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STRUCTURE AND ROCK SEQUENCES OF THE CRITICAL ZONE OF THE EASTERN BUSHVELD COMPLEX

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ABSTRACT

Investigations of the Critical Zone of the eastern part of the Bushveld Complex during 1952–55 and 1961 indicate that the zone is divisible along its strike into western, central and southern sectors. In the western sector the zone is poorly exposed; the sequence of rock units within it is poorly indicated. In the central and southern sectors the zone comprises an upper anorthosite series and a lower pyroxenite series. The anorthosite series consists largely of anorthosite and closely related rocks, but feldspathic pyroxenites and associated chromitites occur at two or more horizons in each of various sections across the zone. In the central sector, the pyroxenite series consists largely of pyroxenite and mafic norite but includes units of norite, anorthosite and olivine-bearing rocks, together with numerous chromitites. The sequence of major units in the pyroxenite series is remarkably constant throughout the sector, although the units vary in thickness. In the southern sector, the pyroxenite series varies markedly along strike both in thickness and sequence of units. In both sectors, there are several different patterns of repetition of rock types.

Despite the presence of disconformities at certain horizons, the outstanding structural feature of the Critical Zone is the gross concordance of units. This and numerous gradations between rock types are inconsistent with the hypothesis of multiple intrusions. Compaction structures, deformation and dismemberment of layers, and chromitites along fractures in anorthosite are local features. Taken together, both broad and local features appear consistent with evolution of the Critical Zone by fractional crystallization and sedimentation, influenced by intermittent motion of the magma and by periodic disturbance of the magma chamber.

INTRODUCTION

During 1952–55, chromite deposits on six farms in the eastern part of the Bushveld Complex were mapped in detail by the author, H. E. Abendroth, Robert A. Bell, L. Yehle and B. L. Berman. Mapping was followed by diamond drilling on two of the farms. During June–August, 1961, the author reviewed the previous work and made further studies of the chromite deposits and associated rocks. This work and correlative laboratory studies since 1953 have yielded much new information on the structure and sequences of rock units in the Critical Zone. These features are important with regard to the evolution of the zone, because they provide the framework within which other features must be interpreted.

ACKNOWLEDGMENTS

The author is deeply indebted to many individuals and organizations in connection with the work. Union Carbide Ore Company, for whom the mapping was done in 1952–55, has generously permitted use of scientific data obtained and has supported laboratory investigations at the University of Wisconsin through the Union Carbide Fellowship in Economic Geology. Mr. D. F. Frasché, Manager, Mineral Survey Department of the company, has given steady encouragement to the work. Mr. O. T. van der Merwe, Managing Director, Chrome Corporation of South Africa, Pty., Ltd., has given generous aid in innumerable ways. The author is profoundly grateful to both these men. Mr. and Mrs. G. E. van Schalkwyk were cordial and helpful hosts during the field season of 1961. Mr. Nugent Comyn, Manager, E. J. Lavino, Pty., Ltd., gave generously of his time and his experience with chromite deposits. Anglo-American Corporation assisted with maps of farms and permission to make studies on the farms. Other property owners and operators of mines were uniformly generous in their cooperation. Field work during 1961 and a part of the laboratory investigations since July 1960 have been made possible by a grant from the National Science Foundation.

PREVIOUS INVESTIGATIONS

The literature of the Bushveld Complex is far too voluminous to review fully in a brief paper of this kind. For a summary of early work, the reader is referred to the memoir by Hall (1932). More recently, Willemse (1959) has given a comprehensive discussion of the relations of the eastern part of the complex to its floor. The geology of the area around the Driekop platinum pipe has been discussed by Heckroodt (1959), and the geology of the area east and southeast of Steelpoort by Hiemstra and van Biljon

(1959). Cameron and Emerson (1959) have described certain chromite deposits on Farms Jagdlust and Winterveld (343).

Critical Zone of the Eastern Bushveld Complex

The location of the eastern norite belt is indicated in Fig. 1, and a generalized geologic map is given in Fig. 2. For a more detailed representation, reference may be made to the map by Willemse (1959). The rocks of the norite belt were divided by Hall (1932) into five successive zones (Fig. 3). The term Critical Zone was applied to the highly differentiated rocks from a horizon just below the lowest chromite seam to the base of the Main Norite Zone, not far above the Merensky Reef. Rocks of Critical Zone types, with associated chromite deposits, occur west of the Olifants River in the area south of Chuniespoort, but the boundaries of the zone could not be indicated on Fig. 2. East and south of the Olifants River, the Critical Zone is better exposed, and the approximate boundaries of the zone are indicated on the map.

During 1952–55, Farms Scheiding, Jagdlust, Winterveld (343), Mecklenburg, Hendriksplaats, and Annex Grootboom were mapped by the writer and associates at 1:10,000, and portions of Farms Mooihoek, Onverwacht, Doornbosch, Winterveld (424), and Grootboom were examined. In 1961, the writer supplemented this work by chain-compass traverses across all or part of the Critical Zone along various lines as far south as Farm Thorncliffe. Chromite deposits and associated rocks on Farm Naboom were examined briefly. The work indicates that between Chuniespoort and Farm Thorncliffe the Critical Zone is divisible along strike into three sectors, a western sector extending from south of Chuniespoort to the Olifants River, a central sector extending from the Olifants River south to Steelpoort, and a southern sector extending from Steelpoort to Farm Thorncliffe and thence beyond the limits of Fig. 2. This threefold division provides a convenient framework for discussion of the Critical Zone.

