

SOME PETROLOGICAL ASPECTS OF MAFIC ROCKS FROM FOUR BOREHOLE
SECTIONS BETWEEN THE MERENSKY REEF AND THE MAIN-ZONE GABBRO
IN THE WESTERN AND EASTERN BUSHVELD COMPLEX.

by

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ABSTRACT

Some petrological aspects of rocks from four borehole sections in the Main Zone of the Western and Eastern Bushveld Complex were investigated. Of these boreholes, two were drilled near Rustenburg, one near Northam, and the fourth one about 55 miles to the east of Potgietersrus. Rock types with similar volumetric mineral composition and texture occur in the same sequential positions in these boreholes and this makes it possible to distinguish ten zones. In some of these zones layering is very well developed.

Some well developed changes in the volumetric mineralogical composition and texture, and particularly pyroxenite inclusions, seem to show beyond doubt that several heaves of magma were emplaced at intervals so that each heave normally came to rest upon the previous emplacement. These heaves of magma probably changed more or less systematically in chemical composition.

The different associated rock and textural types which were distinguished, in order of decreasing abundance, are: hypidiomorphic hyperite, norite, and gabbro; synophitic hyperite and norite; ophitic to nesophitic hypidiomorphic hyperite; subophitic hypidiomorphic hyperite; hypersthene- and bronzite-bearing mottled anorthosite and mottled leucohyperite; spotted anorthosite and spotted leuconorite; anorthosite; and leucohyperite.

Plagioclase, orthopyroxene, and clinopyroxene are the main constituents of these rocks and seem to be mostly cumulus crystals.

The hypersthene in the synophitic hyperite and norite and in the hypersthene-bearing mottled anorthosite and mottled leucohyperite originally crystallized as pigeonite which on slow cooling inverted to hypersthene. The inversion was in the majority of cases of such a nature that none of the original crystallographic axes were retained as is evident from the random orientation of sets of (001)-augite exsolution lamellae

and blebs in the hypersthene. In the synophitic hyperite large clusters of hypersthene "grains" with very nearly the same optical orientation were formed when diversely orientated pigeonite grains inverted to hypersthene. A number of features in the hypersthene such as the spacing of inversion nuclei, the size and spacing of augite blebs, and the development of vermicular exsolution seem to be temperature controlled.

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COMPLEX

I. INTRODUCTION

A. Material and aim of the investigation

This thesis is based on the study of cores obtained from boreholes KLG2, TRF1, AB1, and US13 drilled by the Johannesburg Consolidated Investment Co., Ltd., in the mafic rocks of the Bushveld Igneous Complex. The localities at which these boreholes were drilled are shown in Plate I. All the holes were drilled to intersect the Merensky Reef and the upper chromitite seams. The rocks above the Merensky Reef were studied in some detail, but no special attention was given to the Merensky and Bastard Reefs.

Of the four boreholes, KLG2 was drilled from the highest position in the sequence. The lower portion of this borehole did, however, deflect to such a degree from the vertical that it was decided to join up the core from this hole with that from borehole TRF1 at a distinct marker band occurring in both the boreholes. The combination of these cores was treated as one section and was chosen as a reference column.

The aim of the investigation was to divide the rocks in the three sections investigated into zones on the basis of prominent markers, to summarize some of the more important hypotheses proposed for the formation of layering, and to find some explanation for the textural and structural differences in the rocks.

The present thesis is to a certain extent intended to supplement the study made by Van Zyl (1960).

B. Previous work

The following workers have recently made a petrological study of parts of the Main Zone: Van Zyl (1960), Raal (1965), and Von Gruenewaldt (1966).

The upper 2000 feet of the zone studied by Van Zyl (1960) overlaps with the lower portion of the rocks treated in this thesis. Van Zyl (p. 98) suggests that different heaves of homogeneous magma were emplaced at intervals on top of the previously emplaced magma which was, in some cases, virtually completely crystalline, and that fractional crystallization and gravity differentiation took place with each new heave of magma.

Raal (1965) made a mineralogical and petrological study of the transition between the Main and the Upper Zones of the Bushveld Complex in the vicinity of the Bon Accord Dam and on the farm Kopje Alleen about ten miles northeast of Northam. His Bon Accord Unit seems to form the upper part of a zone, a few thousand feet thick, only the lower part of which was intersected in borehole KLG2.

Von Gruenewaldt (1966) mapped the geology of the Bushveld Complex east of the Kruis River Cobalt Occurrence, North of Middelburg. Amongst other things he describes hyperite containing inverted pigeonite and gabbro containing pyroxenite inclusions which occur in a band.

C. Methods of investigation

Samples were taken from the borehole cores at irregular intervals according to the degree of homogeneity of the rocks encountered. Where the rock was fairly homogeneous the spacing of samples was about 50 feet apart. At some important ratio-form contacts (Jackson, 1967, p. 22) samples were taken

right across such contacts to form continuous sections.

Virtually all thin sections were cut more or less parallel to the length of the 4cm thick core.

Micrometric analyses were made according to Chayes' (1949, pp. 2-3) point-counting method. In rocks with hypidiomorphic texture the volumetric mineral^{ogical} composition obtained from point-counts on one thin section may be fairly reliable, but in inequigranular rocks the point-count obtained from one thin section does not give a reliable average volumetric mineral^{ogical} composition of the rock. Consequently the average of a large number of point-counts on different thin sections of the same rock may be considered to represent the average volumetric mineral^{ogical} composition. The same applies to grain size determination.

Van Zyl (1960) measured the length and breadth of grains in thin sections, and from these measurements determined the average grain size. This grain size is not the true grain size, as grains are intersected randomly in a thin section. To speed up the determination of the average grain size a graph was constructed in which the average traverse distance can be converted directly into the average grain size. To obtain this graph the average grain size was determined by measuring the length and breadth of 100 grains encountered in traverses across a thin section using a mechanical stage on a microscope. The mechanical stage was also used on a microscope to determine the average traverse distance. The distance was noted over which 50 grains were intersected more or less parallel to the igneous lamination, and also the distance over which 50 grains were intersected in a direction perpendicular to the first traverse. The two values were added and divided by 100 to give the average traverse grain size. In eight thin sections both the average grain size and the average traverse grain size were determined and plotted on the graph in Plate II. A straight line passes more or less through these points enabling one to convert the average

traverse distance directly into the average grain size.

The composition of the plagioclase was determined according to the method devised by Tatarskij (1956, pp. 204-208). The refractive index values N_g' and N_p' were converted to anorthite values using Chayes' diagram (Deer, Howie, and Zussman, 1963, vol. 4, p. 130).

The composition of the orthopyroxene was determined by measuring 2V on the universal stage. The 2V values were converted to Of values using Deer, Howie, and Zussman's (1963, vol., 2, p. 28) diagram. Although the orthopyroxene is often somewhat zoned, no difficulty was experienced in determining an average 2V for such zoned crystals.

No study was made of the compositional changes of the augite (clinopyroxene).

Numerous reversals and sudden changes in the mineral composition, the Pr ratios, and the volumetric mineral^{ogical} compositions in boreholes KLG2 and TRF1 (Plate IV) tend somewhat to obliterate the general trend. The column of rock intersected in these two boreholes was divided arbitrarily into three equal lengths of 1903 feet. Over this distance, in each third, the various compositions and Pr values were taken at intervals of 50 feet. These compositions were then averaged out and plotted at the mid-point of each third to show the general trend (Plate V).

II. NOMENCLATURE

A. Rocks

On the basis of the volumetric mineral^{ogical} compositions five rock types have been distinguished, namely: anorthosite, pyroxenite, norite, gabbro, and hyperite. The nomenclature adopted for these rock types is based essentially on Rosenbusch's (1896) classification. The two prefixes leuco- and mela- (Shand, 1947, p. 235) are used for some norite, hyperite, and gabbro containing 10 to 30 and 30 to 90 per cent of dark minerals respectively.

The rock types are defined as follows:

Anorthosite: A rock containing at least 90 per cent of calcic plagioclase and not more than 10 per cent of pyroxene and other accessory minerals (Van Zyl, 1960, Fig. 5).

Pyroxenite: A rock containing at least 90 per cent of pyroxene and up to 10 per cent of calcic plagioclase and other accessory minerals (Van Zyl, 1960, Fig. 5).

Norite: A rock containing 10 to 90 per cent of calcic plagioclase and 10 to 90 per cent of orthopyroxene and accessory augite.

Gabbro: A rock containing 10 to 90 per cent of calcic plagioclase and 10 to 90 per cent of clinopyroxene and accessory orthopyroxene.

Hyperite: A rock intermediate between norite and gabbro consisting of 10 to 90 per cent of plagioclase and 10 to 90 per cent of orthopyroxene and clinopyroxene. Both the clinopyroxene and orthopyroxene can individually constitute from 25 to 75 per cent of the total pyroxene content.

B. Textures

Since the study was confined mainly to the textural and structural features of the rocks in the four boreholes, it was

found convenient to subdivide rock types according to their characteristic and easily recognizable textures. The main varieties are ophitic, subophitic, coronophitic to coronosubophitic, nesophitic, and synophitic. These textural types are defined as follows:

Ophitic texture: The term ophitic is used to denote a texture in which the pyroxene is optically continuous over relatively large areas and completely encloses a considerable number of plagioclase laths (Walker, 1957, p. 2). See Plate IX, Fig. A.

Subophitic texture: The term subophitic is used to describe a texture in which the pyroxene is optically continuous over relatively large areas and partly encloses a considerable number of plagioclase laths. Some plagioclase laths may be completely enclosed by the pyroxene. See Plates VIII, Figs. A and B; IX, Fig. B; and X, Figs. A and B.

Coronophitic to coronosubophitic texture: The term coronophitic is applied to a texture in which orthopyroxene occurs as single crystals or as isolated patches, partly or completely rimmed by augite, together with plagioclase inclusions (Wells, 1952, pp. 919-921). If plagioclase is mainly partly enclosed by the augite the texture is coronosubophitic. See Plates VIII, Fig. B and X, Fig. A.

Nesophitic texture: The term nesophitic is used to denote a texture in which the bonzite is interstitial to plagioclase and occurs in isolated but optically continuous areas (like islands in a sea), though connected in three dimensions. A very low pyroxene/plagioclase ratio occurs in these nesophitic areas. Areas up to 5 cm across extinguish uniformly (Walker, 1957, p. 2). See Plates VII, Fig. A and IX, Fig. A.

Synophitic texture: The term synophitic ^{is proposed for} describes a texture in which a number of interconnected hypersthene "grains", with very nearly the same optical orientation over relatively large areas, produce an ophitic texture (Plates VI, Fig. B; XII, Figs. A and B; and XIV, Fig. B). Von Gruenewaldt (1966, p. 84)

referred to this texture as nesophitic, but this term does not adequately describe the texture.

Some of the textures may grade into one another, whereas in other instances, rocks with different textures may be in contact without gradation.

C. Exsolution in pyroxene

In the rocks investigated the pyroxene contains fine, and sometimes coarse, exsolution lamellae. The orthopyroxene always contains fine (100)- augite exsolution lamellae. In addition to the fine (100)- augite exsolution lamellae, the hypersthene contains sets of broad augite lamellae or blebs. In the augite (100)- exsolution lamellae are always present, but exsolution parallel to (001) is often not developed.

(001)- augite exsolution in pigeonite and hypersthene:

Pigeonite, on slow cooling before inversion, exsolves relatively broad and somewhat widely spaced (001)- augite exsolution lamellae (Poldervaart and Hess, 1951, p. 482) so that the a-, b-, and c-axes of the augite and the host pigeonite coincide. After inversion of pigeonite to hypersthene these (001)- augite exsolution lamellae lie mostly in any random plane in the hypersthene structure and are referred to as ~~remnant~~^{relict} (001)- augite exsolution lamellae (Plates XIV, Fig. B and XVI, Fig. A).

(100)- augite exsolution lamellae in orthopyroxene: On slow cooling hypersthene (inverted pigeonite) and bronzite both exsolve narrow, closely spaced (100)- augite exsolution lamellae (Poldervaart and Hess, 1951, pp. 481-482). In some hypersthene these lamellae are thicker, wider spaced, less continuous and occasionally cross-cutting, and are referred to as (100)- augite exsolution lamellae of the extraordinary type (Plate XV, Fig. B).

(001)- hypersthene exsolution in augite: Above the pigeonite-orthopyroxene inversion curve, augite on slow cooling exsolves

relatively broad pigeonite exsolution lamellae parallel to the (001) plane (Poldervaart and Hess, 1951, p. 483). The a-, b-, and c- crystallographic axes of the exsolved pigeonite coincide with the same crystallographic axes in the host augite. The pigeonite on cooling may or may not invert to hypersthene. See Plates X, Fig. B and XVII, Fig. B.

(100)- exsolution in augite. At temperatures below the inversion curve augite on slow cooling will exsolve fine, closely spaced (100)- hypersthene lamellae (Poldervaart and Hess, 1951, p. 483). Thin sections, however, indicate that the material exsolved in the (100) plane of the augite is not simply hypersthene but perhaps orthopyroxene together with hematite (Plate XVII, Fig. B).

D. Layering and lamination.

Different types of layering occurring in the rocks investigated can be ascribed to the orientation of minerals, variations in the amount of the various constituents, the rather inconspicuous gradual variations in the chemical composition of the minerals from the base of the mafic rocks upwards in the sequence, and to rocks with different textures.

Igneous lamination is the pronounced parallelism caused essentially by tabular plagioclase and the long dimensions of ferromagnesian minerals orientated parallel to the plane of igneous lamination (Wager and Deer, 1939, pp. 37-38 and 271-273).

Rhythmic layering is the conspicuous banding solely due to changes in the relative proportions of the minerals, rhythmically repeated and constant over wide areas which gives layers forming almost plane surfaces (Wager and Deer, 1939, p. 37).

Cryptic layering is the inconspicuous and for the most part gradual change in composition of successive layers which is due to the changing composition of the minerals (Wager and

Deer, 1939, p. 37).

Large-scale textural layering is a term used to describe a sequence of rocks comprised of layers with different or specific textural features.

E. Grain Size

The terminology adopted for grain size as previously defined is based on Tyrrell's (1926, p. 83) classification which is as follows:

- fine-grained is less than 1 mm;
- medium-grained is from 1 to 5 mm;
- coarse-grained is more than 5 mm.

III. ZONES IN THE BOREHOLES CONTAINING SIMILAR ROCK TYPES

The rocks intersected in the boreholes may be described by referring them to several zones. Ten large-scale textural layers, referred to as zones, have been recognized on the basis of marker horizons each of which are characterized by certain specific or distinguishing^{textural} features (Plate III).

A. Melanic types

Mafic rocks of the melanic type were subdivided on the basis of distinct textural differences. The rocks mostly contain 30 to 90 per cent dark minerals, but some of the rocks of the leucocratic type that have the same texture as the rock of the melanic type are included in this section. The main textural varieties and the zones in which the melanic rock types occur are as follows:

1. Hypidiomorphic hyperite, norite, and gabbro

In hand specimens these rocks are generally hypidiomorphic and individual grains of plagioclase and bronzite can usually be quite readily distinguished. Igneous lamination is generally well developed in these rocks. Hypidiomorphic hyperite, norite, and gabbro occur mainly in Zones I, III, V, VII, and IX.

a. Zone I

This zone occurs between the bottom of the Merensky Reef and the bottom of the Bastard Reef. The thickness of this zone ranges from 33 to 63 feet (Plate III). In all three boreholes anorthosite (mottled or spotted) grades downwards into hyperite, eventually into pyroxene-rich hyperite and finally into pyroxene-rich porphyritic melanorite and bronzitite. In the porphyritic melanorite and bronzitite orthopyroxene is the primary precipitate, and in addition augite

and interstitial plagioclase, interprecipitate sulphides, and disseminated chromite occur. At the base of the Merensky Reef (porphyritic melanorite and bronzitite) there usually occurs a chromitite band 0.5 to 3 cm thick. A similar chromitite band, though much thinner and far less continuous, sometimes also occurs at the top of the Merensky Reef. From the base to the top of this zone in borehole TRF1 the composition of the plagioclase and orthopyroxene changes as follows: An_{73} to An_{79} and Of_{18} to Of_{31} (Plate IV). In the mottled anorthosite below the Bastard Reef in borehole TRF1 the composition of the plagioclase is An_{79} and the composition of the bronzite is Of_{29} , whereas in the Bastard Reef the composition of the plagioclase is An_{70} and the composition of the bronzite is Of_{17} . The grain size is generally fine to medium, but in the porphyritic melanorite and bronzitite the grain size is very coarse.

b. Zone III

The base of this zone is at the top of the mottled anorthosite of Zone II and the top of this zone is at the bottom of the zone containing subophitic hypidiomorphic hyperite. The thickness of this zone ranges from 1140 to 1842 feet (Plate III). Hyperite and norite are virtually the only rock types in this zone in the three borehole sections investigated. Bands of mottled and spotted anorthosite are not uncommon in borehole US13.

The three sudden changes in the mineral proportions occurring in this zone in borehole TRF1 (Plate IV) could not be correlated with sudden changes in the mineral proportions also occurring in this zone in the other two boreholes. With the exception of the lower portion, the composition curves for the plagioclase and the orthopyroxene show only slight variations in borehole TRF1 (Plate IV). The composition of the plagioclase ranges from An_{67} to An_{71} and orthopyroxene from Of_{23} to Of_{29} (Plate IV).

The grain size is essentially fine in boreholes TRF1 and AB1, but in borehole US13 the rock is mostly fine to medium

grained. Although, the orthopyroxene crystals are generally rather round, in some fine-grained hypidiomorphic norite, especially in borehole US13, the orthopyroxene is prismatic and has a length to breadth ratio of up to 10 : 1. The length of these orthopyroxene crystals lie with random orientation in the plane of igneous lamination. Since prismatic bronzite occurs only in fine-grained norite, relatively quick cooling was probably responsible for its formation.

Two ~~ratio~~-form contacts (Jackson, 1967, p. 22) occur at 2266 feet and 2407 feet in borehole US13. In both instances, as one approaches the contact from above, the grain size decreases and the rock contains more pyroxene. There then occurs what looks like shearing and one then passes into a band of fine-grained anorthosite 2.5 cm thick in which igneous lamination is very well developed. Below this occurs coarser-grained, altered leucohyperite, in which the pyroxenes have a dark green tinge, ~~a few centimetres thick~~. This altered rock then grades quickly into hyperite below.

Pyroxenite inclusions occur in the hyperite in borehole US13 at a depth of 2740 and 2750 feet. The hyperite in which the pyroxenite inclusions occur is more plagioclase rich than the hyperite occurring above and below the pyroxenite inclusions. In one pyroxenite inclusion the plagioclase is An_{60} and the bronzite is Of_{21} , whereas in the hyperite immediately above the inclusion the plagioclase is An_{72} and the bronzite Of_{24} . It is most probable that the pyroxenite inclusions occur in bands.

c. Zone V

This zone occurs between two markers, i.e., between the subophitic hypidiomorphic hyperite at the base and the zone containing mainly mottled anorthosite at the top (Zone VI). The thickness of this zone ranges from 487 to 623 feet (Plate III). The rock is almost entirely fine- to medium-grained hyperite, but minor bands of mottled anorthosite occur in boreholes TRF1 and US13. The curves drawn for the volumetric mineral ^{ogical} compositions and the compositions of the plagioclase

and orthopyroxene in borehole TRF1 indicate only minor variations (Plate IV). The plagioclase ranges from An₆₇ to An₇₂ and the orthopyroxene ranges from Of₂₆ to Of₃₀ (Plate IV).

A Pilanesberg nepheline syenite dyke was intersected in borehole KLG2 at a depth of 4449 to 4617 feet. The dyke rock is of no significance as far as the mafic rocks of the Bushveld Complex are concerned, but the rock immediately in contact with the dyke seems to be of interest, since it is somewhat anorthositic for a few inches and then grades quickly into hyperite.

d. Zone VII

This zone occurs between two markers, i.e., between the zone containing mainly mottled anorthosite (Zone VI) at the base and ophitic to nesophitic hypidiomorphic hyperite at the top. Borehole US13 starts in this zone. In boreholes TRF1 and AB1 this zone is 789 and 1046 feet thick respectively. Hypidiomorphic hyperite and norite are by far the most common rock types, but some narrow bands of mottled anorthosite also occur. The curves drawn for the volumetric mineral^{ogical} composition and the composition curves drawn for the plagioclase and orthopyroxene in borehole TRF1 indicate some sharp variations at a depth of 1468 and 1533 feet (Plate IV). The composition of the plagioclase ranges from An₆₅ to An₇₀ and the orthopyroxene ranges from Of₂₇ to Of₃₅ (Plate IV). The grain size is fine to medium. Generally the plagioclase in the hyperite in all the zones is greyish white in colour, but in the middle of Zone VII in borehole AB1 several hyperite bands occur in which the plagioclase is greyish white with a pink tinge.

e. Zone IX

This zone occurs between two markers that are megascopically rather similar. In borehole KLG2 this zone stretches from about 2000 to 2378 feet. Only the lower 60 feet of this zone was available from borehole AB1. Hyperite and leucohyperite are the commonest rock types in borehole KLG2 (Plate IV) and in addition a number of mottled anorthosite bands occur.

The composition of the plagioclase ranges from An₆₇ to An₇₅ and the orthopyroxene ranges from Of₂₇ to Of₂₉ (Plate IV). The grain size is fine to medium. Two types of hyperite with different textures occur in this zone. In the upper portion, i.e., from 2000 to 2200 feet the rock is inequigranular and the pyroxene especially the bronzite is much coarser than the plagioclase. In the lower portion, i.e., from 2200 to 2378 feet the rock is equigranular.

A ratio-form contact occurs in borehole KLG2 at 2272 feet (Plate IV). The same contact was also intersected at the same horizon in borehole TRF1. The core obtained from boreholes AB1 and US13 is below this zone and consequently, it is not known if this contact is confined to the Rustenburg district or not. As the ratio-form contact is approached from above the rock contains more pyroxene, but there is no decrease in grain size as in the other two instances in Zone III in borehole US13. At the contact possible shearing occurs, and below this the rock is anorthositic for a few inches with some dark-green pyroxenes. In the hyperite that contains more pyroxene the orthopyroxene is more magnesium-rich and the plagioclase is more calcium-rich than in the rocks immediately above and below.

The rocks in the lower 60 feet of Zone IX in borehole AB1 have a rather different texture to the rocks in the lower portion of this zone in borehole KLG2. Bands of fine- and medium-grained hyperite, a band of mottled anorthosite and a band of subophitic hypidiomorphic hyperite occur. In addition an extraordinary hyperite occurs in which bands of fine-grained hyperite alternates with bands of medium-grained hyperite. These bands range in thickness from 0.2 to 2 cm.

2. Synophitic hyperite and norite

In hand specimens these rocks are almost indistinguishable from the ophitic to nesophitic hypidiomorphic hyperite described in the next section. Close inspection reveals that the orthopyroxene has the same optical orientation over relatively large

areas. The rock is homogeneous and all the minerals are more or less evenly distributed. The orthopyroxene and clinopyroxene are not concentrated in specific areas as in the ophitic to nesophitic hypidiomorphic hyperite. If the orthopyroxene has the same orientation over about 5 cm or more, one can be reasonably certain that the rock is synophitic hyperite or norite.

The study of synophitic hyperite and norite was based on core obtained from Zone X in borehole KLG2 occurring at a depth of 79 to 2000 feet and on hand specimens from Brits and Bon Accord Quarry. Since no other core that intersects this zone was available no further division was possible. The actual thickness of this zone is not known, because borehole KLG2 starts in this zone. Synophitic hyperite and norite are virtually the only rock types in this zone. The composition of the plagioclase ranges from An₆₄ to An₆₉ and the hypersthene ranges from Of₃₀ to Of₃₅ in Zone X (Plate IV). A reliable grain size determination of the rock could not be made. Fine-grained synophitic hyperite at 686 to 820 feet in borehole KLG2 has given rise to three subzones of Zone X in each of which the rock has some distinct characteristics. The base of Zone X is taken where the orthopyroxene shows no sign of representing inverted pigeonite, i.e., where the Of content falls below 30 per cent. The curves drawn for the volumetric mineral^{ogical} composition and the composition of the plagioclase and hypersthene show only minor variations (Plate IV). However, a sudden change in the uniformity of the mineral proportions occurs at the base of the fine-grained synophitic hyperite at 820 feet (Plate IV).

3. Ophitic to nesophitic hypidiomorphic hyperite

In hand specimen the ophitic to nesophitic hypidiomorphic hyperite is virtually indistinguishable from the synophitic hyperite and norite. Close inspection reveals that individual pyroxene crystals are not well defined. The orthopyroxene has

the same orientation over areas of up to 3 cm in diameter. Thin sections, however, show that the texture is quite different from that of the synophitic hyperite and norite.

Ophitic to nesophitic hypidiomorphic hyperite occurs in Zone VIII in boreholes KLG2, TRF1, and ABl (Plate III). At the upper contact mottled anorthosite occurs and at the base the rock grades into hypidiomorphic hyperite. Borehole US13 was drilled below this zone. It is thus uncertain whether these rocks also occur as a layer in the eastern sector of the Bushveld Complex. The thickness of this zone is at least 300 feet. Some uncertainty exists regarding the lower contact of this zone in borehole ABl, since samples were taken too far apart. The ⁷ curves drawn for the volumetric mineral ^{ogical} compositions ^{show} vary considerably ^{variation} because the rock is rather inequigranular and point-counts obtained from thin sections do not give reliable percentages for the rock as a whole. The composition of the plagioclase ranges from An₆₅ to An₆₆ and the composition of the bronzite is Of₂₃. The grain size is fine to medium.

At a depth of 2510 feet in borehole KLG2 and at a depth of 680 feet in borehole TRF1, in both cases more or less in the middle of Zone VIII, occurs a band of hyperite at the base of which is a ratio-form contact and an anorthosite band which is 0.5 cm thick. The hyperite immediately above the anorthosite band is distinct because the areas in which orthopyroxene occurs has ophitic texture. These orthopyroxenes are particularly prominent because they are surrounded by a narrow plagioclase-rich rim which becomes megascopically less prominent upwards over a distance of 3 feet. It is not known why this ratio-form contact occurs in the middle of a zone of rock with the same texture. Boreholes KLG2 and TRF1 have been joined up at the thin anorthosite band. This thin marker band has not been observed in borehole ABl.

4. Subophitic hypidiomorphic hyperite

In hand specimen brown spots of phenocrystic bronzite, each

surrounded by a plagioclase-rich zone, are evenly distributed in the rock. The rock is fine to medium grained and contains bronzite which is about 0.5 cm in diameter with an average spacing of 0.5 to 0.75 cm. Close examination of a hand specimen reveals that small relatively inconspicuous augite occurs concentrated between the phenocrystic bronzite with plagioclase-rich areas. Igneous lamination is not conspicuous.

Subophitic hypidiomorphic hyperite is particularly well developed in Zone IV in all the boreholes investigated and in a thin band in borehole ABL in Zone IX. Subophitic hypidiomorphic hyperite does not occur in Zone IX in borehole KLG2. The importance as a marker of the thin band in Zone IX is therefore rather limited. The thickness of Zone IV is very variable (Plate III). Some subophitic hypidiomorphic hyperite grades over tens of feet into hypidiomorphic hyperite without subophitic patches. In borehole US13 this zone is divided in two between 1724 and 1784 feet by a band of hypidiomorphic hyperite with gradational contacts. The volumetric mineral^{og'ca.} composition and the composition of the plagioclase and orthopyroxene in the subophitic hyperite in borehole TRF1 fall well in line with similar compositions of the hypidiomorphic hyperite above and below Zone IV (Plate IV). The composition of the plagioclase and orthopyroxene is An₆₈ and Of₂₇ respectively.

