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POSTCUMULUS CHANGES IN THE EASTERN BUSHVELD COMPLEX

EUGENE N. CAMERON *Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706.*

ABSTRACT

Cumulus crystals in certain rocks of the Transition and Critical Zones of the eastern Bushveld Complex in part were free to enlarge after settling, in part were trapped and thus shielded from enlargement. Measurements of the two sets of crystals show that average diameters of unshielded crystals in some rocks were increased by a factor of three or more, a change too great to be due to simple extension of crystals into interstices of a crystal mush. More than half the volumes of such rocks are therefore due to crystallization or recrystallization during the post-cumulus stage. Size distributions and compositions of coexisting cumulus phases must be interpreted accordingly. Grain size analysis can be used as a key to mechanisms of crystal accumulation only in rare cases in which initial sizes of two cumulus phases are preserved.

Postcumulus changes in grain size are indicated only in certain cumulates having special textural features. In most cumulates of the Critical and Transition Zones, changes are indeterminate, but percentages of pore minerals serve as a rough index of degree of enlargement. In the bronzitites, the ratio of bronzite to pore minerals in general declines upward in the rock sequence. Similarly, dunites at higher horizons have higher contents of pore minerals than dunites at lower horizons. It is inferred that the major control over degree of enlargement was progressive displacement of the magma composition toward the plagioclase boundary on the liquidus, owing to withdrawal of bronzite and olivine by crystal settling. The trend is consistent with the concept that the two zones, despite the complexity of their rock sequences, are parts of a magmatic differentiation sequence.

INTRODUCTION

In recent years, the formation of layered igneous complexes has been discussed largely in terms of processes of magmatic sedimentation, and a wide range of textures and structures analogous to those of surface sediments has been described. As in ordinary sediments, two main stages of formation have been recognized: (1) a cumulus stage, during which crystals settled to the floor of accumulation, and (2) a postcumulus stage, during which adcumulus enlargement of cumulus crystals, reaction between crystals and liquid, and crystallization of pore material took place, singly or in combination. The distinction of these two stages and the evaluation of their consequences are fundamental to the understanding of any cumulate (Wager and Deer, 1939, p. 127; Hess, 1939, p. 430–432; Wager, Brown and Wadsworth, 1960; Jackson, 1967, p. 21–22).

A completely satisfactory terminology for cumulates is difficult to formulate. The term "cumulus," in the strict sense (Wager, Brown, and Wadsworth, 1960, p. 73; Jackson, 1967, p. 22–23) designates settled crystals as originally precipitated from the magma. Adcumulus material

(Wager, Brown, and Wadsworth, 1960, p. 77) designates material deposited as overgrowths or enlargements of settled crystals (material formed by postcumulus overgrowth, Jackson, 1967, p. 23). In practice, the distinction between cumulus and adcumulus material can seldom be made quantitatively, and in the present paper, except as noted, "cumulus" designates both cumulus and adcumulus material. Minerals formed by filling of the spaces left after adcumulus enlargement are termed "pore material," following Wager *et al.*, (1960, p. 77). "Postcumulus reaction material" designates material formed by reaction between cumulus crystals and liquid. The writer follows Jackson (1967, p. 23) in using the term "postcumulus material" as a general term covering adcumulus, pore, and reaction material.

In this connection, it is important to determine whether the sizes of cumulus grains have been significantly altered during the postcumulus stage. If they have not, then it is logical to apply to magmatic sediments the techniques of grain-size analysis that have been developed with respect to ordinary sedimentary rocks, in the hope of shedding light on mechanisms and conditions of magmatic sedimentation. Thus Jackson (1961) has used this type of analysis in examining textures of ultramafic rocks in the Stillwater Complex, and Irvine (1965) has presented size data for certain rocks of the Duke Island Complex. Cameron and Emerson (1959) used grain sizes as evidence for processes of formation of chromite seams in the eastern Bushveld Complex. More elaborate studies of grain size and sorting coefficients of minerals in Bushveld rocks have since been made at the University of Wisconsin by Macdonald (1967) and by Sundeen (1964). Additional studies of cumulates of the eastern Bushveld Complex have been made by the writer since 1964, together with studies of textural features. The present paper deals mainly with postcumulus changes in grain size in these cumulates and with the mechanisms involved. The bearing of such changes on interpretation of grain size and phase compositions is also examined.

Postcumulus processes in magmatic sediments, including adcumulus enlargement, have been discussed by a number of authors, but few quantitative data are available for the percentages of total rock volumes contributed by postcumulus crystallization. It has generally been inferred that in any given cumulate, barring replacement of cumulus crystals by a postcumulus phase, the percentage is approximately equivalent to the porosity of the initial crystal mush; *i.e.*, that postcumulus material, both adcumulus and intercumulus, merely filled the interstices of settled crystals. Wager and Deer (1939, p. 127) estimated the amount at about 20 percent. Brown (1956, p. 49) suggested 30 to 50 percent, depending on packing. Wager, Brown, and Wadsworth (1960, p. 75–76) suggested 35 to

45 percent from an experiment simulating settling of plagioclase in the lower part of the Skaergaard intrusion. Hess (1960, p. 109) estimated 26 to 29 percent for cumulates of the Stillwater Complex, making no allowance for adcumulus material. Jackson (1961, p. 58–62) calculated enlargement in rocks of the Ultramafic Zone of the Stillwater Complex by subtracting the volume of interstitial material from the initial porosity, which was estimated to average 25 to 40 percent in various rocks. Enlargement in these rocks (in volume percent of total rock) was calculated at 6 to 29 percent in various specimens, the amount ranging generally from 17 to 24 percent, depending on grain size, sorting, and shape of the cumulus phases.

Direct evidence of postcumulus increase in size of settled crystals may be provided by compositional zoning. In most cumulates, however, direct evidence is lacking (*cf.* Upton, 1961, p. 12), and it is difficult or impossible to determine how much individual crystals have grown since settling. This is the case for the majority of the cumulates of the eastern Bushveld. In certain of these cumulates, however, special textures permit a comparison between initial or near-initial cumulus grain sizes and sizes after postcumulus crystallization. This comparison indicates that in some rocks crystal sizes have been greatly altered by postcumulus processes. Present grain sizes and size distributions must therefore be interpreted in terms of the postcumulus stage. In addition, in such a cumulate, much more than half the final rock volume derives from the postcumulus stage. The results therefore direct attention to postcumulus processes as important keys to the composition of coexisting cumulus phases.

Cumulates of the Critical and Transition Zones

Sequences of rock units in the eastern part of the Bushveld Complex have been described in previous articles (Cameron, 1963, 1964; Cameron and Desborough, 1969). The sequence discussed in the present paper is that which is almost continuously exposed by drillholes, mine workings, and outcrops on Farms Jagdlust and Winterveld (Fig. 1) and is shown in columnar section in Figure 2. Some of the rocks (bronzitite, dunite, anorthosite, chromitite) contain a single cumulus mineral, others (harzburgite, chromite-anorthosite, norite, chromite-pyroxenite, and chromite-dunite) have two cumulus species, and still others (chromite-norite, gabbro-norite, chromite-harzburgite) have three cumulus species. In this paper, the rock name expresses the cumulus species present. Thus any rock containing both cumulus bronzite and cumulus plagioclase is a norite, and a rock with olivine as the only cumulus mineral is a dunite. Adjectives express the presence of postcumulus minerals; *e.g.*, felspathic dunite.