Western sector. The western sector is poorly exposed,

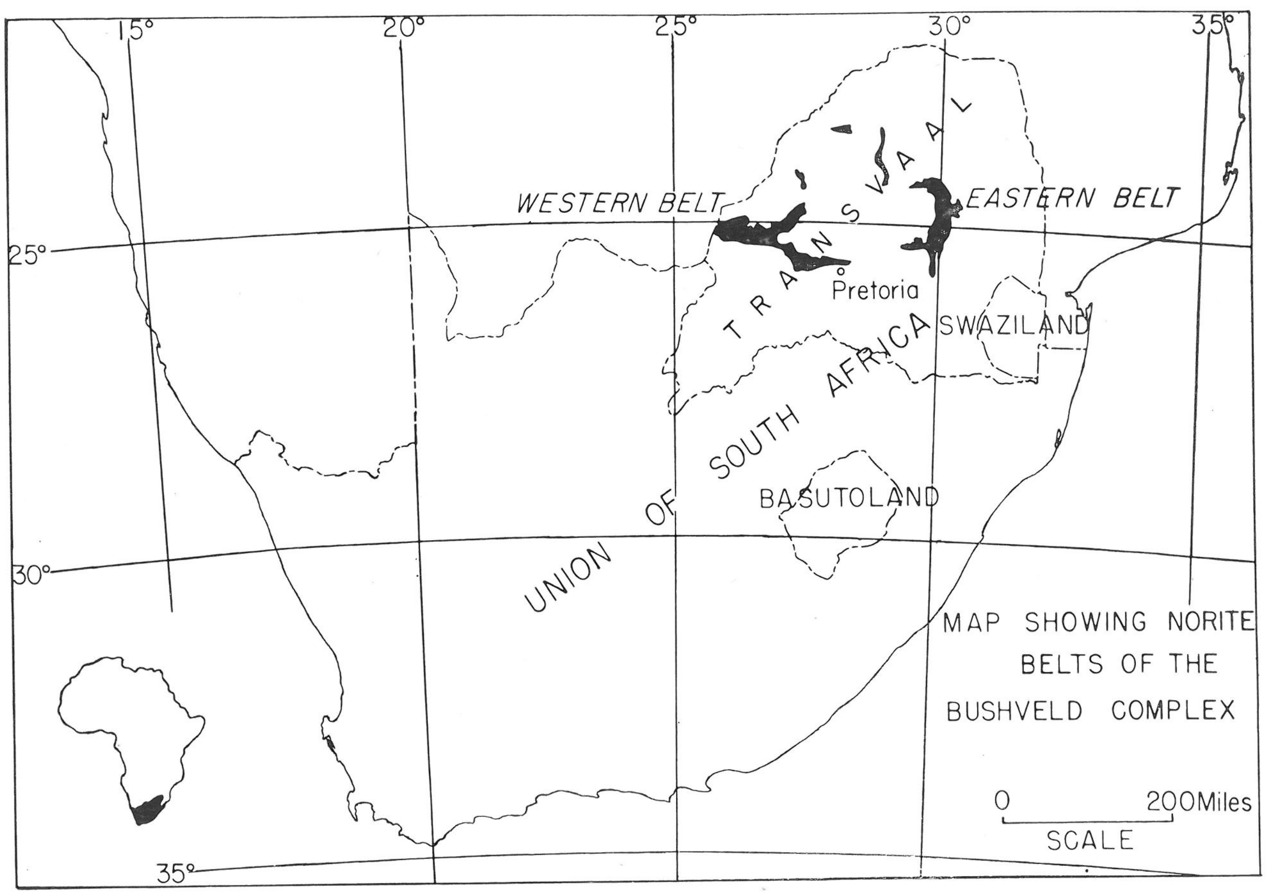

Fig. 1

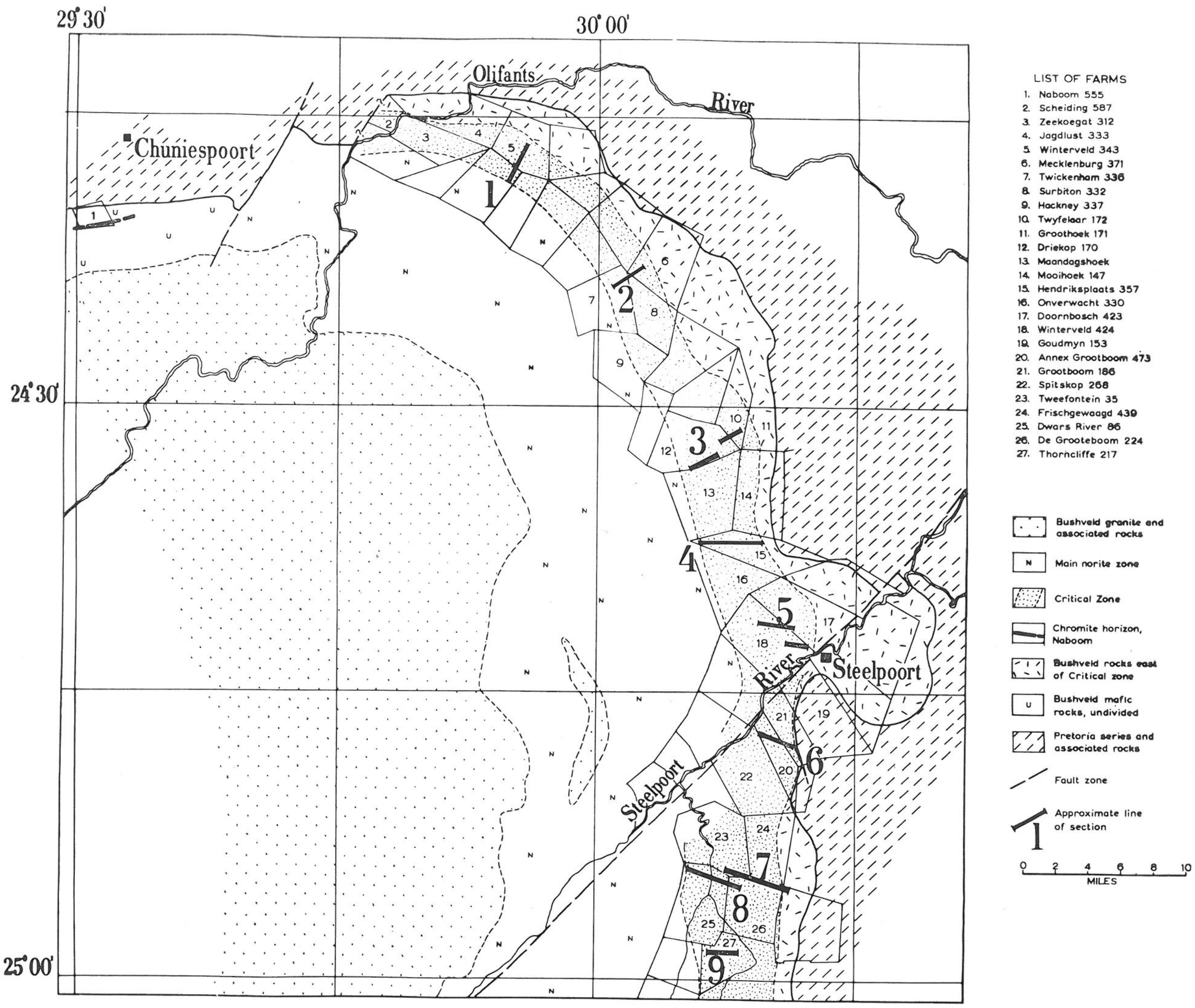

FIG. 2. Generalized geologic map of the northeastern part of the Bushveld Complex, from various sources.

and no adequate section of the Critical Zone in it can be given. It is clear only that the sequence of rock units in this sector differs from that of the central sector.

Central sector. In the central sector, from the Olifants River to Steelpoort, the Critical Zone is extensively exposed. On Farms Jagdlust, Winterveld (343), and Umkoanes Stad (immediately south of Winterveld) the zone has been exposed continuously from just above its base nearly to the Merensky Reef, by two drill holes totalling 2720 feet, two long adits, and a natural gorge. Along line 1 (Fig. 2) a total thickness of 3750 feet of the zone has therefore been accessible for field study and sampling. Detailed laboratory studies of the rocks of this section have been under way for some time at the University of Wisconsin. Sections along lines 2 to 5 across the Critical Zone are based largely on surface mapping and chain-compass traversing. Sections based on this work are not as accurate as section 1 but indicate clearly the sequences of major units.

Sequences of units along lines 1 to 5 across the central sector are given in Fig. 4. Descriptions of the units are given in Table 1. Throughout the sector,

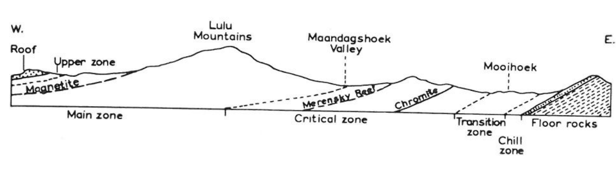

FIG. 3. Section of Bushveld norite north of Steelpoort, after A. L. Hall. Section is 19 miles long.

