# Unusual textures and structures associated with a magnetitite layer in the Bushveld Complex: a contribution to the adcumulus debate

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**Abstract**

In the Brits area of the Bushveld Complex, the stratigraphically lowermost magnetitite layer of the Upper Zone is underlain by an anorthosite containing discrete, euhedral magnetite crystals, measuring 0.1–0.3 mm in diameter, which form thin layers (1 mm–1 cm thick) and laminae (commonly one grain in thickness). Discordant relationships between laminae and layers indicate a consistent younging direction upwards towards the contact with the overlying magnetitite. Our interpretation is that these crystals are cumulus and have escaped modification by postcumulus overgrowth. They also record, in places, the morphology of the floor onto which they accumulated. Their preservation is largely attributed to adcumulus growth of plagioclase before, during and after, accumulation, but may also indicate that there was only a limited supply of magnetite to the floor, thus precluding grain contact and prohibiting grain enlargement. The results of a study of compositional variations across individual plagioclase grains suggest that the presence of magnetite within the crystallising mush hindered the development of an ideal plagioclase adcumulate.

KEYWORDS: Bushveld Complex, Upper Zone, magnetitite, adcumulus growth, anorthosite.

## Introduction

AN intriguing, and as yet unresolved problem in the study of layered intrusions is the formation of rocks which exhibit adcumulus texture—that is, cumulates containing little or no recognisable interstitial material. One approach to an understanding of the textural evolution of adcumulates is to study examples in which the cumulus crystals are preserved (often by oikocrysts) at different stages during progressive elimination of the initial porosity, ideally covering the interval between accumulation and complete solidification. In this way, a tentative reconstruction of events can be made. This paper documents some unusual small-scale structures formed by discrete, euhedral magnetite crystals within an anorthosite immediately below a prominent magnetitite layer, from the Upper Zone of the Bushveld Complex, South Africa. It is argued that the primary (*cumulus*) grain sizes of the magnetites, and the structures that they display, have been preserved by adcumulus growth of plagioclase before, during and after accumulation of the magnetite. A tentative reconstruction of the solidification history can be attempted for these cumulates.

## Geological background to the study material

The uppermost zone, or Upper Zone, of the Bushveld layered sequence, which is of particular interest here, probably contains the widest variety of cumulus minerals in the Complex. In general terms, magnetite (+ plagioclase) first occurs in two-pyroxene gabbroic cumulates at the base of the zone; upwards, normal gabbros give way to fayalitic olivine gabbros and diorites; and finally, apatite, and even hornblende, appear in the upper, most highly fractionated rocks (see Willemse, 1969; Molyneux, 1970; Von

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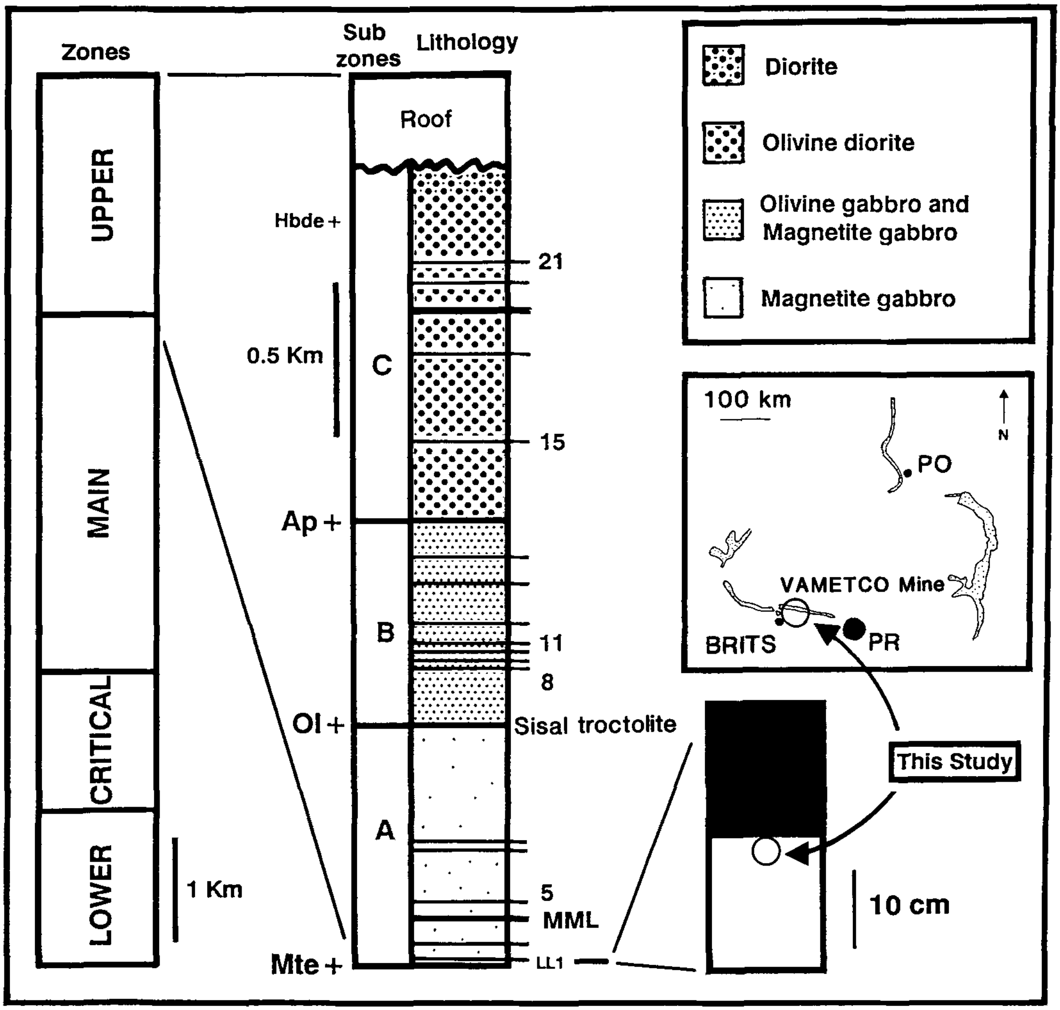


FIG. 1. Summary diagram showing: generalised zonal subdivision of the Bushveld Complex; detail of the Upper Zone (compiled from data collected by Molyneux (1970) and Von Gruenewaldt (1973) in the eastern Bushveld); and stratigraphic and geographic position (inset) of the specimens reported here. Horizontal lines in Upper Zone profile indicate magnetite layers (some are numbered); information on incoming and outgoing cumulus phases is also given. LL1 (interpreted to be Lower Layer 1); MML (Main Magnetite Layer). Inset shows distribution of Upper Zone cumulates only. PO: Potgietersrus; PR: Pretoria.

Gruenewaldt, 1973; and Reynolds, 1985*a*, for further details).

