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# FILLING THE BUSHVELD COMPLEX MAGMA CHAMBER: LATERAL EXPANSION, FLOOR INTERACTION, MAGMATIC UNCONFORMITIES, AND CHROMITITE AND PGE DEPOSITS

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**by**

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This Information Circular has been submitted to a Special Issue of ***Mineralium Deposita*** for the ***Fermor Meeting Papers*** Convened by A.J. Boyce.
"His mind was like a soup dish - wide and shallow; …" - Irving Stone on William Jennings Bryan

## ABSTRACT

Willemse's (1969) statement that the 65,000km$^2$ Bushveld Complex is "the largest repository of magmatic ore deposits in the World" has become a truism. However, the magnitude and origin of these magmatic ores need examining *at the scale on which they occur*.

A compilation of the Sr-isotopic stratigraphy of the Bushveld Complex shows that the evolution of the magma chamber occurred in two major stages. During the lower, open-system, *Integration Stage* (Lower, Critical and Lower Main Zone), there were numerous influxes of magma of contrasting isotopic composition with concomitant mixing, crystallization and deposition of cumulates. Larger influxes correspond to the boundaries of the zones and subzones and are marked by sustained isotopic shifts, major changes in mineral assemblages and the development of unconformities. During the upper, closed system, *Differentiation Stage* (Upper Main Zone and Upper Zone), there were no major magma additions (other than that which initiated the Upper Zone), and the thick magma layers evolved by fractional crystallization.

*The Lower and Lower Critical Zones* are restricted to a belt that runs from Steelpoort and Burgersfort in the northeast, to Rustenburg and Northam in the west, and to an outlier of the Lower and Lower Critical Zone, up to the LG4 chromitite layer, in the far western extension north of Zeerust. It is only in these areas that thick harzburgite and pyroxenite layers are developed and where chromitites of the Lower Critical Zone occur. These chromitites include the economically important, approximately 1m-thick, LG6 chromitite layer that is exposed around both the eastern and western lobes of the Bushveld Complex.

*The Upper Critical Zone* has a larger lateral extent than the Lower Critical Zone and overlies, but also onlaps the floor rocks to the south of the Steelpoort area. Furthermore, the source of the magmas appears to have been towards the south as the MG chromitite layers degrade and thin northward, whereas the LG layers are very well represented in the north and degrade southward.

Sr and Os isotope data indicate that the major chromitite layers, including the LG6, MG1 and UG2, originated in a similar way. Extremely abrupt and stratigraphically restricted increases in the Sr isotope ratio imply that there was massive contamination of intruding melt which "hit the roof" of the chamber and incorporated floating granophyric liquid, the latter forcing the precipitation of chromite (Kruger, 1999; Kinnaird *et al*., 2002). Therefore, each chromitite layer represents the point at which the magma chamber expanded and eroded and deformed its floor. Nevertheless, this was achieved by *in situ* contamination of the intruding Critical Zone liquids with an orthopyroxenitic to noritic lineage.

The *Main Zone* is present in the eastern and western lobes of Bushveld Complex where it overlies the Critical Zone, and onlaps the floor rocks to the south and the north where it is

also the basal zone in the northern lobe. The new magma first intruded the northern lobe north of the Thabazimbi-Murchison Lineament, interacted with the floor rocks, incorporated sulphur, and precipitated the “Platreef” along the floor-rock contact before flowing south into the main chamber. This exceptionally large influx of new magma then eroded an unconformity on the Critical Zone cumulate pile, and initiated the Main Zone in the main chamber by precipitating the Merensky Reef on the unconformity.

The *Upper Zone* magma flowed into the chamber from the southern “Bethal” lobe. This gigantic influx eroded the Main Zone rocks and caused very large-scale unconformable relationships, clearly evident as the “Gap” areas in the western Bushveld Complex. The base of this influx, which is also coincident with the Pyroxenite Marker, is the petrological and stratigraphic base of the Upper Zone.

Sr isotope data has shown that all the PGE-rich ores (including chromitites) are related to influxes of magma, and are thus related to the expansion and filling of the magma chamber dominantly by lateral expansion; with associated transgressive disconformities onto the floor rocks coincident with major zone changes. These positions in the stratigraphy are marked by abrupt changes in lithology and erosional features over which succeeding lithologies are draped. The outcrop patterns and the concordance of geochemical, isotopic and mineralogical stratigraphy, indicates that during crystallization, the Bushveld Complex was a wide and shallow, lobate, sill-like sheet, and the deposits are quasi-continuous over the whole intrusion.

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# FILLING THE BUSHVELD COMPLEX MAGMA CHAMBER: LATERAL EXPANSION, FLOOR INTERACTION, MAGMATIC UNCONFORMITIES, AND CHROMITITE AND PGE DEPOSITS

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## FILLING THE BUSHVELD COMPLEX MAGMA CHAMBER: LATERAL EXPANSION, FLOOR INTERACTION, MAGMATIC UNCONFORMITIES, AND CHROMITITE AND PGE DEPOSITS

### INTRODUCTION AND GEOLOGICAL SETTING

The *c.* 2060 Ma old (Walraven *et al.,* 1990) Bushveld Complex[1] in South Africa (Fig. 1), is the largest mafic layered intrusion on earth (*c.* 65 000 $km^2$), and hosts the largest known deposits of Cr, V and platinum group elements (PGE) (Willemse, 1969). Furthermore, this is the largest mafic magma chamber in which the products of intrusion and crystallisation can be directly observed, and the large-scale processes giving rise to the layered rocks deduced.

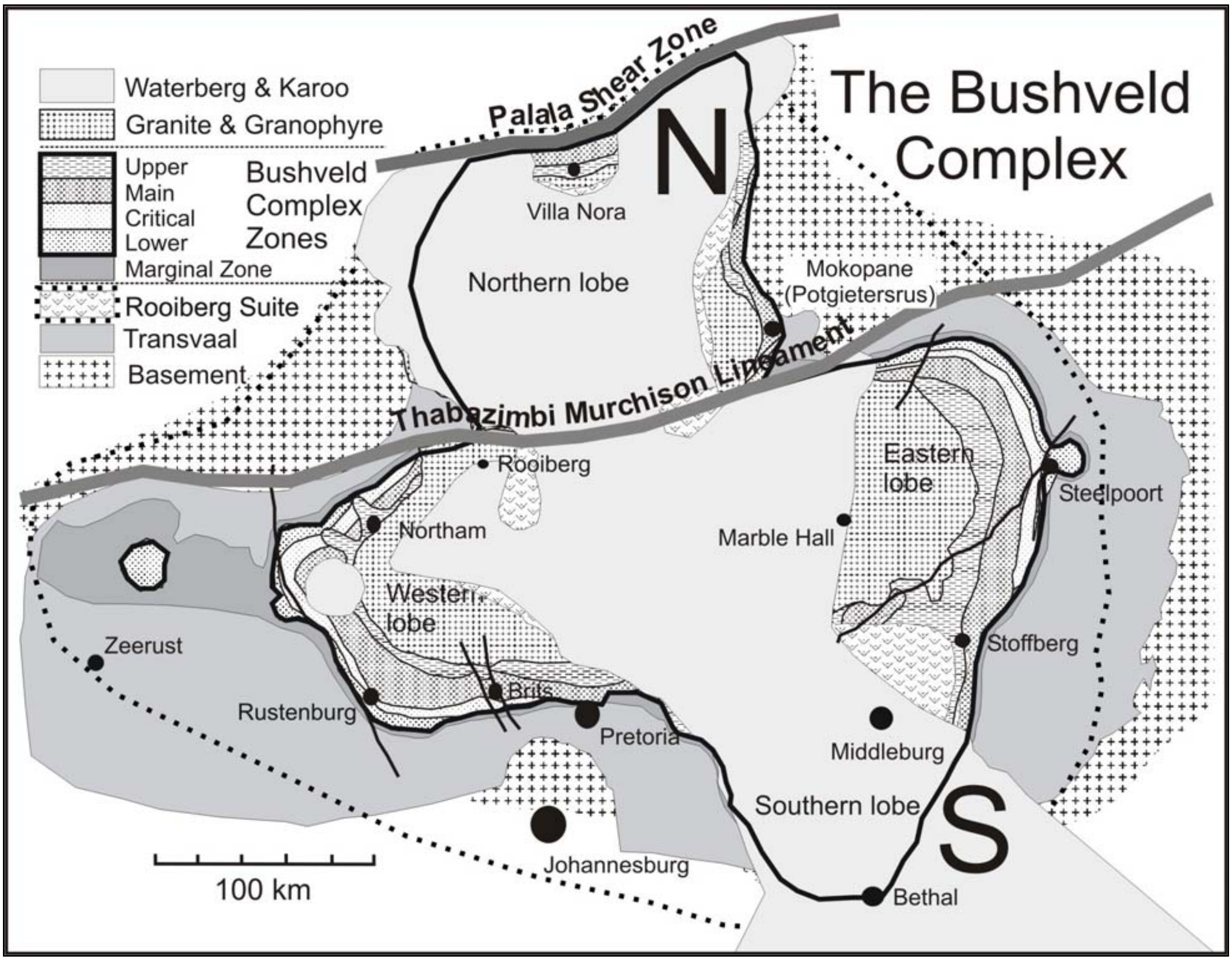


***Figure 1:*** *Map of the Bushveld Complex showing the major subdivisions and the possible lateral extent of the Rooiberg volcanism.*

The Bushveld Magmatic Province, as a whole, comprises five major magmatic suites: (1) the bimodal Rooiberg volcanic suite (see Twist, 1985; Buchanan *et al.,* 2002); (2) the mafic layered rocks of the Bushveld Complex *per se*; (3) a suite of marginal pre- and syn-Bushveld sills and intrusions (Willemse, 1969; Frick, 1973; Sharpe, 1981; Cawthorn *et al.,* 1981),

[1] The term '*Bushveld Complex*' is used for the mafic layered rocks (Rustenburg Layered Suite of S.A.C.S., 1981) as this is short, clear and unambiguous, has historical precedence and is in common use (see Kruger, 1990; 1991 and Mitchell and Scoon, 1991 for further discussion).

including the outer satellite intrusions of the complex (Hall, 1932; Coetzee and Kruger, 1989); (4) the Rashoop Granophyre Suite (Walraven, 1985); and (5) the Lebowa Granite Suite (Walraven and Hattingh, 1993). The emplacement of the Bushveld Complex on the northern margin of the Kaapvaal Craton was preceded by the extrusion of the vast, bimodal Rooiberg Suite (Fig. 1) and the intrusion of sills of mafic composition into the sediments of the Transvaal Supergroup, especially the Pretoria Group. In some places these sills may have thickened sufficiently to form differentiated bodies, remnants of which form part of the Marginal Zone of the Bushveld Complex.

Most studies of the Bushveld Complex focus on relatively small parts of the stratigraphy both vertically and laterally. The magnitude and origin of the very large units that make up the complex and the magmatic ores it hosts need to be assessed *at the vast scale on which they occur*.

## HOST ROCKS OF THE BUSHVELD COMPLEX

The Transvaal Supergroup was initiated by the deposition of the Black Reef Formation consisting of quartzite and conglomerate, which, although only a few tens of metres in thickness, has a vast lateral extent. It lies unconformably on the Archaean Basement of the Kaapvaal Craton with the exception of areas close to the *Thabazimbi-Murchison Lineament* (TML, Fig. 1), where relatively small proto-basins (e.g., the Wolkberg Basin) precede the Black Reef Formation. The TML is central to understanding the tectonics, as it is a long-lived, continuously reactivated feature; active before, during and after intrusion of the Bushveld Complex (Good and De Wit, 1997).

Overlying (and including) the Black Reef Formation, the Chuniespoort Group, which may reach a thickness of 2 km, comprises a succession of dolomitic rocks with chert and limestone bands, and is locally capped by a banded iron formation and black shales (the Penge and Duitschland Formations). A regional angular unconformity, indicating a major hiatus in sedimentation, and the development of a karst surface (marked by the "Bevets' Conglomerate"), separates the Chuniespoort Group from the Pretoria Group. The Pretoria Group consists predominantly of shales and quartz arenites with subordinate carbonates and volcanic rocks with a total thickness of about 2 km. It is only preserved on the northern and western part of the Kaapvaal Craton and also thickens toward the north and west, the main axis of deposition being immediately to the south of the TML. For a more detailed overview, the reader is referred to Eriksson *et al*. (1995).

The Transvaal Supergroup is unconformably capped (Cheney and Twist, 1991) by the *c*. 2061Ma, bimodal Rooiberg Group volcanic rocks (Walraven *et al.,* 1990), which immediately preceded the intrusion of the mafic suite at *c.* 2054 Ma. These rocks comprise a sequence of basaltic andesites at the base (Dullstroom lavas), followed by more evolved pyroclastic lavas of dacitic to rhyolitic composition (the Rooiberg "felsites"). This sequence may reach a thickness of 4 km, although in many areas it is extensively thinned or removed by erosion (for overviews see Buchanan *et al.,* 2002; Twist, 1985; Twist and French, 1983), and is inferred to have covered a far larger area than where it is currently exposed (see Fig. 1).

