Corroded plagioclase feldspar inclusions in orthopyroxene and olivine of the Lower and Critical Zones, Western Bushveld Complex

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Abstract

The occurrence of spheroidal, ovoid or deeply embayed plagioclase inclusions within cumulus bronzite and olivine grains of both pyroxenites and norites here implies the existence of plagioclase feldspar in melts prior to the separation of ultramafic cumulates from these melts. Variations of Sr-isotope initial ratio are shown to exist within the feldspar populations of such rocks, even on a grain-to-grain scale. Five separate stratigraphic intervals within the Lower and Critical Zones exhibit this texture, and in each case these are intervals wherein normal fractionation trends (decline in both whole-rock and orthopyroxene $Mg/(Mg+Fe^{2+})$; decline in Cr contents of orthopyroxene) became reversed. The data support a model for evolution of the texture during major episodes of influx of hot, primitive magmatic liquid into the chamber. Progressive mixing of the new liquid with resident liquids (bearing feldspar on the liquidus) effected progressive changes in the composition of the hybrid liquids produced, and resorption and imposition of reversed zoning upon the inclusions.

KEYWORDS: Bushveld Complex, magma mixing, resorption, plagioclase.

Introduction

THE Bushveld layered complex of South Africa underlies an area of some 450 × 370 km, with the mafic rocks of its Rustenburg Layered Suite (S.A.C.S., 1980) being assigned an age of 2025 ± 40 Ma (Lee and Butcher, 1990). In terms of outcrop and sub-outcrop, at least five separate limbs or chambers are recognisable. The present paper focuses on the Western limb which extends westwards for 150 km from the Pretoria district to the Pilanesberg (see inset map, Fig. 1), and from there northeastwards for a further 80 km. Overlying a basal Marginal Zone of pyroxenites and norites is a mafic-ultramafic succession, *c.* 7 km thick, which is divisible into the Lower (hereafter L.Z.), Lower Critical (L.C.Z.), Upper Critical (U.C.Z.), Main (M.Z.) and Upper (U.Z.) Zones. The L.Z. and L.C.Z. comprise an ultramafic assemblage of dunites, harzburgites, bronzite pyroxenites and chromitites. The first appearance of cumulus plagioclase feldspar in the type area defines the base of the U.C.Z., below which feldspar is intercumulus only. Within the U.C.Z., norites and anorthosites appear. Olivine and chromite leave the paragenesis at the top of the U.C.Z., and the succeeding M.Z. is represented by norites, gabbronorites, gabbros and anorthosites. Within the more highly fractionated U.Z., titanomagnetite, iron-rich olivine and cumulus apatite join the paragenesis.

A distinctive texture (see Fig. 2) in which small, partially resorbed plagioclase feldspar grains appear in abundance as inclusions within cumulus bronzite crystals in the UG1 Footwall Unit at the Union Section of Rustenburg Platinum Mines, Ltd., was described by Eales *et al.* (1990*a* and *b*). It is within the pyroxenites (normally bearing intercumulus plagioclase only) that the genetic significance of the texture is most obvious, but the cumulus orthopyroxene grains of associated norites host similar inclusions. These inclusions are quite different in form from the elongate, euhedral or skeletal forms, or stellate clusters, within pyroxene oikocrysts of plagioclase–olivine cumulates that were attributed by Mathison (1987) to supercooled crystallisation. Microprobe, Sr-isotopic and whole-rock chemical data (Eales *et al.*, loc. cit.) led to the conclusion that the texture we describe arose out of the mixing of partially crystalline magma, bearing feldspar on the liquidus, with fresh inputs of hotter, more primitive magma.