Cumulus magnetite, although present in most rocks of the Upper Zone, is not evenly distributed throughout it. Characteristically, it forms anchi-monomineralic layers (magnetitites), and 25 such layers have been clearly identified in the eastern Bushveld (Fig.1, and Molyneux, 1970). Lower contacts of magnetitite layers are often knife sharp, with footwall lithologies typically comprising a plagioclase adcumulate (anorthosite), ranging in thickness from as little as 1 cm or as much as 3 m, in which magnetite is either intercumulus in habit, or absent. This is typically underlain in turn by magnetite-rich gabbro, containing 8–10% magnetite by volume. Upper contacts are quite different (see Molyneux, 1970, Fig. 4), being gradational upwards over several centimetres, from pure magnetitite into feldspathic magnetitite and finally to magnetite-rich gabbro. The relative proportions of pure magnetitite to overlying feldspathic magnetitite, as well as the combined thicknesses of these lithologies, are highly variable from one layer to the next (see Von Gruenewaldt, 1973, for further details).

During field investigations in the Brits area of the Bushveld Complex (Fig. 1), which formed part of a wider investigation into the origin of Upper Zone magnetitites (Butcher and Merkle, 1986; Merkle and Von Gruenewaldt, 1986; Butcher *et al.*, 1989; and Harney *et al.*, 1990*b*), sampling was carried out in the open-cast pit at the VAMETCO magnetite mine, which affords exposures through a layered succession at the base of the Upper Zone, comprising magnetitites, magnetite-gabbros and anorthosites.

The footwall anorthosite below the lowest magnetitite layer (likely to be equivalent to Lower Layer 1 in the eastern Bushveld, although to date no detailed correlation has been attempted) contains a scattering of small cumulus magnetite grains. The resultant speckled texture is quite distinct from the more typically mottled anorthosites containing poikilitic crystals of intercumulus magnetite and pyroxene (Von Gruenewaldt, 1973).

In view of this find, sampling of the anorthosite was carried out in as much detail as the exposure allowed (limited to 3 m of strike length, mainly because of mining activity); all specimens collected were orientated before extraction, and ideally contained an intact contact between anorthosite and the magnetitite layer. Careful logging of the sequence up-stratigraphy within the pit suggested that the collected samples are unique to this particular horizon. Unfortunately, mining activities in the pit after our visit have made resampling of this horizon extremely unlikely in the future.

The lateral extent of the anorthosite beyond the area exposed by mining could not be determined because outcrop in this part of the Bushveld is extremely poor, and where present, exposures are often highly altered, particularly the plagioclase-rich cumulates, which are especially susceptible to weathering.

## Textural features of the footwall anorthosite

### *Observations from polished slabs*

Initially, all specimens were cut and polished, and then inspected under a binocular microscope. Figs. 2 and 3 record some of the features observed, which include: magnetitite laminae commonly only one grain in thickness; thin magnetitite layers developed on both a mm- and a cm-scale; discordant (truncation) relationships between one lamina and another, one layer and


FIG. 2. Accurate composite sketch of four sides (all cut 90 degrees to each other) of a polished block of footwall anorthosite from the VAMETCO mine near Brits. Each dot represents a single magnetite crystal; solid black is the magnetitite layer, presumed to be equivalent to Lower Layer 1 in the eastern Bushveld; and unornamented area represents plagioclase. Arrow indicates way-up of specimen as determined when collected. Apparent cross-cutting relationships are well displayed in the middle 2 panels.

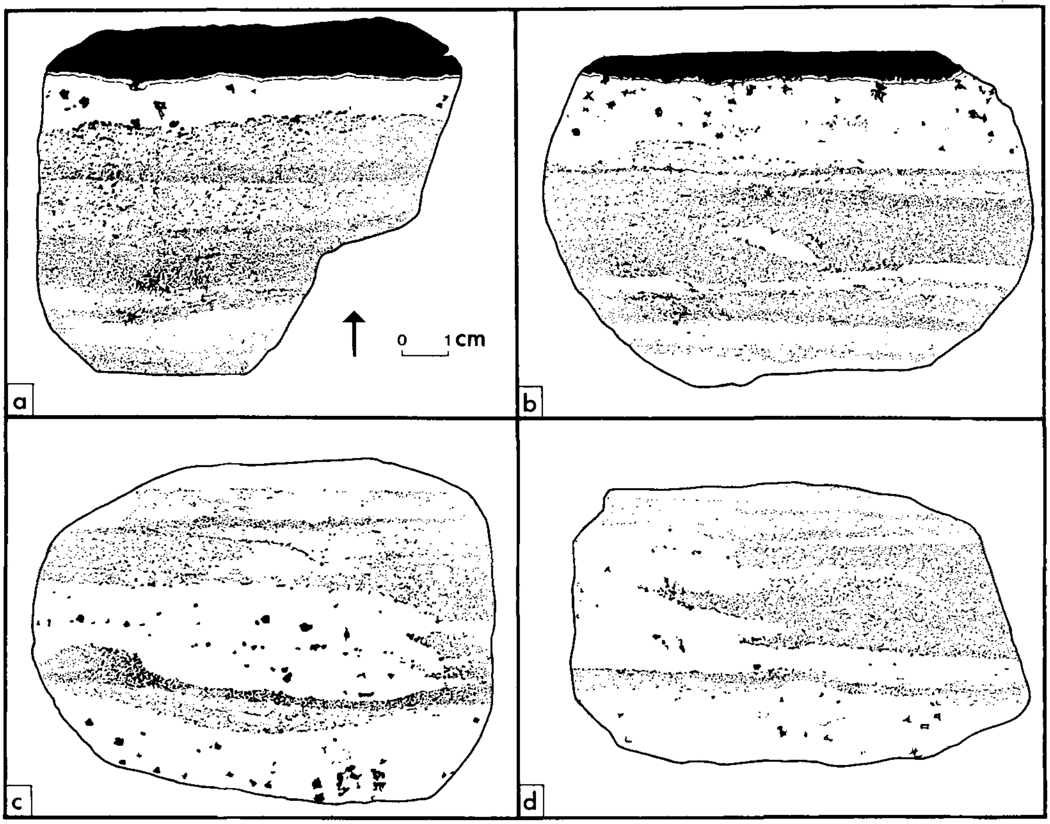


FIG. 3. Accurate reproduction of structures displayed by polished specimens of footwall anorthosite. Dots represent single magnetite crystals; unornamented area is plagioclase; and solid black, magnetitite. Scales and way-up directions are the same for all specimens. More detail on (*c*) is given in Fig. 5.

another, and between laminae and layers, all indicating a consistent younging direction upwards towards the anorthosite–magnetite contact. Highly irregular clusters of magnetite occur in the anorthosite immediately beneath the contact.

### *Observations from thin sections*

The anorthosite is essentially bi-mineralic, comprising only plagioclase and magnetite. Clusters, comprising magnetite and associated alteration products, which often enclose numerous, tiny plagioclase crystals (Fig. 5*c*), are interpreted as areas once occupied by intercumulus pyroxene (now altered).

*Magnetite grain size.* Under high-power magnification, individual magnetite grains appear euhedral, often forming well-developed octahedra (Fig. 4*a, b, d*), and can therefore be considered to have cumulus status. In reflected light, the magnetite is clearly altered to varying degrees—a common phenomenon in the Bushveld, even within the freshest of drill core material (Reynolds, 1985*b*).

