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The Bushveld Complex, a product of interaction among magmas derived from a mantle plume

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Chromite and PGE-enriched layers in the Bushveld are modelled on a process of the cooling of resident lower zone magma by subsequent magmas parental to the lower critical zone, upper critical zone and main zone, respectively. The hot lower zone magma is considered to be derived from a mantle diapir which halted in the lower crust. Flattening of the diapir led to melting of the lower crust and formation of the lower critical zone magma. Cumulates from this crustal melt were remelted to produce the upper critical zone magma. The main zone magma is a higher-level melt of more hydrous crust.

Introduction

The Bushveld Complex is a large magmatic province of uncertain origin. Its perceived immensity has attracted speculations of extraterrestrial origin by meteorite impact (Hamilton, 1970; Rhodes, 1975) or internal origin by mantle diapirism (Sharpe *et al.*, 1981).

Unsatisfactory as these apparently non-uniformitarian hypotheses may be, attempts to apply a uniformitarian plate tectonic hypothesis to the Bushveld Complex (Van Biljon, 1976; Hatton and Sharpe, 1989) are undermined by the demonstration that the Bushveld intrusives and associated volcanics are stratigraphically divorced from the underlying sediments (Schweitzer and Hatton, 1994). Plume tectonics are increasingly summonsed to account for unusual chemistries observed in Archaean komatites (Xie *et al.*, 1993, McCuaig *et al.*, 1994) and the associations of granite rocks with komatites (Hill *et al.*, 1990), and may find application in the Bushveld Complex.

Certain features of the Bushveld Complex are consistent with a plume origin. These are the radial distribution of intrusive centres and satellite bodies (Sharpe *et al.*, 1981) and the increasing contribution of radiogenic Sr and Pb, possibly of crustal origin, during the evolution of the mafic intrusives (Krüger and Marsh 1982; Sharpe, 1985; Auret *et al.*, 1989; Krüger, 1989). Accordingly this communication will attempt to assess the application of a plume hypothesis to the Bushveld complex. To that end the character of the Bushveld parental magmas and the interactions between them will be reviewed and the genesis of the chromite and PGE-enriched layers will be considered in the framework of these interactions. The essential role that intrusion of colder magma plays in the genesis of these enriched layers and the possibility that plume tectonics might generate such cold magmas are the twin themes of this communication.

The four magma hypothesis

Field-work carried out in the marginal rocks of the eastern Bushveld Complex identified three groups, designated B1, B2 and B3 (Sharpe, 1981) (Fig. 1). The B1

