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ARTICLE

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Filling the Bushveld Complex magma chamber: lateral expansion, roof and floor interaction, magmatic unconformities, and the formation of giant chromitite, PGE and Ti-V-magnetitite deposits

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Abstract

> "His mind was like a soup dish—wide and shallow; ..." - Irving Stone on William Jennings Bryan

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, crystallisation and deposition of cumulates. Larger influxes correspond to the boundaries of the zones and sub-zones and are marked by sustained isotopic shifts, major changes in mineral assemblages and 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 crystallisation. 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 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 *c.* 1 m thick LG6 and MG1 layers exposed around both the Eastern and Western lobes of the Bushveld Complex. The *Upper Critical Zone* has a greater lateral extent than the Lower Critical Zone and overlies but also onlaps the floor-rocks to the south of the Steelpoort area . The source of the magmas also 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 which forced 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 by roof-rock melt of the intruding Critical Zone liquids that had an orthopyroxenitic to noritic lineage. The *Main Zone* is present in the Eastern and Western lobes of the 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 as well as the TML. 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 and a troctolitic layer in the Northern lobe, is the petrological and stratigraphic base of the Upper Zone. Sr-isotope data show that all the PGE rich

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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, indicate that during crystallisation, the Bushveld Complex was a wide and shallow, lobate, sill-like sheet, and the rock-strata and mineral deposits are quasi-continuous over the whole intrusion.

Keywords Bushveld Complex · Differentiation · Layered intrusion · Stratigraphy · Magma influxes · Magma mixing · Unconformities · Chromitite · PGE mineralisation

Introduction and geological setting

The 2.06 Ga old (Walraven et al. 1990) Bushveld Complex[1] in South Africa (Fig. 1), is the largest mafic layered intrusion (*c*. 65,000 km^2), and hosts the largest known deposits of Cr, V and platinum-group elements (PGE), on Earth (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 and the associated mineralisation, deduced.

The Bushveld Magmatic Province, as a whole, comprises five major magmatic suites: the bimodal Rooiberg volcanic suite (see Twist 1985; Buchanan et al. 2002); the mafic-layered rocks of the Bushveld Complex per se; a suite of marginal pre- and syn-Bushveld sills and intrusions (Willemse 1969; Frick 1973; Sharpe 1981 ; Cawthorn et al. 1981), including the outer satellite intrusions of the complex (Hall 1932; Coetzee and Kruger 1989); the Rashoop Granophyre Suite (Walraven 1985), and 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 Sequence, 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*.

The host rocks of the Bushveld Complex

The Transvaal Sequence 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 rests 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, is the Chuniespoort Group, which may reach a thickness of 2 km. This 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 3.3 km in the west and up to 7 km in the east. It is only preserved on the northern and western part of the Kaapvaal Craton and also thickens toward the north, 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 Sequence, is unconformably capped (Cheney and Twist 1991) by the bimodal Rooiberg Group volcanic rocks (*c*. 2,061 Ma Walraven et al. 1990), which immediately preceded the intrusion of the mafic suite at *c*. 2,054 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 (see Buchanan et al. 2002; Twist 1985; Twist and French 1983 for overviews); and is inferred to have covered a far larger area than where it is currently exposed (see Fig. 1).

The 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); intruded at the boundary between the Rooiberg Group,

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[1] The term '*Bushveld Complex*' is used for the mafic-layered rocks (in preference to Rustenburg Layered Suite—RLS—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).

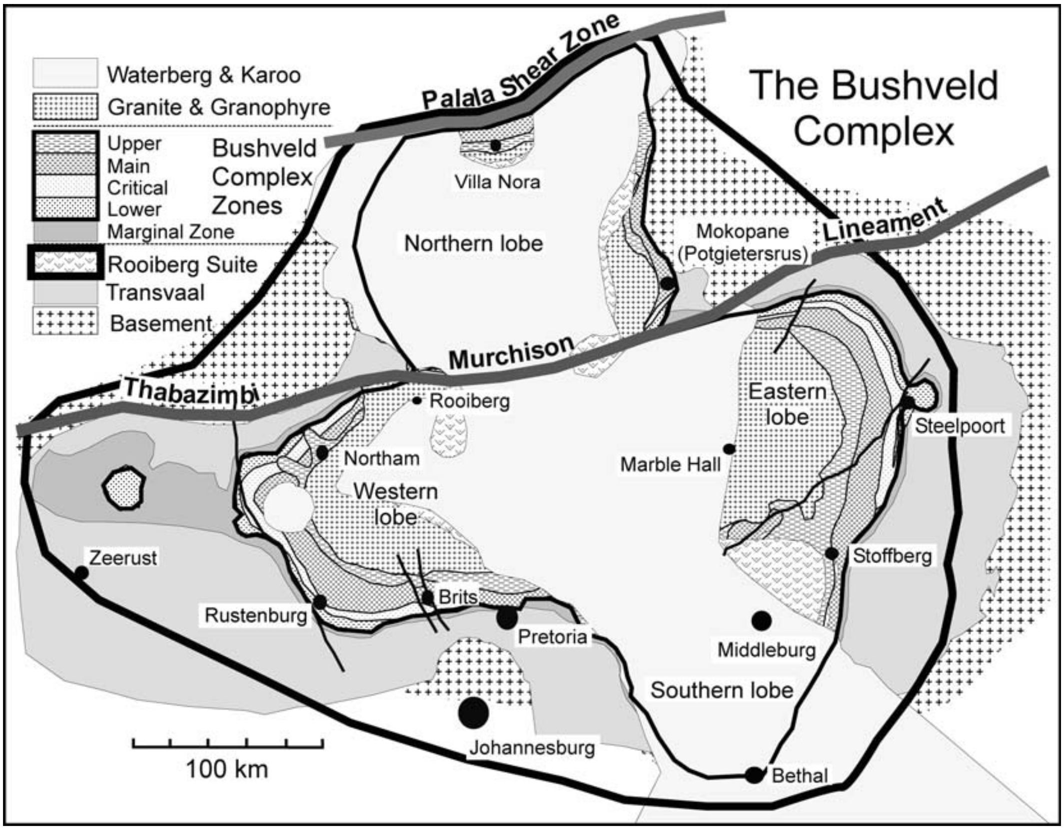

Fig. 1 Map of the Bushveld Complex showing the major subdivisions and the possible lateral extent of the Rooiberg volcanism

and the Transvaal Sequence 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].

First, the early investigations of Molengraaff, Daly, Merensky, Wagner and Hall (see Hall 1932 for an overview) noted a marked stratigraphic correlation between the Eastern and Western lobes and 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[3] near Potgietersrus (now Mokopane). To do this, he utilised the fact that the *hangingwall* stratigraphy of the Merensky Reef was consistent from east to west, and that the mineralisation was located near the base of the gabbronoritic Main Zone (MZ) succession. The more modern isotope stratigraphic data (Hamilton 1977; Kruger and Marsh 1982; Sharpe 1985; Kruger et al. 1987, 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. Second, Hall (*op. cit.*) also noted 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 MZ and Critical Zone (CZ) (e.g. Scoon 2002). Many geological interpretations, e.g. von Gruenewaldt (1979), assume interconnection of the Eastern and Western lobes at least from the MZ upward. Third, palaeomagnetic investigations (e.g. Gough and van Niekerk 1959) have shown 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

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[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' (Oxford English Dictionary) is therefore preferred to 'limb'. In this work, the different lobes are designated Eastern and Western which are in common use; Northern lobe for the Potgietersrust or Villa Nora extension, and Southern for the so-called Bethal lobe.

[3] The short and convenient term "Platreef" (sic) now in universal use for the Cu-Ni-PGE sulphide mineralised contact facies of the MZ in the Northern lobe, was introduced by van der Merwe (1976) as a replacement for the term "Platinum Horizon" used by Wagner (1929).

sequence cooled to less than the Curie temperature for magnetite (*c*. 570°C). 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. Fourth, 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 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, fifth, 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 1995; 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; McBirney 1996) models of the Skaergaard intrusion.