## SHAPE AND LATERAL EXTENT OF THE BUSHVELD COMPLEX

Bushveld Complex is a very large, mafic intrusion, up to 9 km thick and greater than 350 km in diameter (excluding the far western extension of about 100 km), which was intruded at the unconformable boundary between the Rooiberg Group and the Transvaal Supergroup and basement rocks of the Kaapvaal Craton. Several important pieces of stratigraphic, geochemical and geophysical information allow us to assess if the Bushveld Complex is laterally continuous, beneath the cover between the different exposed "limbs" or "lobes" [2]. These include:

(1) the early investigations of Molengraaff, Daly, Merensky, Wagner and Hall (for an overview see Hall, 1932) which revealed a marked stratigraphic correlation between the eastern and western lobes and from which it was deduced that the form of the complex was a "lopolith". This correlation enabled Merensky to extend the discovery of the Merensky Reef from the eastern to the western lobe, and to locate the Platreef near Potgietersrus (now Mokopane). To do this, Merensky utilised the fact that the *hangingwall* stratigraphy of the Merensky Reef was consistent from east to west, and that the mineralization was located near the base of the gabbro-noritic Main Zone succession. The more modern isotope stratigraphic data (Hamilton, 1977; Kruger and Marsh, 1982; Sharpe, 1985; Kruger *et al.,* 1987; Kruger, 1994), coupled with the detailed lithological and geochemical data, indicate stratigraphic concordance between the eastern and western lobes, which strongly suggests that they were contiguous early in the evolution of the Bushveld Complex;

(2) Hall (1932) noted further that in the eastern lobe the dips of the lowermost parts of the layered sequence, close to the margin, are significantly steeper than stratigraphically higher units towards the interior and closer to the upper contact. Indeed, in the area around Stoffberg, the layering close to the contact with the overlying granites and granophyres is near horizontal. This is also the case in areas to the northeast, where drill holes have penetrated the felsic roof rocks and encountered horizontal Upper Zone (UZ) as well as updomed parts of the Main Zone (MZ) and Critical Zone (CZ) (e.g., Scoon, 2002). Many geological interpretations (e.g., Von Gruenewaldt, 1979), assumed a sill-like form for the intrusion at least from the MZ upward, even if not explicitly stated;

(3) palaeomagnetic investigations (e.g., Gough and Van Niekerk, 1959) showed that the layering was near horizontal when remnant magnetisation was acquired. Therefore, the currently observed dips (and other structures not directly related to the intrusion and crystallisation) were imposed on the rocks *after* the sequence cooled to less than the Curie temperature for magnetite (*c.* 570ºC). Thus, the layers were near horizontal at the time of their formation, and the inward dips may only be on the margins of the intrusion and may flatten out toward the centre;

(4) the reinterpretation of the gravity data by Walraven and Darracott (1976) in the western lobe concluded that the "… mafic layering of the complex may be horizontal for some distance …", and Cawthorn *et al.* (1998) deduced that if the Moho beneath the Bushveld

[2]As shown in this work, the Bushveld Complex is a sill-like or 'lopolithic' intrusion, with a lobate exposure. The term 'lobe' – 'a roundish and flattish projecting part' (O.E.D.) is therefore preferred to 'limb'.

Complex was depressed, the gravity data support a model where the mafic rocks are continuous, east to west over the entire intrusion, under the central felsic cover; and

(5) this re-interpretation of the gravity data is strongly supported by Wright *et al*. (2003), whose interpretation of independent seismic data shows that beneath the Bushveld Complex, the Moho *is* depressed and the crust thickened by *c.* 10 km.

Taken together, these considerations imply that the Bushveld Complex is a lobate, interconnected, *wide and shallow*, sill-like intrusion with upturned margins; rather like a flat-bottomed soup-dish. This is in sharp contrast to the disconnected, *deep and narrow*, ring-like troughs (Cousins, 1959; Hatton and Schweitzer, 1995; Sharpe *et al*., 1981) or, steeply dipping, wedge-shaped, cone-intrusions inferred by Kleywegt and Du Plessis (1986) and Meyer and De Beer (1987). Compare these models of the Bushveld Complex, to the older wedge-shaped (Wager and Brown, 1967) and modern dish-shaped (e.g., McBirney and Naslund, 1990) models of the Skaergaard intrusion.

## MECHANISM OF INTRUSION OF THE BUSHVELD COMPLEX

The evidence, examined above, strongly suggests that the Bushveld Complex intruded as a flat, sill-like sheet at the boundary between the felsic rocks of the Rooiberg Group and the underlying Pretoria Group. The Rooiberg Group formed a low density, clastic volcanic (tuff) blanket, which covered a vast area, under which the more dense mafic magmas of the layered sequence crystallized. This further implies that the Rooiberg Group, which was much less dense than the mafic magmas, floated on the mafic liquids as a thin "skin" or "carapace". The *floating portion* of this carapace had a lateral extent that increased from <100 km wide during crystallization of the Lower Zone (LZ) and Lower Critical Zone (LCZ) up to *c.* 400 km during crystallisation of the UZ. In turn, this implies that the dense mafic magmas could not escape through the felsic carapace as lavas; nor could the carapace act as a vessel to sustain pressure changes (e.g., Cameron, 1978, 1980, 1982) or exert lateral forces. This also demands that the Bushveld Complex magma chamber, and the magma-carapace interface, were horizontal relative to the gravity field on the scale of the intrusion as a whole, *where there was liquid magma in the chamber*. In the model presented here, all the magma that intruded the chamber remained in the chamber, which increased in volume dominantly by lateral expansion and sill intrusion, lesser floor depression and minor upward elevation. Furthermore, this inflation occurred dominantly toward the west, parallel to the TML, where a remnant of LZ and LCZ, in the area north of Zeerust, represents what may have been a substantial part of this chamber. The magma chamber may have extended even further into the Molopo Farms Complex, which is considered as one of the satellite intrusions (Coetzee and Kruger, 1989), but may have been contiguous. This westward extension may help to explain the "Cr-paradox" (see Eales, 2000).

This model for the intrusion of the Bushveld Complex, contrasts with that of Cawthorn and Walraven (1998) who invoked the argument that a vast amount of mafic magma was evacuated as lavas from the magma chamber to account for the "Cr-paradox". No mafic lavas are known above (or peripheral to) the Rooiberg Group and there is, therefore, no field evidence to support magma evacuation. Therefore, the magmas were retained within the intrusion and its possible lateral extensions such as the Molopo Farms Complex. Thus, the Rooiberg blanket of low-density felsic rocks *is the primary reason why a mafic plutonic (layered) intrusion could form*. Without the Rooiberg carapace, the mafic magmas would have extruded as lavas to form a series of flood basalts as originally suggested by Daly and Molengraaff (1924). Therefore, sheet cooling through the carapace occurred, as lateral heat losses were negligible; the heat flux was vertical, and crystal accumulation was dominantly from the bottom up. Furthermore, the intrusion and crystallisation of the Bushveld Complex was extremely rapid, and is inferred to have occurred in <100 000 years (Cawthorn and Walraven, 1998).

In such a *wide and shallow* magma chamber, tectonic disturbance due to influx and loading by new magma, structural deformation, and lateral and vertical inflation, would have significant transient and sustained effects on the floor and margins of the chamber, and on the near solid cumulate pile. Up-warps may be eroded off or have thinner successions, and downwarps may accumulate a thicker succession. Very large up-warps may impinge the roof rocks and form domes with off-lap and on-lap relationships with respect to earlier cumulates (e.g., the Zaaikloof Dome; Scoon, 2002). New magma influxes may flow laterally, and depending on their source and volume, may scour, erode, and redistribute the footwall crystal pile, or flow around larger floor domes, and dam up against arches. Where these major transient events - and the unconformities they produced - occurred, is vital to the understanding of the Bushveld Complex and its mineralization.

## MAJOR MAGMATIC INFLUXES, UNCONFORMITIES AND MINERALIZATION

The stratigraphy of the Bushveld Complex is made up of four zones (Fig. 2), which have distinctive mineralogical, geochemical and petrological characteristics, and distinctive styles of mineralization, and are bounded by significant unconformities or major petrological changes (see Kruger, 1990, 1992, 1994). These are: (1) the “harzburgitic” LZ, which with the “orthopyroxenitic” LCZ form the ultramafic part of the intrusion; (2) the “noritic” Upper Critical Zone (UCZ); (3) the “gabbronoritic” MZ; and (4) the differentiated “ferro-gabbronoritic” UZ, which build the mafic part of the intrusion. In the LCZ, major chromitite layers are developed, of which the LG6 and MG1 are major chromium resources. The UCZ is a layered succession with an overall noritic composition, comprising Cr-rich orthopyroxenite, norite and anorthosite and hosting major PGE enriched chromitite layers (in particular, the UG2 PGE resource). The MZ is a dominantly gabbronoritic unit, with very Cr-poor pyroxene at the base, on which is situated the unconformity where the famous Merensky Reef is developed. Where the MZ interacts directly with S-rich floor rocks, the Platreef is developed. The MZ is further subdivided into a layered and diverse Lower Main Zone (LMZ) which is present in the eastern and western lobes, and a differentiated Upper Main Zone (UMZ) which is present in the eastern, western and northern lobes. The UZ also has a basal unconformity (co-incident with the Pyroxenite Marker) over the MZ**,** and is a single, differentiated sequence that extends to the roof of the intrusion (Kruger *et al*., 1987). As with the MZ, the UZ is present in the northern, eastern and western lobes, but is also the only zone present in the southern lobe. The UZ is very highly layered with gabbronorite, anorthosite, pyroxenite, ferro-harzburgite and more than twenty Ti-V-magnetitite layers. The Main Magnetitite Layer, near the base, is the world’s largest vanadium resource (Cawthorn and Molyneux, 1986).

A remarkable feature of the Bushveld Complex is that the well-developed igneous layering and diagnostic and well-represented layers such as the Merensky Reef, are extremely thin and laterally extensive. This vertical (stratigraphic) heterogeneity and lateral homogeneity, allows good correlation of the stratigraphy from east to west, despite different locations being

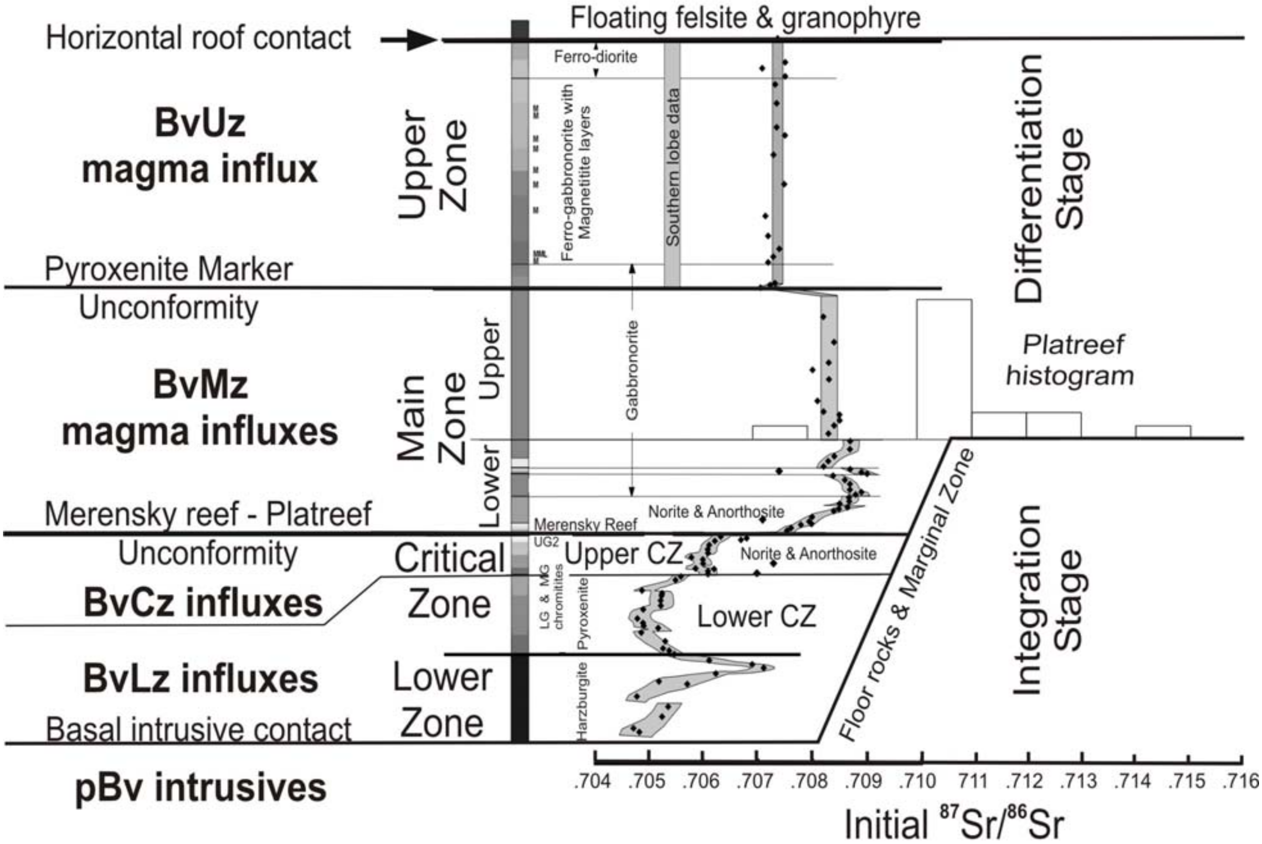


***Figure 2:*** *Stratigraphic and Isotope summary showing the mineralogical variation, isotope compositions and the location of major unconformities of the Bushveld Complex. The isotope profile is from Kruger (1994), the histogram of Platreef and northern lobe rocks is from Cawthorn et al. (1985) and work in progress of Kruger, Kinnaird and others and will be reported in full elsewhere. The data from the southern lobe is reported in Appendix 1.*

separated by hundreds of kilometres. Furthermore, the major breaks in geochemical and mineralogical stratigraphy, such as those between the LCZ and UCZ (first plagioclase cumulate), the CZ and MZ (Merensky Reef), and the MZ and UZ (Pyroxenite Marker), are also marked by unconformable relationships that are due to major inflation of the magma chamber and erosion of the cumulate pile, at those points.