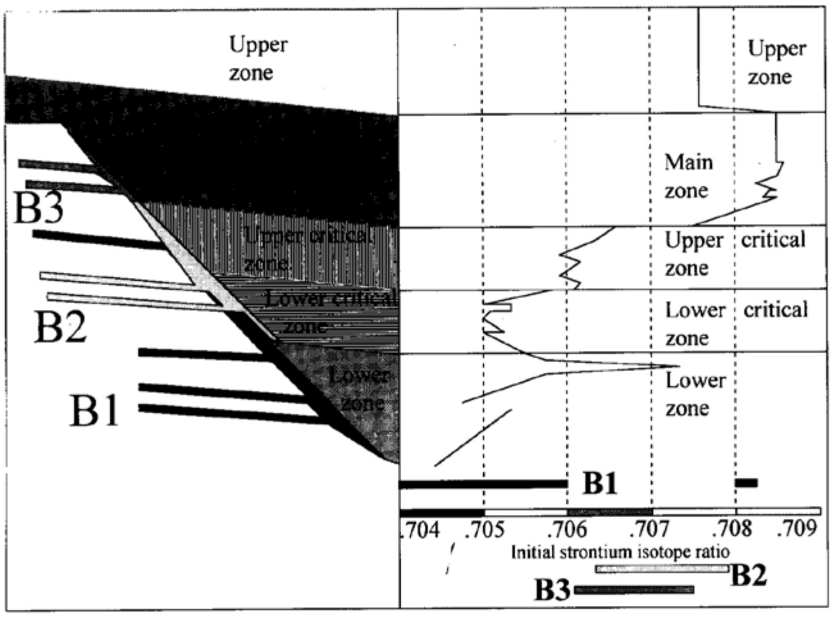

Figure 1: Diagram outlining relation of marginal rocks to the layered suite (after Sharpe, 1985), isotopic variations in the layered suite (after Kruger, 1989) and isotopic compositions of marginal rocks (after Harmer and Sharpe, 1985). It is apparent that the main zone has initial strontium isotope ratios higher than the marginal rocks.

group is adjacent to the lower zone, B2 to the critical zone and B3 adjacent to the main zone. These groups were considered to be representative of magmas intruded during the development of the zones against which they abutted. However, subsequent isotope determinations prohibit this interpretation.

Krüger and Marsh (1982) observed a major increase in the initial strontium isotope ratio from the critical to the main zone, and Sharpe (1985) measured a large number of samples through the main zone, finding a small range of about 0.7085 to 0.709. A more detailed traverse by Krüger (1989) found similar values (Fig. 1). Harmer and Sharpe (1985) determined the initial strontium isotope ratios in the marginal rocks. None have values in excess of 0.7085 (Fig. 1) and the B3 group, although abutting the main zone cannot be representative of the main zone magma. Some samples from the B I group do have high initial strontium isotope ratios (Harmer and Sharpe, 1985, Fig. 1), but these are stratigraphically well below the main zone. Accordingly Hatton (1989) concluded that the main zone magma was not represented in the marginal rocks and attempted to calculate its composition from mass balance considerations. This magma is designated B4, for consistency with Sharpe's (1981) terminology (Table 1).

It is concluded that B 1 is parental to the lower zone, B2 to the lower critical zone (Pyroxenite subzone in Sharpe, 1981), B3 to the upper critical zone, and B4 parental to the main zone. Sharpe (1985) proposed that the upper zone represents magma uplifted by intrusion of the main zone magma, so no new magma influx is necessary to account for the upper zone. Cawthorn *et al.* (1991) challenged this proposal on the grounds that the REE contents of B3 are too low for it to be parental to the main zone. However, this argument only confirms the strontium isotope evidence, (that B3 cannot be parental to the main zone) and it is only necessary to suppose that B4 had the requisite REE content to invalidate the argument for new addition of magma of the level of the upper zone. For the purposes of further discussion, it is assumed that only four magma types were involved in the genesis of the Bushveld Complex.

The cold magma hypothesis

Experimental work carried out by Sharpe (Sharpe and Irvine, 1983; Sharpe *et al.*, 1983; Irvine and Sharpe, 1986) established two vital features of the potential parental magmas; the lower zone magma is one, hotter and two, lighter than the lower critical zone magma. Hatton (1988) found that calculation supported this evidence and extended the argument to conclude that the lower zone magma was hotter and lighter than all subsequent parental magmas (Fig. 2). The consequence is that subsequent magmas intrude below the lower zone magma, chilling the basal layer of the lower zone magma and inducing crystallisation of orthopyroxene and sulphide (Fig. 3a). The orthopyroxene-enriched layer then detaches and sinks through the subsequent magma (Fig. 3b). Mixing of the magmas results in crystallisation of chromite (Irvine *et al.*, 1983; Sharpe and Irvine, 1983). During mixing, the sulphides have the opportunity to scavenge PGEs and the sulphides which accumulate at the base of the chamber are PGE-enriched (Fig. 3c). This hypothesis can be generalised to apply to several of the chromite and PGE-enriched layers in the critical zone (Reichhardt, 1989; Hatton *et al.*, 1989) but has been specifically applied to the genesis of the Merensky Reef by Hatton (1989) and Krüger (1992). Some of the potential complexities involved are considered by Hat-