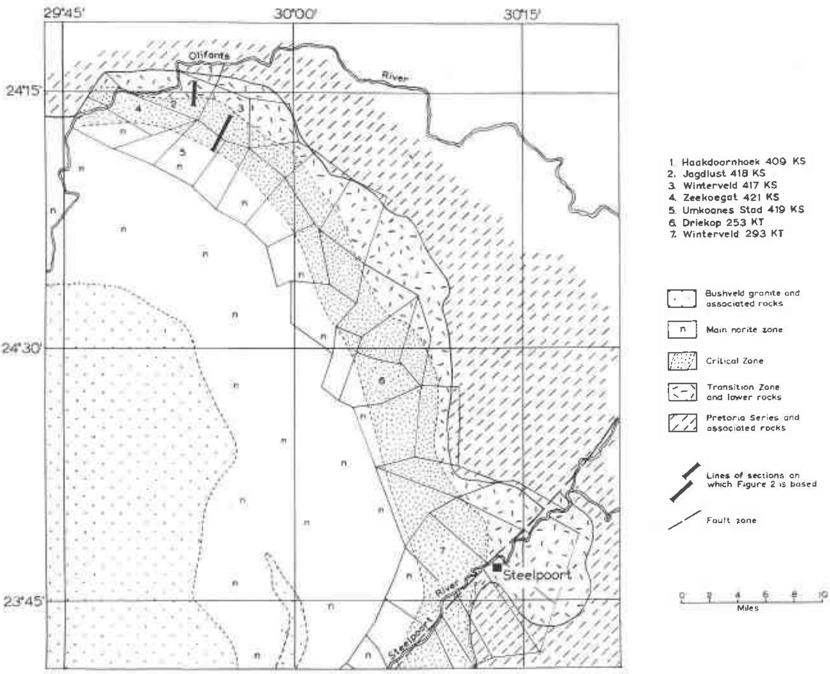

FIG. 1. Generalized geologic map of part of the eastern Bushveld Complex, compiled from various sources.

Of particular interest are rocks in which the cumulus minerals form 90 to 99.8 percent of the bulk composition by volume. Certain bronzitites are examples (Fig. 3). Such rocks cannot form by crystal settling alone. Experimental settling of bronzite in our laboratory indicates that minimum porosity of a bronzite cumulate is about 28 percent. With loose packing, porosities range up to 45 percent. Such porosities are comparable with those cited for various cumulates by Wager, Brown, and Wadsworth (1960, p. 75–76) and Jackson (1961, p. 72). Assuming a noritic interstitial liquid and minimum porosity, then about 14 percent bronzite could be added by crystallization of interstitial liquid. Total cumulus plus postcumulus bronzite would be about 86 volume percent. A rock like that of Figure 4 should result. Higher percentages of bronzite indicate filling of interstices or their eradication by recrystallization during the postcumulus stage. Chromitites that are 90 to 97 percent chromite by volume, as are numerous chromitites in the sequence of Figure 2, are an especially severe problem, because crystallization of interstitial noritic liquid could not add more than 1 or 2 percent chromite to settled crystals.

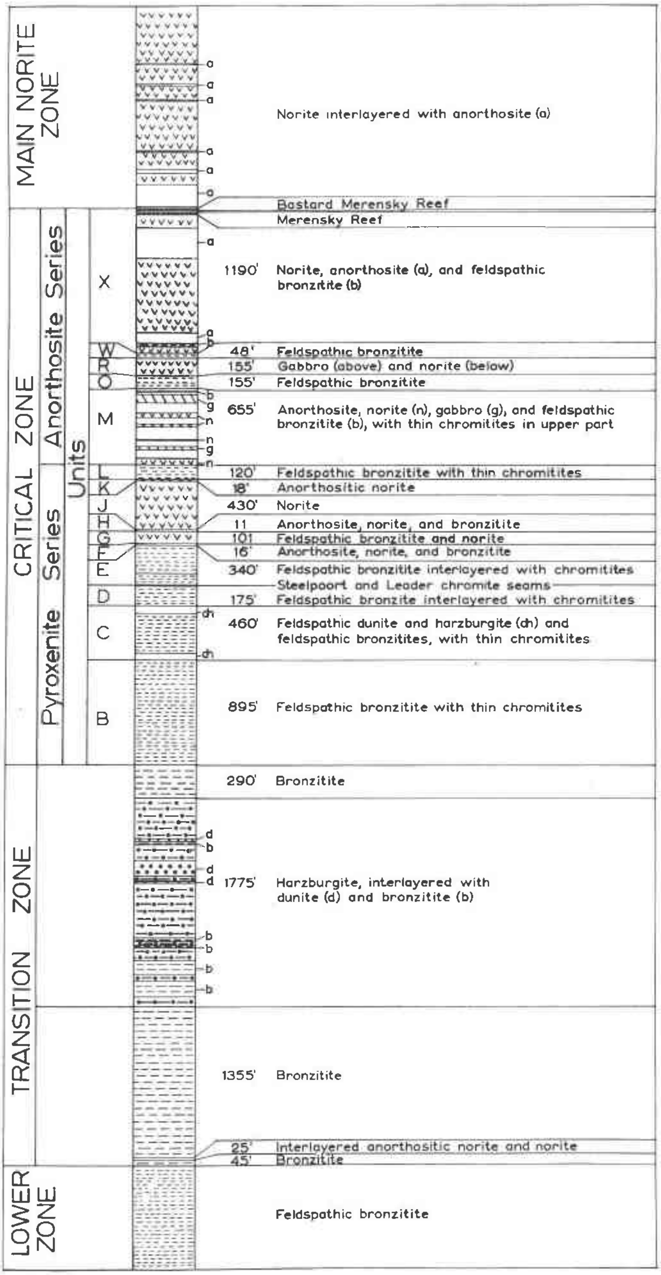

FIG. 2. Sequence of rock units compiled from sections across Umkoanes Stad, Winterveld, Jagdlust, and Haakdoornshoek (See Fig. 1). For explanation of nomenclature see text.

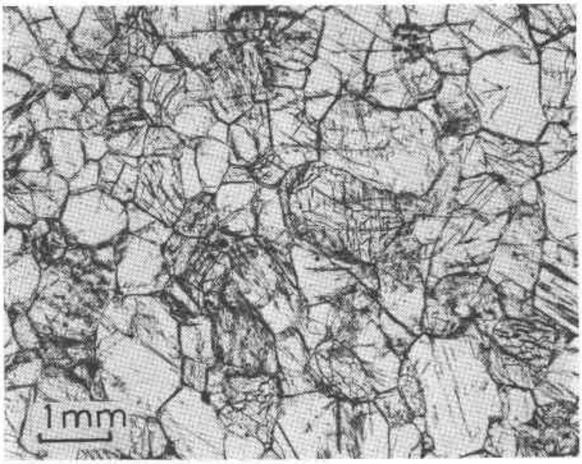

FIG. 3. Bronzitite from upper part of Transition Zone, Jagdlust. The rock averages 99.3 percent bronzite by volume. Apart from traces of alteration products, no other mineral is present in the area shown in the photograph. Plain light.

A supplementary process is required for chromitites with more than about 75 percent chromite.