B. Leucocratic types

Rocks of the leucocratic type have been subdivided on the basis of distinct textural and structural differences. The rocks contain 70 to 100 per cent of plagioclase and 0 to 30 per cent of pyroxene. The following rocks have been distinguished: mottled anorthosite and mottled leucohyperite, spotted anorthosite and spotted leuconorite, and anorthosite. Since, these rocks occur closely associated with one another, it is best to describe them first and then to refer to Zones II and VI in which

they occur most commonly.

1. Anorthosites

a. Mottled anorthosite and mottled leucohyperite

In hand specimen mottles of dark pyroxene are more or less evenly spaced in the anorthosite. The diameter of the round mottles ranges from 0.5 to 4.0 cm. The spacing of the mottles varies from about 1.0 to 5.0 cm. Mottled anorthosite and mottled leucohyperite often occur associated with spotted anorthosite and spotted leuconorite. Most mottled anorthosite and mottled leucohyperite contain hypersthene. The plagioclase, occurring between the pyroxene areas, in the hypersthene-bearing mottled anorthosite and mottled leucohyperite is greyish white and the mottles are not always clearly defined. However, in the bron-zite-bearing mottled anorthosite and mottled leucohyperite the plagioclase occurs between well defined pyroxene areas and is yellowish grey.

b. Spotted anorthosite and spotted leuconorite

In these rocks spots of dark minerals (mostly orthopyroxene) 1 to 3 mm in diameter are evenly distributed in a plagioclase matrix. The spacing of the spots seems to vary considerably for different horizons.

c. Anorthosite

The anorthosite is light grey in hand specimen and seems to consist only of plagioclase. Igneous lamination is sometimes well developed in these rocks. The anorthosite is usually rather rare and mostly occurs in bands less than one foot in thickness. The rock may occur associated with the mottled anorthosite and mottled leucohyperite and with the hypidiomorphic hyperite.

d. Zones containing mainly mottled anorthosite and mottled leucohyperite

Zones II and VI contain mainly mottled anorthosite and mottled leucohyperite, some spotted anorthosite and spotted leuconorite, some hypidiomorphic hyperite, and occasional anorthosite

bands.

(i) Zone II

The lower contact of this zone is at the bottom of the Bastard Reef and the upper margin is at the top of the mottled anorthosite occurring immediately above the Bastard Reef. The thickness of this zone ranges from 208 to 224 feet (Plate III). The most common rock types are fine- to medium-grained hypersthene- and bronzite-bearing mottled anorthosite and mottled leucohyperite. The Bastard Reef makes up only a small fraction of the total thickness at the base and is somewhat similar to the pyroxene-rich hyperite above the Merensky Reef. In the upper hypersthene-bearing mottled anorthosite and mottled leucohyperite the plagioclase is greyish white and the mottles are relatively indistinct, whereas in the lower bronzite-bearing mottled anorthosite and mottled leucohyperite the plagioclase is yellowish white and the mottles are very clearly defined. Since these two mottled anorthosite and mottled leucohyperite layers are so distinctive, they are used as markers for locating the Merensky Reef.

The ~~curves drawn for the~~ volumetric mineral ^{ogical} compositions ~~of the rock~~ ^{ics} vary considerably, because the rock is non-homogeneous for the small area covered by a thin section, with the result that point-counts obtained from thin sections do not give reliable percentages for the rock as a whole. The ~~curves drawn for the~~ composition of the plagioclase and orthopyroxene ^{is} ~~are~~ also highly variable. In Zone II the anorthite content of the plagioclase decreases markedly from the base upwards. In borehole AD1 and US13 the change is somewhat gradational, but in borehole TTF1 there is an anorthite decrease in the plagioclase of more than 10 per cent within a few feet (Plate IV).

The difference in colour of the upper and lower mottled anorthosite and mottled leucohyperite in Zone II in borehole TTF1 is probably due to the difference in the chemical composition of the plagioclase which is An_{72} and An_{81} respectively. Similarly the orthopyroxene increases in iron content upwards.

There is a very sudden enrichment in iron shown by the change in composition of the orthopyroxene from Of_{17} to Of_{33} (Plate IV).

A single pyroxenite inclusion more or less 2.5 cm in diameter was so intersected in borehole US13 (at a depth of 3110 feet) that only part of it occurs on one side of the core. The texture of the hyperite does not change at this inclusion nor below it.

(ii) Zone VI

This zone is an excellent marker and ranges in thickness from 313 to 389 feet (Plate III). Mottled anorthosite and mottled leucohyperite, hyperite, and spotted anorthosite and spotted leuconorite are the commonest rocks. The rocks are fine to medium grained. Individual bands of rock in this zone cannot be correlated directly with those in the other boreholes. There seems to be the tendency in all three boreholes for a band of mottled anorthosite, more or less 100 feet thick, to occur at the top and a similar band of mottled anorthosite and mottled leucohyperite, perhaps a little thinner, at the base. Between these two bands several rock types such as hypidiomorphic hyperite, mottled anorthosite and mottled leucohyperite, spotted anorthosite and spotted leuconorite, and leucohyperite occur. The mottled anorthosite and mottled leucohyperite all contain hypersthene. The plagioclase between the pyroxene mottles is greyish white. The curves drawn for the volumetric mineralogical compositions vary considerably in Zone VI in borehole TRF1 (Plate IV). These variations are mainly due to alternating bands of different rock types and due to the small area covered by thin sections, particularly in rock containing mottles. The composition of the plagioclase ranges from An_{66} to An_{74} and the orthopyroxene ranges from Of_{27} to Of_{45} (Plate IV).

2. Leucohyperite

Leucohyperite has a mineral composition which falls between anorthosite and hyperite. In hand specimen the leucohyperite is sometimes indistinguishable from hypidiomorphic hyperite, norite, and gabbro. In the leucohyperite there often

occur spots of pyroxene up to 6 mm in diameter which are relatively closely spaced in an anorthosite matrix. The effect of spotting is, however, less distinct than in the spotted anorthosite and spotted leuconorite. Rocks of this type are well developed in Zone IX in borehole KLG2.

IV. IGNEOUS LAYERING

A. Observations

The various types of layering occurring in the rocks studied can be ascribed to the orientation of the minerals, variation in the grain size, inconspicuous gradual variations in the chemical composition from the bottom to the top, variation in the amounts of minerals present, and variation in the texture. Some of these variations have already been described.

1. Igneous lamination

Most hand specimens obtained from the mafic rocks of the Bushveld Complex which contain plagioclase laths display igneous lamination (Wager and Deer, 1939, pp. 37-38 and 271-273). Some of the ferromagnesian minerals have their long axis in the plane of igneous lamination. However, the igneous lamination is not always equally well developed in all these rocks. Van den Berg (1946, p. 175) noted that the plagioclase is flattened parallel to the (010) plane and that nearly 70 per cent of all the plagioclase laths have this plane parallel or approximately parallel to the plane of igneous lamination.

2. Rhythmic and cryptic layering

Perhaps the most ideal rhythmic layering occurs in Zone I (p. 10) and in Zone II (p. 19) where in each zone pyroxene-rich rock grades upwards into anorthositic rocks. Such well developed rhythmic repetitions as in Zones I and II have not been observed in the borehole core above Zone II. In some instances the hyperite may be homogeneous over hundreds of feet and show no visible changes in the volumetric mineral^{ogical} composition. In other instances pyroxene-rich hypidiomorphic hyperite may occur

over a few feet and then grade upwards into hypidiomorphic hyperite. The lower contact in such instances may be sharp or gradational. Ratio-form contacts occur in Zones III and IX. Mottled anorthosite and mottled leucohyperite, and spotted anorthosite and spotted leuconorite are often interlayered with hypidiomorphic hyperite, norite, and gabbro. Thick layers of mottled anorthosite and mottled leucohyperite, and spotted anorthosite and spotted leuconorite tend to be confined to certain zones in the boreholes investigated, yet some of these rocks, occurring in thin bands up to 20 feet thick, may occur interlayered in hypidiomorphic hyperite. The contact between mottled anorthosite and hyperite is usually quite sharp, but often the one grades into the other. In the mottled anorthosite and mottled leucohyperite, and the spotted anorthosite and spotted leuconorite the bottom or upper contacts or both may be gradational or sharp. The orthopyroxene occurring in the rocks immediately above the mottled anorthosite and mottled leucohyperite may have the same composition, ^{or may} be more magnesium-rich or more iron-rich than in the mottled anorthosite and mottled leucohyperite below.

Numerous reversals or sudden changes tend somewhat to obliterate the gradual changes in the curves of the volumetric mineralogical composition, the Pr values, and the composition of the plagioclase and orthopyroxene (Plate IV). The iron enrichment in the orthopyroxene and the sodium enrichment in the plagioclase is evident upwards in the sequence of rocks (Plate V). The amount of clinopyroxene increases upwards. The orthopyroxene at first decreases upwards, but then increases again. The plagioclase content does not vary much upwards at first, but in the upper third it decreases. The Pr value rises in the lower third as a result of the decrease in the clinopyroxene content and an increase in the orthopyroxene content.

The curves drawn for the composition of the plagioclase and orthopyroxene (Plate IV) fall closer together in the hyperite than in the mottled anorthosite and mottled leucohyperite. In

the hyperite more iron-rich orthopyroxene tends to occur together with plagioclase that is less calcic than in the case of the hyperite containing less iron-rich orthopyroxene. In the mottled anorthosite more iron-rich interprecipitate orthopyroxene occurs together with more calcic plagioclase than in the hyperite. The reason for the variation of the composition of the plagioclase and orthopyroxene seems to be that in the mottled anorthosite and mottled leucohyperite cotectic crystallization took place during the late stage of crystallization, whereas in the hyperite cotectic crystallization most probably began early in the history of crystallization.

B. Discussion

1. Igneous lamination

Igneous lamination is believed by Wager (1968, pp. 613-614) to have been formed as a result of crystals settling under the action of gravity. Hess (1960, pp. 139-144) indicates that the settling rate of early-formed crystals was very slow. Van den Berg (1946, p. 199) points out that in the mafic rock with igneous lamination the crystals probably sank with their smallest faces perpendicular to the direction of sinking, so as to ensure the minimum resistance. As soon as they were arrested, however, they are regarded to have assumed the present orientation, which would be one of maximum stability. Wager and Deer (1939, pp. 271-272) assume igneous lamination to be a structure which could not have developed without flow of the magma. They believe that rough orientation of the long directions of the tablets developed parallel to the direction of flow of the magma. If flow of magma was responsible for the texture of igneous lamination, as suggested by Wager and Deer, one would expect the long axes of the prismatic bronzite in Zone III in borehole US13 (p. 12) to have a linear arrangement in the plane of igneous lamination. Since

this is not so, flow of magma is here not considered essential for the formation of igneous lamination. Van den Berg (1946, p. 155) found that the plagioclase and orthopyroxene of the gabbro studied by him lie in the plane of igneous lamination, and that the longest axes of these crystals have random orientation in this plane. Hess (1960, p. 127) also comes to the conclusion that no horizontally moving currents were present in most places, at least within a few feet above the "floor" of the magma body in the Stillwater Igneous Complex.

2. Cryptic layering

The gradual systematic changes in the chemical composition of the plagioclase and orthopyroxene and the general variations in the volumetric mineral^{ogical} compositions of the ~~three main mineral~~^{rock} ~~als~~ could only have developed in one of two ways:

a. Wagner (1929, pp. 43-47) and Hall (1932, pp. 278-283) suggest that tholeiitic basaltic magma was emplaced as one heave which underwent differentiation in situ under the dominating, but not exclusive, influence of gravity.

b. Lombaard (1932, pp. 171-172 and 1934, p. 52) suggests that supplies of magma which were continuously changing in composition were emplaced at intervals. The magma was generated by refusion of the crystalline products in the same order, as they were formed in the intra- or sub-crustal reservoir. In the order in which the magmas were generated, they were emplaced by successive heaves which normally came to rest upon the previous emplacements. Each heave of magma then followed at short intervals close upon the preceding one when the latter was still liquid or at much longer intervals after the preceding supply had already consolidated. Further differentiation then took place in situ by the gravitational accumulation of crystals, with the result that pyroxenites, hyperites, and anorthosites were formed.

~~3. Ratio form contacts and pyroxenite inclusions~~

3. Ratio-form contacts and pyroxenite inclusions

The anorthositic rock on both sides of the Pilanesberg dyke intersected in borehole KLG2 was probably formed as a result of the alteration of the hyperite perhaps caused by reheating. The narrow bands of anorthositic rock on both sides of the Pilanesberg dyke seems to be closely related to the anorthositic rock with dark-green pyroxene occurring just below the ratio-form contacts described in Zones III and IX. The anorthosites with some dark-green pyroxenes overlain by pyroxene-rich hyperite were probably formed by the emplacement of magma that was relatively hotter than the crystalline rock below, resulting in reheating and alteration of the hyperite. If these contacts were formed as a result of intrusion of magma into relatively cool hyperite one would expect to find, in addition to fine-grained contact rocks due to chilling, anorthosites with dark-green pyroxene on both sides of such an intrusion as occurs on both sides of the Pilanesberg dyke. Since, however, contacts of the type described occur only at the base of a layer of rock, intrusion of different magma with different chemical composition resulting in the formation of different rock types as envisaged by Reuning (cited by Van Zyl, 1960, p. 87), Schwellnus (1956, pp. 169-171), and Coertze (1958, p. 387) cannot be held responsible for the emplacement of the various rock types investigated in the boreholes.

In the case of the two bands of hyperite containing pyroxenite inclusions in Zone III in borehole US13 the nearest pyroxenite layer, from which the pyroxenite inclusions could have been derived, is the Bastard Reef which occurs 550 feet below these two bands. These inclusions were probably brought up by heaves of magma.

Ferguson and Botha (1963, pp. 267-268) do not exclude the possibility that pegmatitic pyroxenite inclusions in the "boulder anorthosite" 110 feet below the Merensky Reef have grown in situ as a result of diffusion or secretion. It is, however, rather extraordinary that the boulders in the "boulder anorthosite" all tend to have the same size and that they are all pegmatitic.

Hess (1960, p. 149) believes that pyroxene with a mean radius of 1 mm would settle in a magma with a viscosity 3000 poises at a rate of 160 m per year. A spherical mass of magma 0.006 gm/cc denser than the surrounding magma and 1 m in radius would settle at a rate 10,000 times as fast, once it reached terminal velocity (5 cm/sec.). The quicker settling rate of pyroxenite inclusions is illustrated by the fact that they occur in bands and not evenly distributed throughout the mafic rocks. As a result of the quicker settling rate of the pyroxenite inclusions, it may perhaps be safely assumed that any pyroxenite inclusion say more than 3 cm in diameter has come to rest more or less on the "floor" that existed at the time when such an inclusion was brought up by a heave of magma.

Inclusions were probably only formed when the channels of the previously emplaced magma were closed, most probably as a result of crystallization of the magma in such channels. Thus a new pulse of magma probably forced its way through the already consolidated floor of the basal portion, and in the process broke loose smaller and larger fragments or blocks from the wall rock. Thus the pyroxenite inclusions were probably formed during the early period of emplacement. The pyroxenite inclusions in the "tennis ball" marker described by Von Gruenewaldt (1966, pp. 54-57) could not all have been emplaced at once, otherwise they should occur only as closely packed inclusions in a layer. It seems that once the new channel was completely established virtually no wall rock was further derived from the channel and as a result no further inclusions were formed. The speed of flow of the new magma in a vertical direction, must have been faster than the settling rate of the inclusions, but as soon as the magma began to flow parallel to the layering, it could no longer hold the inclusions in suspension, and they immediately began to settle out. Under the conditions described the largest inclusions should settle out first and further away from the point of emanation progressively smaller

inclusions should settle out.

The rounding of the pyroxenite inclusions may have taken place as a result of mechanical abrasion against the wall rock of the fissure or pipe through which they passed. If the anorthite content of the plagioclase in the pyroxenite inclusion is always much lower, as was found in one instance, then the plagioclase occurring interstitially between the grains of orthopyroxene could have been melted completely, particularly near the margin, and the grains of orthopyroxene could have become detached from the pyroxenite inclusion. In the angular portions of the pyroxenite inclusions the detachment of the orthopyroxene was probably more easily accomplished thus resulting in the rounding of the pyroxenite inclusions.

Pyroxenite inclusions and some ratio-form contacts seem to show beyond doubt that new pulses of magma were emplaced. Since no inclusions were intersected at the ratio contacts, it is evident that not all the new heaves of magma carried inclusions, at least not sufficient to form bands, or else the temperature of some heaves of magma was initially much higher than in the case of others and any inclusions that existed were then probably melted and assimilated. If the inclusion in Zone II borehole KLG2 (p. 20) had not been intersected there would have been no indication that new magma was emplaced. Thus there may be good evidence indicating the emplacement of a new heave of magma, or there may be no indication whatsoever.

The hyperite investigated in which the pyroxenite inclusions occur and the hyperite at some ratio-form contacts show no sign of chilling. No chilling of newly emplaced magma at its basal contact could have resulted from newly emplaced, superheated magma which partly melted the "floor" rock, magma emplaced on rock which was still very hot, or from magma which mixed completely with the rest liquid of the previous emplacement.

At some ratio-form contacts, such as at the base of the Bastard Reef, and the ratio-form contact more or less in the

middle of Zone IX in borehole KLG2, the newly emplaced magma gave rise to more magnesium-rich orthopyroxene than had crystallized from the rest liquid of the previous emplacement. This does however not necessarily mean ~~to say~~ that the chemical composition of the newly emplaced magma had changed, since the previous magma may already have undergone fractional crystallization before the new heave of magma was emplaced.

Although there is sufficient evidence suggesting that heaves of magma were emplaced at intervals on top of the previously partly or completely crystalline magma emplacements in the three borehole sections investigated, it could not be determined from these three borehole sections, whether the heaves of magma, which were emplaced at intervals on top of one another, changed systematically in chemical composition or not.

Transgression of a new heave of magma suggests that the previous heave of magma must have crystallized completely so that no plane of least resistance existed along which new magma could be emplaced. Schwellnus (1956, p. 140) describes transgression of gabbro downwards through norite, anorthosite, pyroxenite, and eventually the gabbro even transgresses downwards through Magaliesberg quartzite. Coertze (1958, p. 390) and Coertze and Schumann (1962, p. 1) describe ferrogabbro north of Pilanesberg which transgresses from the top of the basic rocks to their base in two localities. Such transgressions as described by these authors could only have taken place if the previous emplacement was fully crystalline. The composition of the gabbros is different from the rocks occurring below, but the composition falls well in line with the progressive compositional changes occurring in the mafic portion of the Bushveld Complex. Therefore heaves of magma emplaced at intervals probably changed more or less systematically in chemical composition.

Since it was possible to divide the rocks obtained from the four borehole sections into zones which can be correlated with one another, it is evident that the rocks in the western and

eastern mafic portions of the Bushveld Complex were formed under virtually the same conditions and from similar magmas. Although gravity anomalies suggest that the western and eastern sectors of the mafic rocks are separate igneous bodies (Cousins, 1959, pp. 182-185), it is somewhat problematic how the close analogy existing between the rocks of the zones described could have developed in two separate igneous bodies. It is, therefore, more likely that the mafic rocks of the western and eastern portions of the Bushveld Complex are cone sheets as suggested by Willemsse (1964, p. 113). Since one can correlate the rocks in the two portions, it seems likely that the large-scale textural layers are continuous and crystallized more or less at the same time under somewhat similar physical conditions from the same interconnected emplacements of magma.

4. Rhythmic layering.

Most rhythmic variations, such as the occurrence of bands of mottled anorthosite and mottled leucohyperite, and spotted anorthosite and spotted leuconorite in hypidiomorphic hyperite; some gradations of pyroxene-rich rock upwards into normal hypidiomorphic hyperite; and some well defined changes in the mineral content of the rock were probably not only due to the emplacement of new magma coupled with differentiation in place. Van Zyl (1959, pp. 24-26) sums up most of the existing hypotheses on the formation of rhythmic layering and suggests his own hypothesis. In addition to Van Zyl's summary of the existing hypotheses some other hypotheses have been summarized.

Coates (cited by Van Zyl, 1959, pp. 24-25) envisages the following: If two kinds of crystals form simultaneously, both will settle towards the bottom, and under suitable conditions the sinking of the heavier ones will tend to displace the adjacent fluid upwards. The viscosity of the liquid and the slow rate of settling of the lighter crystals, cause these crystals to be displaced upwards, and a layer rich in this

mineral is formed. There is thus a partial separation of the light and heavy minerals. When the lighter layer becomes sufficiently thick it is able to support the newly formed heavy crystals and a repetition of the process takes place.

Hess (cited by Van Zyl, 1959, p. 25) offers a solution which depends upon magma-chamber conditions similar to those suggested by Coates, but in which the state of quiescence in the magma is periodically disturbed by short spells of mild and irregular turbulence, resulting in temporary delays in the sinking of the lighter crystals.

Van Zyl (1950, p. 72) suggests that the specific gravity of the magma lies between those of the femic and salic minerals crystallizing from it. The femic minerals, having a higher density than the magma, would tend to sink, and the salic minerals which may have a density less than that of the magma, would tend to rise. However, Hess (1960, p. 139) estimates that the density of the magma in the Stillwater Igneous Complex was lower than that of the crystals which crystallized from it. Van Zyl states: "If the magma is relatively viscous, the crystals numerous and the rate of movement slow, it may be visualized that the crystals would mutually interfere with each other in the process of moving up and down respectively. In this manner certain planes of relative stagnancy may arise through mutual interference, forming a network of crystals, partly impenetrable to crystals moving vertically. At this stage there is a very delicate balance which may be easily disturbed by magma flow. However, salic constituents continuing to accumulate from below and femic being continuously added from above would serve to stabilize such a zone and would form a dark band above and a light one below the initial zone of relative impermeability. Then between any two such stabilized zones the process may be repeated...."

Daly (1933, p. 354) postulates a slow basining of the floor of the chamber as a cause of rhythmic layering. The basining would have the effect of oscillating the temperature and pressure

in the magma chamber, resulting in successive showers of crystals. A variable inflow or escape of magma or fugitive constituents would have a similar effect. As a result of the occurrence of a large number of rhythmic layers, it is highly unlikely that each rhythmic unit could coincide with basining.

Wager and Deer (1939, p. 272) ascribe the near-perfect banding of the layered series of the Skaergaard Intrusion to a rhythmic variation in the velocity of currents, primarily of convection. Strong streams would maintain the light crystals in suspension, whereafter a reduction of flow would lead to a shower very rich in these minerals.

It has been suggested by Yoder (cited by Brown, 1956, p. 48), on the basis of experimental work on the system diopside-anorthite-water, that the rhythmic layering of basic layered intrusions such as the Stillwater or Bushveld Complexes might be explained solely on the basis of variation in water vapour pressure within the cooling magma over a critical range, allowing alternatively a pyroxene or a plagioclase to crystallize and settle out.

Van Zyl (1959, p. 27) suggests that, if metastable conditions as a result of undercooling were to ^{alternate} ~~intervene~~ periodically or rhythmically with stable conditions, there would be repeated periods of no crystallization followed by rapid generations of crystals. Under these circumstances it is possible to have crystals arriving at the base of an intrusion due to repeated generations of crystals of one mineral only; due to repeated generations of crystals of more than one mineral simultaneously so that a banded structure could be formed as a result of the differential rates of sinking of light and heavy minerals; or due to alternating generations of crystals, first of one and then another mineral so that a banded structure would arise regardless of the rate of sinking.

Wager (1959, pp. 75-79) suggests a process rather similar to that of Van Zyl (1959) in that primary precipitate crystals

in the rhythmic units were due to their respective powers of nucleation and that crystallization had taken place from a somewhat supercooled single magma intrusion. On slow cooling supersaturation with metastable conditions is believed to alternate with equilibrium conditions. Different powers of nucleation combined with irregularities in cooling resulting from convection are considered by Wager to be responsible for the variety in the crystal accumulates of layered intrusions.

Hawkes (1967, p. 474 and Fig. I) points out that in the system diopside-albite-anorthite there occurs below the liquidus surface, a surface on which abundant crystal nucleation takes place on undercooling. The distance of the sub-liquidus surface below the liquidus will vary for each mineral. In the example which Hawkes discusses, it is assumed that the distance is less for diopside than for plagioclase. The boundary curve or cotectic curve is as a result displaced from the equilibrium cotectic towards the field of plagioclase. If a liquid at the cotectic is undercooled, the liquid will fall vertically below the cotectic onto the sub-liquidus curve where diopside will separate under labile conditions. Because of the separation of diopside the liquid will move towards the sub-liquidus surface for plagioclase. At the sub-liquidus surface for plagioclase diopside will be joined by labile plagioclase. The liquid will then move almost vertically towards the plagioclase liquidus. The heat of crystallization will cause the liquid to become unsaturated with respect to diopside, and plagioclase will crystallize alone. In most cases it is probable that the latent heat will be sufficient to raise the temperature to the original equilibrium value, and as a result the liquid will emerge on the plagioclase liquidus and will move to the cotectic trough at a point below the original temperature. The cycle of undercooling and delayed nucleation may then be repeated.

It is not possible to decide with any certainty which process or processes were the most significant in bringing about the formation of rhythmic layering.

V. TEXTURE, MINERALOGY, AND PETROGRAPHY

The texture, mineralogy, and petrography of the rocks investigated will be discussed in the same order in which the rocks have already been described.

A. Melanic types

Four rock types have been distinguished on the basis of distinct textural differences.

1. Hypidiomorphic hyperite, norite, and gabbro

In the hypidiomorphic hyperite, norite, and gabbro the plagioclase occurs as laths, whereas the bronzite and the augite occur mostly as more or less equidimensional grains with elongation parallel to the c-axis. The three main minerals in the rock are generally equigranular (Plate VI, Fig. A) or may be seriate especially in the case of the plagioclase. The grain size of the rock ranges from 0.5 to 1.5 mm.

A wavy boundary very often separates the plagioclase from the pyroxene. Inclusions of one mineral may occur in any of the other two major minerals. Somewhat phenocrystic bronzite may enclose plagioclase partly or completely. In some instances augite is somewhat interstitial to plagioclase and bronzite and may even form a margin partly enclosing the latter two minerals. Bent plagioclase and bent bronzite are not uncommon. Very rarely plagioclase and quartz form a myrmekite type of intergrowth.

The volumetric mineral^{ogical} composition of some of these hypidiomorphic rocks is given in Table I. The composition of the plagioclase in the hypidiomorphic rock in boreholes KLC2 and TRF1 ranges from An₆₅ to An₇₃ and that of the bronzite from Of₂₃ to Of₃₀.

TABLE I

Volumetric mineral^{ogical} composition of hypidiomorphic hyperite, norite, and gabbro.

Borehole number	Specimen number	Depth in feet	Plagio- clase	Bronzite	Augite	Accessories
KLG2	M94	2192	69.1	0.4	30.3	0.2
TRF1	M305	1275	83.2	7.6	9.1	1.1
TRF1	M336	1507	62.2	28.1	7.9	1.8
TRF1	M359	1649	72.8	15.8	10.3	1.1
TRF1	M442	2186	66.1	28.0	5.5	0.4
TRF1	M447	2294	70.1	24.2	5.2	0.5
TRF1	M494	2738	64.5	24.9	9.3	1.3
TRF1	M534	3223	63.5	30.2	5.9	0.4
TRF1	M583	3496	40.7	52.6	6.1	0.6
TRF1	M628	3702	71.3	21.0	7.6	0.1
Average			66	23	10	1

Interstitial magnetite is quite common and strongly pleochroic biotite is often associated with it. Magnetite was probably one of the last minerals to have crystallized from the magma. Strongly pleochroic biotite associated with the magnetite replaces plagioclase and pyroxene and was therefore probably formed after the magma had completely crystallized.