	LOWER ZONE	L. CRITICAL ZONE	U. CRITCAL ZONE	MAIN ZONE	LOWER CRUST
	B1	B2	B3	B4	
SiO_2	55.7	49.9	50.8	49.4	54.4
TiO2	0.33	0.68	0.39	0.9	1
Al2O3	11.3	16.2	16.1	19.3	16.1
Cr2O3	0.13	0.02	0.04	0.01	
Fe2O3	1.83	2.18	1.89	1.5	
FeO	7.67	9.99	7.19	8.3	10.6
MnO	0.18	0.2	0.16	0.15	
MgO	13	6.94	8.26	6.6	6.3
CaO	6.38	11.6	11.5	9.7	8.5
Na2O	1.73	2.15	2.32	2.6	2.8
K2O	0.89	0.15	0.2	0.36	0.34
LOI	0.22	-0.3	-0.15	0.9	
H2O	0.07	0.06	0.07	0.1	
Rb	99.43	99.77	98.77	99.82	100.04
Sr	33	2	3		
T liquidus	182	347	330		
Density	1290	1200	1203	1260	
	2.63	2.704	2.663	2.662	

Table 1: Compositions of Bushveld parental magmas and the lower crust (Taylor and McLennan, 1985). B1, B2 and B3 are averages of the compositions given by Harmer and Sharpe (1985) and B4 is as calculated by Hatton

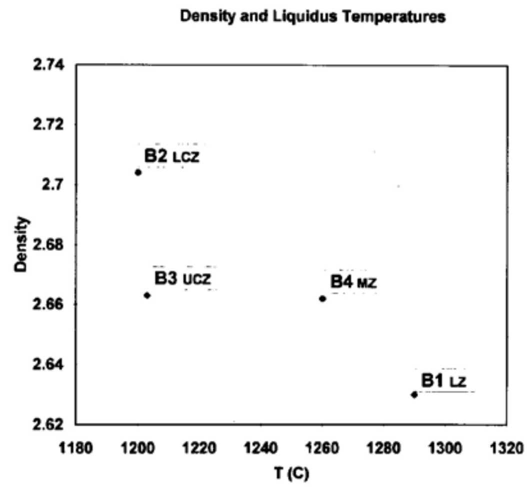

Figure 2: Liquidus temperatures of the parental magmas (after Sharpe and Irvine, 1983; Hatton, 1989) and densities calculated from Lange and Carmichael (1987). The compositions used in the density calculations are the averages of B1-B3 from Harmer and Sharpe (1985) and the calculated B4 composition of Hatton (1989).

ton (1989), and the hypothesis can also be extended to account for regional variations in the critical zone. For example Hatton and von Gruenewaldt (1987) record that the lower group of chromite layers is not developed in the southern portions of the Bushveld Complex, where the lower zone is very thin. Instead norites are present at levels in the lower critical zone where these layers are to be expected. The thin development of the lower zone allows rapid heat loss of the newly intruded lower critical zone magma, so that it would quickly become too viscous to allow efficient mixing, with consequent crystallisation of norite rather than chromitite.

Eales *et al.* (1989) specifically reject models which advocate addition of aluminous magmas, such as the B2, B3 and B4 magmas, on the grounds that magma addition is generally associated with the re-appearance of primitive orthopyroxene compositions. However, the hypothesis advanced here counters this argument by proposing that addition of cold magma triggers crystallisation of primitive orthopyroxene from the lower zone magma which overlies the newly intruded magma.

From the aforementioned it is argued that the development of an initial hot, light magma and subsequent development of subsequent colder and denser magma are essential features in any hypothesis for the origin of the Bushveld magmas. The remainder of this communication explores a hypothesis which incorporates these features.