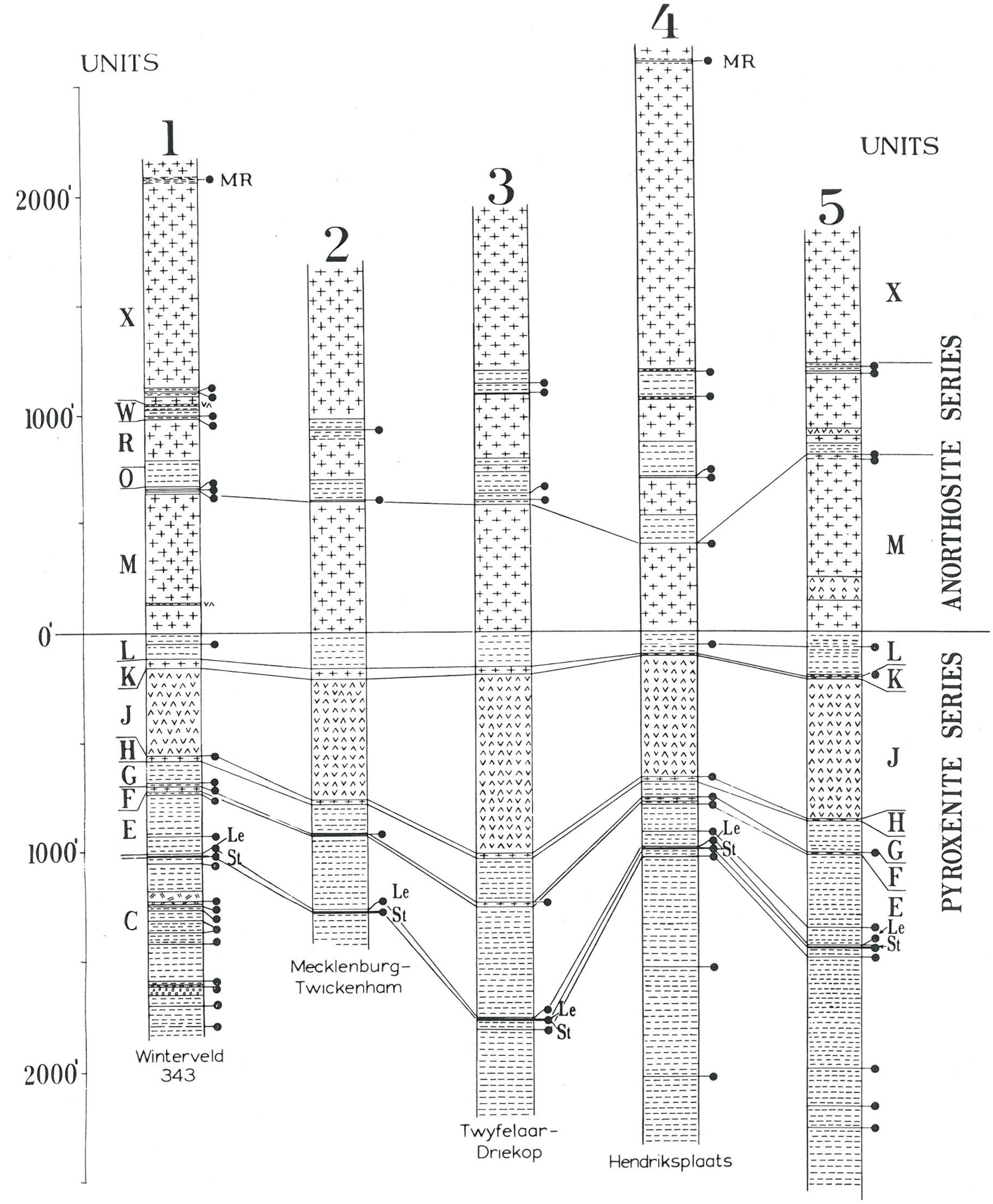

Figure 4. Sequences of rock units in the Critical Zone, Olifants River to Steelpoort.

TABLE 1. ROCK UNITS OF THE CRITICAL ZONE, CENTRAL SECTOR

Unit	Description
MR	Merensky Reef. Pegmatitic diallage norite or feldspathic pyroxenite.
X	Interlayered medium to coarse-grained, massive to regularly or irregularly banded pyroxene-anorthosite, noritic anorthosite, and norite; pyroxenite and mafic norite with thin chromitite seams near base.
W	Feldspathic pyroxenite with thin chromitite seams at and near base.
R	On Winterveld (343) upper 158 feet anorthosite, lower 52 feet pyroxenite, thin layers of anorthosite, and mafic norite.
O	Feldspathic pyroxenite.
M	Mostly anorthosite and anorthositic norite with subordinate norite and mafic norite, mostly in lowest portion. Thin layers of chromitite and pyroxenite near top.
L	Mafic norite grading downward into massive pyroxenite. Two persistent groups of thin chromitite seams in middle and upper parts in north; at least one in south. From Doornbosch southward has thick chromitite seam near base.
K	Interlayered pyroxene-anorthosite and anorthositic norite in various proportions.
J	Mafic norite and norite on Jagdlust and Winterveld (343) with a thin chromitite seam near the base and another nearer the middle.
H	Variable. Anorthosite or interlayered anorthosite and norite, with or without thin chromitites.
G	Mafic norite and feldspathic pyroxenite.
F	In north consists of norite separating two units of anorthosite with associated thin or impure chromitites. In south, anorthosite or interlayered anorthosite and norite with one or more impure chromitites.
E	Pyroxenite and mafic norite interlayered with chromite-pyroxenite and chromitites.
D	Leader and Steelpoort chromitite seams separated by $2\frac{1}{2}$–3 feet of pryoxenite.
C	Mostly mafic norite and pyroxenite interlayered with chromitites and chromite-pyroxenite, and locally with troctolite and peridotite.

Note: Rock designations subject to revision based on quantitative petrographic study.

the Critical Zone is divisible into two major series of rocks, a lower pyroxenite series, predominantly pyroxenite and norite, and an upper anorthosite series, predominantly anorthosite and noritic anorthosite. In any one section, each series consists of a sequence of major units. The pyroxenite series is characterized by the remarkable persistence of major units throughout the central sector, over a distance of approximately forty-five miles. The correlation of these units from section to section is indicated on the chart. The units vary somewhat in thickness, even allowing for errors in calculating thicknesses from mapping and traverses, and the C, F, H and L units vary in lithology along strike, but their continuity from end to end of the sector is beyond doubt. The most remarkable units in this series are the chromitite seams. The continuity of the Steelpoort seam throughout the sector, apart from local interruptions by faults and diabase dikes, is firmly established by mine workings, drill holes, and surface exposures. The Leader seam is continuous from Steelpoort to Farm Zeekoegat, just east of the Olifants River. There are other thinner seams, however, that are continuous over distances measured in miles. For lack of exposures, however, their full extent has not as yet been determined.

The anorthosite series consists of thick anorthosite and noritic anorthosite units interrupted in various sections by two to four pyroxenite units, some accompanied by chromitite seams. Some units are known to persist for miles along strike. The M and X units are probably continuous over the full length of the sector, apart from minor structural breaks. The anorthosite series is less continuously exposed than the pyroxenite series, however, and correlation of units from section to section is incomplete.

Over portions of the sector measurable in a few miles, the regularity of the entire Critical Zone is nothing short of phenomenal. On Farm Winterveld (343), a drill hole put down at a point 5750 feet back of the outcrop intersected the Steelpoort seam at a depth of 2336 feet, just 36 feet beyond the depth predicted from surface mapping. An error of half a degree in calculating the average dip from mapping would account for this discrepancy.

Repetition of rock types in the sequence. As noted by many previous investigators, the Critical Zone is characterized by repetition of layers of pyroxenite, norite, anorthosite and chromitite. The present work shows also that on Winterveld (343) and Jagdlust olivine-bearing rocks occur in the lower part of the C unit. The lower of the two horizons, exposed only on Winterveld, consists of interlayered bronzitite and peridotite. At one extreme, the repetition occurs on a scale large enough to be indicated in Figure 4; on the other it may occur within a vertical distance of a few feet (Fig. 7) or within the compass of a hand specimen. The patterns of repetition are obviously important to an understanding of the evolution of the Critical Zone. Discussing the pyroxenites of the central sector, Kuschke (p. 60) pointed out that they occur at various horizons in the stratigraphical succession.