In the hypidiomorphic rocks the three main minerals crystallized cotectically to form an adcumulate (Wager, Brown, and Wadsworth, 1960, pp. 77-78).

2. Synophitic hyperite and norite

In the synophitic hyperite and norite the most significant feature is that large numbers of hypersthene "grains" have virtually the same optical orientation over large areas (Plate VI, Fig. B). This feature was also observed by Lombaard (1934, p. 26), Nel (1940, pp. 54-55), Van den Berg (1946, p. 163), Raal (1965, pp. 15-17) and Von Gruenewaldt (1966, pp. 81-88). Raal found that the hypersthene belonging to one cluster with

closely aligned optical orientation consists of individual "grains" which did originally not form part of a large crystal. Such hypersthene "grains" may merge directly into one another; they may be connected by hypersthene stringers; or else there may be no direct observable connection. The clusters of hypersthene "grains" with similar optical orientation have given rise to the synophitic texture. The size of the hypersthene clusters varies considerably and ranges from about 2 mm in diameter to diameters far greater than the area covered by a single thin section. In one thin section the hypersthene has virtually the same optical orientation over an area of 5.5 by 4.0 cm. The fine-grained synophitic hyperite and norite usually have much smaller clusters of hypersthene "grains" with similar optical orientation than the coarser-grained synophitic rock. Most hypersthene "grains" seem to lie with their long axes in the plane of igneous lamination (Plate XIV, Fig. B).

The optical orientation of one set of hypersthene "grains" with respect to another set of hypersthene "grains" is always quite different. Von Gruenewaldt (1966, p. 86) points out that in such groups hypersthene has a common orientation with its crystallographic c-axis parallel to the plane of igneous lamination. In a specimen from Brits a number of relatively small sets of hypersthene "grains" with similar optical orientation occur. The crystallographic c-axes of these sets of hypersthene clusters did not fall on a great circle of the stereogram, as one would expect if all crystallographic c-axes were lying in one plane. Thus the crystallographic c-axes of the hypersthene clusters do not all lie in the plane of igneous lamination.

Zone X in borehole KLG2 was subdivided into three sub-zones. In the Upper Subzone (79 to 686 feet) the somewhat interconnected hypersthene tends to be rather round (Plate XI, Fig. A). Large clusters of hypersthene "grains" with similar optical orientation occur. Extinction is not always quite simultaneous from one "grain" to another belonging to the same

set of hypersthene "grains".

In the Middle Subzone fine-grained synophitic hyperite occurs. The hypersthene "grains" are rather round and the optical orientation seems to be the same over a smaller area than in the synophitic hyperite and norite above and below this zone. Extinction seems to be slightly less simultaneous than in the Upper and Lower Subzones.

In the Lower Subzone (820 to 2000 feet) the optical orientation of the hypersthene is the same over large areas. The hypersthene forms larger more continuous areas (Plate XI, Fig. B) and the extinction is much more simultaneous for the hypersthene "grains" belonging to the same set than in the case of the Upper and Middle Subzones. Individual "grains" of inverted pigeonite may be recognizable in the upper portion of the Lower Subzone, but tend to become for the most part less recognizable with increasing depth.

In the hypersthene broad augite lamellae and/or blebs occur as well as fine augite lamellae parallel to (100) of the hypersthene.

Augite associated with the synophitic hyperite and norite occurs evenly distributed in the rock and may be interstitial to plagioclase and hypersthene (Plate XII, Fig. A) or it may be equidimensional (Plate XII, Fig. B). The augite grains do not seem to show a preferred orientation. The interstitial augite usually forms much larger crystals than the equidimensional augite.

Hypersthene-bearing coronophitic to coronosubophitic clots are quite common. Patches of similarly orientated, round to highly irregular hypersthene are partly or completely enclosed by augite. Often the hypersthene extends beyond the confines of one augite crystal and may then also be partly enclosed by other augite and/or plagioclase crystals (Plate XII, Fig. B). Some hypersthene clusters contain several augite crystals with included hypersthene (Plate XII, Fig. B). Three types of hypersthene inclusions can be distinguished in augite:

Firstly hypersthene inclusions in augite may have the same optical orientation as the set of hypersthene "grains" surrounding it. Here none of the crystallographic axes of the hypersthene coincide with those of the host augite (Plate XII, Fig. A).

Secondly hypersthene inclusions with similar optical orientation, occurring in one augite crystal, may have an optical orientation differing from that of the surrounding hypersthene "grains" with similar optical orientation. These inclusions are usually so orientated that their b- and c- crystallographic axes coincide with those of the host augite (Plate XII, Fig. B). If a number of augite crystals surround a hypersthene crystal, only one of them can share a common b- and c-axis with the hypersthene inclusion.

Thirdly hypersthene inclusions in augite may occasionally have no crystallographic axes in coincidence with the host augite nor with that of the surrounding hypersthene "grains" with similar optical orientation (Plate XII, Fig. A).

The volumetric mineral^{ogical} composition of ~~the three main minerals occurring in~~ the synophitic hyperite and norite is given in Table II. In addition the following accessory minerals may occur: quartz, biotite, and magnetite.

TABLE II

Volumetric mineral^{ogical} composition of synophitic hyperite and norite.

Borehole number	Specimen number	Depth in feet	Plagio-clase	Hypers-thene	Augite	Accessories
KLG2	M2	168	62.4	11.8	23.8	2.0
KLG2	M7	377	68.0	27.4	4.6	-
KLG2	M15	552	60.8	14.7	24.2	0.3
KLG2	M25	736	59.9	25.8	14.3	-
KLG2	M27	817	50.3	38.3	11.3	0.1
KLG2	M28	822	55.3	24.2	19.9	0.6
KLG2	M36	1030	58.1	18.3	23.4	0.2
KLG2	M43	1228	59.1	17.5	23.2	0.2
KLG2	M48	1479	54.9	21.5	23.4	0.2
KLG2	M52	1629	68.8	9.5	21.6	0.1
KLG2	M53	1676	83.6	10.5	5.5	0.4
KLG2	M66	1933	69.2	19.5	10.7	0.6
Average			63	20	17	

In the hyperite and norite with synophitic texture plagioclase, pigeonite, and augite seem to have crystallized cotectically. The minerals seem to be cumulus crystals forming an adcumulate, but during inversion pigeonite inverted to hypersthene (discussed on pp. 54-73).

3. Ophitic to nesophitic hypidiomorphic hyperite

The area covered by bronzite in these rocks is generally more or less 2 cm in diameter and the texture in this area grades from ophitic to nesophitic. The plagioclase has much the same grain size in the nesophitic patches as in the areas between the large bronzites (Plate VII, Fig. A). However, where the rock has ophitic texture the plagioclase enclosed by the bronzite is somewhat smaller than the plagioclase between the large bronzite areas (Plate VII, Fig. B). Thin sections reveal that the orthopyroxene forms more or less large round crystals or mottles.

This effect of mottling, however, only becomes apparent under the microscope. It was not possible to determine the average spacing of these bronzite areas. Where the rock has nesophitic texture the plagioclase is in excess of the bronzite and occurs in specific areas (Plate VII, Fig. A). The plagioclase laths may form straight or somewhat wavy contacts with one another and may in part be separated from one another by narrow tongues or wedges of interstitial bronzite. Many small randomly oriented plagioclase laths are completely enclosed by the bronzite. Similar nesophitic patches also occur in the bronzite-bearing mottled anorthosite and mottled leucohyperite (compare Plates VII, Fig. A and IX, Fig. A). In some bronzite areas the plagioclase is aligned parallel to the igneous lamination of the rock. Only rarely are the bronzite areas rimmed by a narrow plagioclase-rich, **augite-poor zone**. In the ophitic areas the small plagioclase inclusions tend to increase in grain size from the centre to the margin.

Augite occurs essentially as round evenly spaced grains together with plagioclase laths between the large ophitic and nesophitic areas. Only the outer margin of the augite is often somewhat interstitial with respect to the plagioclase. The augite has generally much the same grain size as the plagioclase, but in one instance it is much coarser than the plagioclase occurring with it. The average grain size of the rock is 0.64 mm. In the central portion of the ophitic to nesophitic areas very small augite inclusions may occasionally occur in the bronzite, but close to the margins of these areas, augite inclusions in the bronzite are still rare, but more common and much larger than in the central portion of the bronzite-plagioclase areas.

One thin section of this rock is too small to give a reliable point count, but the average volumetric mineral^{ogical} composition from seven thin sections is as follows: plagioclase 62 per cent, bronzite 20 per cent, augite 17 per cent, and accessory minerals 1 per cent.

To emphasize the marked difference in the volumetric mineral composition in the bronzite-plagioclase areas and the augite-plagioclase areas, the volumetric mineral composition for these two kinds of area in one thin section is given in Table III.

TABLE III

Volumetric mineral^{ogical} composition in the bronzite-plagioclase area and in the intervening augite-plagioclase area as obtained from thin section number "M109b" (borehole KLG2 at a depth of 2387 feet).

	Plagio- clase	Bronzite	Augite	Accessories
Bronzite-plagioclase area	63.4	35.6	1.0	-
Augite-plagioclase area	76.4	-	21.0	2.6

An increase in the grain-size of the plagioclase in some ophitic areas from the centre towards the margin suggests that at least some of the bronzite began to crystallize early and in some instances the central areas may even represent primary precipitate or cumulus crystals. The nesophitic patches in which the igneous lamination and the grain size of the plagioclase in the bronzite and between these large bronzites is the same, strongly suggest that this texture was developed in place. The entire bronzite may have developed in place or the centre may be a cumulus crystal with a broad interstitial or inter-cumulus margin. The bronzite areas vary in texture from ophitic to nesophitic, thus these two extremes and all intermediate variables^{+ ions} must be genetically related.

The explanation of the origin of the nesophitic patches is based on two assumptions each of which is discussed separately. In the first place bronzite is assumed to have crystallized annularly so that, as soon as the plagioclase laths were enclosed in the bronzite, they were cut off from the rest liquid. Secondly bronzite is assumed to have formed an initially sponge-like open structure enclosing plagioclase and

rest liquid. The rest liquid is considered to have been directly connected with the rest liquid that surrounded the bronzite areas, with the result that ionic diffusion could take place readily. Thus, if, the plagioclase laths in the nesophitic areas were shut off from the rest liquid as they were enclosed in the bronzite, the bronzite must have begun to crystallize when the plagioclase crystallization had virtually come to completion.

Considering the matrix area between the bronzite crystals, it is evident that the plagioclase and the augite crystallized cotectically. The question then arises, why large augite inclusions do virtually not occur in the bronzite area. The few small augite crystals occurring in the bronzite area suggest that the augite ~~should~~^{must} have crystallized essentially after the bronzite and in turn after the plagioclase. This is contrary to the texture in the matrix area between the large bronzites. One could perhaps postulate that for some unknown reason the augite was expelled by the crystallizing bronzite. If the augite was expelled from the bronzite area one would, besides many difficulties, at least expect that the igneous lamination should have been destroyed in all the nesophitic patches, and that each bronzite area should be surrounded by an augite-rich, plagioclase-poor zone. Thus the bronzite could not have crystallized radially shutting off the plagioclase laths from the rest liquid as they became enclosed by bronzite.

Since plagioclase occurs in the bronzite as inclusions, it is most likely that the plagioclase crystallization had started well before the bronzite began to crystallize. The bronzite began to crystallize at widely spaced centres of nucleation and probably developed relatively quickly in all directions forming an open network in the case of the nesophitic areas and a less open network in the case of the ophitic areas. The small plagioclase laths enclosed directly by the bronzite probably represent the grain size which the plagioclase had when the orthopyroxene began to crystallize. The bronzite crystallized in

such a manner, that it did not disturb the igneous lamination of the plagioclase in the bronzite area or in the rock as a whole. Once the open bronzite crystals had nearly reached their present dimensions, augite probably began to nucleate from relatively closely spaced centres between the ophitic and nesophitic patches. At this stage the three major minerals probably crystallized most readily, and the bronzite perhaps used up all available Mg, and any Mg diffusing into the open sponge-like bronzite structure was probably readily taken up to crystallize as bronzite, with the result that there was no Mg available for the formation of augite in the bronzite area. Thus Ca probably diffused out of the bronzite areas and then, when it came into contact with Mg and the other necessary constituents, augite was probably formed.

If the three main minerals crystallized cotectically and crystallization came to completion more or less at the same time as suggested, the plagioclase within the nesophitic areas could have much the same grain size as the plagioclase surrounding the large bronzite. Although the textural relationships are perhaps well explained by the latter hypothesis, there is no certainty why the bronzite should have formed at widely spaced centres from which the crystallization developed relatively quickly in all directions and why the augite should have grown relatively slowly at closely spaced centres of nucleation.

4. Subophitic hypidiomorphic hyperite

The texture of the subophitic hypidiomorphic hyperite (Plate VIII, Fig. A) is somewhat similar to that of the ophitic to nesophitic hypidiomorphic hyperite (Plate VII, Figs. A and B), in that the bronzite encloses plagioclase and sometimes also augite towards the margin and that the augite forms somewhat round grains in the areas between the bronzite. Only the outer margin of the augite is sometimes somewhat interstitial towards plagioclase.

The bronzite in the subophitic hypidiomorphic hyperite

is much smaller and much more closely spaced than in the ophitic to nesophitic hypidiomorphic hyperite. The subophitic hypidiomorphic hyperite is rather distinct, because the bronzite areas include only about 5 to 15 per cent of plagioclase and are surrounded by a relatively broad plagioclase-rich, augite-poor zone. The plagioclase laths which are completely enclosed by the bronzite are on the whole much smaller than the plagioclase laths occurring between the bronzite areas. The outer margin of the bronzite is generally interstitial with respect to plagioclase and sometimes augite. In the bronzite some relatively large augite grains, smaller however than the augite between the bronzite areas, are sometimes enclosed in the margin.

The volumetric mineral^{ogical} composition of ~~the three main minerals~~ in the subophitic hypidiomorphic hyperite is given in Table IV.

TABLE IV

Volumetric mineral^{ogical} composition of the subophitic hypidiomorphic hyperite.

Borehole number	Specimen number	Depth in feet	Plagio-clase	Bronzite	Augite	Accessories
TRF1	M483	2593	58.8	29.0	10.1	2.1
US13	M797	1480	62.3	23.3	14.4	-
AB1	M1033	936	63.1	29.4	7.5	-
AB1	M1147	3435	63.7	15.7	20.5	0.1
Average			62	24	13	1

Since the plagioclase laths enclosed directly by bronzite are much smaller than the plagioclase occurring between the bronzite areas, it is highly unlikely that the bronzite formed an initial sponge-like, open structure. The small plagioclase laths enclosed in the bronzite were probably shut off from the rest liquid as soon as they were enclosed.

A problem is created by the plagioclase-rich, augite-poor zone that surrounds virtually all the bronzite areas.

The plagioclase-rich zone around the bronzite crystals could not have developed as a result of normal crystal settling. Furthermore, the general absence of igneous lamination ~~does~~ also suggests that the three main minerals do not represent a normal cumulate on the "floor" of the magma body.

A plagioclase-rich margin and the other textural features could most probably have developed as a result of crystallization in place coupled with ionic diffusion. Once the plagioclase had more or less the grain size of those enclosed directly by the bronzite, the bronzite probably began to crystallize relatively quickly at more widely spaced centres of nucleation than the plagioclase and augite. The augite probably began to crystallize at closely spaced centres of nucleation after the bronzite had begun to crystallize. The relative power of crystallization of the bronzite was then probably stronger or more vigorous than that of the augite. In the bronzite areas all available Mg was probably taken up to form bronzite and in addition the Mg from the immediate vicinity probably also diffused towards the crystallizing bronzite. There was no free Mg available near the bronzite, thus Ca probably diffused out of these areas to come in contact with available Mg and other ions necessary to form augite. This process is the same as postulated for the formation of ophitic and nesophitic patches in ophitic to nesophitic hypidiomorphic hyperite. Plagioclase is relatively rich in Al and for plagioclase to form Al probably had to diffuse towards the area taken up by the plagioclase-rich rim. It is possible that diffusion over a distance of only a few millimetres could have taken place. Hess (1960, p. 146-148) even postulates that diffusion took place over a distance of 3 m in the rest liquids of crystal cumulates.

If metamorphism were responsible for the formation of the plagioclase-rich zone around the bronzite areas, the main minerals could then perhaps represent cumulates in which accumulus growth resulted in the crystallization of the outer margin of the crystals. If metamorphism had caused the plagioclase-

rich zones in the subophitic hypidiomorphic hyperite, the ophitic to nesophitic hypidiomorphic hyperite which has a rather similar texture on a larger scale should have been subjected to the same metamorphic conditions, and this rock should then also have developed plagioclase-rich zones around the bronzite areas. Since, however, this is not the case it is perhaps more likely that these plagioclase-rich margins developed under magmatic conditions.

B. Leucocratic types

1. Anorthosites

a. Hypersthene-bearing mottled anorthosite and mottled leucohyperite

The hypersthene occurs as mottles not associated with augite or closely associated with it. The hypersthene closely associated with augite gives rise to coronophitic to coronosubophitic clots. The hypersthene mottles sometimes have large areas without inclusions of plagioclase particularly near the centre. Towards the margin of these mottles the hypersthene is interstitial to plagioclase. A hypersthene mottle may be made up of a single hypersthene crystal or several pyroxenes (hypersthene and/or augite) may collectively form a mottle (Plate VIII, Fig. B). A highly irregular contact may separate two pyroxenes that are in contact with one another. In the coronophitic to coronosubophitic clots irregular or round grains of hypersthene occur in augite as separate optically continuous patches. The irregular hypersthene is mostly completely enclosed by the augite, whereas the somewhat round hypersthene is often only partly enclosed by the augite. These coronophitic to coronosubophitic clots are somewhat similar to the coronophitic to coronosubophitic clots occurring in the synophitic hyperite and norite.

Wavy and irregular border relationships often exist at the plagioclase and pyroxene margins. The plagioclase laths enclosed by somewhat round pyroxene are usually rather small and

randomly orientated. Where the pyroxene is interstitial the plagioclase laths enclosed are much larger than the small plagioclase laths in round pyroxene and display igneous lamination. Bent plagioclase laths are quite common.

The volumetric mineral^{ogical} composition of the ~~three main minerals~~ in the hypersthene-bearing mottled anorthosite and mottled leucohyperite is given in Table V. The plagioclase ranges in composition from An₇₅ to An₇₈ and the hypersthene from Of₃₀ to Of₄₅. The accessory minerals are quartz, biotite, hornblende, and magnetite.

TABLE V

Volumetric mineral^{ogical} composition of the hypersthene-bearing mottled anorthosite and mottled leucohyperite.

Borehole number	Specimen number	Depth in feet	Plagio- clase	Hypers- thene	Augite	Accessories
KLG2	M61	1779	90.0	5.4	3.3	1.3
KLG2	M68	1933	94.0	5.2	0.1	0.7
KLG2	M74	2014	93.1	1.7	2.4	2.8
KLG2	M90	2182	95.1	1.0	1.9	2.0
TRF1	M316	1384	83.1	11.9	4.3	0.7
TRF1	M341b	1527	87.6	4.4	7.1	0.9
TRF1	M369	1697	91.0	1.9	6.1	1.0
TRF1	M384	1806	92.4	1.1	1.2	5.3
TRF1	M633	3724	80.4	10.1	9.0	0.5
TRF1	M637	3753	86.1	9.2	3.7	1.0
TRF1	M648	3818	83.0	10.1	5.6	1.3
AB1	M1046	1910	84.9	7.5	5.9	1.7
Average			88	6	4	2

Interprecipitate quartz often encloses several small plagioclase crystals (Plate XIII, Fig. A). Since the quartz is interstitial, it must have been one of the last minerals to crystallize. It is, however, not quite clear why the plagioclase laths associated with the quartz should generally be smaller than the plagioclase not associated with the quartz. Perhaps, in

areas where no quartz occurs, interstitial rest liquid gave rise to the overgrowth of the plagioclase crystals, resulting in the formation of larger crystals, whereas in the areas where the quartz occurs, the quartz crystallized interstitially and the plagioclase laths did not grow to larger sizes.

Some of the hypersthene crystals have a hornblende rim which may be partly or completely developed. Such rims are best developed on interstitial hypersthene (Plate XIII, Fig. B). Some augites have similar rims, but they tend to be much narrower and far less continuous. Together with the hornblende rims there usually occur biotite crystals which are less pleochroic than the biotite associated with magnetite. This weakly pleochroic biotite has developed more or less parallel to the (100) exsolution in the hypersthene. This phenomenon may occur less well developed in the augite. The biotite crystals usually cut across the contact between the pyroxene and plagioclase, and they also cut across the intervening hornblende rim, if the latter is present. The biotite occurs parallel to (100) of the pyroxene penetrating plagioclase for a longer distance than the pyroxene. It is much wider in the plagioclase and on joining up with augite does so not necessarily along the (100) exsolution lamellae but anywhere parallel to this plane. Thus the pyroxene seems to have controlled this direction. The hornblende rims may occur without cross-cutting biotite, but where the cross-cutting biotite occurs, a hornblende rim is usually associated with it. The hornblende rims and cross-cutting biotite were probably formed as a result of late magmatic water concentrates which reacted with the pyroxene and the plagioclase to form a hornblende rim and the cross-cutting biotite. Since biotite cuts across the hornblende rim it was probably formed after the hornblende.

The interstitial pyroxene in the hypersthene-bearing mottled anorthosite and mottled leucohyperite probably crystallized from the pore liquid. Where somewhat round pyroxene or coronophitic to coronosubophitic clots occur, the central area of the pyroxene is most probably primary precipitate. The plagioclase laths in

the rock seem to be cumulus crystals but the outer margin of these crystals may have crystallized from the pore liquid.

b. Bronzite-bearing mottled anorthosite and mottled leucohyperite

In the bronzite-bearing mottled anorthosite and mottled leucohyperite ophitic and nesophitic areas occur. The areas in which the augite occurs always seem to be ophitic (Plate IX, Fig. A), whereas the areas in which bronzite occurs may be nesophitic (Plate IX, Fig. A) or ophitic. A mottle may be made up of a single pyroxene crystal which is interstitial to plagioclase, or it may be made up of a number of bronzite and/or augite crystals that are interstitial to plagioclase. In the case of the nesophitic areas large plagioclase grains occur concentrated in the areas between patches of similarly orientated bronzite. Some small grains of plagioclase are enclosed directly by the bronzite. In the augite laths of plagioclase are more or less evenly distributed.

In the bronzite-bearing mottled anorthosite and mottled leucohyperite thin sections were cut to intersect the mottles, thus these thin sections do not give reliable point-counts of the rock as a whole. The bronzite area in the mottle of the mottled anorthosite shown in Plate IX, Fig. A consists of 70 per cent of plagioclase and 30 per cent of bronzite, whereas the augite area in the same thin section consists of 69 per cent of plagioclase and 31 per cent of augite. Thus the total volume of bronzite and augite per unit area is here much the same. The composition of the plagioclase ranges from An_{75} to An_{82} and the bronzite from Of_{24} to Of_{30} . Van Zyl (1960, p. 18) found no difference in the composition between the plagioclase in the mottles and the plagioclase surrounding the mottles. The average grain size for one specimen is 0.80 mm. In the same specimen the average grain size of the plagioclase laths in the mottle is 0.58 mm and that of the plagioclase surrounding the mottle is 0.63 mm. The plagioclase occurring within the mottles investigated, is generally randomly orientated.

Between the mottles the plagioclase laths do however show signs of igneous lamination.

In these rocks the pyroxene is always interstitial to plagioclase. Since a mottle is often made up of a cluster of different pyroxenes (bronzite and/or augite), it could perhaps be that once a centre of nucleation had developed, others developed close to it. Ions from the interstitial liquid may then have diffused towards these centres resulting in anorthosite between the mottles. Since the grain size of the plagioclase laths enclosed by pyroxene and the plagioclase laths surrounding the mottles is much the same, the pyroxene probably began to crystallize when the plagioclase crystallization had already reached an advanced stage. Once the bronzite and augite began to crystallize, the three main minerals crystallized cotectically.

c. Spotted anorthosite and spotted leuconorite

In the spotted anorthosite and spotted leuconorite the spotted effect is caused by the orthopyroxene which usually has a plagioclase-free centre, whereas the outer margin tends to be somewhat interstitial to plagioclase (Plate IX, Fig. B). Augite, where it does occur, is interstitial in relation to the plagioclase and bronzite. The spotted anorthosite and spotted leuconorite is closely related to leucohyperite (compare Plates IX, Fig. B and X, Fig. A). The difference is, however, that the augite content is much lower in the case of the spotted anorthosite and spotted leuconorite than in the leucohyperite. The grain size in these rocks ranges from 0.5 to 1.2 mm.

The volumetric mineral^{ogical} composition of the ~~three main minerals~~ in the spotted anorthosite and spotted leuconorite is given in Table VI. The composition of the plagioclase ranges from An₆₉ to An₈₁ and the bronzite from Of₂₃ to Of₃₀.

TABLE VI

Volumetric mineral^{ogical} composition of spotted anorthosite and spotted leuconorite.

Borehole number	Specimen number	Depth in feet	Plagio-clase	Bronzite	Augite	Accessories
TRF1	M342	1528	88.1	10.1	0.4	1.4
TRF1	M404	1871	89.7	7.8	0.8	1.7
TRF1	M425	1960	88.3	9.8	1.2	0.7
TRF1	M453b	2336	96.3	2.2	0.6	0.9
TRF1	M606	3651	94.6	5.0	0.4	-
Average			91	7	1	1

d. Anorthosite

The anorthosite is made up virtually only of plagioclase laths. However, very small amounts of pyroxene, quartz, magnetite, and biotite may also occur in this rock.

2. Leucohyperite

The texture of the leucohyperite is closely related to the texture occurring in the hypidiomorphic hyperite, norite, and gabbro. The orthopyroxene varies from somewhat round crystals, in which only the outer rim is interstitial to plagioclase (Plate X, Fig. A), to orthopyroxene which is intergrown subophitically with plagioclase (Plate X, Fig. B). The augite varies from round to interstitial crystals. The plagioclase enclosed in the pyroxene is generally much smaller and non-orientated in comparison with the surrounding plagioclase. The average grain size of leucohyperite ranges from 1.0 to 1.3 mm.

Coronophitic to coronosubophitic clots are quite common in the leucohyperite. In these clots usually none of the crystallographic axes of the bronzite (occasionally hypersthene) coincide with the crystallographic axes of the host augite (Plate X, Fig. A). In the leucohyperite some of the plagioclase inclusions in the same bronzite crystal are sometimes partly or completely rimmed by narrow augite margins. These augite

margins usually have different optical orientations from one plagioclase inclusion to the other (Plate XIV, Fig. A).

The volumetric mineral^{ogical} composition of the ~~three main min-~~
~~erals in~~ leucopyrite is given in Table VII. The composition of the plagioclase ranges from An₆₇ to An₇₆ and the orthopyroxene from Of₂₈ to Of₃₂.

TABLE VII

Volumetric mineral^{ogical} composition of leucopyrite.