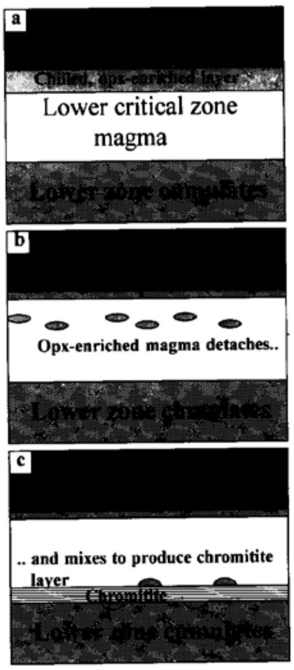

Figure 3: Diagram illustrating (a) the chilling of lower zone magma by newly intruded magma, (b) detachment of the basal orthopyroxene-enriched layer, and (c) mixing to produce chromitite layers.

Plume hypothesis

Parental magma compositions

Noteworthy features of the lower zone magma include its high K_2O and Rb contents (Table 1) which are nonetheless associated with low initial strontium isotope ratios (Fig. 1). Since high Rb contents will in time lead to high strontium isotope ratios it must be argued that Rb was introduced shortly before emplacement of the lower zone magma.

The noteworthy features of the lower and upper critical zone are the lower REE contents and the more pronounced Eu anomaly in the upper critical zone magma, relative to the lower critical zone magma (Fig. 4). Initial strontium isotope ratios of these magmas are similar (Fig. 1) (Harmer and Sharpe, 1985) and a possible relationship between them is that the upper critical zone magma is enriched in cumulates relative to the lower critical zone magma. Remelting of cumulates, by a very large heat source, is a hypothesis which is explored in a

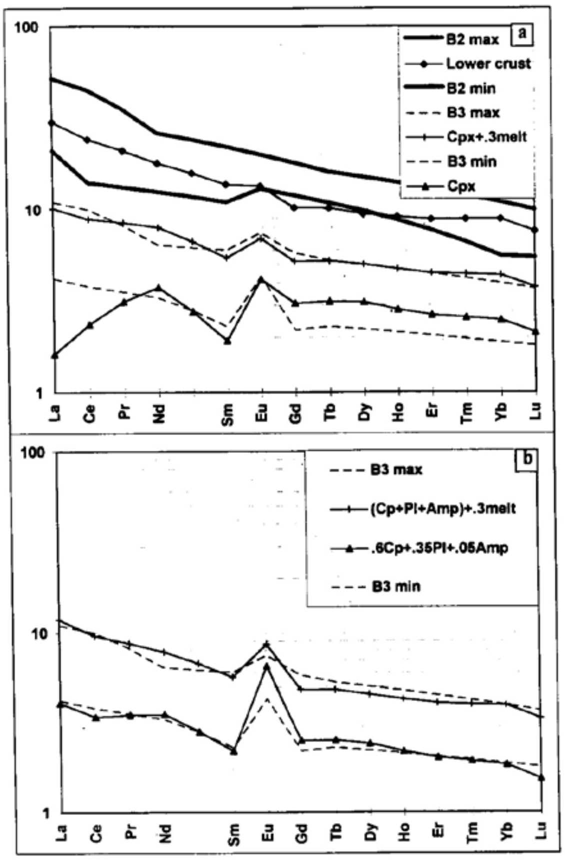

Figure 4: (a) REE patterns of the B2 group, parental to the lower critical zone; of the B3 group, parental to the upper critical zone; and of the lower crust (Harmer and Sharpe, 1985; Taylor and McLennan, 1985). The pattern for the clinopyroxene cumulate was calculated with distribution coefficients given in Table 2. (b) REE patterns in the B3 group, and in a cumulate consisting of 0.6 clinopyroxene, 0.35 plagioclase and 0.05 amphibole. A mixture of this cumulate with 30% of molten lower crust is also shown.

