Regional trends of chemical variation and thermal erosion in the Upper Critical Zone, Western Bushveld Complex

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Abstract

A comparison of R.P.M. Union and Amandelbult Sections reveals close geochemical and stratigraphic correlations, but the sequence at the latter is more complex. Mafic members at Union Section are consistently more magnesian than their equivalents at Amandelbult Section and (where available data allow comparisons) than at Rustenburg Section. This, taken together with regional patterns of progressive attenuation and elimination of leucocratic rocks beneath harzburgitic layers, identifies Union Section as proximally located with reference to an irruptive centre from which primitive liquids were injected along the floor/supernatant liquid interface. Successive injections led to thermal erosion of the floor, causing 'dimpling' and 'potholing' on a local scale, and elimination of noritic-anorthositic layers on a regional scale. Such erosion of the floors beneath new inputs of magmatic liquid is likely to be initiated by only partial remelting, mainly of lower-temperature phases (sodic rims to zoned plagioclase grains, and Fe-enriched pyroxenes) within intercumulus space. It is argued that resultant contamination of the primitive liquids may have led to direct superposition of anorthosites (accompanied by rare troctolite) upon harzburgite, without intervening pyroxenite members, as in the Pseudoreef Multicyclic Unit.

KEYWORDS: Bushveld complex, Critical Zone, geochemistry, South Africa.

Introduction

THE Bushveld Complex is of such size and thickness that detailed studies of variations in the succession along strike constitute an essential prerequisite to any understanding of the genesis of the complex. The present paper offers an analysis of some striking similarities, as well as differences, between two sections through the uppermost part of the Critical Zone that are *c.* 30 km apart, and separated along strike by outcrops of Upper Zone ferrogabbros some 10 km in width (Fig. 1). A model for the development of the Upper Critical Zone at Rustenburg Platinum Mines (R.P.M.) Union Section has been developed by Eales *et al.* (1986). In the present paper we summarise the more important data gathered during more recent studies centred on R.P.M. Amandelbult Section, where there is more significant development of harzburgitic layers within the section, and where the interval between the UG2 and Merensky Units is more complex. The same analytical techniques are employed as in the earlier studies.

The layered succession

Stratigraphic sequence. Existing detailed accounts of the succession at R.P.M. Union and Amandelbult Sections (van Zyl, 1969; Viljoen *et al.*, 1986*a*, *b*; Eales *et al.*, 1986; Scoon and de Klerk, 1987) render it superfluous to present more than a summary outline here. The locality map of Fig. 1 shows the areas to which the sections of Fig. 3, 4, and 6–9 relate; the latter figures summarize the rock successions, the correlations adopted, and the nomenclature employed. The present paper makes only passing reference to the Main Zone which overlies the Critical Zone, hence no description of it is offered here.

We draw the boundary between the Critical and Main Zones at the top of the Bastard Unit, i.e., at the upper contact of the Giant Mottled Anorthosite (see Fig. 3). This stance is dictated by abrupt geochemical inflections that are apparent at this horizon, and by our interpretation of the pattern of change in Sr-isotope initial ratios through the succession exposed at Union Section (Eales *et al.*,

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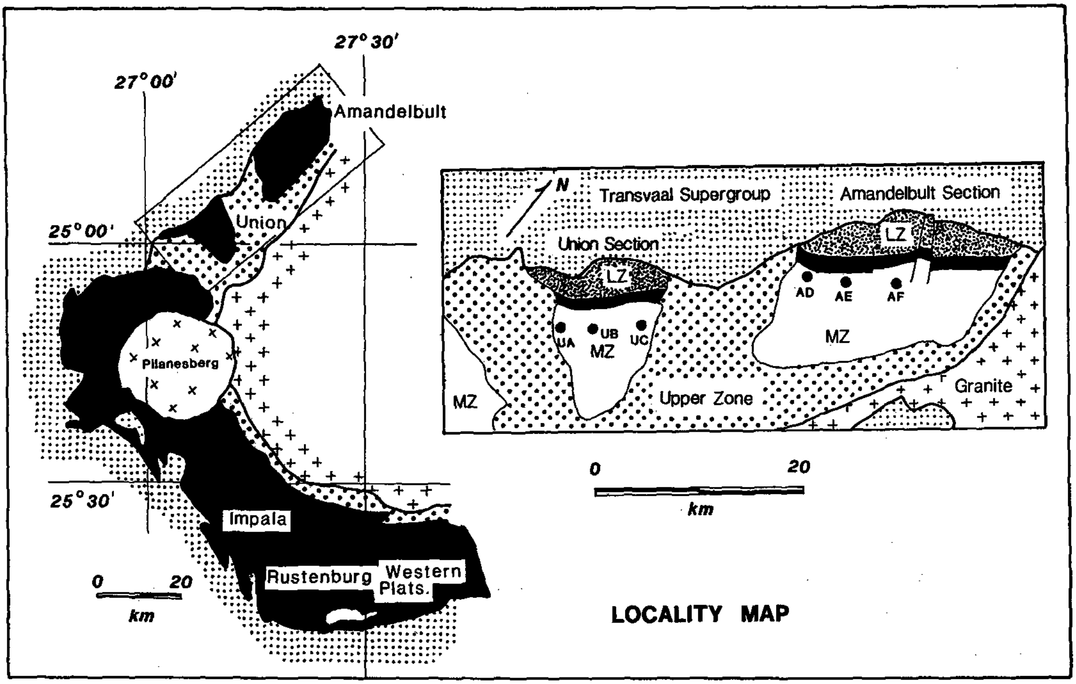

FIG. 1. Locality map showing (left) western limb of Bushveld Complex with Lower, Critical and Main Zones (black), Upper Zone (coarse stipple), Bushveld granite (vertical crosses), Pilanesberg alkaline complex (diagonal crosses) and Transvaal Supergroup floor rocks (medium stipple). Inset shows Union and Amandelbult Sections with Lower Zone (close stipple), Critical Zone (black), Main Zone (unshaded) and Upper Zone (coarse stipple), and borehole intersections UA–AF from which geochemical data in this paper are drawn.

1986). Our most recent (unpublished) Sr-isotope studies, in cooperation with Dr F. J. Kruger at the University of the Witwatersrand, have demonstrated that the trends at Amandelbult Section are virtually identical to those reported for Union Section.

Despite differences in detail between separate exposures of the uppermost part of the Critical Zone in the western Bushveld Complex, it is a useful simplification to use a seven-fold breakdown of the sequence. Resting upon a norite-anorthosite assemblage (the upper part of the UG1 Footwall Unit) are two essentially pyroxenitic units, each showing robust development of basal chromitite layers (the UG1 and UG2 Units). There follows a variable succession of dominantly leucocratic rocks floored by olivine-rich pyroxenites, or harzburgites (Pseudoreef Multicyclic and Merensky Footwall Units) succeeded in turn by two well developed cycles of pyroxenite-norite-anorthosite (Merensky and Bastard Units). The dominantly leucocratic interval between the Merensky and UG2 Units is a single unit, 17–27 m thick, at Union Section, but 30–40 m thick at Amandelbult, where geochemical data establish that it is divisible into several discrete cycles. Along the southwestern rim of the complex this same interval is up to 110 m thick at Impala Mine (Leeb-du Toit, 1986) and *c.* 130 m at Rustenburg (Viljoen and Hieber, 1986) but chemical data are not presently available to establish how many geochemical cycles might exist there.

Nomenclature of pyroxene-plagioclase cumulates. In any rock assemblage such as this, showing every gradation between anorthosite and pyroxenite, rock nomenclature is subjectively influenced by field terms, textural features, and tradition. Usage of terms such as melanorite, norite and leuconorite is not consistent. Accordingly, we adopt here a scheme in which the range of compositional variation between anorthosite and pyroxenite, defined by the C.I.P.W. normative composition plotted against whole-rock Al_2O_3 (Fig. 2) is subdivided on modal proportions of feldspar, as close as practicable to those advocated by Streckeisen (1973). Whereas the latter author's definition requires anorthosite to be constituted of > 90% feldspar, we adopt a value of 85% in order to avoid controversial re-definition of entrenched terms such as 'Giant

Mottled Anorthosite' as 'Giant Mottled Leuconorite'. Accordingly, anorthosites are here recognised as rocks with > 85% plagioclase feldspar (> 28% Al_2O_3; Fig. 2), leuconorites 65-85% feldspar (21-28% Al_2O_3), and norites 35-65% feldspar (11-21% Al_2O_3). Recognizing that pyroxenites of the upper critical zone contain appreciable intercumulus feldspar, the division between melanorite and feldspathic pyroxenite is here placed at 6.5% Al_2O_3 (*c*. 21.5% feldspar). Linear regression of the data portrayed in Fig. 2 yields the expression: total feldspar = 2.95 $Al_2O_3 + 2.22$ (correlation coefficient 0.9995).

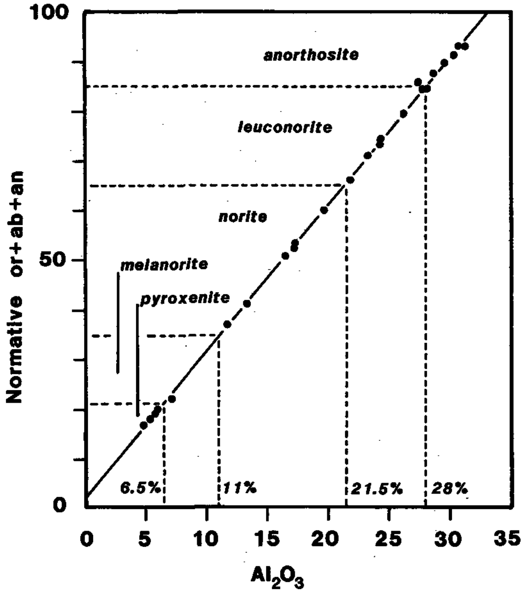

FIG. 2. Nomenclature adopted for orthopyroxene-plagioclase rocks, based on plot of normative *or* + *ab* + *an* against whole-rock Al_2O_3.

