et al. (2015) demonstrated the practical application of such a process.

(Mondal and Mathez 2007) on the grounds of Cr budget inadequacies. Latypov et al. (2016) supplemented floor-derived chromium with chromite precipitated by magma mixing within the resident liquid column and have separately proposed pressure decrease during magma ascent from the upper mantle (e.g. Latypov et al. 2018b) as an additional mechanism for inducing chromite precipitation from the host melt, thereby relieving the pressure (so to speak) on the footwall as the sole source for chromium.

As alternatives to models where the modally variable suite is an internally differentiated entity, as described above, or where the anorthositic strata are induced by the intrusion of hot overlying magmas, Hunt et al. (2018) have suggested that the apparent cyclicity of the Merensky Reef specifically is an artifact of the introduction of at least five separate magma influxes, based primarily on existing geochemical indicators, supported by crystal size distribution analysis.

## CONSTRAINTS ON MINERALIZATION MODELS

The magmatic models for chromium and PGE-bearing sulphide accumulation in Critical Zone reefs have been summarized in many recent publications (e.g. Naldrett et al. 2012; Maier et al. 2013; Latypov et al. 2016), and so will only be briefly listed here, rather than comprehensively analyzed.

Irvine (1975) proposed chromite-only precipitation by siliceous contamination of olivine or olivine-chromite crystallizing melts; sulphur-saturation driven by crustal contamination, inducing immiscible sulphide melt formation and subsequent metal scavenging, is also well established (e.g. Naldrett 1989). Irvine (1977) later cast doubt on his crustal contamination model, noting the stabilization of olivine by the coexisting alkali elements (K, Na), such that unless the contaminant was