Borehole number	Specimen number	Depth in feet	Plagio- clase	Ortho- pyroxene	Augite	Accessories
KLG2	M72	2001	81.8	8.6	9.1	0.5
KLG2	M80	2097	69.4	21.2	8.7	0.8
KLG2	M86	2156	83.3	13.6	3.0	0.1
TRF1	M315	1376	77.2	12.6	8.4	1.8
TRF1	M389	1837	74.1	16.7	7.5	3.5
TRF1	M398	1864	74.3	13.4	10.5	1.8
TRF1	M528	3107	75.1	19.1	5.0	0.8
TRF1	M615	3658	85.6	9.7	3.0	1.7
TRF1	M642	3777	86.1	6.8	6.3	0.8
Average			78	14	7	1

The pyroxene may have hornblende rims and cross-cutting biotite. Interprecipitate quartz tends to be quite common and small plagioclase laths are often associated with it. Magnetite and strongly pleochroic biotite usually occur together, but the two minerals may also occur on their own.

VI. EXSOLUTION PHENOMENA IN THE PYROXENES

All the pyroxenes in the rocks investigated show some form of exsolution. The various types of exsolution ~~occurring~~ may be subdivided according to their general characteristics.

A. Exsolution phenomena in bronzite

Bronzite occurs in the following rocks: hypidiomorphic hyperite, norite, and gabbro; ophitic to nesophitic hypidiomorphic hyperite; subophitic hypidiomorphic hyperite; mottled anorthosite and mottled leucohyperite; spotted anorthosite and spotted leuconorite; and leucohyperite. In all these rocks the bronzite is characterized by very fine, evenly spaced, continuous lamellae developed parallel to the (100) plane. Depending upon how these lamellae are intersected they do or do not show up. Together with these fine lamellae there often occur towards the middle of the bronzite grains somewhat thicker more irregular lamellae also parallel to the (100) plane. These lamellae have relatively high birefringence suggesting that they are most probably augite.

B. Exsolution phenomena in hypersthene

Hypersthene occurs in the following rocks: synophitic hyperite and norite, mottled anorthosite and mottled leucohyperite, and occasionally leucohyperite. In all these rocks hypersthene has normal or extraordinary (100)-augite exsolution lamellae. Normal (100)-augite exsolution lamellae are identical to those in bronzite, whereas extraordinary (100)-augite exsolution lamellae are thicker, wider spaced, less continuous,

and occasionally cross cutting. In addition to the (100) exsolution lamellae sets of broad augite lamellae (or blebs) have any random orientation in relation to the hypersthene structure.

1. ^{Relict} Remnant (001)- augite exsolution lamellae and blebs in hypersthene.

For the sake of convenience, it is perhaps best to number the observations that are of interest.

(i) ^{Relict} Remnant (001)- augite exsolution lamellae commonly occur in the hypersthene-bearing mottled anorthosite and mottled leucohyperite (Plate VIII, Fig. B) and in the synophitic hyperite and norite from Brits and Bon Accord Quarry (Plate XIV, Fig. B).

(ii) ^{Relict} Remnant (001)- augite exsolution lamellae in the hypersthene of Zone X in borehole KLG2 are rather rare, their place being taken by round or oval augite blebs. The small exsolution blebs occurring in the fine-grained synophitic hyperite in the Middle Subzone of Zone X in borehole KLG2 at a depth of 686 to 819 feet (Plate XV, Fig. A) are much smaller, much more closely spaced, and much more numerous than in the coarser-grained synophitic hyperite and norite in the Upper and Lower Subzones of Zone X.

(iii) ^{Relict} Remnant (001)- augite exsolution lamellae ^{in hypersthene} have a width ranging from 0.01 to 0.1 mm and a spacing that ranges from 0.04 to 0.3 mm.

(iv) Augite lamellae and blebs with common optical orientation quite commonly occur together in the same hypersthene crystal (Plates VIII, Fig. B; XIV, Fig. B; XV, Figs. A and B; and XVI, Fig. A).

(v) Sometimes the lamellae and blebs do not reach the margin of the hypersthene (Plates VIII, Fig. B; XIV, Fig. B; and XV Figs. A and B).

(vi) Large patches are not uncommon where no broad augite lamellae or blebs occur (Plates XIV, Fig. B and XVI, Fig. B).

(vii) In the hypersthene-bearing mottled anorthosite the more iron-rich interstitial hypersthene only contains a few

^{relict}
~~remnant~~ (001)- augite exsolution lamellae or blebs. This observation is well in line with the observation made by Deer, Howie, and Zussman (1963, vol. 2, p. 149) that the more ferriferous pigeonites generally do not show the same degree of exsolution as those that are less ferriferous.

(viii) Sets of ^{relict}
~~remnant~~ (001)- augite exsolution lamellae with similar orientation lie virtually always with any random orientation in relation to the hypersthene structure (Plate XIV, Fig. B).

(ix) Up to five sets of augite blebs with different optical orientation have been observed in what appears to be the same hypersthene crystal (Plate XV, Fig. A).

(x) In most cases none of the crystallographic axes of the augite lamellae or blebs coincide with the crystallographic axes of the host hypersthene.

(xi) A coronosubophitic clot in hypersthene-bearing mottled leucohyperite (Plate VIII, Fig. B) consists of separate, similarly orientated hypersthene patches (possibly connected in three dimensions). The hypersthene contains ^{relict}
~~remnant~~ (001)-augite exsolution lamellae which lie parallel to the present (102) plane of the hypersthene. The optical orientation of these augite lamellae is the same as the augite forming a partial rim around the hypersthene. Universal stage measurement revealed that the b- and c- crystallographic axes of the hypersthene and augite coincide.

(xii) In the synophitic hyperite and norite ^{relict}
~~remnant~~ (001)-augite exsolution lamellae tend to lie more or less perpendicular to the length of the hypersthene "grains", which in turn is more or less perpendicular to the plane of igneous lamination (Plate XIV, Fig. B).

(xiii) Some hypersthene "grains" are divided more or less in half, each half belonging to a different set of hypersthene "grains" with similar optical orientation. ^{Relict}
~~Remnant~~ (001)-augite exsolution lamellae have the same optical orientation in

both halves of such a hypersthene "grain" (Plate XV, Fig. B).

(xiv) In one specimen of the hypersthene-bearing mottled leucohyperite (Plate XVI, Fig. A) a single set of ^{relict} remnant (100)-augite exsolution lamellae with similar optical orientation cross two hypersthene crystals and pass well into a third one. The hypersthene crystals have different optical orientations with respect to one another. The ^{relict} remnant (001)-augite exsolution lamellae have the same (optical) orientation as three bordering augite crystals which are probably connected in three dimensions. No crystallographic axes of the two hypersthene crystals were found to coincide with those of the augite. A somewhat similar situation occurs in another hypersthene-bearing mottled leucohyperite (Plate XVI, Fig. B) in which the augite exsolution blebs with similar optical orientation occur in three optically differently orientated hypersthene crystals.

2. (100)-augite exsolution lamellae in hypersthene

In the synophitic hyperite and norite of the Upper and Lower Subzones in Zone X in borehole KLG2 the (100)-augite exsolution lamellae in the hypersthene are normal and of the same type as those in the bronzite. These lamellae are very narrow, evenly spaced and have the same optical orientation. They thus lie in the same plane over large areas in the same set of hypersthene "grains" with similar optical orientation.

In contrast, in the fine-grained synophitic hyperite (or Middle Subzone) in Zone X in borehole KLG2, in the synophitic hyperite from Brits and Bon Accord Quarry, and in most ^{of the} hypersthene-bearing mottled anorthosite and mottled leucohyperite the (100)-augite exsolution lamellae in the hypersthene are of the extraordinary type (Plate XV, Fig. B). These lamellae are similar to the (100)-augite exsolution lamellae in bronzite and the normal type of (100)-augite exsolution described above in that these lamellae are parallel to the (100) plane. The extraordinary (100)-augite lamellae, however, are far less continuous, slightly

thicker, and more widely spaced. In places they tend to be vermicular and are then not parallel to (100). In other instances these lamellae terminate and join up obliquely with those of the neighbouring lamellae. The lamellae terminate before reaching the margin of the hypersthene and also before reaching the ~~remnant~~^{relict} (001)-augite exsolution lamellae or blebs. In many instances patches exist in the hypersthene where these lamellae have not developed.

In one instance the hypersthene (Plate XVI, Fig. A) contains relatively thick (100) lamellae in addition to the normal type of (100) exsolution, and it is very likely, judging by the birefringence, that these lamellae are augite.

2. Vermicular exsolution

This type of exsolution occurs only in the hypersthene in the upper part of the mottled anorthosite and mottled leucopyrite in Zone II of borehole KLG2. In this rock the exsolution in the hypersthene is angular, elongated, curved as well as very irregular (Plate XVII, Fig. A). It is sometimes evident that the vermicular exsolution represents remnants of ~~remnant~~^{relict} (001)- and (100)-augite exsolution lamellae. Sometimes the augite exsolution may be so irregular that one cannot always decide with certainty what the original direction of the exsolution lamellae had been. The vermicular exsolution may often be confined to one hypersthene crystal, whereas in the other hypersthene crystals in the same thin section the exsolution may be normal.

C. Exsolution phenomena in augite

Augite occurs in all the rocks investigated and always contains (100)-exsolution lamellae, but (001)-hypersthene exsolution lamellae are not always present, particularly not in the augite that is interstitial to plagioclase and orthopyroxene.

Thus (001)- hypersthene exsolution lamellae ~~do~~ generally^{do} not occur in the augite of the mottled anorthosite and mottled leucopyroxite and in the spotted anorthosite and spotted leuconorite.

1. (001)- hypersthene exsolution lamellae in augite

These lamellae are much thicker, much wider spaced, and far less continuous than the (100)-exsolution lamellae in augite. The thickness of the (001)- hypersthene exsolution lamellae ranges from 0.02 to 0.1 mm and the spacing ranges from 0.02 to 1.0 mm or more. The spacing of these lamellae is rather irregular and sometimes they only occur in one part of an augite crystal. The lamellae ~~do~~ usually^{do} not traverse the entire augite crystal. Augite containing (001)- hypersthene exsolution lamellae occurs together ⁱⁿ ~~with~~ both bronzite- and hypersthene-bearing rocks. Universal stage measurements of the (001)- hypersthene exsolution lamellae revealed that the b- and c-crystallographic axes of the hypersthene coincide with corresponding axes of the host augite.

2. (100) exsolution lamellae in augite

These lamellae are relatively narrow, continuous, and closely spaced. Under high magnification the exsolution lamellae, if correctly intersected, display a black wedge-shaped mineral occurring in rows parallel to the (100) plane of the host augite. The length of these wedges seem to lie parallel to the (001) plane of the same host mineral (Plate XVII, Fig. B). The thicker portions of these wedges are black under the microscope, but where they become narrow, they are pale pink to pale brown. Although the material between these ~~dark~~^{black} wedge-shaped minerals may be orthopyroxene, these ~~dark~~^{black} minerals are most certainly not. These wedges are unfortunately too small to be determined optically. Perhaps they are hematite exsolution lamellae?

VII. INTERPRETATION OF THE EXSOLUTION STRUCTURES
AND THE RÔLE OF INVERSION

In this section the possible origin of the exsolution structures and their rôle in interpreting the formation of certain structures in the synophitic hyperite and norite, and in the hypersthene-bearing mottled anorthosite and mottled leucohyperite are discussed.

A. Exsolution phenomena in bronzite

A certain degree of confusion still exists in the literature regarding the composition and origin of the (100)-augite exsolution lamellae in bronzite. These lamellae have been ascribed to translation gliding, to twinning, and to exsolution.

Scholtz (1936, p. 112) states that the lamellation, which is not related to the composition of the mineral, is developed parallel to (100), the lamellae having the a-axis, in common, whereas the b- and c-axes of different sets are inclined to each other usually at angles of 5 to 11 degrees.

Henry (1942, p. 184) showed that the a- and c-axes of the lamellae are inclined at angles up to 15 degrees to the host bronzite crystal in the (010) plane. In some cases the b-axis of the two sets of lamellae can be detected, so that the displacement is not always strictly in the (010) plane. Henry concluded that the structure is not one of regular twinning and he (p. 187) ascribes the structure to a process of translation on (100) in the direction $[100]$, accompanied by bending about $[010]$.

Poldervaart and Hess (1951, p. 481-482) consider these lamellae to be exsolution lamellae and that the material exsolved is a member of the diopside-hedenbergite series. Hess (1960, p. 30) suggests that the exsolution takes place in such a way that the

lamellae and the host orthopyroxene have their b- and c- axes and the (100) plane in common. Hess (1960, p. 23) refers to orthopyroxene containing only this type of exsolution as orthopyroxene of the Bushveld type.

B. Exsolution and inversion phenomena in hypersthene

In addition to the exsolution and inversion of pigeonite to hypersthene, the origin of some related features and structures such as inversion nucleation, the formation of blebs from ~~rem-~~^{relict}nant (001)-augite exsolution lamellae, and the formation of vermicular exsolution are discussed.

1. ~~Remnant~~^{Relict} (001)-augite exsolution lamellae and inversion of pigeonite to hypersthene.

On the basis of experimental data Bowen and Schairer (1935, p. 165) come to the conclusion that the pyroxenes form two solid solution series: the monoclinic, stable at high temperatures; and the orthorhombic, stable at low temperatures. In dry mixtures the inversion temperature falls from 1140 °C at the pure magnesian end member to 955 °C at the iron-rich extreme. Hess (1960, p. 40) found that in both the Stillwater and the Bushveld Complexes the cooling curve of the magma intersects the pyroxene inversion curve at a Mg : Fe ratio of 70 : 30. When the orthoferrosilite content is less than 30 per cent, bronzite or enstatite will crystallize directly and when the orthoferrosilite content exceeds 30 per cent pigeonite will crystallize first. Poldervaart and Hess (1951, p. 475) point out that the maximum Ca⁺² acceptable at high temperature in the pigeonite structure is about 10 per cent of the total Ca⁺², Mg⁺², and Fe⁺². The pigeonite eventually passes through an inversion upon cooling and by doubling of the monoclinic cell along the a-axis with a slight shift of the (SiO₄)⁴⁻ chains, becomes orthorhombic in

symmetry. This change involves a slight contraction, so that Ca^{+2} ions can enter this structure only up to 3.5 per cent of the total Ca^{+2} , Mg^{+2} , and Fe^{+2} ions. Thus under suitable conditions, i.e., slow cooling ^{Ca^{+2}} up to 6.5 per cent of ^{the total Ca^{+2} , Mg^{+2} and Fe^{+2}} augite _^ may be exsolved from the pigeonite. This exsolution occurs in the form of rather coarse lamellae parallel to the (001) plane of the pigeonite before inversion to hypersthene. Hess (1960, p. 31) points out that the exsolution plane may be related to the ease of migration of the ions in the structure. The ions would migrate parallel to the $(\text{SiO}_4)^{4-}$ chains. Brown (1957, p. 532) found that exsolved augite is more ferriferous in composition than the grains of augite in the same rock.

Poldervaart and Hess (1951, p. 483) found that in the majority of cases at inversion of pigeonite to hypersthene, the hypersthene develops in such an orientation, that it retains the b- and c- crystallographic axes of the parent pigeonite. In the one case described (see p. 56 and Plate VIII, Fig. B) ^{relict} ~~remnant~~ (001)- augite exsolution lamellae lie in the (102) plane of the hypersthene. The augite lamellae have the same optical orientation as the bordering augite. In the case described inversion probably took place as described by Poldervaart and Hess. Thus original pigeonite probably had all crystallographic axes in coincidence with the bordering augite. On slow cooling (001)- augite exsolution lamellae were exsolved from the pigeonite that had the same optical orientation as the augite corona. Inversion took place so that the b- and c-axes were retained by the hypersthene so as to coincide with the corresponding axes in the augite corona. Only the a-axis has undergone reorientation. One may therefore refer to this form of inversion as inversion with a-reorientation. Similar situations were observed by Bruynzeel (1957, p. 508-511) and Brown (1957, p. 532).

Brown (1957, p. 530 and 533), Bruynzeel (1957, p. 513), Bown and Gay (1960, p. 386), Mc Dougall (1961, p. 682), Maske (1966, pp. 56-63), and Von Gruenewaldt (1966, pp. 84-88) report

that in the majority of cases there is no crystallographic relationship between the ~~remnant~~^{relict} (001)-augite exsolution lamellae or blebs and the host hypersthene. As pointed out (p. 56 and Plate XIV, Fig. B) ~~remnant~~^{relict} (001)-augite exsolution lamellae occur in any plane in hypersthene. Thus in virtually all instances none of the crystallographic axes in the ~~remnant~~^{relict} (001)-augite lamellae coincide with the hypersthene. As a result of the randomness in orientation of these sets of lamellae or blebs in the hypersthene the question arises whether these lamellae are really exsolution lamellae of the type described by Poldervaart and Hess. Since the lamellae have similar thickness and spacing as those described by Hess (1960, p. 28), it is assumed that these lamellae represent exsolution lamellae which were exsolved from diversely orientated pigeonite crystals so that the crystallographic axes of the exsolved augite and host pigeonite coincided.

Maske (1966, p. 61) suggests that clusters of diversely orientated pigeonite crystals inverted collectively to orthopyroxene of a single orientation, the augite lamellae of each patch marking the original orientation of the individual pigeonite. Maske concludes that the uniformly orientated "pseudo-poikilitic hypersthene" with many diversely orientated sets of (001) lamellae reveal extreme randomness, since in all but one set, rotation of the axes must have been involved during inversion. He suggests that owing to the sluggishness of the structural rearrangement, inversion was probably not instantaneously accomplished at the appropriate temperature. Maske further considers the possibility that primary hypersthene was first precipitated from the interstitial liquid surrounding these pigeonite grains below the inversion temperature to form the lamellae-free rims of the "pseudo-poikilitic crystals". According to Maske the presence of this stable orthorhombic phase triggered the inversion of the pigeonite and the structural rearrangement was of such a fashion that the secondary orthopyroxene was contin-

uous with the late hypersthene mantle. Only the orientation of the augite lamellae would then disclose the original random orientation of the individual pigeonite grains in the cluster.

Von Gruenewaldt (1966, p. 87) points out that (001)-augite exsolution lamellae generally reach the margin of the hypersthene "grains". This is also true for some of the hypersthene investigated. Thus no hypersthene rim could have crystallized before pigeonite underwent inversion as suggested by Maske. It is also doubtful if rest liquids could have existed at inversion temperatures. Poldervaart and Hess (1951, pp. 472-481) point out that exsolution and inversion ~~is a~~^{are} phenomena that take place under solvus conditions. Von Gruenewaldt (1966, p. 87) suggests that original diversely orientated pigeonite grains on cooling exsolved augite lamellae parallel to the (001) plane of each pigeonite grain. Von Gruenewaldt (p. 86) states that hypersthene clusters are optically so orientated that the c-axis lies in the plane of igneous lamination. He thus suggests that when the inversion temperature was reached, directed pressure of the accumulating crystals developed and the first pigeonite to invert was that ^{of the one} which after inversion produced an orientation most stable under the prevailing conditions of pressure. The pigeonite grains with-different orientation would then take longer to invert owing to the sluggishness of inversion. He then suggests that the first formed orthopyroxene could set off the inversion in an adjoining grain, which would adopt an orientation continuous with that which triggered off the reaction.

It has already been pointed out (see p. 37) that in a specimen from Brits there is evidence suggesting that not all the crystallographic c-axes lie in the plane of igneous lamination. However, evidence obtained from one thin section is ⁱⁿ sufficient for any generalization. Therefore the possibility is not excluded that the c- crystallographic axes in sets of hypersthene "grains" may perhaps generally lie more or less in the plane of igneous lamination. If directed pressure caused inversion to

as suggested by Von Gruenewaldt (1966) take place in pigeonite ~~with such an orientation, that they would be most stable under the prevailing conditions of pressure,~~ one could expect that the crystallographic c-axes would lie virtually without exception perpendicular to this pressure direction. Since this was not found and since it is in any case difficult to envisage how directed pressure could occur under conditions of load pressure, where one would expect the pressure to be virtually the same in all directions, directed pressure is not considered to be a controlling factor.

The formation of synophitic hyperite and norite may perhaps have taken place in one of the following two ways, depending upon whether the crystallographic c-axes of the hypersthene clusters lie with random orientation, or whether the crystallographic c-axes of the hypersthene clusters lie in the plane of igneous lamination.

There can be little doubt that the hypersthene "grains" with similar optical orientation were in fact diversely orientated pigeonite grains. It may well be that as soon as pigeonite-bearing rock cooled to temperatures below the inversion curve, the pigeonite became unstable. Perhaps at this stage widely spaced centres of hypersthene nuclei developed and grew in size in all directions. It is proposed to refer to this type of nucleation as inversion nucleation. The first formed hypersthene nuclei formed so that none of the a-, b-, and c- crystallographic axes coincided with the same crystallographic axes of the original pigeonite. The type of inversion described could be referred to as inversion with abc-reorientation. The first formed hypersthene nuclei then triggered off inversion in the neighbouring differently orientated pigeonite grains, all adopting the same crystallographic or structural orientation as these hypersthene nuclei. For such a process to be operative pigeonite crystals must be in contact with each other.

Before inversion the c-axes, corresponding to the longest dimension of the original pigeonite grains, were probably orientated randomly in the plane of igneous lamination. The direc-

tion of the (001)-augite lamellae in pigeonite makes an angle of 74° or 106° with the c-axis. Thus, since the original pigeonites presumably lay with their c-axes in the plane of igneous lamination, these exsolution lamellae have a general preferred orientation more or less perpendicular to the plane of igneous lamination (Plate XIV, Fig. B). If Von Gruenewaldt's (1960, p. 86) findings that hypersthene clusters generally have their c-axes more or less in the plane of igneous lamination is correct, inversion may have taken place first in one pigeonite crystal, which was one of many, if not most, having its c-axis in the plane of igneous lamination. In such a pigeonite crystal the inversion might have occurred so that the b- and c-axes of the original pigeonite were retained in the first formed hypersthene crystal, i.e., inversion with a-reorientation. (001)-augite exsolution lamellae should lie in the (102) plane of this first formed hypersthene crystal and in addition the b- and c-axes of these augite lamellae should coincide with the same axes in the hypersthene. Poldervaart and Hess (1951, p. 483) regard this as the general case. The first formed hypersthene crystal then triggered off inversion with abc-reorientation in the surrounding pigeonite grains as already described.

Inversion with a-reorientation, because of minor rearrangement of the atoms, most probably requires less free energy than does inversion with abc-reorientation, where complete rearrangement of the atoms takes place. Since inversion of pigeonite to hypersthene is considered to be due to slow cooling, one could expect highest free energy to occur during the early stages of hypersthene nucleation or inversion nucleation. It is thus somewhat doubtful if inversion with a-reorientation, a process which should require relatively low free energy, would take place during the early stages of inversion when relatively high free energy is available. As a result of the free energy problem, it is believed that the first hypersthene nuclei to form were mainly of the abc-reorientation type. Although inversion with abc-reorientation for the first formed hypersthene nuclei is given pref-

erence, the possibility of occasional initial inversion with a-reorientation is not excluded.

One example of inversion with a-reorientation was observed in the hypersthene of mottled leucohyperite (see p. 62 and Plate VIII, Fig. B). Yet in another instance abc-reorientation has taken place in the hypersthene of the same type of rock in such a manner that a set of ^{relict} remnant (001)-augite exsolution lamellae, which has the same optical orientation as three bordering augite crystals, occurs in two hypersthene crystals (see p. 57 and Plate XVI, Fig. A). None of the crystallographic axes of the augite coincide with the crystallographic axes of the hypersthene. The area in which the ^{relict} remnant (001)-augite exsolution lamellae (and some blebs) have the same optical orientation and follow the same plane was probably covered by one pigeonite crystal. It may thus be that the pigeonite and the augite originally crystallized together with their crystallographic axes in coincidence, and that subsequently on slow cooling augite was exsolved along the (001) plane of the pigeonite so that their crystallographic axes not only coincided with one another but also with the adjacent augite crystal. However during inversion, inversion with abc-reorientation took place from at least two hypersthene nuclei. Thus the orientation assumed by the newly formed hypersthene crystals was here not controlled by the original pigeonite structure. On the whole the spacing of the hypersthene crystals in the mottled anorthosite and the mottled leucohyperite is usually much the same as the spacing of the original pigeonite crystals.

In comparing the spacing of the hypersthene nuclei with the spacing of the original pigeonite, it must be kept in mind that grains of pigeonite were most probably primary precipitate that settled out of a magma, whereas inversion nucleation of hypersthene took place in a solid state.

In the case of the synophitic hyperite and norite investigated, centres of hypersthene nuclei during inversion were much more widely spaced than the spacing of the original pigeonite

grains, whereas in the case of the mottled anorthosite and mottled leucohyperite the inversion nuclei of the hypersthene must have had much the same spacing as that of the original pigeonite crystals. Brown (1957, p. 533) found numerous cases, especially at the middle gabbro horizon of the Skaer-gaard Intrusion, in which a single crystal of pigeonite has inverted to two or more crystals of orthopyroxene, optically discontinuous with one another. Thus inversion nucleation may have a spacing which may be much wider, more or less the same or much closer than the spacing of the original pigeonite crystals.

~~As has been pointed out (see p. 71)~~ The close analogy between the fine-grained synophitic hyperite and the formation of small clusters of hypersthene "grains" with similar optical orientation, suggests that under magmatic conditions as well as under solvus conditions the degree of cooling was more pronounced (although still slow) than in the coarser-grained synophitic rock. The relatively quicker cooling in the fine-grained synophitic rock under solvus conditions probably also resulted in a less complete rearrangement of the ions causing irregularities in the extinction of the hypersthene.

Although the hypersthene-bearing mottled anorthosite and mottled leucohyperite have grain-sizes which are about the same as that in the coarser-grained synophitic rock, features such as the close spacing of inversion nucleation, the ^{relict} remnant (001)-augite exsolution lamellae, and the extraordinary (100)-augite exsolution lamellae observed in these rocks are rather similar to those in the fine-grained synophitic hyperite. If the relatively coarse grain size in the hypersthene-bearing mottled anorthosite and mottled leucohyperite is considered to be due to slow cooling of the magma, slow cooling should also have taken place under solvus conditions and should have resulted in the formation of large hypersthene crystals and other features that occur in the coarser-grained synophitic ^{hyperite} and norite. According

to Tamman (Tyrrell, 1926, p. 59) the velocity of crystallization of any constituent is increased by the presence of other substances. Hence, other things being equal, a multicomponent igneous rock should be of finer grain than one of simpler composition. Tyrrell (1926, p. 59) quotes gabbro and anorthosite as examples. The more complex type, gabbro, is usually of finer grain than the anorthosite. Thus despite the coarser grain size of the hypersthene-bearing mottled anorthosite and mottled leucohyperite cooling was probably quicker during crystallization and under solvus conditions than in the case of the coarser-grained synophitic rock. A factor which may also have partly contributed to the closer spacing of the hypersthene nuclei in the mottled anorthosite and mottled leucohyperite is that original pigeonite formed disconnected crystals.

In the present synophitic hyperite and norite inversion of original diversely orientated pigeonite grains may have been rather sluggish resulting in widely spaced inversion nuclei of hypersthene. Once inversion nuclei were formed it seems that inversion took place readily, radially about these centres in all directions, only coming to a stop when ^{hypersthene} they came in contact with hypersthene developing in a different direction, or where pigeonite crystals were not in contact with one another. Hypersthene that developed in all directions may have met in the middle of an original pigeonite crystal as in the case where one set of ^{relict} remnant (001)-augite exsolution lamellae or blebs now occur in two different crystals of hypersthene (p. 56 and Plate XV, Fig. B).

Bruynzeel (1957, p. 514) attributes the origin of the ^{relict} remnant (001)-augite exsolution lamellae in hypersthene to replacement rather than to exsolution. According to Maske (1966, p. 63) the replacement theory does not explain the lack of intergrowth texture in the magnesian orthopyroxene (bronzite) and the chemical mechanism which would remove or otherwise utilize large quantities of calcium from the rock during the final stages of their consolidation. In addition replacement does most certainly not explain

why sets of similarly orientated broad augite lamellae lie in any random plane in the hypersthene crystals, rather than follow crystallographic planes or cleavage directions.