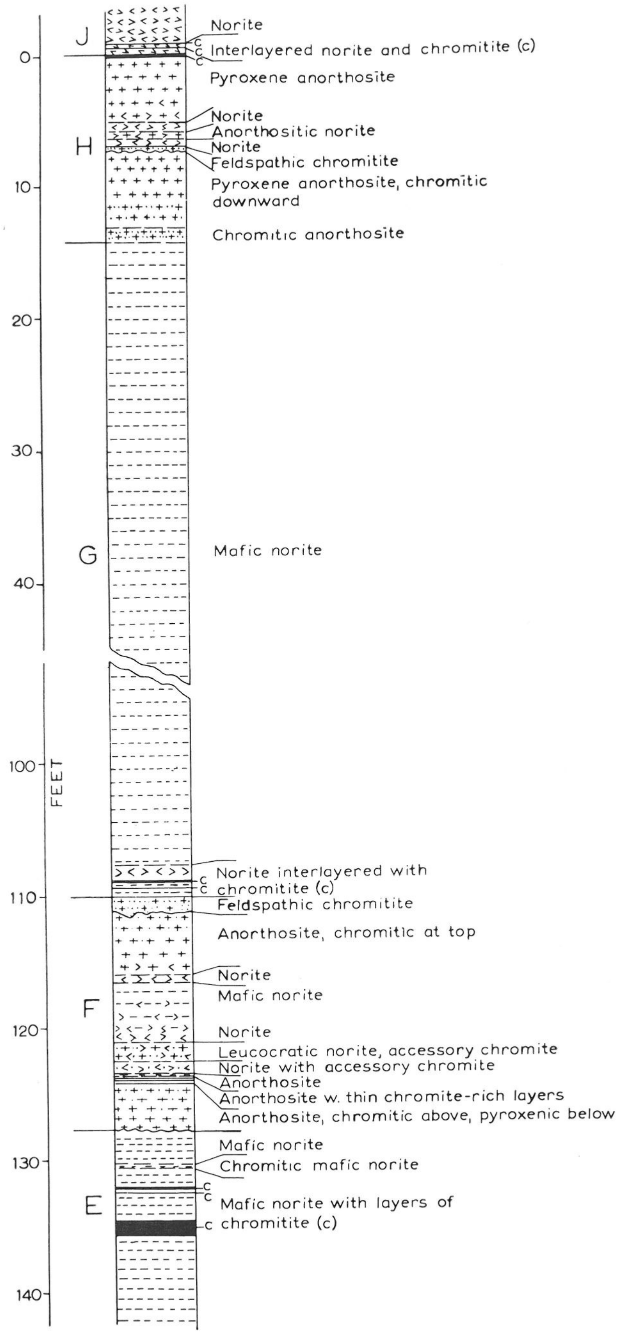

FIG. 5. Section of F, G, and H units, Jagdlust, showing lithologic sequences. Solid lines are sharp contacts, broken lines gradational contacts. Mixed symbols show broad gradations.

"The relation of the pyroxenites to the rocks above them is one of gradual transition through various stages from pyroxenites to pyroxenitic gabbros and gabbros; the lower contact of the pyroxenites is usually sharp and abrupt."

He regarded this relationship as supporting the view that the pyroxenites owe their origin to the settling of crystals. Further (pp. 75–77), he used the repetition of such transitional series as evidence of differentiation *in situ* of successive heaves of magma.

The writer's observations confirm the presence of upward transitions of the kind Kuschke described, but repetition of the series pyroxenite to gabbro is far from being the only pattern of repetition in the Critical Zone. Relationships in places are actually the reverse of those described by Kuschke. For example, in the adit on Jagdlust, mafic norite coarsens downward (stratigraphically) and becomes more feldspathic from a point 1800 feet from the adit portal to a point 1775 feet from the portal, where an abrupt change to medium-grained mafic norite takes place. Modal analyses by Guilbert (1962) show that at 1800 feet, the rock (by volume) has 77.2 per cent bronzite, and 13.2 per cent plagioclase. The rock at 1775 feet, just above the contact, has 71.9 per cent bronzite and 22.6 per cent plagioclase, whereas the rock below the contact has 82.2 per cent bronzite and 13.2 per cent plagioclase. This pattern is shown in other parts of the sections exposed in the Winterveld and Jagdlust adits.

The F unit provides further examples of departures from the sequence described by Kuschke. The basal member of the F unit on Winterveld (343) and Jagdlust (Figs. 5, 6) is a pyroxene-anorthosite which rests with abrupt and disconformable contact on mafic norite interlayered with chromitic pyroxenite

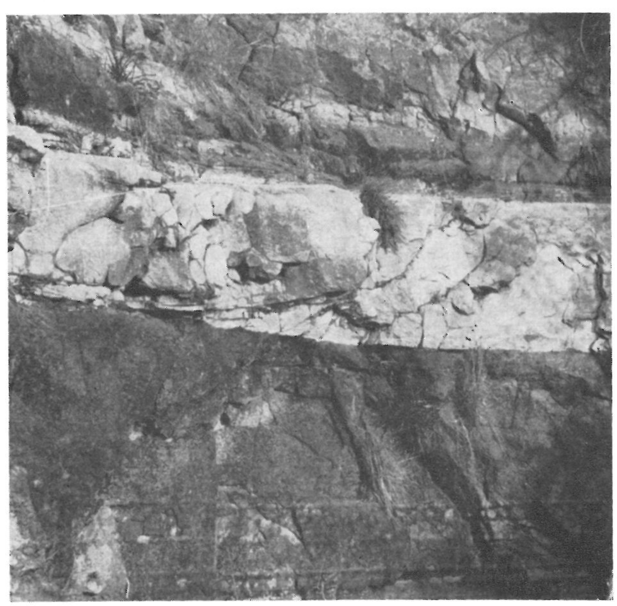

FIG. 6. Basal anorthosite member (white) of F unit, resting with sharp, slightly undulating contact on mafic norite of E unit, Jagdlust. Anorthosite is about 3 feet thick at this point.

and chromitite. The top member (Fig. 5) is feldspathic chromitite in sharp contact with mafic norite. Between the two members, the sequence of rock types is chromitic anorthosite, norite, leucocratic norite, norite, mafic norite, anorthosite, chromitic anorthosite, and feldspathic chromitite; all contacts are gradational, except that the contact between feldspathic chromitite and underlying chromitic anorthosite is an erosional disconformity. The lower part of the feldspathic chromitite contains inclusions of the anorthosite. The H unit provides an interesting contrast with the F unit. The lithologic types present in the two units are remarkably similar, but as shown in Fig. 5, the sequences of types are not the same in the two units.

The K unit is another departure from the pattern described by Kuschke. On Winterveld (343) the lower contact with norite is a disconformity; the upper contact with pyroxenite is gradational. In addition, field observations as well as detailed logging of 2340 feet of core extending from the lower part of the X unit to the Steelpoort seam on Winterveld (343) show that reversals of the sequence described by Kuschke occur at various horizons in the anorthosite series. There is no single pattern of repetition of rock types in the central sector. Instead, we have a variety of patterns of repetition (Figs. 7, 8, 9).

Southern sector. The central sector ends at Steelpoort, and the southern sector begins. In the northern part of the southern sector, the Critical Zone again consists broadly of an upper anorthosite series and a lower pyroxenite series. Sequences of units along lines 6, 7, 8, and 9, of Fig. 2 are shown in Fig. 10, together with the sequence of units along line 5 at the south end of the central sector for comparison. The anorthosite series has the same general character as in the central sector, consisting essentially of thick anorthosite units separated by pyroxenite units with or without chromitites. Some units of this series have been traced thousands of feet, or even miles, but correlation from section to section is uncertain pending further detailed mapping.

The pyroxenite series of the southern sector is markedly different from that of the central sector. The sequence of section 5 and that of section 6 hold for points only 3 miles apart, yet the units in the pyroxenite series in the one sector do not agree at all with those in the other. Along line 6, the pyroxenite series, so far as exposed, is a monotonous succession

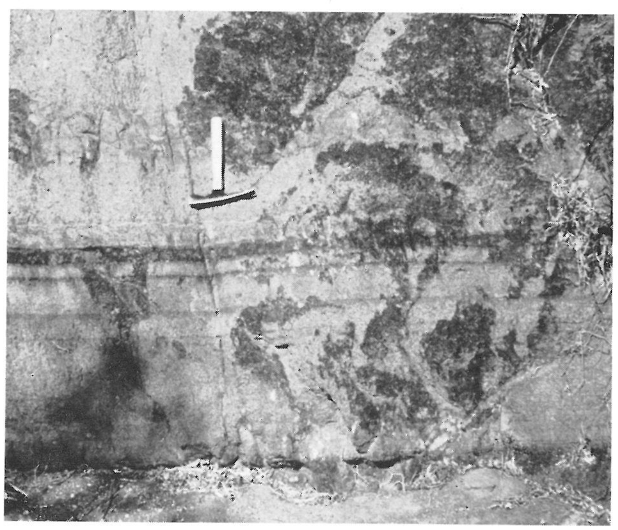

FIG. 7. Mafic norite interlayered with thin chromite seams and chromite-rich mafic norite (under hammer handle) on Jagdlust. The upper part of a 14-inch chromitite seam is exposed at the lower right.

FIG. 8. Interlayered pyroxenite and peridotite at entrance to adit on Winterveld (343).