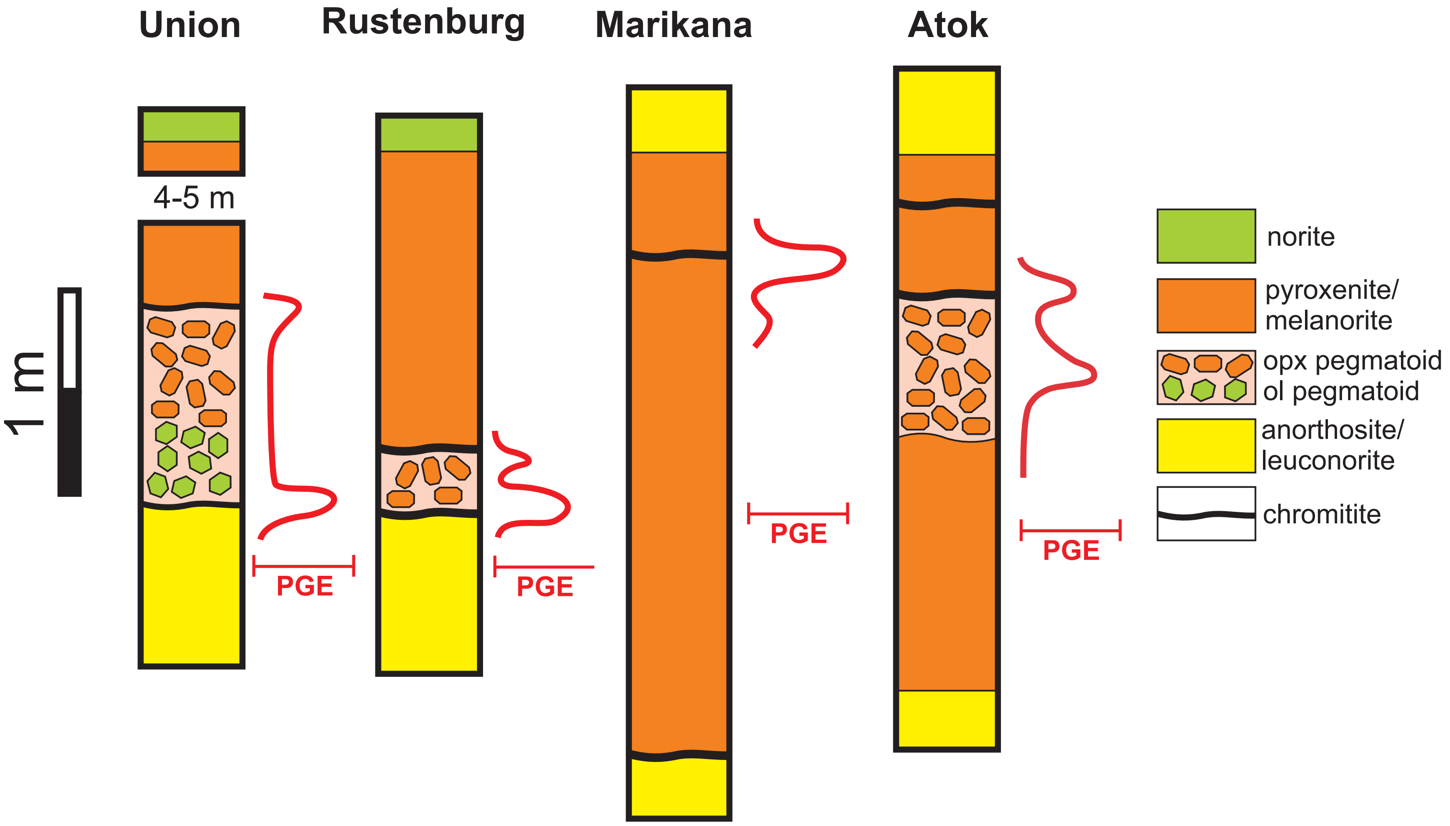

**Figure 11.** Summary of various Merensky Reef facies, modified after Campbell et al. (1983). The sections are presented from west to east, with Atok as the only representative of the Eastern Lobe of the Bushveld Igneous Complex (BIC). A case could be made for interpreting trends from Union to Marikana as proximal to distal facies changes. Qualitative PGE abundance profiles are indicated as red lines, showing the association of PGE with chromitite seams and pegmatoid rocks, generally.

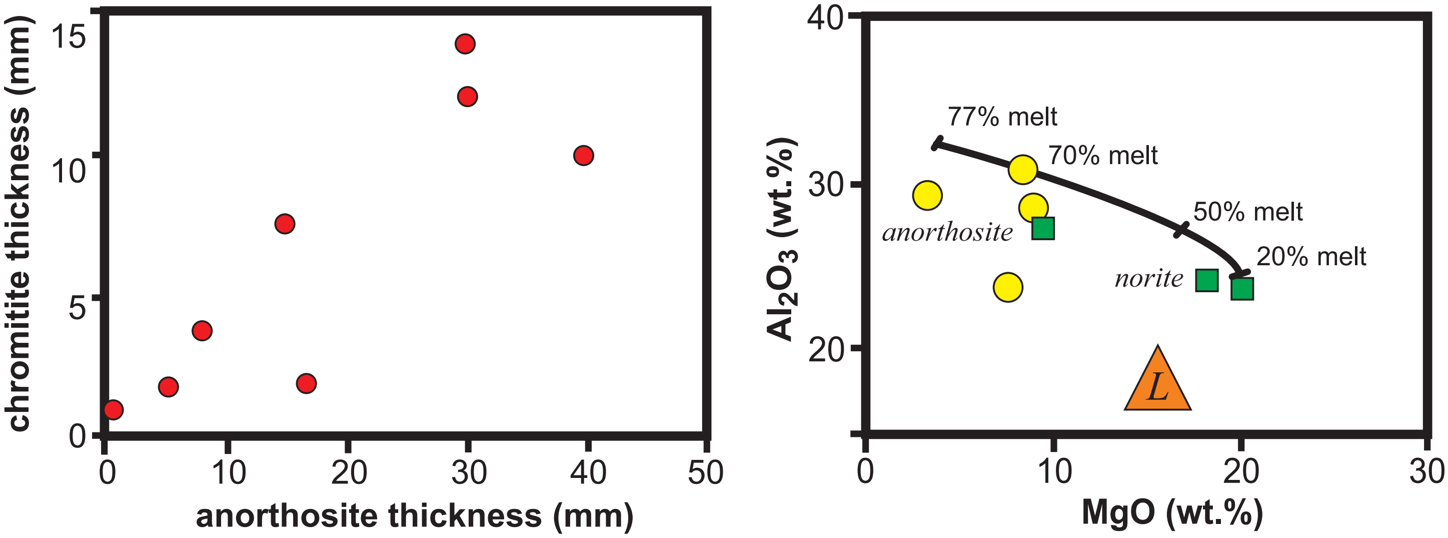

**Figure 12.** A) Correlated thicknesses of chromitite and corresponding underlying anorthosite from the Merensky Reef in the Rustenburg area, after Nicholson and Mathez (1991); B) Modelled partial melting of noritic host rocks (green squares) for the UG-2, consistent with production of residual anorthositic footwall as mixtures of partial melt residues (along the curve) and the liquid (L), after Mungall et al. (2016).