The 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 crystallised. 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 may have increased from <100 km wide during crystallisation 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, with 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 (see Reichhardt 1994), which is considered as one of the satellite intrusions of the Bushveld Complex (Coetzee and Kruger 1989), but alternatively, may have been contiguous. This westward extension may help to explain the "Cr-paradox"[4].

This model for the intrusion of the Bushveld Complex, contrasts with that of Cawthorn and Walraven (1998) who invoke 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 hence there is no field evidence to support magma evacuation. Therefore, the magmas were probably 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, lateral and vertical inflation would have significant transient and sustained effects on the floor and margins of the chamber, and the near solid cumulate pile. Up-warps may be eroded off or have thinner successions, and down-warps may accumulate a thicker succession. Very large up-warps may impinge the roof rocks, and form domes with off-lap and onlap relationships with respect to earlier cumulates—e.g. the

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[4] The "Cr-paradox" refers to the fact that the LZ and CZ contain a vast amount of Cr dissolved in orthopyroxene and chromite (including thick chromitite layers) with very little evidence for Cr depletion due to differentiation, and the residual magma in the chamber is thus inferred to be undepleted with respect to Cr. Therefore, to account for the quantity of Cr in the LZ and CZ stratigraphy, the residual volume of magma from which the Cr-rich lithologies crystallised is inferred to have been more than the thickness of the MZ and UZ combined. However, as shown in this work, and by Eales (2000), this Cr-rich residual magma is not present in the MZ and UZ stratigraphy and is inferred to have been swept out, or that the chromite came in with new magma as suspended grains which were deposited in layers (see Eales 2000). This paradox is not yet resolved.

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 mineralisation.

Major magmatic influxes, unconformities and mineralisation

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 mineralisation, and are bounded by significant unconformities or major petrological changes (see Kruger 1990, 1992, 1994). 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 Fig. 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 mineralisation. In brief, boundaries between major subdivisions (zones and sub-zones) 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 sub-zones. 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. For an overview of the "traditional" subdivisions, and where they differ from those used in this work, the reader is referred to Eales and Cawthorn (1996).

The major zones of the Bushveld Complex are: the "harzburgitic" LZ, which with the "orthopyroxenitic" LCZ form the ultramafic part of the intrusion; the "noritic" Upper Critical Zone (UCZ), the "gabbronoritic" MZ and the differentiated "ferro-gabbronoritic"

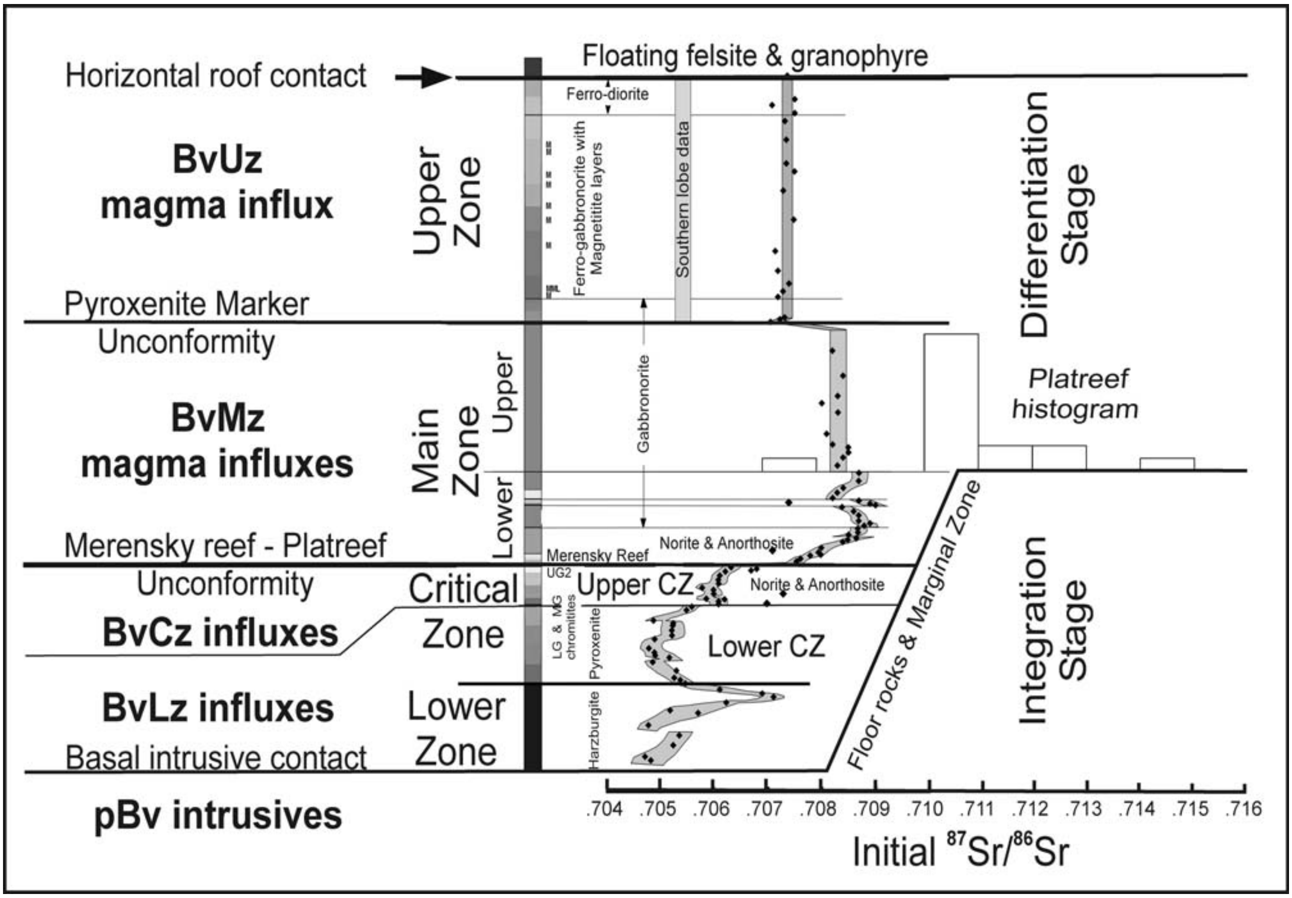

Fig. 2 Stratigraphic and isotope summary showing the mineralogical variation, isotope compositions and the location of major unconformities of the Bushveld Complex. The isotope profile is from Kruger (1994), the data for the histogram of Platreef rocks, and the data from the Southern lobe are reported in Tables 2 and 3

UZ, which build the mafic part of the intrusion. In the LCZ major chromitite layers are developed, of which the LG6 and MG1 are the 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 of which is the unconformity on which the famous Merensky reef is developed. In the Northern lobe, the Platreef (where the magma interacts directly with the S-rich floor-rocks) marks the base of the MZ (van der Merwe 1976). 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 a very highly layered sequence with gabbronorite, anorthosite, pyroxenite, olivine ferro-diorite and more than twenty Ti-V-magnetitite layers; the Main Magnetitite Layer, near the base, being 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 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 discordant relationships that are due to major inflation of the magma chamber and erosion of the cumulate pile, at those points.

Despite the overall 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 Steelpoort valley) are at an angular discordance to underlying UCZ and in close proximity to the up-warped floor-rocks. Also, in the area to the west of Lydenburg the UCZ onlaps the floor-rocks at the level of the UG2 chromitite, 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, *op. cit.*). Similarly, the Steelpoort fault (Cawthorn, personal communication), and the area around Grasvally (south of Mokopane) may be feeders to the LZ and LCZ.