Mineralogical Magazine, September 1991, Vol. 55, pp. 479–486

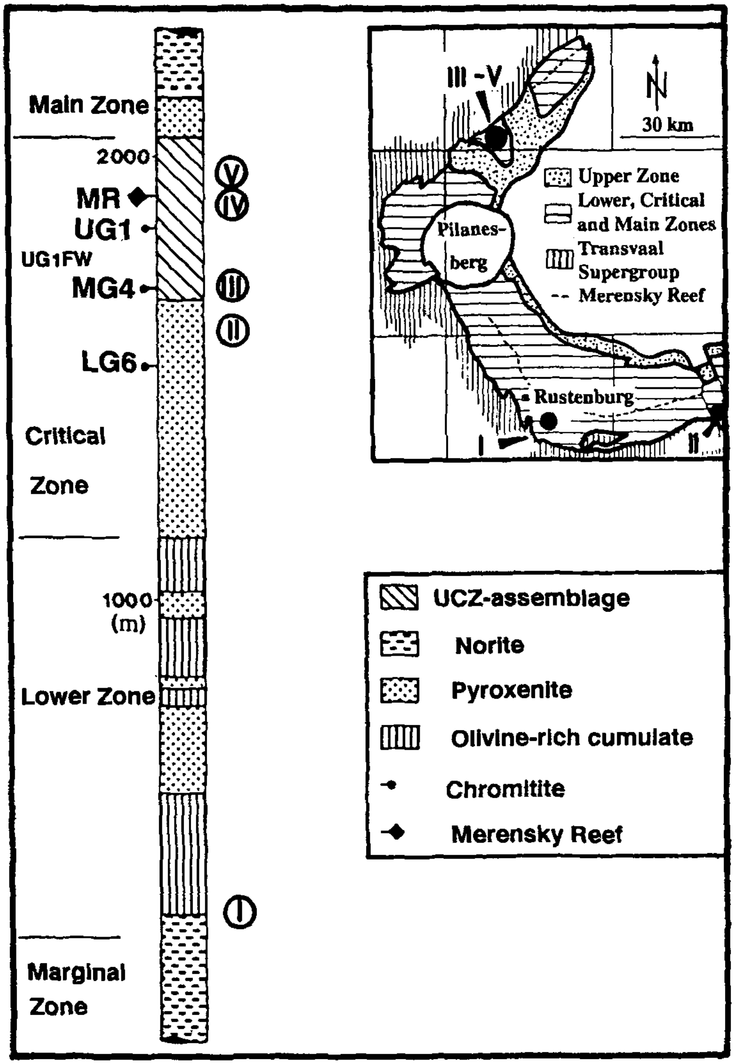

FIG. 1. Locality map and generalised section through Marginal, Lower and Critical Zones of the western limb of the Bushveld Complex. Prominent marker horizons LG6 Chromitite, MG4 Chromitite, UG1FW Unit, UG1 Chromitite and MR (Merensky Reef Unit) are indicated. Localities referred to in text are designated I to V.

Cameron (1982) commented briefly on the existence of this intergrowth in equivalent layers of the Eastern limb of the complex, but he did not discuss its petrographic significance. Maier (1991) and Teigler (1990) have recently established the persistence of this texture along the full strike length of the U.C.Z. in the Western limb, and have shown that it is also developed at higher and lower stratigraphic levels. The present paper presents these new data.

Nature and occurrence of partially resorbed plagioclase inclusions

The occurrence of partially resorbed plagioclase inclusions is currently established within five intervals in thje U.C.Z., L.C.Z. and L.Z. These intervals are indicated (intervals I–V) on the generalised stratigraphic column of Fig. 1.

(*a*) *Base of the U.C.Z., Union Section* (*Interval III of Fig. 1*). The first appearance of plagioclase