pure silica, the associated alkali elements would require extreme (> 50 wt.%) amounts of crustal contamination in order to pull the melt composition into the field of chromite-only crystallization. He proposed an alternative model of magma mixing instead, which avoided the problem of alkali stabilization and of requiring the introduction of an external component (the contaminant). This mixing model was also subsequently proposed as a mechanism for inducing sulphide precipitation (e.g. Naldrett and von Gruenewaldt 1989) during the same process, to account for the typical broad association of sulphide phases and chromitite. This process would thus allow for a new pulse of relatively primitive magma, mixing with the evolved residue of a previous pulse of the same or similar magma, to induce both chromite and sulphur saturation. However, recent reanalysis of this model by Li et al. (2001) and Cawthorn (2002) has demonstrated that the mixed magma resulting from such a process will not lie in the field of sulphur oversaturation. While this by no means rules out mixing of two dissimilar magmas as a mechanism, it does suggest that a simple replenishment model may not be appropriate for the production of coincident chromitite and (largely) sulphide-hosted PGE-bearing mineralized horizons.

Alternative mechanisms for generating either or both spinel and sulphide saturation have been proposed in order to account for features of mineralized reefs including, but not limited to:

- absence of cryptic, modal or whole-rock geochemical variation across immediate footwall and hangingwall rocks to chromitite or magnetitite reefs (e.g. Mondal and Mathez 2007), which offers no obvious evidence for mixing of dissimilar magmas;
- inconsistent relationship of pegmatoid bodies to mineralized reefs (such as shown in Fig. 8), which complicates the perception of mineralization models dependent on high water contents in melts;
- the ability to instigate mineral precipitation with comparable metal contents (e.g. Cr contents in chromite, V contents in magnetite, PGE contents in sulphide minerals), apparently simultaneously over large lateral distances across the intrusion.

These models include ephemeral pressure change, such as that proposed for Stillwater chromitite by Lipin (1993) and subsequently applied to the Bushveld Complex for chromitite and sulphide reef formation by Cawthorn (2005). Pressure increase may be derived by degassing of ascending magmas (Lipin 1993), and/or loading of new magmas onto an existing liquid-crystal pile (Cawthorn 2005). This process has the benefit of offering a mechanism for pervasive instantaneous pressure change, thereby shifting the phase boundaries for spinel relative to coexisting silicate minerals, and to be virtually untestable in terms of mineral chemical evidence, always an attractive feature for such models. The amount of pressure change suggested by Lipin (1993) for shallow crustal magmas is on the order of 0.25 kbar, which realistically would be undetectable in terms of mineral chemistry in slow-cooling magmatic systems. A problem with pressure change models is that there is no associated primary process that would include the introduction of radiogenic material coincident with the mineralization, such as that evident for the Bushveld chromitite layers specifically (Fig. 7). Phenomena like this, and the presence of associated pegmatoidal phases, would have to be attributed to later magmatic or post-magmatic processes not directly related to ore formation.

Other processes, such as inducing spinel oversaturation by magma oxidation, are similarly rather difficult to assess and have not been much tested directly, but have been proposed for other intrusions based on stable isotopic evidence for carbonate assimilation which has stimulated either chromite and sulphide saturation in the Uitkomst Complex (Gauert 2001) or magnetite oversaturation in the Panzhihua layered mafic intrusion (China) (Ganino et al. 2013). The concept of immiscible metal-rich liquids, proposed but discarded early on in evaluations of evolved Bushveld rocks (Reynolds 1985), has re-emerged in light of studies of thick Fe–Ti–V oxide deposits in China over the past decade or so (Zhou et al. 2013; Fischer et al. 2016; Nielsen et al. 2017).