Raal (1965, p. 48) believes that for synophitic hyperite and norite to form a complete feldspathic crystalline mush existed on the "floor" of the magma in which pigeonite crystallized interstitially from widely spaced nuclei which were propagated imperfectly on crystallization in a three dimensional way resulting in variations in the optical orientation. If crystallization takes place as envisaged by Raal one would at least expect an ophitic or nesophitic texture to have developed.

Furthermore, in the ophitic texture as in the bronzite-bearing mottled anorthosite and mottled leucohyperite no appreciable variation in optical orientation has been observed within the same crystal. Von Gruenewaldt (1966, p. 85) points out that the presence of lamellae of clinopyroxene, of different optical orientation and orientated at random in this optically continuous orthopyroxene indicates that in this case Raal's explanation does not hold, because the augite lamellae should then still show a constant orientation in the slightly disturbed nesophitic pigeonite (hypersthene "grains" with the same optical orientation).

Furthermore, hypersthene inclusions in augite occurring quite commonly with optical orientation different from those of the surrounding hypersthene "grains" belonging to one set, pose a great problem (see p. 39 and Plates XII, Figs. A and B). If the hypersthene clusters were single, interprecipitate, inverted pigeonite crystals which had crystallized from widely spaced centres of nucleation as suggested by Raal (1965, p. 48) then "closely spaced" centres of pigeonite must have existed as is indicated by the hypersthene inclusions in some of the augite within the "widely spaced" centres of the pigeonite. Two sets of differently spaced centres of nucleation for the same mineral could not have existed. It is thus far more likely that differently orientated

pigeonite grains underwent inversion to hypersthene with abc-reorientation. Those pigeonites which were not in contact with the surrounding pigeonite crystals did not form part of the hypersthene "grains" with similar optical orientation, but instead inverted on their own, perhaps just after the synophitic texture had developed.

2. (100)-augite exsolution lamellae in hypersthene

The two varieties of (100) lamellae in hypersthene are probably both due to exsolution of augite as suggested by Poldervaart and Hess (1951, p. 481) and must have developed during subsolvus cooling. As a result of the different nature of the extraordinary (100)-augite exsolution lamellae, Brown (1957, p. 531) suggests that these lamellae were exsolved from the pigeonite rather than from the orthopyroxene subsequent to inversion. If this were so the (100)-augite exsolution lamellae should also have random orientation in the hypersthene just as the ~~remnant relict~~ (001)-augite exsolution lamellae have. If the finer grain size in the synophitic rock were due to more pronounced cooling than in the case of the coarser-grained synophitic rock, one could perhaps also expect the degree of cooling under solvus conditions to be more pronounced than in the coarser-grained rock. Thus it could perhaps be that quicker cooling in the finer-grained rock under solvus conditions gave rise to irregular (100)-augite exsolution lamellae, whereas conversely regular (100)-augite exsolution lamellae may have been formed as a result of slower cooling under solvus conditions than in the fine-grained rock. The formation of irregular (100)-augite exsolution lamellae must also be partly due to the composition of the hypersthene, since no irregular type of (100)-exsolution lamellae was observed to occur in ^{finer} fine-grained bronzite. The general absence of "(100)-augite blebs" ~~does~~ suggests that the fine augite exsolution lamellae are structurally closely related to the orthopyroxene in which they occur.

Since these fine lamellae follow the (100) plane in the hypersthene "grains" with similar optical orientation in the synophitic hyperite and norite, it is evident that the hypersthene must have acquired structurally similar orientation first, before these lamellae were developed. The hypersthene "grains" must therefore have acquired structurally similar orientation after the formation of the (001)-augite exsolution lamellae and before the formation of the (100)-augite exsolution lamellae, i.e., during inversion.

3. Vermicular exsolution

For some reason or other both the ^{relict} remnant (001)-augite exsolution lamellae and the (100)-augite exsolution lamellae have been partly or completely deformed in some of the hypersthene occurring in the hypersthene-bearing mottled anorthosite and mottled leucohyperite of Zone II (see p. 58 and Plate XVII, Fig. A). A factor that may have brought about such a deformation could well have been reheating. If the vermicular exsolution were the result of metamorphism subsequent to the emplacement of the Bushveld Igneous Complex, one would not expect this form of exsolution to be confined only to one zone. Poldervaart and Hess (1951, pp. 482-483) suggest that the magnesian pigeonite of hypabyssal rocks, having crystallized at temperatures slightly above its inversion temperature, will invert readily to the orthorhombic form. They suggest that this happens before the regular augite plates along (001) can exsolve. Hence almost twice as many Ca^{2+} ions would be trapped in the orthorhombic structure as it can normally hold. These are rapidly expelled at the time of inversion as irregular blebs of diopsidic clinopyroxene in a type of exsolution phenomenon which has been called a "graphic intergrowth" by Walker and Poldervaart (1949). The vermicular exsolution in the hypersthene of the mottled leucohyperite was probably not formed in the same manner as the "graphic intergrowth" described by Poldervaart and Hess, since remnants of the ^{relict} remnant

(001)- augite exsolution lamellae and (100)- augite exsolution lamellae can sometimes still be recognized.

4. Formation of blebs from ^{relict} remnant (001)- augite exsolution lamellae

Virtually only augite blebs occur in the hypersthene of the synophitic hyperite and norite in Zone X of borehole KIG2 (Plate XI, Figs. A and B), whereas the hypersthene in hand specimens from Brits and Bon Accord Quarry contain mainly remnant (001)- augite exsolution lamellae (Plates XIV, Fig. B and XV, Fig. B). Raal (1965, pp. 14-20 and 46-51) studied the upper part of the Main Zone of the Bushveld Complex and describes hypersthene in the synophitic hyperite and norite in which broad augite lamellae occur. The hand specimens from Brits and Bon Accord Quarry most probably come from the same layer of the Main Zone investigated by Raal. Thus borehole KIG2 was most probably ~~only~~ drilled through ^{only} the lower portion of a sequence in which the synophitic rock contains hypersthene with blebs at the base and grades upwards over thousands of feet into synophitic rock in which the hypersthene contains essentially only ^{relict} remnant (001)- augite exsolution lamellae.

Brown (1957, p. 529) found that in the Skaergaard Intrusion upward in a thick sequence of rock lamellae also develop in place of the blebs in the hypersthene, at first incomplete and irregular, but finally becoming regular traversing each hypersthene "grain".

The exsolution blebs may have been formed in one of the following ways:

On slow cooling the (001)- augite exsolution lamellae may have drawn together into blebs. Experiments carried out by Tuttle and Bowen (1958, p. 138) on a chalcopyrite-bornite specimen revealed that relative^{ly} quick cooling resulted in the unmixing of chalcopyrite along grain boundaries as well as within the grains in the form of lamellae, whereas slow cooling of the same

minerals resulted in the formation of chalcopyrite blebs. In the case of the fine-grained synophitic hyperite in borehole KLG2 the original (001)- augite exsolution lamellae may have drawn together into numerous, small, more or less spherical blebs perhaps as a result of quicker cooling under solvus conditions in comparison with the coarser-grained synophitic hyperite and norite. In the coarser-grained synophitic rock slower cooling probably resulted in the formation of more widely spaced centres to which the material of the augite lamellae migrated.

The augite blebs in hypersthene may have developed directly as exsolution blebs without first passing through a lamellae stage. However, since, occasionally augite blebs occur together with ~~remnant~~^{relict} (001)- augite exsolution lamellae in similar orientation, it seems more likely that bleb development took place as a result of the drawing together of (001)- augite exsolution lamellae into blebs. Brown (1957, p. 529) suggests that irregular augite blebs were probably formed before they could be arranged as lamellae parallel to distinct structural planes in the pigeonite. As far as the blebs are concerned, it seems highly unlikely that they developed on their own without first passing through the lamellae stage, ~~for~~^{This appears from} the following reasons: If only blebs were developed directly, it is not clear why sets of blebs should have the same optical orientation. The exsolved augite components from the pigeonite travel a shorter distance if (001)- augite exsolution lamellae are formed than if blebs are formed. A spherical augite bleb has a surface area which is smaller than the surface area of tabular augite. Turner and Verhoogen (1960, p. 462) point out that all surface particles, and hence the surface itself, are subject to a force acting toward the interior of the phase, tending therefore to reduce the area of the surface.

Thus on slow cooling under solvus conditions the (001)- augite exsolution lamellae formed first with their a-, b-, and c- axes in common with the host pigeonite. It is not quite certain whether the bleb development then took place during inversion or

subsequent to inversion. During inversion the temperature would be constant for some time. At that stage the pigeonite would have been in an unstable condition and one would expect that blebs could therefore have developed. On the other hand, subsequent to inversion sets of lamellae had random orientation in the hypersthene and as a result there could be no structural link between the hypersthene and the (001)-augite lamellae with the result that the lamellae would be structurally independent of the host hypersthene and could therefore have formed blebs. In the hypersthene-bearing mottled anorthosite and mottled leucohyperite well preserved ~~remnant~~^{relict} (001)-augite exsolution lamellae sometimes lie in the (102) plane of the host hypersthene (Plate VIII, Fig. B). The augite and the host hypersthene have their b- and c-axes in coincidence. Sets of ~~remnant~~^{relict} (001)-augite exsolution lamellae may, however, occur just as well preserved at any random plane in the host hypersthene and have no crystallographic axes in coincidence with ~~it~~^{them} (Plates XIV, Fig. B and XVI, Fig. A). Although, the latter type of lamellae are independent of the hypersthene structure, ~~remnant~~^{relict} (001)-augite lamellae are also well preserved. If cooling were relatively rapid under solvus conditions the ~~remnant~~^{relict} (001)-augite exsolution lamellae would remain intact, or if the augite lamellae did not quite reach the margin, they may have drawn together partially. Slow cooling would result in the breaking-up of the original lamellae into numerous augite blebs, whereas very slow cooling would give rise to the breaking-up of the lamellae into widely separated centres which consequently formed much larger blebs.

C. Exsolution phenomena in augite

Poldervaart and Hess (1951, p. 483) suggest that the clinopyroxenes more Fe-rich than about Q_{15} exsolve (001)-pigeonite exsolution lamellae which have their crystallographic axes in

coincidence with ^{those} ~~that~~ of the host augite and on further cooling of the pyroxene below the orthopyroxene-pigeonite inversion temperature, these lamellae may invert to orthopyroxene in which the b- and c-axes coincide with those of the host augite. These deductions are strengthened by the findings of Bown and Gay (1960, p. 387) in connection with pyroxenes from Skaergaard in which the (001)- pigeonite lamellae in augite have mostly not inverted to orthopyroxene. All the (001)- lamellae in the augite investigated have the b- and c-crystallographic axes in coincidence with similar axes of the host augite and probably represent inverted pigeonite. In contrast to Poldervaart and Hess (1951, p. 483), Binns and Long (1963, p. 778) conclude on the basis of electron-probe traverses across (001) lamellae in two augites that the (001) lamellae are clinopyroxene lamellae which belong to the clinoenstatite-clinoferrrosilite series rather than the pigeonite series.

Poldervaart and Hess (1951, p. 483) suggest that after inversion on slow cooling orthopyroxene is exsolved parallel to the (100) plane in the augite. It has already been pointed out (p. 59) that orthopyroxene and hematite are probably exsolved together in the (100) plane of the augite investigated.

VIII. CORONOPHITIC TO CORONOSUBOPHITIC CLOTS

Coronophitic to coronosubophitic clots occur in the synophitic hyperite and norite, the hypersthene-bearing mottled anorthosite and mottled leuconorite, and in the leucohyperite. In the first two rock types the augite may form a complete or partial rim around the hypersthene, whereas in the leucohyperite the augite may form a similar rim around the bronzite.

A. Hypersthene-bearing coronophitic to coronosubophitic clots

The hypersthene enclosed in the augite in the synophitic hyperite and norite (see p. 39 and Plate XII, Figs. A and B), and in the hypersthene-bearing mottled anorthosite and mottled leucohyperite (see p. 47 and Plate VIII, Fig. B) may have been formed ^{in any of the following ways.} ~~as follows:~~ Lombaard (1934, p. 26) was of the opinion that the augite rims resulted from a reaction of the hypersthene (pigeonite?) with the magma, whereas Van Zyl (1960, p. 31) comes to the conclusion that the hypersthene inclusions are the result of an intergrowth between these two pyroxenes. A third possibility could perhaps be that early-formed pigeonite crystals may have been enclosed by the augite which began to crystallize before the pigeonite crystallization came to completion.

Van Zyl (1960, p. 28) points out that similarly orientated orthopyroxene grains in the same augite crystal could not have developed as a result of reactive solution of the orthopyroxene caused by reaction with rest liquid, because then one would expect disconnected hypersthene occurring in the augite to have different optical orientations. Van Zyl further points out that if reaction between orthopyroxene and magma took place at an early stage as suggested by Lombaard (1934, p. 27) one could at least expect that most of the hypersthene crystals

~~should~~ ^{would} show signs of reaction. Van Zyl suggests that if reaction did take part in the formation of the clinopyroxene, it must have done so during a late stage of crystallization accompanied by diffusion. Poldervaart and Hess (1951, p. 479) also come to the conclusion that augite and any one of the following minerals have no reaction relationship: olivine, orthopyroxene, and pigeonite.

In dolerite from Mount Arthur pigeonite was observed to occur as two similarly orientated inclusions in augite. These two separate pigeonite inclusions and the host augite have their crystallographic axes in coincidence. Where the b- and c-axes of the hypersthene and the host augite coincide (Plates VIII, Fig. B and XII, Fig. B), the original pigeonite probably also had all crystallographic axes in coincidence with those of the host augite. These observations all seem to strengthen Maske's (1966, p. 60) view that pigeonite crystallizes against the augite in such an orientation that the two phases share the three crystallographic axes. In fact the crystal structures of these two clinopyroxenes are very similar (Deer, Howie, and Zussman, 1963, vol. 2, p. 144), whereas their crystal symmetry is identical. Since no reaction relation is believed to have existed between pigeonite and augite, the two minerals must have crystallized together forming an intergrowth. When two such crystallographically similar clinopyroxene crystals form an intergrowth it appears that virtually no internal stress is set up when the crystallographic axes coincide. Thus an intergrowth between these two minerals may take place freely in any form and in any direction as long as the crystallographic axes coincide. Disconnected pigeonite intergrowth may even have started to develop from different centres in the same augite crystal.

Where the (001)- hypersthene exsolution lamellae in the augite occur together with the hypersthene inclusions the original pigeonite could have had a random orientation, but on inversion the original (001)- pigeonite exsolution lamellae may

have undergone inversion with a-reorientation, whereas at the same time the pigeonite inclusions may have undergone inversion with abc-reorientation assuming the same crystallographic orientation as the (001)- hypersthene lamellae in the augite.

Those hypersthene, particularly in the synophitic hyperite and norite, that have neither crystallographic axes nor optical orientation in coincidence with either the host augite or the hypersthene cluster (see p. 39 and Plate XII, Fig. A), probably simply represent original diversely orientated pigeonite crystals mantled by augite. These diversely orientated pigeonites did then not invert so that the b- and c- crystallographic axes coincide with those of the host augite. Here no irregular intergrowth texture developed.

Inversion with abc-reorientation ~~does~~ well explains why some of the hypersthene inclusions in the synophitic rocks have the same optical orientation as the surrounding hypersthene "grains" with similar optical orientation. It appears that those hypersthene inclusions which have optical orientations different from the hypersthene "grains" with similar optical orientation probably had a "protective shell" made up of one or more augite crystals and occasionally ^{of} ~~by~~ some plagioclase. The effect of such a "protective shell" would have been that the original pigeonite inclusions which were enclosed mainly in the augite could not come in contact with the pigeonite grains which underwent inversion with abc-reorientation. Thus these original pigeonite inclusions were prevented from growing into optical continuity with the surrounding hypersthene cluster. Where a "protective shell" was not complete inversion with abc-reorientation might have taken place, resulting in the same optical orientation for the hypersthene inclusion as the surrounding hypersthene "grains". Sometimes only a portion of the original pigeonite inclusion in the augite has acquired the same optical orientation during inversion as the optical orientation of the surrounding hypersthene "grains" (Plate XII, Fig. A). This suggests that the original pigeonite was not continuously connected in the augite.

B. Bronzite-bearing coronophitic to coronosubophitic clots

In the bronzite-bearing coronophitic to coronosubophitic clots where no crystallographic axes of the somewhat round bronzite grains coincide with the augite margin (see p. 52 and Plate X, Fig. A), the bronzite probably represents inclusions in the augite.

IX. SUMMARY

Some petrological aspects of rocks from four borehole sections between the Merensky Reef and the Main-Zone Gabbro and some hand specimens from Brits and Bon Accord Quarry were investigated. The boreholes were drilled by the Johannesburg Consolidated Investment Co., Ltd., near Rustenburg, north-east of Northam, and in the north-eastern Bushveld Complex east of the Olifants River.

On the basis of the volumetric mineral^{ogical} compositions five rock types were recognized in the four boreholes investigated. It was convenient to subdivide these rock types according to their characteristic and easily recognizable textures. The different rock and textural types which were distinguished, in order of decreasing abundance, are as follows: hypidiomorphic hyperite, norite, and gabbro; synophitic hyperite and norite; ophitic to nesophitic hypidiomorphic hyperite; subophitic hypidiomorphic hyperite; hypersthene- and bronzite-bearing mottled anorthosite and mottled leucohyperite; spotted anorthosite and spotted leuconorite; anorthosite; and leucohyperite.

In the hypidiomorphic hyperite, norite, and gabbro the three main minerals are cumulus crystals the outer margins of which had probably crystallized from the pore liquid.

The synophitic hyperite and norite are similar to the rocks with hypidiomorphic texture in that the three main minerals are cumulus crystals, but the original diversely orientated pigeonite grains in these rocks have inverted in such a way that large clusters of hypersthene "grains" with very nearly the same optical orientation developed.

In the ophitic to nesophitic hypidiomorphic hyperite both the plagioclase and augite seem to be cumulus crystals. In these rocks numerous, relatively large plagioclase inclusions occur in the bronzite areas, whereas small augite inclusions in the bronzite areas are rather rare. As a result of the

extraordinary textural relationships, it ~~was~~^{is} postulated that the bronzite in the bronzite areas (ophitic and nesophitic patches) crystallized relatively early as open sponge-like structures and that the augite could not have crystallized freely in these bronzite areas.

The texture in the subophitic hypidiomorphic hyperite is somewhat similar to that of the ophitic to nesophitic hypidiomorphic hyperite. However, the bronzite areas are much smaller, contain only a few small plagioclase inclusions, and are surrounded by a plagioclase-rich rim. The crystallization of the orthopyroxene probably did not begin with the formation of open sponge-like structures. For some unknown reason the plagioclase-rich rims were probably formed by ionic diffusion during cotectic crystallization of the pyroxenes and plagioclase.

In the anorthosites the plagioclase laths seem to be cumulus crystals. The central plagioclase-free area in some of the pyroxenes may also be cumulus crystals, whereas the pyroxene interstitial to plagioclase most probably crystallized from the pore liquid as did the outer margin of the plagioclase laths.

The various types of layering ~~occurring~~ in the rocks investigated can be ascribed to igneous lamination, cryptic layering, rhythmic layering, variation in the grain size, and large-scale textural layering.

Some of the layering is believed to be due to new heaves of magma which were emplaced at intervals so that each of them came to rest on top of the previous emplacement, whereas other layering may be due to such processes as differential rates of crystal sinking, power of nucleation, and undercooling. The cryptic layering is probably due to fractional crystallization and/or magma which changed systematically in chemical composition emplaced at intervals.

Since one can correlate the rocks of the western and eastern mafic portions of the Bushveld Complex, it seems likely that the corresponding large-scale textural layers are continuous and crystallized more or less at the same time under somewhat

similar physical conditions from the same interconnected emplacements of magma.

The pyroxenes in all the rocks investigated show some form of exsolution. The bronzite has one set of fine continuous (100)-augite exsolution lamellae. The hypersthene has normal or extraordinary (100)-augite exsolution lamellae and in addition contains sets of relatively broad ^{relict} ~~remnant~~ (001)-augite exsolution lamellae and/or blebs. The sets of ^{relict} ~~remnant~~ (001)-augite exsolution lamellae usually lie in any random plane in relation to the hypersthene structure. The vermicular exsolution in the hypersthene of Zone II seems to be partly or completely deformed ^{relict} ~~remnant~~ (001)-augite exsolution lamellae and (100)-augite exsolution lamellae. The augite always contains (100)-exsolution lamellae which seem to consist of orthopyroxene and hematite, but the (001)-hypersthene exsolution lamellae are not always present, particularly not in the augite which is interstitial to plagioclase and/or orthopyroxene.

The relatively broad ^{relict} ~~remnant~~ (001)-augite exsolution lamellae and blebs occurring in hypersthene were originally exsolved on slow cooling parallel to the (001) planes of diversely orientated pigeonite crystals. These (001)-augite exsolution lamellae most probably had all their crystallographic axes in coincidence with the corresponding crystallographic axes of the host pigeonite. The inversion of pigeonite to hypersthene was occasionally of such a nature that the b- and c-axes were retained, as ^{is} ~~was~~ indicated in one specimen where ^{relict} ~~remnant~~ (001)-augite exsolution lamellae lie in the (102) plane of the host hypersthene with which they also have their b- and c-axes in coincidence. Only the a-axis has undergone reorientation and this form of inversion was therefore referred to as inversion with a-reorientation.

In the majority of cases, as was indicated by the random orientation of sets of ^{relict} ~~remnant~~ (001)-augite exsolution lamellae in relation to the hypersthene structure, especially in the synophitic hyperite and norite, inversion of pigeonite to

hypersthene was of such a nature that none of the crystallographic ~~his~~ axes of the original pigeonite were retained. Since all crystallographic axes have undergone reorientation this form of inversion ~~was~~^{is} referred to as inversion with abc-reorientation.

The nuclei from which inversion has taken place ~~were~~^{was} referred to as inversion nucleation centres. From these nuclei inversion seems to have taken place radially where original pigeonite grains were in contact with one another. The late-~~teral~~ growth of the hypersthene was impeded only when two hypersthenes developing in different directions came into contact with one another or when pigeonite crystals were not in contact with one another. It seems that the spacing of the inversion nuclei, was much wider, more or less the same, or much more closely spaced as compared with the spacing of the original pigeonite crystals. The spacing of these nuclei was probably controlled by the degree of cooling under solvus conditions, i.e., relative^{ly} quicker cooling resulted in closer spacing of nuclei than slower cooling.

The size and spacing of augite blebs in hypersthene, which are believed to have been derived from ~~remnant~~^{relict} (001)-augite exsolution lamellae, and the formation of extraordinary (100)-augite exsolution lamellae in hypersthene, were probably also both essentially controlled by the rate of subsolvus cooling.

In the hypersthene-bearing coronophitic to coronosubophitic clots in the synophitic hyperite and norite and in the hypersthene-bearing mottled anorthosite and mottled leucohyperite the original pigeonite may have formed an intergrowth with the augite or it may be enclosed by the augite. In these clots original pigeonite seems to have undergone inversion with either a-reorientation or abc-reorientation. In the synophitic hyperite and norite the type of reorientation of the original pigeonite within the augite depends upon whether the pigeonite was in contact with the surrounding pigeonite grains or not. The bronzite in the bronzite-bearing coronophitic to

coronosubophitic clots was probably mostly formed as a result of the late interstitial crystallization of the augite.

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PLATE I

Locality map of boreholes in the western and eastern mafic zones of the Bushveld Igneous Complex.