Changes in sequence along strike. The Bastard-Merensky-Merensky Footwall Unit sequences are closely matched in the Union and Amandelbult areas. Well defined cyclicity is exhibited by a transition from pyroxenite, through melanorite, norite and leuconorite to anorthosite in the Bastard and Merensky Units (Fig. 3), with the transitions from leuconorite to the uppermost mottled anorthosites being abrupt and mappable as distinct contacts. The coarse-grained, pegmatoidal Merensky Reef has no lithological counterpart at the base of the Bastard Unit. The Merensky Footwall Unit is, at both localities, dominated by feldspathic rocks in which inch-scale layering is developed at equivalent horizons, and it displays trivial development of a chromitite-harzburgite-olivine-pyroxenite-melanorite basal facies (the Pseudoreef Marker at Union Section and the mafic facies enclosing the P2 Hangingwall Marker at Amandelbult Section—see Fig. 4). At Union Section this is in turn underlain by the Upper Pseudoreef (Fig. 5*a*), a feldspathic harzburgite (the 'Tarentaal') and the Lower Pseudoreef, a pegmatoidal feldspathic harzburgite in which the grain size may reach several centimetres (Fig. 5*b*). This rests upon the UG2 Unit. At Amandelbult the sequence is more complex. Here the harzburgite member beneath the Footwall Unit is the P2 Marker of Viljoen *et al.* (1986*b*) and is *c*. 4 m in thickness. In the southwestern exposures at Amandelbult Section, the P2 Marker is split by the P2 Middling member—up to 1-2 m of anorthosite grading to a troctolitic facies. Towards the northeast, this Middling member thins along strike and disappears (Viljoen *et al.*, 1986*b*). A further, but more substantial, anorthositic assemblage separates the P2 Marker harzburgite from the underlying P1 Marker harzburgite (Fig. 4). Beneath the latter, in turn, is 0.5-1.5 m of pegmatoidal feldspathic pyroxenite or harzburgite which Viljoen *et al.* (1986*b*) include with the P1 Marker, to constitute the Lower Pseudoreef, but which might arguably be regarded as a discrete unit. In this paper we adapt (Fig. 4) the usage of Scoon and de Klerk (1987). The pegmatoidal harzburgite or equivalent olivine pyroxenite resting upon the UG2 pyroxenite is, at both Union and Amandelbult Sections, assigned to the Lower Pseudoreef. All overlying harzburgites beneath the Footwall Unit are Upper Pseudoreefs, of which there is thus one at Union Section and up to three at Amandelbult. Upper and Lower Pseudoreefs, together with intercalated chromitites and leucocratic rocks, constitute the Pseudoreef Multicyclic Unit. Not only is this grouping justified by matching textures, whole-rock analytical data and Ni/Mg ratios of constituent olivines, but it leads to a clearer understanding of regional patterns described later (see Fig. 10).

There are no significant differences between the UG2 and UG1 Units as exposed at Union and Amandelbult Sections. At both localities these two units are floored by prominent chromitite layers, there is significant accumulation of olivine at the base of the UG2 unit, and there is an abrupt transition to anorthositic rocks beneath the UG1 chromitite.

In summary, the sequences are strikingly similar at the two sections, apart from the interval between the base of the Footwall Unit and the feldspathic pyroxenites of the UG2 Unit. The key to understanding these relationships lies undoubtedly in

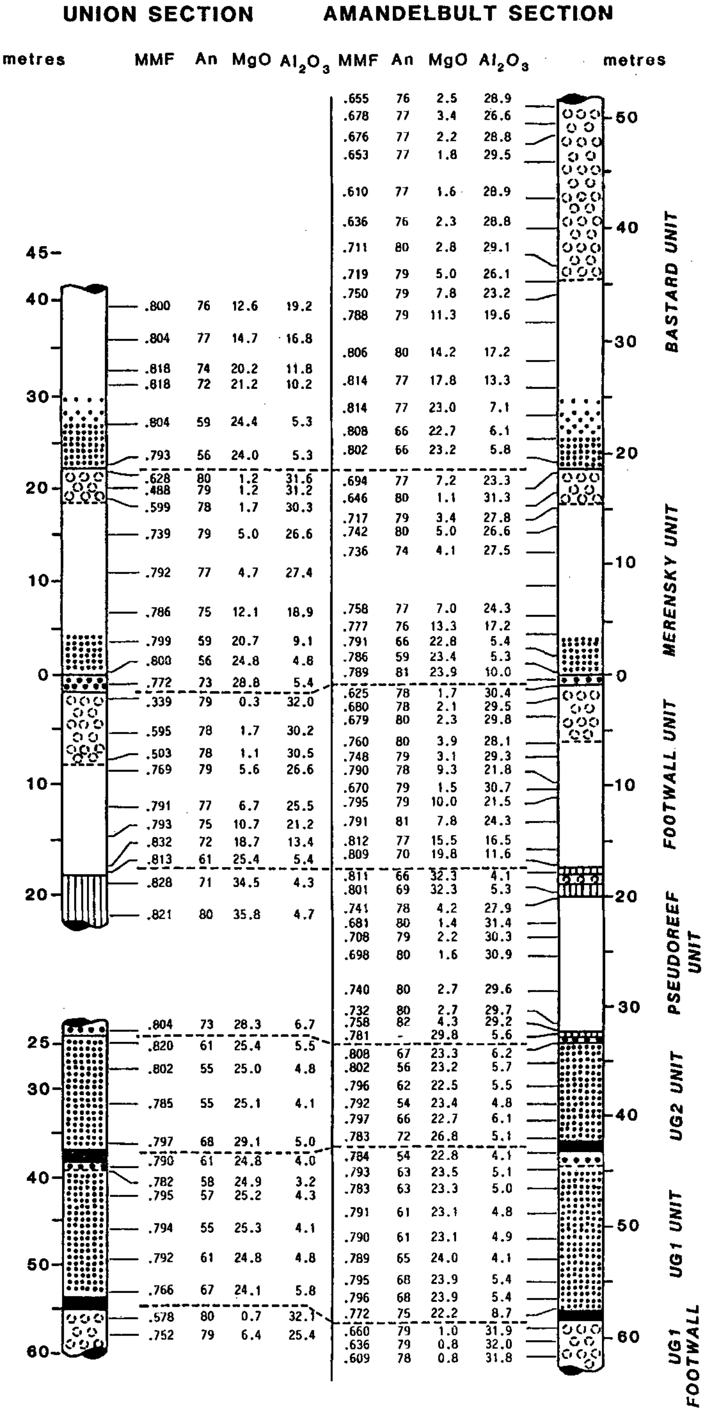

FIG. 3. Generalized profiles through Union and Amandelbult Sections, summarizing whole-rock analytical data. MMF: atomic ratio Mg/(Mg+Fe) where all Fe is expressed as Fe^{2+}; An: molecular percentage *an* in feldspar, from norm; MgO and Al_2O_3 are in wt. %. Heavy stipple: Lower Pseudoreef and Merensky Reef; hatch: Upper Pseudoreefs.

