Introduction

It is well known that the platinum group element (PGE) mineralization in the Merensky and UG2 chromitite reefs is restricted to a very narrow vertical interval of rocks (Wagner, 1929). In the UG2 chromitite there is essentially no PGE above or below the chromitite layer that rarely exceeds 1 m thick. In the Merensky Reef a very large proportion of the PGE is confined within 1 m vertically in many cases, although there are some thicker intervals, and occasionally the mineralization becomes split with impoverished intervals between. Even within the relatively narrow reefs there is considerable variation in the exact location of the highest grades with respect to different host rock types. Variation in the silicate mineral rock types and PGE distribution has led to the definition of different reef facies (e.g. Wagner, 1929; Viljoen, 1999). This paper examines the published data on the distribution of PGE within the Merensky and UG2 reefs and uses this information to discuss models for the origin of the mineralization. There are geological and structural anomalies in the reefs, such as potholes, in which the mineralization may have a different distribution from the surrounding layered reefs, but these issues will not be discussed in detail here (see Carr et al., 1994).

Historical descriptions of the reefs and grade distribution

In the first five years after Merensky’s discovery in 1924, the rate of acquisition and publication of information about the Merensky Reef was truly astounding. Wagner’s
summary in (1929) contains an enormous wealth of information from the eastern, western and northern limbs. Details have been added, but no fundamental change in his overview has emerged. Because of the Great Depression further exploration and mining ceased and did not resume until 1933 and remained at a very low level until 1948 (Edwards and Silk, 1976). Thereafter, competition and secrecy meant that little further information on the reef was published. A major review by Vermaak (1976) provided much information on the host rocks, but the distribution of PGE within the reef was not included. The publication of the Mineral Deposits of South Africa by the Geological Society of South Africa in 1986 provided a further significant increase in knowledge from all the platinum mines, but it was only the Rustenburg Platinum Mines for which detailed distribution of PGE within the reef was presented (Viljoen and Hieber, 1986; Viljoen et al., 1986a; Viljoen et al., 1986b). Subsequently, more quantitative data have become available for most of the mines.

The publication of such data merely confirmed the observations of Wagner (1929), who recognized various facies of the reef for which the distribution of the PGE was not confined to a specific rock type. The different distinct facies are shown in Figure 1. He did not quantify the detailed PGE abundance distribution, usually quoting average grade over a mining thickness. More quantitative data for analyses of short vertical intervals through the reef have been provided in many subsequent publications, and are included in Figure 1. Wagner (1929) produced much information for the Rustenburg area, since it was recognized as the area with the most consistent mineralization and most likely to be exploited. Vermaak’s (1976) review of the reefs, again focused on the Rustenburg mines. As a result, many subsequent publications have considered the thin reef at Rustenburg to be typical of the Merensky around the entire Bushveld Complex. Possibly the most important omission in many of these subsequent contributions is the recognition about the distribution of the mineralization, summarized by Wagner (1929; page 102), as follows: ‘Where [the reef is] thick, the platinum values are confined to its uppermost portion.’ Wagner also stated (page 137) that where the reef is thin, as in the Kroondal facies, which can occur on any of the Impala, Rustenburg and Lonplats Mines, significant mineralization occurs in the footwall anorthosite. This variability in the vertical location of the PGE mineralization relative to the different rock types is fundamental to understanding the genesis of the ore as discussed below.

In contrast, to the non-publication of details of grade distribution for the Merensky, several important studies on the UG2 chromitite became available from the outset of mining (Hiemstra, 1979; 1985; McLaren and de Villiers, 1982), albeit mainly from one mine, Lonplats.

**Detailed illustrative vertical sections through the Merensky Reef**

Assorted generalized plots of the grade distribution were compiled by Viljoen and Schärmann (1998) and Cawthorn et al. (2002; 2005), but to illustrate the irregularity of distribution vertically the following specific sections are described. Detailed vertical sampling needs to be undertaken to visualize the vertical distribution. Mining and exploration companies routinely analyse samples 20 cm thick, or occasionally slightly less, where obvious lithological contacts occur. More detailed studies are usually undertaken only for research and academic studies. Publications from mining companies, compiled in Figure 1, tend to be more generalized, but are the average of a great many analysed sections. Examples of several very detailed studies of sections through the reef on different mines have been given by Mitchell and Scoon (2007) and Naldrett et al. (2009). What these different profiles show is that the mineralization can be very irregularly distributed vertically, especially for the thicker intersections of Merensky Reef, creating challenges to correct selection of the section to be mined. However, as discussed by Viljoen et al. (1986b), related to their Figure 13, the total PGEs within the Merensky Reef is much the same over large areas, regardless of reef width.