Such rocks might result through expulsion of liquid by compaction, if this were attended by re-solution of crystals at points of contact and re-deposition in interstices. The importance of this is difficult to assess, but the process has found little favor with students of magmatic sediments,

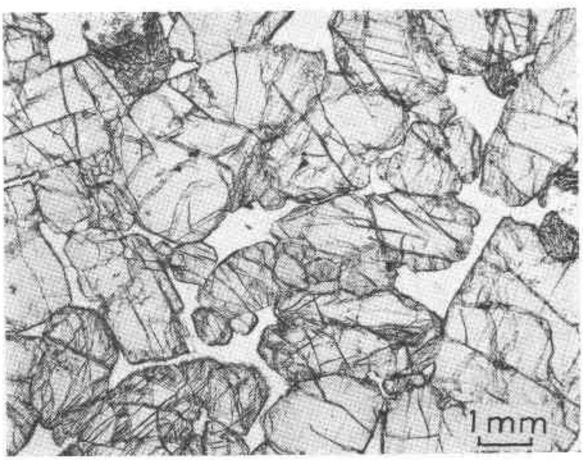

FIG. 4. Feldspathic bronzitite, E unit, at depth of 2145 feet, drillhole 15, Winterveld 417 KS. Bronzite content is 83 volume percent; the remainder is feldspar (white). Plain light.

for lack of evidence. The preferred explanation has been that settled crystals continued to grow either after shallow burial, by diffusion into the mush down a slight temperature gradient (Hess, 1939, p. 431; 1961, p. 113), or by enlargement while still in direct contact with supernatant magma (Jackson, 1961, p. 113), or by both mechanisms (Wager, Brown, and Wadsworth, 1960, p. 77, 81; Wadsworth, 1961, p. 27–28).

If settled grains enlarge simply by extension into interstitial spaces, neither the absolute grain sizes of the cumulus crystals nor their size distribution will be greatly changed. Size analysis should therefore give parameters consistent with conditions of initial crystallization and accumulation. Sundeen (1964, p. 39–40) discussed this matter in connection with textural studies of rocks of the B and C units (Fig. 2) on Farm Winterveld. The difficulty is that in most cumulates of the sequence of Figure 2, features indicating the magnitude of postcumulus changes in grain size are absent. The pyroxenites of Figures 3 and 4, for example, represent thousands of feet of such rocks.

In two classes of rocks, initial or near-initial sizes of cumulus crystals appear to be preserved. One class consists of rocks in which cumulus olivine or bronzite is embedded in cumulus chromite. In such rocks, the chromite outlines the original silicate grains. Grain-size analyses of silicates in such rocks can properly be interpreted in terms of conditions of cumulus crystallization and accumulation. The second class consists of those in which the cumulus grains in part were free to grow after settling, in part were trapped by growth of postcumulus material and thus were prevented from enlarging. The trapped grains preserve their initial or near-initial sizes. Comparison of trapped and free grains gives a measure of the degree of enlargement of the latter. In cases of this kind thus far discovered, the enlargement of free grains in much too great to be accounted for by filling of interstitial spaces. Examples of both classes of rocks are discussed below.

Grain Sizes in Chromite-Olivine Cumulates

The C unit of Figure 2 is characterized by two subunits consisting largely of layers in which the cumulus minerals are olivine and chromite in various proportions. Some of these rocks have been described by J. M. Guilbert (1962) and S. P. Sundeen (1964). In layers containing more than 20 percent chromite, chromite grains form networks enclosing isolated olivine crystals. After the two minerals settled, reaction between olivine and magma caused partial to complete replacement of olivine by bronzite (Fig. 5), but the distribution of chromite preserves the original outlines of the olivine grains, or at least their outlines before bronzite began to form. Bronzite also crystallized outward from the margins of olivine crystals, so that adjacent chromite grains are poikilitically enclosed in bronzite optically continuous with bronzite that has replaced the nearest olivine grain. Similar rocks occur in the Stillwater Complex (Jackson 1961, p. 47–49). Chromite immediately adjacent to the original olivine forms euhedral crystals that are commonly much smaller than tightly packed anhedral chromite crystals interstitial to the olivine-chromite-bronzite units (Guilbert, 1962, p. 30). Outward from the margin of an original

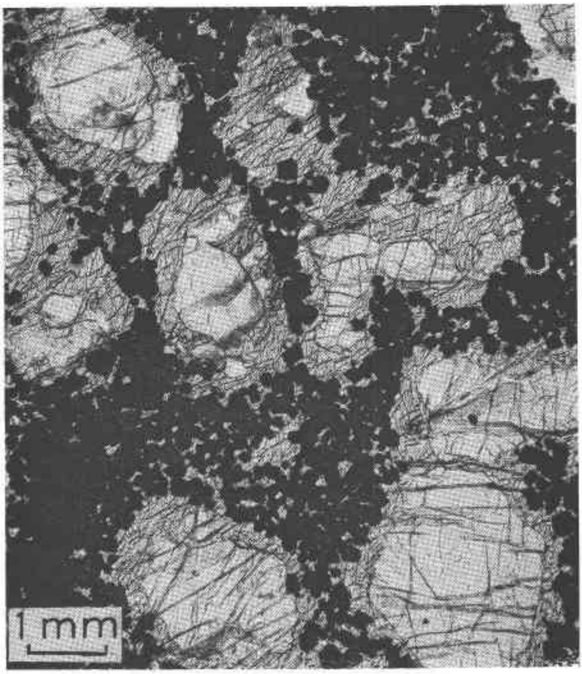

FIG. 5. Olivine-chromitite from C unit, adit on Winterveld 417 KS. Olivine (white grains with irregular, widely-spaced fractures) with bronzite reaction rims (gray, with cleavage) surrounded by chromite (black). Bronzite extends between chromite grains and fills all interstices; all bronzite present is part of a single poikilitic crystal. Plain light.

olivine grain, as noted by Guilbert, the chromite may show a progressive increase in average diameter. Enlargement of chromite crystals was apparently taking place simultaneously with growth of the bronzite fringes, the last chromite crystals to be trapped being those farthest from the boundaries of the original olivine grains.

In these rocks, initial or near-initial sizes of both cumulus phases appear to be determinable, hence grain sizes and size distributions should be functions of conditions of nucleation and settling of crystals.

Grain Sizes in Chromite-Bronzite Cumulates

In the sequence of Figure 2 there are many layers in which the cumulus minerals are bronzite and chromite in various proportions. These are the chromite-bronzitites and the bronzite-chromitites. In most of these, the chromite grains, being smaller, occupy the interstices of the larger bronzite grains. Nothing in such rocks indicates how much enlargement of grains has taken place since settling. In certain bronzite-chromitites, however, optically continuous fringes grew on the settled bronzite crystals, extending between adjacent chromite crystals and shielding them from further enlargement (Cameron and Emerson, 1959, Figs. 31, 38). Outward from the inner edges of such fringes, there is a progressive enlargement and progressively tighter packing of chromite grains. Interstitial to the bronzite units is a mosaic of anhedral chromite grains as much as three times greater in average diameter than chromite grains trapped in inner parts of the bronzite fringes. In these cases, owing to special textural features, we have a record of the minimum enlargement of both bronzite and chromite.

The writer concludes that in such rocks, as in the chromite-olivine cumulates, initial or near-initial grain sizes of both phases appear to be determinable, hence grain-size data reflecting conditions of accumulation of the cumulus minerals can be obtained.