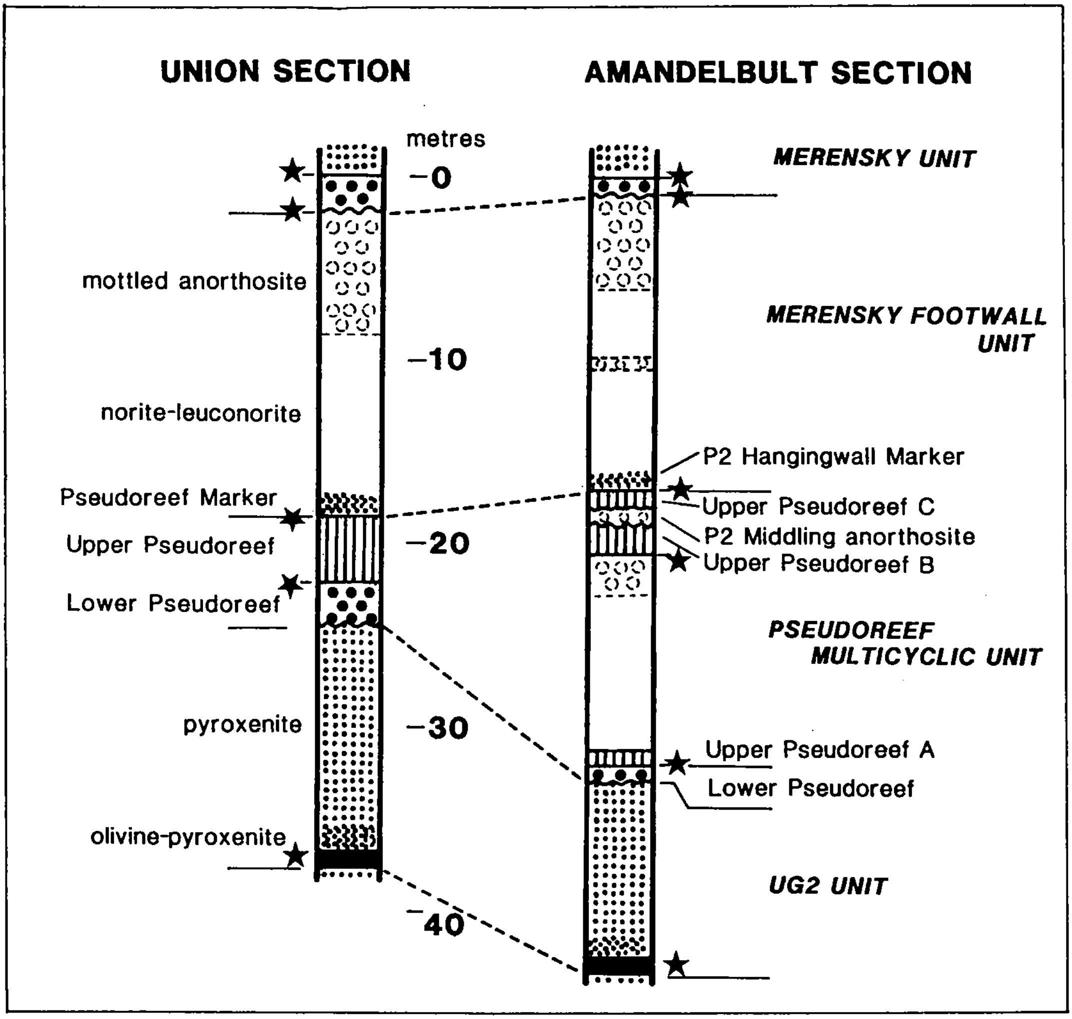

FIG. 4. Detailed profiles to illustrate correlation of Upper and Lower Pseudoreefs. Asterisks denote chromitite layers.

the unravelling of the enigmatic harzburgite anorthosite association at the base of the Merensky Unit at both localities, and within the Pseudoreef Multicyclic Unit at Amandelbult.

Features of genetic significance. Whichever genetic model is adopted as the most persuasive—cumulus deposition, deposition from density currents, *in situ* fractionation, or some process of liquid mixing with or without liquid stratification—it must be recognized that the cyclicity of the Bastard and Merensky Units is imperfectly simulated by the immediately underlying units. The UG1 and UG2 Units appear to be units with the upper, feldspathic facies missing. By contrast, the abrupt transitions from feldspathic harzburgite to Middling anorthosite within the P2 Marker, or from feldspathic harzburgite to a substantial mass of anorthosite above the Upper Pseudoreef A, raise questions about the mechanism whereby olivine-rich ultramafic members are followed directly by leuconorite or anorthosite members, with little or no development of an intervening pyroxenitic facies.

The nature of harzburgite-anorthosite contacts may be highly pertinent. As is widely commented upon in the literature, the base of the Merensky Reef is 'dimpled' or undulatory, rather than planar, where it rests upon the Footwall anorthosite. This dimpling transgresses the layering within the underlying anorthosite, and we regard it as a small-scale manifestation of the same phenomenon

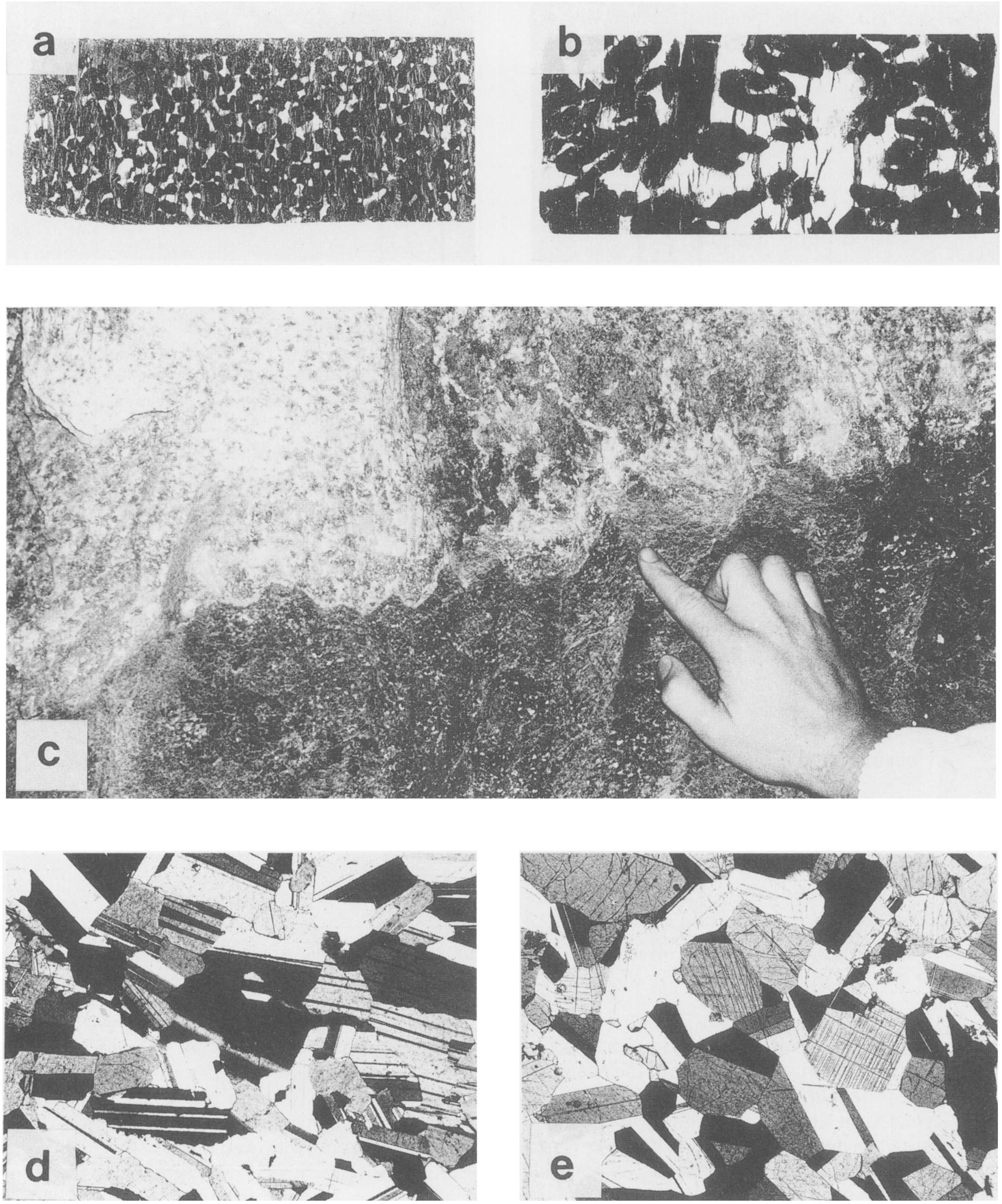

FIG. 5 (*a*–*b*). Polished surfaces of drill core (8 cm lengths; top towards left) of (*a*) 'Tarentaal' or Upper Pseudoreef feldspathic harzburgite and (*b*) Lower Pseudoreef pegmatoidal feldspathic harzburgite, Union Section. (*c*) Scalloped contact of Upper Pseudoreef B harzburgite (dark; lower half of photograph) with P2 Middling anorthosite (lighter; upper half). (*d*) Anorthosite, 2 m below contact with Upper Pseudoreef B, showing preferred orientation of feldspar laths parallel to layering (field width 4 mm). (*e*) P2 Middling anorthosite, showing equant crystals meeting along triple junctions, 20 mm below contact with Upper Pseudoreef C (field width 4 mm).

that causes progressive elimination of the entire Footwall unit within 'pothole structures', until platiniferous reef rests directly upon the Pseudoreef harzburgite. Residual pillars of the Footwall Unit beneath the Merensky Reef (Leeb-du Toit, 1986, p. 1099) and within potholes (lens-type reef of Viljoen *et al.*, 1986*a*) suggest that the lacuna was created by assimilation, or 'thermal erosion' of the Footwall Unit. Less widely reported are the scalloped contacts of P2 harzburgite with both the bottom (Fig. 5*c*) and top of the Middling anorthosite (Viljoen *et al.*, 1986*a*; Scoon and de Klerk, 1987). A further feature is the obliteration, along such contacts, of the normal fabric of anorthosites showing preferred orientation of zoned feldspar laths parallel to the layering (Fig. 5*d*). This is replaced by a dense mosaic of equant grains meeting along triple junctions (Fig. 5*e*) and all trace of zonal structure of feldspar grains disappears. In summary, the 'dimpling', the fabric of the anorthosite selvages, the wedging-out of the P2 Middling anorthosite along strike within Amandelbult Section, and the lack of any significant development of pyroxenite between harzburgite and anorthosite (Fig. 3), are anomalous features not readily reconciled with simple, progressive accretion on a crystalline floor, whether by crystal settling or by *in situ* growth.