Despite the sill-like character, some features of a funnel-shaped intrusion are evident: the LZ outcrop is discontinuous, and the UCZ and MZ transgress the floor rocks in places as shown in the eastern Bushveld Complex (Fig. 1), and the MZ extended laterally over the presently exposed LZ and CZ before erosion to its present disposition. This is illustrated in the area immediately south of Steelpoort where remnant outliers of MZ and Merensky Reef (to the east of the sub-outcrop in the valley) are at an angular discordance to underlying UCZ and are in close proximity to the up-warped floor rocks. Also, in the area to the west of Lydenburg (farm Everest) the UCZ onlaps the floor rocks at the level of the UG2, forming basin-like outliers of UG2 with thin "marginal" norites below. Transgressive relationships are also present between the MZ and UZ in the "Gap" areas around Northam (e.g., Wilson *et al.*, 1994). This being the case, the magma and cumulate volumes are not linearly related to stratigraphic thickness, as the chamber inflated laterally as well as vertically during intrusive episodes (*inter alia* Hall, 1932; Willemse, 1959; Eales, 2002).

Feeders to the intrusion were probably pipe-like (e.g., Eales *et al.,* 1988), but dyke-like feeders are also possible (e.g., Kinnaird *et al*., 2002), as no feeders have been unequivocally identified. The practice of equating present-day positive gravity anomalies in the Bushveld Complex to feeders, is fallacious: the inward dip and surface exposure of such enormous volumes of dense mafic rocks, enhance gravity anomalies, and, since these were imposed *after* the rocks had solidified, cannot be used to divine feeder dykes or conduits. Furthermore, any conduit is orders of magnitude smaller than the intrusion, and would be hidden beneath the vast thicknesses of rock. Nevertheless, the geochemical data and interpretation of Eales *et al.* (1988) and Maier and Eales (1994) strongly suggest that the Union Section Mine (near Northam) is close to a major feeder, which may have resulted in more compositional variation as small pulses of magma are identifiable in that study section. This may also be the reason for the more complex stratigraphy in the Northam area, relative to elsewhere in the western Bushveld Complex (Maier and Eales, 1994). Similarly, the Steelpoort Fault, and the area around Grasvally (south of Mokopane), may be feeders to the LZ and LCZ.

The stratigraphic subdivisions of the Bushveld Complex are the subject of considerable dispute, and Kruger (1990) made a detailed assessment of the various proposals. That work and the subsequent criticism (Mitchell and Scoon, 1991) and response (Kruger, 1991) form the basis of the subdivisions shown in Figure 2. These subdivisions and boundaries are retained here, as the breaks evident in the stratigraphy, mineralogy and geochemistry are ubiquitous, and of fundamental importance to mapping and location of mineralization. In brief, boundaries between major subdivisions (zones and subzones) are located where there are major unconformable relationships, usually associated with major magma influxes (see Kruger, 1994); and the subdivisions themselves have petrologic coherence in terms of mineralogy, geochemistry and magma lineage. Smaller magma influxes of the same lineage as the resident magma, or other changes in petrology or petrography, mark the boundaries of lesser subdivisions of the major zones and subzones. In this work, these major subdivisions are viewed as *unconformity bounded sequences* with internal subdivisions, lesser unconformities, and conformable layers that can be correlated over wide areas.

During the *Integration Stage*, this process of magma addition is recorded in the changes of $^{87}Sr/^{86}Sr$ initial ratio and mineralogy of the rocks (Kruger, 1994), as well as erosional unconformities that are evident in the stratigraphy. As shown in Figure 2, during this stage, the magmas changed from precipitating harzburgite in the LZ (initial $^{87}Sr/^{86}Sr \approx 0.705$) to orthopyroxenite in the LCZ, norite and anorthosite in the UCZ (initial $^{87}Sr/^{86}Sr \approx 0.7064$) and finally, norite and gabbronorite in the LMZ (initial $^{87}Sr/^{86}Sr \approx 0.7064 – 0.709$) (see *inter alia* Cameron, 1978, 1982; Molyneux, 1974; Kruger, 1994). The major chromitite layers, which are diagnostic of the CZ**,** and the well-known Merensky Reef at the base of the MZ**,** were deposited as a result of magma influxes during this stage (Kruger and Marsh, 1982, 1985; Campbell *et al.,* 1983; Naldrett *et al.,* 1987; Kruger, 1999, 2003; Kinnaird *et al.,* 2002).

The UMZ (initial $^{87}Sr/^{86}Sr = 0.7084$) and UZ (initial $^{87}Sr/^{86}Sr = 0.7072$) comprise the *Differentiation Stage* of the Bushveld Complex. During this stage the evolution of the magma chamber occurred as a closed system; except for the single, very large and final, influx that occurred at the position of the Pyroxenite Marker (Kruger *et al.,* 1987; Cawthorn *et al.,* 1991). This position is clearly identifiable in both the eastern (e.g., Molyneux, 1974; Sharpe, 1985) and western (e.g., Nex *et al*., 1998; Kruger *et al*., 1987) lobes of the Bushveld Complex. The strong layering evident in the alternating magnetite, anorthosite, harzburgite and pyroxenite layers in the UZ were deposited from an initially homogenous magma, and are not the result of multiple intrusion (Kruger *et al*., 1987).

Eales (2002) listed a number of possible parental magmas, and discussed the merits of each, but although the possible parent to the Marginal Zone, LZ and LCZ are quite well defined, the magmas parental to the UCZ and MZ are not. This is because, in general, the marginal rocks adjacent to these zones represent mixtures of earlier magmas and new magmas. The UZ parental magma is, however, quite well estimated, as Davies and Cawthorn (1984) have identified marginal dykes of this magma type. Due to this confusion, and other problems with identifying different magma types, as reviewed in Eales (2002), a simplified scheme is introduced that relates the magma types directly to the stratigraphy; pBv for clearly pre-LZ Marginal Zone rocks as discussed above; BvLz for the olivine- and orthopyroxene-bearing magma that is parental to the LZ and LCZ; BvCz for the plagioclase, PGE and Cr-rich noritic magma dominating the UCZ; BvMz for the Cr-poor gabbronoritic magma, which dominates the MZ from the Merensky Reef and Platreef upward, and, finally, BvUz**,** a Fe- and S-rich ferro-gabbronoritic magma that dominates the UZ from the Pyroxenite Marker upwards. In this scheme, the BvLz (and pBv?) magma composition is taken to be that defined by Davies *et al.* (1980) for the major elements, and the isotope composition is taken from the lowermost parts of the layered sequence (Kruger, 1994), and that of the BvUz magma is for the chemical composition (Davies and Cawthorn, 1984), and this work (southern lobe) is for the isotope composition. The BvCz and BvMz magmas are not yet clearly defined, but are estimated based on published data on marginal chills and layered sequence for both chemical and isotope parameters, bearing in mind the caveats of Eales (2002). These four (five if pBv proves to be significantly different) magma types and their mixtures (coupled with floor and roof-rock interactions and contamination), build the stratigraphy of the Bushveld Complex.

## MARGINAL ZONE: PRE-BUSHVELD SILLS AND SYN-BUSHVELD CHILLS

In some areas, a thin, relatively fine-grained Marginal Zone is developed between the layered suite and the country rocks. It is usually related to the immediately adjacent cumulate rocks, but in some places, it has been partly disrupted and incorporated by subsequent magma injections (see Eales, 2003 for an overview). However, in the case of the Marginal Zone beneath the LZ**,** the marginal rocks may represent an earlier pBv magma of a similar lineage: in this work, this early pBv magma is provisionally linked to the BvLz magma. This magma is represented by the Hendriksplaats Norite (Schwellnus *et al.*, 1962) or the Maruleng Norite (Willemse, 1959) now referred to as the Shelter Norite (SACS, 1980) in the east; the Kolobeng Norite (SACS,1980) in the west near Rustenburg, and the Marico Hypabyssal Suite (Engelbrecht, 1990) in the far west, north of Zeerust. This noritic sequence may reach a thickness of 400m in the belt between Burgersfort and Zeerust. The sill-like intrusions may extend as far south as Bethal, as Buchanan (1975) reported high Mg# Marginal Zone rocks in this area, and Coetzee and Kruger (1989) showed that the Losberg intrusion may be a sill-like extension of the Bushveld Complex, and the presence of magnesian harzburgite may indicate true LZ is represented. Thus, the most primitive Marginal Zone rocks may be outward, sill-like extrusions of early representatives of the LZ; resolution of this problem awaits further research.

In general, aside from the early true pBv magmas discussed above, the marginal sills associated with the layered sequence may represent outward expansion of the magma chamber by mixed new and residual magmas as envisaged by Clarke *et al.* (2000), rather than being pre-Bushveld sills or “parental” magmas flowing into the chamber as suggested by Sharpe (1981). The magmas extruded from the magma chamber are more akin to a chill zone of mixed magmas and not parental magmas: true parental magmas probably being restricted to dyke-like bodies or sills close to feeders.

## LOWER AND LOWER CRITICAL ZONES: BvLz MAGMA PARENTAL TO THE CR-RICH CHROMITITE LAYERS

The LZ consists of harzburgite and pyroxenite layers and is petrologically contiguous with the LCZ**,** the latter consisting of orthopyroxenite interbanded with harzburgite and chromitite layers. The magma that crystallized these rocks was "ultramafic" in nature and is here termed the BvLz magma type. This magma is equivalent to the B1 magma of Sharpe (1981) and Hatton and Sharpe (1989) and the parental magma of Davies *et al.* (1980) and Cawthorn *et al.* (1981), and has the right crystallization sequence for this part of the succession (Cawthorn and Davies, 1983).

The pBv and BvLz magmas, as a whole, share some common characteristics and may have a broadly similar source area. These two magmas all have a broadly harzburgite-orthopyroxenite-norite character, high Cr (900-1000 ppm), high $SiO_2$ (~ 55%), high MgO (~12.5%) with a relatively primitive Mg# (>0.70) (see Davies *et al*., 1980). In addition, magmas also have relatively low $^{87}Sr/^{86}Sr$ (~0.7050) and a low $^{187}Os/^{188}Os$ (~0.122), which is slightly higher than contemporary mantle (see Kruger, 1994; Schoenberg *et al*., 1999).

As shown in Figure 2, the LZ comprises a layered sequence of harzburgite to orthopyroxenite cyclic units, that in the central area south of Mokopane (Grasvally), reaches a thickness of >1600 m. This part of the succession is described in detail by Hulbert and Von Gruenewaldt (1982, 1985) and Von Gruenewaldt *et al.* (1989). Chromitite is a significant accessory phase, and chromitite layers are a feature of the LCZ otherwise dominated by feldspathic pyroxenite. Detailed descriptions of the stratigraphy are available from Cameron (1978, 1980) in the northern part of the eastern limb, and Teigler (1990), summarised by Eales (2002), for the western lobe.

### Intrusion and lateral extent

LZ rocks occur extensively from Burgersfort in the east to Zeerust in the west, and may be present as thin sills and outliers as far south as Bethal (Buchanan, 1975), and as minor intrusive tongues north of the TML (e.g., Uitloop; Van der Merwe, 1975), the thickest development being on the TML south of Mokopane as discussed above. This implies that the marginal and part of the LZ initially had a large lateral extent. However, sustained influx of the BvLz magma along the TML resulted in down-warping and the formation of an elongate half-graben that progressively deepened with the deposition of dense ultramafic cumulates south of the TML. The southern edge of the TML formed the steep northern wall of this half-graben, and the southern margin is more gently shelving, with the axis of the arch between Stoffberg in the east and Zeerust in the west (Fig. 3). This half-graben geometry was sustained to at least the UCZ, which is why the thickest part of the Bushveld Complex is immediately south of the TML axis.