Textural Features in Chromitites

Nodules in chromitites. Chromitites are layers of the sequence that have chromite as sole cumulus phase. Bronzite and plagioclase occur in accessory to subordinate amounts as postcumulus minerals. Bronzite commonly occurs as 6- to 17-mm nodules (Fig. 6), in most cases single crystals, poikilitically enclosing chromite. Plagioclase forms similar nodules in some seams. A few seams consist largely or almost entirely of such nodules. More commonly, however, the nodules are scattered sparsely or abundantly through a seam and are embedded in a matrix of tightly packed chromite grains with accessory interstitial plagioclase or bronzite, or both. In each nodule the silicate host forms a tenuous sponge-like matrix for the chromite, which has a loose-packed arrangement (chromite-bronzite ratio as low as 55:45) often described as "chain texture".

Nodules and the chain textures in them have been described many times. Wagner (1923, p. 323) suggested that the chromite crystals were trapped in bronzite crystals growing in the magma, and that subsequently the resulting poikilitic crystals settled to the floor of the magma chamber. Sampson (1929, p. 639–640; 1932, p. 127) concluded that nodules formed in situ by simultaneous crystallization of bronzite and chro-

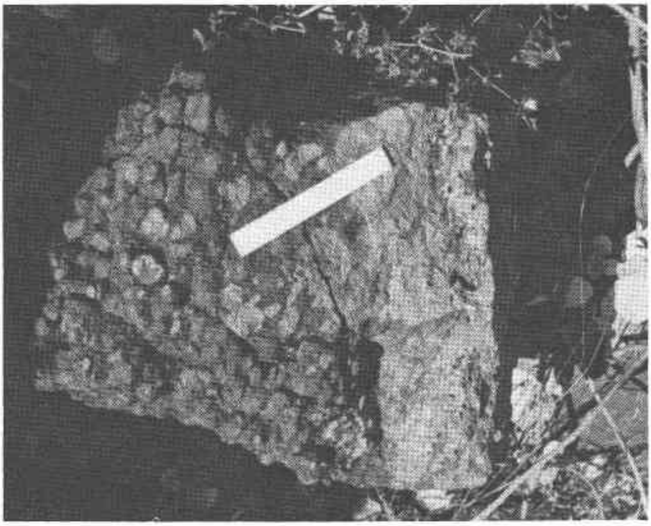

FIG. 6. Extreme development of nodules in Steelpoort chromitite seam, Winterveld 293 KT. Scale is 6.5 inches long. Note coarse chromite between nodules.

mite. Cameron and Emerson (1959, p. 1199, 1200) concurred. This conclusion now appears to be partially incorrect. The nodules have a simple explanation that is consistent with their features and, unlike the hypothesis of simultaneous crystallization, requires no late-stage Cr- and Fe-rich liquid at variance with available physico-chemical data. Chromite in the nodules represents settled grains that were trapped by *in situ* nucleation and growth of postcumulus bronzite or plagioclase and so were shielded from overgrowth. The features of the Steelpoort Seam discussed by Cameron and Emerson (1959, p. 1199–1201) are consistent with this mechanism, likewise the widespread occurrence and characteristics of postcumulus bronzite and plagioclase in the rocks of the Critical Zone. Striking examples in certain chromite-anorthosites are discussed below. The fact is that nodules are by no means confined to chromitites.

Macdonald (1967, p. 198–199, Fig. 22) interprets the nodules here discussed as due to subsolidus replacement of orthopyroxene by chromite. The writer disagrees. Such a reaction would release substantial amounts of silica, yet no quartz is present. In addition, the process affords no satisfactory explanation of chain structure, which is simply explained as the loose-packed structure of settled chromite (Jackson, 1961, p. 35) and can be essentially duplicated in the laboratory by settling chromite in a liquid. Finally, subsolidus equilibration between chromite and bronzite would be accomplished by exchange of ions by solid diffusion (Irvine, 1967), not by replacement of bronzite by chromite.

The same considerations apply to subsolidus reaction as an explanation of poikilitic fringes on xenoliths, described below, and poikilitic fringes on cumulus bronzite in the chromite-bronzite cumulates.

The writer concludes that nodules in chromitites preserve a record of initial or near-initial sizes of cumulate chromite grains at time of settling to the floor of accumulation. Outside the nodules, grains were unshielded and were free to enlarge by overgrowth. The typical final product outside the nodules is a close-packed mass of anhedral chromite grains (up to 97 percent chromite by volume). The growth of chromite outside the nodules, however, was not merely a filling of interstices of settled grains, for in a typical case the close-packed grains outside the nodule average 0.4 mm in maximum diameter, whereas those inside the nodules average 0.1 mm. As chromite grains are nearly equant, maximum and mean diameters would not differ significantly. Figure 7 shows the texture of a thin chromitite in the L unit. The chromitite is made up largely of poikilitic plagioclase and bronzite crystals irregularly separated by tightly-packed anhedral chromite. Here again the loose packing of the original settled grains is preserved in the poikilitic crystals. These grains average 0.12 mm in mean diameter, whereas grains outside the crystals average 0.38 mm. Again we have a measure of the relative enlargement of chromite grains since the growth of bronzite and plagioclase, and the en-

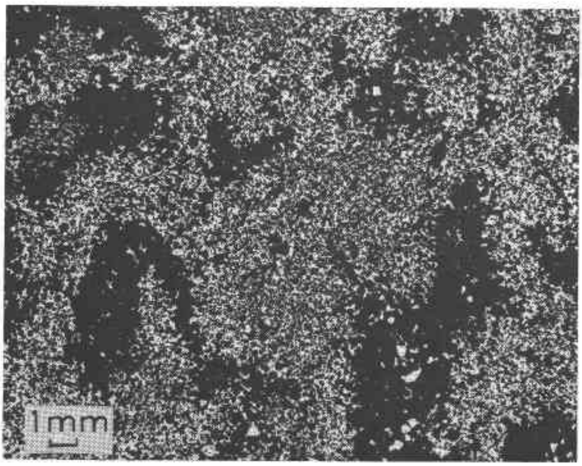

FIG. 7. Photomicrograph of thin chromitite seam in the L unit. Mottled black and white areas are bronzite and plagioclase crystals poikilitic with fine-grained chromite; the crystals are partly separated by coarser chromite (solid black). Central part of photograph is occupied by two poikilitic bronzite crystals. Other poikilitic crystals (e. g., along left side of photograph) are mostly plagioclase. Plain light, ×5.

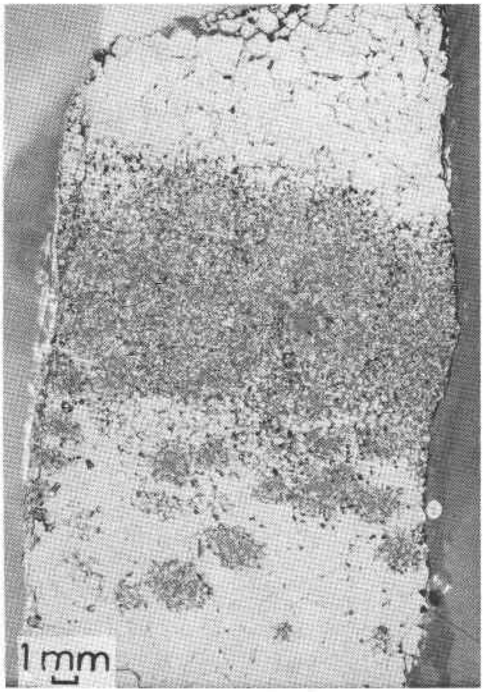

FIG. 8. Polished section across nodule layer in Steelpoort chromitite seam, Chrome Corporation mine, Steelpoort, 4 level. Chromite white, bronzite darker gray. Note separate nodules in underlying layer. Plain light.

largement is much more than can be accounted for by simple filling of interstitial spaces.