Almost all of the magnetite grains are discrete, although occasionally a pair of crystals can be found attached to each other, but a euhedral form is still apparent (Fig. 4*d*). Examples of three or more crystals in contact are exceptionally rare, and the maximum found in any thin section studied was five (Fig. 4*a*). Again, an octahedral form is still discernible.

The grain size of the magnetite crystals remains remarkably consistent within all specimens of anorthosite studied (despite the 2-D limitations of thin sections), and lies in the range 0.1–0.3 mm (diameter). There appears therefore to be no correlation between magnetite grain size and layer thickness. An exceptional grain measuring 1 mm in diameter was found in one specimen where it occurred in complete isolation within pure anorthosite (Fig. 4c). (In the magnetitite layer directly overlying the anorthosite (LL1?), magnetite crystal diameters commonly exceed 10 mm, and can be as much as 20 mm.)

*Relationships between magnetite and plagioclase.* Taking the simplest case first, i.e. that of a single magnetite *lamina* one crystal thick (Fig. 5*a*), it is apparent that the magnetite crystals which define the lamina almost always lie on, or close to, plagioclase grain boundaries. This relationship generally holds true whether the lamina is parallel to surrounding structures (other laminae or layers), or whether it is clearly discordant (Fig. 5*a*). Exceptions to this rule can be found but only by tracing individual laminae for several cms and observing their relationships to surrounding plagioclases in extreme detail. In one sample (Fig. 6), a distinctive couplet of magnetitite laminae was found where, in places, the upper lamina appeared to cut across plagioclase grains, while the lower lamina remained on, or close to, grain boundaries.

Structures developed within the footwall anorthosite on a much larger scale include thin *layers* (1 mm–1 cm) of magnetitite set in a matrix composed only of plagioclase (see Fig. 5*b* and Fig. 7). The following is a summary of typical features displayed by these layers:

(*a*) contacts with under- and overlying anorthosite are abrupt;
(*b*) layers are often laterally impersistent, and apparent erosional characteristics are evident (see Fig. 5*b*, and *d* for an interpretation);
(*c*) magnetite-rich layer (or matrix) plagioclase is always much finer-grained than that in the contiguous anorthosite. As grain shapes are characteristically anhedral, there is no tendency for matrix plagioclase to develop a preferred orientation (igneous lamination);
(*d*) mutual grain boundaries of plagioclases within layers are highly irregular, whereas those outside in the anorthosite are either straight or slightly curved, often resulting in 120° triple junctions;
(*e*) there is no indication of mineral grading within layers, either in terms of grain size or mode;
(*f*) there is little or no evidence of coalescence of individual magnetite crystals.

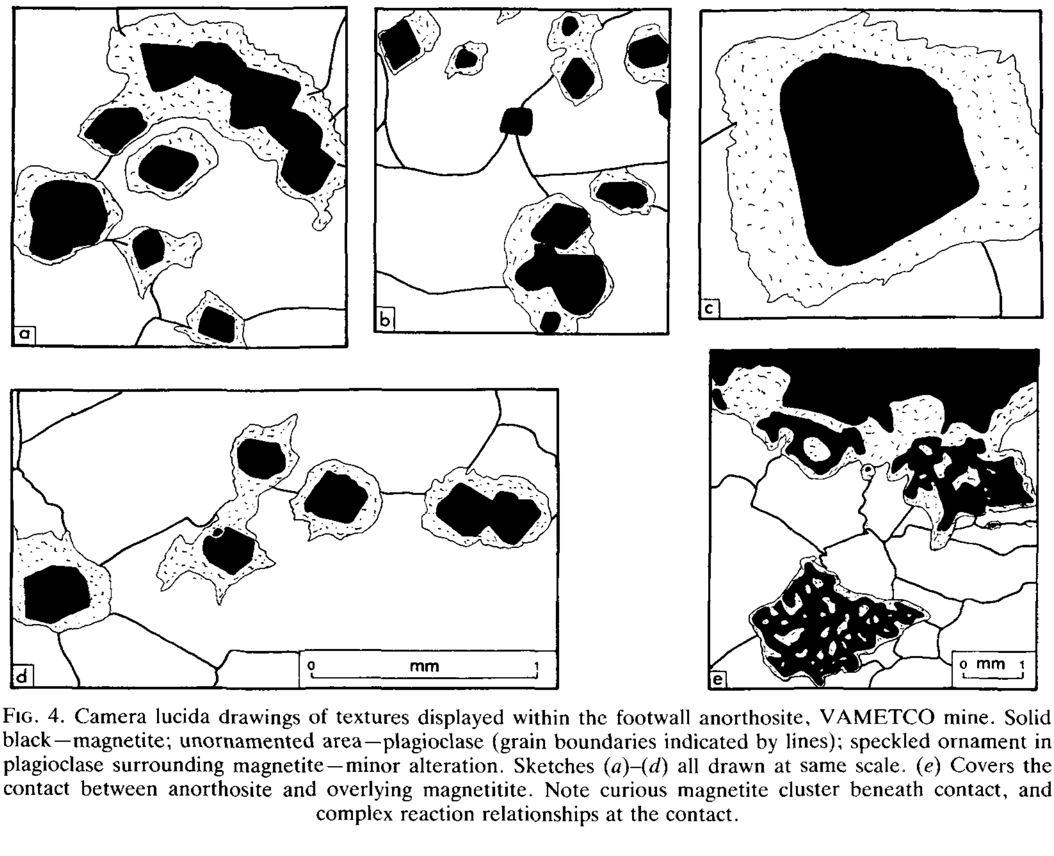


FIG. 4. Camera lucida drawings of textures displayed within the footwall anorthosite, VAMETCO mine. Solid black—magnetite; unornamented area—plagioclase (grain boundaries indicated by lines); speckled ornament in plagioclase surrounding magnetite—minor alteration. Sketches (*a*)–(*d*) all drawn at same scale. (*e*) Covers the contact between anorthosite and overlying magnetitite. Note curious magnetite cluster beneath contact, and complex reaction relationships at the contact.

## Micro-compositional data

The electron microprobe has been used to investigate the relationships between plagioclase composition and textural setting. Unfortunately, it was not possible to study the magnetite composition, due to the degree of alteration. The technique of detailed mineral analysis employed here (referred to as 'micro-mapping'), is similar to that used by Butcher (1985) and Butcher and Merkle (1986). This involves mapping the compositions of individual grains onto specially prepared A4-sized photomicrographs (or camera lucida drawings) of the thin section under analysis. The micro-mapping is undertaken at the same time the specimen is probed, thus allowing the compositional relationships of one grain to another to be determined immediately, which in turn acts as a useful guide for selecting further grains for analysis. Thus, the end result is a mineral compositional map of a thin section, and a full record of all minerals analysed.

Presented below are the compositions of individual plagioclase grains, as determined by detailed microprobe traverses (operating conditions are given in the Appendix), in 3 contrasting textural settings. Each traverse was undertaken to investigate rim–core–rim relationships.

*Plagioclase associated with magnetite laminae*

In Fig. 6, a parallel couplet of magnetitite laminae, set in a coarse-grained plagioclase matrix, is illustrated. Prior to probing, it was noted that some plagioclase grains had highly irregular mutual boundaries, while others were straight or slightly curved. This difference appeared to be related to whether the boundaries had developed close to laminae (irregular), or, far away from laminae (straight).

