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THE ORIGIN OF THE MERENSKY CYCLIC UNIT: Sr-ISOTOPIC AND MINERALOGICAL EVIDENCE FOR AN ALTERNATIVE ORTHOMAGMATIC MODEL

F.J. KRUGER

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THE ORIGIN OF THE MERENSKY CYCLIC UNIT: Sr-ISOTOPIC AND MINERALOGICAL EVIDENCE FOR AN ALTERNATIVE ORTHOMAGMATIC MODEL

by

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ABSTRACT

Mineralogical, Sr-isotopic and field data on the Critical and Main Zones of the Bushveld Complex indicate that the major input of magma at the Merensky level was fundamentally different to the resident magma. Mineralogical and isotopic data from above and below the Merensky Reef indicate that:

1) The En content of the orthopyroxene and the An content of the plagioclase of the Critical Zone cumulates immediately preceding the Merensky reef are higher than those in the Main Zone above the Merensky cyclic unit.
2) The Main Zone magmas started to precipitate substantial cumulus augite in addition to pigeonite and the new magma was therefore gabbronoritic or gabbroic in character, in contrast to the noritic resident liquid.
3) Olivine is rare in the Main Zone, and the large influx of magma and the mixing associated with the Merensky cyclic unit resulted in only minor precipitation of chromite (c. 20mm). This is in contrast to the major layers of chromitite, including the PGE-rich UG-2 ($>$1mm), produced by apparently smaller influxes of magma in the upper part of the Upper Critical Zone.
4) The Sr-isotopic initial ratio of the upper part of the Upper Critical Zone (0.7064) is substantially different from that of the Main Zone (0.7064-0.7090) and this change is initiated at the base of or within the Merensky cyclic unit.

These data indicate that the new magma was fundamentally different and more evolved and hence probably compositionally and thermally denser than the resident magma. This implies that the influxes were of a "fountain" type, and involved the input of cool dense "gabbroic" magma with a high Sr-isotopic initial ratio (c. 0.7090) into the chamber containing warm buoyant "noritic" magma with a lower initial ratio (0.70635). The first fountain of magma entrained and mixed with the resident magma in the chamber, and the blended liquid then flowed along the interface between the resident liquid and the crystalline floor. This cooler magma fountain resulted in the evolution of two phase (bronzite + liquid) blobs as well as immiscible sulphide from the overlying warmer liquid. These plunged through the new liquid layer to form the Merensky reef. The sulphide scavenged sufficient PGE, Ni and Cu from the overlying resident magma to account for the quantity and areal distribution in the Merensky reef.

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INTRODUCTION

The initial Sr-isotopic composition (R_0) of the mafic layered part of the 2060 Ma old (Walraven *et al.*, 1990) Bushveld Complex (Figure 1) is extremely variable with highly radiogenic R_0 signatures (up to 0.709) in the Main Zone (Hamilton, 1977; Kruger and Marsh, 1982; Sharpe, 1985; Kruger and Mitchell, 1985; Eales *et al.*, 1986; Kruger *et al.*, 1987). The vertical distribution of initial $^{87}Sr/^{86}Sr$ ratios (R_0's) suggests that the earlier magma was less radiogenic and that subsequent additions were more radiogenic (Kruger, 1989). The large isotopic discontinuity associated with the Merensky cyclic unit (Hamilton, 1977; Kruger and Marsh, 1982) implies a large influx of a magma different to that resident in the chamber at that point in the stratigraphy. However, there is no direct evidence for the chemical composition of the new Main Zone magma, and therefore the available field, mineralogical and isotopic data on the cumulates must be used to infer its properties.