A special case of nodule development is shown in the mine of the Chrome Corporation of South Africa at Steelpoort. In one part of the mine, at a horizon 11 inches above the base of the massive middle member of the Steelpoort chromitite seam, bronzite nodules are present at intervals. Down-dip the spacing of nodules decreases, and finally the horizon becomes a continuous half-inch layer of tightly-packed bronzite chromite nodules (Fig. 8), a small minority of which have nonpoikilitic bronzite cores. The average maximum diameter of chromite in the nodule layer is 0.08 mm, whereas the average maximum diameter of the tightly packed chromite above and below the layer is 0.52 mm. Now it might be supposed that during formation of the pyroxene-rich layer only very small crystals of chromite were settling, whereas during formation of the enclosing layers of chromitite much coarser chromite crystals were

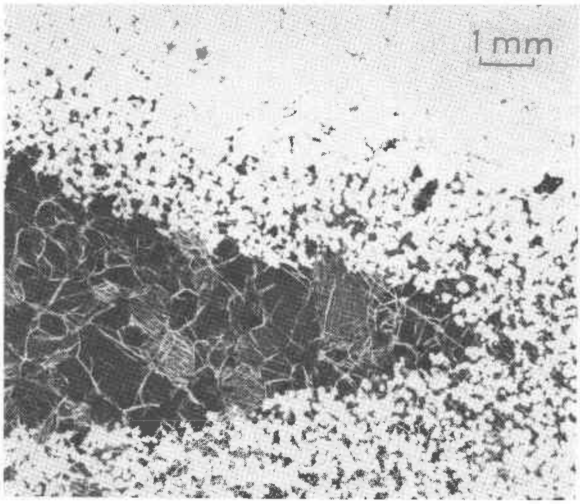

FIG. 9. Bronzitite inclusion in middle member of Steelpoort chromitite seam. Bronzite gray, chromite white. Speckled fringe on inclusion consists of poikilitic extensions of marginal bronzite crystals. Negative photograph. (Cameron and Emerson, 1959).

settling. However, scattered nodules of poikilitic bronzite occur (Fig. 6) in the underlying layer, and the mean diameter of chromite grains in these nodules is the same as in the nodule layer. The size difference between massive and poikilitically included chromite is therefore a measure of the minimum enlargement of cumulate chromite outside the nodules and the nodule layer.

Textural features associated with xenoliths. Xenoliths of silicate rocks are common in chromitites in the sequence of Figure 2. Figure 9 shows part of a small bronzitite xenolith in the Steelpoort chromitite. Fringing the xenolith is fine-grained chromite (average max. diam. 0.1 mm) poikilitically enclosed in bronzite overgrowths formed on the marginal bronzite crystals of the xenolith. These chromite crystals are here interpreted as original cumulate grains that were trapped by the bronzite overgrowths. If this is so, the trapped grains give us a measure of the maximum size (allowing for possible overgrowth preceding bronzite overgrowth) of the original settled grains. Outside the fringe, close-packed chromite grains average 0.4 mm in diameter. The difference is then a measure of the enlargement of chromite grains since settling.

Summary. In summary, in the typical chromitite of the rock sequence of Figure 2, and indeed in chromitites of the Critical Zone of the Eastern

Bushveld in general, settled grains of chromite not trapped by the early growth of bronzite or plagioclase commonly have been greatly enlarged since settling, so that average diameters have been increased by a factor of 3 or more. Grain size analysis of total chromite in these rocks will not give data on sizes of original settled grains. Sizes and size distributions of grains in nodules, however, should closely approximate those of the original settled grains.

Textural Features of Anorthosites

Anorthosites are important components of the F, H, M, and higher units of the rock sequence of Figure 2. The typical anorthosite is a fine-grained or medium-grained rock 92 to 99.8 percent plagioclase by volume. Igneous lamination, in varying degrees of perfection, is commonly present. Such rocks present the same problem of the consequences of overgrowth of settled crystals as do the pyroxenites and dunites. Enlargement by overgrowth must have taken place. The question is whether diameters of settled grains have been significantly increased.

In many anorthosite layers, there is nothing to indicate the answer. In some, however, as in the chromitites, early postcumulus growth of bronzite, less commonly clinopyroxene, has trapped settled grains of plagioclase. Striking examples are found in certain anorthosites of the F and H units. A detailed log of the H unit is given in Figure 10. The anorthosites range from nearly pure to those containing various amounts of chromite or bronzite or both. Where chromite is present, its distribution enhances the igneous lamination. Most interesting, however, are the mottled anorthosites that constitute a large portion of the unit. In mottled anorthosite, bronzite, or locally clinopyroxene, forms scattered irregular crystals up to 25 mm in diameter. Each crystal is a thin-walled sponge (Figs. 11 and 12) with pores occupied by cumulate plagioclase and chromite crystals. In other words, the aggregate is a nodule in the same sense as the nodules in chromitites. In a typical case, the nodules consist of 33 percent bronzite and 67 percent plagioclase plus chromite. This is the ratio that would result from filling of the interstices of a moderately close-packed plagioclase-chromite crystal mush. Crystals of plagioclase in a typical nodule average 0.12 mm in mean diameter, whereas crystals in the main body of the rock average 0.35 mm in mean diameter.

Plagioclase grains included in bronzite are somewhat rounded, and marginal resorption of the crystals may have taken place during or before formation of bronzite. The fabric and the bronzite/cumulus mineral ratio indicate, however, that this can account only in very small part for the difference in size of plagioclase inside and outside the bronzite crystals.