Traverse *o–p* (Fig. 6) details the compositional behaviour across a single plagioclase grain, together with rim compositions of contiguous grains. The results, presented in terms of anorthite content (An), and cation proportions of K and Fe, show that with respect to An-content, the grain is essentially unzoned for the most part (average composition $An_{60}$). However, weak

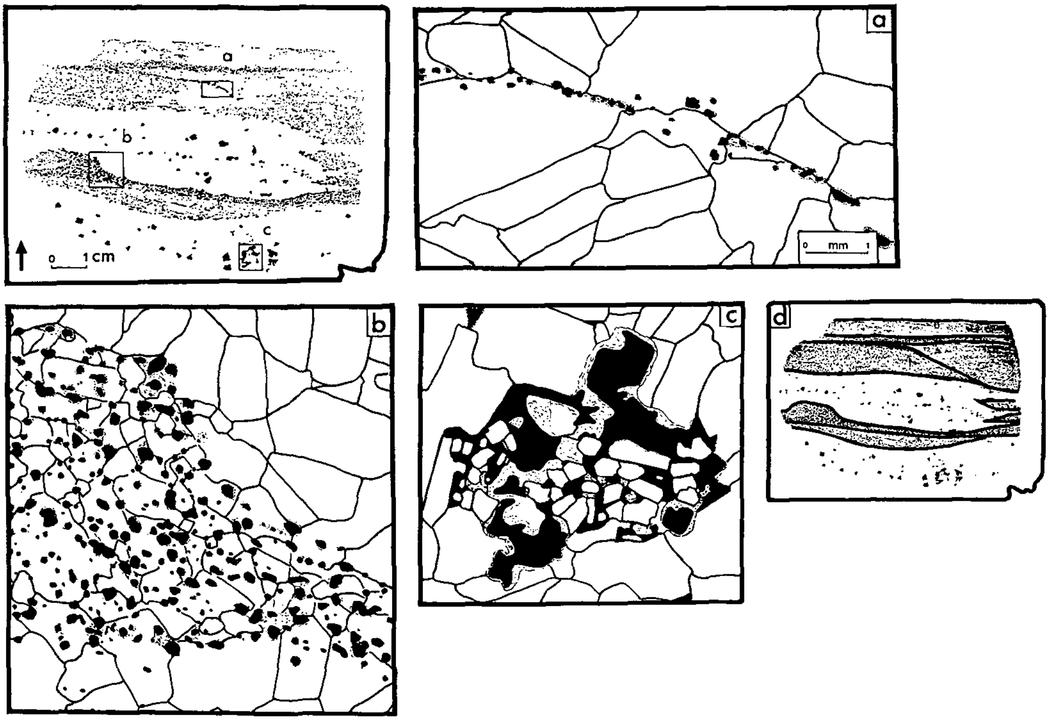


FIG. 5. Camera lucida drawings made from an extra-large thin-section of footwall anorthosite. (*a*) Detail of a discordant magnetite lamina; (*b*) detail of a thin magnetite layer showing erosional characteristics on upper contact; (*c*) interstitial magnetite (plus silicate alteration products, stippled ornament) enclosing several euhedral to subhedral (cumulus?) plagioclase crystals; (*d*) an interpretation of the structures, emphasising the discordant nature and erosional characteristics of many of the layers and laminae, and consistent younging direction (arrow). Scales for (*a*)–(*c*) are the same.

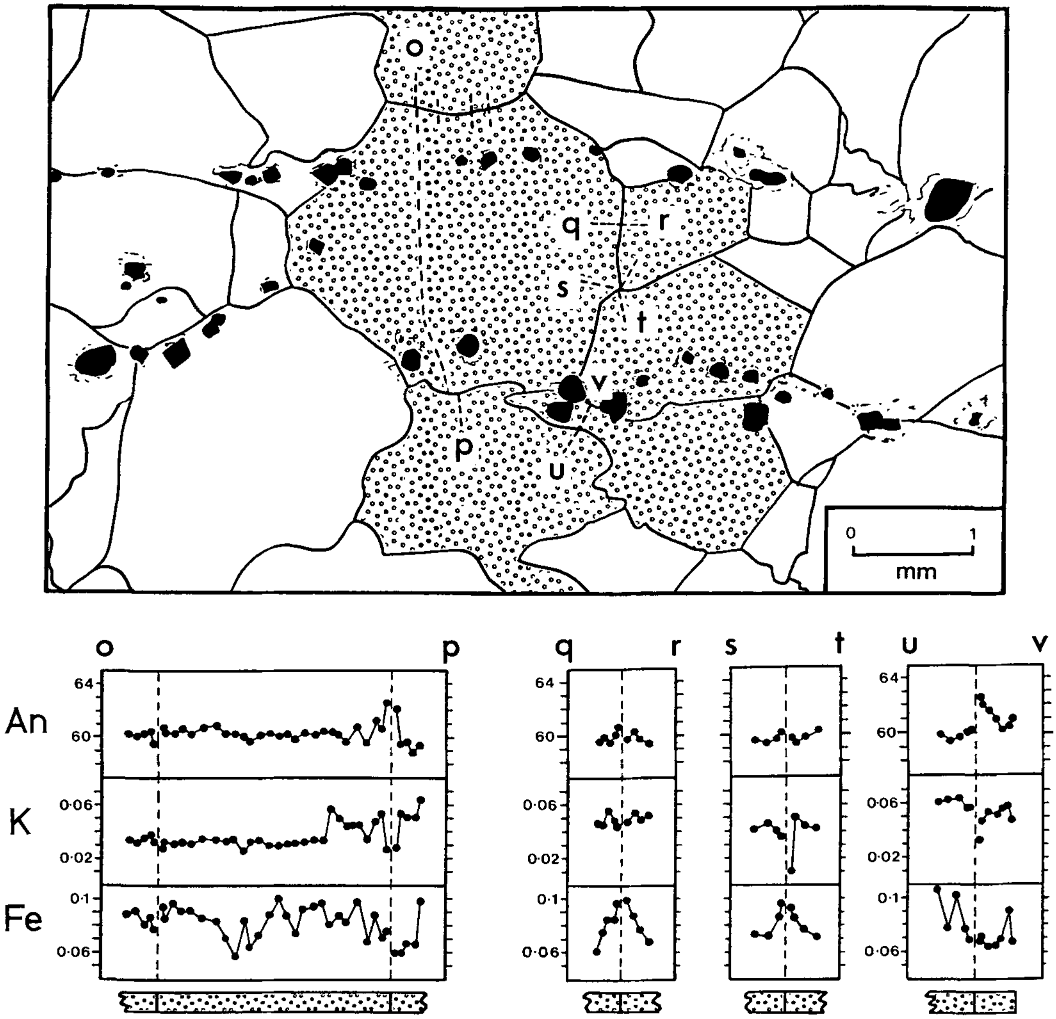


FIG. 6. Camera lucida drawing of a magnetitite laminae couplet showing the positions of microprobe traverses (dashed lines) in relation to plagioclase grain boundaries (solid lines) and magnetite crystals (solid black). Underneath are the composition profiles for traverses *o–p*, *q–r*, *s–t*, and *u–v*; each dot represents a single microprobe analysis; vertical dashed lines are grain boundaries. Plagioclase grains which were investigated are ornamented for clarity.

anorthite-enrichment (i.e. reverse zoning) is evident towards the rim in the direction of *p*, where the mutual grain boundary is complex. Interestingly enough, no such Ca-enrichment is found in the direction of *o*, where the boundary is straight or slightly curved. Touching grains appear to match this asymmetry in the chemistry. A similar but antithetic trend is displayed by K. Iron-contents are highly variable.