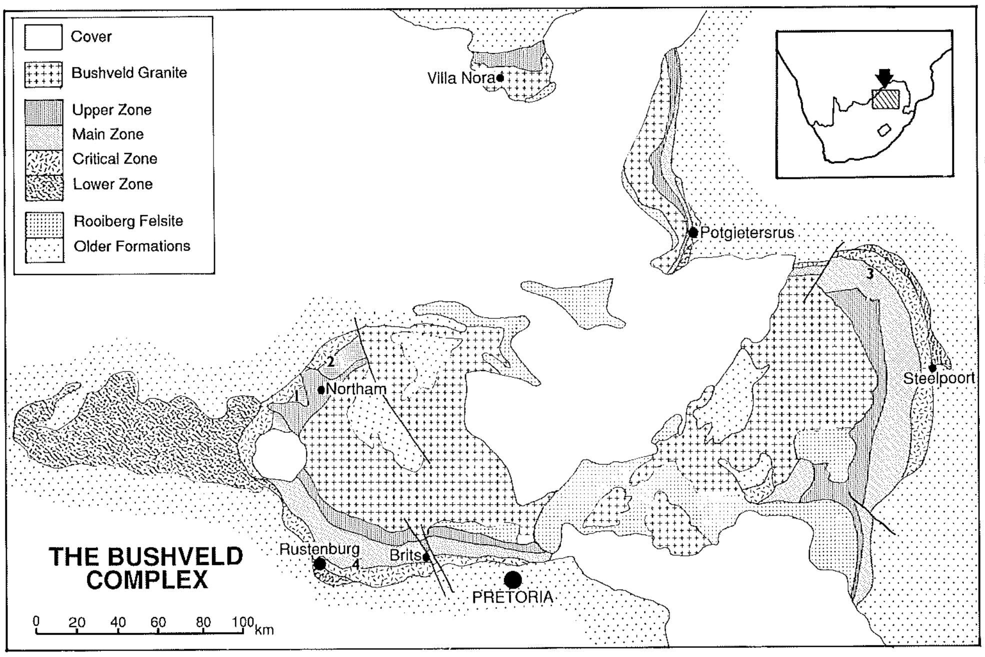

Figure 1: Map of the Bushveld Complex showing the locations of the Sr-isotopic profiles discussed in the text and shown in Figure 3. (1) Union Section, (2) Amandelbult Section, (3) Atok Mine and (4) Rustenburg Section.

The Merensky cyclic unit with its basal Platinum Group Element (PGE) and Ni- and Cu-rich Merensky Reef has been the subject of extensive study and contrasting models have been proposed for its generation. These models fall into two broad groups, viz. the upward infiltration models and the orthomagmatic models. In the former, PGE-enriched fluids are thought to have percolated upward and then precipitated the metals within the Merensky reef (e.g. Lauder, 1970; Ballhaus and Stumpfl, 1986). In the latter, the PGE are thought to have been precipitated during magma mixing (Kruger and Marsh, 1982; 1985; Campbell *et al., 1983;* Naldrett *et al., 1987),* and any fluids merely redistributed the components within the reef (see Barnes and Campbell, 1988). There are several orthomagmatic models for the origin of the Merensky reef. These can be characterised as the "parental magma plume models" (e.g. Campbell *et al.,* 1983); "lateral accretion models" (e.g. Irvine *et al.,* 1983), "suspended magma models" (Sharpe, 1985; Hatton, 1989) and "primitive magma fountain models" (e.g. Eales *et al.,* 1988).

FIELD RELATIONS AND STRATIGRAPHY

The base of the Merensky cyclic unit marks the stratigraphic position at which a new magma influx was initiated, causing a major lateral and vertical inflation of the magma chamber. This was coupled with deformation and erosion of the crystal pile which resulted in an unconformity. The presence of this compositional, erosional, and transgressive break led Kruger and Marsh (1982, 1985) and Kruger (1990, 1991) to suggest that the rocks above the unconformity should be included in the Main Zone.

The lithologically and petrographically similar Merensky and Bastard cyclic units are grouped together as the Transitional Macro-unit by Kruger (1990). These cyclic units start with chromite stringers at the base and grade upwards through orthopyroxenite, norite and mottled anorthosite, and have been described in detail for the four areas under consideration by *inter alia* Vermaak (1976), Kruger and Marsh (1985), De Klerk (1982), Viljoen *et al.* (1986a, b), Viljoen and Hieber (1986), Eales *et al.* (1986; 1988), and Lee and Butcher (1990). Both have sharp basal contacts, but the upper contact of the Bastard anorthosite with the leuconorites that form the rest of the lower part of the Lower Main Zone, is gradational. In some areas (e.g. Rustenburg) there is a suggestion of a further cyclic unit above the Bastard cyclic unit (Vermaak, 1976; Kruger, 1983; Kruger and Marsh, 1985). Recently, De Klerk (1989) has shown that the mottled anorthosite overlying the Bastard unit can be divided into three sub-layers, the lowermost of which is the Bastard anorthosite proper.