During the *Integration Stage*, the process of magma addition is recorded in the changes of initial $^{87}Sr/^{86}Sr$ and mineralogy of the rocks (Kruger 1994), as well as erosional unconformities that are evident in the stratigraphy. As shown in Fig. 2, during this stage, the magmas changed from crystallising harzburgite in the LZ (initial $^{87}Sr/^{86}Sr \sim 0.705$) to orthopyroxenite in the LCZ, norite and anorthosite in the UCZ (initial $^{87}Sr/^{86}Sr \sim 0.7064$) and finally, norite and gabbronorite in the LMZ (initial $^{87}Sr/^{86}Sr \sim 0.7064$–$0.709$) (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, Fe-rich gabbro and pyroxenite layers in the UZ were deposited from an initially homogenous magma, and are not the result of multiple intrusion (Kruger et al., *op. cit.*).

Eales (2002) lists a number of possible parental magmas, and discusses 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 (*op. cit.*), a simplified scheme is introduced that relates the magma types directly to the stratigraphy (see Table 1): 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 cumulates of the LZ (Kruger 1994), and that of the BvUz magma is Davies and Cawthorn (1984) for the chemical composition, and this work (Southern lobe) for the isotope composition. The BvCz and BvMz magmas are not yet clearly defined, but are estimated based on the published data on marginal chills and layered sequence for both chemical and isotope parameters, bearing in mind the caveats of Eales (*op. cit.*). 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. These magmas are briefly summarised in Table 1.

The 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 2002 for an overview). However, in the case of the Marginal Zone beneath the LZ, the marginal rocks may represent 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 Maruleng Norite (Willemse 1959) now referred to as the Shelter Norite (SACS 1981) in the east; the Kolobeng Norite (ibid.) 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 400 m in the belt between

Table 1 Summary of the stratigraphy, major unconformable or petrological discontinuities, and the order of intrusion of the magmas that filled the Bushveld Complex

Order of influx	Magma	Zone	Where present	Mineral assemblage and associated mineralisation
5	BvUz	Upper Zone	All lobes and some satellite bodies	Ferrogabbronorite with Ti-V-magnetitite layers and is highly differentiated
Pyroxenite Marker level unconformity. Base of the Upper Zone				
4	BvMz	Main Zone	Eastern, Western and Northern lobes	Gabbronorite. LMZ is layered with some pyroxenite and anorthosite layers, and represents the crystallisation products of a progressive mixture of residual BvCz and intruding BvMz magmas. UMZ is a differentiation sequence
Merensky Reef and Platreef. Base of the MZ				
3	BvCz	Upper Critical Zone	Eastern and Western lobes	Dominantly norite with pyroxenite and anorthosite layers. MG3& 4 and UG1, 2& 3 chromitite layers
First appearance of cumulate plagioclase (anorthosite layer above MG2 chromitite)				
2	BvLz	Lower Zone& Lower Critical Zone	Eastern, Western and Far Western lobes	Harzburgite and orthopyroxenite which is feldspatic in the LCZ. Cr-rich and has up to 9 chromitite layers in LCZ
1	pBv	Marginal Zone	South of TML. Thickest beneath the LZ	Norite. Up to 400m thick but predates the Lower Zone. May be related to the LZ and LCZ

Burgersfort and Zeerust. The sill-like intrusions may extend as far south as Bethal, as Buchanan (1975) reports high Mg# Marginal Zone rocks in this area, and Coetzee and Kruger (1989) show 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.

The 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 crystallised 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 crystallisation 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 (900–1,000 ppm), high SiO_2($\sim$ 55%), high MgO ($\sim$12.5%) with a relatively primitive Mg# ($>$0.70) (see Davies et al. 1980). In addition, magmas also have relatively low initial $^{87}Sr/^{86}Sr$ ($\sim$0.7050) and a low initial $^{187}Os/^{188}Os$ ($\sim$0.122), which is slightly higher than contemporary mantle (see Kruger 1994, Schoenberg et al. 1999).

As shown in Fig. 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 $>$1,600 m and is described in detail by Hulbert and von Gruenewaldt (1982, 1985) and von Gruenewaldt et al. (1989). This part of the LZ stratigraphy is also unusual in that there is significant crystallisation of chromite of a very high quality $Cr_2O_3 > 55\%$,, and cyclic units also contain olivine with a very high Mg content ($>Fo_{90}$) and may therefore represent the earliest most primitive part of the LZ. Detailed descriptions of the stratigraphy elsewhere, are available from Cameron (1978, 1980) in the northern part of the Eastern lobe; 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 intrusive tongues north of the TML (e.g. Uitloop; van der Merwe 1976, 1978), the thickest development being close to the TML south of Mokopane as discussed above. This implies that the Marginal zone and part of the LZ initially had a large lateral extent and may have intruded in a position close to a feeder zone in the TML, which fed magma both to the north and to the south prior to significant development of the half-graben to the south. 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 (up to 9 km) of the Bushveld Complex is immediately south of the TML axis.

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 emphasised 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).

Mineralisation

There are two significant chromitite layers in the thick Grasvally succession south of Mokopane (see Hulbert

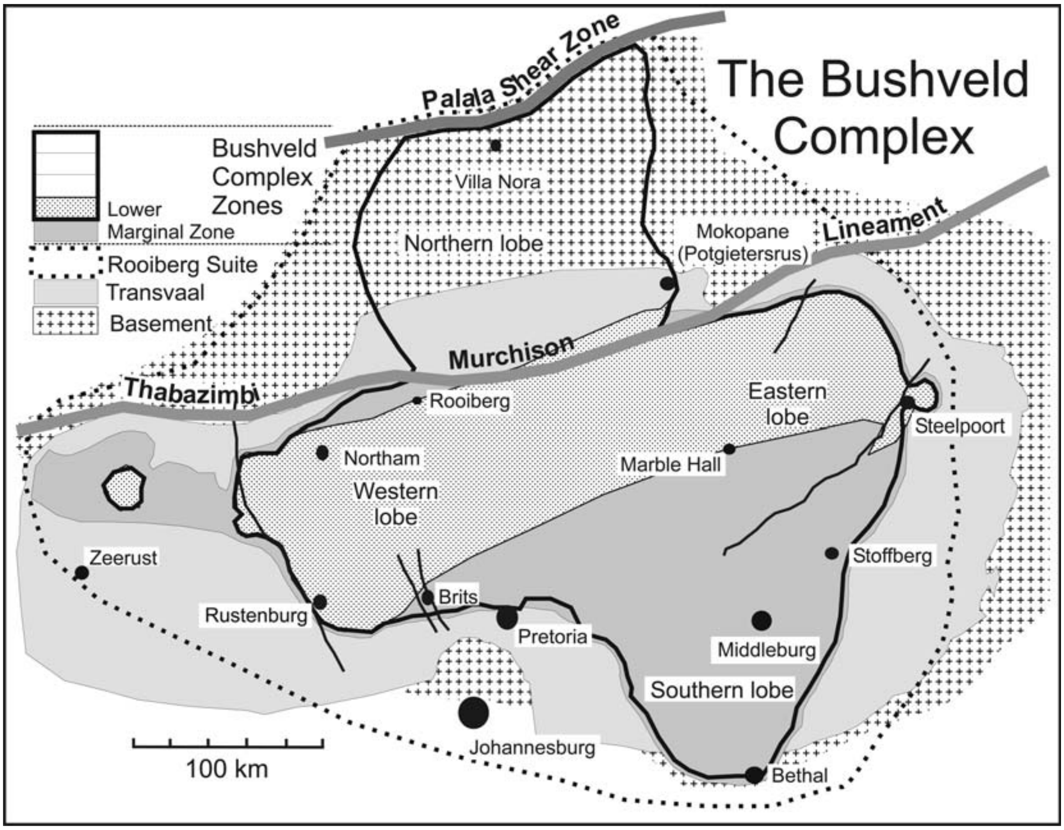

Fig. 3 The lateral extent of the Lower and Lower Critical Zones derived dominantly from the BvLz magma

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 mineralisation (the Volspruit subzone sulphide mineralisation). No other significant mineralisation 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 wall and roof-rock interactions such as those invoked by Kinnaird et al. (2002), may account for the mineralisation.