This relationship between grain boundary geometry and the presence or absence of rim zoning was investigated further by performing traverses across a selection of grains exhibiting different types of junction (Fig. 6): *q–r* (straight boundary), *u–v* (irregular) and *s–t* (a triple point). The results confirmed the earlier findings:

(*a*) where grain boundaries are straight or curved, An-contents of touching plagioclases are the same, and there is no evidence of marginal zoning in terms of this parameter (Fig. 7 *q–r*; *s–t*). Fe-contents, however, increase markedly towards the rims;

(*b*) weak enrichment in An-component of rims is

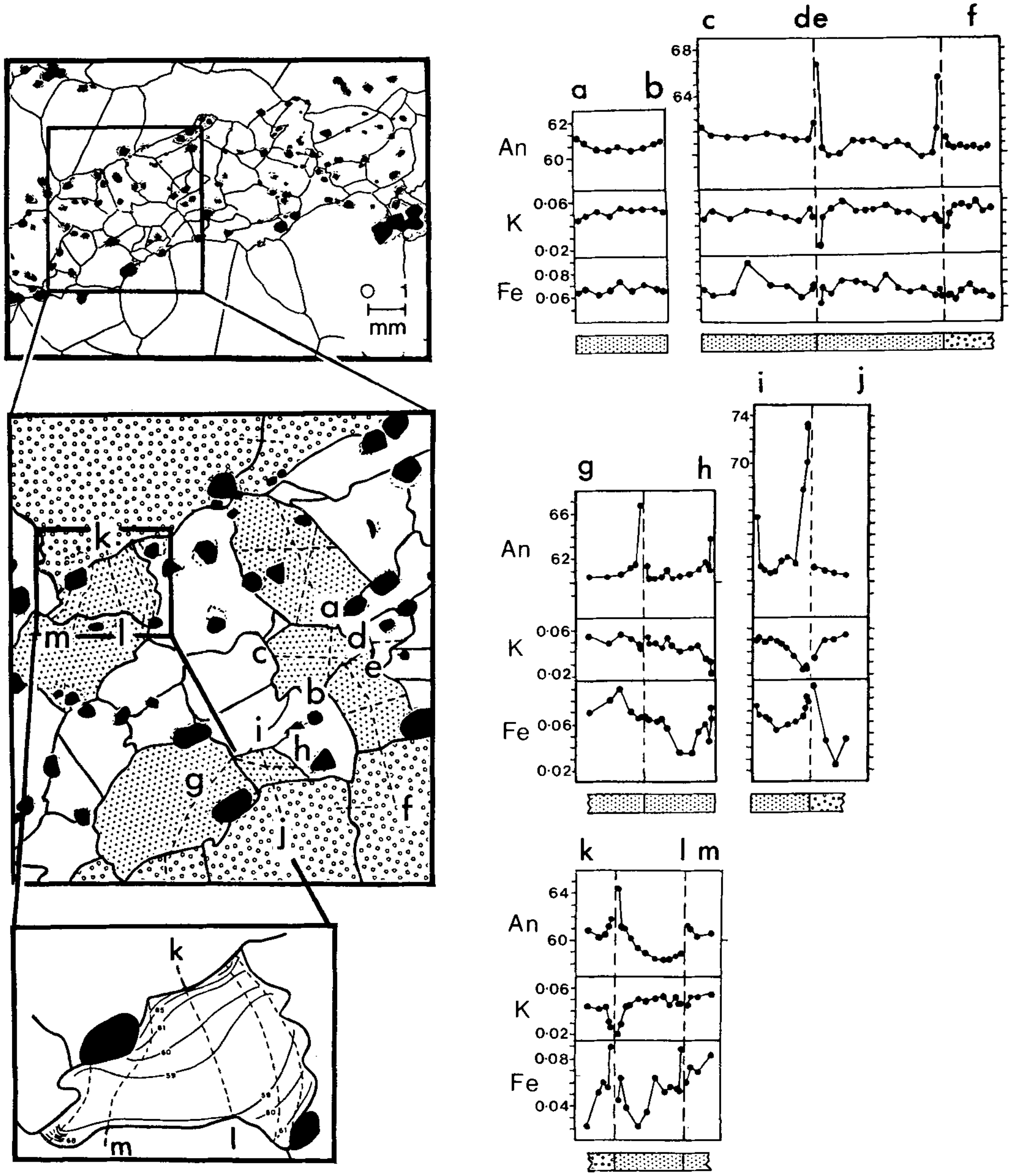


FIG. 7. Left-hand side: drawings of a thin magnetite layer within the footwall anorthosite from VAMETCO magnetite mine. Traverse lines indicated by dashes (those for which compositional data are presented are labelled by letter); plagioclase grain boundaries by solid lines; and magnetite crystals, by solid black. Ornamented plagioclases are those analysed within the layer (dot stipple) or in the surrounding anorthosite (open-circle stipple). Small inset is an enlargement of a grain contoured in terms of anorthite component. Right-hand side: compositional profiles for traverses indicated on drawings. Vertical dashed lines are plagioclase grain boundaries.

apparent in touching grains that have complex mutual grain boundaries (Fig. 6*u–v*), and this is accompanied by Fe- and K-depletion.

In summary, then, there appears to be a clear relationship between grain boundary geometry and zonation in plagioclase on the one hand, and proximity of magnetite crystals to those grain boundaries on the other.

*Plagioclase associated with magnetitite layers*

For this purpose, a well-defined layer approximately 3 mm thick was chosen (Fig. 7). The composition profiles of plagioclases above, below and within the layer were investigated. Inspection of Fig. 7 reveals that, in terms of An-content, the analysed plagioclase grains are homogeneous within their core regions (most lie in the range $An_{60-61}$—the same as that for plagioclase near laminae), but are always reversely zoned at their rims. This zoning may be weak (2–3% An), marked (6–8% An; profile *e–f*) or extreme (up to 14% An; profile *i–j*). It can also be highly variable in width, even within a single crystal (typical range 10–300 μm) often leading to a marked asymmetry in the composition profile. An extreme example of this asymmetry (the grain encountered in profile *k–l–m*) is illustrated in Fig. 7, where 5 detailed profiles across the grain have enabled a compositional map to be constructed. Note that rim compositions more calcic than $An_{61}$ are not developed everywhere.

The profiles for K-contents along plagioclase grains are less impressive, although an antithetic behaviour with An-content is evident; variation in Fe-content is less clear, but in some cases (profiles *g–h*; *i–j*), an enrichment towards the rim is apparent.

Note in Fig. 7 that large grains in contact with the magnetitite-*layer* plagioclases (traverses *e–f* and *i–j*) also show subdued marginal zoning.