Geochemical features

Frequency maxima. Despite the existence of all gradations between anorthosite and orthopyroxenite, and orthopyroxenite and harzburgite, the frequency distribution of rock types is markedly biased towards frequency maxima in the Upper Critical Zone. This is illustrated by the histograms of Fig. 6, based on 109 available whole-rock analyses by Field (1986) and de Klerk (1982). The sample density and spacing do not meet the requirements for rigorous statistical analysis, but the frequency maxima are clear enough. That at 4-6% Al_2O_3 depicts mafic cumulates (pyroxenites and harzburgites) with intercumulus feldspar, and that at 26-32% Al_2O_3 leuconorites and anorthosites. The frequency maxima of MgO are at 0-8% (anorthosites and leuconorites) and 22-26%

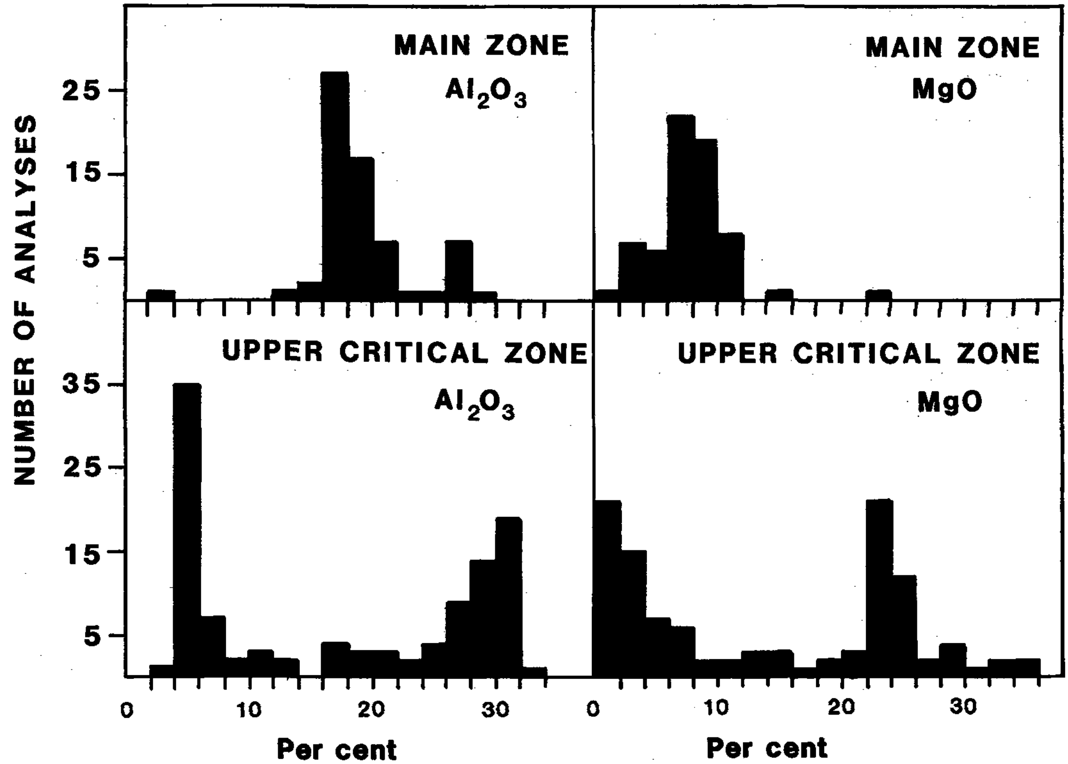

FIG. 6. Histograms showing frequency distribution of Al_2O_3 and MgO in 109 analyses of rocks in UG1–Bastard Reef interval (this study) and 65 analyses of Main Zone rocks (data from Mitchell, 1986). Analyses calculated L.O.I.-free, with all Fe as Fe_2O_3.

(pyroxenites). Norites, melanorites and feldspathic harzburgites are poorly represented. This bimodality in the frequency distribution is reflected also by Lee's (1983) study of the Merensky Unit at Rustenburg. Analyses of 20 samples taken at roughly even intervals through the unit reveal that 65% contain 27-31% Al_2O_3, and 30% < 11% Al_2O_3. None falls within the range 11-24% Al_2O_3.

A comparison with equivalent data emphasizes the differences between the Upper Critical Zone and Main Zone sequences (Fig. 6). Lithological variations within the latter are subdued, with neither the more mafic nor the highly feldspathic variants being conspicuous.

These data cannot be interpreted in the same way as for fine-grained rocks, inasmuch as the maxima do not depict liquids, but cumulates. The mean composition of the Upper Critical Zone (UG1 to Bastard Units) is, in fact, not grossly different to that of the basal 500 m of the Main Zone. Averages compiled from the data of Field (1986) and Mitchell (1986) indicate, for the Upper Critical Zone (58 analyses), and lowermost Main Zone (13 analyses), respectively: SiO_2 50.8% and 51.9%; Al_2O_3 18.7% and 19.4%; Fe as Fe_2O_3 6.7% and 6.3%; MgO 12.3% and 9.0%; and CaO 9.5% and 11.5%. As such, the differing patterns of distribution portrayed in Fig. 6 should be regarded as dependent on processes rather than upon gross differences in original liquid compositions. The processes within the Main Zone were clearly less effective in producing rock diversity than those in the Upper Critical Zone.

The definition of discrete units. The analytical data reveal recognizable and consistent compositional differences between the Giant Mottled, Merensky, Merensky Footwall, and UG1 Footwall anorthosites, but a remarkable degree of correspondence between these members, along strike, at Union and Amandelbult Sections. Respective mean values for Sr are 341 and 345 ppm for the Bastard anorthosite, 396 and 394 ppm for the Merensky anorthosite (402 ppm at Rustenburg Section), 460 and 468 ppm for the Merensky Footwall anorthosite, and 466 and 461 ppm for the UG1 Footwall anorthosite. These relationships are better displayed by the linear regressions of Sr *vs.* V, and Sr *vs.* Co, shown in Fig. 7. Here, data points from the geographically separate areas are combined, but regression nevertheless yields correlation coefficients between −0.971 and −0.996, while the regression lines have different slopes. The significance of these regressions lies in the demonstration that the data are consistent, not only for anorthosite and leuconorite, but for the underlying norite-melanorite-pyroxenite members within each unit. That is, the separate units are geochemically coherent between the lowermost pyroxenite (or melanorite) and uppermost anorthosite in each case, but each unit is geochemically discrete.

A distinction between the different units at Union Section was drawn by Eales *et al.* (1986) on a basis of Sr-Al relationships. After adjustment of whole-rock Al_2O_3 levels so as to exclude Al held in pyroxenes, $Sr/Al_2O_3^*$ ratios are calculated (for methods of calculation, see Eales *et al.*, loc. cit.). Fig. 8 compares the earlier data relating to Union Section with new data for Amandelbult Section. Individual samples which are anomalously enriched in Sr (e.g. Merensky Reef) are found to contain large modal proportions of mica and are ignored here. The similarities between the two sections are clear, and permit the following generalizations to be stated: (*a*) each unit displays characteristic ranges of $Sr/Al_2O_3^*$ ratios, which relate essentially to the composition of the feldspar phase; (*b*) the ranges remain constant, within experimental error, between what has traditionally been defined as the mafic base and the feldspathic top of each unit; (*c*) the differences in the ranges spanned, between one unit and the next, warrant their recognition as discrete units; and (*d*) the lowermost 3-5 m of the Bastard, Merensky and UG2 units, as well as the UG1 Unit at Union Section, carry the chemical signature of the respective underlying units. This is attributed to infiltration, or 'leakage', of residual liquid into the intercumulus space at the bases of these units.

The Merensky Footwall and Pseudoreef Multicyclic Units have, in many respects, the same geochemical signature. $Sr/Al_2O_3^*$ ratios are the same, and Co and V data from these two intervals may be merged to yield single regression lines of the type shown in Fig. 7. It may therefore be tempting to define the entire sequence of cumulus feldspar-bearing rocks between the Merensky and UG2 Units as a single unit at Amandelbult, but other data do not support this approach. Insofar as bulk distribution coefficients are greater for Ni than for Sc in mafic rocks, the ratio Ni/Sc is a useful indicator of increasingly primitive character towards the bases of cyclic units. Discrepant values may be introduced by the presence of sulphides, but such samples are recognizable by virtue of anomalously high levels of Cu, and may accordingly be rejected. These ratios, presented in Fig. 9, indicate an obvious cyclicity in each of the Merensky Footwall and Pseudoreef Multicyclic Units, and support their recognition as discrete entities. Electron microprobe data relating to orthopyroxenes (Fig. 9) unequivocally support this interpretation.

