THE TRANSITION BETWEEN THE MAIN AND THE UPPER ZONE OF THE BUSHVELD COMPLEX IN THE WESTERN TRANSVAAL

by

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ABSTRACT

The concept which incorporates the term "unit" is suggested for the grouping of the mafic rocks of the Bushveld Igneous Complex.

Each unit has definite boundaries. The upper surface of an anorthosite band forms such a boundary in two instances. The contact between the Main and the Upper Zone of the Bushveld Complex is interpreted as representing a hiatus in crystal deposition from the magma.

A magma of slightly different composition is required for each unit. One complete and two incomplete units are described, one following the other. They are designated in order: "The Bon Accord Unit" which represents the uppermost portion of the Main Zone, "Unit 1" which forms the lowermost unit of the Upper Zone, and "Unit 2" which follows on Unit 1.

Two rock types belonging to the lowest unit exhibit a most extraordinary texture, which has been termed the texture of the Bon Accord Hyperite. It consists of plagioclase as cumulate and interstitial orthopyroxene crystals. The latter are in groups orientated in the same way.

Seven distinct rock types comprise Unit 1 of the Upper Zone and it is 300 feet thick. This unit, in contrast to the Bon Accord Unit which is free from solid phases of iron oxide, contains 11.6% oxide minerals by volume calculated over its total thickness.

The lower portion of Unit 2 of the Upper Zone consists of three rock types, which have an average content of 19.3% iron oxides. Two major and numerous minor magnetitite bands are interbedded in Units 1 and 2.

Crystal settling from the magma played a dominant role in regard to the petrogenic history of the various rock types. Only one rock type, the magnetite troctolite of Unit 1 of the Upper Zone, is considered to have originated as a result of an increase in confining pressure.

"Fresh" and weathered magnetite specimens from the same magnetitite band consist of different minerals. The microscope reveals "fresh" unweathered magnetite ore as consisting of magnetite, ilmenite and some minor accessories. The texture of this rock, which has originated through exsolution, consists of interlocking anhedral grains of magnetite and ilmenite.

Weathered surface samples of magnetite ore consist predominently of maghemite, ilmenite, an unknown reddish-brown mineral and some minor accessories. The reddish-brown mineral is tentatively regarded as a further alteration product of maghemite and has not been positively identified.

Phenomena, depending on the bireflectance of "fresh" and weathered magnetite ore, are classified into five patterns and each pattern is fully described.

CONTENTS

I. INTRODUCTION

A detailed mineralogical and petrological study of a thousand foot portion of the layered series of the Main Plutonic Phase of the Bushveld Igneous Complex north-west of Pretoria was undertaken.

This portion straddles the Main Magnetitite Band, and constitutes the transition between the Main and the Upper Zone of the Bushveld Complex. Material for this thesis was collected mainly from three areas.

Firstly, material was collected from an area north of Pretoria in the vicinity of the Bon Accord Dam. A study of the rock samples, gathered from surface outcrops in this area, was informative with regard to the nature of the rocks underlying the Main Magnetitite Band (Diagrams 1 and 2).

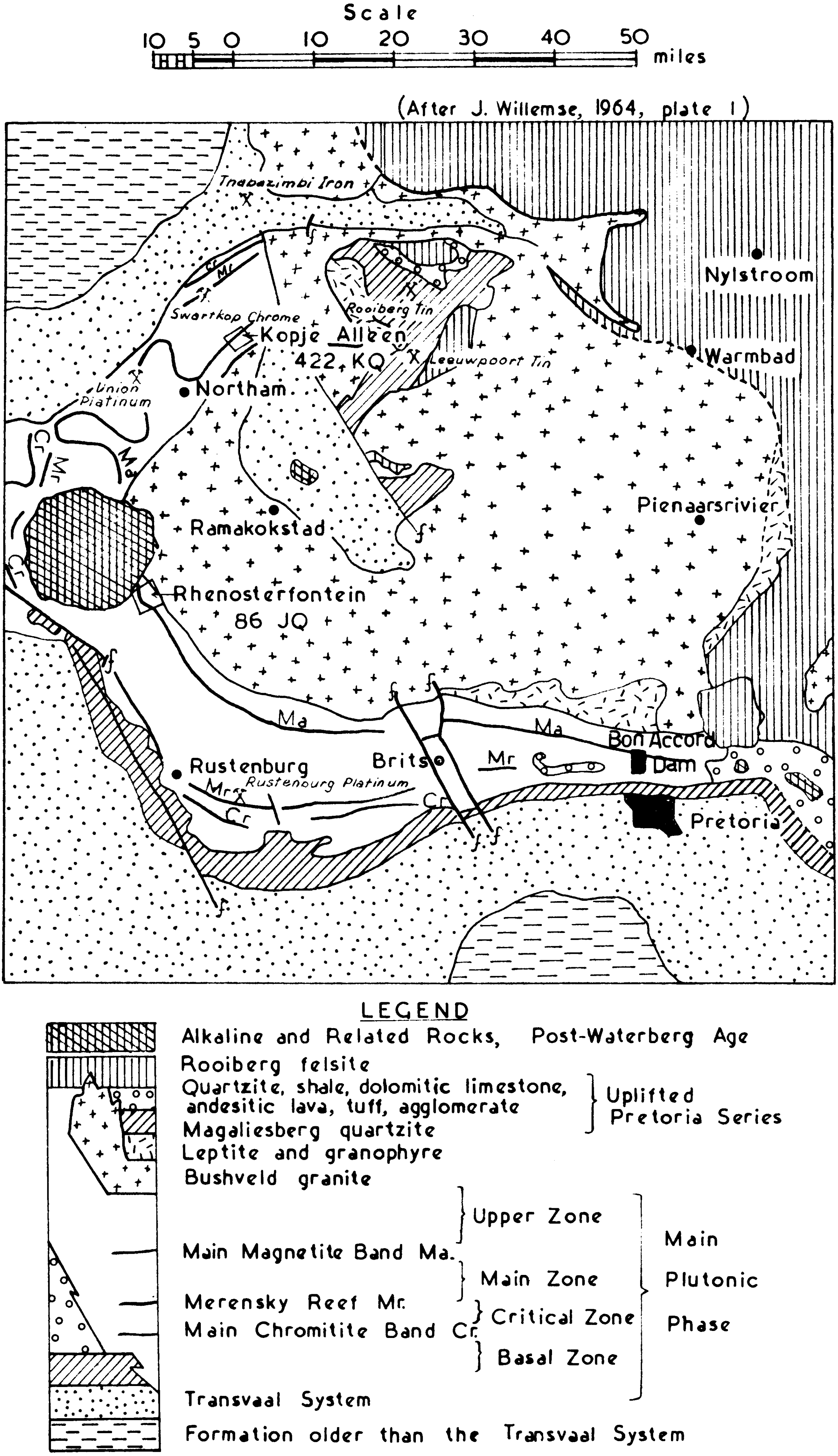
Secondly, diamond bore-hole no KA1, situated on the farm "Kopje Alleen" about ten miles north-east of Northam, yielded valuable information on the rocks which occur above the Main Magnetitite Band (Diagrams 1 and 3).

The bulk of the material was obtained from the farm "Rhenosterfontein JQ86" situated 25 miles due north of Rustenburg, on the eastern edge of the Pilanesberg Mountain. African Metals Corporation investigated this farm intensively during the latter half and early part of 1962-63. The object of their investigation was to ascertain the economic potentialities of the vanadium-bearing magnetic iron ore which outcrops on this farm (Diagrams 1 and 4). The author was responsible for the logging of the core and the siting of the bore-holes in this prospecting project.