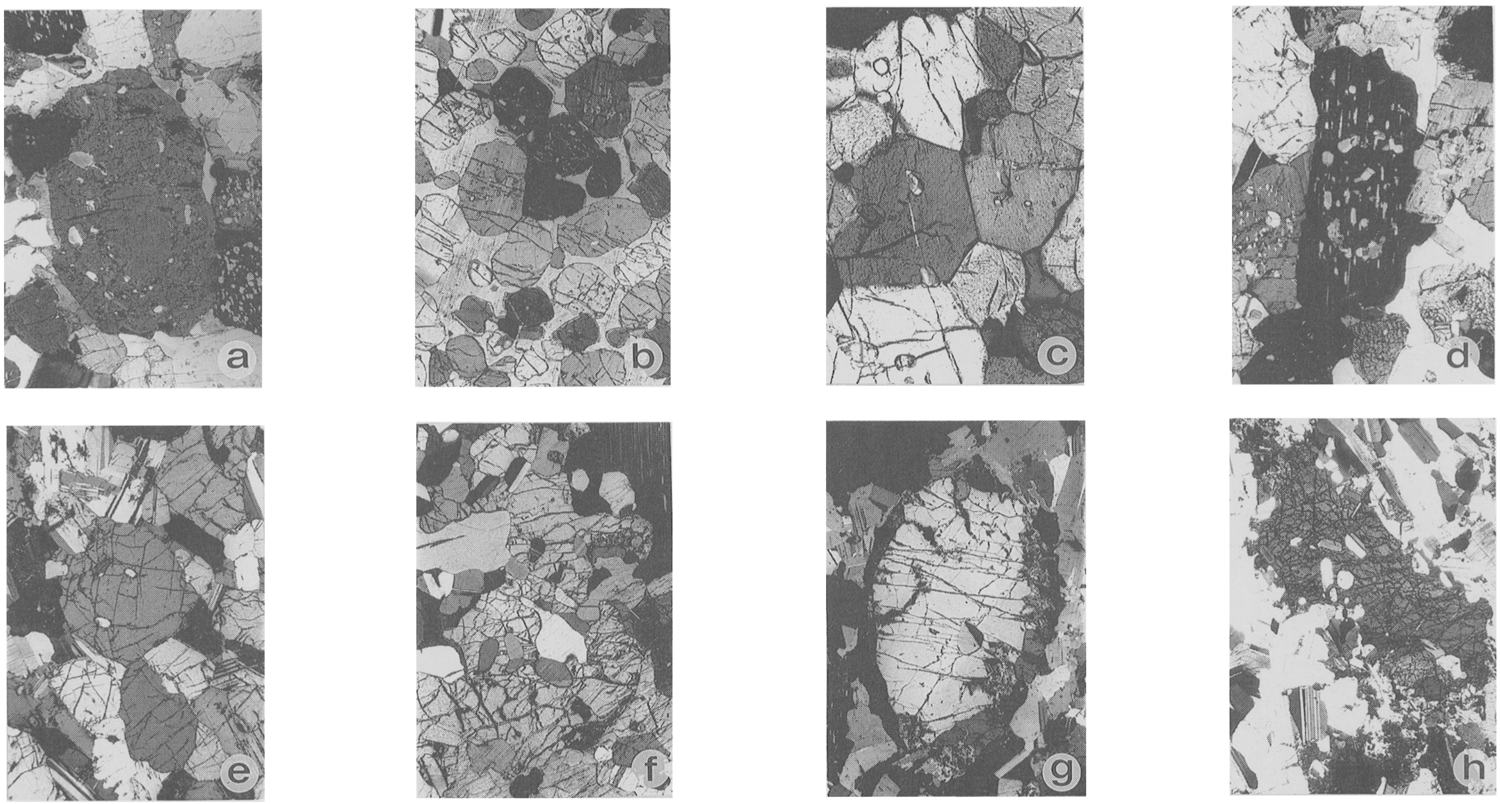

FIG. 2. (*a*) Bronzite grain showing abundant embayed plagioclase inclusions surrounding inclusion-free core. Bronzite orthocumulate, UG1FW Unit, Union Section I. Field width 0.6 mm. (*b*) Bronzite orthocumulate showing plagioclase inclusions. All bronzite grains set in optically continuous clinopyroxene crystal. UG1FW Unit, Union Section. Field width 2.5 mm. (*c*) Bronzite adcumulate with small, spheroidal plagioclase inclusions. UG1FW Unit pyroxenite, Union Section. Field width 0.6 mm. (*d*) Bronzite grain (at extinction) hosting corroded plagioclase inclusions, many of which are disposed around an oval core. Longer streaks are exsolved clinopyroxene. UG1FW Unit pyroxenite, Union Section. Field width 1.5 mm. (*e*) Bronzite grain enclosing three ovoid plagioclase inclusions. Norite of Interval II in text. Field width 2.5 mm. (*f*) Olivine grains showing numerous, highly embayed plagioclase inclusions. Olivine norite at contact of Marginal and Lower Zones (Interval I of text). Field width 2 mm. (*g*) Olivine, mantled by orthopyroxene in olivine norite 8 m above the UG2 pyroxenite at Impala, Bafokeng North Mine. One ovoid, twinned, partially resorbed inclusion is seen. Field width 1.5 mm. (*h*) Anhedral olivine grain hosting plagioclase inclusions of varying size and degree of rounding. Inclusions are significantly smaller than surrounding cumulus feldspar grains. Troctolite, 30 m above UG2 pyroxenite at Impala, Wildebeestfontein North Mine. Field width 1.5 mm.

cumulates in the U.C.Z. here occurs beneath a prominent marker horizon, the MG3 chromitite layer. Some 20 m below these cumulates, plagioclase inclusions appear in pyroxenites, becoming abundant within the succeeding MG3 and UG1 Footwall (UG1FW) Units. Examination of samples taken at 1–10 m intervals establishes that the distinctive texture does not occur in the 1600 m column of underlying rocks.