*Plagioclase in anorthosite (magnetite-free)*

For completeness, the compositions of a few plagioclases in areas completely free of magnetite (i.e. pure anorthosite) were checked. They all appear to be unzoned, with An-contents indistinguishable from core compositions of grains associated with magnetite laminae and layers.

## Summary and discussion

The characteristic euhedral habit of the magnetite grains in the footwall anorthosite strongly suggests that they are cumulus crystals. The uniformity of grain size (0.1–0.3 mm), irrespective of textural setting (i.e. layer or lamina), might indicate that they are all of the same generation. The lack of evidence of grain coalescence suggests that little or no post-depositional growth has taken place. Thus, the preserved crystals provide insights into the morphology and crystal size of Bushveld magnetite primocrysts. The question as to whether such depositional grain sizes also applied to the overlying massive magnetitite layer (where the final grain size commonly exceeds 1 cm) remains unanswered at this stage.

The apparent discordant relationships displayed by magnetite laminae and layers suggests that the floor onto which they accumulated was periodically scoured. The exact nature of this scouring process (mechanical or thermo-chemical) is difficult to establish, although the observation made above that magnetite crystals often lie on, or close to, present-day plagioclase grain boundaries, is obviously pertinent. Neither process can be completely ruled out at this stage, mainly because the Bushveld magma types have not yet been fully characterised in terms of precise composition, and temperature–density–viscosity relations (see Hatton and Sharpe, 1989, for a recent review). However, convincing evidence is now mounting that thermo-chemical erosion *was* operative on a regional scale in the Bushveld, at least during Upper Critical Zone times (Eales *et al.*, 1988). This process (as envisaged by Eales *et al.*, op. cit.) relies on the input of primitive liquids along the floor of the magma chamber. Available geochemical data for the Upper Zone tend to be contradictory with regard to open-system versus closed-system behaviour: whole-rock, and mineral, cryptic variations have been used to argue *for* magma replenishment (Merkle and Von Gruenewaldt, 1986), while Sr-isotope data has been used to argue *against* it (Kruger *et al.*, 1987). Clearly, more work is required to resolve this controversy.

This leads onto consideration of the mode of accumulation of the magnetite and plagioclase, an issue which remains central to any discussion on layered intrusions. Various possibilities exist, including: *in situ* or bottom growth (for example, McBirney and Noyes, 1979; McCarthy and Cawthorn, 1983; Cawthorn and McCarthy, 1980 and 1981; Kruger and Smart, 1987); simple gravitative accumulation in the absence of convection currents (e.g. Wager and Brown, 1968); deposition by currents bearing crystals in suspension (e.g. Irvine, 1987); and flotation of crystal suspensions (e.g. Campbell *et al.*, 1978) and eventual incorporation into the solidification front.

Arguing on grounds of differences in density of cumulus phases alone, it is within the Upper Zone where we should expect to find the effects of gravitative settling best developed. This is because the density contrast between the two main cumulus phases is greater here than anywhere else in the intrusion (plagioclase, 2.5; and magnetite, 4.7 gm/cm$^3$).

The lack of clear modal grading within individual magnetite layers of the footwall anorthosite suggests that if settling *was* the dominant process for magnetite accumulation, then it either took place over a limited range (a few cm) or, sedimentation rates were too rapid to allow for hydrodynamic separation. On the other hand, it has been suggested that *in situ* accumulation, at least in the case of chromitite in the Bushveld, is manifested by the growth of primocrysts onto existing, structurally-related grains, leading to the formation of distinctive textures, referred to as chain structures by Eales and Reynolds (1986). No such chains have been identified in the samples studied here.

Crystals of plagioclase within magnetite-free domains of the anorthosite show many of the characteristics typical of an adcumulate texture: less than 7% interstitial material [Irvine, 1982; straight or curved grain boundaries; 120° triple junctions (Hunter, 1987); lack of obvious optical zoning (Wager *et al.*, 1960)]. For this reason, the mode of accumulation of plagioclase in the footwall anorthosite is likely to have been partly or, completely, obscured by continued grain growth during the postcumulus stage of crystallisation. The preservation of tiny (cumulus?) plagioclase grains (Fig. 5*c*), apparently arrested from further development by crystallisation of intercumulus phases, supports this assertion.

With this in mind, then, it is clear that the key to an understanding of many of the textural relationships observed in the anorthosite must lie in the consideration of micro-compositional variation within individual grains. The fact that all analysed plagioclase crystals from the footwall anorthosite have essentially the same core composition ($An_{60-61}$), no matter what their textural setting, indicates to us that a common parental liquid was involved during the cumulus stage of their development. Differences between grains are seen only at the rims (e.g. some are reversely zoned with respect to An- and K-contents), which presumably reflects differences in the postcumulus and subsolidus histories of these grains.

Below, an attempt is made to interpret the textures and microprobe data that have been documented. Four possible solidification histories for the footwall anorthosite are considered (see Fig. 8). In each case, the scenario starts immediately following initial concentration of plagioclase primocrysts at the floor:

(1) Continued growth of cumulus plagioclase crystals (presumably *in situ* growth, directly on the floor), which resulted in complete elimination of porosity, and development of a monomineralic cumulate rock displaying adcumulate characteristics (e.g. equilibrium grain boundary relationships). All crystals are typically unzoned from core to rim with respect to An-content—this is because equilibrium conditions were maintained at all times during postcumulus grain enlargement.

(2) Interruption of processes operating in (1) above by the accumulation, on the floor, of a small quantity of cumulus magnetite crystals to form a lamina, either by gravitative sedimentation or nucleation *in situ*. If erosion of the floor (by a mechanical or thermo-chemical mechanism) precedes formation of the lamina, individual magnetite grains might preserve the morphology of the floor onto which they accumulate (see Fig. 5*a*, *d*; and Fig. 6). Following the lamina-forming event, crystallisation of plagioclase resumes uninterrupted. The presence of magnetite crystals within the crystal pile hinders the solidification process by inhibiting grain growth within the crystal pile, and as a result, plagioclase grains in the immediate vicinity of the lamina develop textural features indicative of disequilibrium conditions (e.g. irregular mutual grain boundaries). Effective expulsion of residual intercumulus melts by postcumulus growth of plagioclase is similarly disrupted by the presence of the magnetite, and the marginal zoning detected in grains close to the lamina simply reflects crystallisation from and/or reaction with, these late-stage liquids and/or fluids (Figs. 6 and 8).

The reason why the rims are always reversely zoned (i.e. rims become more An-rich towards boundaries) is puzzling, although it is by no means a unique phenomenon in layered intrusions (Morse and Nolan, 1984; Dymek and Schiffries, 1987; Harney *et al.*, 1990*a*,*b*). Several mechanisms have been proposed and include: increases in $P_{H_2O}$ in the interstitial melt, which has the effect of lowering the crystallisation temperature of plagioclase; hydrothermal infiltration metasomatism (Schiffries, 1982), where the Ab-component is preferentially dissolved, leaving the crystal enriched in calcium; growth from intercumulus liquid enriched in augite component (Morse and Nolan, 1984). At this stage, a plausible alternative cannot be offered, but evidence presented earlier, that the magnetites have suffered an episode of alteration, suggests that the first two mechanisms cannot be rejected without careful consideration.