Effectively in parallel to the pursuit of the various magmatic models, the role of aqueous magmatic fluids as agents of primary metal distribution has been proposed, mainly based on models developed from studies on the Stillwater Complex (U.S.A.) and then subsequently applied to Bushveld Critical Zone rocks (Nicholson and Mathez 1991; Willmore et al. 2000; Boudreau 2008; Chutas et al. 2012). Vapour-rich late magmatic environments may have played a significant role in the development of both chromite and sulphide ores, and pothole-related mineralization, if not pothole development. The specific mechanics of aqueous fluid movement through a compacting crystal–liquid mush has been favourably analyzed by Boudreau (2016) and critically perceived by Mungall (2015), for example. As with other high profile mineralization geological settings, such as Sudbury or the Witwatersrand Basin, it is with great trepidation and reluctance (what in Afrikaans, one of the languages of the Bushveld Complex, is idiomatically described as to *eet met long tande*, or to "eat with long teeth") that the hot, dry, primary magmatic model is even slightly abandoned for a dip in the pool of late magmatic fluid petrogenesis. The fundamentals of the hydromagmatic models were established in the 1980s and 1990s, and continue to be refined subsequently, if not (yet) widely embraced.

## NATURE AND EXTENT OF CONTAMINATION

One of the distinctive features of the Bushveld Complex is the relatively large and pervasive extent of crustal contamination, as revealed by the radiogenic isotopic compositions. The Sr isotope stratigraphy of the complex was established in the 1990s (Kruger 1994 and others), complemented by some common lead isotope work, but the last two decades have seen the application, at least locally, of Sm–Nd, Lu–Hf, Re–Os and other exotica. This review will refer the reader to a recent (Boudreau 2019) review of the state of the isotopic literature over this time. His review summarizes and attempts to reconcile the various efforts to effectively characterize the Rustenburg Layered Suite rocks and to rationalize the models devised to explain the isotopic evidence for mineral disequilibrium particularly evident near the interface between the Critical and Main Zones, within which the Merensky Reef is hosted. Proposed models range from mixing of cumulate mushes (Roelofse and Ashwal 2012) to magmatic fluid control (Chutas et al. 2012).

The trace element composition of the B1 and B2 magmas is consistent with extensive contamination of the former by upper continental crust, and the latter by lower continental crust (Arndt 2005; Barnes et al. 2010). This conclusion is also consistent with interpretations of oxygen isotopic compositions (Harris and Chaumba 2001; Harris et al. 2005), as well as Sm–Nd isotope systematics (Maier at al. 2000; Prevec et al. 2005), suggesting on the order of up to 30 to 40 wt.% crustal contamination for parts of the Bushveld, although lesser quantities (< 30 wt.%) of more ancient (3.5–3.1 Ga) crust have also been proposed as alternatives (Prevec et al. 2005; Roelofse and Ashwal 2012). This would also be consistent with the suggestion that an isotopically enriched source, such as specifically a metasomatized subcontinental lithospheric mantle (SCLM), interacting with a mantle plume, was the primary melt source, requiring lesser amounts of syn-emplacement crustal contamination subsequently (Barnes et al. 2010; Maier et al. 2018).

## NATURE OF THE PLATREEF

The nature of the Rustenburg Layered Suite in the Northern Lobe has gained attention in the past two decades because of the economics of platinum during much of that time period. The initial mapping of the lobe (van der Merwe 1978), which remains robust, indicated that while the Main and Upper Zone correlative rocks were relatively well-developed, the extent of the Critical and Lower Zones was less clear (e.g. von Gruenewaldt et al. 1989; Yudovskaya et al. 2013b). Recent reviews offer a useful overview of the developments in Northern Lobe research as of about five years ago or so (Kinnaird and McDonald 2005 and accompanying papers; McDonald and Holwell 2011). The lobe has been distinguished by the presence of PGE–Cu–Ni-sulphide ores hosted in deposits that are distinctively different from the 'normal' Bushveld Critical Zone-hosted ores that have been the subject of the preceding discussion. Specifically, the ores to date are hosted in massive sulphide phases, with extensive interaction with a variety of footwall lithologies, and without the presence of associated laterally continuous chromitite layers, and the nature of the parent magma to the ores has been only tentatively correlated with the Critical Zone magma as characterized elsewhere. Consequently, the ore-hosting unit has been known as the Platreef, to signify this distinction of the Northern Lobe stratigraphy. The Platreef mineralization style is much more reminiscent of that of the Uitkomst Complex than of traditional Upper Critical Zone PGE ore deposits. Stable isotope (S, O) compositions are consistent with significant footwall-derived contributions to the Bushveld magma, but also may indicate both local and pre-emplacement contamination and sulphur saturation, as well as secondary fluid involvement (Sharman-Harris et al. 2005). More recent examination of Re–Os and S isotopes in sulphides specifically indicates that while the Lower Zone ultramafic rocks show evidence for local S, the overlying Platreef is dominated by magmatic mantle sulphur (Yudovskaya et al. 2017a). Due to the heterogeneous nature of the local footwall (which includes granite, banded iron formation, carbonate rocks and shale), the nature of the magmatic-hosted footwall-rich basal breccia displays significant lateral variation, further complicated by structural control on the footwall (Nex 2006). The apparent consensus at that time (in that compilation) was for a genetic model for the Platreef involving multiple injections of relatively ultramafic sills (Kinnaird 2005), and that this mineralization process preceded the emplacement of the overlying Main Zone (Holwell et al. 2005), contrasting with models based on the Western and Eastern Lobes as described earlier.