**Contact or thin reef**

Typical Rustenburg thin reef (Figure 1a) distribution has been shown by Viljoen and Hieber (1986). It appears to be the most common of all non-potholed reefs on Bafokeng Rasimone (Moodley, 2008) and becomes frequent through Impala, Rustenburg and Western mining properties. Mining companies report that PGE grade continues into, and is mined from, the footwall. Note that in this section there is only one chromitite layer and no pegmatitic pyroxenite facies.

**Pegmatitic pyroxenite reef**

In this facies (Figure 1b and c), also found across the above-mentioned mines, there are two chromitite layers that may be separated by only a few cm to several tens of cm. Better grades are associated with the two chromitite layers, as can be seen as the separation increases (Figure. 1c). The interval between is usually a pegmatitic pyroxenite, with a normal grain-sized pyroxenite above the upper chromitite layer. The distribution of PGE may be seen (Figure 2a) in the detailed study (albeit for one section) from Barnes and Maier (2002) and so its representativity is not known. Unfortunately, they sampled to a depth of only 20 cm into the anorthosite below the chromitite layer and even there...
the grade was still 7 g/t combined Pt and Pd. Hence, the total depth of significant mineralization below the chromitite was not assessed, but can be traced to a depth of 1.5 m below the chromitite layer (Cawthorn, 1999a).

**Thick reef**

To the east of the Lonplats properties, and in the Marula (Mitchell and Scoon, 2007) and Lebowa mines the reef package becomes thicker and lithologically more variable (Figure 1d and e). There is a basal chromitite above an anorthosite or norite. The chromitite usually carries a small amount of mineralization. Above the chromitite there can be a variable package of pyroxenite within which there may be pegmatitic lenses, bounded at the top by another chromitite layer. Similarly, at Union and Amandelbult mines the entire interval between the two chromitites may be pegmatitic and often contains olivine (Viljoen et al., 1986a, 1986b). Very occasionally there is an intermediate chromitite layer that will also carry minor mineralization. Above the top chromitite is a pyroxenite grading into a norite. In most cases the best mineralization occurs in the top metre associated with, and below, the top chromitite layer.

**Genetic models for the Merensky Reef**

Various hypotheses have been proposed for the origin of the PGE mineralization and these are reviewed in the light of these variable profiles.

**Upward infiltration of fluid**

The model of upward migration of a fluid (Boudreau, 2008) involves the following stages. A great thickness of footwall rocks accumulated. Final crystallization of the residual magma deep in this pile of crystals produced a water-rich vapour. This vapour percolated upward, dissolving a portion of any sulphide and PGE present. When this vapour encountered a layer of crystal mush where the interstitial magma was undersaturated in water, the vapour (and its sulphur and PGE) dissolved into this interstitial magma. The high water content acted as a flux and caused significant remelting in that zone with the subsequent formation of coarse-grained textures (pegmatitic pyroxenite) and precipitation of PGE-rich sulphides. A quantitative geochemical model for this process was described by Boudreau (2008). The PGE distribution profile that he was aiming to produce is shown in Figure 3. This model requires that the PGE mineralization be associated entirely with the pegmatitic layer, and occupies an extremely thin zone. As shown in the various actual vertical sections in Figure 1 the PGE mineralization may occur either below or above this pegmatitic pyroxenite. It may be that there is no pegmatitic pyroxenite present anywhere in the succession, but there is still the same PGE grade as elsewhere. A further petrological issue also arises. If the precursor layer is significantly remelted then the overlying cumulate package ought to have collapsed into it, or the volatile-enriched melt ought to have migrated upward because of its lower density than the overlying cumulate rocks. Wagner (1929) commented on this same debate, and concluded: ‘No instances were noted in all the hundreds of sections which the writer has examined of the normal Merensky Reef or feldspathic pyroxenite or harzburgite sending off apophyses into the hanging wall.’ I know of one example of a short vertical protuberance of Merensky pegmatitic pyroxenite into overlying pyroxenite, but that is at the bottom of a pothole where considerable slumping and disruption of the succession has occurred (Carr et al., 1999). Hence, it is not clear if this event represents a magmatic upward incursion or merely deformation of a crystal mush.
In summary, the observed geological relations are not consistent with this model of upward infiltration of a PGE-rich fluid. This conclusion does not deny the existence and migration of fluids, but to suggest that they did not transport or redistribute the PGE.

**Downward accumulation of a PGE-enriched sulphide liquid**

This model assumes that the PGE were concentrated in an immiscible sulphide liquid that sank to the instantaneous floor of the magma chamber (the anorthosite-norite below the Merensky unit). This model has had many variations that have emphasized different aspects, mainly in trying to produce an immiscible sulphide liquid (Campbell et al., 1983; Naldrett and von Gruenewaldt, 1989), in trying to explain the high PGE content of the sulphide which is so radically different from many other magmatic sulphide ores (Campbell and Naldrett, 1979), and simultaneously producing the distinctive geochemical features associated with this mineralization.