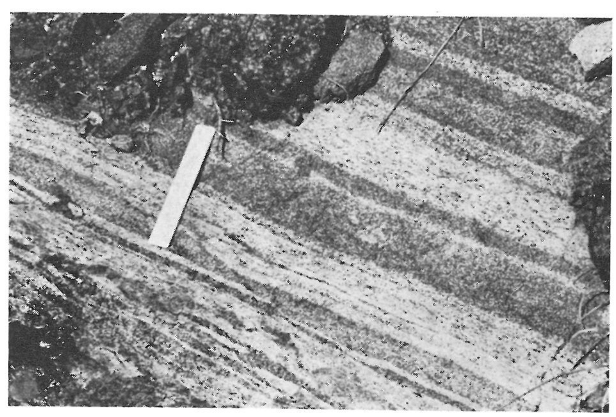

FIG. 9. Interlayered anorthosite (light) and norite (dark) in K unit, Jagdlust. Scale is $6\frac{1}{2}$ inches long.

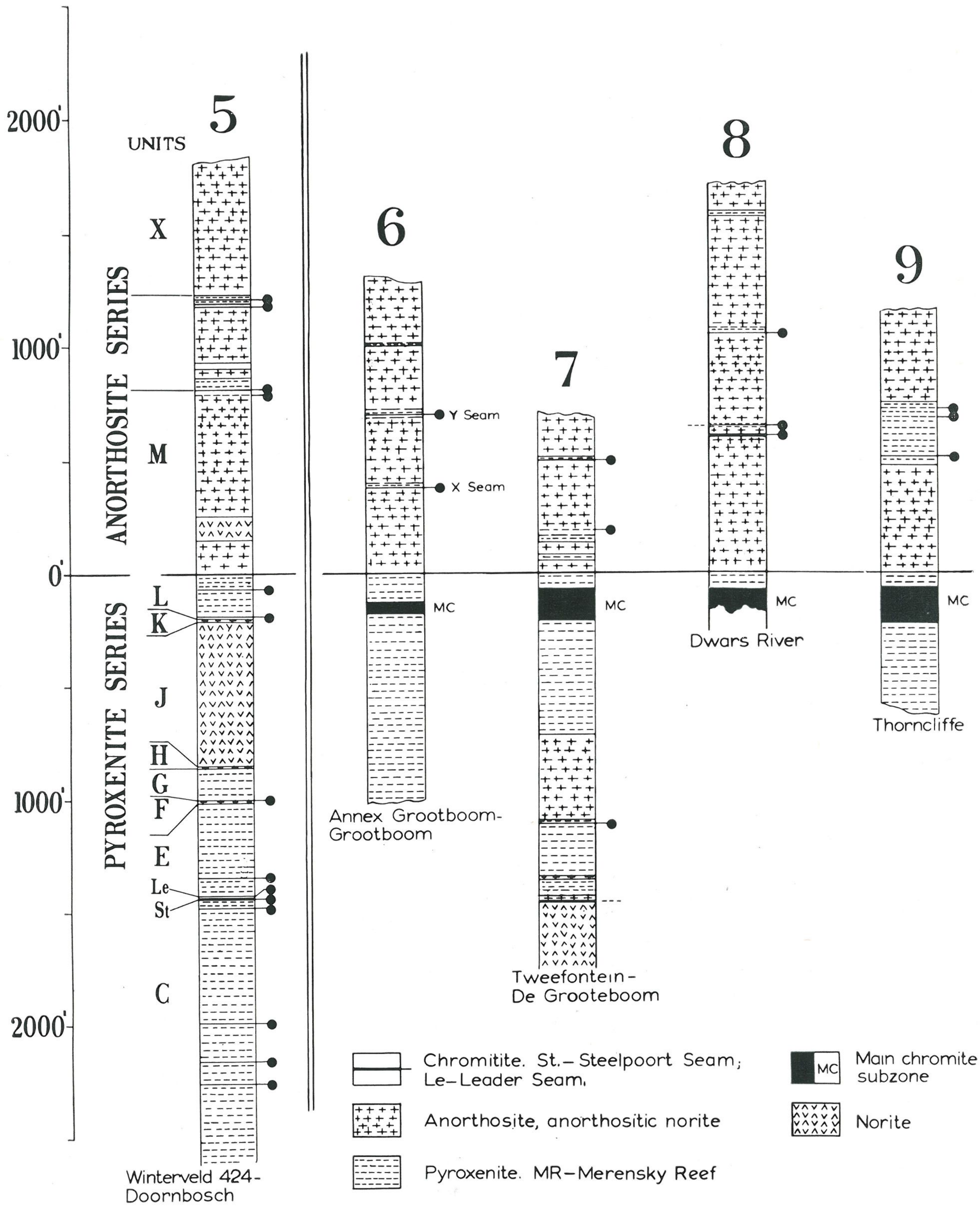

FIG. 10. Sequences of rock units in the Critical Zone, Steelport to Thorncliffe.

of feldspathic pyroxenites interrupted near its top by a zone of interlayered chromitites, anorthosites, and pyroxenites 65 to perhaps 80 feet thick, shown in Fig. 10 in black and designated the Main Chromite Subzone.

The Steelpoort River Valley (Wagner, 1929, p. 151; Willemse, 1959) is known to be a belt of disturbance cutting across the complex and the rocks of the floor of the complex. Outcrops in the valley bottom east of the river bed and south of Steelpoort show a wide range of attitudes within short distances. Faulting, possibly complicated by minor folding, is indicated (*cf.* Willemse, 1959), but neither the amount nor the direction of gross displacement is clear. The writer has entertained the hypothesis that the difference in sequences of the central and southern sectors is due to the fact that faulting has brought the southern sector, consisting at its northern end of rocks lying near to the edge of the complex, in juxtaposition with a deeper portion of the complex represented in the central sector.

This notion is prompted by three features of the Critical Zone of the southern sector. First, units of the pyroxenite series and the lower part of the anorthosite series thin rapidly toward the floor of the complex south-eastward along the extension of the line of section 6, Fig. 10, This is shown by a comparison of section 6 with Fig. 11, a section along a line parallel to and about a quarter-mile west of the floor on Farm Annex Grootboom (Fig. 2). Second, as shown in Fig. 10, the pyroxenite series varies in sequence of units within the 15-mile strike distance represented by sections 6 to 9. In section 7, a thick anorthosite unit appears well above the base of the pyroxenite series, and two thinner ones appear lower down. The Main Chromite Subzone is much thicker than in section 6 and shows a different sequence of chromite seams. The full sequences along lines 8 and 9 have not been determined, but in section 9 the Main Chromite Subzone shows a different sequence than in section 7. Such rapid changes seem more likely near the edge of a crystallizing complex than in its deeper lying portions. The third feature is that on Farm Annex Grootboom, the Bushveld rocks appear to interfinger locally with floor rocks. The structure here and on Farm Spitskop is complicated, however, and extremely detailed mapping is needed to resolve the relationships.

Structure of the Critical Zone

(a) *Concordance of units*

The outstanding structural feature of the Critical

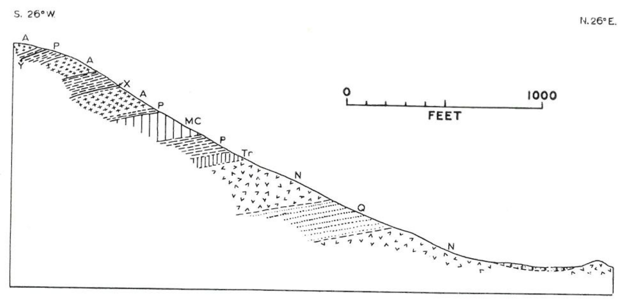

FIG. 11. Section of northeast side, Spitskop-Annex Grootboom boundary hill. A-anorthosite, MC-main chromite subzone; N-norite; W-quartzite, Tr-transition. X-X chromitite, Y-Y chromitite.