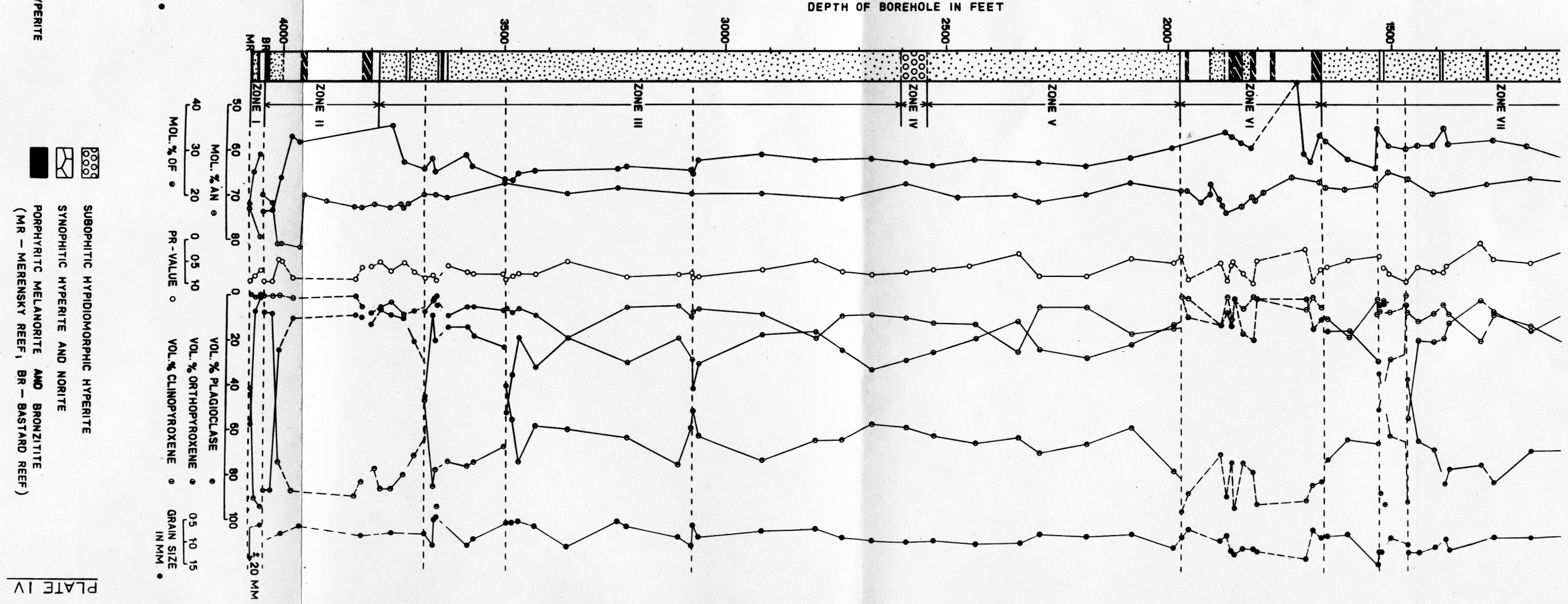
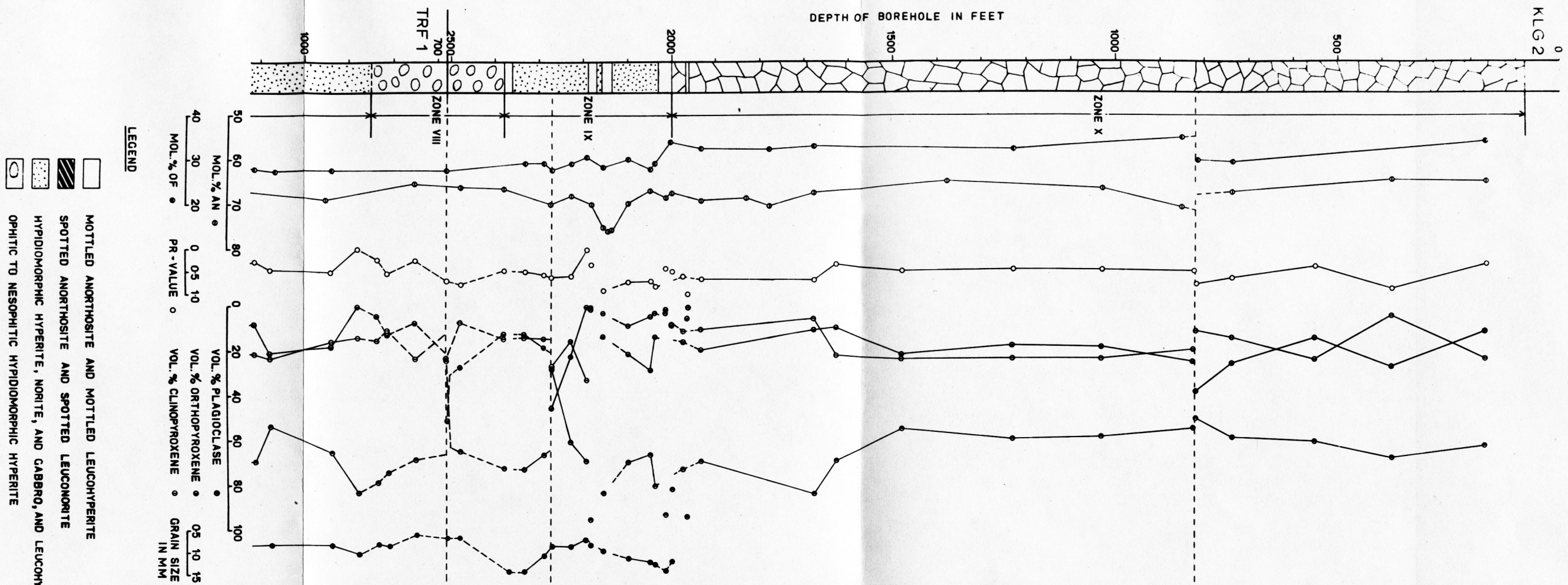


PLATE IV

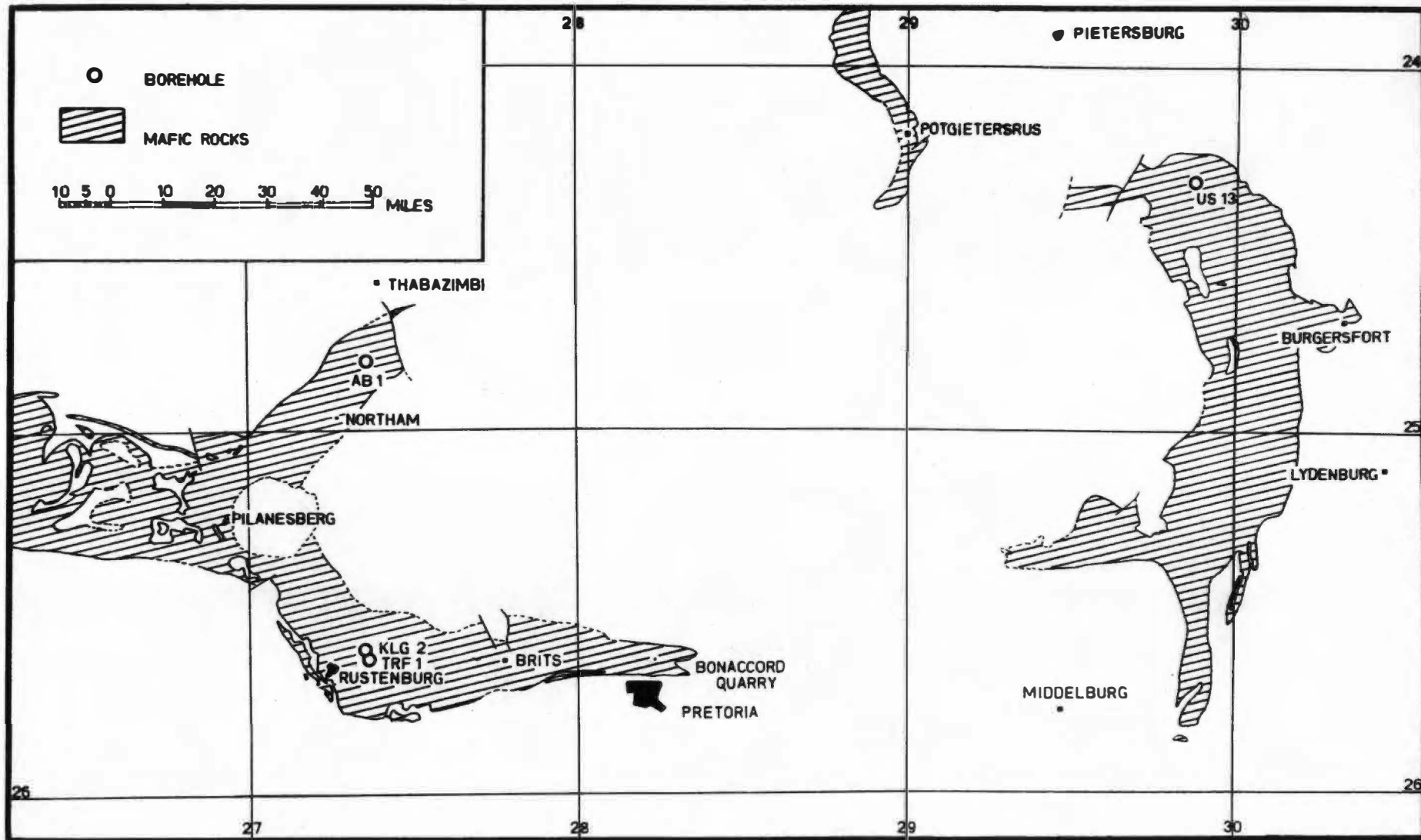


PLATE II

Graph for the conversion of average micrometric traverse distance to average grain size.

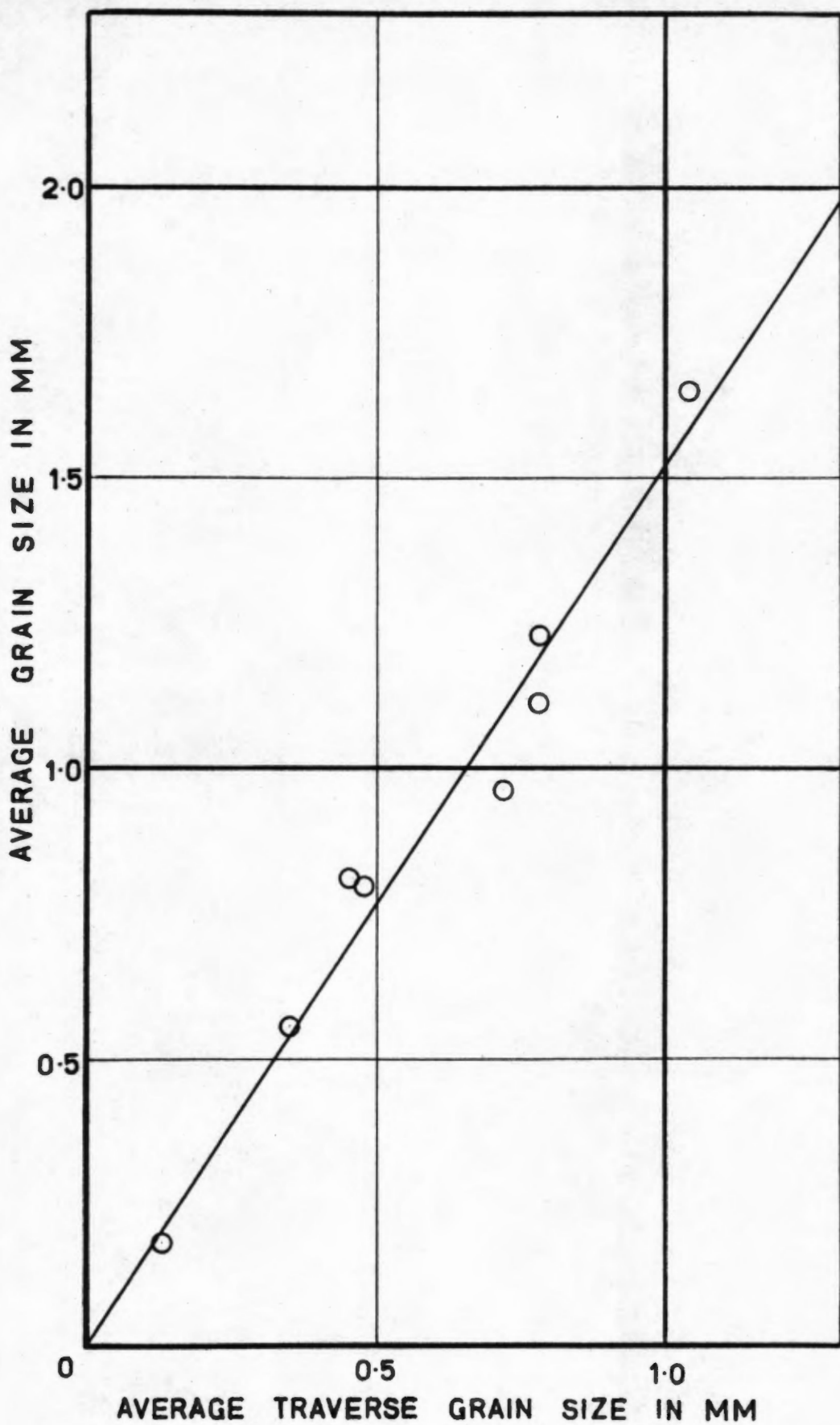


PLATE III

Correlation of zones in boreholes KLG2 and TRF1 (joined up to give a continuous section), AB1, and US13.

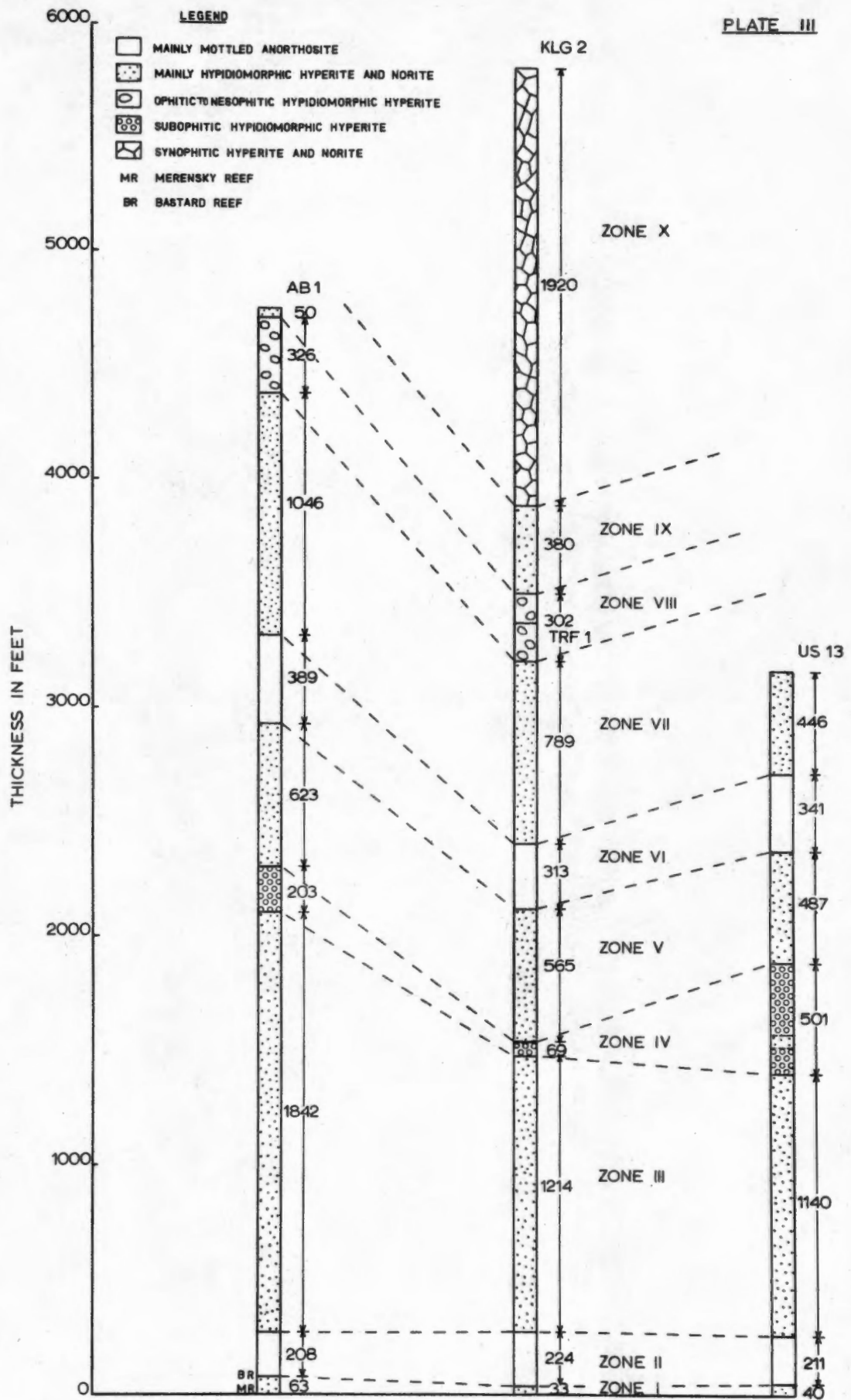


PLATE IV

Quantitative

~~Variations in the curves of the volumetric mineral compositions~~ of the pyroxenes and plagioclase, the Pr value, the composition of the orthopyroxene and plagioclase, and the grain size in boreholes KLG2 and TRF1. The two boreholes were joined up to give one continuous section.

PLATE V

Quantitative

~~General~~ variations in the curves of the volumetric mineral compositions of the pyroxenes and plagioclase, the Pr value, and the composition of the orthopyroxene and plagioclase in boreholes KLG2 and TRF1. The two boreholes were joined up to give one continuous section.

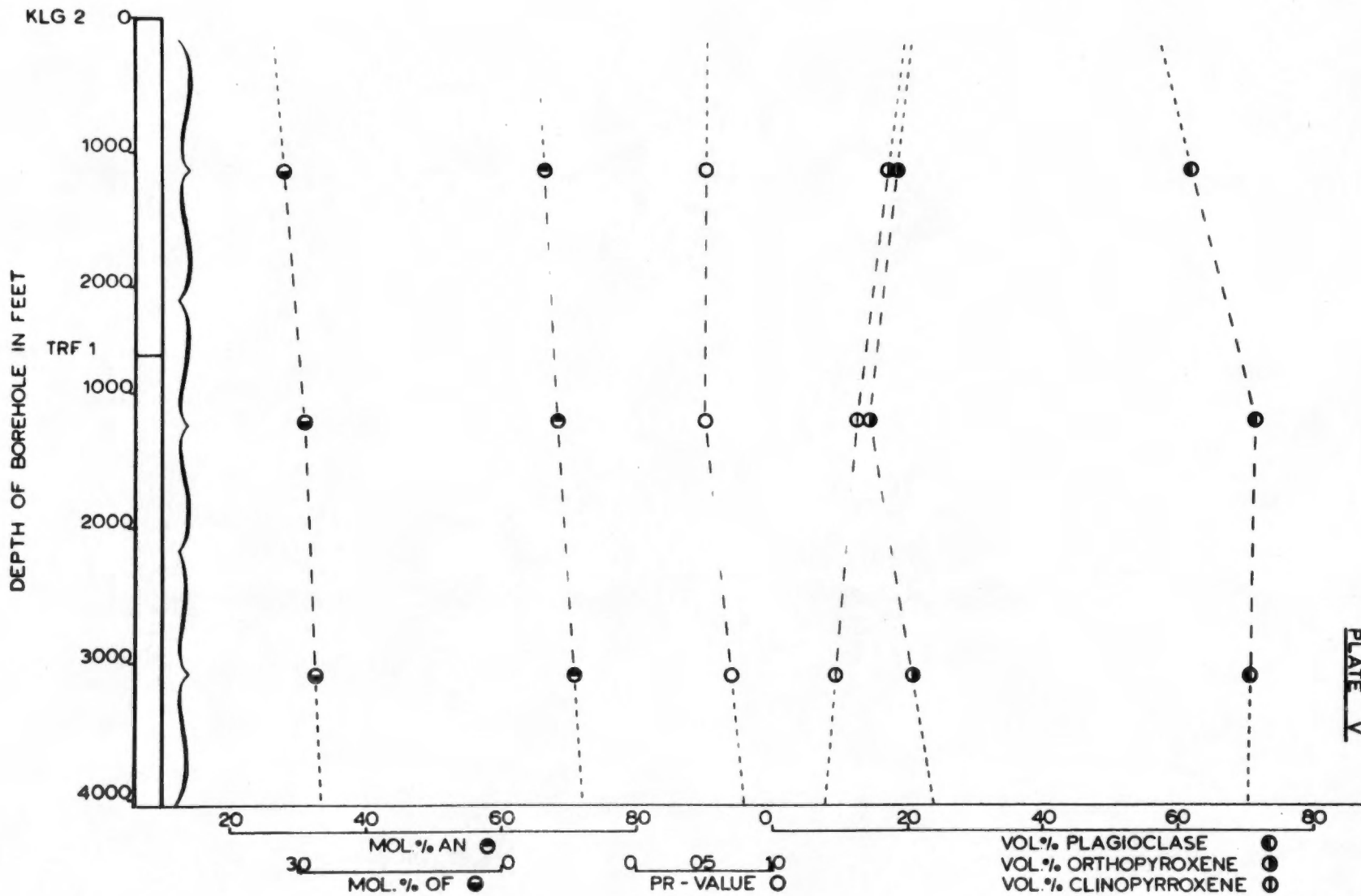


PLATE V

PLATE VI

Figure A. Hypidiomorphic hyperite from Zone VII in borehole TRF1 consisting of equigranular, diversely orientated grains of bronzite (wide hatching with thick outer margin), augite (narrow hatching), and plagioclase (blank).

Figure B. Synophitic norite from Brits containing portions of three small diversely orientated sets of hypersthene "grains". Each set of hypersthene "grains" has virtually the same optical orientation. Thick lines were drawn for the middle set so that the three sets can be depicted most readily. The plagioclase and augite are indicated as in Figure A.

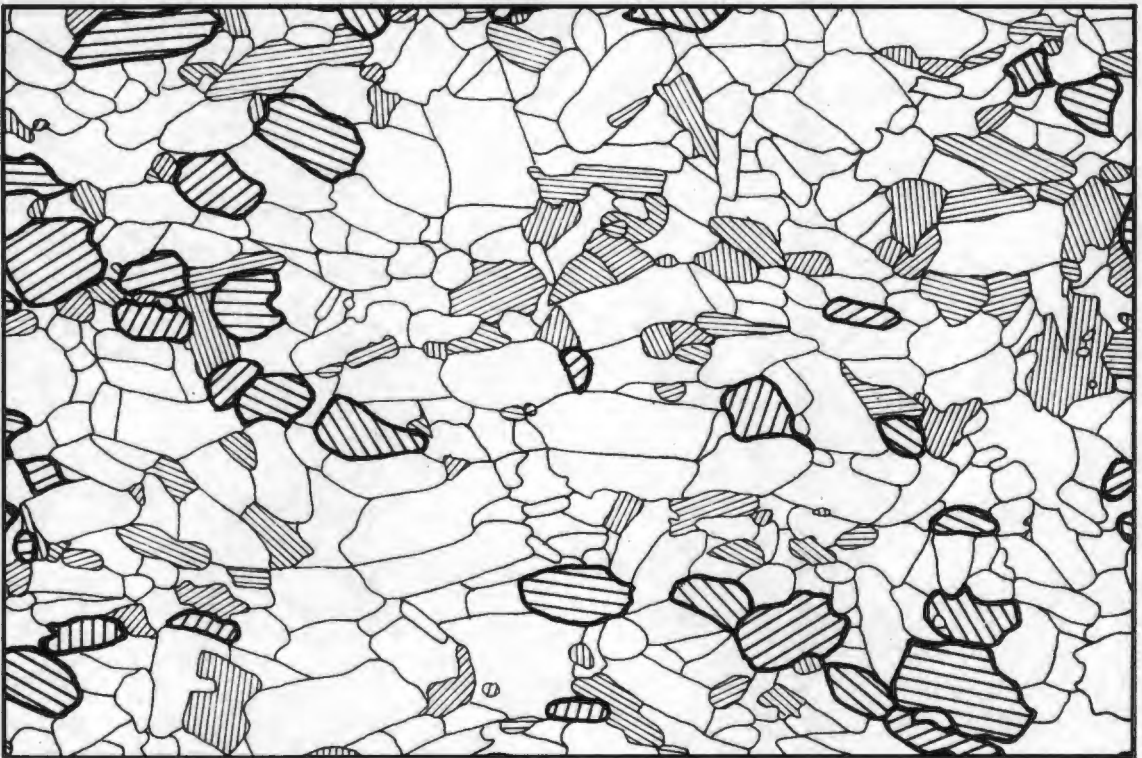


FIGURE A

IMM

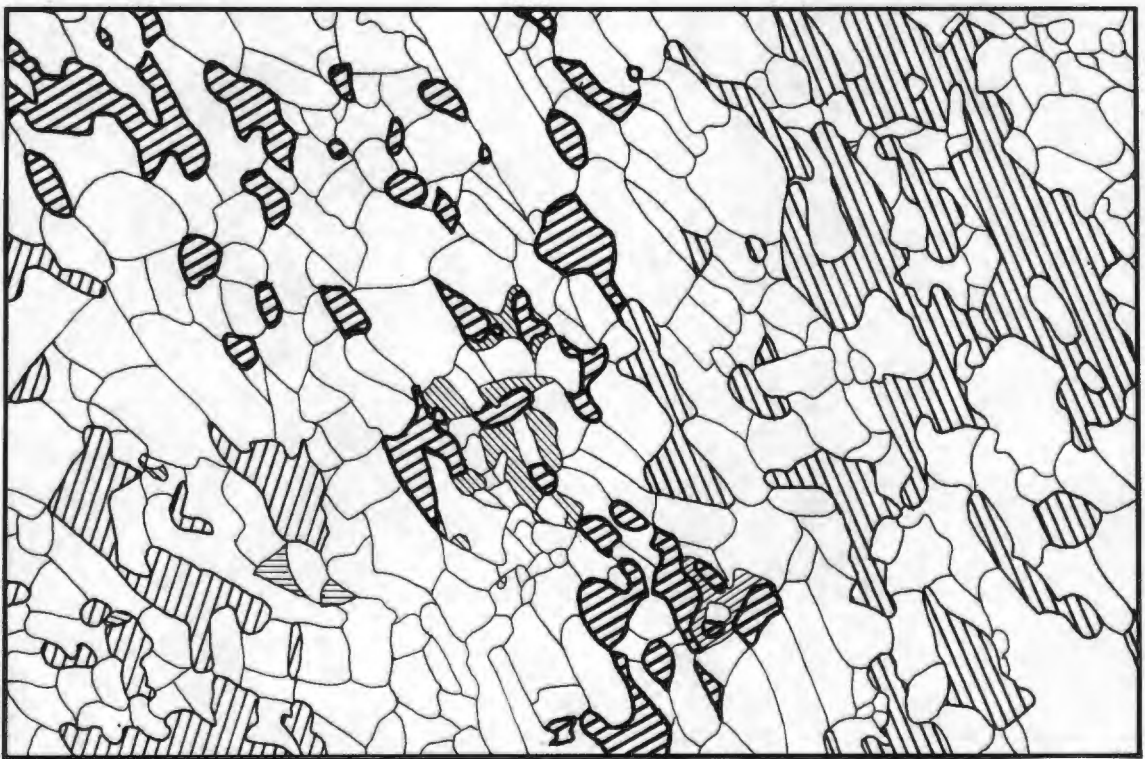


FIGURE B

IMM

PLATE VII

Figure A. Ophitic to nesophitic hyperite from Zone VIII in borehole KLG2 containing a nesophitic area consisting of patches of bronzite with the same optical orientation (wide hatching in the same direction) and plagioclase (blank) surrounded by a hypidiomorphic area in which diversely orientated augite (narrow hatching) and plagioclase occur.

Figure B. Ophitic to nesophitic hyperite from Zone VIII in borehole TRF1 containing two ophitic areas in each of which the bronzite (wide hatching) has the same optical orientation. The hypidiomorphic area between the bronzite areas is similar to that in Figure A.

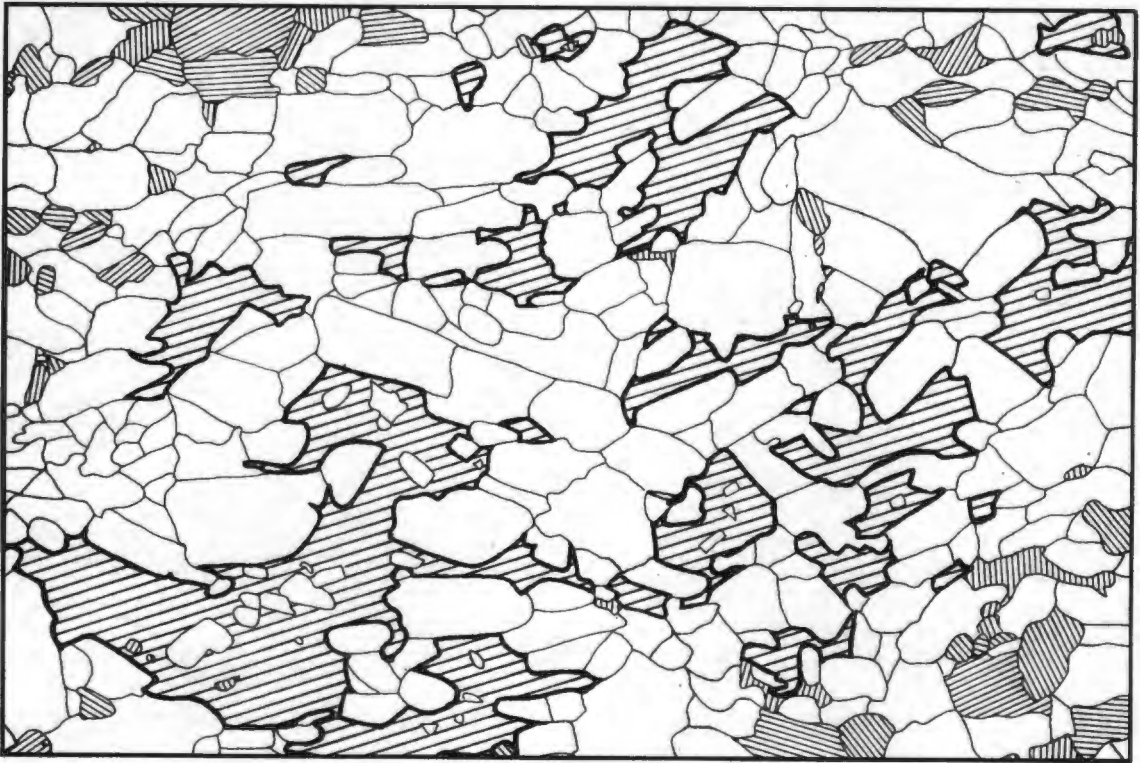


FIGURE A 1MM

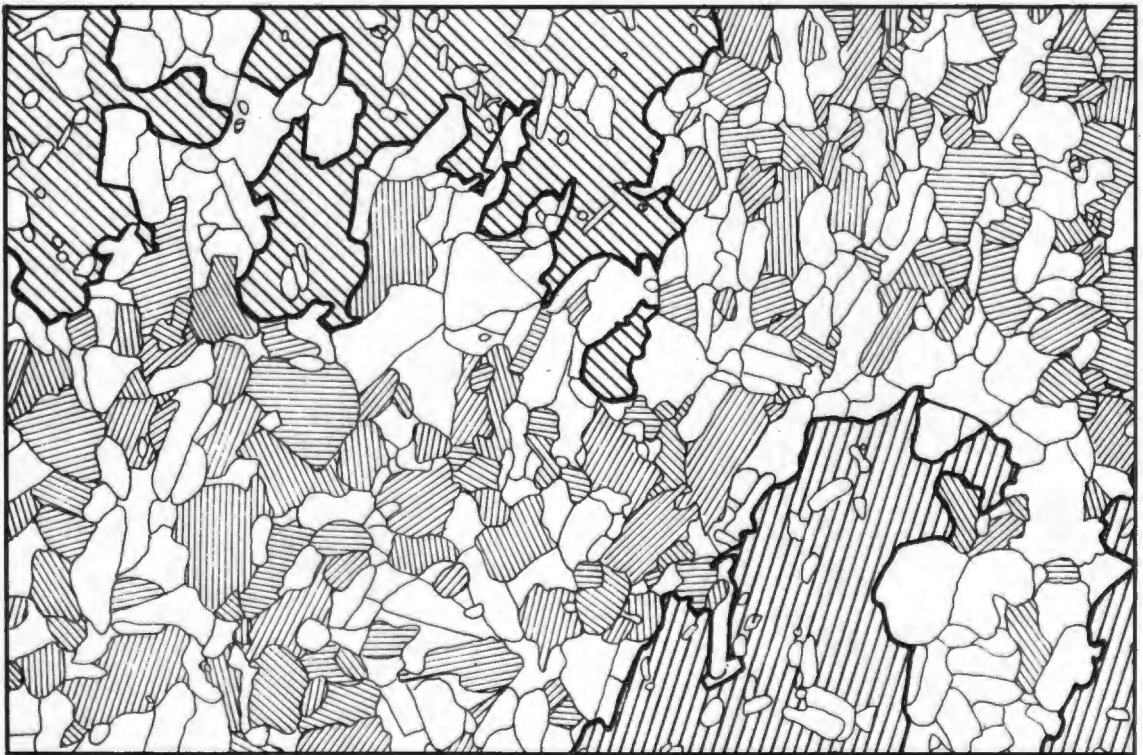


FIGURE B 1MM

PLATE VIII

Figure A. Subophitic hypidiomorphic hyperite from Zone IV in borehole US13 with subophitic texture in the bronzite areas (wide hatching) and hypidiomorphic texture between the bronzite areas where it consists of equigranular augite (narrow hatching) and plagioclase (blank). The bronzite is surrounded by a plagioclase-rich margin and the augite occurs concentrated furthest from the bronzite.