In the model by Campbell et al. (1983), addition of new magma and its mixing with resident magma caused an immiscible sulphide liquid to form that scavenged the PGE. The added magma was assumed to have had a similar composition to that which had formed the previous succession. The problem is that there is a very abrupt increase in the initial $\delta^{18}O/\delta^{16}O$ value from 0.706 to over 0.708 within a very short vertical interval (Hamilton, 1977; Kruger and Marsh, 1982). This change in ratio suggests that a totally different magma had been added. The nature of this added magma creates a great deal of uncertainty to the model, because the composition, and hence density and temperature of this added magma are all unknown, and so whether it could mix with the resident magma in the way described by Campbell et al. (1983) must be considered uncertain. Further, this model requires the complete and thorough mixing of an extremely large volume of magma. The total thickness of the combined magmas (new and resident) has never been stated in these models, but using the likely PGE of basic magmas and its extractability into the sulphide liquid many hundreds of metres to kilometres are required (Cawthorn, 1999b).

Furthermore, this mixing must occur over an area of 30,000 km$^2$ since the Merensky is found in the eastern and western Bushveld. Such enormous areas and thicknesses of mixing have been questioned by Cawthorn (1999b), and more recently has been accepted as a major flaw to this model by Naldrett et al. (2009, p. 654).

Because of the implausibility of mixing such large volumes, it was suggested by Scoon and Teigler (1994) that the added magma was only a thin layer. However, neither its thickness nor the PGE contents of either magma was stated, and so it was not possible to quantify this model. A rather similar model was developed by Naldrett et al. (2009) who did attempt to quantify it. They suggested that the added layer was in the order of 12 m thick. The problem of the huge mass of PGE that had to be sequestered from the liquid was recognized in their model and so they suggested that the new magma contained 200 ppb Pt. The authors admitted that such values far exceeded those reported for the maximum solubility of PGE in basaltic magmas.

There are a number of issues that these models fail to recognize. The emplacement of a thin (12 m) layer of liquid places implausible constraints on the geometry of the instantaneous floor of the magma chamber (see Figure 4). In both models, the new magma is considered to have been denser than the resident magma and so must have flowed along the floor of the chamber. If there had been a topographic variation in height of this footwall succession of more than 12 m then the new liquid would not have been able to flow over the footwall, but would have flowed round such topographic elevations. Thus, no Merensky Reef would have developed on any topographic high greater than 12 m in the footwall rocks. There are no reported examples of Merensky pinching out against small-scale or irregular topographic highs of footwall succession. Hence, for this thin magma layer model to have operated the entire floor to the chamber from east to west must have had a topographic relief of less than 12 m over an area of 30,000 km$^2$. I suggest that is very implausible, and question the thin-magma-layer model.

It needs to be mentioned that the above statement implies that the eastern and western limbs of the complex were part of one large chamber, certainly by the time the Merensky package was forming. This was the original concept for the Bushveld lopolith (e.g. Hall, 1932). It was challenged by Cousins (1959) who used gravity data to suggest that each limb was well separated from the others. However, Cawthorn et al. (1998) showed that Cousins' model had neglected the effect of isostasy, and that the gravity data...
were consistent with a single connected lopolith between east and west. Connectivity between these and the northern limb is less certain, and so the correlation of the Merensky Reef and Platreef is moot. Scoon and Mitchell (2009) continued to suggest that the limbs are discrete. However, it should be noted that both limbs contain a number of very distinctive, verging on unique, layers and sequences of rocks. Thus, the LG6, LG7, MG1, MG2, MG3, MG4, UG1, UG2, Merensky and Bastard packages occur in both limbs (Cawthorn et al., 1998). Also the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in both limbs follow the same sequence of changes in values and at the same stratigraphic levels. The idea that two discrete intrusions could have produced such identical sequences and diagnostic layers is considered totally implausible.

The second issue concerns the Sr isotopic data referred to above. In this model the new magma added had the composition and isotopic ratio of the lower rocks of the Bushveld Complex, i.e. type 1 magma. It was intruded into a chamber which contained magmas already influenced by the magma that made the Main Zone according to Mitchell and Scoon (2007) and Naldrett et al. (2009). Thus, addition of this basal surge of primitive, type 1 magma ought to have lowered, not raised, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the Merensky unit package.

In all these models there is a geochemical paradox that arose from the study of the Cr content of orthopyroxene throughout the entire Bushveld Complex, as summarized by Eales (2000). He noted that there was a massive decrease in this Cr content close to the Merensky Reef, and attributed it to addition of a fundamentally chemically different magma type. A more detailed examination of this break showed that it occurred several metres above the Bastard Reef (Cawthorn, 2007). Thus there is a chemical anomaly, namely that the Cr in orthopyroxene data suggest that new magma was added several metres above the Bastard Reef, whereas the Sr isotope break suggests that addition was close to the top of the ultramafic rocks of the Merensky Reef.