The main features of this occurrence (Eales *et al.*, 1990*a*) are:

(i) inclusions are commonly in the size range 0.02–0.25 mm;

(ii) inclusions are spheroidal, ovoid, or irregularly embayed, suggesting partial resorption (Fig. 2*a*);

(iii) inclusions occur within cumulus bronzite grains of bronzite orthocumulates (Fig. 2*b*) and adcumulates (Fig. 2*c*), and norites;

(iv) inclusions may show a zonal disposition within host-grains, sometimes around an inclusion-free core (Fig. 2*a*). More generally, the margins of host-grains in orthocumulates are inclusion-free (Fig. 2*d*);

(v) sporadic, large cumulus feldspar grains are entrapped between pyroxene grains;

(vi) inclusions most commonly show reversed zoning, but normally zoned, or unzoned crystals, are encountered;

(vii) compositions range from An_{60} to An_{75}, maintaining a rough equivalence of composition with intercumulus and cumulus plagioclase in the host rocks;

(viii) separation of samples into pyroxene and feldspar fractions has shown that Sr-isotopic disequilibrium may prevail between the fractions (see Fig. 3) or between discrete, large cumulus plagioclase grains trapped within the fabric of pyroxenites.

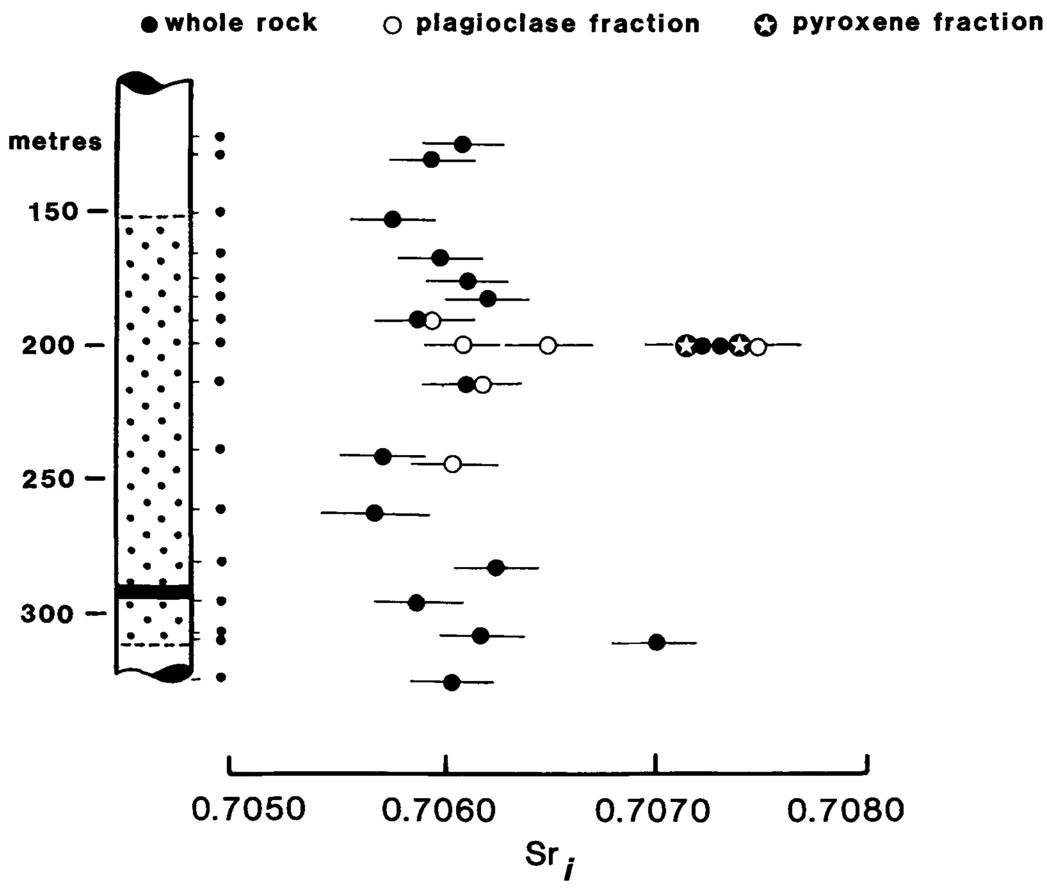

FIG. 3. Sr-isotope initial ratios as determined for pyroxenites of UG1FW Unit, Union Section. Filled circles—whole-rock data; open circles—plagioclase fractions; circled stars—pyroxene fractions; dots next to column—sample positions. Original data and methods of analysis are given in Eales *et al.* (1990*a*). Depths are given in metres below UG1 chromitite marker horizon. Layer shown in solid black depicts MG4 chromitite layer.