Zone in the central and southern sectors is the concordance of successive units in the zone. Local irregularities of contact are found at numerous places, and relationships of the rocks of the Critical Zone along the contact with floor rocks on Grootboom and Annex Grootboom are complex, but these are features that must be viewed against the perspective of the large-scale structure. Anyone who does detailed mapping of the rocks of the Critical Zone shortly finds that the geometry is that of a pile of sedimentary rocks, and that this geometry, as in the study of sediments, can be used to decipher structure, predict outcrop belts, and guide exploration. Crosscutting of one unit by another is never seen, although crosscutting relationships within units are present locally and certain contacts between units are disconformable in detail. Even where new units appear along the strike of the Critical Zone, as in the southern sector, they have concordant contacts and internal layering parallel to external layering of enclosing rocks. In other words, they have the same thinly lenticular habit as the members of a concordant sedimentary pile.

The relationships involved are well illustrated in the northeastern part of De Grooteboom and the southern part of Frischgewaagd, in which the rocks of the lower part of section 7, Fig. 10, are well exposed. A section of the side of a deep valley on De Grooteboom is given in Fig. 12. In every unit, internal layering is parallel to contacts with enclosing units, where these are exposed. Furthermore, the traces of the units along the face of the ridge and across the ridge and a second valley and its branches to the north clearly indicate concordance of the various units.

Contacts between rock units. The nature of contacts between rock units is the second important aspect of the

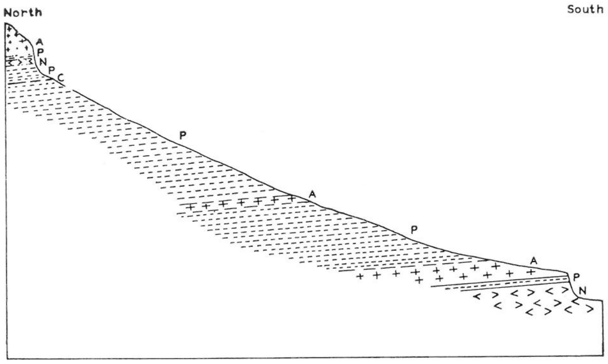

FIG. 12. Section of lower part of pyroxenite series, De Grooteboom. A—anorthosite, C—chromitite, N—norite, P—pyroxenite, Solid lines indicate exposed contacts, broken lines gradational contacts.

structure of the Critical Zone in the central sector. For the eastern Bushveld Complex, this subject has been discussed most recently by Cameron and Emerson (1959), who point out that both gradational and sharp contacts are observed, that regular, even layers with straight, parallel contacts are the commonest type, but that irregular contacts having the nature of disconformities are found at certain horizons. Subsequent observations by the writer confirm these statements, but it should be added that gradational or abrupt contacts are not characteristic of particular pairs of rock types; any pair of rock types such as pyroxenite and anorthosite can be found at certain horizons in sharp contact with one another, at others in gradational contact. A second feature of contacts that should be added was described by Wagner (1929, pp. 122, 123) many years ago from observations of the Merensky Reef. In places, apophyses of an overlying member of a sequence of units extend downward into an underlying member, inclusions of which may be present in the overlying member. The writer has seen this feature at the top of the H unit on Surbiton, on the hill just north of the Mutse River. The H unit is overlain by a $3\frac{1}{2}$-inch layer of mafic norite. The top of this layer is straight and regular. The bottom is irregular, and the norite projects downward as much as 2 feet into the H unit anorthosite along fractures. Wagner nowhere found projections of an underlying rock into an overlying rock. He pointed out that relations described obviously indicate that the order of superposition of the layers involved is their order of formation.

Compaction structures. Compaction structures are not common in the rocks of the Critical Zone, but the fact that they exist at all is worthy of note. The best examples seen by the writer are in an incline on Farm Driekop (Fig. 13), one of a series driven along a chromite seam at intervals for far more than a half mile along strike. The seam, 39–45 inches thick in the incline, underlies norite, with which it is in sharp contact, and overlies pyroxenite that is chromite-rich in its top few inches. The basic structure of the seam is an even, regular alternation of chromite-rich and feldspar-rich layers that are fractions of an inch to six inches thick and remarkably straight in section. This simple and regular layering is interrupted locally, however, by flat lenses of anorthosite and by inclusions of fine-grained pyroxenite, the largest seen 11 feet long and 12 inches in maximum thickness. Figure 13 is a detailed scale drawing of the upper part of the seam, showing two of the inclusions. Overlying layers are arched and thinned, immediately underlying layers are depressed and thinned, and layers next to the ends of the inclusions are crumpled. These are features characteristically developed by compaction of unconsolidated sediments around resistant objects. The basal contact of the seam is straight and even, and the inclusions are petrographically dissimilar to the immediately underlying chromitic pyroxenite.

Deformation structures. Deformation structures in the rocks of Critical Zone have been discussed by Cameron and Emerson (1959). The structures are of two principal kinds. One consists of chromite filling low-angle fractures in anorthosite. Examples are shown in Figs. 13, 14, 15. These can only be interpreted as produced by movement of chromitic material (as a mush of crystals and liquid?) into dilatant fractures. The relationships shown in Fig. 13 would seem to confirm the conclusion of Cameron and Emerson that these features arose during consolidation. Such features are shown at numerous places in the anortho-

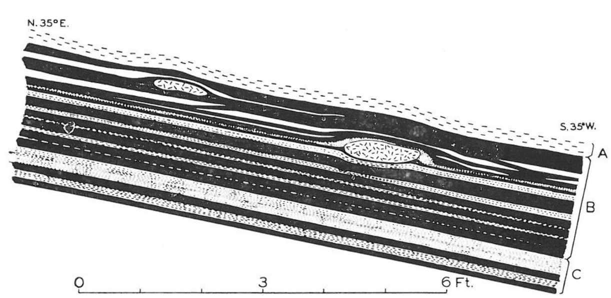

FIG. 13. Drawing of part of chromite seam in wall of incline, Driekop. A—norite. B—interlayered chromitite (black), feldspathic chromitite (dashed lines), and anorthosite (white), with two inclusions of pyroxenite (random dashes); drawn in detail to scale. C—interlayered chromitite (black) and chromitic anorthosite (dashed lines); layers diagrammatic, Footwall of seam not shown.

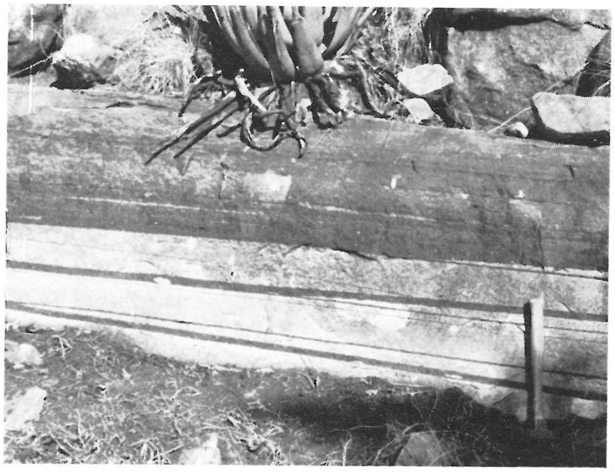

FIG. 14. Interlayered feldspathic chromitite and chromitite (dark) underlain by anorthosite (white) cut by thin chromitites along low-angle fractures. Onverwacht.

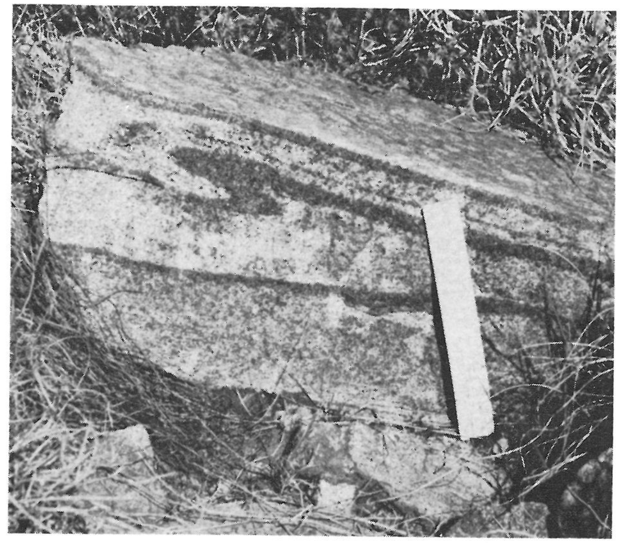

FIG. 16. Folded layer of pyroxenite (dark) enclosed in pyroxene-anorthosite (lighter). Loose block from upper part of M unit, Winterveld (343). Scale is 6½ inches long.

site series and, more rarely, in the pyroxenite series of the southern sector, for example in the old mine workings on Grootboom.