The decoupling of cryptic variations in plagio-

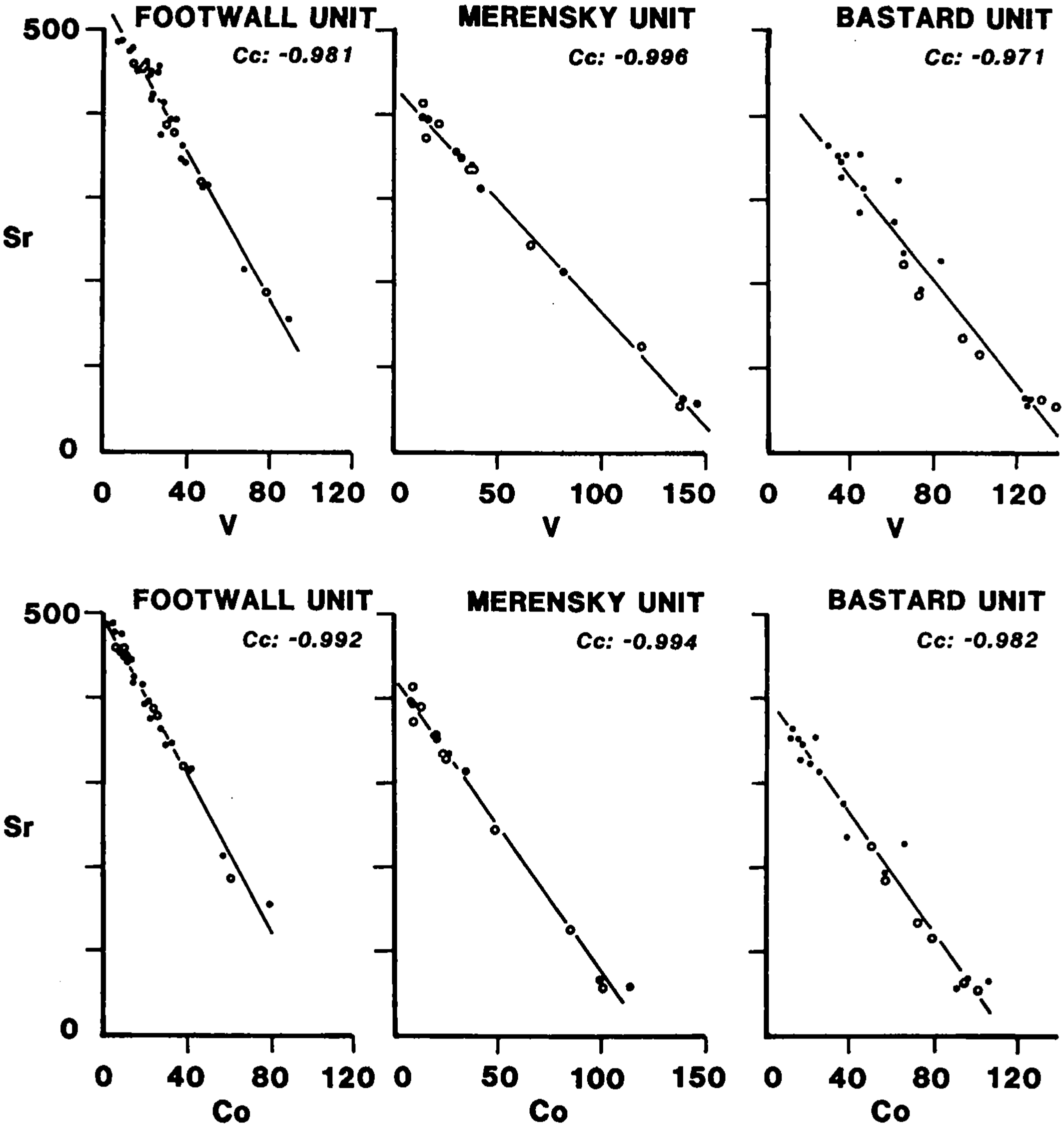

FIG. 7. Plots of Sr *vs.* V and Sr *vs.* Co for Footwall, Merensky and Bastard Units. Open circles: Union Section data; filled circles: Amandelbult Section data; Cc: correlation coefficient. All data in ppm.

clase feldspar and orthopyroxene, respectively, was stressed as a characteristic feature of the succession at Union Section by Eales *et al.* (1986). This relationship is substantiated by both whole-rock normative data of Fig. 3 and the electron microprobe data of Fig. 9, pertaining to Amandelbult Section. Mg/(Mg+Fe^{2+}) ratios decline, with increasing height (Fig. 9) from 0.81-0.85 to 0.75-0.77, while plagioclase feldspar becomes more calcic (Footwall and Merensky Units) or shows no detectable change (Pseudoreef Unit). Only within the top of the Bastard Unit, immediately beneath the base of the overlying Main Zone, is there a detectable decline in the Ca content of the feldspar phase. This is accompanied by a profound decline in the MMF ratio of orthopyroxene to *c.* 0.67. The sodic character of intercumulus feldspar within pyroxenites and olivine-bearing members, indicated by the whole-rock data of Fig. 3, is confirmed by the microprobe analyses presented in Fig. 9.

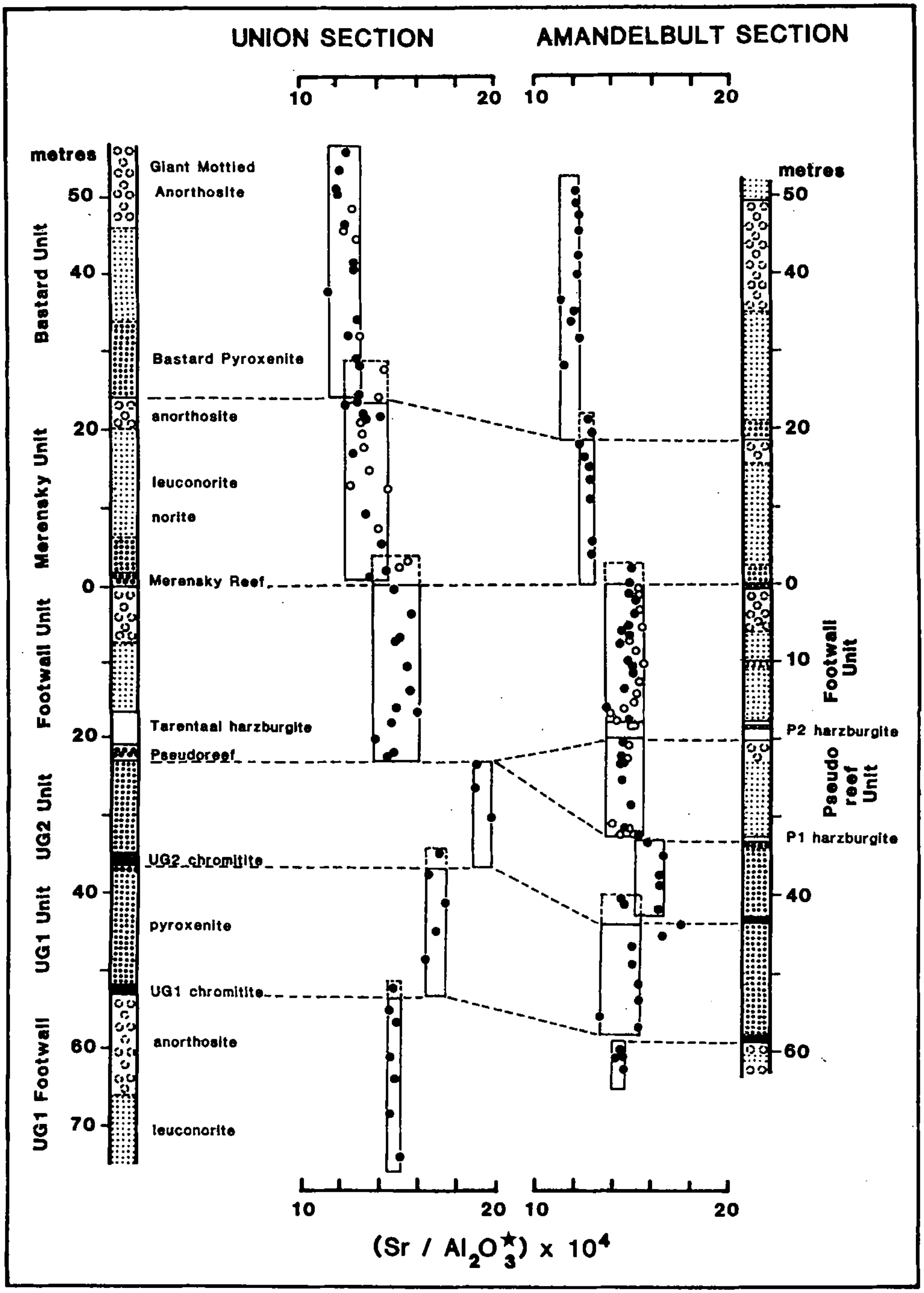

FIG. 8. Plots of Sr/Al_2O_3* ratios for Union and Amandelbult Sections (for method of calculation see Eales *et al.*, 1986). Open circles included in Union Section data depict plagioclase separates from Rustenburg Section (Kruger, 1983). Open and filled circles in Amandelbult Section data depict different areas studied by Scoon (1985) and Field (1986). Broken-line boxes at tops of some fields suggest infiltration of residual liquids from underlying units.

Summary of relevant data

The plethora of hypotheses that exist, at present, to account for the features and the origin of layered complexes, and the mutually exclusive properties of some of these hypotheses, serve effectively to emphasize how little is firmly established, beyond debate, about the processes active within magma chambers. The structure of this paper has therefore been to fix some significant constraints that any viable hypothesis must address. Those that we regard as most pertinent to the Western Bushveld Complex are summarized below.

(*a*) A remarkable degree of geochemical equivalence exists along strike for exposures of matching members of the Bastard, Merensky, Footwall, UG2 and UG1 units at Amandelbult and Union Sections. Fragmentary data for Rustenburg Section suggest that this compositional match might persist into that area. It is difficult to accept that this could have been achieved without efficient communication between the now separate exposures.

(*b*) Linear regression of trace element data reveals geochemical signatures that are distinctive of the Bastard, Merensky and Footwall Units. A distinction between the anorthositic members of these units may be drawn on a basis of Sr levels, and between more mafic members on a basis of compatible elements such as Co and V (see Fig. 7).