In the LCZ, there are up to nine chromitite layers (LG1-LG7 and the MG1-MG2) two of which (the LG6 and the MG1) are sufficiently 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 1985). As indicated by Scoon and Teigler (1994) the chromitite layers of the LCZ are of a high quality as a Cr resource but are poor 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) mineralisation 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 deposit could form.

The Upper Critical Zone: *BvCz* magma parental to the PGE-rich chromite layers

The UCZ has chromitite, feldspathic orthopyroxenite, norite and anorthosite layers with some olivine-bearing layers. 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). The stratigraphy is, however, dominated by norite with anorthosite layers that form "cyclic units"; the most complete of which, 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

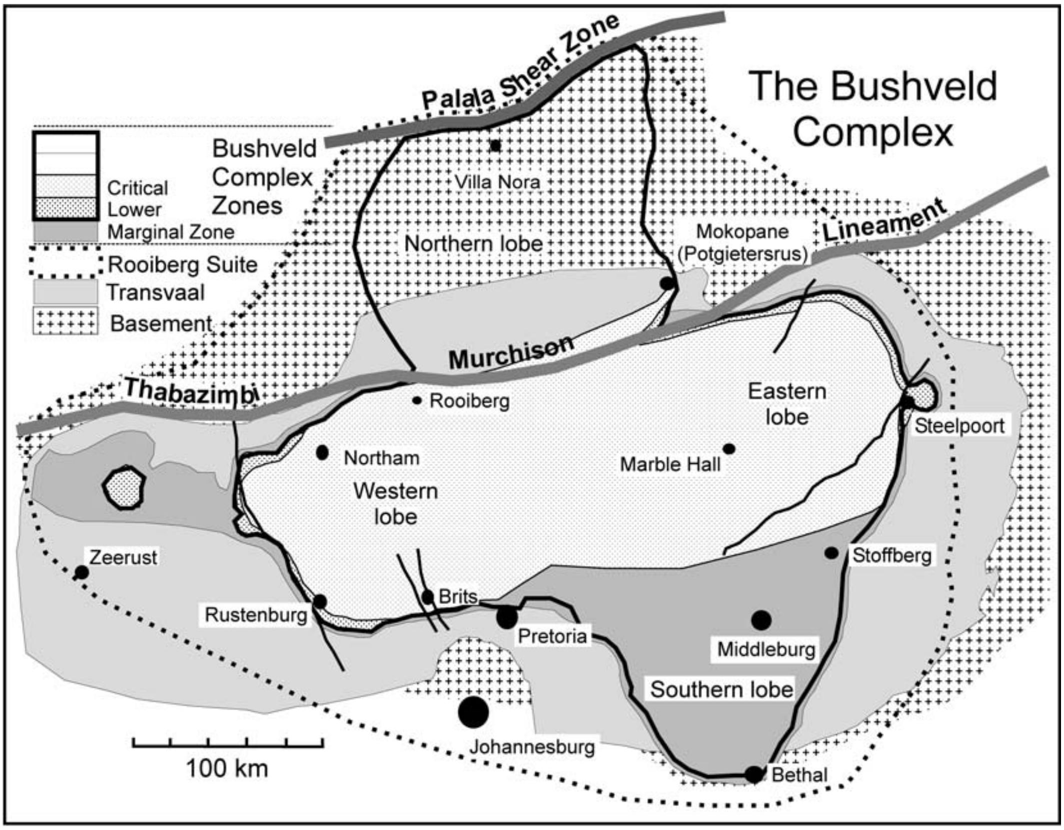

Fig. 4 The lateral extent of the Upper Critical Zone derived dominantly from the BvCz magma

at the famous Dwars River locality, is one of the most spectacular in the Bushveld Complex (see Nex 2002, 2004) for an overview and new interpretation of the UG1 phenomenon).

The BvCz magma has a noritic lineage and in common with the BvLz magma, a high Cr-content (*c.* 600 ppm), but has a basaltic chemistry: $SiO_2 \sim 50\%$, $Al_2O_3 \sim 16\%$, $MgO \sim 7.5\%$ and 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. These characteristics are culled from the works of Scoon and Teigler (1994), Harmer and Sharpe (1985), Sharpe (1985), Eales (2000; 2002), Eales et al. (1986, 1990), Schoenberg et al. (1999) and others.

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, 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. Furthermore, there are significant differences in the thickness of UCZ in the different parts of the Bushveld Complex between the UG2 and the base of the MZ. This varies between 20 and 40 m depending on potholes in the Western lobe near Northam, to over 350 m in parts of the Eastern lobe close to the main axis of deposition parallel to the TML. This tenfold difference implies that there was differential subsidence along the half graben.

In the Northern lobe, there is a chromite-bearing noritic sequence to the south of Mokopane, unconformably covered by the Platreef and MZ, which van der Merwe (1976) assigns to the UCZ. Thus, if this is true, UCZ and not a possible pBv norite, it confirms the order of intrusion and crystallisation in the Northern lobe. Furthermore, in this position, the Platreef is the same relationship to the CZ as the Merensky reef, and supports correlation of the Merensky Reef with the Platreef.

Mineralisation

The UCZ chromitite layers, as a whole (MG3 and MG4 and the UG1 and 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 mineralised 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 part of the Eastern lobe and thins toward the south (with the progressive loss of lower units—onlap relationship); it also thins toward the west (with progressive thinning of individual units).

The 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 (*op. cit.*) further divided the MZ into two sub-zones: 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 layers in the well-known 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, 1978) indicates that there is no significant CZ exposed, except a sliver of chromite-bearing pyroxenite and norite south of Mokopane tentatively correlated with the UCZ, and the Platreef rocks directly overly these. The Platreef is the marginal facies of the MZ, which is the basal zone in the Northern lobe. The internal stratigraphy of the MZ in the Northern lobe is not as yet well-established, and the data of van der Merwe (1978) show that it is quite strongly layered and differentiated. It is here tentatively correlated with the UMZ south of the TML as there are no layers that can be directly correlated with the LMZ, and the isotope composition is similar to that of the UMZ. A pyroxenite layer, possibly equivalent to the Pyroxenite marker, is present within the Northern lobe succession (Ashwal et al. 2005; van der Merwe 1976) but its exact relationship is uncertain and the position of the MZ–UZ boundary in this lobe is thus not certain and requires further work. Furthermore, these authors identify a magnesian olivine-bearing troctolite layer within the Northern lobe succession that is of uncertain provenance and could also be a lateral equivalent of the Pyroxenite marker (Kruger 2005). If this is the case, as suggested by Kruger (op. cit.), then a major intrusive centre is indicated for the UZ in the southern part of the Northern lobe.

Thus, the only certainty is that MZ rocks are in contact with the Platreef and magnetite-bearing UZ rocks occur near the roof of the succession. The contact is not yet clearly defined but on most maps is placed at the first appearance of magnetite, a position that gives a distorted view of the magmatic relationships. Furthermore, the detailed mapping of van der Merwe (1978) shows large scale cross-cutting relationship between the magnetitite-bearing UZ and the underlying MZ north of 24° 30′S reminiscent of the “gap” areas near Northam in the Western lobe.