The second type consists of folding or dismemberment, or both, of thin layers of chromitite or pyroxenite enclosed in anorthosite (Figs. 16, 17). As in the Stillwater Complex (Hess, 1960), deformation features at any one locality are confined to stratigraphic thicknesses of a few feet. Underlying and overlying rocks are undisturbed. They evidently arose, like fracturing, prior to complete crystallization, for the textural fabrics of the rocks in thin sections are the same as those of enclosing rocks. Cataclastic textures are lacking.

Inclusions. Inclusions of one rock type in another in the Critical Zone have been noted by numerous investigators and have recently been discussed by Cameron and Emerson. Some, as in Figs. 17, 18, are obviously of local derivation, either by erosion along disconformities, or by dismemberment. Others, such as those of Fig. 13, occur in settings that require transport of the inclusions from sources at least beyond the limits of very sizable outcrops; *i.e.*, for distances of at least feet, tens of feet, or hundreds of feet. Orientation with long dimensions parallel to stratification is characteristic. Deformed inclusions occur in places (Fig. 19), but again, rocks overlying and underlying the horizon containing the inclusions are undeformed.

Structural features and hypotheses of origin. An acceptable hypothesis of origin of the Critical Zone must be consistent with the structural features described above. They provide, then, a first basis for

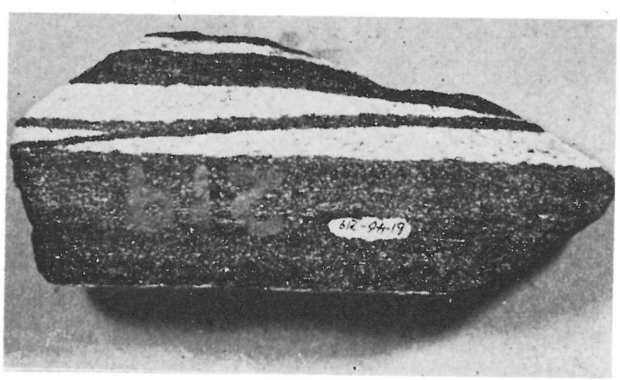

FIG. 15. Anorthosite parting (white) cut by chromitite (speckled black) along low-angle fractures, Driekop. Specimen is 8½ inches long.

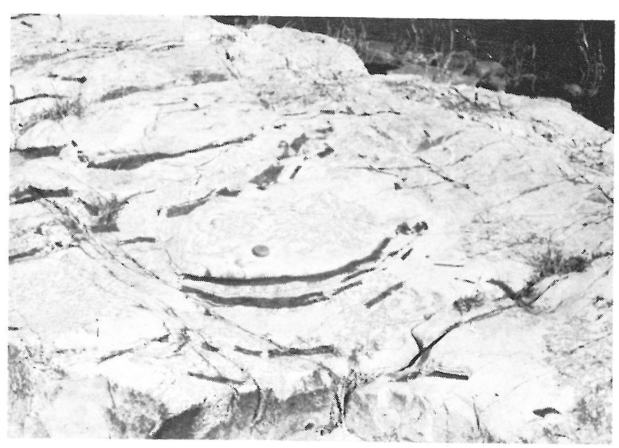

FIG. 17. Dismembered chromitite seams (black) in anorthosite, Dwars River. Pocket tape is 2 inches in diameter.

FIG. 18. Contact of L and M units, Winterveld (343). Noritic anorthosite (above, lighter gray) contains inclusions derived from underlying mafic norite (darker gray) of L unit. Scale is $6\frac{1}{2}$ inches long.

evaluation of current hypotheses. One is the hypothesis of multiple intrusions, proposed by Reuning (1927) and revived more recently by F. C. Truter (1955, p. 84). Truter recognizes seven or eight major members of the Critical Zone as defined in the present paper. He regards all these as separate intrusions, giving as evidence

1) that of any two lithological zones higher up in the succession, the higher one contains inclusions of the lower one at or near the contact, (2) some of the lithological units have a lenticular habit and are consequently in contact with several rock types along their peripheries, and (3) pyroxenite units in the Critical Zone differ markedly in mineralogy and texture.

Total emplacement of the Complex, including the Critical Zone, he regards as accomplished in successive surges, each one being emplaced immediately above the one that preceded it and lifting the sedimentary roof of the complex. He further states (*loc. cit.*):

"Excluding the possibility of gravitative settling of chromite in the pyroxenite, there is similarly no evidence of differentiation *in situ* anywhere in the complex."

The writer's observations are difficult to reconcile with these conclusions. The mechanism of multiple intrusions is inconsistent wth the remarkable concordance and persistence of major units in the Critical Zone. The problem involved is clearly posed by the results of mapping on Farms Jagdlust and Winterveld. On these two farms, the units shown in section 1, Fig. 4, have been mapped by plane-table and telescopic alidade on a scale of 1:10,000. The continuity and concordance of units C to X for a distance of 6 miles along strike have been established by walking out lines of outcrop (for some units nearly continuous), by examination of mine workings, and by 14 diamond drill holes. A drill hole 5750 feet back of the outcrop of the Steelpoort main seam on Winterveld intersected the same sequence of units as that indicated by surface mapping. Included in this sequence are units F, H and K. The first two are nowhere more than 30 feet thick anywhere in the central sector, and the last is nowhere more than 45 feet thick. These units are not only continuous on Winterveld and Jagdlust but are present in every section the writer has run across the 45-mile length of the central sector. It seems scarcely possible that these are separate intrusives. Layers of pyroxenite in anorthosite with straight parallel contacts for distances of hundreds of feet pose a similar problem, though on a small scale.

The writer believes that the features cited as evidence of multiple intrusions can be better explained in other ways. Inclusions of one rock in another are evidence that the host rock formed later than the rock of the inclusions, but they are not necessarily evidence of intrusion. Movement of magma over a growing pile of crystal accumulates, with intermittent erosion of the upper part of the pile, and local de formation of the kinds described above account for

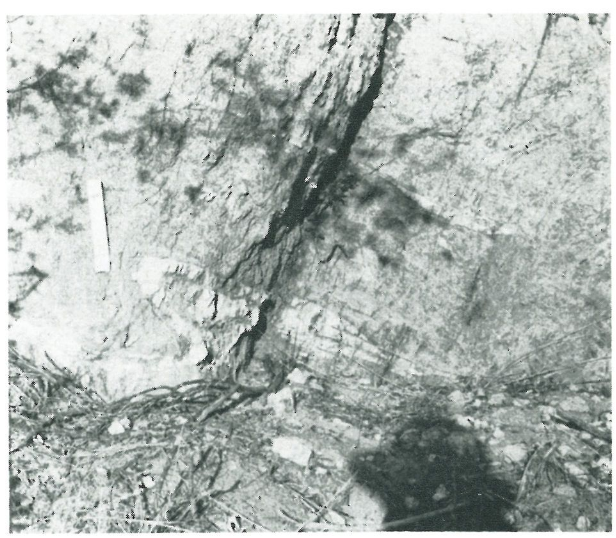

FIG. 19. Folded inclusion of anorthosite in norite, middle member of H unit, Jagdlust. A faint banding in norite adjacent to the inclusion follows the boundaries of the inclusion. Scale is $6\frac{1}{2}$ inches long.

the derivation of inclusions in ways that are more consistent with the large-scale concordance and persistence of major units. Concordant lenses seem more reasonably explained by sedimentation of crystals along the floor of a magma chamber, distribution and thickness of units being controlled by magmatic currents and by configuration of the floor. Contrasts in composition and texture of pyroxenite units are to be expected as a consequence of changes in conditions of differentiation *in situ;* such contrasts are not evidence of successive intrusions.