(*c*) Cyclic variations in ratios such as Mg/(Mg + Fe^{2+}) and Ni/Sc, from primitive to evolved values,

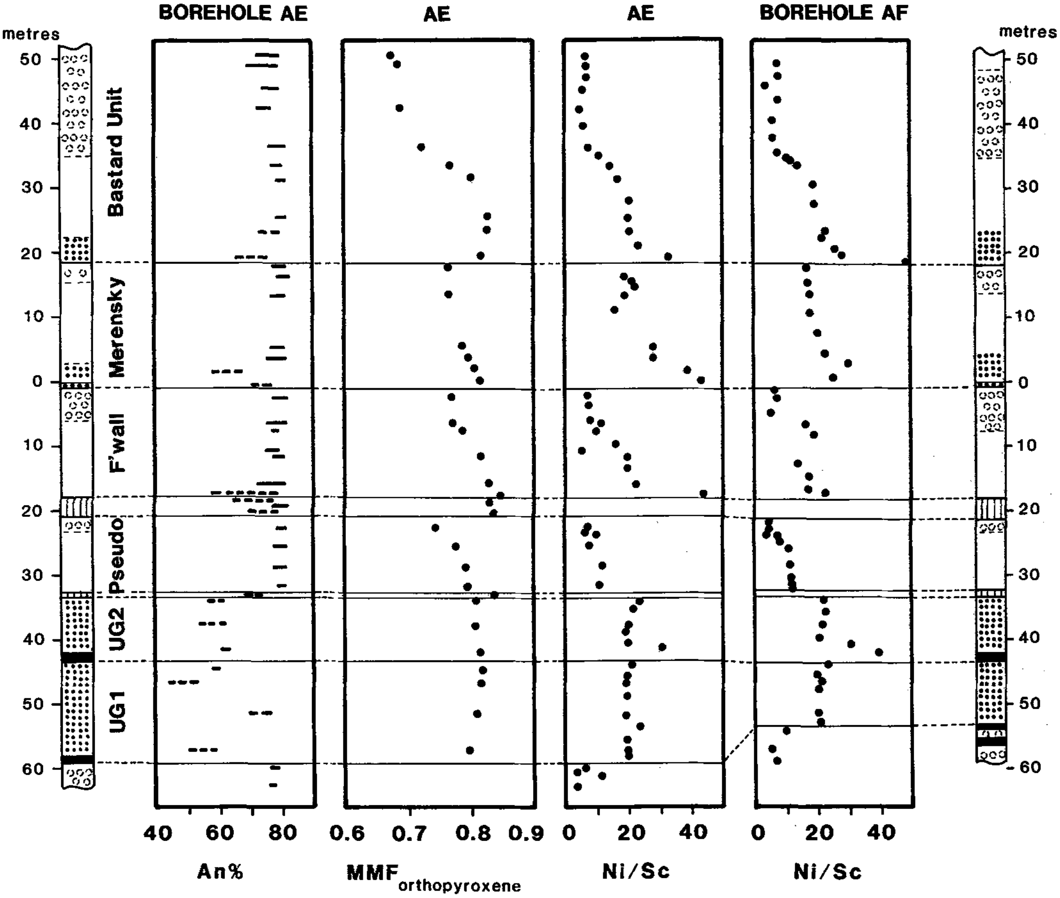

FIG. 9. Data from boreholes AE and AF (Amandelbult Section; see Fig. 1) showing compositions of cumulus plagioclase (solid lines) and intercumulus plagioclase (broken lines) given by microprobe analysis; Mg/(Mg + Fe^{2+}) ratios of orthopyroxene from microprobe analysis; and Ni/Sc ratios from whole-rock XRF analysis. Pseudoreefs shown by vertical hatching; Merensky Reef by heavy stipple; pyroxenites by lighter stipple; mottled anorthosites by broken circles.

show that sequences such as the Bastard and Merensky Units conform with the traditional concept of cyclic units, i.e. mafic rocks constitute the bases of units. Characteristic ranges of $Sr/Al_2O_3^*$ ratios, which differ in the Bastard, Merensky and Footwall Units, support this contention.

(*d*) Parameters such as Sr/Al_2O_3 ratios, and depression of $Mg/(Mg+Fe^{2+})$ ratios at the base of units (Kruger and Marsh, 1985; this paper, Fig. 9) indicate that leakage of residual liquids from the tops of units may modify the composition of the lowermost 5 m of the overlying units.

(*e*) Abrupt transitions such as chromitite-anorthosite-chromitite, harzburgite-anorthosite-harzburgite, and leuconorite-anorthosite-leuconorite, introduce serious contradictions to a simplistic concept of cycles of gravitational settling of crystals.

(*f*) The decoupling of trends of cryptic variation in feldspars and pyroxenes, discussed by Eales *et al.* (1986), is substantiated at Amandelbult Section by detailed electron microprobe studies.

(*g*) Despite mottled anorthosites displaying commonly abrupt, mappable basal contacts against underlying leuconorites, closely spaced sampling (Fig. 9) reveals that geochemical parameters may change continuously across such contacts.

(*h*) Troctolite is a rare rock type in the Upper Critical Zone, but within the P2 Middling Member (*c.* 1 m thick) sandwiched between two discrete layers of harzburgite, anorthosite grades upwards into leucotroctolite. Here small, rounded and embayed feldspar grains are abundantly enclosed within poikilitic olivine hosts *c.* 1 cm in size.

(*i*) The contacts of anorthosites with overlying harzburgites exhibit features suggestive of thermal erosion and/or recrystallization of the anorthosites. This, taken together with insignificant development of pyroxenite or melanorite between Pseudoreef harzburgites and their respective overlying leuconorites or anorthosites, raises fundamental questions about the manner of emplacement of some of these olivine-rich members. The 'rippling' or 'dimpling' of anorthosites at such contacts is repeated at the Merensky Reef-Footwall Anorthosite contact, an horizon at which the well-known 'pothole structures' are initiated, and where large-scale elimination of the Footwall Unit starts.

(*j*) At both sections under review, one feldspathic harzburgite (Upper Pseudoreef) rests directly upon another, or its olivine-pyroxenite equivalent (Lower Pseudoreef). Elimination of the leucocratic members of the Footwall Unit by 'potholing' may then yield a triplet of superposed ultramafic layers—Pothole Merensky Reef upon Upper Pseudoreef upon Lower Pseudoreef, as at Union Section.

(*k*) The spectacular layering and rock diversity of the Upper Critical Zone are in marked contrast to the muted layering of the overlying Main Zone (Fig. 6). The mean composition of the Upper Critical Zone is not grossly different to that of the lowermost 500 m of the Main Zone, a feature that emphasizes the differences in processes that must have been active in the two zones.

Discussion

It has been argued by Eales *et al.* (1986), that the Upper Critical Zone at Union Section developed during a period of repeated influxes of primitive magma, emplaced along the interface between the floor and the supernatant column of residual liquid. Largely on a basis of wide variations in the proportions of leuconorites and anorthosites within cyclic units, the decoupling of cryptic variations in pyroxenes and feldspars, and variations of Sr-isotope ratios between bases and tops of units, the latter authors (loc. cit.) argue that the lower, ultramafic members of units are derivatives of such mafic influxes; the upper, leucocratic members crystallized during progressive hybridization of the fractionated residua of each influx with the supernatant liquid column. The present study establishes congruency of chemical trends at Union and Amandelbult Sections, and strengthens the data base upon which these arguments are based.

The new data highlight features that are less evident at Union Section, viz., that the succession from the UG1 to the Bastard Units lacks predictable order, insofar as the successive units are not mere repetitions of a simple sequence. Three types of unit should be recognized here: (*a*) ostensibly complete units displaying a gradation from peridotite and pyroxenite to anorthosite, i.e. the Merensky and Bastard Units; (*b*) units represented by ultramafic members, such as the UG1 and UG2 units, with near-basal chromitite layers, and with or without a harzburgitic facies at the base of the pyroxenite member; and (*c*) units constituted largely of leucocratic rocks underlain by peridotitic members, with little or no intervening pyroxenite or melanorite (Pseudoreef and Footwall Units). Figs. 3 and 8-9 show that, at Amandelbult, pyroxenite constitutes some 20% of the Bastard, 15% of the Merensky, and 3% of the Footwall Units. In the Pseudoreef Multicyclic Unit there is direct transition from feldspathic peridotite (30% MgO) to overlying orthopyroxene-spotted anorthosite (29% Al_2O_3). Our explanation of these features is embodied in Fig. 10, which introduces regional aspects of the problem.