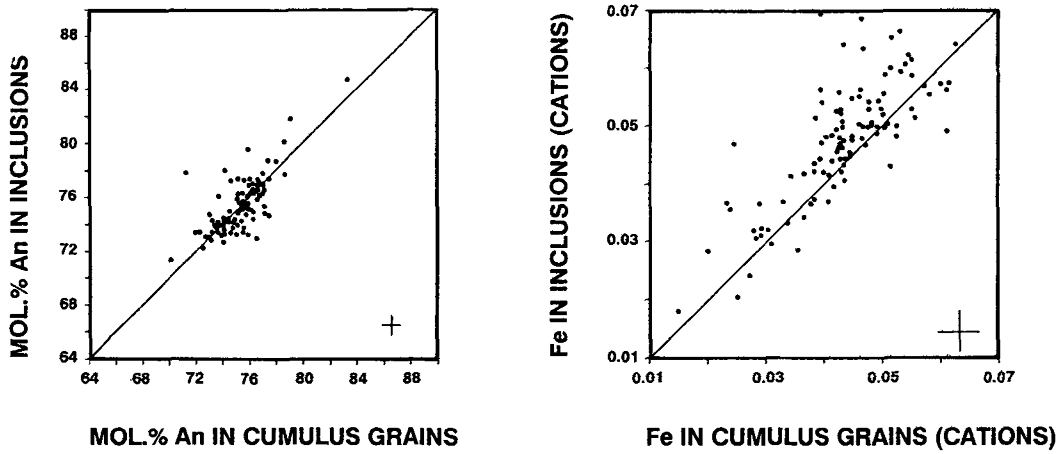

FIG. 4. Plots showing (*a*) average anorthite content, and (*b*) Fe content (cations per 32 oxygens) in corroded plagioclase inclusions, against equivalent values for cumulus plagioclase in the same samples (crystal core compositions only). Data compiled from microprobe studies of 99 samples of norite underlying Merensky Unit of western limb of complex. Averages for each sample compiled from 4–15 microprobe analyses of each textural type of plagioclase. Crosses in bottom right of diagrams indicate average standard deviation for each plotted point.

Since the report cited above was published, it has emerged from the study of core from boreholes drilled into the deep footwall of mining operations at Union Section (Teigler, 1990) that not only do inter- and intragranular crystals of plagioclase occur within pyroxenites of the UG1FW unit, but that pods (*c*. 2–40 mm) and schlieren of anorthosite are entangled with pyroxene cumulates. These disrupted schlieren are aligned parallel to the layering of the rock.

(*b*) *Base of the Lower Zone* (*Interval I of Fig. 1*). The stratigraphically lowest interval at which plagioclase inclusions have been recognised occurs at the contact of the noritic Marginal and ultramafic Lower Zones, near Kroondal (*c*. 8 km east of Rustenburg), within olivine norites. Because of significant thinning of the ultramafic cumulate pile (Hatton and von Gruenewaldt, 1987) in the southern section of the Western limb, this occurrence is only *c*. 140 m below the LG6 chromitite layer of the L.C.Z.

(*c*) *Cumulates of the L.C.Z.* (*Interval II of Fig. 1*). In contrast to the type sequence at Union Section, plagioclase cumulates occur within the L.C.Z. 55 km east of Rustenburg, and here the inclusions make their appearance c. 110 m below the top of the L.C.Z. (Teigler, 1990). This horizon is thus *c*. 90 m lower, stratigraphically, than that of the Union Section occurrence.

In both Intervals I and II the rocks are olivine norites or norites characterised by numerous inclusions of plagioclase within both sub- and anhedral orthopyroxene (Fig. 2*e*) and olivine (Fig. 2*f*). In general, inclusions are more abundant and more highly resorbed in olivine than in orthopyroxene. In these rocks there is a gradation from small, highly resorbed, ovoid or irregularly embayed crystals to others which are virtually unresorbed and lath-like in shape.