Of particular interest was the Main Magnetitite Band, which constitutes the transition between the Main and the Upper Zone of the Bushveld Complex. In contrast to the Eastern Transvaal, where a very distinctive main band is evident, the Western Transvaal contains two main bands separated vertically by 300 feet of norite and allied rocks. These two bands are distinctive, as the lower band averages 4½ feet in

DIAGRAM 1

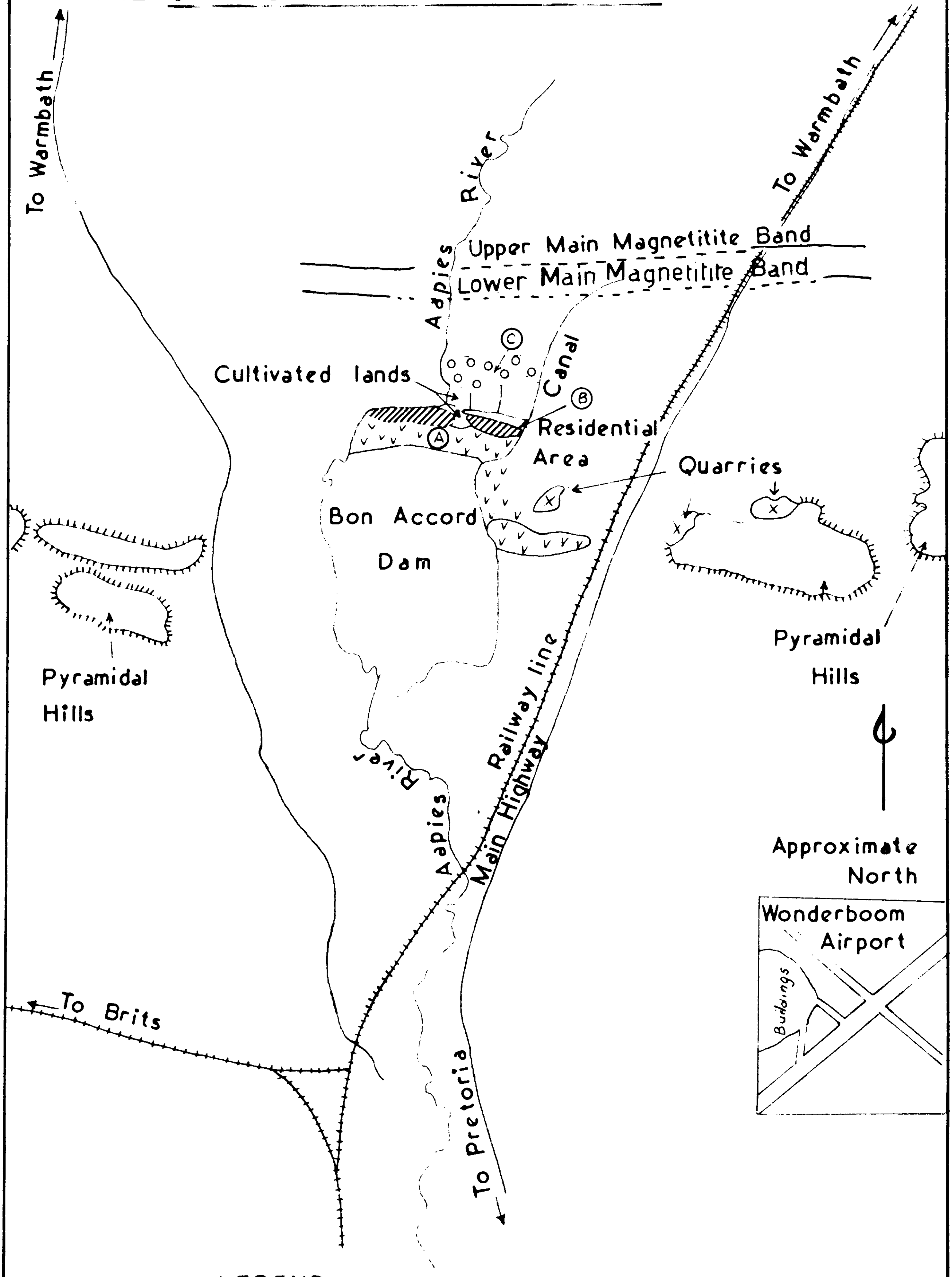
PORTION OF THE BUSHVELD IGNEOUS COMPLEX



(After J. Willemse, 1964, plate 1)

DIAGRAM 2

THE GEOLOGY OF THE VICINITY OF BON ACCORD DAM



LEGEND

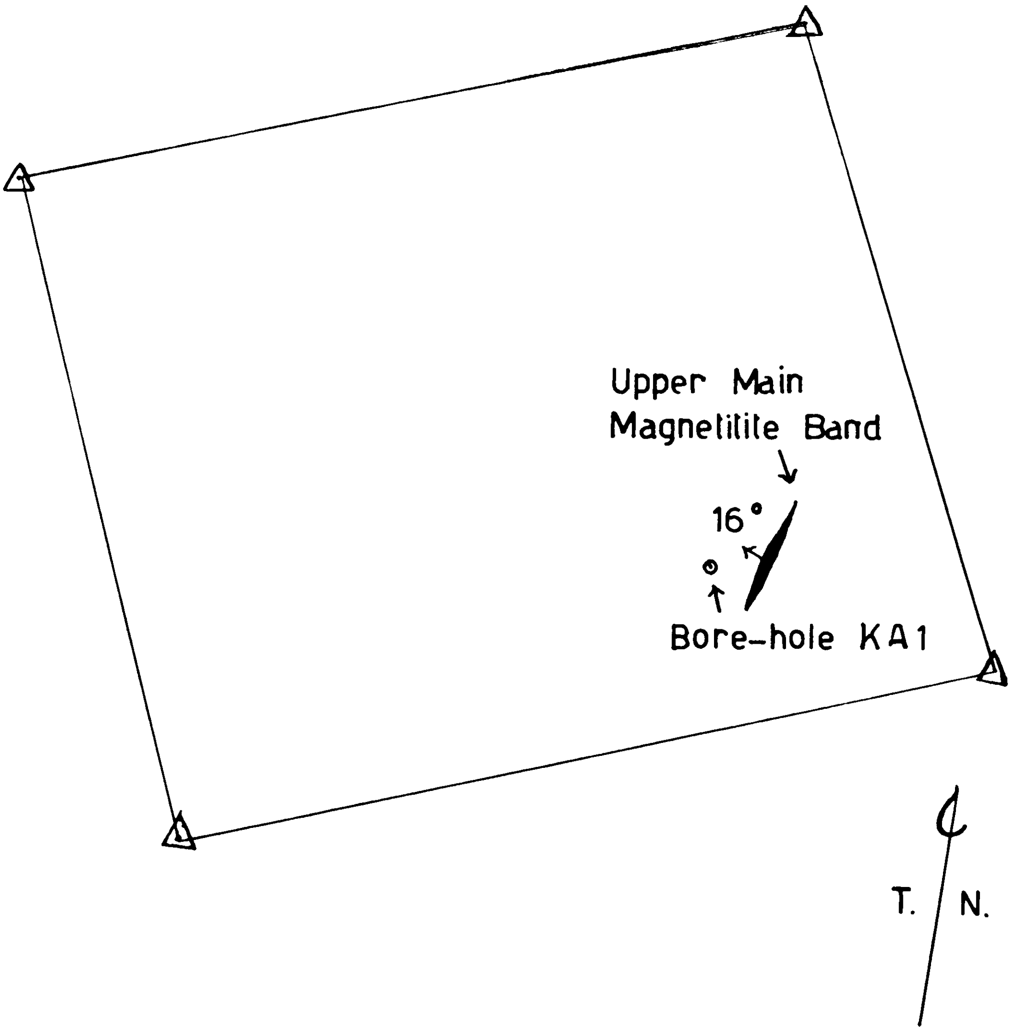
○ ○ ○	Anorthosite-Gabbro
▨	Anorthosite-Norite
v v v	Hyperite
Ⓐ	Sample No. and Locality

SCALE 1 : 36,000
appr.