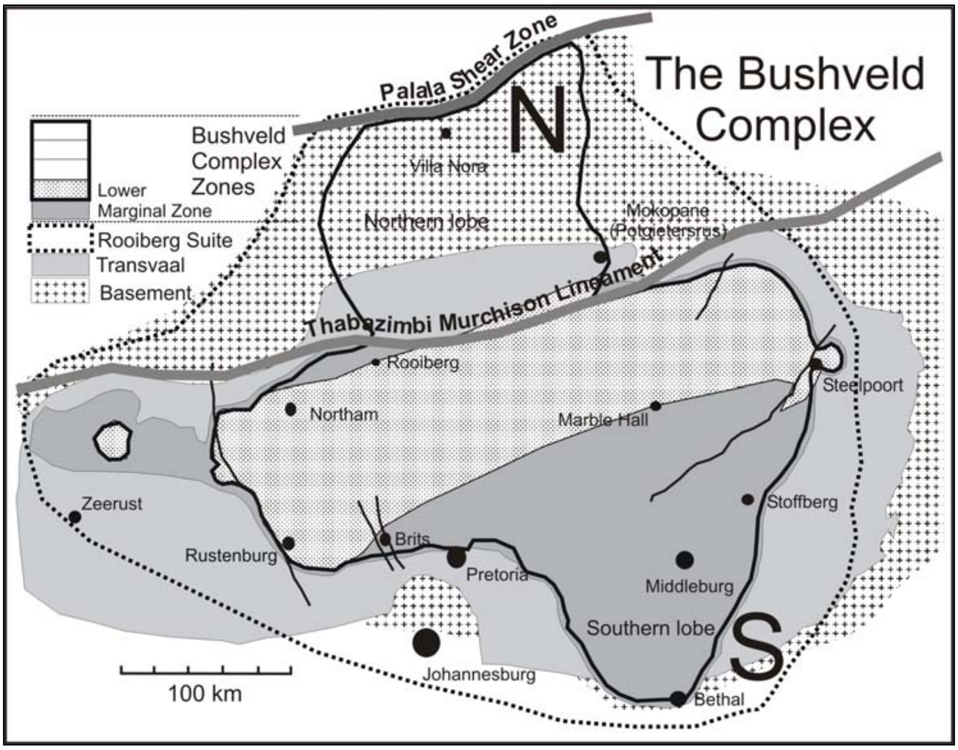


***Figure 3:*** *The lateral extent of the Lower and Lower Critical Zones derived dominantly from the BvLz magma.*

Significant development of the LCZ is restricted to a belt from Steelpoort to Rustenburg, with an outlier in the Zeerust (Nietverdient) area. There are significant differences in the stratigraphy and lateral extent of the LZ and LCZ in different parts of the Bushveld Complex, indicating that during the early stages of intrusion the magma chamber comprised a network of connected sub-chambers oriented in an east-west direction south of the TML. Feeder zones close to the centre of this axis are likely. This is emphasized by the presence of the far western (Nietverdient) outlier of LZ and LCZ rocks (Engelbrecht, 1985, 1990) to the south of the western part of the TML. This linear belt may extend as far as the Molopo Farms Complex to the west of Zeerust in Botswana (see Coetzee and Kruger, 1989). The Steelpoort Fault and the ultramafic rocks below the Burgersfort "bulge" may represent a feeder to the LZ or crystal mushes that extruded out of the LZ (Sharpe and Hulbert, 1985). This is in marked contrast to the similarity from east to west in the case of the UCZ, MZ and UZ (*cf. inter alia* this work; Cameron, 1978, 1980, 1982; Eales *et al.*, 1988, 1990; Hulbert and Von Gruenewaldt, 1982, 1985; Sharpe, 1985; Kruger *et al.*, 1987; Kruger, 1994; Teigler, 1990; Teigler and Eales, 1996).

## Mineralization

There are two significant chromitite layers in the thick Grasvally succession south of Mokopane (see Hulbert and Von Gruenewaldt, 1982, 1985) that have very high Cr/Fe ratios and are hosted in LZ rocks. The same succession also has an unusual Ni-Cu-PGE sulphide mineralization. No other significant mineralization is known in the LZ: the Grasvally chromitite and PGE deposits are thus enigmatic, but, nevertheless, strongly suggest a feeder zone close to the TML in this area, where roof-rock interactions such as those invoked by Kinnaird *et al.* (2002), may account for the mineralization.

In the LCZ there are up to nine chromitite layers (LG1-LG7 and the MG1and 2), two of which (the LG6 and the MG2) are thick and extensive enough to be a major chromium resource. The far western extension of the complex (Nietverdient near Zeerust) also has an erosional remnant of LZ and LCZ with chromitite layers LG1-LG4 preserved (see Engelbrecht, 1995). As indicated by Scoon and Teigler (1994) the chromitite layers of the LCZ are of a high quality as a chromite resource, but are very low in PGE as well as being dominated by the Ru-Ir-Os group. Furthermore, the Os-isotope results of Schoenberg *et al.* (1999) and McCandless *et al.* (1999) show that the Os has a "normal" or slightly enriched mantle isotope character.

There is also no significant "marginal" (sulphide) mineralization associated with the LZ and LCZ despite being in direct contact with the floor rocks and in some cases incorporating large xenoliths. The chromitites also have very little sulphide associated with them. This implies that the pBv and BvLz magmas have very little intrinsic sulphur in solution, and sulphur addition from some outside source was required before any Ni-Cu sulphide deposits could form.

## THE UPPER CRITICAL ZONE: BvCz MAGMA PARENTAL TO THE PGE-RICH CHROMITITE LAYERS

The UCZ has chromitite, feldspathic, orthopyroxenite, norite and anorthosite layers with some olivine-bearing layers. The stratigraphy is, however, dominated by norite with anorthosite layers, which form "cyclic units". The most complete of these is that starting with the MG4 chromitite at the base and capped by the thick anorthosite that forms the footwall to the UG1. This "cyclic unit" has been extensively studied by Eales *et al.* (1990). The interlayered chromitite – anorthosite in the upper part of this succession, well exposed at the famous Dwars River locality, is one of the most spectacular in the Bushveld Complex (see Nex, 2002 and in press) for an overview and new interpretation of the UG1 phenomenon). The first appearance of plagioclase as a cumulus mineral immediately above the MG2 chromitite layer marks the dominance of the BvCz magma over the earlier BvLz magma, which was residual in the chamber at that point. Furthermore, from this point up in the succession, all the cumulates derive from a mixed lineage of magmas, as is shown by mixing relationships within the UCZ (Eales *et al.*, 1986).

In common with the BvLz magma, the BvCz magma has a noritic lineage and a high-Cr-content (*c.* 300 ppm), but basaltic $SiO_2 \approx 50\%$, $MgO \approx 7.5\%$ , and $Al_2O_3 \approx 16\%$, and a Mg# ≈ 0.50. The magma also had a higher $^{87}Sr/^{86}Sr$ (~ 0.7065-0.7075), higher $^{187}Os/^{188}Os$ (~ 0.140) and a higher PGE content with a higher (Pt+Pd+Rh)/(Ru+Ir+Os) than the LCZ.

### Intrusion and lateral extent

In the UCZ, plagioclase is a major phase and orthopyroxenite, norite and anorthosite the dominant rock types (Eales *et al.,* 1990; Teigler *et al.*, 1992; Maier and Eales, 1994). The UCZ extends south over the LCZ and onlaps the floor. It is confined to the eastern and western lobes, and is not known further west (Fig. 4). In the eastern lobe of the Bushveld Complex there are transgressive relations within the UCZ. At Tweefontein, south of Steelpoort, the MG chromitites are very well-developed thick layers (Schürmann *et al.,* 1998), whereas at Jagdlust, to the northwest, they are thin and poorly developed (Cameron, 1980). Furthermore, towards the south,

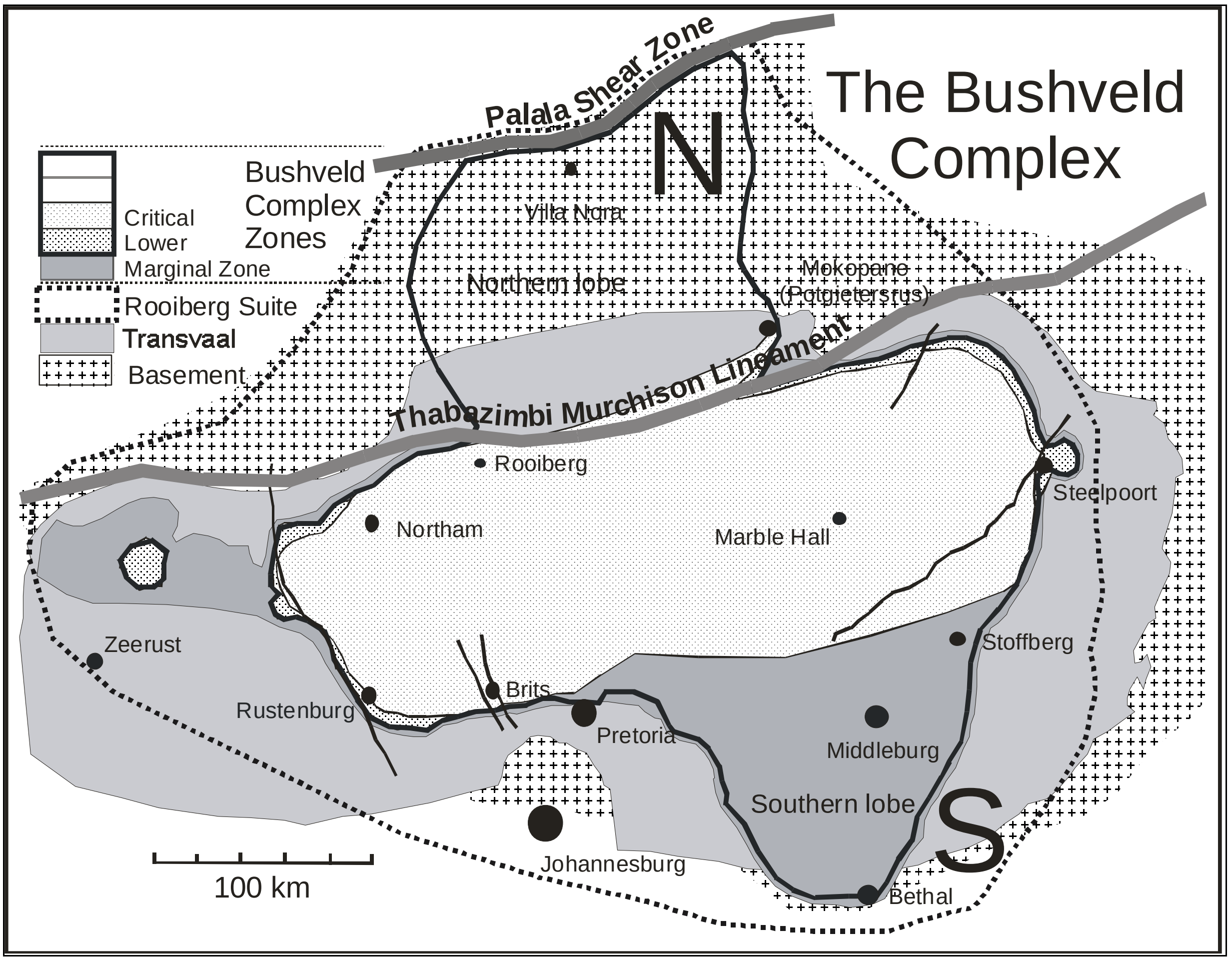


***Figure 4****: The lateral extent of the Upper Critical Zone derived dominantly from the BvCz magma.*

the lower part of the stratigraphy is cut out against the floor rocks, and in the region between Stoffberg and Lydenburg, the UG2 is developed close to the floor rocks (e.g., Viljoen and Schürmann, 1998) and no middle group layers are present. Similar relationships prevail in the western Bushveld Complex between Brits and Pretoria.

## Mineralization

The UCZ chromitite layers, as a whole (MG3, MG4 and UG1,UG2) are richer in feldspar gangue, have a higher PGE content and a higher (Pt+Pd+Rh)/(Ru+Ir+Os) than those of the LCZ (e.g., Lee, 1996), but the UG2 is economically mineralized and is the most extensive. The isotopic character of the BvCz magma was clearly more enriched both from a Sr and an Os isotope viewpoint (e.g., Kruger, 1994; Schoenberg *et al.*, 1999; McCandless *et al.*, 1999). The mechanism by which these (and other) chromitites formed, has been outlined by Kruger (1999) and Kinnaird *et al.* (2002). In most areas of UCZ exposure, the UG2 is a “doublet”, in that the lower part is clearly differentiated from the upper, in terms of grade and metal ratios (McLaren and De Villiers, 1982; Hiemstra, 1985). In the northern part of the eastern Bushveld Complex the UG2 splits, such that the upper part of the “doublet” forms the UG3, with up to 25 m of noritic rocks between the two chromitite layers. Thus, to account for the UG2, at least two influxes of BvCz magma are required.

### Summary

The UCZ is much more widespread toward the south than the LCZ, but does not (now) extend significantly west of the Pilanesberg, although there has been significant erosion in that area leaving only a remnant of LCZ. Therefore, the UCZ may have extended significantly to the west before erosion to its present disposition. It is thickest in the northern and eastern part of the chamber and thins (with the progressive loss of lower units) toward the south.

## MAIN ZONE: BvMz MAGMA PARENTAL TO THE MERENSKY REEF AND THE PLATREEF

### Stratigraphy and lateral extent

The MZ of the Bushveld Complex, comprises a *c.* 2.5 km-thick succession of dominantly gabbronoritic rocks, in the interval between the base of the *Merensky Cyclic Unit* and the *Pyroxenite Marker* (Kruger, 1990) (see Fig. 2). Kruger (1990) further divided the MZ into two subzones: the LMZ and the UMZ. The LMZ is dominated by repeated magma influxes, and is part of the *Integration Stage* of the Bushveld Complex, whereas the UMZ is purely a differentiation sequence and part of the *Differentiation Stage*. Besides norite and gabbronorite, layers of anorthosite, pyroxenite and norite occur in the LMZ, including the well-known layers in the Merensky and Bastard cyclic units. The UMZ is dominantly gabbronorite with cryptic variation of plagioclase and pyroxene compositions (see *inter alia* Kruger, 1990,1994; Mitchell, 1990; Mitchell *et al.*, 1998; Nex *et al.,* 1998 and other references in these works).

Extensive mapping of the northern lobe of the Bushveld Complex by Van der Merwe (1976) indicates that there is no significant CZ exposed, and that the Platreef is directly associated with the MZ. Therefore, the MZ is the basal unit of the northern lobe, and the Platreef is its marginal facies. The internal stratigraphy of the MZ in the northern lobe is not, as yet, well established, but appears to be similar to the UMZ south of the TML. A pyroxenite layer, equivalent to the Pyroxenite Marker is present and divides the MZ from the UZ.