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 by 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 $^{87}Sr/^{86}Sr \sim 0.7084$ 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

Based on fundamental geological criteria, the CZ–MZ boundary is placed at the base of the Merensky Cyclic

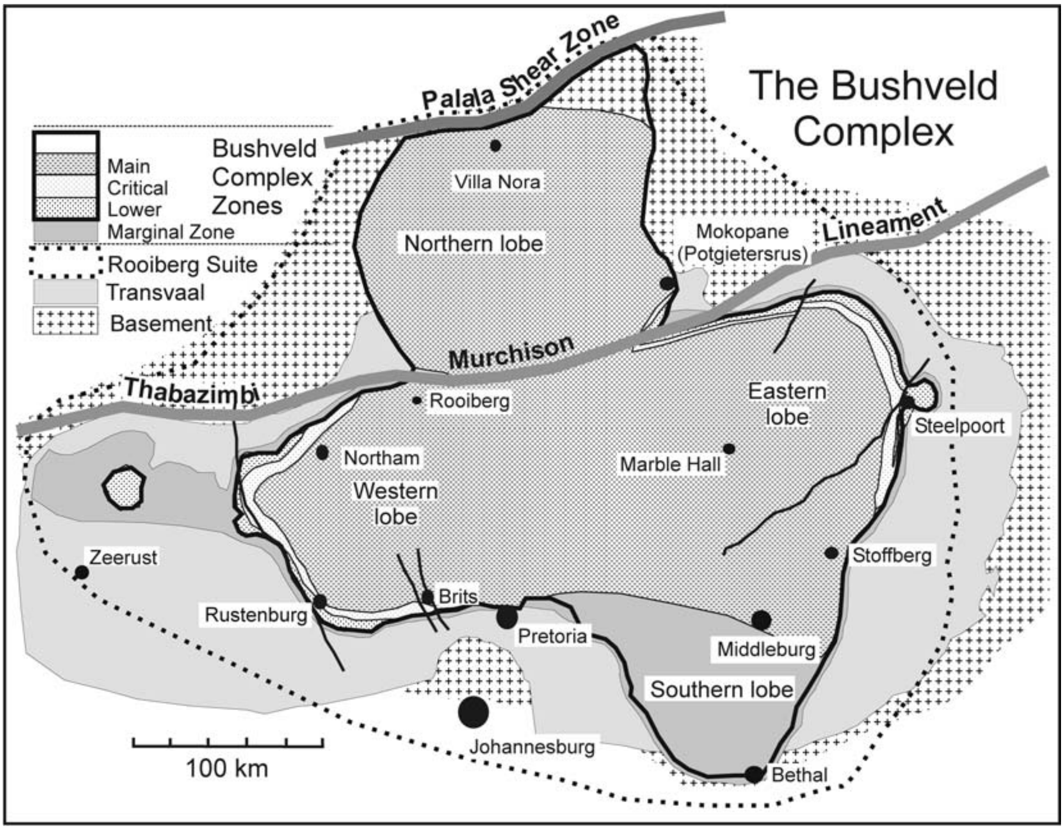

Fig. 5 The lateral extent of the Main Zone derived dominantly from the BvMz magma

Unit (Kruger 1990). 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; Seabrook et al, 2005). The Merensky Reef is therefore the product of the interaction of residual BvCz magma in the chamber and the new influx of BvMz magma.

The lower part of the succession straddling the UCZ–LMZ boundary 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), Cawthorn (1996) 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 are: firstly, is this new magma of the same lineage as that added to the UCZ, and became dominant at the Merensky Reef (e.g. Eales 2002), or, is it an entirely different magma, and secondly, is the magma that interacted with the floor-rocks to form the Platreef the same as that which formed the Merensky reef? This author believes 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), unmixed, chilled versions have not been directly characterised, and its properties are only indirectly inferred (e.g. Kruger 1992; Cawthorn 1996).

Furthermore, this view is in sharp contrast to the views of Maier and Barnes (1999) and Barnes and Maier (2002) who attribute all the compositional variation in the CZ and MZ of the Bushveld Complex to only two magmas (essentially the A and U magmas of Irvine and Sharpe 1982, 1986). They group the Merensky and Bastard units together with other units in the CZ and LMZ; and attribute the lithophile element characteristics of the Merensky Reef to a mixture of "the two parental magmas of the Bushveld Complex (a high-Mg basaltic andesite and a tholeiitic basalt)". The magma dominant in the MZ is thus assumed to be similar to the rocks sampled by Harmer and Sharpe (1985) in the Eastern lobe (their B2/B3 magmas). Unequivocal evidence for a marked change in the composition of the intruding magma at the Merensky Reef, in contrast to the other units in the CZ (described by e.g. Kruger and Marsh 1985; Kruger 1992, Cawthorn 1996 and reviewed below) was ignored by them.

Nevertheless, a number of features of the new BvMz can be derived from the study of the CZ-MZ interaction. These indicate that the magma was more Fe- and Na-rich and Cr-poor than any CZ magma; is of a gabbronoritic and not noritic lineage; had a lower Sr-content and very much higher $^{87}Sr/^{86}Sr$ ratio (>0.710) than that added to the CZ (see Kruger and Marsh 1982, 1985; Kruger 1992, 1994). The PGE chemistry has to some extent been characterised by Davies and Tredoux (1985) and Maier and Barnes (1999) who showed that the $(Pt+Pd)/(Os+Ir+Ru)$ of the MZ rocks (~100) is much greater than the rocks below the Merensky reef (~1–20). Therefore, (excluding pBv) BvMz is taken to be the third magma type to intrude the complex and is not represented in the CZ (*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.

In the Northern lobe of the Bushveld Complex, the lower part of the succession comprises MZ rocks and detailed mapping by van der Merwe (1976, 1978) shows that the Platreef is related to the MZ and cross-cuts inferred CZ and LZ rocks which it intrudes or stratigraphically overlies. Furthermore, all the available Sr-isotope data strongly suggest that the magma parental to the Platreef is also of a MZ lineage. Barton et al. (1986) showed that the MZ is the hangingwall contact of the Platreef, and their model invokes “Merensky” magma as parental to the Platreef. The average $^{87}Sr/^{86}Sr$ of the MZ in the Northern lobe is 0.7086 ± 15 (1σ on 17 samples) (data from Barton et al. *op. cit*.; Kruger and Kinnaird (unpublished)). However, data from the Western and Eastern lobes (Kruger 1994; Sharpe 1985) indicate ratios up to 0.7091 in the upper part of the LMZ (see Fig. 2). Thus, the magmas added to these lobes and that mixed with the residual CZ magma had a ratio in excess of 0.709. The rocks of the Platreef itself, in general have, high $^{87}Sr/^{86}Sr$ usually in excess of 0.710 at Overysel and Sandsloot north of Mokopane (Barton et al. op. cit.), interpreted by them as resulting from infiltration of a contaminant. However, new $^{87}Sr/^{86}Sr$ data from the Platreef near Mokopane (Turfspruit) (Table 2) and plotted as a histogram in Fig. 2 indicate that there is a strong tendency for fine-and coarse-grained noritic rocks that have little indications of contamination to cluster around 0.710–0.711. Others have significantly higher ratios that could be attributed to contamination are the very high ratios (>0.711) reported by Barton et al. (*op. cit*.). These rocks are interpreted here as being representative of the first influxes of BvMz magma into the chamber, that in places were chilled onto floor-rocks and xenoliths which locked the isotope character in high Sr, plagioclase rich, noritic rocks. The large volume of overlying MZ magma that had mixed with some residual CZ magma (resulting $^{87}Sr/^{86}Sr \sim 0.7086$), later reheated the whole package. These observations indicate that the new BvMz magma had an $^{87}Sr/^{86}Sr$ of between 0.7091 and 0.711. If this interpretation is correct, it implies that the new magma which intruded did so first in the Northern lobe, but that a link with the rest of the magma chamber occurred very early in the evolution of the MZ. However, given the differences between the MZ stratigraphy north and south of the TML, and the dearth of isotope data on the