Figure B. Hypersthene-bearing mottled leucohyperite from Zone X in borehole KLG2 with mottles made up of a number of hypersthene (wide hatching) and augite (narrow hatching) crystals. A number of hypersthene-bearing coronophitic to coronosubophitic clots occur. In the central coronosubophitic clot ~~remnant~~^{relict} (001)-augite exsolution lamellae, having the same optical orientation as the augite corona, lie in the (102) plane of the host hypersthene with which they also have their b- and c-axes in coincidence. Plagioclase is indicated as in Figure A.

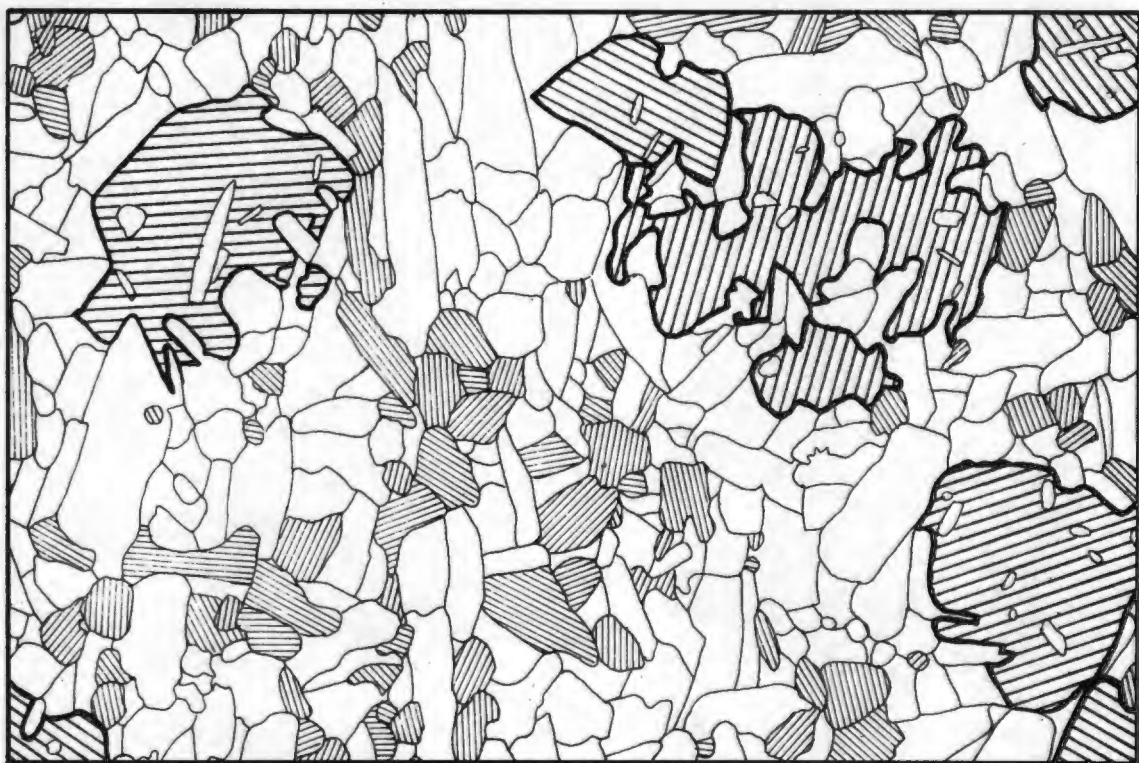


FIGURE A

1MM

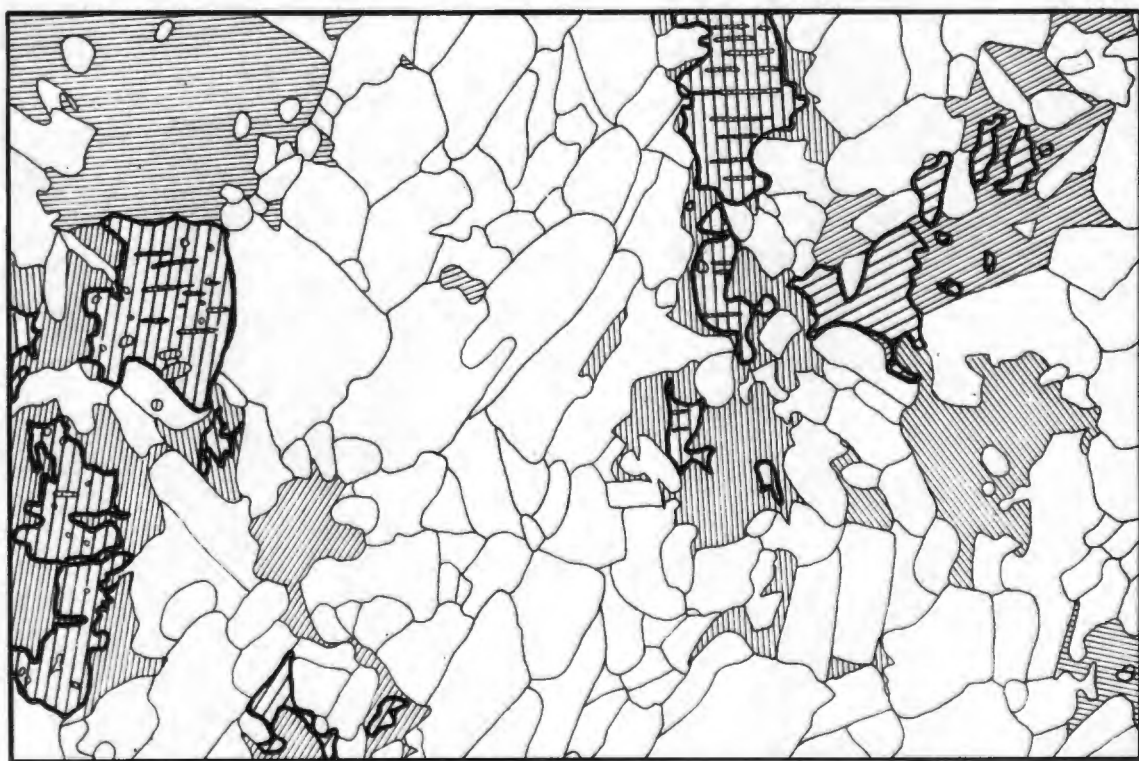


FIGURE B

1MM

PLATE IX

Figure A. Part of a mottle in bronzite-bearing mottled anorthosite from Zone II in borehole TRF1 in which the bronzite (wide hatching) and the augite (narrow hatching) are each optically continuous. In the bronzite area the rock has a nesophitic texture and in the augite area the rock has an ophitic texture. The blank areas are plagioclase.

Figure B. Spotted anorthosite from Zone III in borehole US13 in which the spotted effect is caused by relatively ~~round~~ ^{equidimensional} orthopyroxene (wide hatching) with margins interstitial to plagioclase (blank). Interstitial augite (narrow hatching) is an accessory mineral.

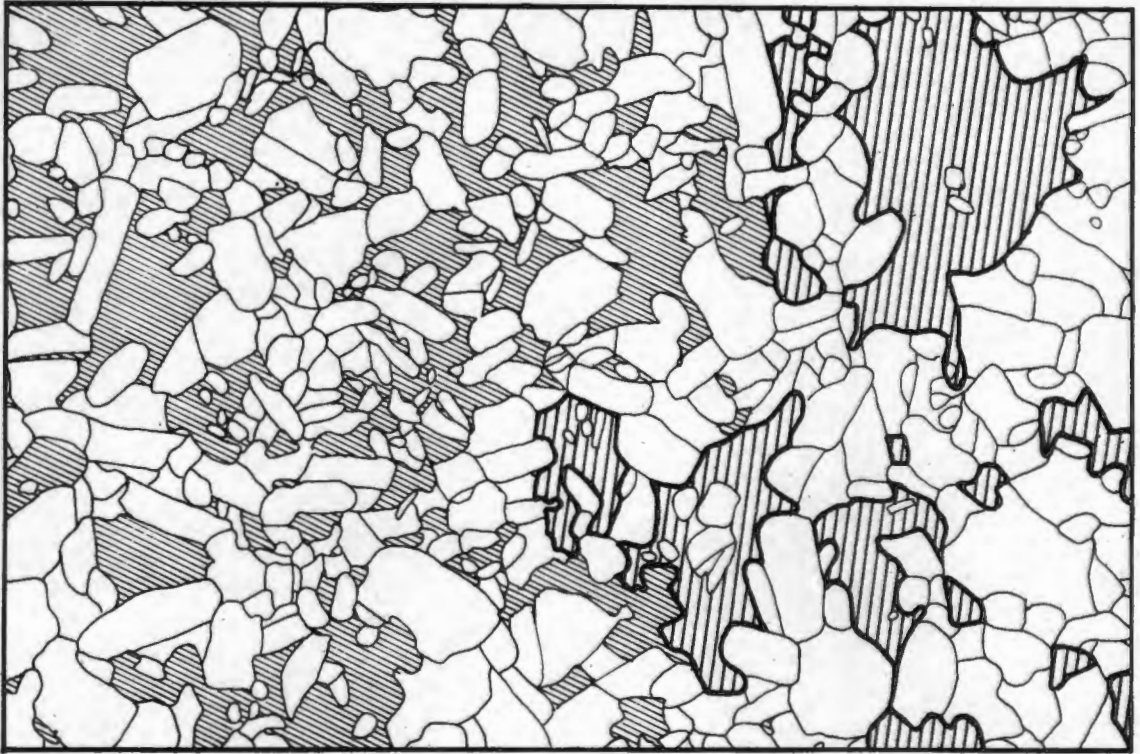


FIGURE A

1MM

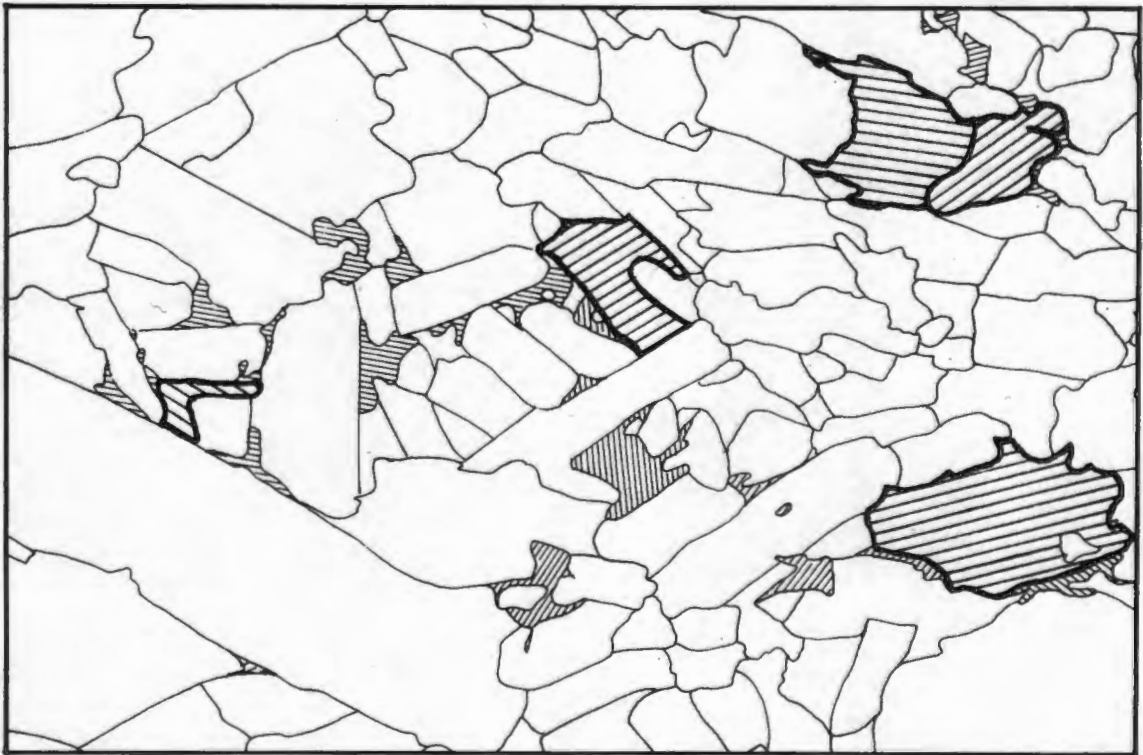


FIGURE B

1MM

PLATE X

Figure A. Leucohyperite from Zone VI in borehole TRF1 containing augite (narrow hatching) which forms a corona around three differently orientated bronzite grains (wide hatching). The two minerals also occur separately. The blank areas are plagioclase.

Figure B. Leucohyperite from the upper part of Zone IX in borehole KIG2 with essentially subophitic texture in the bronzite (wide hatching) and augite (narrow hatching) areas. Some of the augite crystals have (001)-hypersthene exsolution lamellae. The plagioclase is indicated as in Figure A.

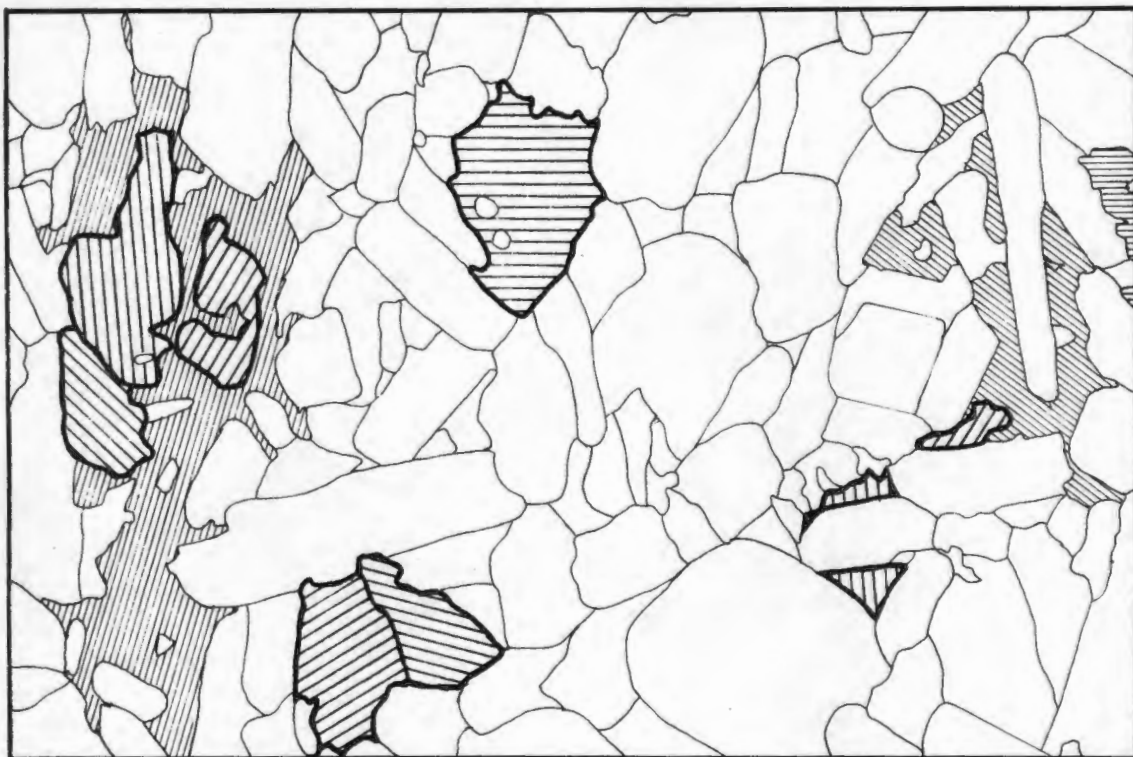


FIGURE A

1MM

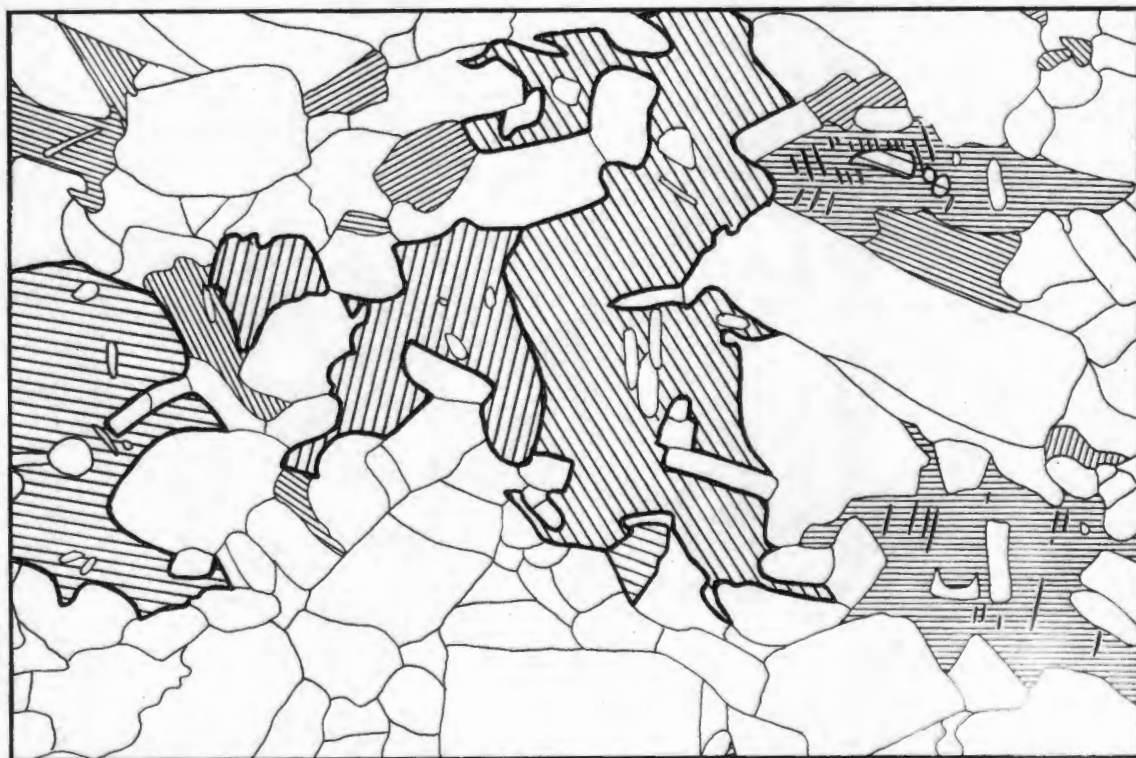


FIGURE B

1MM

PLATE XI

Figure A. Synphitic hyperite from the Upper Subzone of Zone X in borehole KLG2 with somewhat interconnected, rather ~~round~~^{equidimensional} hypersthene "grains" with similar optical orientation (wide hatching) containing augite exsolution blebs (narrow hatching). The plagioclase and augite crystals are not shown.

Figure B. Synphitic hyperite from the Lower Subzone of Zone X in borehole KLG2 in which the hypersthene "grains" with similar optical orientation are ~~more~~^{equidimensional} more interconnected, more continuous, and less ~~round~~ than those shown in Figure A. Augite exsolution ~~ion~~ blebs are indicated by narrow hatching. The plagioclase and augite crystals are not shown.

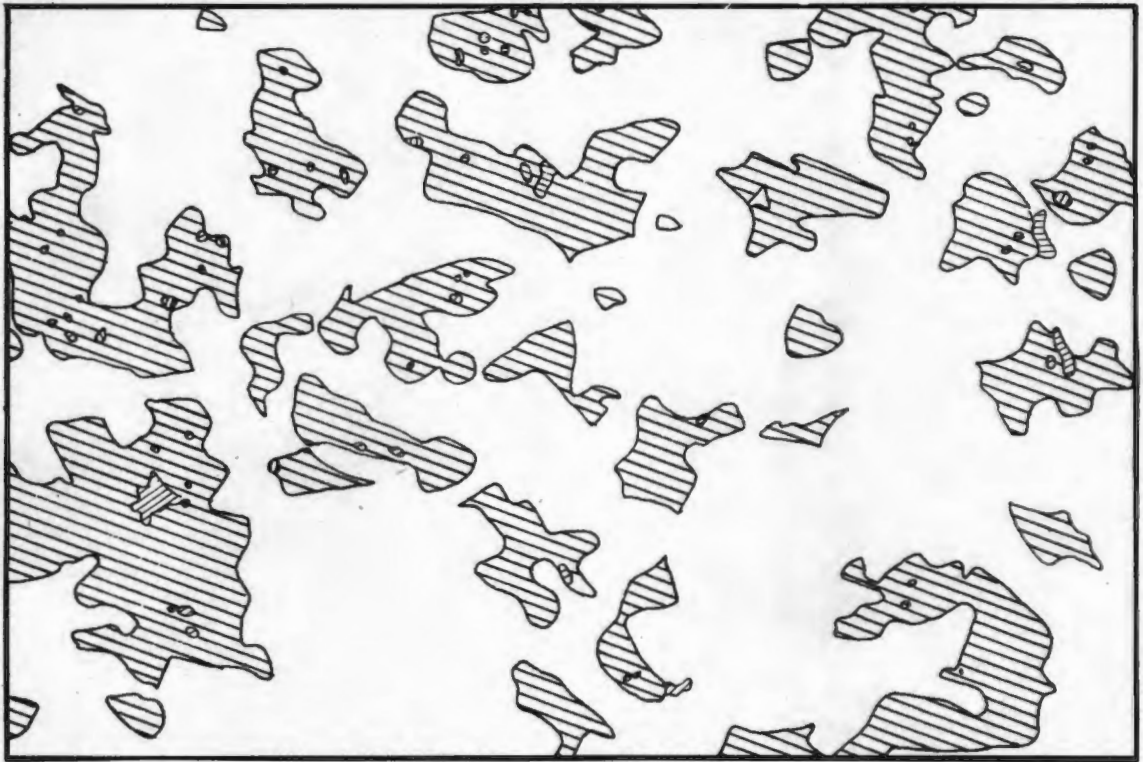


FIGURE A

IMM

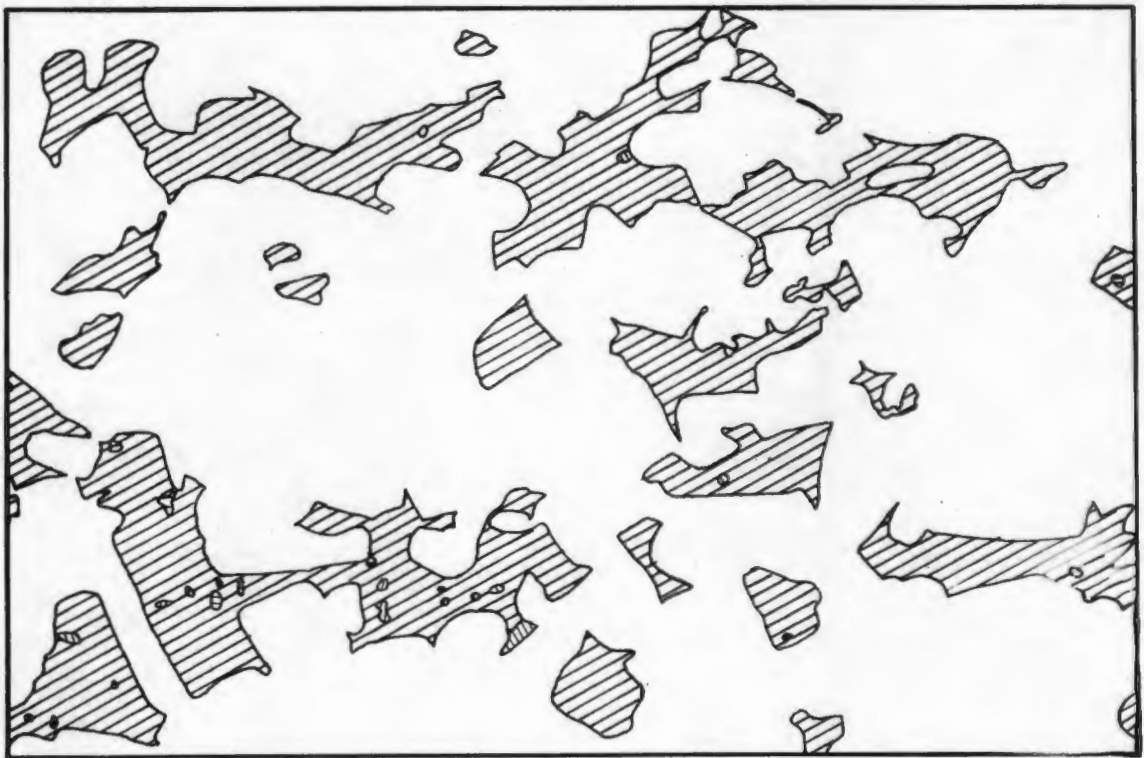


FIGURE B

IMM

PLATE XII

Figure A. Synophitic hyperite from the Bon Accord Quarry with most of the hypersthene inclusions (wide hatching) in the coronosubophitic clot showing the same optical orientation as the hypersthene surrounding the augite (narrow hatching). The two hypersthene inclusions to the left of the coronosubophitic clot have optical orientations differing both from that of the surrounding hypersthene "grains" which have similar optical orientation and from that of the host augite. The ~~remnant~~^{relict} (001)-augite exsolution lamellae have also been indicated in the hypersthene "grains" by lamellae with narrow hatching. The blank areas are plagioclase.