(*d*) *Footwall of the Merensky Unit* (*Interval IV of Fig. 1*). Study of the stratigraphic interval between the bases of the UG2 and Merensky Units by Maier (1991) has established the presence of partially resorbed plagioclase inclusions within troctolites, olivine norites and norites along the full strike length of the Western limb. The UG2 pyroxenite and harzburgitic Pseudoreef within this interval are, however, virtually free of this texture. The hosting grains are both olivine (Fig. 2*g*–*h*) and bronzite. Microprobe analyses show that core compositions of the plagioclase inclusions, and their zonal patterns, are the same in both hosts. Sizes of inclusions vary from perfectly spheroidal grains close to the limit of optical resolution to tabular grains >0.5 mm in length, where resorption is not obvious.

The results of microprobe analysis of both inclusions and cumulus plagioclase (core compositions) in 99 samples from 8 boreholes are presented in Fig. 4. Sympathetic compositional variation is demonstrated, with no consistent difference between the texturally discrete varieties. Some bias is shown in the Fe contents in so far as 70% of inclusions display Fe-enrichment relative to cumulus grains. Separation of samples on a basis of geographic locality (Table 1) suggests a regional trend, with inclusions being generally the more calcic in the northwest

Table 1. Average values for core compositions of cumulus plagioclase grains, and inclusions, along 170 km of strike of the Merensky Footwall Unit in the Western limb ('n' refers to the number of separate samples investigated at each locality with 4-15 grains of each textural type being analysed in each sample).

	An (mol.%)			Fe (cations)			n
	Cum.	Incl.	Diff.	Cum.	Incl.	Diff.	
Amandelbult	75.8	77.2	1.37	0.041	0.044	0.003	10
Union	76.4	77.3	0.89	0.035	0.038	0.003	5
Impala North	77.1	77.7	0.59	0.037	0.043	0.006	7
Impala South	76.7	76.8	0.14	0.038	0.037	-0.001	13
Wolhuterskop West	73.8	74.1	0.33	0.047	0.052	0.005	22
Wolhuterskop East	75.3	75.2	-0.08	0.049	0.053	0.004	23
Crocodile River Mine	75.2	74.5	-0.70	0.049	0.054	0.005	13
All Samples	75.4	75.7	0.30	0.044	0.048	0.004	82

(Amandelbult and Union Sections) and more sodic towards the southeast (Crocodile River Mine). Zonal variations in compositions of inclusions, at different localities along strike, have been investigated by rim-to-rim microprobe traverses across 19 grains. Reversed zoning was established in 15 cases (average core composition 75.2 ± 1.4% An; average rim 77.2 ± 1.2% An) with a maximum difference of 6% An. Weakly expressed normal zoning was found in 4 cases.

(*e*) *The Bastard Unit* (*Interval V of Fig. 1*). The occurrence of spheroidal plagioclase within olivine grains occurring in the lower, pyroxenitic member of the Bastard Unit, at Union Section, has been recorded by Eales *et al.* (1986). The composition of this olivine ($Fo_{78.5}$ to $Fo_{80.5}$, with Ni contents of 2800 ppm) is as magnesian as that within the relatively primitive, harzburgitic Pseudoreef located at a deeper level of the U.C.Z. This observation rules out the possibility that this olivine is a paragenetically late phase.

Discussion and conclusions

The enclosure of bladed or lath-like plagioclase crystals by pyroxene (ophitic or poikilophitic texture) is characteristic of many gabbros and dolerites, and some coarser-grained basalts. The intergrowth implies early crystallisation of plagioclase within the melt, or cotectic crystallisation with pyroxene. The textures described in this paper are, however, more paradoxical in that they imply the existence of plagioclase at an early stage within melts, and then partial resorption before encapsulation within orthopyroxene or olivine, or both, prior to the filling of available pore space by intercumulus feldspar. Rocks hosting this texture may be pyroxenites or norites, with or without olivine.

Of various possible modes of origin, the following appear to be the most plausible:

(*a*) inclusions represent aberrations in the normal order of crystallisation of phases;

(*b*) inclusions represent plagioclase nucleated within a bottom zone enriched in the components of feldspar, consequent upon *in-situ* growth of pyroxenites on the floor of the complex;

(*c*) the texture is the result of subsolidus recrystallisation, or solution and reprecipitation in crystal mushes, as described by Hunter (1987);

(*d*) inclusions represent feldspar crystals that settled from higher liquid layers in a stratified liquid column;

(*e*) the texture is produced by the mixing of evolved, residual liquids bearing feldspar on the liquidus, with batches of more primitive liquid.