It can be argued that such poikilitic pyroxene crystals developed in a

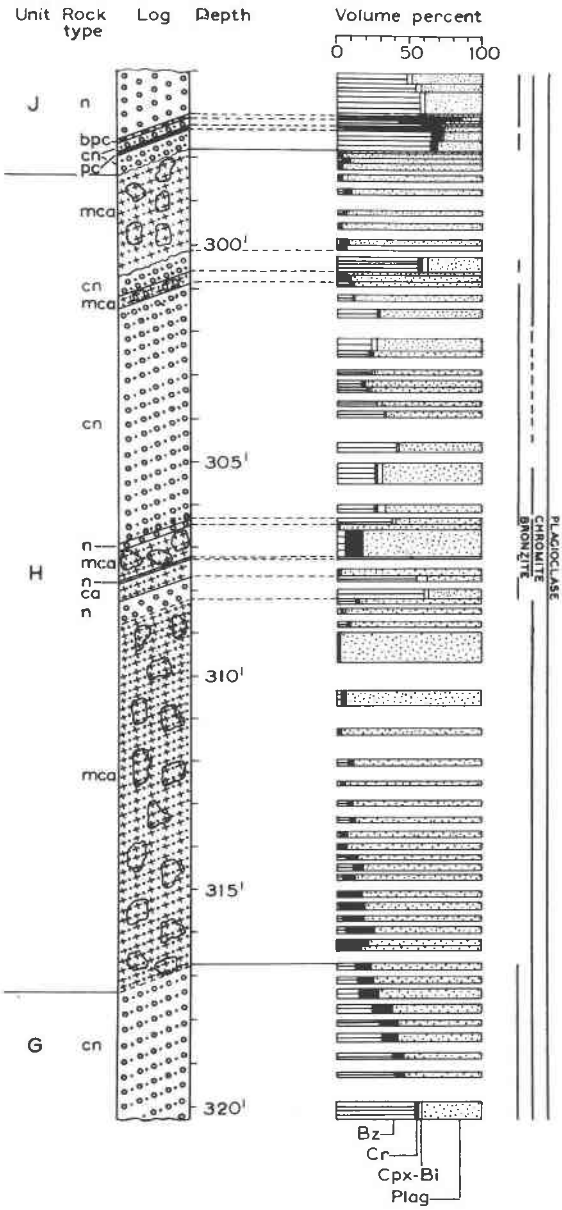

FIG. 10. Log of H unit, drillhole 8, Jagdlust, with analyses of total modes. Vertical lines at right indicate phases settling as unit accumulated. Bz-bronzite, Cr-chromite, Cpx-Bi-clinopyroxene and biotite, Plag-plagioclase, n-norite, bpc-bronzite-plagioclase-chromite, pc-plagioclase-chromitite, cn-chromite-norite, mca-mottled chromite-anorthosite. Based on continuous core.

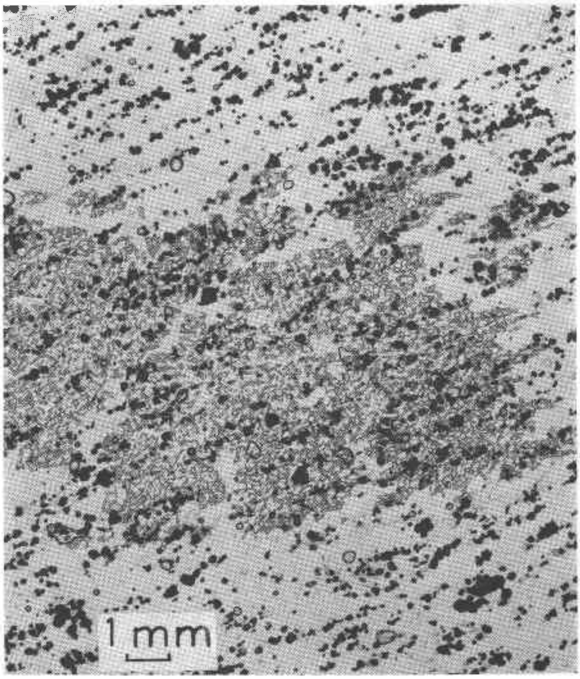

FIG. 11. Mottled chromite-anorthosite, H unit, Jagdlust. Upper and lower portions consist of chromite (black) and plagioclase (white). Central area consists of a single bronzite crystal (gray) highly poikilitic with chromite and plagioclase. Note that gneissoid texture passes through the poikilitic area without interruption. Plain light.

zone of crystallization above the floor in which swarms of small plagioclase crystals were trapped in rapidly growing pyroxene crystals; the resulting aggregates then settled to the floor. Wagner (1923, p. 323) suggested this mechanism as the origin of bronzite nodules in chromitite. In the anorthosites in which igneous lamination is well developed, however, the lamination passes through the poikilitic crystals (Fig. 11; *cf.* Jackson, 1961, p. 11). This is strikingly shown in the more chromitic anorthosites. The poikilitic pyroxenes in anorthosite are therefore postcumulus in origin. The views of Hess (1960, p. 114) regarding such poikilitic crystals are therefore supported, rather than the views of Sampson (1932) and Wells (1952). The disparity in grain size of plagioclase inside and outside the poikilitic crystals is shown in Fig. 12. The conclusion is inescapable that the individual grains of plagioclase outside the bronzite crystals were on the average enormously enlarged at the postcumulus stage.

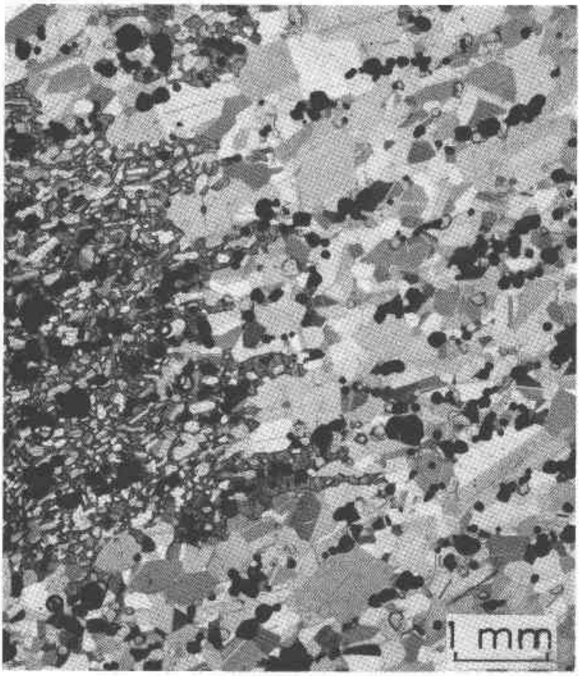

FIG. 12. Part of same thin section as Figure 9. At left is marginal portion of poikilitic bronzite crystal. Note contrast in size of plagioclase inclusions in bronzite and plagioclase crystals outside. Oblique nicols.

LIMITATIONS ON USE OF GRAIN-SIZE ANALYSES

Certain parts of the rock sequence of the Critical Zone are characterized by fine-scale alternation of layers that differ in cumulus mineral proportions. Thus the lower 40 feet of the C unit (Fig. 2) consists of more than 200 layers differing in ratio of bronzite to olivine, and the upper part of the M unit consists of more than 100 layers differing in ratio of chromite to plagioclase. The object of grain-size analyses of such rocks is to determine whether magmatic currents, by mechanical sorting of grains, have produced the layering. This means determining whether the cumulus phases involved were in hydraulic equivalence at the time of settling.

Of the various rocks described in preceding sections, grain-size analysis is applicable only to the chromite-anorthosites illustrated in Figures 11 and 12, and to rocks similar to that of Figure 5. In the H unit, in which the chromite-anorthosites occur, erosional disconformities at two horizons, together with transported xenoliths, indicate that there was at least intermittent motion during formation of the unit. Mechanical sorting is therefore a possibility.

Considering the rock of Figures 11 and 12, if the density of the magma was 2.7, of chromite 4.4, and of plagioclase 2.8, and if the average diameter of chromite is taken as 0.16 mm, then (if Stokes Law is applicable) to be hydraulically equivalent to chromite, the plagioclase grains trapped inside pyroxene should be 0.66 mm instead of 0.12 mm in average diameter. This is far too great a discrepancy to be explained in terms of errors of measurement or uncertainties as to the density and viscosity of the magma and the effects of particle shape on settling velocities. Mechanical sorting during formation of the rock is therefore not suggested by grain-size analysis.

Unfortunately, most of the anorthosites elsewhere in the Critical Zone lack postcumulus pyroxene, and the significance of grain-size analyses of these rocks is therefore in doubt. A case in point is shown in Figure 13. The grain-size data can be interpreted to indicate mechanical sorting, but the anorthosites closely resemble the pyroxene-free portions of the anorthosites of the H unit; significant postcumulus changes in grain size of plagioclase are likely.

In a rock like that of Figure 5, initial sizes of olivine crystals are preserved, and chromite crystals immediately adjacent to olivine should be approximately at initial sizes. Hydraulic equivalence can therefore be examined. Rocks of this textural type, however, form less than 0.1 percent of the total thickness of cumulates of the Critical Zone.