The MZ had a far larger lateral extent than the underlying units and it onlaps the floor rocks both to the south, as can be seen in the Stoffberg area, and close to Pretoria. Furthermore, it onlaps and is in direct contact with the floor to the north of the TML in the northern lobe where there is little or no CZ developed, and the stratigraphy comprises only MZ and UZ rocks (Fig. 5). The LMZ is characterised by the Cr-deficient nature of the rocks, and in the upper part, the addition of augite to the assemblage, resulted in gabbronorite becoming the dominant rock type. The UMZ is a succession of relatively homogeneous gabbronorite with a constant $^{87}Sr/^{86}Sr \approx 0.7084$ in both the eastern (Sharpe, 1985) and western (Kruger, 1994) lobes.

### Nature of the BvMz magma, and its interactions to form the Merensky Reef and the Platreef

The CZ - MZ boundary is placed at the base of the Merensky Cyclic Unit (Kruger, 1990), since this point represents a major event in the evolution of the Bushveld Complex, in the form of a large influx of a new magma type (BvMz) immediately prior to the deposition of the Merensky Reef (Kruger and Marsh, 1982; Kruger, 1992; Cawthorn and Spies, 2003; Seabrook *et al.,* submitted). The Merensky Reef is, therefore, the product of the interaction of residual

BvCz magma in the chamber and the new influx of BvMz magma.

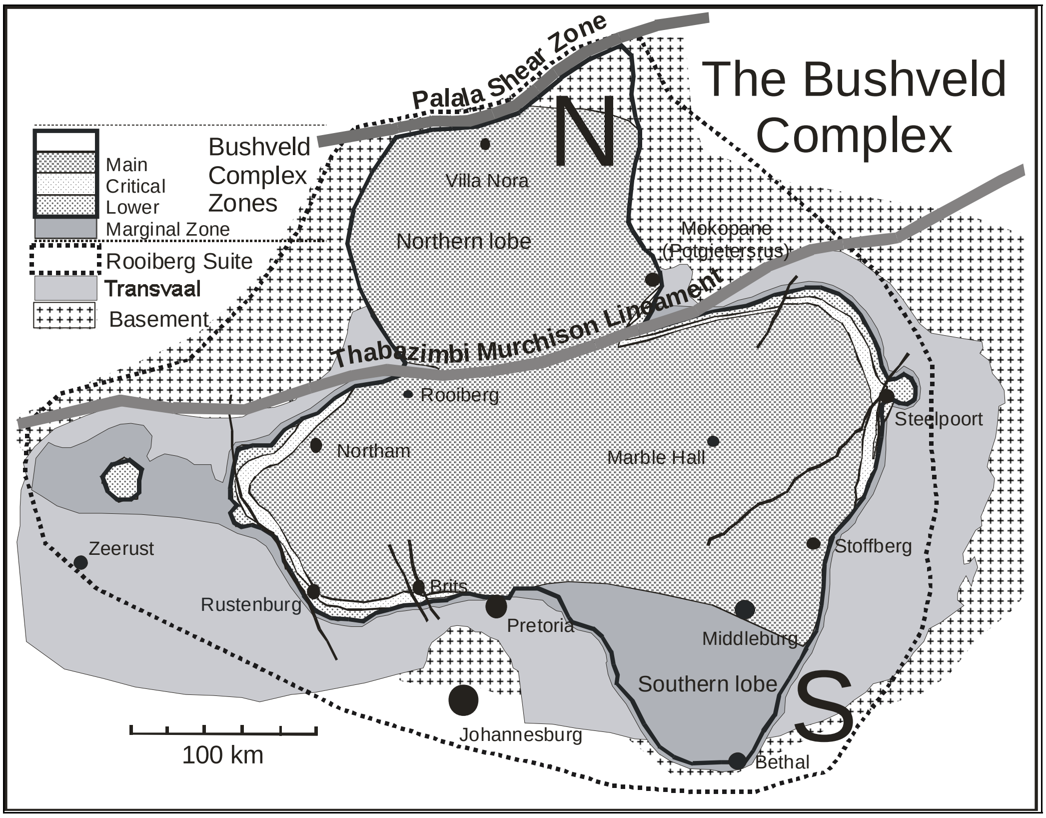


***Figure 5:*** *The lateral extent of the Main Zone derived dominantly from the BvMz magma.*

The lower part of the succession straddling the UCZ and the Transitional Macro-unit has been the subject of numerous other studies, and the reader is referred to *inter alia,* Vermaak (1976), Von Gruenewaldt (1979), Kruger and Marsh (1982, 1985), Naldrett *et al.* (1986), Kruger (1992) and Cawthorn and Spies (2003) for detailed descriptions and contrasting interpretations of the available data. Nevertheless, since the publication of detailed Sr-isotope data (Kruger and Marsh, 1982), the consensus is that the Merensky Reef represents an influx of new magma into the chamber. The disputes involve the following: (1) is this new magma of the same lineage as that added to the UCZ, and which became dominant at the Merensky Reef (e.g., Eales, 2002), or, is it an entirely different magma; and (2) is the magma that interacted with the floor-rocks to form the Platreef the same as that which formed the Merensky Reef?

This author is of the opinion that *an entirely new magma,* BvMz*,* intruded the Bushveld chamber in the northern lobe, there interacting with the floor-rocks to form the Platreef. With continued influx, this magma flowed south into the eastern and western lobes to interact with the residual BvCz magma in those lobes to form the Merensky Reef. Because this magma intruded the Bushveld Complex in a location not sampled by earlier workers, whose field areas were removed from the zone of intrusion (e.g., Harmer and Sharpe, 1985; Cawthorn *et al*., 1981; Sharpe, 1981), it has never been properly characterised.

Nevertheless, a number of features of the new BvMz were derived from the study of the CZ-MZ interaction. These indicated that the magma was more Fe- and Na-rich and Cr poor than any CZ magma, is of a gabbronoritic and not noritic lineage, and had a lower Sr-content and very much higher $^{87}Sr/^{86}Sr$ ratio (>0.710) than the magma added to the CZ (see Kruger and

Marsh, 1982, 1985; Kruger, 1992, 1994). Therefore, (excluding pBv) BvMz is taken to be the third magma type to intrude the complex (*cf.* Eales, 2002). This composition is not sampled in the marginal chills of Sharpe (1981) and Harmer and Sharpe (1985) whose samples are believed to represent mainly mixtures of BvLz and BvCz, or at best, mixtures of resident BvCz liquid and new BvMz liquid.

The rocks comprising the Merensky and Bastard Cyclic Units have mineralogical and geochemical characteristics transitional between the CZ and the rest of the MZ, and Kruger (1990) grouped them in the *Transitional Macro-unit* of the MZ. Nevertheless, they remain as part of the MZ, as it is the unit overlying the major, regionally extensive unconformity at the base of the MZ discussed above. The nature of this transition and the formation of the Merensky Reef on the eroded and "potholed" CZ is examined in more detail elsewhere (e.g., Carr *et al.,* 1999; Kruger, 1994; Cawthorn and Spies, 2003; Seabrook *et al.,* submitted). Within the LMZ, there are some major pyroxenite and anorthosite layers and an unusual spotted "Porphyritic" Gabbronorite Marker (Mitchell, 1990; Mitchell *et al.,* 1998; Nex *et al.,* 1998), and the UMZ is a chemically differentiated and mineralogically homogeneous gabbronorite (Mitchell *et al.,* 1998).

## Mineralization

There are two major PGE-Cu-Ni ore deposits associated with the intrusion of the MZ: (1) the Merensky Reef; and (2) the Platreef. Both these deposits are at the base of the MZ and are MZ- related phenomena resulting from a large influx of BvMz magma.

The Merensky Reef is draped over a major unconformity that terminates the Critical Zone and is the first layer at the base of the MZ. The nature and origin of this unconformity (of which "potholes" are a manifestation) is the subject of many papers (e.g., Carr *et al.*, 1999; Viring and Cowell, 1999; Lomberg *et al.,* 1999 and references therein). The Merensky Reef consists of a layer of pyroxenite, in places composite and normally including one or more thin seams of chromite with disseminated pyrrhotite, pentlandite, chalcopyrite and accessory chromite, and invariably contains low to moderate PGE values (Vermaak and Hendricks, 1976; Vermaak, 1976). This pyroxenite layer may vary in thickness from 10cm to 7.5m in different localities around the Bushveld Complex. A sequence consisting of norite, spotted anorthosite, and finally mottled anorthosite overlies the pyroxenite layer. This whole sequence is again overlain by a very similar succession whose basal pyroxenite layer forms the Bastard Reef. Although a thin chromite band is often developed at the base PGE values are normally very low in the Bastard Reef. In the western limb PGE values are concentrated in a pegmatitic phase generally occurring at the base of the pyroxenite band. The main silicate minerals present in the reef are major cumulus orthopyroxene (bronzite), lesser clinopyroxene, and intercumulus plagioclase. Minor serpentinization of the pyroxenes has taken place liberating secondary magnetite.

The Platreef and the overlying succession from the floor up in the northern lobe, is dominated by magmas with high $^{87}Sr/^{86}Sr$ (see Fig. 2) and gabbronorite mineralogy. It is concluded that the MZ onlaps the floor in this position and that little if any CZ magma was present. Kruger (2003) showed the magma as flowing north over the TML to interact with the floor rocks and thus form the Platreef. However, more detailed Sr-isotope work on the southern part of the Platreef and the overlying MZ shows that the magmas interacting with, and forming the Platreef, have very high initial $^{87}Sr/^{86}Sr$, almost all of which are higher than the bulk of the MZ in the chamber to the south of the TML. These data suggest that the influx to the MZ occurred to the north of the TML, where the intruding magmas interacted directly with the floor rocks that include S-rich black shales (the Duitschland Formation) and reactive, carbonate-rich sediments. This interaction was enhanced by extensive interdigitation of the new magmas and the country rocks, which now form major detached and attached rafts of a diverse hornfels suite within the Platreef package (e.g., the dolomite finger or tongue oriented orthogonal to the rest of the rocks at Sandsloot Mine, north of Mokopane). It also resulted in significant contamination by S, $H_2O$ and $CO_2$ that, with localized fractional crystallization, resulted in a diverse suite of igneous, metamorphic and metasomatic rocks, all bearing sulphides that captured the Ni, Cu and PGE from the intruding BvMz magma. The complex nature of this ore deposit was recognized very early on, and the above description is not significantly different from that of Wagner (1929) and Hall (1932), and more recently by Gain and Mostert (1982) and Cawthorn *et al.* (1985). In the south this package may reach 400 m thick, and is rich in sulphide (see Kinnaird and Nex, 2003), but thins northward with less and less floor rocks being incorporated.

This magma formed the Platreef and then flowed south of the TML, to interact with the residual magma of the CZ and create the unconformity at the base of the Merensky Reef. The Merensky Reef itself is inferred here to have obtained its PGE and sulphide from this new MZ magma, which had interacted with sediments. This is confirmed by limited Os-isotope data from the Platreef (Chaumba *et al.,* 1998), which is similar to the data from the Merensky Reef elsewhere in the Bushveld Complex, but entirely different from the Critical Zone (see Hart and Kinloch, 1989; McCandless and Ruis, 1991; Schoenberg *et al.,* 1999).

**Summary**

In the case of the MZ the new magma influx occurred in the northern lobe where it interacted with the floor pelites and carbonates to form the Platreef, and then continued on to interact with the residual magmas of the CZ and CZ cumulates, eroding an extensive unconformity and terminating the evolution of the CZ when it flowed into the main east-west magma chamber. The Merensky Reef formed during this event covering the unconformity. The Platreef and the Merensky Reef are, therefore, coeval and consanguineous, with respect to their mineralization and parent magma - BvMz. They are both phenomena initiating the evolution of the MZ and are not part of the CZ.

In turn, the MZ was terminated by a similar process of major magma injection, cumulate erosion and chamber expansion, which formed a very extensive unconformity on which the UZ was deposited. Mass balance and stratigraphic thickness considerations, examined below, indicate that the residual magma in the chamber was *c.* 1.2 km thick when the evolution of the UMZ was terminated by the addition of a further *c.* 0.8 km of BvUz magma. These magma layers were the thickest in the entire evolution of the Bushveld Complex.

**Upper Zone: BvUz magma parental to magnetitites**

The base of the UZ is placed at the base of the laterally extensive Pyroxenite Marker, since it records a major intrusive and mixing event in the evolution of the Bushveld Complex, and is the first and most primitive layer of the UZ. As with the CZ, the influx of BvUz magma created an extensive unconformity with very large troughs (Wilson *et al*., 1994) of which the "Gap" areas near Northam, which cut across the entire MZ, CZ and LZ stratigraphy onto the floor in the western Bushveld Complex, are a manifestation. The Pyroxenite Marker is in some ways analogous to the Merensky Reef, and does host weak PGE-Ni-Cu mineralization (Wilhelm *et al.*, 1997). This is followed by a highly differentiated sequence of norite, gabbronorite, ferro-gabbronorite and ferrodiorite, the latter interlayered with numerous anorthosite, ferro-dunite, titaniferous magnetite and apatite layers (Molyneux, 1974; Cawthorn and Molyneux, 1986) that is *c.* 2 km thick. Sr-isotopic data (Kruger *et al.,* 1987) indicated that the UZ is a single magmatic series that crystallized after the influx of magma described above had blended thoroughly with the resident residual BvMz magma ($^{87}Sr/^{86}Sr$ = 0.7084). The initial $^{87}Sr/^{86}Sr$ of the UZ is 0.7073 and that of the unadulterated BvUz magma in the southern lobe *c.* 0.7055 (Fig. 2). The data of Kruger *et al.* (1987) indicated that the resident and new magmas were not significantly different with respect to Sr-concentration. Thus, mass balance indicates that the resident magma comprised *c.* 62% of the mixed UZ liquid. This, in turn, implies that the thickness of residual magma in the MZ was approximately 1.2 km, immediately prior to the BvUz influx of 0.8 km. These magma layers were the thickest attained in the Bushveld Complex.