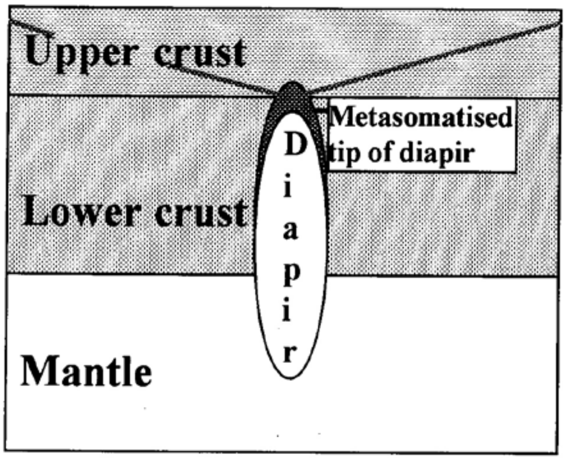

Figure 5: Intrusion and metasomatism of a mantle diapir to generate the lower zone magma.

subsequent section.

The composition of the main zone magma is not based on possible natural examples, and detailed speculation on its origin is not attempted.

Metasomatism of a Mantle Diapir

The lower zone magma possesses high Cr and Mg contents, which are indicative of a primary mantle source. Silica contents are high and this has been linked to crustal contamination. This is not necessarily so as primary mantle melts have high silica contents during high degrees of melting at relatively shallow levels (Jaques and Green, 1980; Takahashi *et al.*, 1993). The strength of the crust is largely contained in the upper 10 - 20 km, and an ascending diapir is likely to be halted at this level (Glazner, 1994). Taking the level at which ascent halted as 15 km, and extrapolating the zero pressure liquidus temperature of 1290°C (Sharpe and Irvine, 1983) gives a pressure of 0.5 GPa and temperature of 1350°C. Under these conditions a mantle melt has a silica content of 53 wt% and MgO of 13 wt% (Fig. 9 in Takahashi *et al.*, 1993). Both these values fall within the range of B 1 compositions given by Harmer and Sharpe (1985) although silica contents are generally higher than 53 wt%. Nevertheless, these data are consistent with origin of the lower zone magma as a primary mantle melt. K_2O contents, however, are almost two orders of magnitude higher than those expected in a primary mantle magma. How can this feature be accounted for? Watson (1982) noted that selective contamination of a basaltic magma was particularly likely for K_2O because of the high diffusivity of K_2O and the strong activity gradient between the magma and broadly granitic crust. Other elements likely to be affected are REE and Zr, both of which are high in the lower zone magma. Significantly, diffusive contamination was considered unlikely to markedly affect strontium isotope ratios (Watson, 1982).

The lower zone magma might therefore have originated by diffusive contamination, or metasomatism of a mantle diapir emplaced into the middle crust (Fig. 5).

Crustal melts and cumulates

The lower critical zone magma has a REE pattern which is similar to the average lower crustal composition of Taylor and McLennan (1985), (Fig. 4a). The major element chemistry also, is reasonably similar, although the calculated lower crust of Taylor and McLennan (1985) is higher in silica and lower in CaO than the lower critical zone magma. Given the likelihood of some regional variation in the composition of the lower crust, it is possible to equate the lower critical zone magma with a high degree melt of the lower crust. Taylor *et al.* (1984) have previously ascribed lower crustal melting to a mantle plume, and flattening out of the mantle plume invoked earlier for the lower zone critical zone magma, could generate the lower critical zone magma (Fig. 6a).

The upper critical zone magma appears to be cumulate-enriched, and the obvious possibility is that plagioclase has been entrained. However, admixture of