Seabrook et al. (2005) resolved this paradox by noting that the Sr is largely held in plagioclase, and so suggested that the orthopyroxene and plagioclase had been derived from two coexisting, but stratified, magmas. In this model, the added magma (type 2) was of a different composition from that existing in the chamber (type 1), and that it underflowed the existing magma because it was denser. No mixing of magmas occurred. Orthopyroxene, chromite and sulphide separated from the upper (resident) magma (type 1) and because they are all denser than the magma sank through the underlying magma layer. The underlying magma layer (type 2) ultimately produced the interstitial plagioclase. This stratified magma column is the exact reverse of that proposed by Naldrett et al. (2009) who arbitrarily added 1% of water into the resident magma that had Main Zone affinities (type 2), but no water to the added primitive magma (type 1) so that the relative densities fitted their thin, dense, basal layer geometry.

Cawthorn et al. (2002) and Mitchell and Scoon (2007) argued that what is considered typical Merensky by many authors, the thin pegmatitic pyroxenite reef (Figure 1), has been so condensed that it is not possible to identify all the events that actually occurred. They both suggested that the thicker reef facies preserved a greater proportion of the evolving succession and allowed the entire sequence to be recognized and deciphered. They suggested the following sequence of events. Magma of the type 1 composition, which is relatively siliceous and with about 13% MgO (Davies et al., 1980), crystallized numerous rhythmic units of chromitite through pyroxenite and norite to anorthosite up to the level of the footwall to the Merensky package. The top of this succession may have been undulating due to primary accumulation effects, or to later erosion or redistribution of the uppermost few metres of anorthosite (Leeb-Du Toit, 1986).

Another similar cycle was initiated at the beginning of the Merensky package. There may have been addition of more of type 1 magma or there may have been convective overturn of an already stratified magma column as has been proposed for the Upper Zone (Tegner et al., 2006). Alternatively, changes in pressure due to tectonic activity may have changed the mineral assemblage crystallizing from the magma (Lipin, 1993; Naslund and McBirney 1996). An increase in pressure in the chamber would have stabilized chromite (Cameron, 1982), pyroxene (Cawthorn, 2003) and sulphide (Mavrogenes and O’Neill, 1999). As a result of this postulated pressure increase, a chromitite and thin (possibly 1 m or slightly more) pyroxenite layer accumulated. A pressure decrease caused a cessation in crystallization. The pyroxene crystal mush was then in contact with a magma that was slightly superheated. Three possible processes could then have occurred as shown in Figure 5 (Cawthorn and Barry, 1992; Cawthorn et al., 2002; Cawthorn and Boerst, 2006). Column 1 in Figure 5 shows the partially formed cycle of chromitite (the lowest layer, Chr 1) and pyroxenite. Another succession could have formed on top of it (shown by the arrow A), producing a chromitite layer (Chr 2) and more pyroxenite (column 2a, Figure 5). The second option (shown in column 2b by the arrow B), was that because the magma was slightly superheated the layer of pyroxenite was thinned and coarsened in texture to produce the pegmatitic pyroxenite. A similar coarsening process was advocated by Viring and Cowell (1999) and Vrijen (1999) who referred to it as reconstitution. It also has similarities with the process proposed by Roberts et al. (2007), but they envisaged the replacement of pre-existing minerals and textures a very short distance into the footwall below chromitite layer 1, whereas the process here is considered to have occurred mainly at the crystal-magma interface. A second injection of magma could have produced a second chromitite above this pegmatitic pyroxenite, as shown in column 3a, Figure 5.

The third possibility (shown by arrow C in column 2c, Figure 5) is that complete dissolution of the pyroxenite and chromitite might have occurred. An uneven upper surface of the footwall anorthosite may have resulted if continued dissolution had occurred of the footwall. In this case, the next injection of magma would have produced a chromitite layer on the footwall anorthosite (column 3b, Figure 5), but it was the second chromitite, not the first, that survived at the contact with anorthosite. These processes were repeated to give all variations from a contact reef where dissolution had removed components of the first and second Merensky packages, leaving only the last event, to a complex and thick reef in which up to three chromitites could be recognized, as shown in the actual examples in Figure 1. These variations and problems with correlation are shown in Figure 6. By this sequence of events, all the pyroxenites (and their pegmatitic reconstitutions) have the initial Sr isotopic ratio of the first magma type.

I suggest that evidence for this remelting and reconstitution can be seen in the Cr contents of pegmatitic and pyroxenitic parts of the reef. In a study of many sections of these rock types from Impala mine, Boerst
(2001) showed that the pegmatitic facies reef had a much higher Cr content than pyroxenitic facies reef (see Figure 7). The pegmatitic reef also often has a higher olivine content than pyroxenitic reef. Both of these features can be explained by the well-known incongruent melting of orthopyroxene. The primary pyroxene grains would have had a Cr content of about 3 000 ppm. However, as they were redissolved olivine was produced, containing essentially no chromium, and the Cr was left as refractory chromite grains.