It is possible, of course, that average grain sizes might be changed without alteration of *patterns* of grain-size distribution. The author has therefore compared patterns of size distribution of trapped and enlarged grains in various rocks of the kinds here described. The results are inconclusive, patterns being changed in some cases but not in others.

Other Inferences from Textural Studies

Mechanisms of postcumulus enlargement. As previously discussed, postcumulus enlargement of settled crystals has generally been pictured as extension of these crystals into the interstices of a crystal mush. In some cumulates (*e.g.*, Wager, 1963, p. 3) this simple process, or a close approximation, may have occurred. In most cumulates of the eastern Bushveld, positive evidence of mode of enlargement is lacking. Simple filling appears to account for part of the enlargement of chromite in certain chromite-olivine and chromite-bronzite cumulates, but it cannot account for the coarse anhedral chromite that is not poikilitically enclosed in bronzite. Similarly, simple filling of interstices cannot have

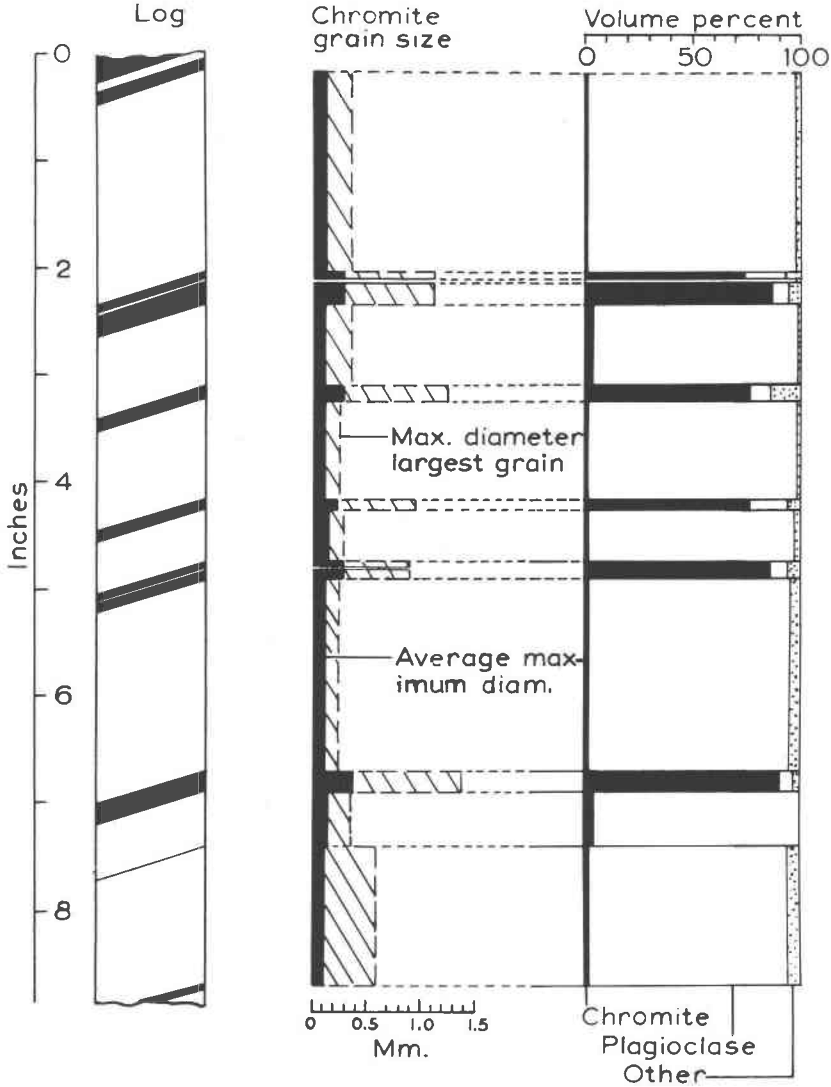

FIG. 13. Log, modal analyses (total modes), and chromite grain sizes in interlayered chromite-anorthosite (blank) and chromitite (solid black) in a section of core from upper part of M unit, drillhole 15, Winterveld 417 KS. Chromite grain sizes for the two pairs of layers 2 inches and 5 inches from the top of the core are in each case based on measurements of grains in both members of the pair. Modal analysis for the lower pair (5 inches from top) does not include the thin anorthosite parting.

produced the large increases in average grain size indicated in chromitites and chromitic anorthosites.

The simplest explanation of these increases is that in a loose crystal mush growing crystals may push each other aside so large increases in diameter may take place prior to the stage at which filling of interstices begins. This might be the explanation of enlargement in the chromitites and in the chromite-bronzite and chromite-olivine cumulates. There is no evidence to the contrary. It cannot be the explanation of enlargement in the cumulus plagioclase of the chromite-anorthosites of the H unit. Nearly a 27-fold increase in volume would be required by the tripling of average grain size of plagioclase outside the bronzite crystals. Since the lamination passes undisturbed through matrix and poikilitic bronzite alike, it is evident that no such enormous increase in volume can have taken place. The process must have been one of enlargement of some grains at the expense of others, a process of recrystallization supplimented by adcumulus growth.

Relative importance of cumulus and postcumulus stages. Settling of crystals has generally been regarded as the principal mechanism by which cumulates have formed, adcumulus precipitation (overgrowth) and intercumulus precipitation playing supplementary but subordinate roles (*cf.* Wager, 1963, p. 2). Harrisites[1] (Wager and Brown, 1951; Brown, 1956, p. 10; Wadsworth, 1961, p. 38–39) and certain rocks (Jackson, 1961, p. 47–52) in which cumulus minerals have been replaced by postcumulus material have been recognized as exceptions. As indicated above, simple filling of interstices seems to be indicated, in certain cumulates, by textural features. For example, in many pyroxene cumulates, interstices are filled with plagioclase, and in some chromite cumulates, interstices are filled with plagioclase or pyroxene, or both. In such rocks, postcumulus material appears to form less than half the total rock volume. In some chromite-olivine cumulates and olivine cumulates, however, postcumulus bronzite formed by replacement of olivine constitutes more than half the total rock volume. In many chromitites and in chromitic anorthosites such as those described above, far more than half the total volume of material must derive from the postcumulus stage.

There are two serious gaps in information. First, most of the dunites, pyroxenites, and anorthosites making up the sequence of Figure 2 lack textural features that would show the relation between initial and final cumulus grain sizes. Second, chemical changes in cumulus minerals

[1] Harrisites (Rhum) are cumulates characterized by coarse olivine crystals believed to have grown upwards from the crystal pile forming the temporary floor of the magma chamber (Wadsworth, 1961, p. 39).

during the postcumulus stage are far from completely known. Changes are directly indicated only in those chromite-dunites that show postcumulus replacement of olivine by bronzite. Here it is evident that settled olivine was not in equilibrium with the liquid phase. Homogeneous crystals, however, can enlarge in either of two ways. If cumulus crystals are in equilibrium with liquid, overgrowth is simply a mantling of crystals with material of the same composition. On the other hand, if the cumulus crystals are in compositional disequilibrium with the liquid, either at the time of settling or after shallow burial, enlargement may be accompanied by adjustment in the composition of the crystals. If equilibrium is reached and homogeneous crystals result, the second case becomes indistinguishable from the first. This is the problem presented by the dunites and pyroxenites.