Figure B. Synophitic hyperite from Zone X in borehole KLG2 containing two coronosubophitic clots. In the smaller coronosubophitic clot the augite corona (narrow hatching) seems to be complete, but in the larger coronosubophitic clot the hypersthene (wide hatching) is enclosed by a number of augite and plagioclase crystals. In this latter clot the b- and c-axes of the hypersthene coincide with the corresponding axes of the main augite crystal which partly enloses it. The optical orientation of the hypersthene in the two coronosubophitic clots does not coincide with that of the surrounding hypersthene "grains" which have similar optical orientation. The plagioclase is indicated as in Figure A.



FIGURE A

1MM

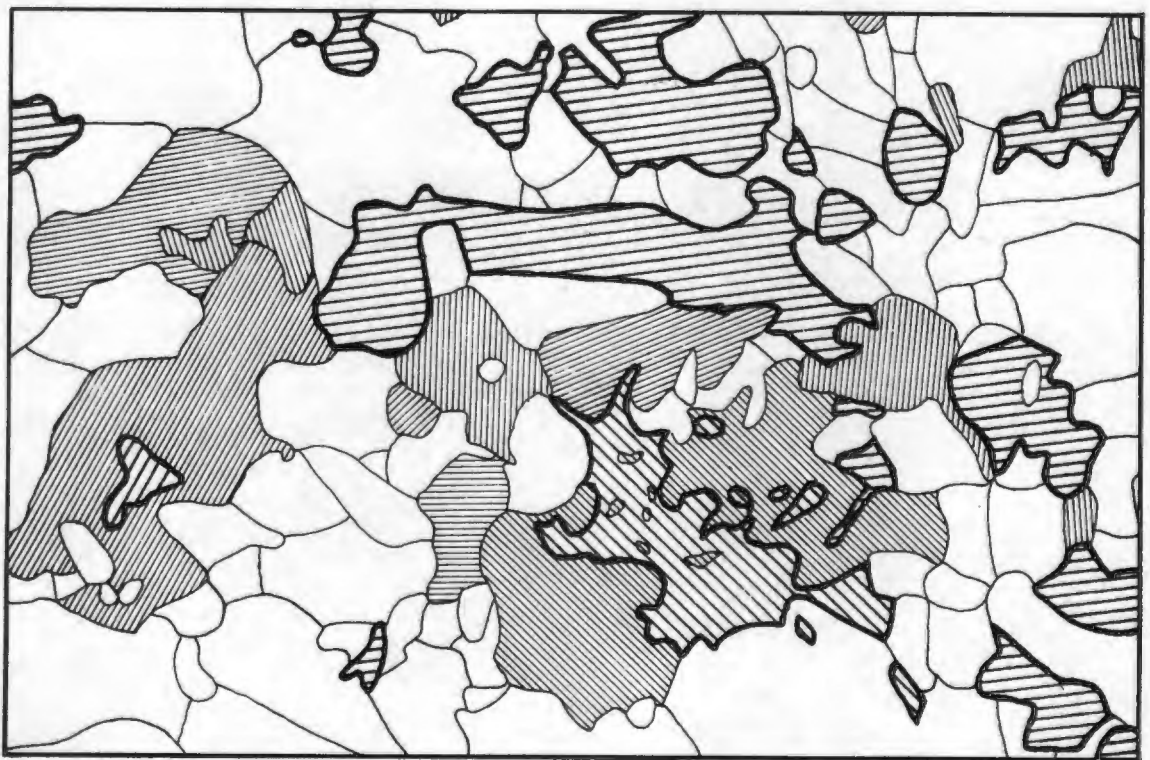


FIGURE B

1MM

PLATE XIII

Figure A. Hypersthene-bearing mottled anorthosite from Zone VI in borehole TRF1 containing a quartz-rich area. The interstitial quartz (spotted) encloses plagioclase laths (blank) which are smaller than the surrounding plagioclase laths not associated with the quartz. Interstitial augite (fine hatching) also occurs.

Figure B. Hypersthene-bearing mottled anorthosite from Zone VI in borehole TRF1 with weakly pleochroic biotite flakes (black) parallel to the (100)-augite exsolution lamellae in the hypersthene (wide hatching) cut ^{ring} across the hypersthene-plagioclase (blank) contact and the intervening hornblende rim (fine spots) where the latter occurs.

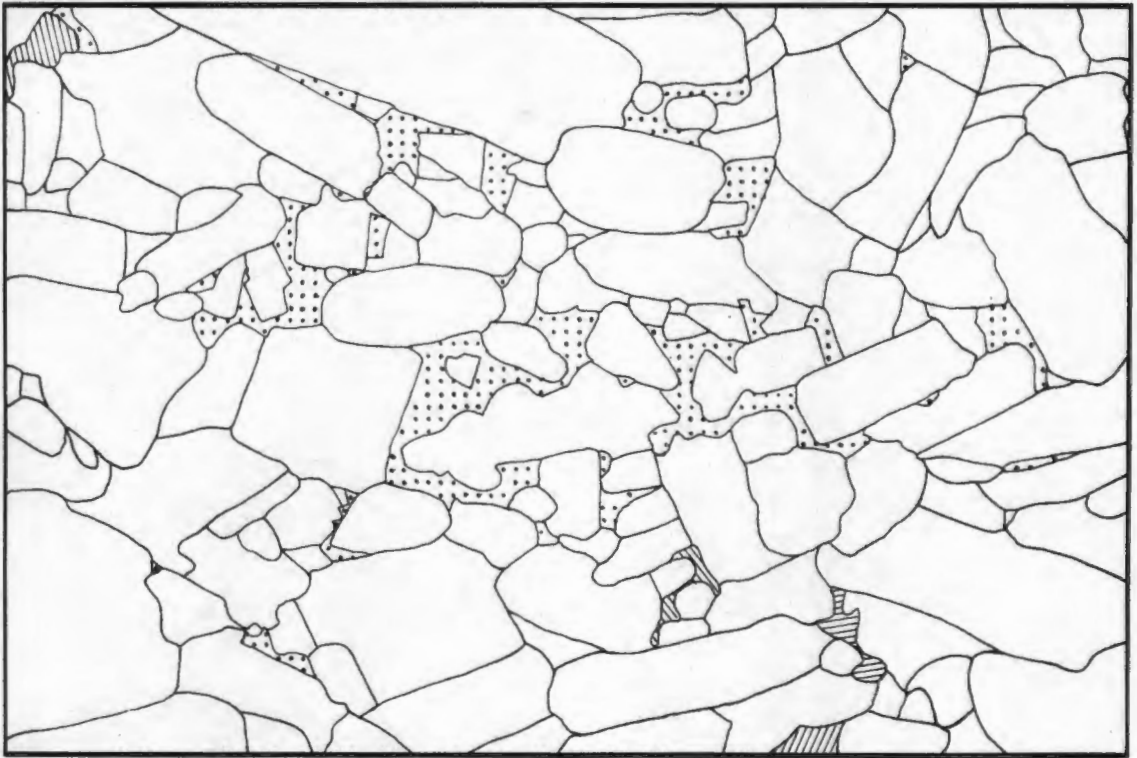


FIGURE A

1MM

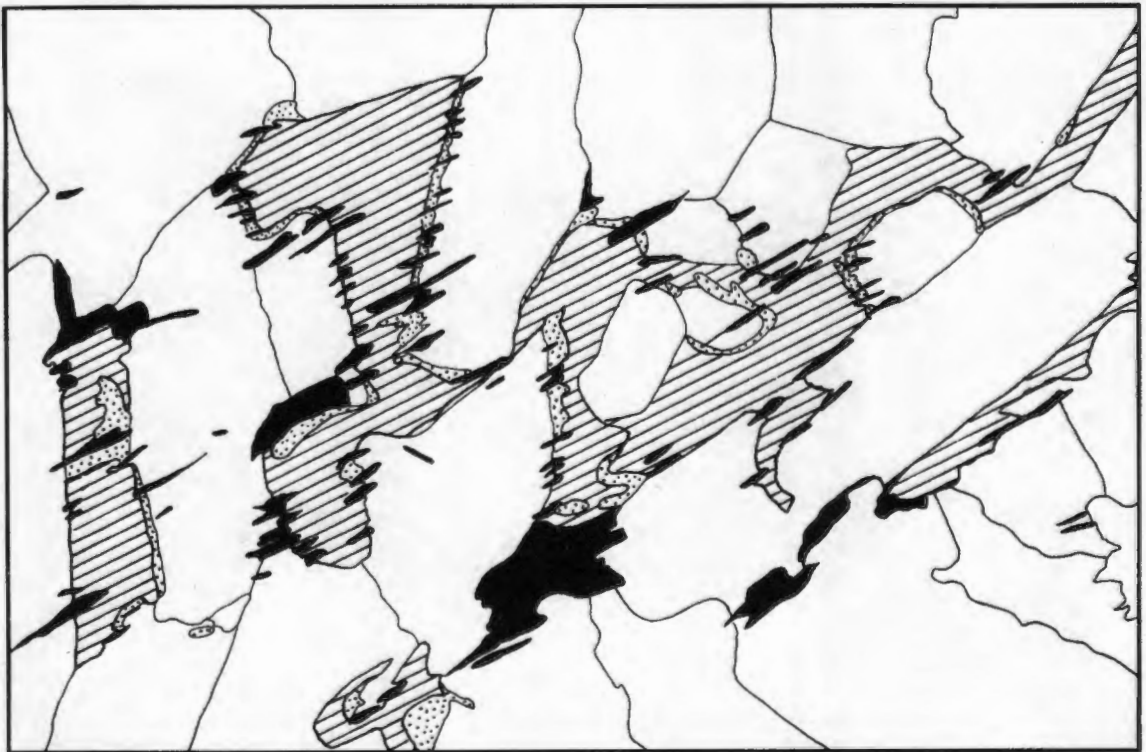


FIGURE B

1MM

PLATE XIV

Figure A. Bronzite area in leucohyperite from Zone III in borehole US13 in which some of the plagioclase inclusions (blank) in the same bronzite crystal (wide hatching) are partly or completely rimmed by narrow augite margins (narrow hatching). These augite margins have different optical orientations from one plagioclase inclusion to the other.

Figure B. Synophitic norite from Brits containing sets of ~~remnant~~^{relict} (001)- augite exsolution lamellae (narrow hatching) which lie in random planes in relation to the hypersthene (wide hatching) structure. The hypersthene structure is more or less the same for the hypersthene "grains" shown. The sets of lamellae lie more or less perpendicular to the length of the hypersthene "grains" which in turn is more or less perpendicular to the plane of igneous lamination. The plane of the illustration is at right angles to the igneous lamination which trends more or less from the upper left-hand corner to the lower right-hand corner of the plate.

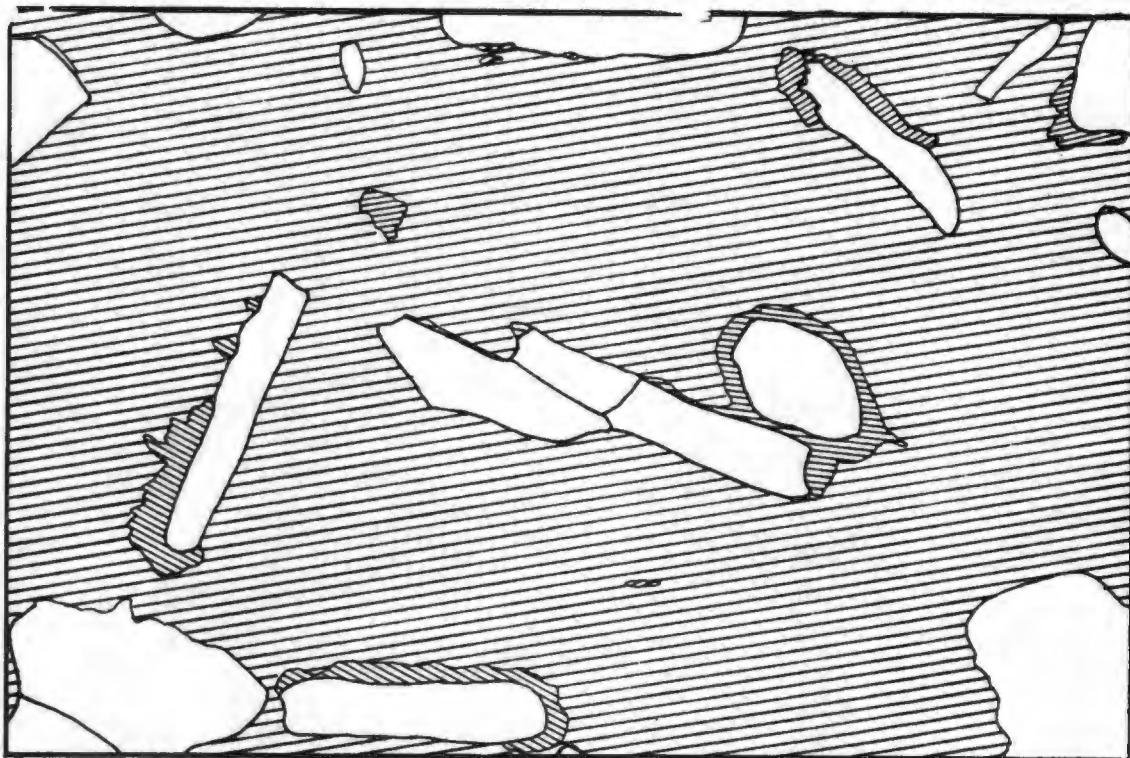


FIGURE A

1MM

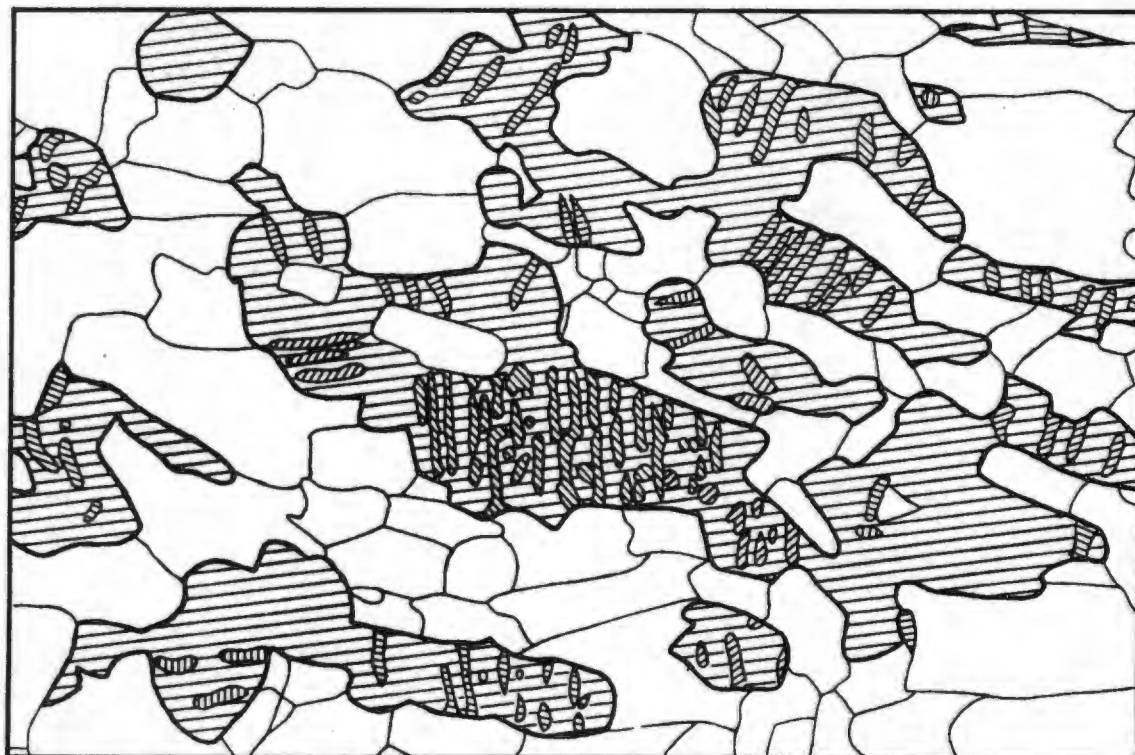


FIGURE B

1MM

PLATE XV

Figure A. Synophitic hyperite from Zone X in borehole KLG2 in which the central hypersthene area (wide hatching) contains at least five sets of augite blebs (narrow hatching). The two ^{relict} remnant (001)-augite exsolution lamellae shown have the same optical orientation as the augite blebs associated with them. The blank areas are plagioclase.

Figure B. Synophitic hyperite from the Bon Accord Quarry in which numerous exsolution lamellae and blebs occur in two hypersthene areas with different optical orientations (shown by the thick lines). The thick line separating the hypersthene areas is the contact between two clusters of hypersthene "grains". ^{Relict} Remnant (001)-augite exsolution lamellae have the same optical orientation for a certain distance on both sides of the contact of the two hypersthene areas (shown by the fine hatching drawn in the same direction). The fine lamellae and some blebs are of the extraordinary type of (100)-augite exsolution lamellae. The plagioclase is indicated as in Figure A.

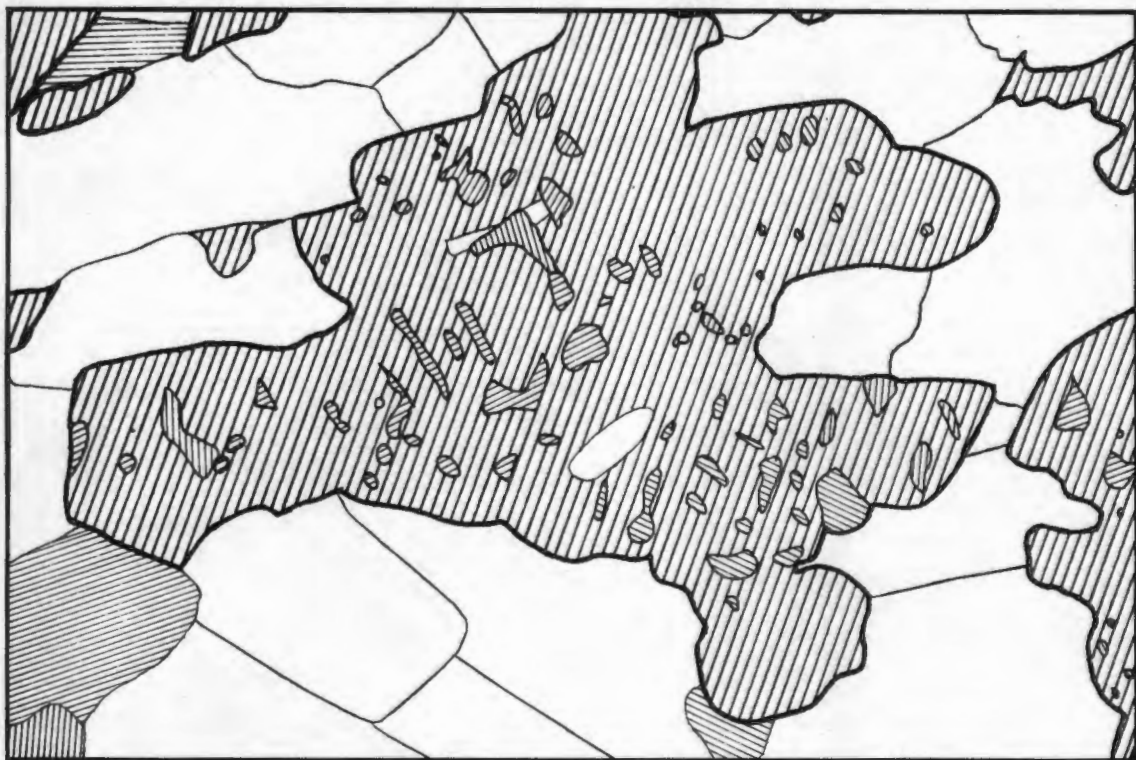


FIGURE A

IMM



FIGURE B

IMM

PLATE XVI

Figure A. Hypersthene-bearing mottled leucohyperite from Zone II in borehole TRF1 in which a single set of ~~remnant~~^{relict} (001)-augite exsolution lamellae with similar optical orientation (shown by the narrow hatching drawn in the same direction) cross^{es} two hypersthene crystals (blank areas containing exsolution lamellae and surrounded by a thick line) and pass well into a third one. The hypersthene crystals have different optical orientations with respect to one another. The ~~remnant~~^{relict} (001)-augite exsolution lamellae have the same optical orientation as three bordering augite crystals which are probably connected in three dimensions. None of the crystallographic axes of the two hypersthene crystals coincide with those of the augite. In addition to the normal type of (100)-augite exsolution lamellae (not shown) relatively thick (100)-augite exsolution lamellae (black) occur. The blank areas are plagioclase.

Figure B. Hypersthene-bearing mottled leucohyperite from the base of Zone III in borehole AB1 in which augite blebs with similar optical orientation (narrow lines in the same direction) occur in three hypersthene crystals (wide hatching) with different orientation. The plagioclase is indicated as in Figure A.

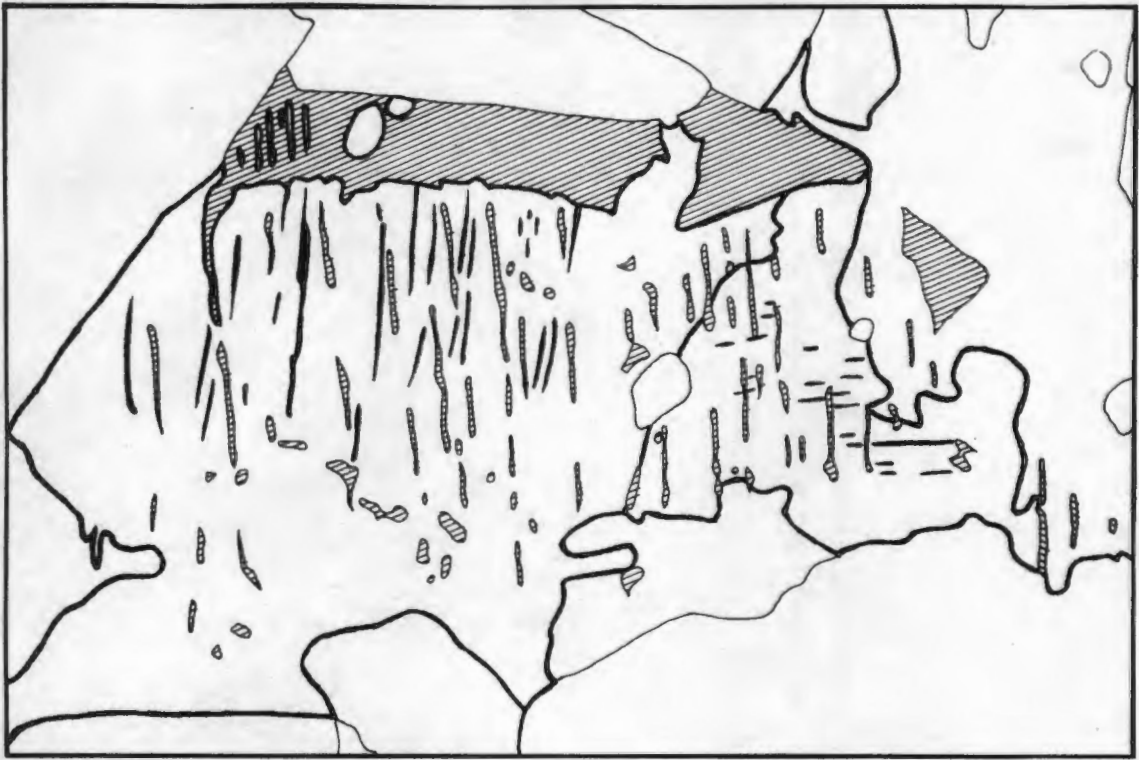


FIGURE A

1MM



FIGURE B

1MM

PLATE XVII

Figure A. Hypersthene-bearing mottled leucohyperite from Zone II in borehole TRF1 containing hypersthene (blank areas surrounded by thick lines) with vermicular augite exsolution (small blank areas surrounded by narrow lines). It is evident that some of the lamellae are ~~remnant~~^{relict} (001)-augite exsolution lamellae. The large blank areas surrounded by narrow lines are plagioclase.

Figure B. Part of an augite crystal from Zone VIII in borehole TRF1 containing (001)-hypersthene exsolution lamellae (hatched) and (100) exsolution. Possible hematite wedges (black) seem to occur in the (100) plane together with possible orthopyroxene (not shown). The thin lines drawn are planes of parting.



FIGURE A | IMM

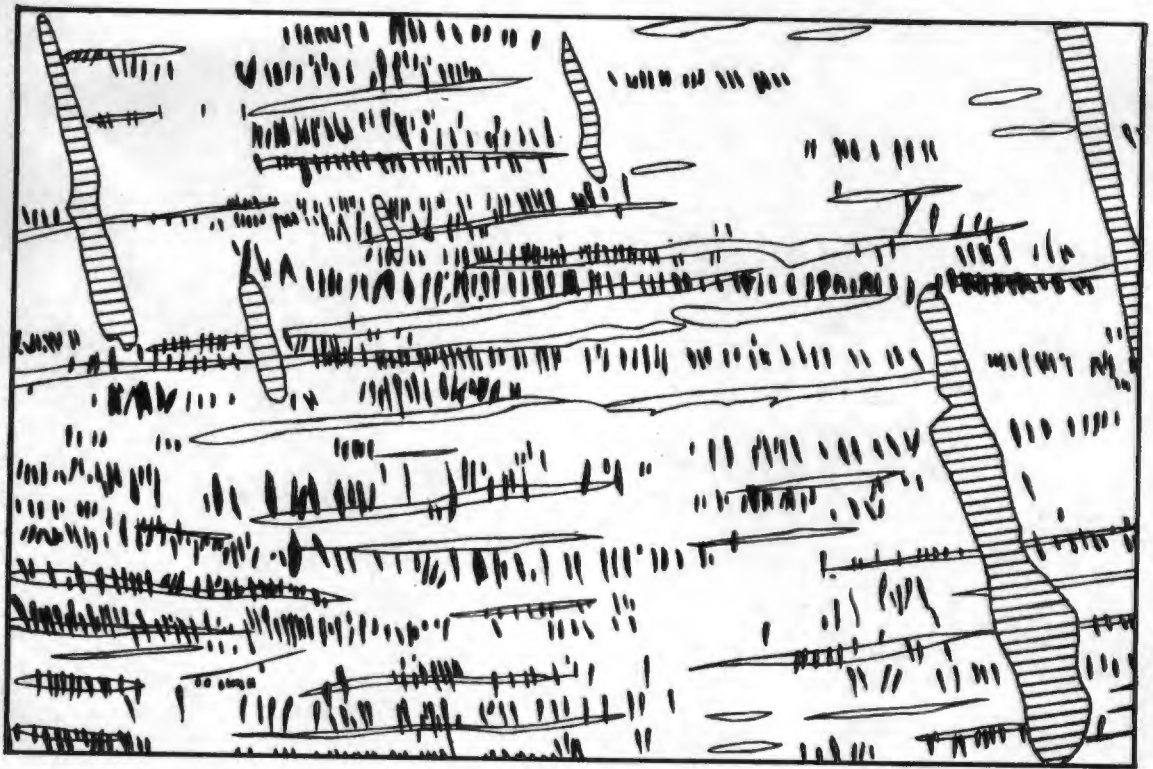


FIGURE B | 0.1 MM