Table 2 Sr-isotopic data for rocks from the Platreef

Sample Number	Mineral	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2se$	$^{87}Sr/^{86}Sr_{2055} \pm 2\sigma$
ATS46/203.7	Plag	2.52	301.5	0.02408	0.711188 ± 20	0.71048 ± 15
ATS46/203.7	Opx	1.14	65.49	0.05000	0.712041 ± 26	0.71056 ± 16
ATS46/206.45	Plag	2.47	330.2	0.02156	0.711282 ± 20	0.71064 ± 15
ATS46/206.45	Opx	0.85	3.04	0.80780	0.734637 ± 33	0.71072 ± 39
ATS46/208.52a	Plag	3.68	251.6	0.04220	0.711873 ± 32	0.71062 ± 15
ATS46/208.52b	Plag	4.33	258.2	0.04835	0.711986 ± 28	0.71055 ± 16
ATS46/210.62	Plag	1.33	254.7	0.01507	0.711038 ± 30	0.71059 ± 15
ATS46/213.21	Plag	6.04	304.3	0.05716	0.712278 ± 28	0.71059 ± 16
ATS46/216.0	Plag	7.12	342.1	0.06000	0.713902 ± 18	0.71213 ± 16
ATS46/217.4	Plag	8.45	351.5	0.06928	0.716639 ± 16	0.71459 ± 16
ATS46/222.3	Plag	6.12	338.1	0.05219	0.712965 ± 33	0.71142 ± 16
ATS46/222.3	Opx	0.46	3.09	0.42819	0.723507 ± 66	0.71083 ± 27
ATS46/226.3	Plag	14.09	274.9	0.14776	0.717352 ± 24	0.71298 ± 19
ATS46/230.2	Plag	2.90	364.0	0.02295	0.711810 ± 24	0.71113 ± 15
ATS46/230.2	Opx	0.15	9.38	0.04558	0.711810 ± 24	0.71046 ± 16
ATS46/235.8	Plag	13.06	373.4	0.10082	0.713488 ± 39	0.71050 ± 17
ATS46/253.6	Plag	76.35	255.0	0.86451	0.732826 ± 26	0.70723 ± 40

Samples from Turfspruit BH (ATS46) courtesy of African Minerals Ltd. Analysed by N. Matsietsi under direction of F.J. Kruger in the Hugh Allsopp Laboratory. Blanks Rb < 100 pg and Sr < 1 ng. The Eimer & Amend Sr standard gave 0.7080 during this work. Sample numbers relate to depth in the borehole. The samples are mainly norites chosen to maximise the Sr-content and minimise the influence of infiltration effects and bulk contamination

In the table above, 2se refers to 2 standard errors and is a within-run statistic on the measured natural $^{87}Sr/^{86}Sr$ of the individual sample. The 2σ (2 SD) statistic on the initial ratio takes into account replication of the natural ratio on duplicates as well as the error associated with 2,055 Ma back calculation and the c. 0.5% (1σ) error on the measured $^{87}Rb/^{86}Sr$

Northern lobe which makes stratigraphic correlation exceedingly difficult, these inferences remain somewhat speculative and await more detailed field, petrological and isotope data.

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, 2005). 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. *op. cit*).

Mineralisation

There are two major PGE-Cu-Ni ore deposits associated with the intrusion of the MZ: the Merensky Reef and 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 CZ 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 that is sometimes composite and normally including one or more thin seams of chromite with disseminated pyrrhotite, pentlandite chalcopyrite and accessory chromite and invariably contains between 3 and 8 g/ton PGE over the mining width (Lee 1996; Vermaak and Hendricks 1976; Vermaak 1976). This pyroxenite layer may vary in thickness from 10 cm to 7.5 m in different localities around the Bushveld Complex. A sequence consisting of norite, spotted anorthosite and finally mottled anorthosite overlies the pyroxenite layer. In the Western lobe, PGE values may be concentrated in a pegmatitic phase occurring at the base of the pyroxenite band, although this is not a ubiquitous feature. 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.

This whole sequence is again overlain by a very similar succession whose basal pyroxenite layer forms the Bastard Pyroxenite. Although a thin chromite band is often developed at the base, PGE values are normally very low (<3 ppm) in the Bastard Reef.

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 (see Table 2) 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 magma and the country rocks, which now form major detached and attached rafts of a diverse hornfels suite within the Platreef package. For example, the dolomite finger or tongue oriented orthogonal to the rest of the rocks at Sandsloot mine, north of Mokopane may represent an extreme version of this phenomenon, but this is not certain as yet. It also resulted in significant contamination by S, H_2O and CO_2 that with localised fractional crystallisation, 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 fluid/rock and magma/country rock interactions of the MZ magma are examined in detail from a δ^{18} O perspective by Harris and Chaumba (2001). They conclude that up to 18% carbonate assimilation occurred in the Platreef itself, but that the MZ magma parental to the Platreef was also already anomalous with very high δ^{18} O $\sim 7.5‰$, and that this assimilation did not severely affect the Sr-isotope character. The complex nature of this ore deposit was recognised very early on, and the above description is not significantly different from that of Wagner (1929) and Hall (1932), and more recently by van der Merwe (1976), Gain and Mostert (1982), Cawthorn et al. (1985) and Armitage et al. (2002). 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.

A simple mass balance calculation indicates that to form one unit of Platreef (*c.* 2 g/ton PGE) approximately 50–100 units of the MZ (BvMz) magma (*c.* 20 ppb PGE) needs to be processed (Cawthorn et al. 2002). The relative proportion of magma processed to reef produced is similar to that inferred by De Wit and Kruger (1990) for the Merensky reef. This could only occur if a significant "through flow" of new magma through the network of channels and xenoliths from which the sulphur was derived could be achieved. This is a “zone refining” type process (not batch equilibration) and is analogous to the model for Norilsk (Naldrett 2004). The processes that led to the formation of the Platreef inferred here, are speculative and need further research.

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 acquired got its PGE and sulphide from this new MZ magma, which had interacted with sediments, but not lost the entrained sulphide (and PGE) until it was deposited as the Merensky Reef. This is supported (but not unequivocally so) 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 a 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 inferred to be consanguineous, with respect to their mineralisation 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 BvUz magma.

The 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 mineralisation (Wilhelm et al. 1997). This is followed by a highly differentiated sequence of norite, gabbronorite, ferro-gabbronorite and ferrodiorite; interlayered with numerous anorthosite,, titaniferous magnetite and apatite-rich layers (Molyneux 1974; Cawthorn and Molyneux 1986) that is *c.* 2 km thick. Sr-isotopic data (Kruger et al. 1987) indicates that the UZ is a single magmatic series that crystallised 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. (op. cit.) indicate 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.* 60% 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 and most laterally extensive attained in the Bushveld Complex, and represent exceedingly large volumes of magma.

The UZ is the most laterally extensive of the Bushveld Complex and it is present in four of the five lobes (Fig. 6). It formed a single sheet, *c.* 2 km thick that extended laterally from the main east-west chamber, over the MZ in the Northern lobe where it onlaps the floor close to the *Palala Shear Zone*, that 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.