MINERALOGICAL DATA

In contrast to the bronzite-rich Critical Zone, the New Main Zone magmas precipitated cumulus augite and pigeonite (Von Gruenewaldt, 1973; Molyneux, 1974). The new magma was therefore gabbronoritic or gabbroic in character and in this respect differed from the noritic resident magma. Furthermore, olivine is rare in the Main Zone and the large influx and mixing associated with the Merensky cyclic unit resulted in a minor precipitation of chromite (c.20mm). This is in contrast to the major layers of chromitite, including the PGE-rich UG-2 (>1m), produced by apparently smaller influxes of magma in the Critical Zone.

As shown in Figure 2, the En content of Main Zone orthopyroxene is significantly less than that in the Critical Zone, and the plagioclase is also more sodic. These data imply that the new magma was probably cooler and compositionally denser than the resident magma and, on intrusion, would have ponded at the base of the magma chamber.

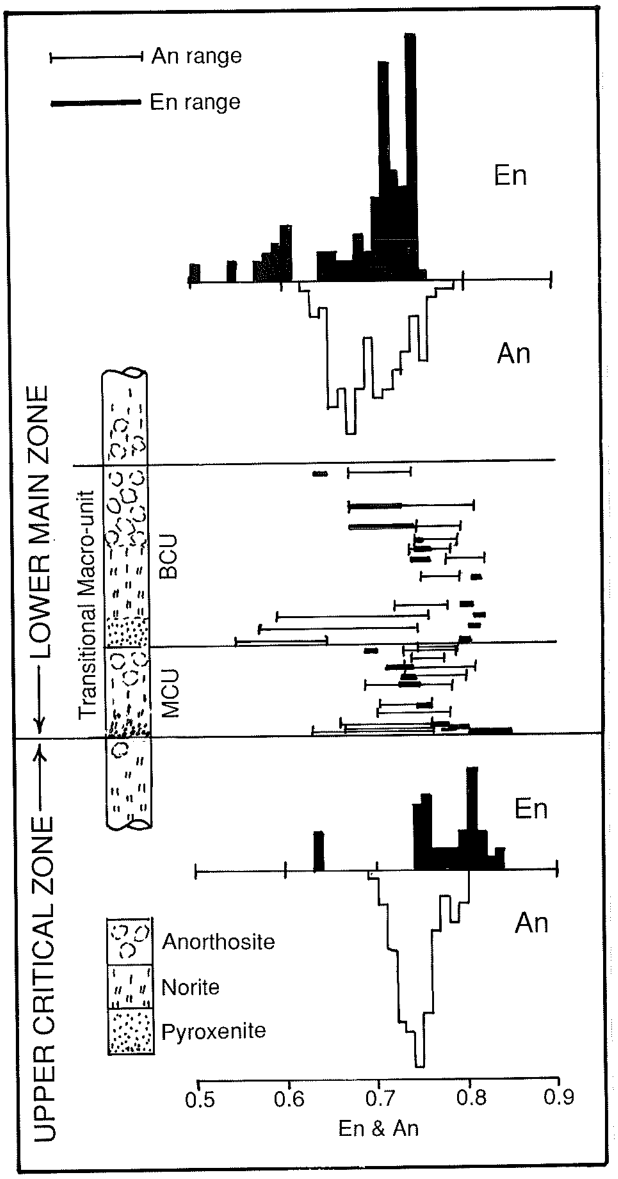

Figure 2: Orthopyroxene En and plagioclase An contents for Bushveld Complex cumulates from the Upper Critical Zone and Lower Main Zone. Electron probe data from Kruger (1983) and Mitchell (1986).