DIAGRAM 3

KOPJE ALLEEN KQ 422

NORTHAM AREA



SCALE 1:50,000

thickness and contains about 1.9% vanadium-pentoxide, whereas the upper band averages about 5 feet in thickness and contains 1.5% vanadium-pentoxide. Both bands have anorthosite developed beneath them. In order to avoid confusion, these two principal bands have been designated the Lower and Upper Main Magnetitite Bands, whereas the anorthosite bands associated with them have been designated the anorthosite of the Bon Accord Unit and the anorthosite of Unit 1 respectively.

The methods used by African Metals Corporation in the exploration of the farm "Rhenosterfontein JQ86" included surface sampling and mapping of the outcrops, trenching and diamond drilling. A total of 30 bore-holes were put down, which yielded a wealth of information concerning the magnetic iron ore and the country rocks (Diagram 4). From these bore-hole cores a large number of thin and polished sections were prepared in the geological laboratories of the University of Pretoria.

A great deal of work has been done previously on the portion of the Bushveld Igneous Complex dealt with in this thesis. The most comprehensive work on the Complex as a whole is, of course, that by A.L. Hall (1932).

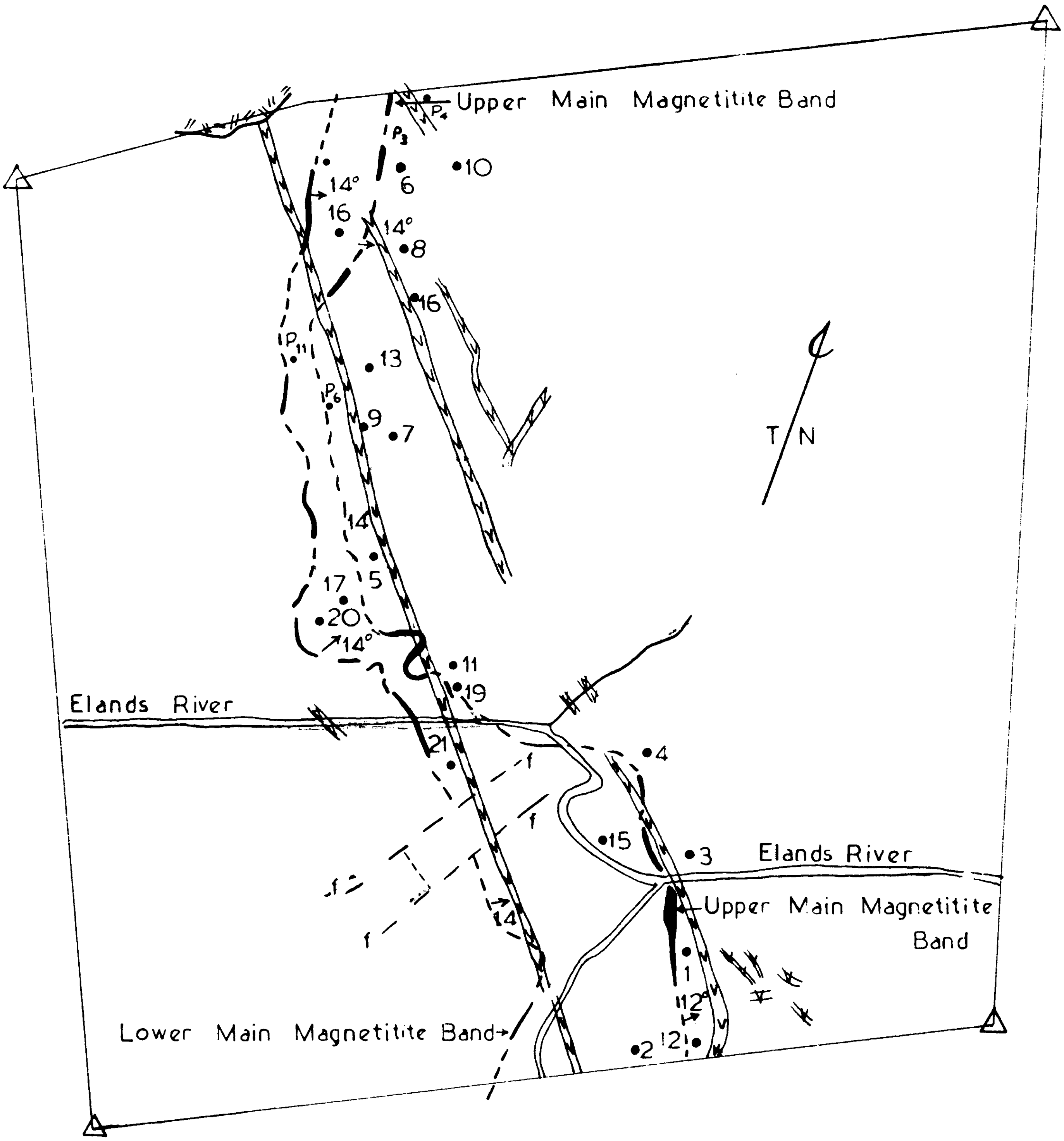
A full description of the basal rocks of the Bushveld Igneous Complex north of Pretoria is given by H. Nel (1941). His work embodies some of the material previously presented by B.V. Lombaard (1934). Both works include a section of the pyramidal "gabbro" hills found at Bon Accord, an area which is contiguous to the Bon Accord Dam profile of this thesis.

In 1946 J.J. van der Berg undertook a detailed petrofabric analysis of the Bon Accord "gabbro". His analysis is useful as it affords an accurate basis for interpreting some of the more puzzling textures.

T.G. Molyneux (1964) mapped a portion of the Bushveld Complex in the vicinity of Magnet Heights in the Eastern Transvaal. The portion mapped and described by him includes rocks from both the Main and the Upper Zone.

DIAGRAM 4

THE MAGNETITITE BANDS ON RHENOSTERFONTEIN JQ 86 RUSTENBURG DISTRICT



LEGEND

—	Magnetitite outcrop
	Pilanesberg dykes
14° •	Bore-hole No. & position
	Norite and allied rocks
	Contact of Pilanesberg Alkali Complex

SCALE 1:30,000

Magnetitite occurrences in the Upper Zone of Bushveld Complex have received a great deal of at from many authors. The relevant literature on th subject is quoted under the heading "Magnetitite"

J. Willemse (1964) presented a general revie the Bushveld Igneous Complex, and incorporates a classification which is of particular interest to thesis.

Throughout this thesis the classification of gabbroic rocks as proposed by J. Willemse (1965) w be adhered to (Table I).