The UZ is the most laterally extensive unit of the Bushveld Complex and it is present in four of the five lobes (Fig. 6). It formed a single sheet, approximately 2 km thick, that extended laterally from the main east-west chamber, over the MZ in the northern limb where it onlaps the floor close to the *Palala Shear Zone*, which marks the northern margin of the Kaapvaal Craton. Furthermore, it extends southward into the southern lobe where it is the only zone present, other than possible early pBv- or BvLz-related marginal rocks discussed above.

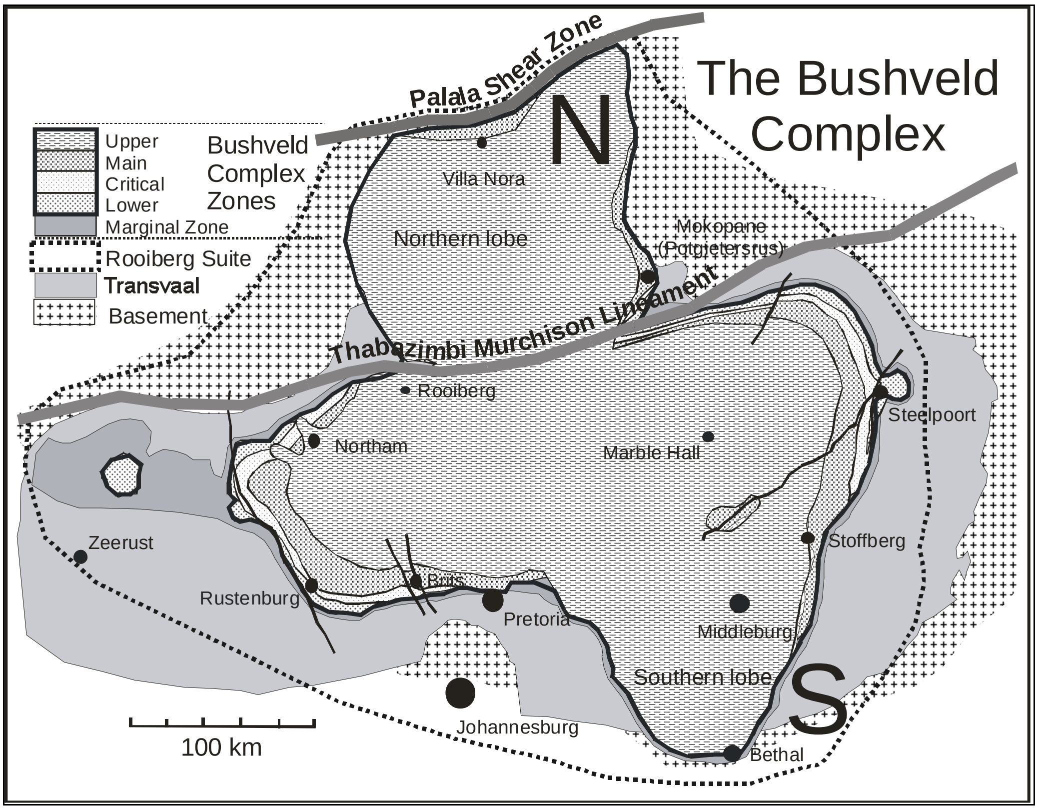


***Figure 6:*** *The lateral extent of the Upper Zone derived dominantly from the BvUz magma.*

The southern limb of the intrusion is crystallized entirely from BvUz magma with no addition of residual BvMz. This is shown by Sr-isotope data which indicate an initial $^{87}Sr/^{86}Sr$ of *c.* 0.7055 from rocks covering the entire succession (samples from the collection of Buchanan [1975; 1977], see Fig. 2 and Appendix 1). Buchanan (1975) also noted that the CZ and MZ are absent from this succession, but a thin ultramafic basal zone is present. The southern lobe UZ is therefore isolated from that elsewhere in the Bushveld Complex, but it is possible that UZ in the eastern, western and northern lobes was fed from the southern lobe. This contention is supported by the field relationships in the Stoffberg area where a large slab or pendant of roof rock is trapped on the MZ – UZ boundary (the Pyroxenite Marker position). This relationship could only come about if the new magma flowed in from the south as shown in Figure 7. The BvUz magma is thus inferred to have flowed into the eastern and western lobes from the southern lobe, and that the latter crystallised from this new magma, possibly as an isolated intrusion (Buchanan, 1977).

This contention is further supported by the observation that satellite bodies of the Bushveld Complex in the south (e.g., Kaffirskraal; Frick, 1975), have magnetite as a significant phase, and have magnetitite layers (see Hall, 1932). These satellite intrusions are inferred here to have been

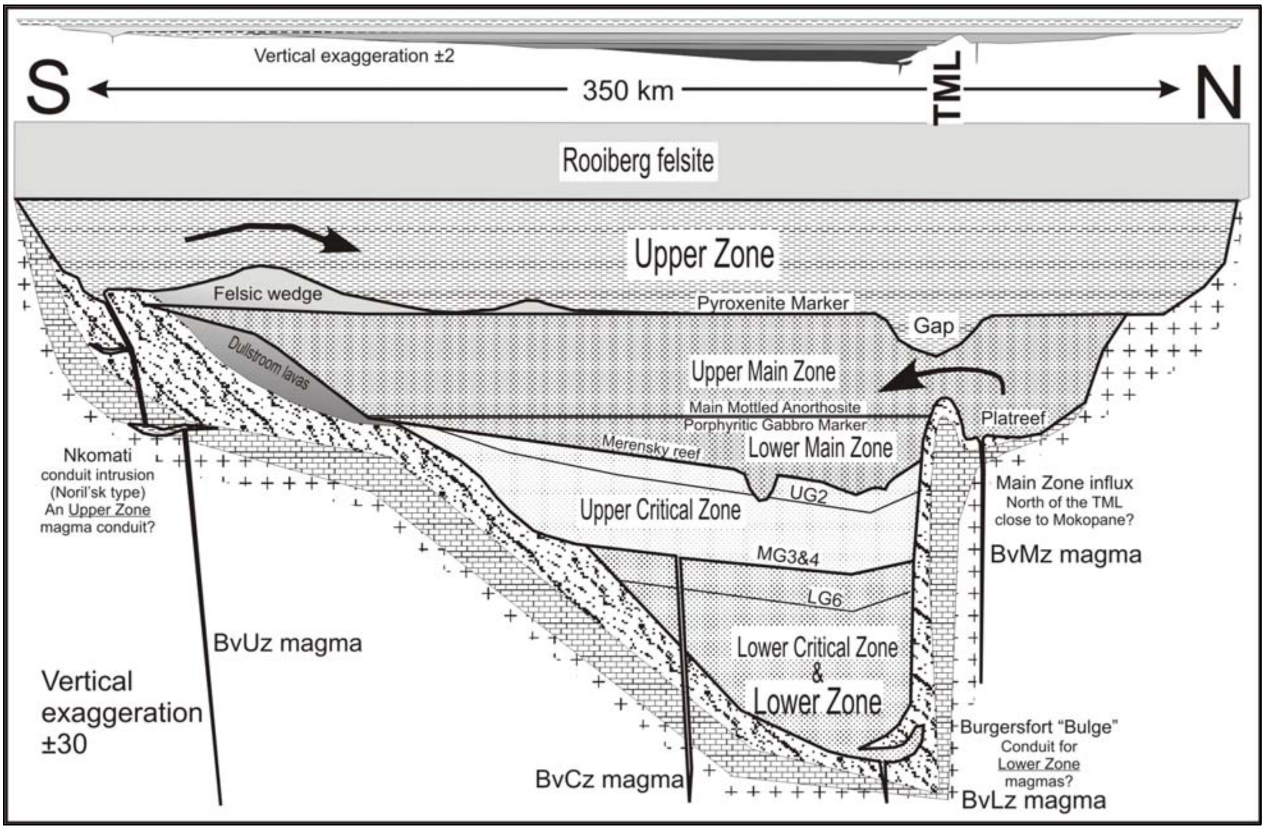


***Figure 7:** N-S schematic section showing the extent of the zones and their direction of influx and possible feeder locations.*

possible feeders to a more extensive southern lobe, or have fed a volcanic or peripheral sill phase, now eroded away (see also De Waal and Armstrong, 2000; De Waal and Gauert, 1997). This contention is speculative at this stage and requires further research.

The UZ differentiated to completion without further magma addition (Kruger *et al.,* 1987) and formed very extensive magnetitite layers, which appear to be strictly internally generated (e.g., McCarthy *et al.,* 1985; Kruger and Smart, 1987), and not the result of multiple intrusion.

## RASHOOP GRANOPHYRE SUITE AND LEBOWA GRANITE SUITE

The entire Bushveld Complex is capped by the Rashoop Granophyre Suite which is a complex series of conformable and cross-cutting granophyric rocks which are described in detail by Walraven (1985). These are, in some cases, clearly Rooiberg roof-rock melts (e.g., at Stoffberg). In other cases, the evidence is equivocal and the granophyric magmas are intrusive into the overlying Rooiberg Suite, which Walraven (1985) interpreted as pre-Bushveld Complex sub-volcanic intrusions of the primary Rooiberg magmas. However, in view of the model presented here, the granophyric roof-rock melt could re-intrude upward into the floating Rooiberg carapace. This is unresolved and requires further work.

The Lebowa Granite Suite intruded the Bushveld-Rashoop-Rooiberg succession along the boundary between the granophyres and the mafic rocks, and obscures the relationship between the granophyres and the Bushveld Complex. These differentiated granite sheets are the final manifestation of the Bushveld Magmatic Province.

## SUMMARY OF THE INTRUSION AND EVOLUTION OF THE BUSHVELD COMPLEX

The lithological variation of the Bushveld Complex, as a whole, broadly represents an apparent differentiation sequence from harzburgite, through orthopyroxenite and norite to gabbronorite and ferro-gabbronorite and ferro-diorite (Fig. 2). However, there is considerable cyclic and rhythmic variation in modal mineralogy and chemistry, superimposed on this sequence. Furthermore, there are a number of breaks and reversals often coincident with unconformable relationships. These breaks and reversals are vital to the understanding of the Bushveld Complex and are also often coincident with mineralization.

A variety of magmas are postulated for the Bushveld Complex. However, because a number of naming conventions have been adopted and then corrupted, an alternative abbreviation scheme is introduced here. The process of intrusion and expansion of the chamber is schematically shown in the N-S section (Fig. 7). The magmas that intruded to build the Bushveld Complex can be summarised sequentially as follows:

(1) pre-Bushveld Complex (pBv) sills and intrusions of a noritic character and a low $^{87}Sr/^{86}Sr$ of *c.* 0.7050;

(2) BvLz, a siliceous picrite magma ($SiO_2 \approx 55\%$; $MgO \approx 12\%$), with olivine and orthopyroxene ($>En_{83}$) as liquidus phases (Davies *et al.*, 1980; Cawthorn *et al.*, 1981) which built the LZ and LCZ. This magma may have evolved towards plagioclase saturation at the top of the LCZ (Cawthorn, personal communication). It was poor in PGE and had a low (Pt+Pd+Rh)/(Ru+Ir+Os), but was rich in Cr and formed major chromitite layers including the LG6. The magma had a relatively low $^{87}Sr/^{86}Sr$ (0.705) and a mantle Os- isotope character;

(3) the third magma (BvCz) to intrude dominated the UCZ and is of a noritic lineage, with a high Cr and Sr content, abundant plagioclase and very little clinopyroxene or olivine. The $^{87}Sr/^{86}Sr$ was *c*. 0.7065-0.7075 and the Os-isotope character higher than the inferred mantle value. This is similar to the B2 magma of Harmer and Sharpe (1985);

(4) the MZ is derived from a fourth magma type (BvMz) that, because it is not directly represented in the sills of the well-exposed eastern Bushveld Complex, is not yet well defined.