Sr-ISOTOPIC DATA

New Sr-isotopic data are presented on a profile from the Amandelbult Section of the Rustenburg Platinum Mines (samples described in Field, 1986). Further data are available from the Rustenburg (Kruger and Marsh, 1982) and Union (Eales *et al.*, 1986) Sections and from the Atok Mine in the eastern Bushveld Complex (Lee and Butcher, 1990). The geographical locations of the profiles are shown on Figure 1.

Experimental methods

The Sr-isotope analyses were done at the Bernard Price Institute of Geophysical Research and the experimental details are in Eales *et al.* (1990). Present day $^{87}Sr/^{86}Sr$ ratios were recovered from the spiked sample. The blank levels were less than 5ng for Sr and 200pg for Rb, and were negligible relative to the 100-200mg aliquots. The NBS-987 Sr standard gave 0.71023 ± 4 (2 sigma) on 9 spiked and unspiked samples during the course of this work. Fourteen replicates of a powdered Bushveld Complex rock, similar in composition to the samples presented here, resulted in a coefficient of variation of 0.53% in the Rb/Sr ratio and 0.0092% in the present day $^{87}Sr/^{86}Sr$ ratio. The unpublished data from Amandelbult section are presented in Table 1.

Table 1: Amandelbult Section Data

Number	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Rb/^{86}Sr$	R_{2060}
			Main Zone - Transitional Macro-Unit		
Bastard Unit					
AE-2	5.39	321.0	0.0485	0.70937±8	0.70793
AE-11	1.41	191.0	0.0213	0.70818±5	0.70754
AE-15	6.26	65.2	0.2777	0.71544±8	0.70720
Merensky Unit					
AE-20	2.81	330.0	0.0247	0.70792±8	0.70718
AE-21	3.14	361.0	0.0252	0.70806±7	0.70731
AE-23	1.53	309.0	0.0143	0.70792±6	0.70750
AE-24	1.10	213.0	0.0149	0.70797±6	0.70752
AE-26	4.33	58.5	0.2131	0.71369±6	0.70736
AE-MR	5.64	155.0	0.1054	0.71072±6	0.70759
			Critical Zone		
AE-30	3.29	447.0	0.0213	0.70706±6	0.70643
AE-35	2.79	456.0	0.0177	0.70694±5	0.70642
AE-43	1.90	450.0	0.0122	0.70682±5	0.70646

$^{87}Sr/^{86}Sr$ present day ratio ± 2 standard errors on c. 100 ratios

R_{2060} is the initial $^{87}Sr/^{86}Sr$ at 2060 Ma

DISCUSSION

The magma which precipitated the Upper Critical Zone rocks had an initial ratio of 0.7064, which is constant throughout the Bushveld Complex. However, the new magma which precipitated the Merensky and Bastard cyclic units was a variable mixture of the new and resident magmas. Therefore, the initial ratio of the new liquid cannot be defined by these rocks. The highest ratio obtained from rocks in the Main Zone is 0.7090 (Kruger and Mitchell, 1985) and this is taken to be the minimum ratio of the intruding liquid. Further support for this value is given by the data of Lee and Butcher (1990). These data indicate that the new magma had a fundamentally different source to the resident magma.

Extreme Sr-isotopic variations are a feature of the Merensky and Bastard cyclic units. There is a major change which occurs within the Merensky cyclic unit (Figure 3) which is only 10 to 20 m thick throughout the whole Bushveld Complex (Vermaak, 1976). As shown in Figure 3, the four sections have different isotopic profiles. At Rustenburg and Union sections there is an increase in the initial ratio from 0.7064 (which is equal to that of the Critical Zone) in the Merensky pegmatoid and pyroxenite, to 0.7075 in the mottled anorthosite. The Bastard cyclic unit as a whole has a relatively constant ratio similar to the Merensky mottled anorthosite.

This pattern is repeated at Atok, for the Merensky cyclic unit, but here the Bastard cyclic unit is in most respects identical to the Merensky unit, in that the base of the unit is similar in isotopic composition to the base of the Merensky cyclic unit. However, one sample at the basal contact of the Bastard cyclic unit has a very high initial ratio (0.7090).