TABLE I

Classification of Gabbroic Rocks

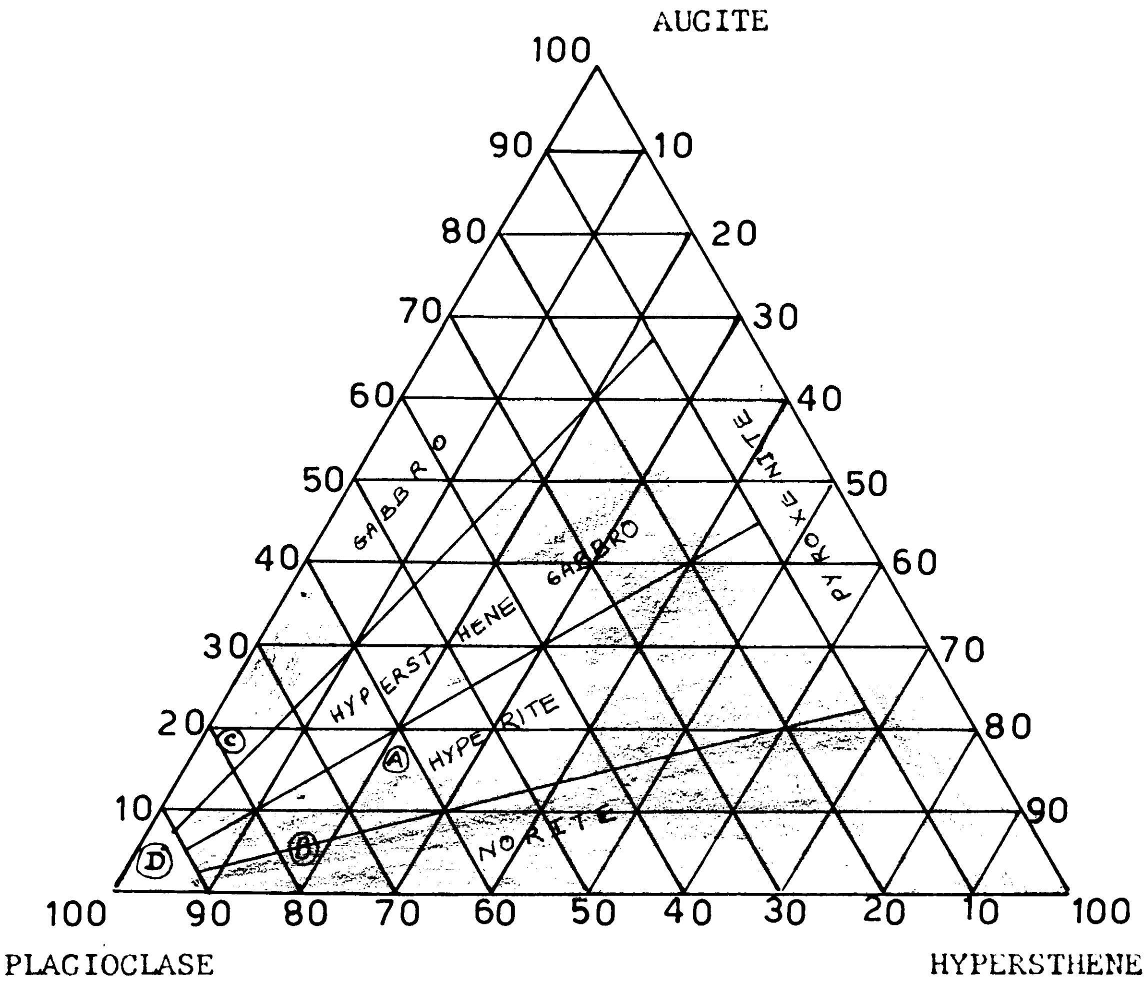
Rock Name	Percentage Orthopyroxene relation to Total Pyroxe
Norite	> 75
Hyperite	75 - 50
Hypersthene Gabbro	50 - 25
Gabbro	< 25

The specific rock names adopted in this thesis are entirely based on their respective volumetric mineral compositions. The colour index plays no part. Names, such as leuco-gabbro, etc. (after Streckeisen, 1964, p.206), are inadequate in pinpoi ing the specific composition of the rock types dealt with in this thesis.

The relevant name of any rock type mentioned in this thesis can easily be deduced from a study of Table I in conjunction with Diagrams 5 and 6.

DIAGRAM 5

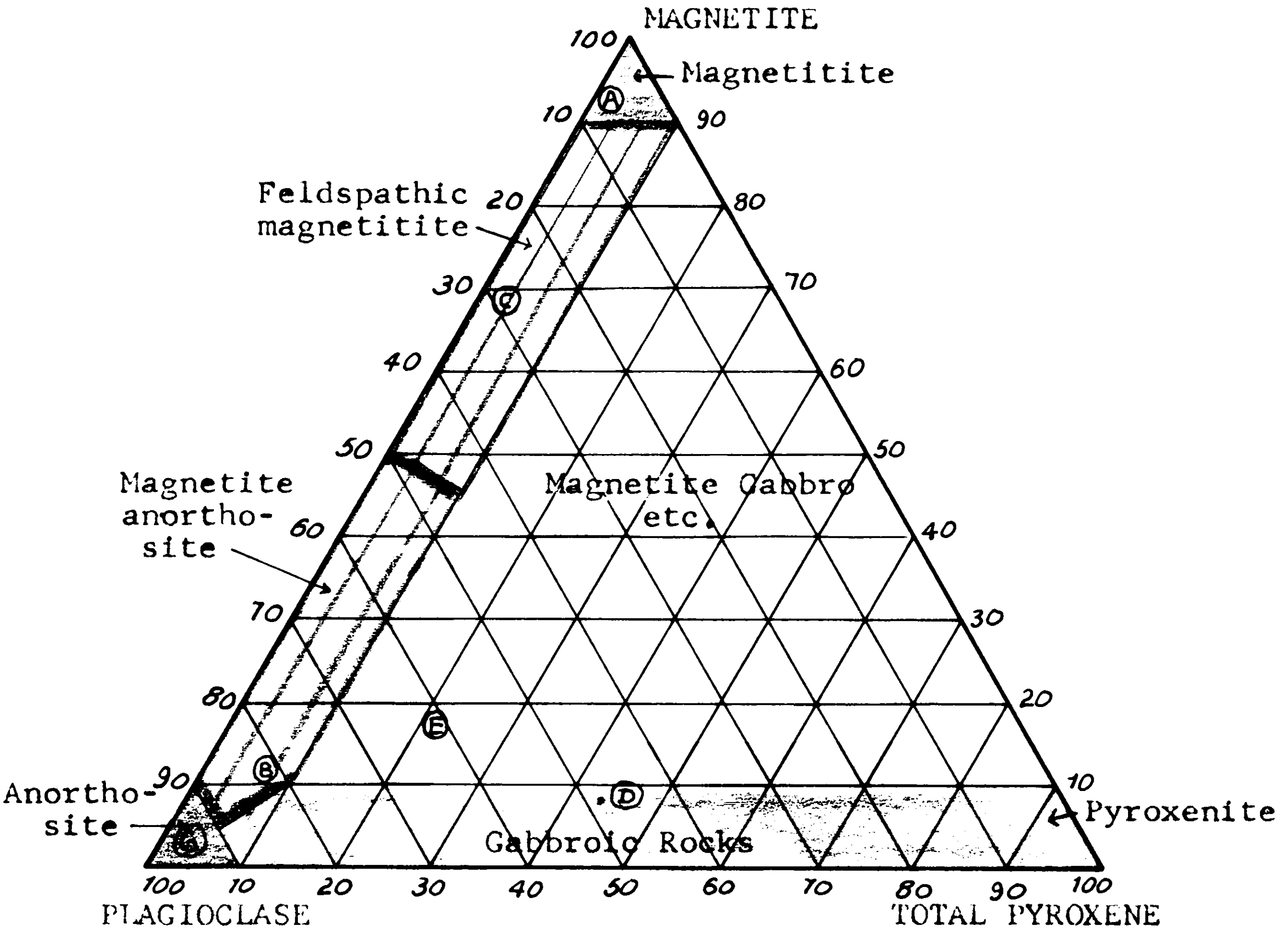
The Volumetric Mineral Composition of the Rock Types of the Bon Accord Unit



D. Anorthosite
C. Anorthosite-Gabbro
B. Anorthosite-Norite
A. Hyperite

DIAGRAM 6

The Volumetric Mineral Composition of the Rock Types of Unit 1



G. Anorthosite

F. Magnetite Troctolite (not represented)

E. Magnetite Hyperite

D. Hyperite

C. Feldspathic Magnetitite

B. Magnetite Anorthosite

A. Magnetitite

ACKNOWLEDGEMENTS

Sincerest appreciation is expressed to:

(i) African Metals Corporation for releasing pertinent information with regard to the exploration programme on the farm "Rhenosterfontein JQ86". All the assay figures and chemical analyses pertaining to the magnetitite quoted in this thesis were obtained from the Corporation's chemical and metallurgical laboratories at Kookfontein, near Meyerton in the Transvaal;

(ii) Anglo American Corporation of South Africa for approving the removal of bore-hole core from the farm "Kopje Alleen";

(iii) Mr. F.J. Basson for financial assistance;

(iv) Prof. J. Willemse for his encouragement, guidance and unfailing interest shown at all times.