It is partly represented as a fine-grained gabbronoritic marginal chill (mixed BvMz and residual BvCz) accepted by Harmer and Sharpe (1985) and Hatton and Sharpe (1989) as parental to the MZ. Pristine BvMz is elusive, and up to now is only theoretically derived using various model dependent calculations using mineral compositions from the layered sequence (e.g., Hatton, 1988; Kruger, 1992; reviewed in Eales, 2002). Nevertheless, recent work has shown that this magma is manifested in the Platreef where fine-grained samples have a gabbronoritic character, and an extremely high $^{87}Sr/^{86}Sr$ (*c.* 0.715) and an Os-isotope character similar to that of the Merensky Reef (Chaumba *et al.,* 1998). The data are indicative of major (upper) crustal contamination in the source region, and *not only locally,* as the entire MZ is dominated by a magma that had an initial $^{87}Sr/^{86}Sr$ in excess of 0.710 to give an average mixed value of 0.7084 (Kruger, 1994). The exact nature of this magma awaits an extensive search for a chilled version that can be shown not to have suffered local contamination in the area around Mokopane (in the south of the northern limb, north of the TML) where the BvMz magma is inferred to have intruded; and finally

(5) the extensive UZ was produced by an influx of magma (BvUz) from the southern lobe of the Bushveld Complex. BvUz was S-saturated, Fe-rich and had a $^{87}Sr/^{86}Sr$ close to 0.7055 and can be characterised as having had a ferro-gabbronorite lineage. Again this magma is probably not represented in the eastern Bushveld sill phase and is therefore also elusive, but Davies and Cawthorn (1984) reportrd on a fine-grained, cross-cutting intrusion of gabbronorite, low in Cr and high in FeO, that could be representative of BvUz or a derivative thereof. This magma intruded the Bushveld Complex from the south, and is the only magma present in the covered southern lobe of the Bushveld Complex. It is inferred to have flowed into the eastern lobe in the Stoffberg area from the southern lobe, and possibly via other feeders to the south. There are a number of plug-like bodies of ultramafic rocks, containing magnetite and clinopyroxene, that are clustered to the south of the Bushveld Complex (Hall, 1932) such as Kaffirskraal (Frick, 1975), that may be potential feeders to the UZ. If these prove to be feeders to the UZ, it would imply an exceptionally large lateral extent for this zone.

## CONCLUSIONS

From the above descriptions of the major zones of the Bushveld Complex, it is inferred that the initial PBv, BvLz and BvCz magmas intruded beneath a blanket of Rooiberg felsites close to the TML. Depression of the crust to the south of the TML initiated an elongate, half-graben-shaped, magma chamber between two major E-W structural lineaments (*viz*., the TML) and a broadly monoclinal arch between Stoffberg and Zeerust. The CZ was terminated, and the MZ initiated by intrusion of BvMz magma from immediately north of the TML where the Platreef and the overlying MZ are overwhelmingly dominated by BvMz. In contrast, the BvUz magmas, which initiated the UZ, intruded from the south and flowed northward under the Rooiberg carapace from as far south as Bethal, Losberg, Kaffirskraal and Vredefort.

The mineralization associated with these magmatic influxes is of two types – *Marginal* and *Stratabound*, and furthermore, one influx could interact in both ways and generate both types. The *Marginal Mineralization* occurs where new magma influxes interact with the floor rocks in two possible ways: first, a proximal type, such as the *Platreef*, where a feeder injects new magma into and through reactive floor rocks; and second, a distal type, such as the *Henderson Reef* in the Mineral Range area near Stoffberg (Kruger and Behr, 2002), where the magma expanded laterally onto reactive floor rocks, and significant interfingering, interaction and incorporation of sulphur-bearing xenoliths occurred.

The *Stratabound Mineralization* (such as the *Merensky Reef, UG2, LG6* and other chromitite layers) is also associated with magmatic influxes and unconformable relationships, but interaction with the pre-existing hot cumulates, residual magma, and roof melts is important (Kruger and Marsh, 1982, 1985; Kruger, 1999; Kinnaird *et al*., 2002). Hence, the mineralization in the Bushveld Complex was brought about and affected by four main events or processes. In order of importance these are:

(1) primary depositional events associated with major magmatic influxes (e.g., Platreef and Merensky Reef). These events resulted in deposition of the main mineralization on, or close to, an unconformity resulting from the influx itself;
(2) a secondary magmatic process of differentiation and accumulation, which may have significantly concentrated the mineralization (chromitites and Merensky Reef) (Kruger, 1992, 1999; Kinnaird *et al*., 2002);
(3) tertiary, subliquidus magmatic processes, where redistribution and reconstitution of the rocks occurred, which may have sharpened the ore profiles (e.g., Boudreau and Kruger, 1990; Willmore *et al*., 2000); and
(4) quarternary, low-temperature alteration processes, where the main magmatic minerals were altered (serpentinisation and talc formation) and some secondary veins of ore formed (e.g., in the Platreef). This served to redistribute metals locally, and in some cases obscured the first three effects due to mineralogical and structural changes. It also takes on great importance due to the bearing on mining and recovery.

The main controversies are related to arguments as to the relative importance of these four processes in creating the PGE and chromitite ore deposits of the Bushveld Complex.

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## REFERENCES

Boudreau AE, Kruger FJ (1990) Variation in the composition of apatite through the Merensky Cyclic Unit in the Western Bushveld Complex. Econ Geol 85:737-745.

Buchanan DL (1975) The petrography of the Bushveld Complex intersected by boreholes in the Bethal area. Trans Geol Soc S Afr 78:335-348.

Buchanan DL (1977) Cryptic variation in minerals from the Bushveld Complex rocks in the Bethal area. Trans Geol Soc S Afr 80:49-52.

Buchanan PC, Reimold WU, Koeberl C, Kruger FJ (2002) Geochemistry of intermediate to siliceous volcanic rocks of the Rooiberg Group Bushveld Magmatic Province South Africa. Contrib Mineral Petrol 144:131-143.

Cameron EN (1978) The Lower Zone of the Eastern Bushveld Complex in the Olifants River trough. Econ Geol 75, 845-871.

Cameron EN (1980) Evolution of the Lower Critical Zone, central sector, Eastern Bushveld Complex. Econ Geol 75:845-871.

Cameron EN (1982) The Upper Critical Zone of the eastern Bushveld Complex – precursor of the Merensky Reef. Econ Geol 77:1307-1327.

Campbell IH, Naldrett AJ, Barnes SJ (1983) A model for the origin of the platinum-rich sulfide horizons in the Bushveld and Stillwater Complexes. J Petrol 24:133-165.

Carr HW, Kruger FJ, Groves DI, Cawthorn RG (1999) The petrogenesis of Merensky Reef potholes at the Western Platinum Mine Bushveld Complex: Sr-isotopic evidence for synmagmatic deformation. Mineral Deposita. 34:335-347.

Cawthorn RG, Davies G (1983) Experimental data at 3 kbars pressure on parental magma to the Bushveld Complex. Contrib Mineral Petrol 83:128-135.

Cawthorn RG, Spies L (2003) Plagioclase content of cyclic units in the Bushveld Complex, South Africa. Contrib Mineral Petrol 145:47-60.

Cawthorn RG, Molyneux TG (1986) Vanadiferous magnetite deposits of the Bushveld Complex. In: CR Anhaeusser and S Maske eds Mineral Deposits of Southern Africa Vol II :1251-1266.

Cawthorn RG, Walraven F (1998) Emplacement and crystallization time for the Bushveld Complex. J Petrol 39:1669-1687.

Cawthorn RG, Cooper GRJ, Webb SJ (1998) Connectivity between the western and eastern limbs of the Bushveld Complex. S Afr J Geol, 101:291-298.

Cawthorn RG, Meyer PS, Kruger FJ (1991) Major addition of magma at the Pyroxenite Marker in the Western Bushveld Complex South Africa. J Petrol 32:739-763.

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

Cawthorn RG, Davies G Clubley-Armstrong A, McCarthy TS (1981) Sills associated with the Bushveld Complex. Lithos 14:1-15.

Chaumba JB, Harris C, Tredoux M (1998) Oxygen, strontium and osmium isotope geochemistry of the Platreef of the northern lobe of the Bushveld Complex South Africa. (8 th Intl Pt Symp Abst) S Afr Inst Mining Metall Symp Ser S18:71-72.

Clarke BM, Uken R, Watkeys MK (2000) Intrusion mechanisms of the southwestern Rustenburg Layered Suite as deduced from the Spruitfontein inlier. S Afr J Geol 103:120-127.

Cheney ES, Twist D (1991) The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. Precamb Res 52:115-132.

Coetzee H, Kruger FJ (1989) The geochronology and Sr- and Pb- isotope geochemistry of the Losberg Complex and the southern limit of Bushveld Complex magmatism. S Afr J Geol 92:37-41.

Cousins CA (1959) The structure of the mafic portion of the Bushveld Igneous Complex. (with discussions and replies). Trans Geol Soc S Afr 26:179-201.

Daly RA, Molengraaff GAF (1924). Structural relations of the Bushveld Igneous Complex, Transvaal. Chicago J Geol XXXII: 1-35.

Davies G, Cawthorn RG (1984) Mineralogical data on a multiple intrusion in the Rustenburg Layered Suite of the Bushveld Complex. Mineral Mag 48:469-480.

Davies G, Cawthorn RG, Barton JM, Morton M (1980) Parental Magma to the Bushveld Complex. Nature, 287, 33-35.

De Waal SA, Armstrong RA (2000) The age of the Marble Hall diorite its relationship to the Uitkomst Complex and evidence for a new magma type associated with the Bushveld igneous event. S Afr J Geol 103:128-140.

De Waal SA, Gauert CDK (1997) The Basal Gabbro Unit and the identity of the parental magma of the Uitkomst Complex Badplaas South Africa. S Afr J Geol 100: 349-362.

Eales HV (2000) Implications of the chromium budget of the western limb of the Bushveld Complex. S Afr J Geol 103:141-150.
Eales HV (2002) Caveats in defining the magmas parental to the mafic rocks of the Bushveld Complex and the manner of their emplacement: review and commentary. Mineral Mag 66 815-832.
Eales HV, De Klerk WJ, Butcher AR, Kruger FJ (1990) The cyclic unit beneath the UG1 chromitite (UG1FW Unit) at RPM Union Section Platinum Mine - Rosetta Stone of the Bushveld Upper Critical Zone? Mineral Mag 54:23-43.
Eales HV, Field M, De Klerk WJ, Scoon RN (1988) Regional trends of chemical variation and thermal erosion in the Upper Critical Zone, Western Bushveld Complex. Mineral Mag 52:63-79.
Eales HV, Marsh JS, Mitchell AA, De Klerk WJ, Kruger FJ, Field M (1986) Some Geochemical constraints upon models for the crystallization of the Upper Critical Zone – Main Zone interval northwestern Bushveld Complex. Mineral Mag 50:567-582.
Engelbrecht JP (1985) The chromitites of the Bushveld Complex in the Nietverdient area. Econ Geol 80:896-910.
Engelbrecht JP (1990) The Marico Hyperbyssal Suite, and the marginal zone of the Bushveld Complex in the Marico District, western Transvaal, South Africa. S Afr J Geol, 93:318-328.
Eriksson PG, Hattingh PJ, Altermann W (1995) An overview of the geology of the Transvaal Sequence and Bushveld Complex. Mineral Deposita 30:98-111.
Frick C (1973) The sill phase and the chill zone of the Bushveld Igneous Complex. Trans Geol Soc S Afr 76:7-14.
Frick C (1975) The geology and petrology of the Kaffirskraal Igneous Complex. Trans Geol Soc S Afr 78:11-23.
Gain SB, Mostert AB (1982) The geological setting of the platinoid and base metal sulfide mineralization in the Platreef of the Bushveld Complex in Drenthe north of Potgietersrus. Econ Geol 77:1395-1404.
Good N, De Wit MJ (1997) The Thabazimbi-Murchison Lineament of the Kaapvaal Craton, South Africa: 2700 Ma of episodic deformation. J Geol Soc (Lond) 154:93-97.
Gough DI, Van Niekerk CB (1959) A study of the palaeomagnetism of the Bushveld Complex. Phil Mag 14:126-134.
Hall AL (1932) The Bushveld Igneous Complex of the Central Transvaal. Geological Survey of South Africa Memoir 28:560pp.
Hamilton PJ (1977) Sr-isotope and trace element studies of the Great Dyke and Bushveld mafic phase and their relation to early Proterozoic magma genesis in southern Africa. J Petrol 18:24-52.
Harmer RE, Sharpe MR (1985) Field relations and strontium isotope systematics of the marginal rocks of the eastern Bushveld complex. Econ Geol 80 813-837.
Hart SR, Kinloch ED (1989) Osmium isotope systematics in Witwatersrand and Bushveld ore deposits. Econ Geol 84:1651-1655.
Hatton CJ (1988) Densities and liquidus temperatures of Bushveld parental magmas as constraints on the formation of the Merensky Reef in the Bushveld Complex South Africa. In. Magmatic Sulphides: the Zimbabwe Volume (MD. Prendergast MJ. Jones editors) Trans Inst Min Metall Lond.
Hatton CJ, Schweitzer JK (1995) Evidence for synchronous extrusive and intrusive Bushveld magmatism. J Afr Earth Sci 21:579-594.
Hatton CJ, Sharpe MR (1989) Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: Boninites and Related Rocks (AJ. Crawford editor) pages 1-49. Unwin Hyman London.
Hiemstra SA (1985) The distribution of some platinum-group elements in the UG-2