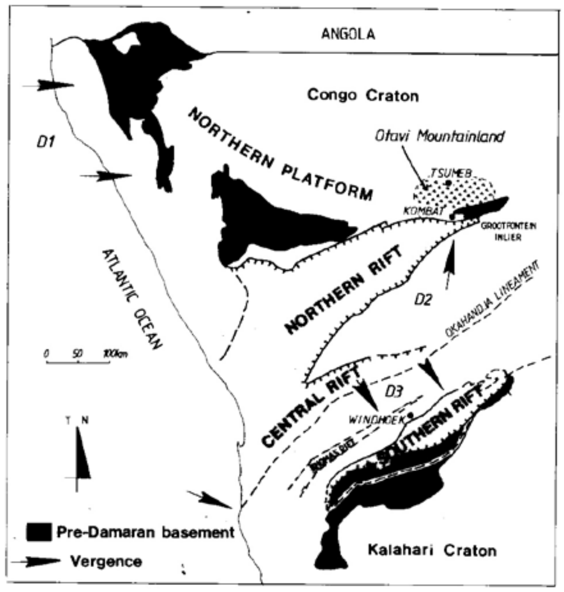

Figure 1: Geological map of the Damara Province showing a: the locality of the Kombat Mine; b: the early rift evolution; c: the dominant structural directions that affected the Kombat area during the Damara orogen; d: the pre-Damara basement inliers. Modified after Miller (1983) and Porada (1985).

plagioclase alone produces a REE pattern (not shown), which has too large a Eu- anomaly and heavy REE contents which are too low to satisfy the observed pattern in the upper critical zone magma.

Mixture of a monomineralic clinopyroxene cumulate, with a composition calculated from distribution coefficients in Table 2, with 30% of the lower crustal composition, produces a pattern which closely reproduces the pattern in REE-rich members of the B3 (upper critical zone) group (Fig. 5a). However, the clinopyroxene cumulate has a light REE pattern which does not match the REE poor members (Fig. 5a). To obtain a closer match it is necessary to include amphibole and plagioclase in the cumulate (Fig. 5b). The Eu anomaly is too large, but otherwise the cumulate is a good match for the REE poor members, and cumulate plus 30% melt matches the REE rich members of the B3 group (Fig. 5b)..

The inclusion of a small amount of amphibole is interesting in that it suggests that the crust which was melted to produce the critical zone magmas (Fig. 6b) was slightly hydrous. The next stage in the evolution of the Bushveld Complex is generation of the main zone magma, and it is an easy step to follow the situation depicted in Fig. 6b with higher level melting of the crust. If the higher level crust was more hydrous, melting would be more extensive; so accounting for the larger volume of the main zone magma relative to the critical zone (Hatton, 1989). Addition of more hydrous magma might be a factor in the observation that contact metamorphism below the lower zone produced anhydrous assemblages, whilst contact metamorphic assemblages above the upper zone are hydrated (Wallmach and Hatton, 1994).

	Lower crust	D(plag)	D(amp)	D(cp)
La	11	0.27	0.17	0.054
Ce	23	0.2	0.26	0.098
Pr	2.8	0.17	0.35	0.15
Nd	12.7	0.14	0.44	0.21
Sm	3.17	0.11	0.76	0.14
Eu	1.17	0.73	0.88	0.31
Gd	3.13	0.066	0.86	0.3
Tb	0.59	0.06	0.83	0.31
Dy	3.6	0.055	0.78	0.33
Ho	0.77	0.048	0.73	0.31
Er	2.2	0.041	0.68	0.3
Tm	0.32	0.036	0.64	0.29
Yb	2.2	0.031	0.59	0.28
Lu	0.29	0.025	0.51	0.28

Table 2: REE contents of lower crust (Taylor and McLennan, 1985) and distribution coefficients for clinopyroxene, plagioclase and amphibole (McKenzie and O'Nions, 1991).

Conclusion

The chilling of early hot and light magma has been advanced as the underlying mechanism in the genesis of the chromite and PGE-enriched layers of the Bushveld Complex. An early phase of focused intrusion of a mantle diapir and associated diffusive contamination is invoked for the genesis of this magma. Flattening of the diapir leads to widespread melting of the crust and generation of the requisite colder, but denser magmas. In the first stage a high degree crustal melt is produced, then cumulates from this melt are remelted. In the final stage widespread melting at shallower crustal levels produces the terminal main zone magma.

Application of the mantle plume model (Hill, 1993) to the Proterozoic Bushveld Complex, suggests that in the Archaean and early Proterozoic plume tectonics may have been a process of equivalent importance to plate tectonics in the generation of the preserved rock record.

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