The final event involved addition of type 2 magma, which was denser than the existing magma (Seabrook et al., 2005). This magma was not in equilibrium with orthopyroxene or chromite, and erosion, both chemical and physical associated with the emplacement of the magma could also have ensued. The increase in pressure associated with the injection of the second magma triggered chromite, pyroxene and sulphide formation in the upper magma which sank into the lower magma layer, making the pyroxenite of normal grain size above the upper chromitite. This process resulted in the highly anomalous situation in the pyroxenite above the Merensky Reef that the cumulus crystals of orthopyroxene with high Cr content formed from type 1 magma (the upper stratified layer), whereas the matrix plagioclase with high Sr isotopic ratio that solidified round these grains was from a different, type 2 magma (the lower stratified layer). In this way, the apparent contradiction that the Cr content of pyroxene indicates type one magma, whereas the Sr isotope ratio indicates type 2 magma, becomes explicable. It should be emphasized that the Sr isotopic break becomes significant only at the top of the pyroxenite. It does not occur at the lower chromitite as would be expected if the major magma addition and Merensky forming event were represented by that lower boundary. In thin reef this distinction in the elevation of the isotopic change is difficult to demonstrate, although it should be noted that in the very first isotopic study, Hamilton (1977) stated that the break occurred 3 m above the reef. However, his sampling was not as close as in many subsequent studies. The isotopic succession through a thick Merensky package has been presented by Shelembe (2006) and is shown in Figure 8. The entire 10 m of pyroxenite has the Sr isotopic ratio of the type 1 magma, but the overlying norite shows increasing values with height due to the crystallization of interstitial plagioclase from type 2 magma.

The grains of chromite and orthopyroxene in the Merensky package formed a framework, initially with considerable porosity. Compaction due to annealing resulted in a decrease in porosity with increasing depth in the crystal pile (Figure 9). The actual permeability, rather than porosity, depends upon grain size as well proportion of pore space. Thus, the permeability in the footwall succession shows a minimum at the chromitite layer because of its fine-grain size. Cawthorn (1999a) suggested that the settling sulphide liquid had low viscosity and high density and so it filtered downward through the uppermost pyroxenite, as shown by the modeling of Mungall and Su (2005). It was partially arrested as it tried to penetrate the chromitite layer, but some did filter through. The rapidly decreasing permeability downward, and the small volume of sulphide available, meant that it did not penetrate more than about 1 m into this crystal mush. Thus, the sulphide is now found slightly below the level it which it first separated. This relationship was first discussed by Wagner (1929; p. 113) who recognized this process in a very
prescient section of his book entitled, 'Effect of movements during and subsequent to consolidation'. It is an issue that has been almost totally neglected in most subsequent publications in which the timing of the formation of sulphides is related to the exact layer in which they are now found. I suggest that this vertical migration of probably about 1 m is crucial in understanding the genesis of the succession. This model explains the fact that in thick reef

PGE grades and ratios

There is one aspect of the grades and ratios of Pt/Pd that is relevant to the genesis of the mineralization. The detailed study by Barnes and Maier (2002) of thin pegmatitic reef on Impala is shown in Figure 2a. Both the Pt + Pd grade and Pt/Pd ratio are shown. It can be seen that the maximum grades coincide with the very thin chromitite layers, and
also that the ratio of Pt/Pd is very much higher in these layers than in the intervening silicate rocks. Note that the chromitite layers are too thin to be analysable separately, and the length of sample cut for analysis included some of the associated silicate rocks. Hence, the grade in the pure chromitite might have been even higher. These relations led Barnes and Maier (2002) to suggest that there were two collection mechanisms operative, one associated with chromite and the other with sulphide. This dual process is shown in Figure 2b–c. This dual collection mechanism was ignored in the calculations made by Naldrett et al. (2009) who assumed that all PGE had been sequestered by sulphides. This issue will be addressed once the mineralization in the UG2 has been discussed.

UG2 chromitite

The UG2 chromitite reef is generally considered to be a single layer of chromitite. However, Lee (1996) pointed out that there was a fundamental textural break in the middle of the layer, the lower part being a massive chromitite and the upper part containing abundant pyroxene oikocrysts. This boundary also coincided with changes in composition, and Lee (1996) suggested that the UG2 is a composite layer. Unlike the Merensky where there is a tail of PGE (albeit quite short) into the hangingwall pyroxenite to norite, above the UG2 there are no reports of any mineralization in the overlying silicate rocks. Below the UG2 there is usually a pegmatitic pyroxenite, although on some mines it is an anorthosite. The presence of PGE in the pegmatitic footwall has been reported, but it appears that it is confined to schlieren of chromitite within the pegmatitic pyroxenite rather than in the silicate host itself. So it can be inferred that the PGE is totally hosted in chromitite. It is also important to note that the amount of sulphide is extremely low, as evidenced by Cu and Ni contents typically less than 0.05% (McLaren and de Villiers, 1982; Hiemstra, 1985; 1986; Lee, 1996).