More recently, new sections have been discovered to the south of the studied sections that display much less disrupted magmatic stratigraphy (Yudovskaya et al. 2017b), and that can be more directly correlated with equivalent Upper Critical stratigraphy elsewhere. These sections have been distinguished from the Platreef by identifying it as "thick reef facies" and, to the south, as "Flatreef" (Grobler et al. 2018) based on regional changes (local flattening) of the stratigraphy as contrasted to that observed to the north. This has allowed for the identification of UG2- and Merensky Reef-equivalent stratigraphy in the Northern Lobe (Yudovskaya et al. 2017b; Grobler et al. 2018), albeit with much more extensive footwall-derived contamination and sulphide-mineralization styles that are consistent with the Platreef setting.

## PROSPECTIVE RESEARCH DIRECTIONS

In addition to the recently enhanced research on previously relatively under-studied areas such as the Northern Lobe, and the application of micro-analytical and penetrative scanning technologies to well-contextualized ore-bearing layers (Godel et al. 2010 and references therein), recent international conferences and workshops have identified a variety of potentially constructive directions in which insight is required. These include experimental studies on Cr spinel stability, which remain relatively poorly constrained, in particular their dependence on factors such as pressure, oxygen fugacity, and water content of the magma. The mobility of the platinum group metals in high temperature systems remains relatively poorly understood, whether this relates to their preference for alloys versus sulphide complexes during magmatic crystallization, or the likelihood of formation of and mobility in metal–chloride complexes in such environments. On a more fundamental scale, the application of material sciences theory relating to the behaviour of crystal-liquid slurry systems, for application to so-called crystal mushes, is poorly understood within the geological community, particularly those involved in layered intrusion study. The distinction between the behaviour of incompressible liquids and crystal–liquid mush systems is perceived to be crucial in our better understanding of layered intrusion evolution. Complementing this would be the application and construction of relevant physical and numerical models to examine magmatic processes, such as those developed and applied by Campbell and others in the 1970s (see Campbell 1996 and references therein) to such great effect.

## CONCLUSIONS

Despite over a century of mining and research study, the Bushveld Complex, South Africa, remains a hotbed of innovation and re-examination. In the two decades since the most substantive review was published (Eales and Cawthorn 1996), the perception of the Bushveld Complex has gone from a suite of discrete intrusions whose behaviour was governed by basic principles of igneous petrology based on the principles developed by Bowen and applied by Wager and others, involving the actions of relatively predictable *in situ* processes in a closed system controlled by density contrasts and phase relationships, fed by basaltic sills, to a situation where virtually none of these precepts have escaped serious re-evaluation. The current paradigms involve boundary layer interactions in a relatively open system of a single, large intrusive complex, probably linked at depth to other laterally equivalent contemporaneous satellite bodies. Fundamental principles of the nature of magma emplacement and the formation of modal layering and stratiform ore deposits have been constrained by detailed isotopic, mineral chemical, geochronological and micropetrological studies, linked to phase theory. The nature of the parental magmas has shifted from the basaltic sills mapped in the floor through boninitic to komatiitic compositions, and the formerly closed system based on a relatively complete differentiated sequence, has been replaced by an open system where the existing complex is perceived as the residue of much larger volumes of primary magma. The role of variations in pressure, oxygen fugacity and water, as well as liquid immiscibility, as controls of primary magmatic evolution, have been re-introduced to the debate. The result is that much more is known about the world's largest known layered intrusion, and probably much less agreed upon, than ever before.

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