The Amandelbult profile shows an unusual relationship in that there is a step-like change in the initial ratio from that of the underlying Critical Zone (0.7064) to the Merensky pyroxenite and pegmatoid (0.7076). This is followed by a slight decrease to 0.7072 in the Merensky anorthosite. The Bastard cyclic unit shows an increase from 0.7072 to 0.7078 from the pyroxenite to the anorthosite, and in this way resembles the other three profiles.

THE "COOL MAGMA-FOUNTAIN" MODEL

The isotopic and mineralogical data discussed above imply that the new magma was more evolved and compositionally denser than the resident magma. These characteristics demand an alternative model to those invoking hot primitive magmas whether denser (Eales *et al.*, 1988) or more buoyant (Campbell *et al.*, 1983; Sharpe, 1985) than the resident magma. An alternative "cool magma-fountain" model which incorporates these characteristics is developed here.

Immediately prior to the formation of the Merensky cyclic unit an influx of new, cool, dense magma with a high Sr initial ratio occurred. This new magma may have risen some way upward into the resident magma as a fountain, in which case some entrainment occurred (see Campbell and Turner, 1989). Alternatively, it flowed into the chamber with little upward momentum, and little or no entrainment of resident magma. This new magma (whether mixed or pristine) then flowed along the interface between the resident magma and the crystal pile. The new magma pulse thermally equilibrated with its surroundings and