(3) Similar to (2) except that a layer, rather than a lamina forms. The large number of magnetite crystals which make up the layer severely inhibit adcumulus growth of plagioclase crystals between them, resulting in the formation of a matrix comprising fine-grained crystals displaying marginal zonation and complex boundary relationships. (It can be argued that the magnetite

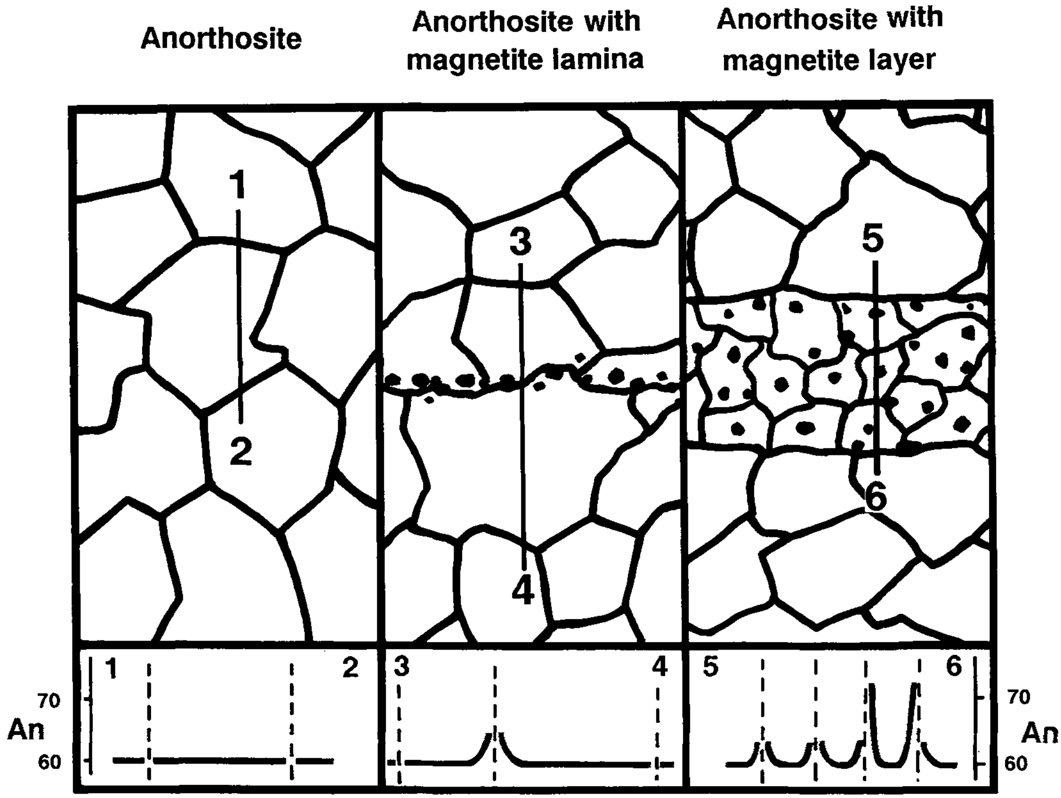


FIG. 8. Idealised textural and micro-compositional variation in: magnetite-free anorthosite; anorthosite containing a magnetitite lamina; and anorthosite with a magnetite layer. The relationships between plagioclase grain boundaries and magnetite primocrysts (black) are shown, together with the variation in An-component, as detected in traverses 1–2, 3–4, and 5–6. Based on information illustrated in Figs. 5 and 6.

crystals promoted nucleation of numerous plagioclase primocrysts, and the fine grain size and chemical zonation simply reflect competition for nutrients during adcumulus growth.) Disequilibrium features also form at layer–anorthosite junctions.

(4) Formation of anorthosite is terminated by the accumulation of copious amounts of cumulus magnetite which, unlike the crystals in laminae and layers, continue to grow at the floor and eventually form a monomineralic adcumulate as exemplified by the massive magnetitite layer which directly overlies the footwall anorthosite (Fig. 1).

**Implications for adcumulus growth mechanisms**

A variety of mechanisms has been suggested to explain the origin of adcumulates. Some rely on diffusion only (Wager *et al.*, 1960); others involve filter-pressing and infiltration metasomatism (Irvine, 1980); while recently, intercumulus convective circulation (Tait *et al.*, 1984; Morse, 1986) coupled with compaction (Sparks *et al.*, 1985) has been proposed. In addition, metallurgical processes such as annealing of loosely packed aggregates (Reynolds, 1985*a*), and coalescence grain growth (Hunter, 1987), have been applied to studies of cumulate rocks.

It is beyond the scope of the present paper to discuss in detail the relative merits of these various mechanisms. Instead, we list below the possible contributions our data can make to the current adcumulus debate.

(1) The small grain sizes of magnetite primocrysts in the footwall anorthosite from VAMETCO mine suggest that the process of adcumulus growth at this locality involved a dramatic grain enlargement (e.g. cumulus magnetite in a typical lamina can be as small as 0.1 mm; adcumulus magnetite in magnetite commonly reaches 10 mm in diameter. But of course this assumes that

primocryst grain sizes were the same in both cases).

(2) If one considers the scale on which the cross-cutting magnetite structures are developed (over a stratigraphic thickness of only 5–6 cm), and the suggestion that erosion often (but not always) preceded magnetite accumulation, it can be argued that solidification of the anorthosite must have been far advanced at the time these features developed. This kind of evidence may prove to be of use in establishing the rate at which adcumulus growth takes place in layered intrusions.

(3) A prerequisite for the development of an adcumulate texture appears to be the accumulation of copious amounts of primocrysts. This encourages grain aggregation which in turn helps facilitate densification (Reynolds, 1985*a*; Hunter, 1987)). In the case of the magnetitite layer at VAMETCO (LL1), the required levels of abundance at which these processes are initiated were reached for magnetite but not for plagioclase. In the underlying footwall anorthosite described here, it would appear that the converse was true.

## Conclusions

Specimens of anorthosite from the Brits area of the Bushveld, which form the footwall to the first major magnetitite layer in the Upper Zone, contain cumulus magnetite grains which have apparently escaped modification by postcumulus overgrowth. The crystals form small-scale structures, such as laminae, often only one magnetite grain thick, and preserve the changing morphology of the substrate onto which they periodically accumulated. Adcumulus growth of plagioclase before, during and after magnetite accumulation, led to their preservation.

From a study of micro-compositional variation across plagioclase crystals, it is possible to demonstrate that the presence of magnetite within the anorthosite mush had the effect of hindering the development of an ideal plagioclase adcumulate. Massive magnetitite layers, where adcumulus growth of magnetite was allowed to proceed to completion, appear to be examples at the other end of the spectrum to the structures described here. All evidence of mode of accumulation has inevitably been destroyed by adcumulus growth in such rocks.

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## References

Butcher, A. R. (1985) Channelled metasomatism in Rhum layered cumulates—evidence from late-stage veins. *Geol. Mag.*, **122**, 503–18.

—— and Merkle, R. K. W. (1986) Postcumulus modification of magnetite grains in the upper zone of the Bushveld Complex, South Africa. *Lithos*, **20**, 247–60.