The PGE grades most frequently reported are for 20 cm lengths through the layer, which is the standard practice for mining and exploration companies. However, I consider the most definitive data were obtained in two studies by Hiemstra (1985; 1986) who sampled every two cm through sections of UG2 from Lonplats mines. Typical mining company data show a basal enrichment of PGE and also a secondary enrichment either nearer the middle or towards the top. However, when analysed in great detail it is seen that there may be three upward depletion trends as shown in Figure 10 (from Hiemstra, 1985; 1986).

Relationship of UG2 and UG3 chromitite layers

Several lines of evidence suggest that the UG3 chromitite that is discrete in the northeastern part of the Bushveld has merged with the top of the UG2 chromitite in all other regions. The existence of a UG3 cyclic unit in the northeastern limb of the Bushveld was first discussed by Gain (1985). In fact, he noted that there was also a UG3A cyclic unit in which there were two discrete thin (15 and 10 mm) chromitite layers and which can be seen on the farm Maandagshoek (Figure 11). I have denoted the two layers as 3A and 3B for clarity. Gain also suggested that these uppermost cycles were not laterally continuous but merged with the underlying cycle, as shown in Figure 11 between layers 3A and 3B. I suggest that the UG3 also merged with the underlying UG2 in most sections of the Bushveld, only being recognizable as a discrete entity in the northeast. These geometrical relations are shown in Figure 12. The data of Gain (1985) showed that the UG3 had a distinctively high Pt/Pd ratio, a feature also revealed by Hiemstra’s detailed profiles at the top of the UG2.
Most models for the genesis of chromitite layers appeal to magma addition and mixing (as originally proposed by Irvine, 1977). He suggested that a slightly differentiated resident magma, equivalent to type 1 when applying Irvine’s model to the Bushveld Complex, mixed with a new injection of primitive type 1 magma. This process is illustrated on a Cr-saturation diagram from Barnes (1986) and Murck and Campbell (1986), shown in Figure 13. The primitive type 1 magma would have had a composition given by P. As a result of its cooling and differentiation it would change composition to D. The chamber was then replenished by more of magma of composition P, P and D mixed. The resultant mixture (M1) was oversaturated in Cr and so formed chromite grains until its composition had changed to M2 (from Murck and Campbell, 1986).

It should be possible to test the concept of magma addition by comparing the 100*Mg/Mg+Fe (mg#) ratio of orthopyroxene above and below a chromitite layer. Magma compositions P and D would be expected to crystallize orthopyroxene with mg# of close to 90 and nearer 80 respectively, and so composition Mought to produce a composition of about mg# 85. Thus, primitive magma addition ought to produce a reversal of several units in the mg# in the pyroxene above a chromitite layer. In his very detailed studies of the eastern limb, Cameron (1980, 1982) did not report any reversals.

A variant on the magma mixing model was proposed by Kinnaird et al. (2002), based on the original model of Irvine (1975), using Sr isotope ratios (Figure 14). They showed that every chromitite layer was associated with an increase in this ratio, which they attributed to crustal assimilation. This model also raises the question as to why it should be such an abrupt event, producing such a sharp basal contact over such a large area. Mondal and Mathez (2007) challenged this model on the grounds that the succession overlying chromitite layers ought to show higher Sr isotope ratios, which they do not. However, in the model of Kinnaird et al. (2002) the assimilation involved reaction between magma and a partial melt from the roof of the intrusion. The chromite crystals then cascaded down from the roof carrying a selvage of the liquid with the high Sr isotope ratio. The Sr isotope ratio of the magma towards the base that was the source of the subsequent pyroxenite was not affected.
Evidence for thinning. Thus this model must be questioned. Layers of chromite, especially the UG2, show remarkable 
dramatically with distance away from the entry point. The 
site of entry, and any layer that formed would thin 
dense slurry of chromite would be dumped quite close to 
its lateral distribution once in the Bushveld chamber. A 
problem than the rest of the evolving type 1 magma. 
this remaining 80%. The Cr imbalance is no bigger a 
another chamber does not resolve the much bigger issue of 
approach demands the question as to what happened to the 
remaining 80% of this magma. Sourcing the chromite from 
Injection of a chromite slurry 
Eales (2000) argued that there was an imbalance in the total 
of amount of Cr (both as chromite and in the Cr-rich 
ortho-pyroxenes) in the Lower and Critical Zones of the 
Bushveld Complex. He therefore appealed to the injection of a 
chromite slurry that had been formed in some deeper magma chamber. The first issue here is the mass balance of 
Eales (2000). He suggested that there is an imbalance in Cr 
in the lower half of the Bushveld, but by inference, no 
imbalance was implied for any other element. The fact is 
that there is a difficult mass balance problem associated 
with the entire lower half of the Bushveld. Using the 
proposed composition for type 1 magma, Cawthorn and 
Davies (1983) showed that the magma would crystallize the 
sequence olivine, orthopyroxene, plagioclase as observed in the 
intrusion. This evolution was modelled quantitatively, 
constrained by the mg# of the pyroxene, by Li et al. (2001), 
who showed that only 20% of the magma had crystallized at 
the level of the Merensky unit. Thus, a mass balance 
approach demands the question as to what happened to the 
remaining 80% of this magma. Sourcing the chromite from 
another chamber does not resolve the much bigger issue of this 
remaining 80%. The Cr imbalance is no bigger a 
problem than the rest of the evolving type 1 magma. 
The problem with an injection of a chromite-rich slurry is its 
lateral distribution once in the Bushveld chamber. A 
dense slurry of chromite would be dumped quite close to 
the site of entry, and any layer that formed would thin 
tragically with distance away from the entry point. The 
layers of chromite; especially the UG2, show remarkable 
uniformity of thickness over their entire occurrence with no 
evidence for thinning. Thus this model must be questioned. 