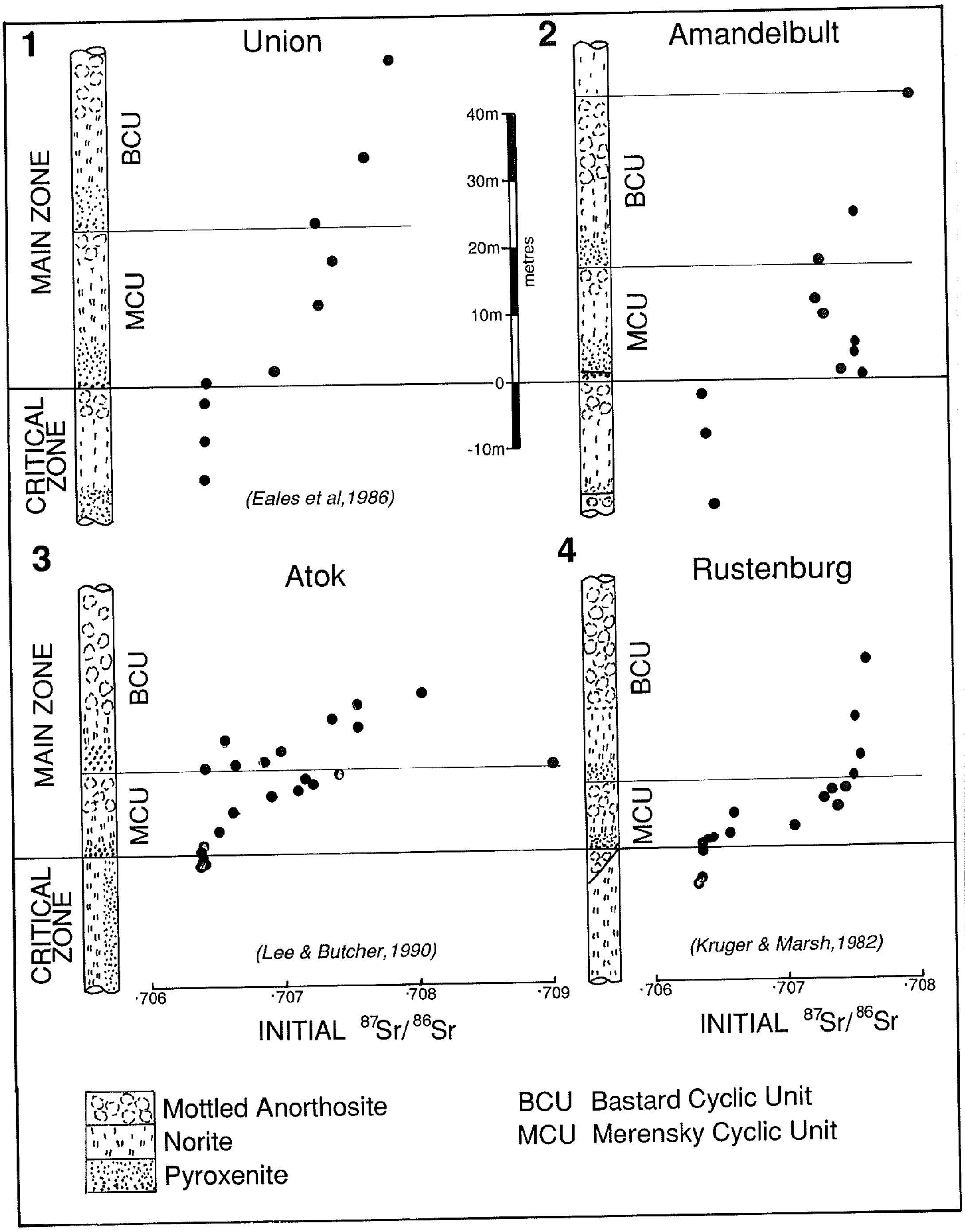

Figure 3: ^{87}Sr / ^{86}Sr initial ratios plotted against stratigraphic height for the different profiles discussed in the text.

therefore became superheated and thus capable of assimilation without concomitant crystallization. However, because it was compositionally denser it remained as a stable basal layer with characteristics relative to the resident magma and crystal pile as indicated in Figure 4.

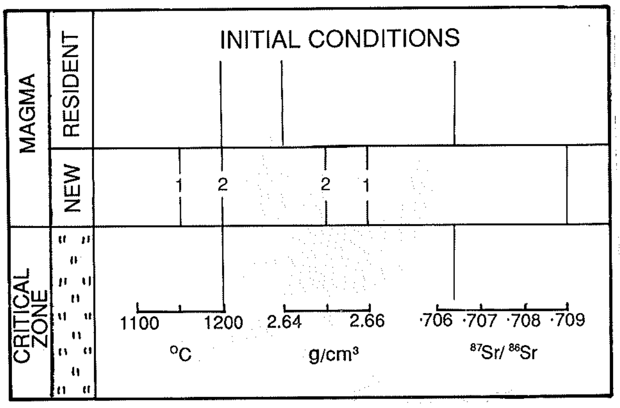

Figure 4: Schematic diagram illustrating the temperature, density and isotopic profile immediately after injection of the new magma (1) and after thermal equilibration (2). The temperatures and densities are hypothetical but to some extent they are based on the work of Hatton (1989).

The new superheated liquid layer would be undersaturated with respect to the underlying plagioclase-rich cumulates and thermochemical erosion, as envisaged by Campbell (1986), would occur causing potholes and an unconformity. The disaggregated plagioclase would have been quite buoyant in this dense liquid (Campbell *et al.*, 1978) and therefore floated to the upper part of the new magma layer, which became highly heterogeneous and unable to convect and mix.

Initially, on intrusion, the new liquid chilled the base of the overlying resident liquid, stopping convection and inducing crystallization of orthopyroxene (with some olivine and chromite) and exsolution of immiscible sulphide droplets from the lower part of the resident liquid. These sulphide droplets then settled through the magma column, thus efficiently scavenging the PGE from the resident magma. Furthermore, as the sulphide droplets settled from different heights in the compositionally stratified magma column, it is expected that the first arrivals would have a different composition to later arrivals. This led to a variation in the composition of the "reef" horizon, comprising the basal Merensky pegmatoid and the bottom part of the immediately overlying Merensky pyroxenite (Kruger and Marsh, 1985). This is also consistent with the view of Hiemstra (1986) that PGE concentration profiles in the Merensky reef indicate a settling mechanism. Mass balance indicates that, to account for the quantity of PGE in the Merensky reef, the sulphide droplets would have to scavenge at least 80% of the PGE from c. 200-300m of the overlying resident magma (De Wit and Kruger, 1990).