Alternatives (*a*)–(*c*) are rejected on the basis that they fail to account for the Sr-isotopic disequilibrium that appears to prevail within the feldspar population. Furthermore, (*a*) and (*b*) do not satisfactorily account for the resorption that must necessarily have followed the initial period of growth. Moreover, the preservation of crystal zoning in both cumulus pyroxenes and feldspars, and the survival of preferred orientation (primary foliation) of well zoned, bladed crystals parallel to the layering, do not encourage development of a model based on (*c*) above.

The choice between alternatives (*d*) and (*e*) is aided by the field and gross chemical relationships of the stratigraphic Intervals I–V. It was established by Eales *et al.* (1990*a*) that the 300 m section embracing Interval III is characterized by at least six minor reversals of normal fractionation trends, each spanning some 10–50 m of section. Within these reversals there are increases, with stratigraphic height, of Mg/(Mg+Fe^{2+}) ratios (in both whole-rock and microprobe data), the Cr contents of bronzite primocrysts, and whole-rock ratios such as Ni/V and Fe/Ti. These reversals offer support for the concept of interruption of the course of fractionation within residual liquids within the chamber by periodic addition of hotter, more primitive liquid.

The new data in this paper confirm a correlation between the occurrence of resorbed plagioclase inclusions, and chemical reversals. It has been shown (Eales *et al.*, 1990*b*) that the 2000 m column embracing the Marginal Zone, L.Z., L.C.Z. and U.C.Z. at Union Section is characterised by four major reversals, each of which culminates in magnesian olivine cumulates. Interval I, where the ultramafic cumulates of the L.Z. overlie norites of the Marginal Zone, lies at the base of the first major reversal, which extends (at Union Section) upwards for *c.* 300 m. There are sound reasons for believing that Interval I is therefore located at the position where a major input of mafic magma was emplaced upon basal, cumulus plagioclase-bearing cumulates. Interval IV, within the footwall of the Merensky Unit, is likewise characterised by a similar reversal of Mg-numbers within a noritic column up to 140 m thick (Maier, 1989, 1991). Similarly, Interval V, within the basal pyroxenite of the Bastard Unit, is marked by a distinct reversal of normal fractionation trends extending through some 10 m of sequence (Eales *et al.*, 1986, Fig. 1). It is within this interval that magnesian olivine makes it final appearance in the Critical Zone. This reversal has been proved by detailed studies (de Klerk, 1991) to persist through all intersections of the Bastard Unit along some 170 km of strike in the Western limb of the complex.

Interval II lies within a petrographically anomalous assemblage of norites and pyroxenites, with thin layers of chromitite, in the L.C.Z. Teigler (1990) has shown, from both whole-rock and microprobe data, that this interval correlates with a major reversal in fractionation trends, extending over a vertical thickness of *c.* 130 m. Whole-rock Mg/(Mg+Fe^{2+}) ratios are shown to increase from *c.* 0.77 to *c.* 0.85 within this interval.

In conclusion, we find that the distinctive texture wherein corroded and frequently reversed-zoned plagioclase inclusions are encapsulated by cumulus bronzite or olivine crystals, appears in every case within parts of the sequence where chemical evidence points to addition of primitive liquid to the crystallising column. Within Intervals designated I, II, IV, and V, cumulus plagioclase occurs within layers underlying these intervals. It may be pictured that feldspar, suspended in the residual supernatant liquids, becomes entrapped within pyroxene or olivine crystals which nucleate in the hybrid liquids produced by mixing-in of influxes of more primitive liquid. In the case of Interval III no plagioclase cumulates are encountered within 100 m of underlying pyroxene and olivine cumulates, but norites join the assemblage 20 m above the first appearance of corroded inclusions within pyroxenites. This points to nucleation and growth of plagioclase crystals in the fractionating liquid column at least 20 m below the level at which *cumulus* feldspar subsequently accumulated to yield norite. Alternatively, bronzite crystals bearing entrapped plagioclase inclusions may have settled under gravity from a higher level in the liquid column, where plagioclase was on the liquidus. This, and the observation that anorthositic pods and schlieren occur beneath the first norite of the U.C.Z., raises the intriguing question of whether the accumulation of anorthosites may have occurred within the liquid column, well above the floor of the complex, as was believed by Vermaak (1976).