An even more extreme version of this model of 
emplacement of a chromite-rich slurry has been proposed by 
Maier and Barnes (2008) and Voordouw and Beukes (2009). They have proposed that the chromite slurry was 
intruded into a pre-existing succession of rocks. In the case 
of the UG2 (to which Maier and Barnes specifically 
referred) this model asks the question as to why it intruded 
exactly along the contact between two different rock types. 
It is also challenging to ask whether a crystal mush could 
intrude over an area of 30 000 km² with such uniform 
thickness. Furthermore, these two publications do not 
address the question as to whether they consider all 
chroomite layers to be intrusive or only the UG2 discussed in 
their publications. If they consider only this one layer to 
be intrusive it is necessary to identify criteria that 
distinguish layers that are intrusive from layers that formed 
by downward accumulation of chromite. 

Pressure change 
The model proposed by Lipin (1993) invoked pressure 
changes that would occur throughout the entire magma 
chamber instantaneously. Thus the entire magma chamber 
could be processed to produce chromite, minimizing the 
mass balance problems. However, it is a very difficult 
model to test because it leaves no effect in the magmatic 
system except the change in the order of crystallization of 
minerals (as reviewed by Naslund and McBirney, 1996). 
Naslund and McBirney also referred to the possibility of 
seismically induced nucleation. As pointed out by Wager 
and Brown (1968, p. 548) the sequence of mineral 
nucleation would likely be in order of structural complexity 
of the minerals, namely, oxide, pyroxene then plagioclase. 
They noted that this order also matches that expected from 
density sorting and normal crystallization from the type 1 
magma, thus a unique solution to the process that causes the 
layering and especially the chromite layers remains 
elusive. 

PGE mineralization in the UG2 
Whatever the mechanism that produced the chromite 
layers, the concentration mechanism of the PGE into the 
chromite requires examination. It should be emphasized 
that all chromitites in the Bushveld Complex contain 
significant concentrations of PGE (Scoon and Teigler, 
1994), and they argued that the concentrations observed in 
the UG2 chromitite are part of a continuum of a pattern 
throughout the entire Critical Zone. 

Sulphide association 
It has been suggested that the chromite layers are associated 
with sulphide formation that actually concentrated the PGE 
(Naldrett and Lehmann, 1987). In this model, the sulphide 
subsequently broke down by reaction with chromite, the 
iron entering the oxide phase and the sulphur being lost as a 
vapour. However, if sulphide had been present, the 
chromitites ought to have contained some Cu and Ni, 
possibly comparable in grade to the Merensky Reef. The 
UG2 chromitite contains typically 0.03 and 0.06% Cu and Ni 
respectively (Hiemstra, 1985, 1986; McLaren and de Villiers, 
0.01 to 0.04% Cu and 0.07 to 0.16% Ni for the UG2, which 
are much less than the grades in the Merensky Reef of about 
0.1 and 0.25%. Although the report does not specify whether 
the analysis is total Ni in whole rock or on acid soluble 
leachate, it is probable that approximately 0.1% of that Ni in
the UG2 resides in the oxide phase (de Waal, 1975), and is not in the sulphide fraction, and so the difference between sulphide Cu and Ni in the two reefs is very significant. Thus, this model requires that much of the Cu and Ni were also lost from the sulphide during the proposed desulphidation process. It would be far more likely that the Ni would enter the oxide phase rather than being released into a vapour. Hence, the suggestion that there was a higher original sulphide content in these chromitite layers must be challenged.

**Solid solution in chromite**

It has been suggested that the PGE can partition into chromite in solid solution (obeying Henry’s law), and that on cooling the PGM exsolved from the chromite grains. However, experimental evidence suggests that significant solution of PGE into chromite is not likely (as reviewed by Finnigan et al., 2008).