Finally, it is not the case that of every contrasting pair of units, the higher contains inclusions of the lower along their contact. As stated in a previous section, pairs of rock types are found in gradational contact with each other at many horizons; the upper unit *may* contain inclusions of the lower, but in the majority of cases does not. Gradational contacts between geometrically regular, persistent, and lithologically distinct units are a fatal objection to the hypothesis of multiple intrusions. It is impossible, moreover, to reconcile their common occurrence in the Critical Zone with Truter's statement that there is no evidence anywhere in the Complex (apart from chromite-pyroxenite relationships) of differentiation *in situ*. The existence of gradations between rock types and the fact that every rock type of the Critical Zone can be found at a number of places gradationally inter-layered with other types is clear evidence that differentiation *in situ* has had a major role in producing the rock sequence.

A difficult feature of the hypothesis of multiple intrusions, in its extreme form, is that it questions the possibility of differentiation *in situ* in the magma chamber exposed, while requiring this same differentiation, in a hidden magma chamber below, in order to account for units of contrasting composition.

The hypothesis of multiple intrusions, in a somewhat different form, has also been adopted by Heckroodt (1959) as the explanation of the rocks of the eastern norite belt. He states that the chronological order of intrusion of the various rocks in an area including Farm Driekop and parts of adjoining farms is as follows:

Youngest	5b. Gabbro	Main Subphase
	5a. Hyperite	
	4. Peridotite	Peridotitic Subphase
	3. Pegmatitic feldspathic Pyroxenite (Merensky Reef)	Critical Subphase
	2. Norite, melanorite, and anorthosite	
	1. Pyroxenite	Pyroxenitic Subphase

He states that

"the subdivision of the Complex into zones based on the stratigraphical position of certain characteristic rocks sometimes places rocks of various ages into one zone. According to this system, the hyperite will be classified in the Critical Zone because of its position in the Complex, whilst the petrographic proof as well as the chronological order of intrusion requires that the rock should belong to the Main Subphase. The reason for this is that some rocks intruded downwards into the older rocks and thus came into another zone."

Section 3, Figure 5, is based on traverses by the writer across the area described by Heckroodt. The hyperite of Heckroodt is apparently in the lower part of the M unit. On Heckroodt's map it is shown as continuous and constant in position in the rock sequence for 4 miles along strike, disappearing beneath valley fill in the north and continuing beyond his map area to the south. In his section it is shown as concordant with overlying and underlying rocks. No field evidence is given that this unit has intruded downward; the field relations were not determined, owing to rubble covering exposures. Heckroodt regards the rock, nonetheless, as an assimilation product formed by intrusion of gabbro into noritic rocks. The evidence given is petrographic and in the writer's judgment inconclusive. The remarkable persistence and concordance of this "intrusive" unit and its constant position in the sequence are not explained.

As a further extension of the hypothesis of multiple intrusions, Heckroodt regards the chromite seams in the anorthosite series on Driekop, with the associated pyroxenite, as wedged off from the upper part of the pyroxenite series, roughly 1000 feet below, by intrusion of norite and melanorite of the M unit of Fig. 3. It is difficult to understand how this process could yield blocks that are persistent for miles, have attitudes concordant with the rest of the units of the Critical Zone, and have internal layering parallel to that of the anorthosite series. The evidence cited is that thin chromite seams in anorthosite in one of the inclines have been disrupted and disturbed. The writer regards these features, however, as due to local deformation during final stages of consolidation. Chromite seams in anorthosite, apart from fracture fillings, appear to have formed by differentiation *in situ;* every gradation between chromitite and anorthosite with accessory chromite is found (Fig. 20) in the anorthosite series.

Closely related to the hypothesis of multiple intrusions is that of successive heaves of magma, which has been supported by a number of students of the Bushveld Complex since it was proposed by B. V. Lombaard in 1934. This concept is difficult to evalu-

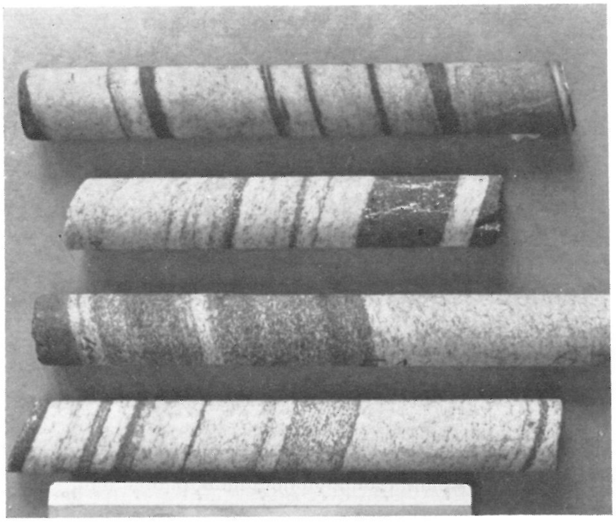

FIG. 20. Drill cores from upper part of M unit, Winterveld (343). Various layers range from anorthosite with accessory chromite (light gray) to nearly pure chromitite (black). 6-inch scale at bottom of photograph.

ate, because the dividing line between the concept of multiple intrusions and successive heaves of magma is not clearcut, and even less clearcut is the dividing line between successive heaves of magma and movement of magma within a chamber during differentiation *in situ*. Movement of magma within its chamber might take place through convective overturn, through turbidity currents generated by warping of the floor, or locally through simple slumping of the pile of accumulates. These various mechanisms, from successive intrusions or heaves of magma to movements of a magma internal to its chamber, are conceivably members of a continuous series. Recognition of a particular mechanism may not be easy, the more so if we deal with results of a combination of mechanisms.

Difficulties involved in the hypothesis of successive heaves of magma have been discussed by Hess (1960, pp. 154–156), to whose work the reader is referred. With reference to Kuschke's work in the central sector, however, the writer would add

(1) that the oscillatory variations in pyroxene composition described were not closely correlated with the sequence of rock units, and (2) that as stated in a previous section, no simple cyclical repetition of units, of the kind required by Kuschke's hypothesis, has been found.

Jackson (1961), moreover, argues that cyclical repetitions of rock units in the lower part of the Stillwater Complex are due to major convective overturns, an alternative to the mechanism of successive heaves. Cameron and Emerson (1959) and Hess (1960) conclude that oscillations in mineral composition may take place due to the operation of processes purely internal to the magma chamber, and that successive heaves of magma are not required to account for them.

The hypothesis of successive heaves of magma has been used by B. G. Worst to account for the sequence of chromite seams alternating with harzburgites in the Great Dyke of Southern Rhodesia. Worst reports that each chromite seam is in sharp contact with underlying pyroxenite or harzburgite but grades upward into overlying harzburgite. He regards each chromite seam as an early product of crystal settling from a new heave of magma.

The writer has attempted to find a parallel in the chromite deposits of the eastern part of the Bushveld, but without success. Some seams have both upper and lower gradational contacts, other seams have both upper and lower sharp contacts, and still others have either the upper or lower contact sharp and the other gradational. Furthermore, what we call chromitites are merely end members of two series, the other end members of which are anorthosite and pyroxenite with accessory chromite (Fig. 20). Some seams are massive, others rhythmically banded. There certainly is no simple cyclical repetition of chromitites and associated rock types.

At the present writing, the structural features of the Critical Zone seem consistent with development by fractional crystallization and gravitative settling of crystals, complicated by local deformation of accumulated layers and by intermittent movements of the magma strong enough to cause sorting of crystals and even disconformities at certain horizons. It seems necessary, therefore, to assign a major role to differentiation *in situ*, a conclusion with which Willemse (1959, pp. lxiii–lxiv) is in general agreement. To what extent these processes may have been complicated by slow inflow of magma, by successive, more or less distinct heaves of magma, or by major convective overturn, it seems impossible at present to say. For one thing, our criteria for the distinction of such processes leave much to be desired. For another, despite the labors of many able investigators over a long period of years, the facts for the Critical Zone of the eastern Bushveld Complex are not all in. Detailed laboratory investigations closely correlated with detailed field studies must provide the necessary information. It is the writer's hope that laboratory studies at the University of Wisconsin, based on the field work here discussed, will contribute toward this end.

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