As a final comment, we note that textures of this sort might easily be overlooked in rocks of noritic type, where ophitic enclosure of cumulus plagioclase by orthopyroxene is in any event common. The significance of the rounded shapes of many of the feldspar inclusions might here not be immediately apparent. It is only when such inclusions occur in associated ultramafic pyroxenites with intercumulus feldspar, that the paradox becomes obvious. A further corollary is that the texture is recognisable only where resorption has been incomplete. Complete resorption, resulting in significant hybridisation of liquids, could have occurred elsewhere without leaving any petrographic evidence.

Acknowledgements

The authors wish to express their indebtedness to GENMIN, Ltd., and the C.S.I.R., for financial assistance during the course of this work. Sample material used in this study was made available by the Director of Geological Survey, and by GENMIN, RAND MINES, and JCI, Ltd., to whom our thanks are offered.

References

Cameron, E. N. (1982) Evolution of the Lower Critical Zone, Central Sector, and its Chromite Deposits. *Econ. Geol.*, **77**, 1307–27.

De Klerk, W. J. (1991) *Petrology and geochemistry of the upper Critical Zone in the Western Bushveld Complex*. Unpubl. Ph.D. thesis, Rhodes University (in prep.)

Eales, H. V., Marsh, J. S., Mitchell, A. A., De Klerk, W. J., Kruger, F. J. and Field, M. (1986) Some geochemical constraints upon models for the crystallisation of the upper critical zone—main zone interval, northwestern Bushveld complex. *Mineral Mag.*, **50**, 567–82.

—— De Klerk, W. J., Butcher, A. R., and Kruger, F. J. (1990a) The cyclic unit beneath the UG1 chromitite (UG1FW unit) at RPM Union section Platinum Mine—Rosetta Stone of the Bushveld Upper Critical Zone?. Ibid. **54**, 23–43.

—— —— and Teigler, B. (1990b) Evidence for magma mixing processes within the Critical and Lower Zones of the northwestern Bushveld Complex. *Chem. Geol.*, **88**, 261–78.

Hatton, C. J. and Von Gruenewaldt, G. (1987) The geological setting and petrogenesis of the Bushveld chromitite layers. In *Evolution of chromium ore fields* (Stowe, C. W., Ed.) Van Nostrand Reinhold Co., New York, 109–43.

Hunter, R. H. (1987) Textural Equilibrium in layered igneous rocks. In *Origins of Igneous Layering* (Parsons, I., Ed.) D. Reidel Publishing Company, Dordrecht, 473–503.

Lee, C. A. and Butcher, A. R. (1990) Cyclicity in the Sr-isotope stratigraphy through the Merensky and Bastard Reef units, Atok Section, Eastern Bushveld Complex. *Econ. Geol.*, **85**, 877–83.

Maier, W. D. (1989) A geochemical and petrological study of lateral variations of lithology within the interval between the UG2 chromitite and the Merensky Reef in the Western Bushveld (Abstr.). In *Conference on the origin of mineralisation in southern African layered intrusions*. University of the Witswatersrand.

—— (1991) *Petrology and geochemistry of the interval between the UG2 and Merensky units along 170 km of strike in the Western Bushveld Complex*. Unpubl. Ph.D. thesis, Rhodes University (in prep.).

Mathison, C. I. (1987) Pyroxene oikocrysts in troctolitic cumulates—evidence for supercooled crystallisation and postcumulus modification. *Contrib. Mineral. Petrol.*, **97**, 228–36.

South African Committee for Stratigraphy (SACS), (1980) *Stratigraphy of South Africa. Part 1 (Comp. L. E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia and the Republic of Bophuthatswana, Transkei and Venda*. Geological Survey of South Africa, Handbook **8**, Pretoria, 690 pp.

Teigler, B. (1990) *Mineralogy, petrology and geochemistry of the Lower and lower Critical Zones, northwestern Bushveld Complex*. Unpubl. Ph.D. thesis, Rhodes University, 247 pp.

Vermaak, C. F. (1976) The Merensky Reef—Thoughts on its Environment and Genesis. *Econ. Geol.*, **71**, 1270–98.

[*Revised manuscript received 25 March 1991*]