The southern limb of the intrusion is crystallised 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 Table 3). Buchanan (*op. cit*) also notes 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 Fig. 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

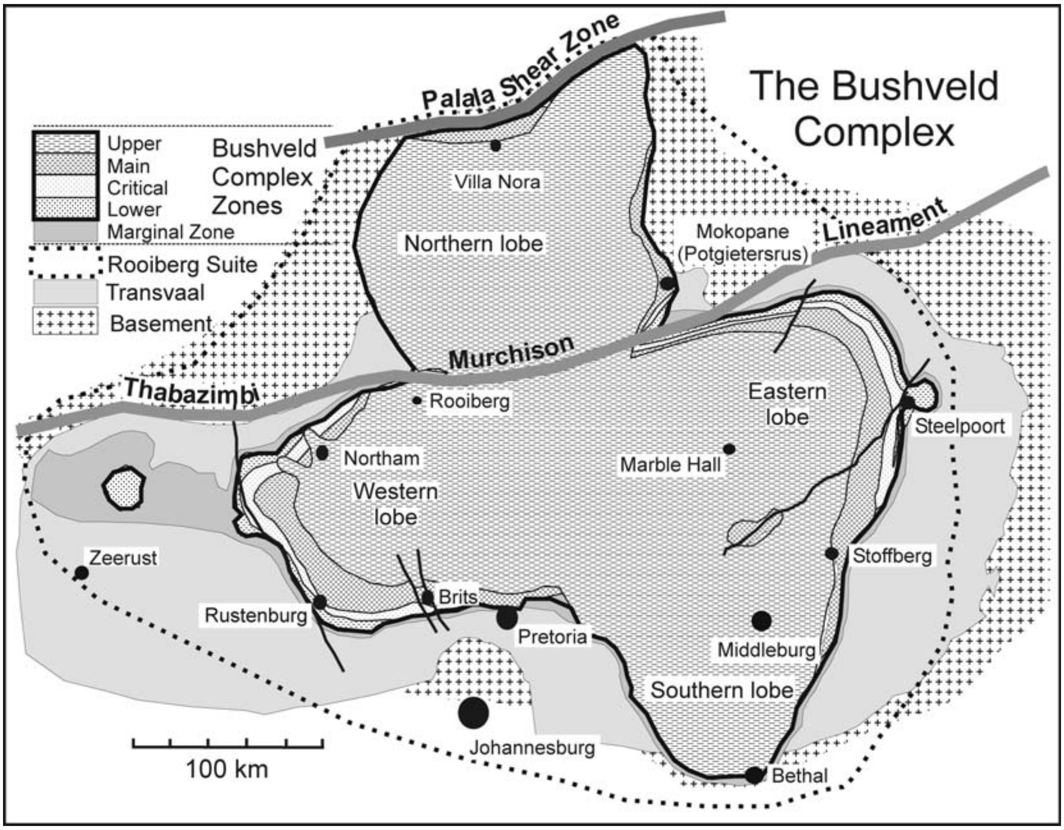

Fig. 6 The lateral extent of the Upper Zone derived dominantly from the BvUz magma

Table 3 Sr-isotopic data for rocks from the Southern lobe

Sample Number	Depth (m)	Rb ppm	Sr ppm	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr ± 2se	^{87}Sr/^{86}Sr$_{2060}$ ± 2σ
KLG1/1769	539.2	1.82	676	0.0078	0.705629 ± 30	0.70540 ± 13
KLG2/2428	740.1	9.92	190	0.1513	0.710284 ± 34	0.70581 ± 17
KLG2/3221	981.8	1.81	904	0.0058	0.705843 ± 33	0.70567 ± 13
KLG2/3399	1036	2.59	610	0.0123	0.705878 ± 34	0.70551 ± 13
KLG2/3399r	1036	2.58	610	0.0123	0.705933 ± 27	0.70557 ± 13
UC361/537	163.7	2.31	303	0.0221	0.706065 ± 23	0.70541 ± 13
UC361/1350	411.5	11.3	464.5	0.0705	0.707224 ± 25	0.70514 ± 15
Mean ratio						0.70550

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.
In the table above, 2se refers to 2 standard errors and is a within-run statistic on the measured natural ^{87}Sr/^{86}Sr of the individual sample. The 2σ (2 SD) statistic on the initial ratio takes into account replication of the natural ratio on duplicates as well as the error associated with 2,055 Ma back calculation and the c. 0.5% (1σ) error on the measured ^{87}Rb/^{86}Sr

1932). These satellite intrusions are inferred here to have been 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.

The 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 (*op. cit.*) interprets 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; and furthermore, there are a number of breaks and reversals often coincident with unconformable relationships. These breaks and reversals are vital to understanding of the Bushveld Complex and are also often coincident with mineralisation.

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 as follows: (a) pre-Bushveld Complex (pBv) sills and intrusions of a noritic character and a low $^{87}Sr/^{86}Sr$ of *c.* 0.7050; (b) BvLz, a siliceous picrite magma (SiO2 $\sim$ 55% MgO $\sim$ 12%), with olivine and orthopyroxene $(>\mathrm{En}_{83})$ 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. (c) The third magma (BvCz) to intrude dominated the UCZ and is of a noritic lineage, with a high Cr and Sr

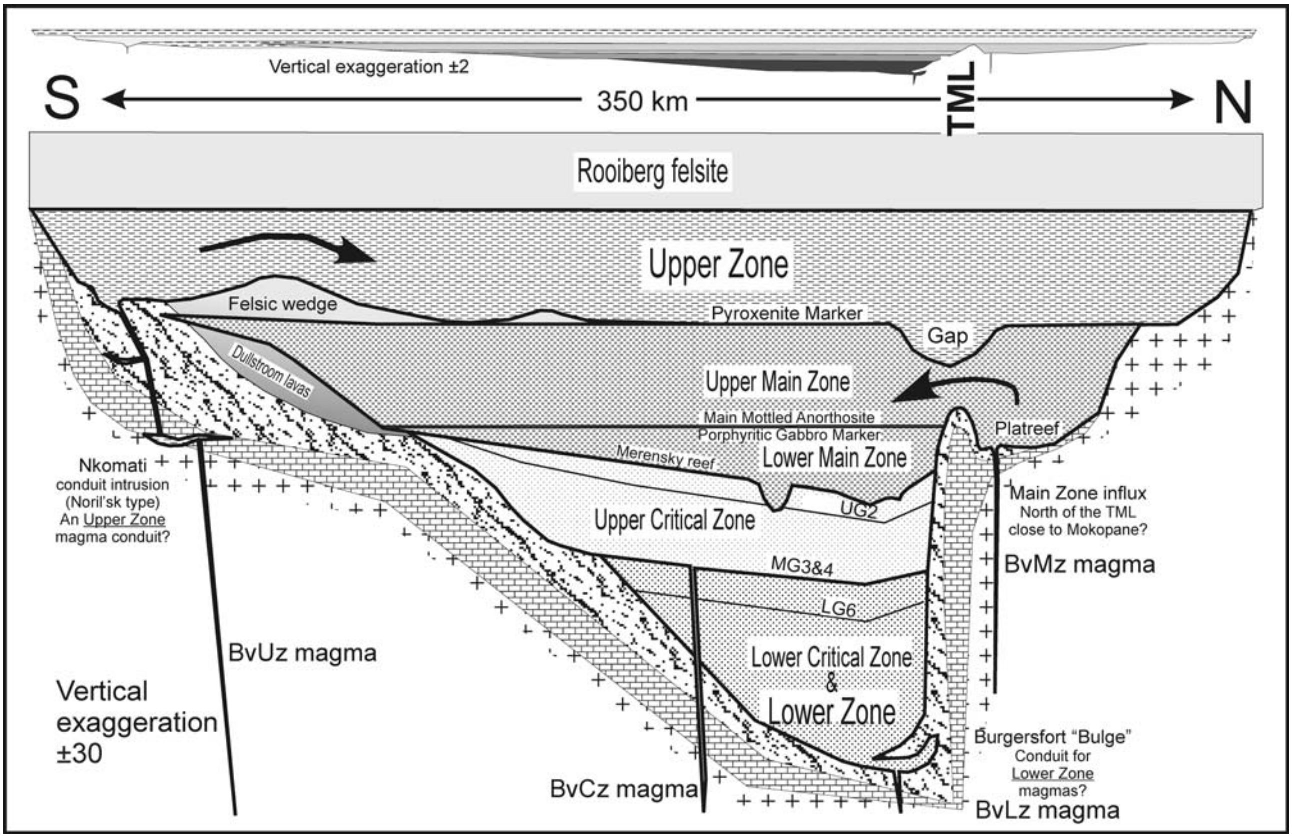

Fig. 7 Schematic N–S cross-section showing the extent of the zones and their direction of influx and possible feeder locations

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). (d) 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.* 0.711) 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 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, for a chilled version that can be clearly shown not to have suffered local contamination.