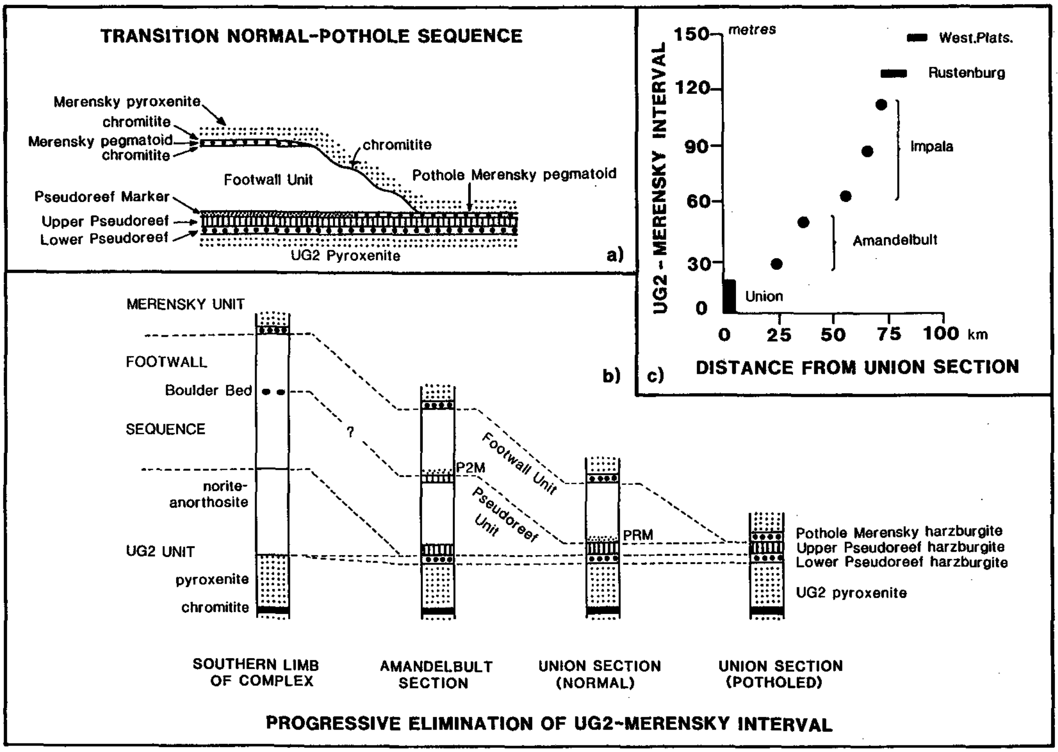

FIG. 10. (*a*) Generalized section to illustrate elimination of Footwall Unit at Union Section by 'potholing'. Scale distorted to clarify relationships. (*b*) Interpretation of proximal (right-hand side) and distal (left-hand side) relationships in uppermost part of Critical Zone, western Bushveld complex. Columns depict sequences established by underground development; broken lines represent inferred elimination of members by thermal and mechanical erosion. PRM depicts Pseudoreef Marker, replaced by mineralized reef within potholes; P2M is P2 Hangingwall Marker at base of Footwall Unit. Scale is distorted to clarify relationships. (*c*) Thickness of column of leucocratic rocks between UG2 pyroxenite and Merensky Reef, plotted against map distance measured from centre of Union Section, regarded as close to an irruptive centre. Averaged data compiled from de Klerk (1982), Farquhar (1986), Field (1986), Leeb-du Toit (1986), Viljoen and Hieber (1986), Viljoen *et al.* (1986*a*, *b*), and present study.

Fig. 10*a* illustrates the essential differences between 'normal' and 'potholed' upper critical zone successions. Progressive elimination of the Footwall Unit within pothole structures has been documented beyond dispute (Viljoen *et al.*, 1986*a*, *b*; Feringa, 1959). The Tarentaal harzburgite forms the floor of the deepest potholes, although even this may be breached on rare occasions. Down-dip development at Union Section has revealed that for strike-lengths of up to 5 km the Footwall Unit is attenuated in this fashion. Insofar as (*a*) refractory ultramafic rock commonly forms the floor of deeper potholes, (*b*) dissolution rates of plagioclase are appreciably greater than those of olivine and, at low levels of superheating, are several orders of magnitude greater than crystallization rates at low degrees of supercooling (Donaldson, 1985), and (*c*) undisturbed relict pillars of the footwall rise from pothole floors, the excavation of these lacunae is best accounted for by thermal and mechanical erosion of leucocratic rocks consequent upon injection of fresh batches of magma, above the feldspar liquidus in T-X space.

Fig. 10*b* offers our interpretation of the superposition of the P1 harzburgites upon UG2 pyroxenite at Amandelbult, by post-depositional stripping of upper, leucocratic members of the UG2 unit. These upper members are well developed in the southern limb of the complex (Viljoen and Hieber, 1986) where there is no development of Pseudoreef harzburgite, but generally absent from Union and Amandelbult Sections, where the Pseudoreefs are found. We interpret, further, the disappearance of the leucocratic rocks of the Pseudoreef Unit at Union Section (Fig. 10*b*) by a similar process. The culmination of this episodic process is deemed to be the elimination of the Footwall Unit at Union Section, and direct superposition of pothole Merensky Reef upon the Tarentaal harzburgite which, in turn, rests directly upon the lower, ultramafic Pseudoreef. While each of the generalized stratigraphic columns presented in Fig. 10*b* is well substantiated by underground development, the broken lines linking them represent our reconstruction of the resorption process.

If this model of episodic cannibalism is correct, four issues of fundamental importance arise. These are (*a*) heat balance, (*b*) the concept of proximal and distal facies, (*c*) the thickness of freshly injected layers, and (*d*) the fate of the resorbed material. Each of these is briefly discussed below.

(*a*) *Heat balance.* Heat loss would be rapid from a thin, basal layer of primitive liquid newly injected beneath a thick, supernatant, cooler liquid column (Huppert and Sparks, 1980), an issue that would cast doubt upon the capacity of such influxes to erode their floor. This objection would largely fall away if the Huppert-Sparks model, which assumes instantaneous emplacement of the basal liquid layer, were to include an earlier stage in which emplacement started with a thin, continuous stream passing over the floor. Fresh reserves of hot, primitive liquid would in this way stream over parts of the floor proximally located with respect to the feeder system. An analogy is provided by the mild thermal metamorphism commonly observed beneath many thick doleritic sills, compared with profound metamorphism (even vitrification) of host rocks adjacent to narrow dykes identified as feeder dykes.

A further, although not wholly appropriate, analogy might be provided by the modelling of thermal erosion of floor rocks beneath komatiites, as by Huppert and Sparks (1985). The theoretical treatment by these authors has shown that the amount of thermal erosion here is dependent upon parameters such as initial temperatures of the flows, flow rates, initial and melting temperatures of the floor rocks, distance from source, and maintenance of adequately high Reynolds numbers. Under conditions of high flow rate and extrusion of large volumes of magmatic liquid, thermal erosion affecting tens of metres of thickness of floor rocks is shown to be feasible within distances up to 10^2 km from the point of issue. Without fundamental data on probable flow rates, and the composition of the primitive liquids, it is not possible to attempt comparable quantitative modelling for the Bushveld complex. It is, however, possible to list relevant parameters that would favour erosion. (i) The initial temperature of the floor rocks is taken to be 0 °C by Huppert and Sparks (loc. cit.) whereas in the Bushveld case the floor rocks beneath surges of fresh magma would have been above their solidus temperatures (see discussion under (*d*) below). (ii) Floor rocks in the Bushveld case need not have been raised to the liquidus for erosional effects to have become significant. Disaggregation by increased melting within intercumulus spaces is envisaged, and a lower density of plagioclase relative to that of the primitive liquid would have assisted the process. Accordingly, liquidus temperatures for intercumulus phases such as clinopyroxene, and the sodic outer rims of zoned plagioclase grains, are more appropriate constraints than liquidus temperatures of anorthosite in the present case. (iii) Rough estimates of temperatures may be made. Experimental determination of phase relations of a chilled, basaltic sample from the edge of the Bushveld complex (Sharpe and Irvine, 1983) puts the feldspar liquidus at *c.* 1200 °C, and the crystallization of clinopyroxene at *c.* 1155 °C. Liquid was present at the lowest temperatures investigated (1120 °C). The accumulation of volatiles within intercumulus space would have depressed solidus temperatures still further during thermal erosion. Estimates of the temperature at which the primitive liquids were emplaced are dependent upon assumptions regarding composition, and whether such liquids were super-liquidus or not. Their capacity to deposit chromite and olivine at the base of units is seen in all units under review, and their Sr-isotope and other geochemical attributes have led Eales *et al.* (1986) to equate them with a primitive, magnesian, Si-poor facies of the tholeiitic B2 type of marginal rock defined by Harmer and Sharpe (1985). Minimum liquidus temperatures of *c.* 1220 °C for such rocks would be not unrealistic (Sharpe and Irvine, 1983; French and Cameron, 1981); actual temperatures could have been appreciably higher if such liquids were superheated. (iv) Units of the Upper Critical zone are characteristically tens of metres in thickness, and exposed over some 200 km of strike in the western limb of the complex alone. It is therefore beyond debate that very large volumes of liquid were involved in the emplacement of these units, and this is an important parameter in thermal erosion of proximally located floor rocks (Huppert and Sparks, 1985). (v) In terms of the arguments above, it is envisaged that feldspathic members at the tops of units could become attenuated in thickness by raising of their temperatures, initially close to or above the solidus, to *c.* 1150° in the vicinity of eruptive centres, as a consequence of emplacement of very large volumes of fresh melts at a minimum temperature of *c.* 1220 °C. In the more distal facies, thermal erosional effects would have been more subdued.

(*b*) *Proximal and distal facies.* If basal liquids are

TABLE 1 MgO LEVELS IN EQUIVALENT MEMBERS

Member	Union Section	Amandelbult Section	Rustenburg Section
Bastard Pyroxenite	24.2	22.9	-
Merensky Pyroxenite	24.8	23.1	22.5 a 22.0 b
Merensky Reef	28.8	23.9	21.9 a 22.2 b
Pseudomarker	25.4	19.8	-
Tarentaal, P1, P2 harzburgite	35.8	31.0	-
UG2 Pyroxenite	25.1	23.0	-
Base of UG2 Pyroxenite	29.1	26.8	-
UG1 Pyroxenite	24.8	23.4	-

All values in MgO % with original data recalculated to 100% H_2O- and L.O.I.-free; all Fe as Fe_2O_3. Data represent averages from present study, with Rustenburg^a data from Kruger (1983) and Rustenburg^b data from Lee (1983). Dashes indicate no data available.

emplaced in the manner suggested, the question arises whether indications of proximal and distal facies exist. In Table 1 it is shown that there is a consistent decline in whole-rock MgO levels in all equivalent mafic members exposed, respectively, at Union, Amandelbult and Rustenburg Sections. Union Section may thus be located closer to an irruptive centre than exposures to the north-east, or along the southern limb of the complex. The Merensky Reef is rich in olivine at Union Section; the amount is variable at Amandelbult, and at Rustenburg the 'reef' is pyroxenite. Pseudoreef harzburgite declines from *c.* 36% MgO at Union to 31% at Amandelbult Section. Viljoen *et al.* (1986*b*) describe the attenuation, degradation into schlieren or stringers of olivine norite, and ultimate disappearance of the Pseudoreef harzburgites towards the north-eastern underground exposures at Amandelbult, which we regard as distally disposed with respect to the area investigated by us. A further correlation, only superficially researched at present, is presented in Fig. 10*c*. Here the thickness of the interval between the top of the UG2 pyroxenite and the Merensky Unit is plotted against the map distance from the geographic centre of Union Section. The variation in thickness is doubtless due to a complex interplay of several factors, but the correlation between inferred proximality to an irruptive centre, and thickness of an interval believed to have been attenuated by post-depositional processes, remains suggestive.