Chemical subsystems in the formation of magmatic sediments. It appears that formation of a magmatic sediment can be extremely complex. Three stages were involved in the formation of the magmatic sediments of the Bushveld Complex and, corresponding to these, three chemical subsystems:

1. The subsystem in which nucleation and initial growth of cumulate phases took place prior to and during settling to the floor of accumulation.
2. The subsystem consisting of settled crystals and supernatant magma.
3. The subsystem consisting of settled crystals and interstitial liquid.

Any given sediment is a product of subsystem (1) plus either subsystem (2) or (3) or both.

Subsystem (2) may have been inoperative if either chemical conditions or rate of accumulation were unfavorable. Where, however, subsystem (2) operated until interstitial liquid was totally expelled, subsystem (3) must have been suppressed. In any event, it is important to recognize that three subsystems may have been involved in the formation of a given magmatic sediment, and that compositions of coexisting phases currently under investigation in our laboratory must be interpreted accordingly.

The last of the three subsystems defined becomes inoperative with the disappearance of the liquid phase. It is succeeded by a fourth or subsolidus system. Information on this system for Bushveld rocks is currently limited to observations on exsolution and other instability phenomena in single phases; *e.g.*, bronzite (Hess, 1960, p. 23–34; Hess and Phillips, 1938), chromite (Younger, 1958, p. 10), and titaniferous magnetite (Ramdohr, 1956; Cameron and Desborough, 1964, p. 210–211).

Vertical Variations in Degree of Postcumulus Enlargement

In rocks in which positive evidence of initial grain size is lacking, the only index of degree of postcumulus enlargement of settled grains is the amount of pore material present, which will vary according to the degree to which interstices have been filled by adcumulus growth. It is an imperfect measure, because initial pore space will be affected by grain habit, grain size distribution, and looseness of initial packing (*cf.* Upton, 1961, p. 11–12). It is likewise a minimal measure if enlargement of grains began before the mush was sufficiently compact so that enlargement was restricted to filling of interstices. Even if allowance is made for these factors, however, short-range vertical (stratigraphic) variations in degree of enlargement of cumulus bronzite are obvious in the rocks of the sequence of Figure 2.

In explanation of such variations, Hess pointed out (1960, p. 113) that since diffusion is involved, enlargement would be favored by a slow rate of accumulation of crystals. Jackson (1961, p. 85–86) concurred. Wager (1961, p. 2) pointed out that heat must be lost to the surroundings in some way, and the rate of heat loss must be a factor in determining degree of enlargement, Wadsworth (1961, p. 61–62) related the extreme overgrowth registered in the harrisites of Rhum to a periodicity of supercooling, and Wager (1963) related adcumulus growth to supersaturation in the Skaergaard magma. Unfortunately, criteria that would indicate which factors are applicable in specific cases in the eastern Bushveld Complex are lacking.

Quite apart from short-range vertical variations in enlargement, even a casual comparison of pyroxenites and dunites from the Transition Zone with those of the Critical Zone suggests a marked difference in degree of enlargement of bronzite or olivine, on the basis of the amount of pore material present, plagioclase with minor amounts (in some rocks) of biotite and clinopyroxene. In Table I, average percent bronzite and

Table 1. Change of Bronzite Content with Level in the Intrusive

Zone	Units	No. of bronzitite samples analyzed	Volume percent bronzite in bronzitites-average	Volume percent bronzite in bronzitites-range
Critical Zone	L-X	26	80	68–85
Critical Zone	D, E	21	83	72–91
Critical Zone	C	19	89	85–94
Critical Zone	B	25	90	85–96
Transition Zone		16	99	97–99.8

range in percent bronzite are given for bronzitites in the various members of the sequence of Figure 2; 107 horizons are represented. Figures in the last column express the short-range vertical variations in percent bronzite (hence in percent pore material) within units of the sequence. Despite the oscillatory variations, however, bronzitites in the Critical Zone show a general decrease in percent bronzite upward, and the maximum percent falls off from 96 to 85 (*cf.* Fig. 4).

Let us suppose that crystals at or close to the top of a cumulus pile are enlarging by overgrowth, and that the temperature of the system is slowly declining. Overgrowth will continue until the temperature falls to the point at which a second phase (or other phases) crystallizes from the intercumulus liquid. As crystallization proceeds, the enlargement of the settled grains will be slowed and finally arrested. Other things being equal, the farther the initial liquid is from the cotectic boundary line on the liquidus, the greater the temperature interval over which enlargement may take place. During the accumulation of the Transition Zone and units B to E of the Critical Zone, bronzite and olivine were withdrawn from the system, and the composition of the liquid was shifted progressively toward the plagioclase field of the liquidus. The average degree of overgrowth declined, the amount of pore material formed, chiefly plagioclase, increased. The progression terminated abruptly with the appearance of cumulus plagioclase in the F unit. At this point the bronzite-plagioclase cotectic was evidently reached, in fact temporarily overshot for reasons that are as yet unclear.

Few pyroxenites above the F unit have more than 82 percent bronzite. The settling experiments described previously indicate that settling of bronzite plus crystallization of interstitial noritic liquid could yield bronzitites with as much as 86 percent bronzite. Little if any overgrowth is therefore needed to account for the bronzite content of the typical bronzitites occurring above the F unit.

In sum, it appears that the major control on degree of enlargement of cumulate bronzite was the changing composition of the magma with respect to the cotectic bounding the plagioclase region of the liquidus. One would expect that the trend in degree of enlargement shown in bronzitites would be reflected in associated dunites. This is so. The olivine content of dunites in the upper part of the Transition Zone ranges from 96.8 to 97.5 volume percent, whereas the maximum olivine content of any dunite in the C unit of the Critical Zone is 86 percent.

In the writer's view, the trends in percentage of pore minerals are strong evidence that the Transition and Critical Zones, despite the complexity of their sequences of rock units, are portions of a magmatic differentiation series, rather than the product of multiple injections of magma as advocated especially by Truter (1955) and Schwellnus and others (1962). A similar conclusion has been reached by Cameron and Desborough (1969) from a study of variations in mineral composition upward in the Critical Zone.

Conclusions

1. Certain cumulates of the eastern Bushveld Complex have special textural features that make it possible to compare initial or near-initial grain sizes with sizes after postcumulus enlargement. Measurements indicate that in some cumulates average diameters of grains have been enlarged, after settling, by a factor of three or more.
2. Postcumulus enlargement has changed size distributions of cumulus grains in some rocks but not in others. Change in grain-size distribution follows no consistent pattern.
3. Hydraulic equivalence or nonequivalence of two cumulus phases in a magmatic sediment can be inferred from grain-size analysis only if a record of initial grain sizes is preserved in the rock.
4. In some cumulates, postcumulus material is much more than half total volume, greatly exceeding the amount that could be deposited by simple filling of interstices of a crystal mush. The material has formed by adcumulus enlargement of settled grains, by reaction between grains and intercumulus liquid, by a process analogous to recrystallization, or by combinations of these processes. Final compositions or coexisting phases must stem from the postcumulus stage.
5. Degree of postcumulus enlargement of bronzite in bronzitites in general declines upward in the Transition and Critical Zones. Likewise, olivine in dunites at higher horizons shows less enlargement than olivine in dunites at lower horizons. The major control on degree of enlargement was probably the progressive displacement of liquid composition toward the plagioclase region, as bronzite and olivine crystallized and settled from the liquid.

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