It is envisaged that the orthopyroxene crystals and sulphide liquid droplets settled to the interface between the two liquids, and then formed dense blobs of crystal-liquid slurry which plunged down through the new liquid layer to accumulate as the Merensky pegmatoid, as first envisaged by Campbell *et al.* (1983). This process carried the isotopic and chemical character of the overlying resident magma down through the new magma to the base of the Merensky cyclic unit as indicated by the three isotopic profiles at the Rustenburg, Union, and Atok mines and shown schematically on the right hand side of Figure 5. Alternatively, if the crystals and sulphide droplets forming in the resident liquid settled individually through the new magma layer and accumulated at the base of the Merensky cyclic unit the new liquid would form the intercumulus (as indicated on the left hand side in Figure 5). The resultant isotopic profile would be like that at Amandelbult, since orthopyroxene and sulphide have low Sr concentrations relative to the intercumulus liquid.

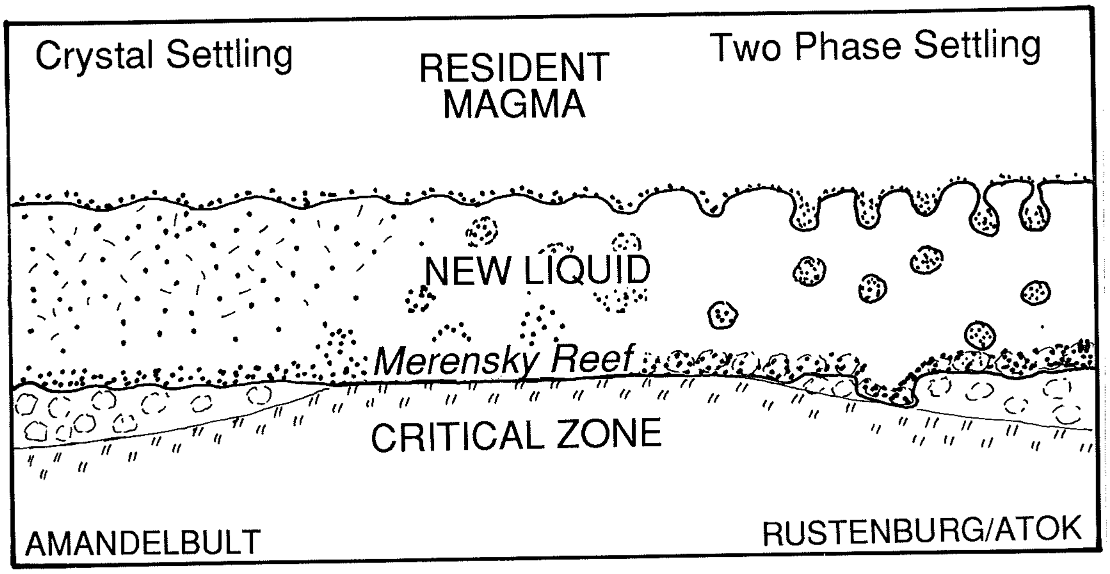

Figure 5: Schematic diagram illustrating the development of the isotopic mineralogical profiles. Accumulation of slurries of crystals and liquid on the right and crystal settling on the left as discussed in the text.

The further development of the cyclic unit would involve the *in situ* crystallization of the upper parts of the new magma layer and the expulsion of interstitial liquid as envisaged by Kruger and Marsh (1985). This could only occur once the new magma layer had changed composition (by footwall assimilation and reaction) or cooled sufficiently to crystallize.

The close similarity of the Bastard cyclic unit with the Merensky unit strongly suggests that this unit formed in a similar way from a second magma influx. In this case, the crystal settling mechanism, as envisaged at Amandelbult, would have been dominant, but the Atok data shows that the two phase packets could occasionally have formed. The resident liquid would have been significantly depleted in PGE by the precipitation of the Merensky Reef which accounts for the very low PGE tenor of the Bastard pyroxenite, despite their having formed by similar mechanisms.

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