(*c*) *The thickness of basal liquid layers.* The absolute levels of some elements within cyclic units have profoundly influenced modelling of the Bushveld Complex. For example, the amount of Cr_2O_3 within chromitites (40–50%) would appear to require an overlying column of source liquid (0.1% Cr_2O_3) not less than 400–500 times thicker than the layer itself. Allowance for Cr within associated pyroxenites, and crystal/liquid partition coefficients, would suggest that estimates of 0.5–2 km would be not unrealistic for the thickness of a basal column of primitive liquid required to deposit the UG2 Unit. Such considerations have been persuasive in support of the concept of magma rising as plumes within, and subsequently mixing with, the resident magma column (Campbell *et al.*, 1983). However, these arguments are model-dependent, and the implied long-range settling of nucleated cumulus phases is not consistent with established features of the UG1 and UG2 Units (Eales and Reynolds, 1986). The paradox encountered by Hiemstra (1985) in attempting to reconcile Rayleigh-type depletion trends followed by platinum group elements in the UG2 chromitite (implying thin source-liquid columns) with the total amount of Cr in the layer, has led him to propose, as we do, the lateral streaming of thin, basal layers of liquid undergoing crystallization.

(*d*) *The fate of the resorbed material.* Abundant evidence for plastic behaviour of anorthositic layers within the upper critical zone (Lee, 1981; Viljoen *et al.*, 1986*a*; Viljoen and Hieber, 1986) indicates that, during the immediately post-depositional stage, they behaved as crystal mushes with super-liquidus, lubricating, intergranular fluid. The stripping of newly deposited leucocratic layers off the tops of older units, upon emplacement of new pulses of hot, dense, primitive liquid does not require their total assimilation, although this will be an element of the process; remobilization could be effected by a combination of mechanical and thermal processes. Until such time as studies are focused upon establishing proximal and distal characteristics within the mafic members, it can only be assumed that mechanical and thermal erosion causes a feldspathic mush to be swept along with the basal liquid being emplaced. Under such conditions, contamination of mafic liquids during the early stages of emplacement of basal flows would be less constrained by density differences than in delicately poised double diffusive convection systems, where small differences assume importance (see Irvine *et al.*, 1983). The implications of this are presented below.

Conclusions

The present paper stresses features of the Upper Critical Zone of the Western Bushveld complex to which insufficient attention has hitherto been paid: (*a*) the occurrence of significant sequences of leucocratic rocks, beneath the Merensky Unit, along the southwestern limb of the complex, and progressive attenuation of these sequences in the Amandelbult and Union Sections, where the harzburgitic Pseudoreefs occur; (*b*) indications of thermal effects imposed on anorthosites by overlying harzburgites; (*c*) harzburgite–anorthosite transitions without intervening pyroxenite, and (*d*) direct superposition of up to three texturally and chemically distinct ultramafic members, separated only by chromitite layers.

Pending the completion of Sr-isotope studies of equivalent members along strike (in progress), our explanation of the features listed above is tentative. Observations stemming from this paper may, however, be drawn together with other relevant data to erect the framework of an explanation. (*a*) Olivine reappears in abundance in the Upper Critical Zone after an interval of *c.* 700 m of olivine-poor rocks. (*b*) The Pseudoreefs and Merensky Reef punctuate the stratigraphic succession at levels where fieldwork demonstrates, or inference suggests, that underlying leucocratic sequences are attenuated, or missing. (*c*) Such attenuation may be attributable to partial assimilation accompanied by mechanical scour, and was most profound in the region we regard as proximally disposed with respect to an irruptive centre, i.e. Union Section. (*d*) Varying degrees of replacement of subhedral and euhedral olivine by coarsely crystalline orthopyroxene are characteristic of the Merensky Reef and Pseudoreefs in the northwestern exposures, suggesting that the pegmatitic texture was imposed upon earlier olivine-rich cumulates. (*e*) Troctolite is rare within the Upper Critical Zone, but within the P2 Middling member anorthosite grades upwards into leucotroctolite. It is significant that this rare association overlies a harzburgite layer which, enigmatically, displays an undulating upper junction with the P2 Middling member, with pinnacles of harzburgite extending upwards into the anorthosite (Fig. 5*c*). This is strongly suggestive of localized resorption of the harzburgite.

These features might be interpreted in terms of production of feldspathic melts by partial remelting of feldspathic cumulates of the floor, close to an irruptive centre, and their rising within and mixing with fresh, hot surges of primitive liquid being emplaced above the floor, leading to hybrid liquids. Such liquids, formed by liquid mixing rather than evolution along conventional fractionation paths, would have the capacity to assimilate earlier cumulates (see Irvine *et al.*, 1983, pp. 1299–1305). Ultimate crystallization of such liquids, where sufficiently contaminated, might yield anorthosite, and then troctolite. Crystallization of pyroxenite and melanorite could be inhibited or even bypassed within parts of the system, allowing for direct superposition of leucocratic rocks upon harzburgites of the Pseudoreef Multicyclic Unit.

Our model is thus one that adopts a variation of the elegant hypothesis of Irvine *et al.* (1983). The latter authors derive hybrid liquids by mixing of anorthositic (A-type) liquids with derivatives of an ultramafic lineage. We suggest that contamination of primitive liquids within the Footwall and Pseudoreef Multicyclic Units is in part effected by assimilation of floor rocks. In this way, a single, common process links together each of the following features: (i) the occurrence of a

harzburgite–anorthosite–harzburgite–
anorthosite–troctolite–harzburgite

sequence at Amandelbult, (ii) direct superposition of the Merensky Reef upon Upper Pseudoreef, upon Lower Pseudoreef at Union Section, (iii) eroded tops of harzburgite layers overlain by anorthosite, (iv) dimpling and scalloping of anorthosite overlain by harzburgite, (v) potholing, (vi) regional patterns of attenuation of feldspathic cumulate layers, with a focus at Union Section, and (vii) the Mg-rich character of members at Union Section, relative to their equivalents at Amandelbult and Rustenburg Sections.

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References

Campbell, I. H., Naldrett, A. J., and Barnes, S. J. (1983) *J. Petrol.* **24,** 133–65.

de Klerk, W. J. (1982) M.Sc. thesis, Rhodes University.

Donaldson, C. H. (1985) *Mineral. Mag.* **49,** 683–94.

Eales, H. V., and Reynolds, I. M. (1986) *Econ. Geol.* **81,** 1056–66.

—— Marsh, J. S., Mitchell, A. A., de Klerk, W. J., Kruger, F. J., and Field, M. (1986) *Mineral. Mag.* **50,** 567–82.

Farquhar, J. (1986) In *Mineral Deposits of Southern Africa* (C. R. Anhaeusser and S. Maske, eds.) Geol. Soc. S. Africa, 1135–42.

Feringa, G. (1959) *Geol. Soc. S. Africa Trans.* **62,** 219–38.

Field, M. (1986) M.Sc. thesis, Rhodes University.

French, W. J., and Cameron, E. P. (1981) *Mineral. Mag.* **44,** 19–26.

Harmer, R. E., and Sharpe, M. R. (1985) *Econ. Geol.* **80,** 813–37.

Hiemstra, S. A. (1985) Ibid. **80,** 944–67.

Huppert, H. E., and Sparks, R. S. J. (1980) *Contrib. Mineral. Petrol.* **75,** 279–89.

————(1985) *J. Petrol.* **26,** 694–725.

Irvine, T. N., Keith, D. W., and Todd, S. G. (1983) *Econ. Geol.* **78,** 1287–334.

Kruger, F. J. (1983) Ph.D. thesis, Rhodes University.

——and Marsh, J. S. (1982) *Nature,* **298,** 53–5.

Lee, C. A. (1981) *J. Geol. Soc. London,* **138,** 327–41.

——(1983) *Mineralium Deposita,* **18,** 173–90.

Leeb-du Toit, A. (1986) In *Mineral Deposits of Southern Africa* (C. R. Anhaeusser and S. Maske, eds.) Geol. Soc. S. Africa, 1091–106.

Mitchell, A. A. (1986) Ph.D. thesis, Rhodes University.

Scoon, R. N. (1985) Ph.D. thesis, Rhodes University.

——and de Klerk, W. J. (1987) *Can. Mineral.* **25,** 51–78.

Sharpe, M. R., and Irvine, T. N. (1983) *Carnegie Inst. Washington Yearb.* **82,** 295–300.

Streckeisen, A. L. (1973) *Geotimes,* Oct. 1973, 26–30.

van Zyl, J. P. (1969) *Geol. Soc. S. Africa Spec. Publ.* **1,** 80–107.

Viljoen, M. J., and Hieber, R. (1986) In *Mineral Deposits of Southern Africa* (C. R. Anhaeusser and S. Maske, eds.) Geol. Soc. S. Africa, 1107–34.

——de Klerk, W. J. Coetzer, P. M., Hatch, N. P., Kinloch, E., and Peyerl, W. (1986*a*) Ibid. 1061–90.

——Theron, J., Underwood, B., Walters, B. M., Weaver, J., and Peyerl, W. (1986*b*) Ibid. 1041–60.

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