II. GENERAL GEOLOGY

(A) THE BON ACCORD DAM PROFILE

The Bon Accord sequence of rocks ranges from two to three thousand feet in thickness and is intermittently exposed over a mile measured at right angles to the strike. These rocks comprise a series which stretches from the northern slope of the pyramidal hills, north of Pretoria, up to the first magnetitite band encountered higher up in the sequence and was investigated in order to obtain a better idea of the rocks underlying the magnetitite bands.

Four major rock types can be recognised. The lowest in the sequence is a coarse-grained hyperit followed by a medium-grained anorthosite-norite, then by a coarse-grained anorthosite-gabbro, and lastly by an anorthosite band. Contacts between these four rock types are not well exposed, and the contact relationships of the four have not been determined.

(B) THE RHENOSTERFONTEIN PROFILE

Results from some 30 bore-holes on the farm "Rhenosterfontein JQ86" indicate that the thickness of the various rock types of this profile is almost 300 feet (Diagram 7).

Rocks belonging to this profile fall into seven distinct types, excluding a number of interlaminated minor magnetitite bands (Table II).

TABLE II

Rock Types of the Rhenosterfontein Profile

Rock Types		Approximate Thickness
7	Anorthosite	90'
5	Magnetite Hyperite	35'
6	Magnetite Troctolite	10 - 20'
5	Magnetite Hyperite	125'
4	Hyperite	20'
3	Feldspathic Magnetitite	7'
2	Magnetite Anorthosite	10'
1	Lower Main Magnetitite Band	4½'

DIAGRAM 7

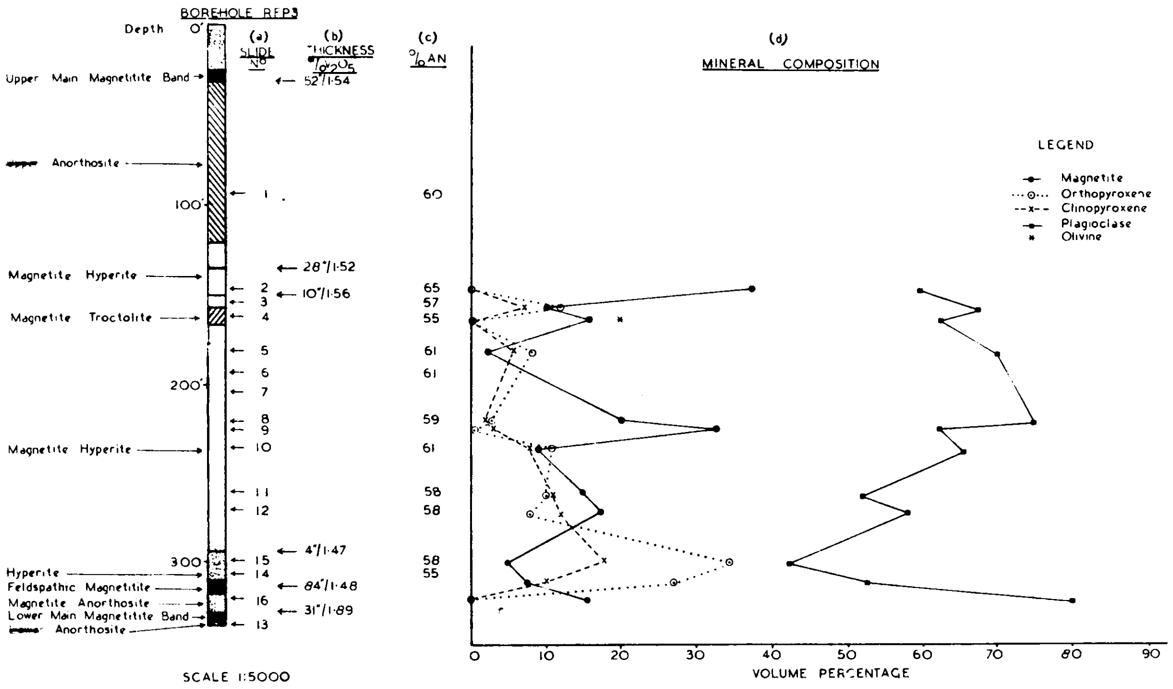
PROFILE THROUGH BORE-HOLE RFP3 SHOWING:

(a) POSITION WHERE SECTIONS WERE CUT;

(b) POSITION, THICKNESS AND VANADIUM PENTOXIDE CONTENTS OF THE MAGNETITITE BANDS;

(c) PERCENTAGE ANORTHITE IN PLAGIOCLASE, AND

(d) MINERAL COMPOSITION EXPRESSED IN VOLUME PERCENTAGE.



The contact between the anorthosite and the Lower Main Magnetitite Band is remarkably smooth and even, which signifies a major change in the character of the rocks below and above it. The change is abrupt, as below it iron- and titanium-oxides are absent, whereas above it vast quantities of these oxides are present in the overlying rocks. A few feet above this contact biotite makes its first appearance, and constitutes nearly 1% of the 700 feet of rock overlying the contact.

(C) THE KOPJE ALLEEN PROFILE (Diagram 8)

This profile represents about 400 feet of rocks superimposed on each other. A five feet thick magnetitite band, the Upper Main Magnetitite, constitutes the base of this profile. The magnetitite band is overlain by about 280 feet of magnetite anorthosite, which is in turn overlain by hyperite. Both the magnetite anorthosite and the hyperite contain a number of interbedded minor magnetitite bands.