chromitite layer of the Bushveld Complex. Econ Geol 80:944-957.
Hulbert LJ, von Gruenewaldt G (1982) Nickel, copper and platinum mineralization in the Lower Zone of the Bushveld Complex, south of Potgietersrus. Econ Geol 77:1296-1306.
Hulbert LJ, von Gruenewaldt G (1985) Textural and compositional features of chromite in the Lower and Critical zones of the Bushveld Complex south of Potgietersrus. Econ Geol 80:897-895.
Kinnaird JA, Kruger FJ, Nex PAM, Cawthorn RG (2002) Understanding chromitite formation – a key to understanding processes of platinum enrichment. Trans Inst Min Metall Sect B Appl Earth Sci 111B:B23-B35.
Kinnaird J, Nex P (2003) Mechanisms of marginal mineralization in the Bushveld Complex. The Geological Society's 2003 Fermor Flagship Meeting World Class Mineral Deposits and Earth Evolution, Cardiff, 18th - 21st August 2003. Trans Instit Min Metall Sect B, Appl Earth Sci 112B:B206-208.
Kleywegt RJ, du Plessis A (1986) On the structure of the Bushveld Complex and the central Transvaal basin. Geocongress 86 (Extended Abstracts ISBN 0-0620-09820-1) 603-607.
Kruger ,FJ (1990) The Stratigraphy of the Bushveld Complex: a reappraisal and the relocation of the Main Zone boundaries. S Afr J Geol 93:376-381.
Kruger FJ (1991) Authors reply to discussion on "The Stratigraphy of the Bushveld Complex" by AA. Mitchell RN. Scoon. S Afr J Geol 94:179-180.
Kruger FJ (1992) The origin of the Merensky cyclic unit: isotopic and mineralogical evidence for an alternative orthomagmatic model. Austral J Earth Sci 39:255-261.
Kruger FJ (1994) The Sr-isotopic stratigraphy of the western Bushveld Complex. S Afr J Geol 97:393-398
Kruger FJ (1999) The Bushveld Complex unconformity related ore deposits: an isotopic perspective. Mineral Deposits: Processes to Processing Stanley *et al.*, (eds). Balkema Rotterdam 737-738.
Kruger FJ (2003) Filling the Bushveld Complex magma chamber: intrachamber magma dynamics and the generation of giant chromitite and PGE deposits. The Geological Society's 2003 Fermor Flagship Meeting World Class Mineral Deposits and Earth Evolution, Cardiff, 18th - 21st August 2003. Trans Instit Min Metall Sect B, Appl Earth Sci 112:B208-209.
Kruger FJ, Behr S (2002 The Henderson Reef in the Dennilton Dome and Mineral Range Areas- A Homologue of the Platreef. 9th Int Pt Symp Billings Montana Ext Abst 4pp.
Kruger FJ, Marsh JS (1982) Significance of $^{87}Sr/^{86}Sr$ ratios in the Merensky cyclic unit of the western Bushveld Complex. Nature 298:53-55.
Kruger FJ, Marsh JS (1985) The mineralogy petrology and origin of the Merensky cyclic unit in the western Bushveld Complex. Econ Geol 80:958-974.
Kruger FJ, Smart R (1987) Diffusion of trace elements during bottom crystallization of double-diffusive convection systems: the magnetite layers of the Bushveld Complex. J Volc Geotherm Res 34:133-142.
Kruger FJ, Cawthorn RG, Walsh KL (1987) Strontium isotopic evidence against magma addition in the Upper Zone of the Bushveld Complex. Earth Planet Sci Lett 84:51-58.
Lee CA (1996) A review of mineralization in the Bushveld Complex and some other layered intrusions. in Layered Intrusions (RG. Cawthorn ed) Elsevier Amsterdam 103-146.
Lomberg KG, Martin ES, Patterson MA, Venter JE (1999) The morphology of potholes in the UG2 chromitite layer and Merensky Reef (pothole reef facies) at Union Section Rustenburg Platinum Mines. S Afr J Geol 102:209-220.
Maier WD, Eales HV (1994) A facies model for the interval between the UG2 and Merensky Reef Western Bushveld Complex. Trans Instit Min Metall Sect B Appl Earth Sci 103:B22-B30.

McBirney AR, Naslund HR (1990) The differentiation of the Skaergaard Intrusion. Contrib Mineral Petrol 104 235-247.
McCandless TE, Ruiz J, Adair BI, Freydier C (1999) Re-Os isotope and Pd/Ru variations in chromitites from the Critical Zone Bushveld Complex South Africa. Geochim Cosmochim Acta 63:911-923.
McCarthy TS, Cawthorn RG, Wright CJ, McIver (1985) Mineral layering in the Bushveld Complex: implications of Cr abundances in magnetite from closely spaced magnetitite and intervening silicate-rich layers. Econ Geol 80:1062-1074.
McLaren CH, De Villiers JPR (1982) The platinum-group chemistry and mineralogy of the UG2 chromitite layer of the Bushveld Complex. Econ Geol 77:1348-1366.
Meyer R, De Beer JH (1987) The structure of the Bushveld Complex from resistivity measurements. Nature 325:610-612.
Mitchell AA. (1990) The stratigraphy petrography and mineralogy of the Main Zone of the northwestern Bushveld Complex. S Afr J Geol 93:818-831.
Mitchell AA, Scoon RN (1991) Discussion on "The Stratigraphy of the Bushveld Complex" by FJ) Kruger. S Afr J Geol 94:183-187.
Mitchell AA, Eales HV, Kruger FJ (1998) Magma replenishment and the significance of poikilitic textures in the Lower Main Zone of the western Bushveld Complex South Africa. Mineral Mag 64:435-450.
Molyneux TG (1974) A geological investigation of the Bushveld Complex in Sekhukhuneland and part of the Steelpoort Valley. Trans Geol Soc S Afr 77:329-338.
Naldrett AJ, Gasparrini EC, Barnes SJ, von Gruenewaldt G, Sharpe MR (1986) The Upper Critical Zone of the Bushveld Complex and a model for the origin of Merensky-type ores. Econ Geol 81:1105-1118.
Nex PAM, Kinnaird JA, Ingle LJ, van der Vyver BA, Cawthorn RG (1998) A new stratigraphy for the Main Zone of the Bushveld Complex in the Rustenburg area. S Afr J Geol 101215-223.
Nex PAM (in press) Domes at Dwars River and underground exposures of the UG1: an explanation for the formation of bifurcating chromitite layers an analogy with sand volcanoes. J Geol Soc Lond.
Nex PAM. (2002) Bifurcating chromitites in the Bushveld Complex South Africa: magmatic analogues of sand volcanoes. Geocongress (2002 Biannual meeting of the Geological Society of South Africa Windhoek Extended Abstracts.
SACS (1981) South African Committee for Stratigraphy. Stratigraphy of South Africa. (LE. Kent compiler). Geological Survey of South Africa Hbk 8:223-241.
Schoenberg R, Kruger FJ, Nägler TF, Meisel T, Kramers JD (1999) PGE enrichment in chromitite layers and the Merensky Reef of the western Bushveld Complex; a Re-Os and Rb-Sr isotope study. Earth Planet Sci Lett 172:49-64.
Schürmann LW, Grabe PJ, Steenkamp CJ (1998) Chromium. in (MGC. Wilson CR Anhaeusser eds) Mineral Resources of South Africa (6th ed) Hbk 16:90-105. Council for Geoscience.
Schwellnus JSI, Engelbrecht LNJ, Coertze FJ, Russell HD, Malherbe SJ, van Rooyen DP, Cooke R (1962) The geology of the Olifants River area, Transvaal. Explanation of sheets 2429B (Chuniespoort) and 2430A (Wolkberg). Geological Survey of South Africa, 87pp.
Scoon RN (2002) A new occurrence of Merensky Reef on the flanks of the Zaaikloof Dome, Northeastern Bushveld Complex: relationship between diapirism and magma replenishment. Econ Geol 971037-1049.
Scoon RN, Teigler B (1994) Platinum-group element mineralization in the Critical Zone of the western Bushveld Complex: I. Sulfide poor chromitites below the UG2. Econ Geol 891094-1121.

Seabrook CL, Cawthorn RG, Kruger FJ (submitted). The Merensky Reef, Bushveld Complex: Mixing of minerals not mixing of magmas. Econ Geol (submitted).

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

Sharpe MR, Bahat D, von Gruenewaldt G (1981) The concentric eliptical structure of feeder sites to the Bushveld Complex and possible economic implications. Trans Geol Soc S Afr 84:239-244.

Sharpe MR (1985) Strontium isotope evidence for preserved density stratification in the Main Zone of the Bushveld Complex. Nature 316:119-126.

Sharpe MR, Hulbert LJ (1985) Ultramafic sills beneath the eastern Bushveld Complex: mobilised suspensions of early Lower Zone cumulates in a parental magma with boninitic affinities. Econ Geol 80, 849-871.

Teigler B (1990) Mineralogy, petrology and geochemistry of the Lower and Lower Critical Zones, Northwestern Bushveld Complex. PhD thesis, Rhodes University, Grahamstown, South Africa, 247pp.

Teigler B, Eales HV (1996) The lower and Critical Zones of the western limb of the Bushveld Complex intersected by the Nooitgedagt boreholes. Bull Geol Surv S Afr 111:126pp.

Teigler B, Eales HV, Scoon RN (1992) The cumulate succession of the Critical Zone of the Rustenburg Layered Suite at Brits, western Bushveld Complex. S Afr J Geol 95:17-28.

Twist D (1985) Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area; Southeastern Bushveld. Econ Geol 80:1153-1165.

Twist D, French BM (1983) Voluminous acid volcanism in the Bushveld Complex: a review of the Rooiberg Felsite. Bull Volc 46:225-242.

Vermaak CF (1976) The Merensky Reef – thoughts on its environment and genesis. Econ Geol 71:1270-1298.

Vermaak CF, Hendricks LP (1976) A review of the mineralogy of the Merensky Reef, with specific reference to new data on the precious metal mineralogy. Econ Geol 71:1244-1269.

Van der Merwe MJ (1976) The layered sequence of the potgietersrus limb of the Bushveld Complex. Econ Geol 71:1337-1351.

Viring RG, Cowell MW (1999) The Merensky Reef on Northam Platinum Limited. S Afr J Geol 102:192-208.

Viljoen MJ, Schürmann LW (1998) Platinum-Group Metals. in (MGC. Wilson CR. Anhaeusser eds) Mineral Resources of South Africa ($6^{th}$ ed) Handbook 16:532-568. Council for Geoscience.

Von Gruenewaldt G (1979) A review of some recent concepts of the Bushveld Complex; with particular reference to sulfide mineralization. Canad Mineral 17:233-256.

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

Wager LR, Brown GM (1968). Layered Igneous Rocks Oliver and Boyd, Edinburgh, 588pp.

Wagner PA (1929) The Platinum Deposits and Mines of South Africa. Oliver and Boyd Edinburgh 326pp.

Walraven F (1985) Genetic aspects of the granophyric rocks of the Bushveld Complex. Econ Geol 80:1166-1180.

Walraven F, Darracott BW (1976) Quantitative interpretation of a gravity profile across the western Bushveld Complex. Transactions of the Geological Society of South Africa, 79 22-26.

Walraven F, Hattingh E (1993) Geochronology of the Nebo Granite Bushveld Complex. S Afr J Geol 96:31-41.

Walraven F, Armstrong RA, Kruger FJ (1990) A chronostratigraphic framework for the north central Kaapvaal craton the Bushveld Complex and the Vredefort Structure. Tectonophysics 171:23-48.

Wilhelm HJ, Zhang H, Chen FL, Elsenbroek JH, Lombard M, De Bruin D (1997) Geochemical exploration for platinum-group elements in the Bushveld Complex, South Africa. Mineral Deposita 32:349-361.

Willemse J (1959) The "floor" of the Bushveld Igneous Complex. Proceedings of the Geological Society of South Africa LXII:xxi-lxxx.

Willemse J (1969) The Geology of the Bushveld Complex the largest repository of magmatic ore deposits in the World. Econ Geol Mono 4:1-22.

Willmore CC, Boudreau AE, Kruger FJ (2000) The Halogen Geochemistry of the Bushveld Complex Republic of South Africa: Implications for Chalcophile Element Distribution in the Lower and Critical Zones. J Petrol 41:1517-1539.

Wilson JR, Cawthorn RG, Kruger FJ, Grundvig S (1994) Intrusive origin for the unconformable Upper Zone in the Northern Gap Western Bushveld Complex. S Afr J Geol 97:462-472.

Wright C, Kwadiba MTO, Kgaswane EM, Nguuri TK (2003) Variations in crustal thickness and uppermost mantle structure across the Kaapvaal Craton from Pn and Sn arrivals and receiver functions. S Afr J Sci 99:447-452.

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## APPENDIX 1

Samples of rocks from the southern lobe (Bethal area) courtesy D.L. Buchanan (see Buchanan, 1975 and 1978 for detailed descriptions of the rocks and location of the borehole sites). The sample number gives the Borehole number and the depth in feet of the sample, and the depth is given in metres in column 2. The data were obtained using the techniques described in Eales *et al.* (1988) and the errors and blanks listed in that work, apply to these rocks. The SRM 987 standard gave $^{87}Sr/^{86}Sr$ 0.71023 when these samples were run.

| **Sample Number** | **Depth (m)** | **Rb ppm** | **Sr ppm** | **87Rb/ 86Sr** | **87Sr/86Sr** | **87Sr/86 Sr2060 ±2** |
|---|---|---|---|---|---|---|
| KLG1/1769 | 539.2 | 1.82 | 676 | 0.0078 | 0.70563 | 0.70540±13 |
| KLG2/2428 | 740.1 | 9.92 | 190 | 0.1513 | 0.71028 | 0.70581±17 |
| KLG2/3221 | 981.8 | 1.81 | 904 | 0.0058 | 0.70584 | 0.70567±13 |
| KLG2/3399 | 1036 | 2.59 | 610 | 0.0123 | 0.70588 | 0.70551±13 |
| KLG2/3399r | 1036 | 2.58 | 610 | 0.0123 | 0.70593 | 0.70557±13 |
| UC361/537 | 163.7 | 2.31 | 303 | 0.0221 | 0.70607 | 0.70541±13 |
| UC361/1350 | 411.5 | 11.3 | 464.5 | 0.0705 | 0.70722 | 0.70514±15 |
| Mean initial ratio | | | | | | 0.70550 |