Finally, the extensive UZ was produced by an influx of magma (BvUz) from the Southern lobe of the Bushveld Complex, and possibly from feeders within the Eastern and Western lobes. BvUz was S-saturated, Fe-rich, had an $^{87}Sr/^{86}Sr$ close to 0.7055, and can be characterised as a ferro-gabbronorite lineage. Again, this magma is probably not represented in the eastern Bushveld sill phase and is therefore elusive, but Davies and Cawthorn (1984) report 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 and west, including feeder zones close to the TML. 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. Insofar as the pipe-like ultramafic intrusions (IRUPS of Scoon and Mitchell 1994) are also iron-rich and have UZ isotopic character, these could also represent conduits for UZ magmas, at least in the case of very large bodies (see also Cawthorn et al. 2000).

Conclusion

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 Critical Zone was terminated, and the Main Zone initiated by intrusion of BvMz magma from immediately north of the TML where BvMz overwhelmingly dominates the Platreef and the overlying Main Zone. In contrast, the BvUz magmas that initiated the Upper Zone had much more widespread centres of intrusion aside from the TML, and may have intruded from as far south as Bethal, Losberg, Kaffirskraal and Vredefort, and flowed northward under the Rooiberg carapace.

The mineralisation 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 Mineralisation* 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, but flow-through was limited.

The *stratabound mineralisation* (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 mineralisation 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 mineralisation 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 mineralisation (chromitites and Merensky reef) (Kruger 1999, 1992; Kinnaird et al. 2002).

3. Tertiary, sub-liquidus 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).
4. Finally, 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 serves to redistribute metals locally, and in some cases obscure 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 with respect to the mineralisation are related to arguments as to the relative importance and lateral and vertical extent of the four processes outlined above, in creating the PGE and chromitite ore deposits of the Bushveld Complex. The main geological disputes relate to the number, nature and volume of the different magma types, and the boundaries, lateral and vertical extent of the stratigraphic units that crystallised from them. As shown here, these two controversial aspects are intimately related, and cannot be understood in isolation.

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References

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

Barnes S-J, Maier WD (2002) Platinum-group element distributions in the Rustenburg layered suite of the Bushveld Complex, South Africa. In: Cabri LJ (ed) The geology geochemistry mineralogy and mineral beneficiation of the platinum-group elements. Canad Inst Min Metall Petro CIM Sp 54:431–458

Ashwal LD, Webb SJ, Knoper MW (2005) Magmatic stratigraphy of the Bushveld Northern Lobe: continuous geophysical and mineralogical data from the 2950 m Bellevue drillcore. S Afr J Geol 108:199–232

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

Boudreau AE, 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 (1996) Re-evaluation of magma compositions and processes in the uppermost Critical Zone of the Bushveld Complex. Mineral Mag 60:131–148

Cawthorn RG, Davies G (1983) Experimental data at 3 k bars 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: Anhausser CR, Maske S (eds) Mineral deposits of southern Africa, Vol II, pp 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, Harris C, Kruger FJ (2000) Discordant ultramafic pegmatoidal pipes in the Bushveld Complex. Contrib Mineral Petrol 140:119–133

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

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. (8th 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

De Wit MJ, Kruger FJ (1990) The Economic potential of the Dufek Complex. In: Splettstoesser JR, Dreschhoff GAM (eds) Mineral Resources of Antarctica. Am Geophysi Union Antarctic Res Ser 51:33–52

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

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, Cawthorn RG (1996) The Bushveld Complex. In: Cawthorn RG (ed) Layered Intrusions, Developments in Petrology. Elsevier, Amsterdam, vol. 15, pp 181–229

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 mineralisation 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 vol 28, 560 pp

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

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

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: Prendergast MD, Jones MJ (eds) Magmatic Sulphides: the Zimbabwe Volume. Trans Inst Min Metall Lond, pp 87–89

Hatton CJ (1995) Mantle plume origin for the Bushveld and Ventersdorp provinces. J Afr Earth Sci 21:571–577

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: Crawford AJ (ed) Boninites and Related Rocks. Unwin Hyman, London, pp 1–49

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 mineralisation in the Lower Zone of the Bushveld Complex, south of Potgietersrus. Econ Geol 77:1296–1306

Hulbert LJ, von Gruenewaldt G (1985) Textural and compositional features of chromite in the Lower and Critical zones of the Bushveld Complex south of Potgietersrus. Econ Geol 80:897–895

Irvine TN, Sharpe MR (1982) Source-rock compositions and depths of origin of Bushveld and Stillwater magmas. Carnegie Inst Wash Ybk 81:294–303

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

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 mineralisation 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–B208

Kleywegt RJ, du Plessis A (1986) On the structure of the Bushveld Complex and the central Transvaal basin. Geocongress 86: 603–607 (Extended Abstracts ISBN 0-0620-09820-1)

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". In: Mitchell AA, Scoon RN 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. In: Stanley et al (eds) Mineral Deposits: Processes to Processing. Balkema, Rotterdam, pp 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–B209

Kruger FJ (2005) The main zone of the Bushveld Complex: source of the Merensky Reef and the Platreef. In: 10th Intl Pt Symp, Oulu, August 2005 Ext. Abst pp 3

Kruger FJ, Behr S (2002) The Henderson Reef in the Dennilton Dome and mineral range areas—A Homologue of the Platreef. In: 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 mineralisation in the Bushveld Complex and some other layered intrusions. In: Cawthorn RG (ed) Layered Intrusions. Elsevier, Amsterdam, pp 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, Barnes S-J (1999) Platinum-group elements in silicate rocks of the lower, critical and main zones at Union section, western Bushveld Complex. J Pet 10:1647–1671

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 (1996) The Skaergaard Intrusion. In: Cawthorn RG (ed) layered intrusions, developments in petrology. Elsevier, Amsterdam, vol. 15 pp 147–180

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" In: Kruger FJ (ed) 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 (2004) Magmatic sulfide deposits: geology, geochemistry and exploration. Springer, Berlin Heidelberg New York, 728pp

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 101:215–223

Nex PAM (2004) Formation of bifurcating chromitite layers of the UG1 in the Bushveld Igneous Complex, an analogy with sand volcanoes. J Geol Soc Lond 161:903–909

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

Reichhardt FJ (1994) The Molopo Farms Complex, Botswana: history, stratigraphy, petrography, petrochemistry and Ni–Cu–PGE mineralisation. Expl Min Geol 3:263–284

SACS (1981) South African committee for stratigraphy. Stratigraphy of South Africa. In: Kent compiler LE (ed) 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: Wilson MGC, Anhaeusser CR (eds) Mineral Resources of South Africa, 6th edn. Council Geoscience, Hbk vol. 16, pp 90–105

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, Mitchell AA (1994) Discordant iron-rich ultramafic pegmatoids in the Bushveld Complex and their relationship to iron-rich intercumulus and residual liquids. J Petrol 35:881–917

Scoon RN (2002) A new occurrence of Merensky Reef on the flanks of the Zaaikloof Dome, Northeastern Bushveld Complex: relationship between diapirism and magma replenishment. Econ Geol 97:1037–1049

Scoon RN, Teigler B (1994) Platinum-group element mineralisation in the Critical Zone of the Western Bushveld Complex: I. Sulfide poor chromitites below the UG2. Econ Geol 89:1094–1121

Seabrook CL, Cawthorn RG, Kruger FJ (2005) 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 111:126

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

Van der Merwe MJ (1978) The geology of the basic and ultramafic rocks of the Potgietersrus limb of the Bushveld Complex. PhD Thesis University of the Witwatersrand 176pp

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: Wilson MGC, Anhaeusser CR (eds) Mineral Resources of South Africa, 6th edn. Handbook Council for Geoscience, vol. 16 pp 532–568

Von Gruenewaldt G (1979) A review of some recent concepts of the Bushveld Complex; with particular reference to sulfide mineralisation. 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, p 588

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. Trans Geol Soci South Afr 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