III. THE GROUPING OF THE ROCKS OF THE BUSHVELD IGNEOUS COMPLEX

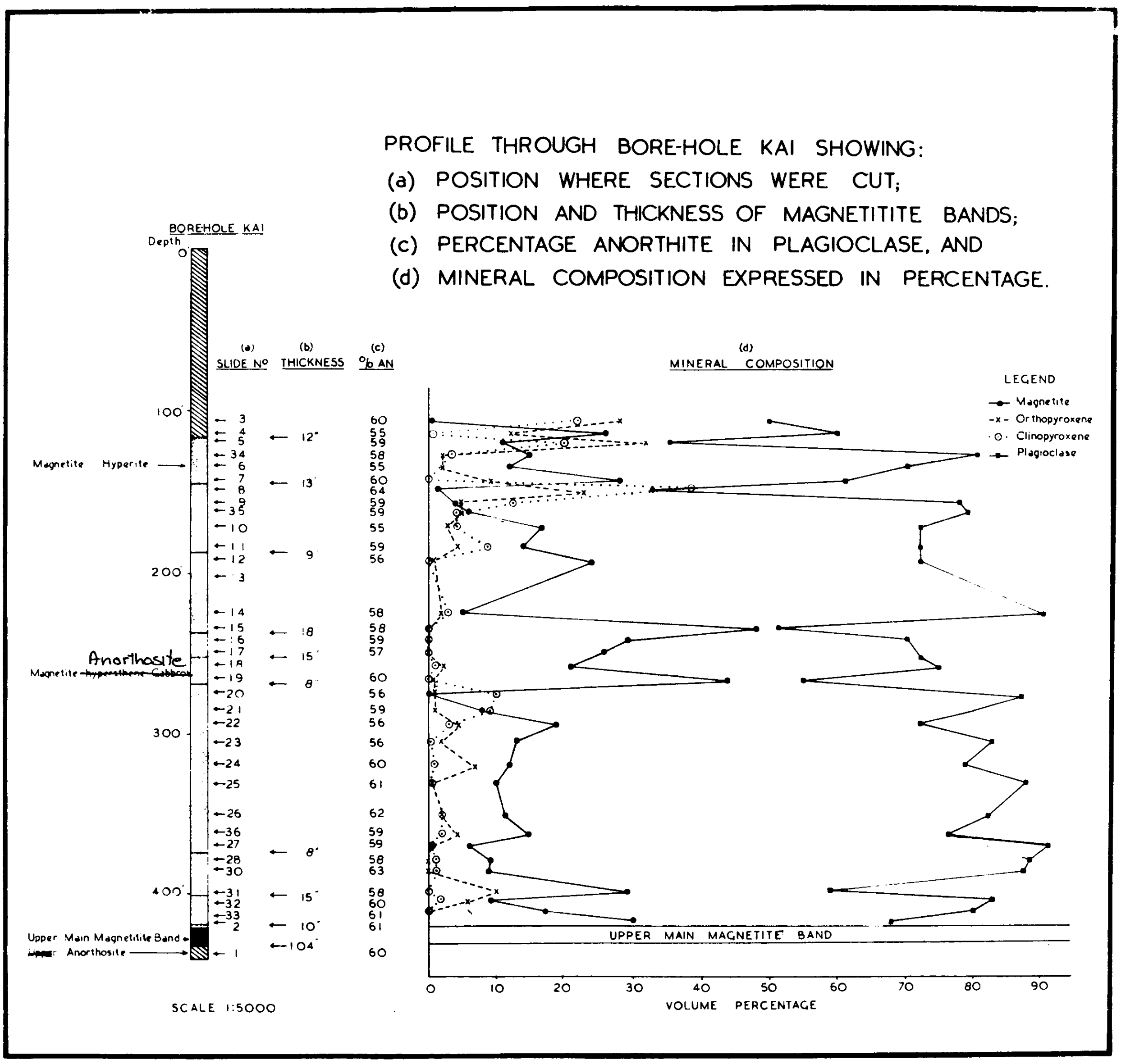
(A) SUBDIVISION OF THE BUSHVELD IGNEOUS COMPLEX

The thickness of the mafic portion of the Bushveld Igneous Complex and the variety of rocks found in the Complex as a whole, necessitates some means of subdivision or classification. This would greatly facilitate an easy reference to some specific portion or to any particular horizon.

At present a diversity of opinion exists as to the method in which to group rocks belonging to a large layered plutonic intrusion.

A.L. Hall (1932, pp.6 - 10), in a thorough study of the whole Complex, was the first to divide it into phases (Table III).

DIAGRAM 8



PROFILE THROUGH BORE-HOLE KAI SHOWING:

(a) POSITION WHERE SECTIONS WERE CUT;

(b) POSITION AND THICKNESS OF MAGNETITITE BANDS;

(c) PERCENTAGE ANORTHITE IN PLAGIOCLASE, AND

(d) MINERAL COMPOSITION EXPRESSED IN PERCENTAGE.

TABLE III

A.L. Hall's Classification of the Bushveld Igneous Complex

I. The First or Earlier Basic Volcanic Phase

This comprises at least 3 horizons of contemporaneous basic amygdaloidal lavas interstratified in the Pretoria Series, i.e.

- (a) The Ongeluk Volcanic Series
- (b) The Machadodorp Volcanic Series
- (c) The Dullstroom Volcanic Series.

II. The Second or Later Volcanic Phase

This consists of acid (felsitic) lavas, tuffs and other pyroclastic rocks interbedded with sediments of the Rooiberg Series, which form the roof of the Complex.

III. The Granophyre or Minor Plutonic Phase

This phase is intimately bound up genetically and geographically with the second phase.

IV. The Sill Phase of Basic Intrusions

Thick sheets of dolerite, gabbro, etc., which penetrate the floor of the Complex, are classified here.

V. The Earlier Main Plutonic Phase or the Norite Zone

This comprises the main body of layered basic rocks emplaced between the underlying Pretoria Series as a floor and the Rooiberg Series as a roof.

VI. The Later Main Plutonic Phase of Red Granite

This comprises rocks found as sheets, dykes, stocks, etc., which may be roofed by sediments of the Rooiberg Series or the Felsitic Lavas.

The Bushveld Igneous Complex was also classified into phases by F.C. Truter (1955, p.81). Only three phases were distinguished by him, namely:

(1) An extrusive phase (felsite and porphyry)
(2) An earlier intrusive phase (basic and ultrabasic sills)
(3) A later intrusive phase, which includes the mafic portion of the Bushveld as well as the Bushveld granite.

According to the view of the Geological Survey o South Africa (G.F. Fourie et al, 1960, p.28) the classification of the Bushveld Complex into "zones", as given by Hall (1932, p.285), is no longer applicab The Geological Survey contends that differentiation in place does not play as big a role as was originally thought and that the basic and ultrabasic rocks form part of a series of intrusions. The Geological Survey gives no classification of the mafic phase of the Bushveld Complex, and only describes the rock types separately

J. Willemse (1964) simplified and clarified Hall's classification (Table IV).

TABLE IV

Primary Classification of the Bushveld
Igneous Complex (after Willemse)

A. THE DEPOSITION OF THE TRANSVAAL SYSTEM including contemporaneous volcanicity.
B. A SILL-PHASE OF DIABASE SHEETS injected into the more or less horizontally disposed sedimentary rocks of the Pretoria Series.
C. AN EPICRUSTAL PHASE represented by the Rooiberg felsite, leptite and granophyre.
D. THE MAIN PLUTONIC PHASE which produced granodioritic, dioritic, mafic and ultramafic rocks.
E. A LATER PLUTONIC PHASE represented by the Bushveld granite.

TABLE V

SUBDIVISIONS OF THE MAIN PLUTONIC PHASE

<table>
<tr><td colspan="5">ROOF OF ALTERED FELSITES, ROOIBERG SEDIMENTS OR GRANITE</td></tr>
<tr><td>A.L. Hall
(1932, p. 285)</td><td>B.V. Lombaard
(1934, p.23)</td><td>J.S.I. Schwellnus
(1956, p. 85)</td><td>J.P. van Zyl
(1960, p. 6)</td><td>J. Willemse
(1964, p. 101)</td></tr>
<tr><td rowspan="2">UPPER ZONE</td><td>UPPER ZONE</td><td>UPPER ZONE</td><td rowspan="2">FERROSODA GABBRO UNIT
Base of the Ferrosoda Gabbro</td><td rowspan="2">UPPER ZONE
Main Magnetitite Band</td></tr>
<tr><td colspan="2">Uppermost Magnetitite Band</td></tr>
<tr><td rowspan="2">MAIN ZONE
Eastern edge of Lulu Mountains</td><td>MAIN ZONE</td><td>MAIN ZONE</td><td rowspan="2">GABBRO UNIT
Base of the Gabbro</td><td rowspan="2">MAIN ZONE
Merensky Reef</td></tr>
<tr><td colspan="2">Merensky Reef</td></tr>
<tr><td>CRITICAL ZONE</td><td>CRITICAL ZONE</td><td rowspan="2">CRITICAL ZONE
Main Chromitite Band</td><td rowspan="2">CENTRAL NORITE-ANORTHOSITE UNIT
Base of Norite and Anorthosite</td><td rowspan="2">CRITICAL ZONE
Main Chromitite Band</td></tr>
<tr><td colspan="2">Lowermost Chromitite Band</td></tr>
<tr><td>TRANSITION ZONE</td><td>BASAL ZONE
Horizon where diabase just appears</td><td>BASAL ZONE
Base of the Pyroxenite</td><td>PYROXENITE UNIT</td><td>BASAL ZONE
Erratic</td></tr>
<tr><td>BASAL OR CHILL ZONE</td><td>NORITE-DIABASE ZONE</td><td>MARGINAL ZONE</td><td>MARGINAL NORITE UNIT</td><td>CHILL ZONE</td></tr>
<tr><td colspan="5">FLOOR OF METAMORPHOSED PRETORIA SERIES</td></tr>
</table>

A further problem exists, however, as to the way in which the rocks belonging to the Main Plutonic Phase (after Willemse) should be grouped.