**The role of micronuggets, nanonuggets and clusters of PGM**

Hiemstra (1979; 1985; 1986) suggested that micronuggets of PGE phases existed, suspended in the magma. Ertel et al. (1999) concluded that they were probably no greater than 0.05 μm, and so would be far too small to sink independently, but remained suspended due to Brownian movement. Hiemstra suggested that once chromite grains formed the PGE micronuggets were attracted to these grains, and thereby carried to the base of the magma chamber with the chromite. Evidence for or against this model is hard to obtain because such micronuggets would anneal into the larger PGMs now identified associated with chromite. Extremely small grains of Pt species are being identified (Ballhaus and Sylvester, 2000; Godel et al. 2007) and determining their original form remains elusive. Ertel et al. (2008) have reviewed the problems of identifying what they call nanonuggets, and predicting their behaviour.

Variations on this chromite-PGM association were developed by Scoon and Teigler (1994), Ballhaus et al. (2006) and Finnigan et al. (2008). The first authors did not specify a process. The second authors suggested that the PGM nucleated on chromite grains, whereas the latter argued that when chromite crystallized it induced a zone of reduced (low oxygen fugacity) liquid composition around the grains, and that lower oxygen fugacity the PGM would nucleate directly and adhere to the growing chromite. The last model depends upon the relative diffusion of rates of the oxygen versus Cr. Unless Cr can diffuse through the magma towards the growing chromite quicker than oxygen can diffuse in the same direction then a zone of low oxygen fugacity around the growing grains cannot be sustained and the PGM will not form.

Yet another variant on this model of Hiemstra (1979) was developed by Tredoux et al. (1995). They noted that the catalytic properties of PGE result from their ability to exist as clusters of atoms, which are highly reactive. They suggested that such clusters would become stabilized by forming surface bonds with either sulphur or iron. (In exactly the same way that catalytic car exhaust converters can be poisoned by sulphur in fuel.) Thus, these clusters may react with, and become incorporated into, either an immiscible sulphide liquid or bonded to oxide (either chromite or magnetite). However, a note of caution needs to be sounded about the intimate association of the PGMs with chromite because the metallurgical processes employed for beneficiation discard a chromite-rich residue very depleted in PGEs.

Any of these chromite-related mechanisms can explain the duality of concentration mechanisms seen in Figure 2, namely that both chromite and sulphide have the chemical or physical properties necessary to concentrate the PGE.

**Variation in PGE content in Merensky and UG2**

Hiemstra (1985; 1986) recognized the great variation in PGE grade upward and its cyclicity and concluded that the first chromite grains to form would attract the greatest proportion of the postulated micronuggets or clusters. Subsequent settling chromite grains would attract progressively fewer of these grains as the magma was swept clear of these particles. If it is accepted that the UG2 may be a composite of two or even three sub-layers, each new chromite-forming event might scavenge a new crop of these micronuggets or clusters. Similarly, in the Merensky Reef the first sulphide droplets would scavenge a high concentration of the particles, with subsequent sulphide droplets finding fewer such particles to attract. In this way, the upward depletion PGE trends noted by Naldrett et al. (2009) for the Merensky Reef become predictable, as postulated by Hiemstra (1986) for the chromitite patterns.

**Summary**

The PGE are very unevenly distributed vertically throughout the Merensky and UG2 chromitite reefs in the Bushveld Complex. In the Merensky Reef, mineralization may be found in the anorthosite below the chromitite and pyroxenite layers in what is called thin or contact reef. Where the reef is thicker, the mineralization can be seen to be top loaded (i.e. near the upper chromitite). The mineralization need not be associated with pegmatitic rocks. It is only where the reef is thickest that the entire sequence of events may be recognized. In thin reef too much of the temporarilry present succession has been removed by syn-magmatic erosion to fully appreciate the processes involved. There may have been up to three injections of magma, each producing a chromitite and pyroxenite, but each subsequent event removed variable amounts of the previous depositional cycle by thermal erosion or reconstitution. The last event produced the most significant proportion of the mineralization, carried down by an immiscible sulphide liquid that percolated through the uppermost metre of crustal mush.

The UG2 chromitite probably did not contain significant sulphide, and the PGE are concentrated mainly by the chromite itself. Various nucleation-triggering processes have been proposed to explain this association of chromite and PGE. The UG2 chromitite is probably not a single event, but represents two or three layers that have been superposed, occasionally with thin, intervening silicate rock lenses. Each layer has its own distinctive upward depletion cycle of PGE content. The uppermost of the three layers may exist as a discrete layer, separated by a significant thickness of silicate rocks from the UG2 in the northeastern Bushveld, where it is termed the UG3 chromitite. It has a high Pt/Pd ratio, but is too thin to mine. This high Pt/Pd signature may be recognized in the uppermost part of the thick UG2 chromitite elsewhere in the Bushveld, and so it is suggested that the UG3 accumulated directly onto the UG2 in most places.
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References


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