—— —— Hatton, C. J., and Auret, J. M. (1989) Compatible trace elements, initial Sr-isotope ratios and small-scale structures as indicators of crystallisation mechanisms in the Bushveld magnetitite layers (abstr.). In *Origin of Mineralisation in Southern African Layered Intrusions, Wits. Univ. Joburg.*

Campbell, I. H., Roeder, P. L., and Dixon, D. M. (1978) Plagioclase buoyancy in basaltic liquids as determined with the centrifuge furnace. *Contrib. Mineral. Petrol.*, **67**, 369–77.

Cawthorn, R. G. and McCarthy, T. S. (1980) Variations in Cr content of magnetite from the upper zone of the Bushveld Complex—evidence for heterogeneity and convection currents in magma chambers. *Earth Planet. Sci. Letters*, **46**, 335–43.

—— —— (1981) Bottom crystallisation and diffusion control in layered complexes: Evidence from Cr distribution in magnetite from the Bushveld Complex. *Geol. Soc. South. Africa Trans.*, **84**, 41–50.

Dymek, R. F. and Schiffries, C. J. (1987) Calcic mermekite: possible evidence for the involvement of water during the evolution of andesine anorthite from St-Urbain, Quebec. *Can. Mineral.*, **25**, 291–319.

Eales, H. V. and Reynolds, I. M. (1986) Cryptic variations within chromitites of the upper Critical Zone, northwestern Bushveld Complex. *Econ. Geol.*, **81**, 1056–66.

—— Field, M., De Klerk, W. J., and Scoon, R. N. (1988) Regional trends of chemical variation and thermal erosion in the upper Critical Zone, western Bushveld Complex. *Mineral Mag.*, **52**, 63–79.

Harney, D., Merkle, R. K. W., and Von Gruenewaldt, G. (1990*a*) Plagioclase composition in the Upper Zone, eastern Bushveld Complex—Support for magma mixing at the Main Magnetitite Layer. *Inst. Geol. Res. Bush. Complex Res. Rep.*, **87**, 1–19.

—— —— —— (1990*b*) Platinum-group element behaviour in the lower part of the Upper Zone, eastern Bushveld Complex—Implications for the formation of the main magnetite layer. *Econ. Geol.*, **85**, 1777–89.

Hatton, C. J. and Sharpe, M. R. (1989) Significance and origin of boninite-like rocks associated with the Bushveld Complex. In *Boninites and Related Rocks* (A. J. Crawford, ed), Unwin Hyman, 174–207.

Hunter, R. H. (1987) Textural equilibrium in layered igneous rocks. In *Origins of Igneous Layering* (I. Parsons, ed), D. Reidel Publishing Company, 185–245.

Irvine T. N. (1980) Magmatic infiltration metasomatism, double-diffusive fractional crystallisation and adcumulus growth in the Muskox intrusion and other layered intrusions. In *Physics of Magmatic Processes* (R. B. Hargraves, ed), Princeton University Press, 325–83.

—— (1982) Terminology for layered intrusions. *J. Petrol.*, **23**, 127–62.

—— (1987) Layering and related structures in the Duke Island and Skaergaard intrusions: Similarities, differences and origins. In *Origins of Igneous Layering* (I. Parsons, ed), D. Reidel Publishing Company, 185–245.

Kruger, F. J. and Smart, R. (1987) Diffusion of trace elements during bottom crystallisation of double-diffusive convection systems: The magnetite layers of the Bushveld Complex. *J. Volcanol. Geotherm. Res.*, **34**, 133–42.

—— Cawthorn, R. G., and Walsh, K. L. (1987) Strontium isotopic evidence against magma addition in the Upper Zone of the Bushveld Complex. *Earth Planet. Sci. Lett.*, **84**, 51–8.

McBirney, A. R. and Noyes, R. M. (1979) Crystallisation and layering of the Skaergaard intrusion. *J. Petrol.*, **20**, 487–554.

McCarthy, T. S. and Cawthorn, R. G. (1983) The geochemistry of vanadiferous magnetite in the Bushveld Complex: Implications for crystallisation mechanisms in layered complexes. *Mineral. Deposita*, **18**, 505–18.

Merkle, R. K. W. and Von Gruenewaldt, G. (1986) Compositional variation of Co-rich pentlandites: Relation to the evolution of the Upper Zone of the western Bushveld Complex, South Africa. *Can. Mineral.* **24**, 529–46.

Molyneux, T. G. (1970) The geology of the area in the vicinity of Magnet Heights, eastern Transvaal, with special reference to the magmatic iron ore. *Geol. Soc. S. Afr., Spec. Publ.*, **1**, 228–41.

Morse, S. A. (1986) Convection in aid of adcumulus growth. *J. Petrol.*, **27**, 1183–214.

—— and Nolan, K. M. (1984) Origin of strongly reversed rims on plagioclase in cumulates. *Earth Planet. Sci. Lett.*, **68**, 485–98.

Reynolds, I. M. (1985*a*) The nature and origin of titaniferous magnetite-rich layers in the Upper Zone of the Bushveld Complex: A review and synthesis. *Econ. Geol.*, **80**, 1089–108.

—— (1985*b*) Contrasted mineralogy and textural relationships in the uppermost titaniferous magnetite layers of the Bushveld Complex in the Bierkraal area north of Rustenburg. Ibid., **80**, 1027–48.

Schiffries, C. J. (1982) The petrogenesis of a platiniferous dunite pipe in the Bushveld Igneous Complex: Infiltration metasomatism by a chloride solution. Ibid., **77**, 1439–53.

Sparks, R. S. J., Huppert, H. E., Kerr, R. C., McKenzie, D. P., and Tait, S. R. (1985) Postcumulus processes in layered intrusions. *Geol. Mag.*, **122**, 555–68.

Tait, S. R., Huppert, H. E., and Sparks, R. S. J. (1984) The role of compositional convection in the formation of adcumulate rocks. *Lithos*, **17**, 139–46.

Von Gruenewaldt, G. (1973) The Main and Upper Zone of the Bushveld Complex in the Roossenekal area, eastern Transvaal. *Geol. Soc. South. Africa Trans.*, **6**, 207–27.

Wager, L. R. and Brown, G. M. (1968) *Layered Igneous Rocks*, Oliver and Boyd, London, 588pp.

—— —— and Wadsworth, W. J. (1960) Types of igneous cumulates. *J. Petrol.*, **1**, 73–85.

Willemse, J. (1969) The vanadiferous magnetic iron ore of the Bushveld Igneous Complex. *Econ. Geol. Mon.*, **4**, 137–208

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## Appendix

An automated JEOL CXA-733 electron microprobe (at Rhodes University) was used for the plagioclase analyses, using well tested international standards and pure synthetic crystals for calibration. Traverses were performed using a focused beam, and step widths of between 30 and 150 μm. Reproducibility was estimated from duplicate analyses of the same spot: 1 sigma error bars for An-contents fall within the area occupied by the dot symbol in Figs. 6 and 7; for K and Fe, 1 sigma reproducibility is given in terms of number of cations: 0.01 (K) and 0.02 (Fe).