Many authors working on the Bushveld Complex have arrived at different groupings. The most important of these are given in Table V.

Irrespective of the terminology used in Table V, it is advisable that the various zones or units should be still further subdivided. Hall (1932, p.290) tackled this problem by dividing his "Critical Zone" into the Basal, Lower, Middle and Upper sections

Neither Lombaard (1934) nor Schwellnus (1956) attempted any further subdivision and only discussed the rock types.

The Central Norite Unit, as defined by van Zyl (1960, p.15), was further subdivided by him into subunits.

(B) SUBDIVISION OF LAYERED INTRUSIONS OTHER THAN THE BUSHVELD IGNEOUS COMPLEX

The term "zone" was used in a primary classification of the Waterfall Gorge Profile at Insizwa by D. Bruynzeel (1957, p.485). Three different zones were distinguished, namely:

(1) Roof Zone
(2) Central Zone
(3) Basal Zone.

No grouping of rocks or rock types within a zone was given.

The rocks of the Great Dyke in Southern Rhodesia were not grouped into subdivisions by B.C. Worst (1958, p. 291), but the rocks were described with reference to the pyroxenite bands, which were numbered from 1 to 12.

A classification of the Skaergaard Igneous Intrusion, East Greenland, was introduced by L. Wager and W. Deer (1939, pp. 54 & 101) (Table VI).

TABLE VI

Classification of the Rocks of the Skaergaard Intrusion

IV.	Marginal Border Group		
III.	Upper Border Group		
II.	Layered Series	(c.	Ferro-Gabbro
		(b.	Middle Gabbro
		(a.	Lower Olivine Gabbro
I.	Hidden Layered Series		

The classification given in Table VI.was amended by L.R. Wager (1960, p. 366). The Lower Olivine Gabbro, Middle Gabbro and Ferro-Gabbro of the Layered Series became the Lower, Middle and Upper Zones respectively.

The Upper Border Group of the old, as well as the Lower and Upper Zones of the revised classification, were further subdivided into sub-zones.

The term "unit" was concisely used by G.M. Brown (1956, p. 8) in subdividing about 2,600 feet of layered ultrabasic rocks of Rhum, Inner Hebrides. These ultrabasic rocks form a succession of differing layers all roughly parallel to each other. A broad rhythm can be discerned, which generally consists of an olivine-rich rock passing gradually upwards into one rich in feldspar. Such a sequence is defined as a "unit". These units average about 200 feet in thickness.

Strangely enough W.J. Wadsworth (1961, p.29) who, as well as Brown, belongs to the Oxford School, subdivided 5,000 feet thickness of layered ultrabasic rocks of the South-West Rhum into five series (Table VII). Each series comprises a distinctive lithological "group" and was distinguished on the basis of field mapping.

TABLE VII

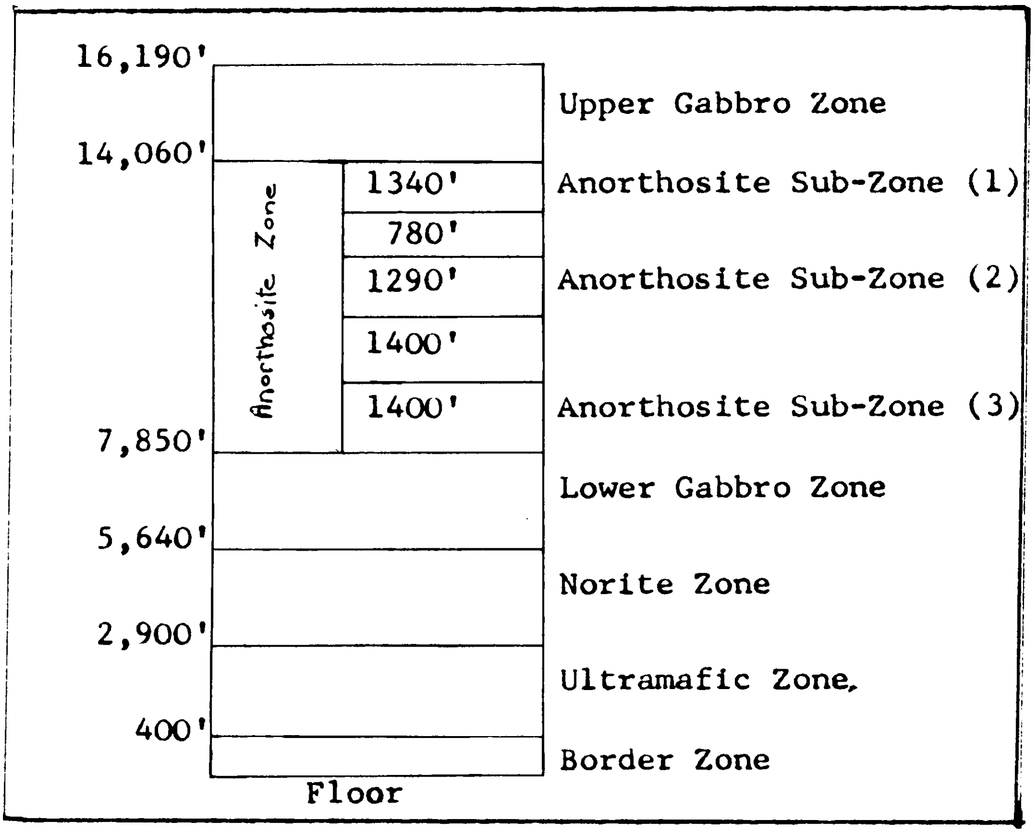
Wadsworth's Classification of the Layered Sequence in South-West Rhum

Units	Approx. Thickness	Lithological Divisions
D	1,000'	(5) Ruinsval Series b. Upper a. Lower
C	1,500'	
B	400' 1,200'	(4) Dornabac Series (3) Ard Mheall Series
	150'	(2) Transition Series
A	400'	(1) Harris Bay Series

In Table VIII the subdivision of the Stillwater Complex, as proposed by H.H. Hess (1960, p.50) is provided.

TABLE VIII

Subdivision of the Stillwater Complex, Montana, according to H.H. Hess



Each petrographical zone was named after its characteristic mineral assemblage, and only the anorthosite zone merited further division into sub-zones.

(C) DISCUSSION

Few authors have commented on, or discussed, Hall's primary classification of the Bushveld into phases. Exception may be taken to the use of the word "phase", as it has a genetic implication. As Hall's phases cover plutonic, hypabyssal and volcanic rocks, this objection is not a serious one. The word "phase" could be retained in conjunction with the primary classification made by Willemse. The secondary classification of the Main Plutonic Phase, as given by Willemse, is superior to the rest. His horizons of demarcation, which separate the "zones", are prominent features of the Bushveld Complex, and are easily recognised in the field.

The use of the word "zone" as a means of subdividing layered igneous intrusions has become so well established both in South Africa and overseas that it should be retained.

The word "unit" as used by van Zyl is inapplicable, as it covers too broad a field. It would be more appropriate to use the word in a tertiary capacity, i.e. it would be equal in status to van Zyl's sub-units. This would also be approximately the context in which Brown used it in his classification of the layered ultrabasic rocks of Rhum.

The diversity of rock types encountered in the Critical Zone of the Bushveld Complex lends itself to the ready application of the term "unit" as a means of subdivision. Both E. Cameron (1959, p.1159) and L.R. Wager (1959, p.76) applied the word "unit" in a strictly "rhythmic" capacity in descriptions of the Critical Zone.

It is accordingly suggested that the rocks which comprise the uppermost portion of the Main Zone, and the lowermost portion of the Upper Zone of the

Bushveld Igneous Complex be grouped into units as indicated on Table IX.

TABLE IX

Lithological Succession of the Transition between the Main and the Upper Zone of the Bushveld Complex

UPPER ZONE	UNIT 2	Hyperite Magnetite anorthosite Upper Main Magnetitite Band
	UNIT 1	Anorthosite Magnetite hyperite Magnetite troctolite Magnetite hyperite Hyperite Feldspathic magnetitite Magnetite anorthosite Lower Main Magnetitite Band
MAIN ZONE	BON ACCORD UNIT	Anorthosite Anorthosite-gabbro Anorthosite-norite Hyperite

It is expected that with further detailed work, more units will be added until a complete tertiary classification of the Main Plutonic Phase is available

IV. THE BON ACCORD UNIT

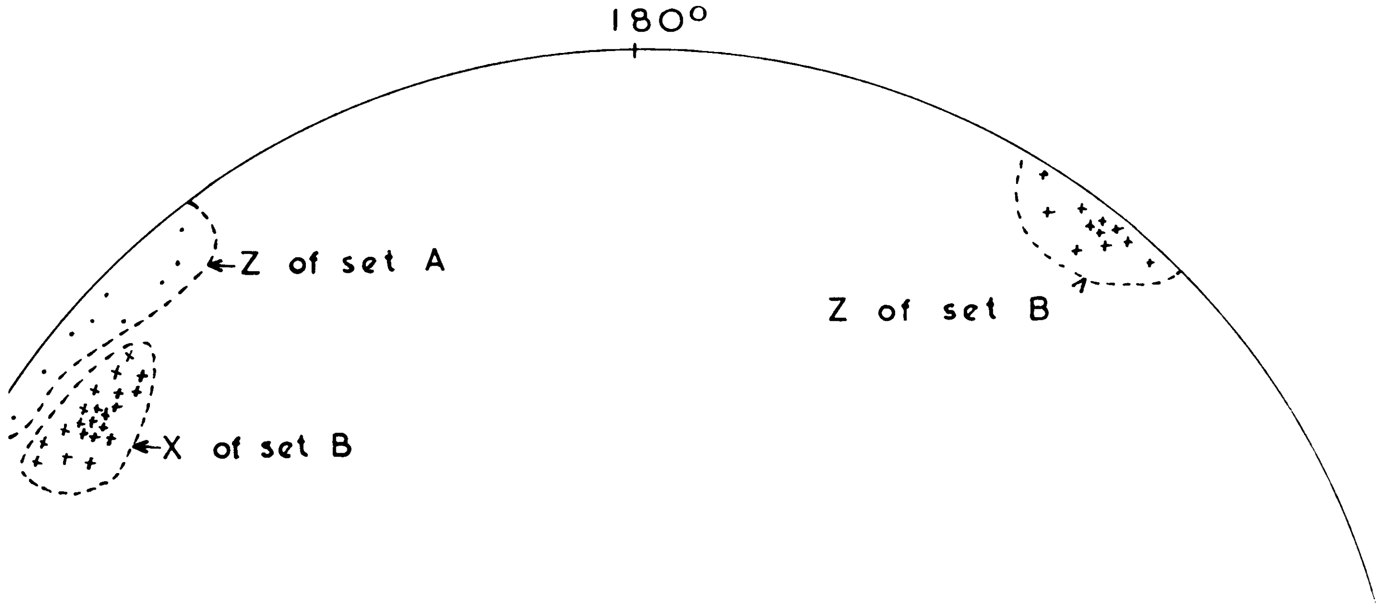
(Diagram 2)

(A) HYPERITE

This rock was first named a norite by Hall (1932, p. 292), and later called a gabbro by H. Nel (1941, p. 51) and van der Berg (1946, p.155). It has now been designated a hyperite in accordance with the classification of the gabbroic rocks in Table I.

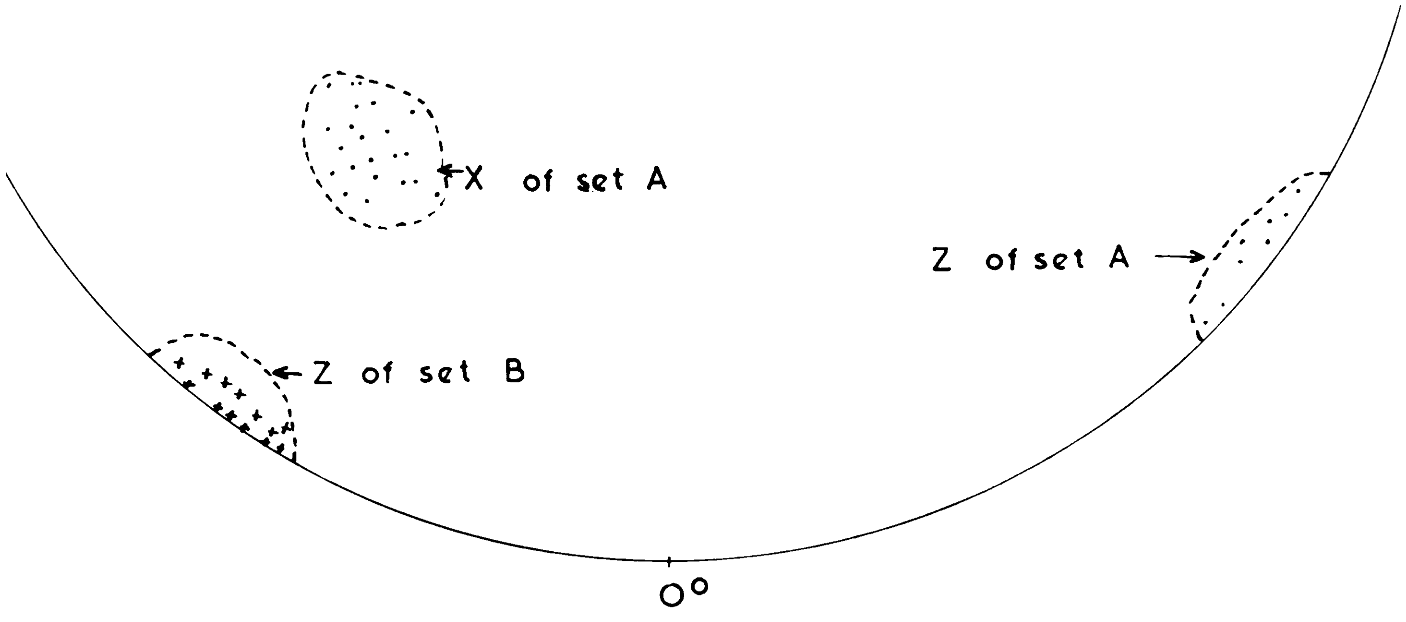
The hyperite is composed entirely of feldspar and pyroxene. The total feldspar content varies somewhat, but averages about 62% of the rock by volume. Orthopyroxene constitutes about 21%, whereas the clinopyroxene content is about 16%.

DIAGRAM 9



STEREOGRAM: X AND Z

OPTICAL DIRECTIONS OF ORTHOPYROXENE (SLIDE RP6/42)



A general feature of this rock is its coarse grain-size. The average length of the feldspar crystals is approximately 5 millimeters, but a smaller size measuring about 1 millimeter lengthwise is also present in small quantities.

A faint, irregular type of banding is visible macroscopically. The layering observed in the quarries dips northwards at about 25 degrees, but higher up in the succession the dip decreases somewhat.

(1) Feldspar

The feldspar in the rock consists entirely of plagioclase laths which, as described by van der Berg (1946, p.175) have a fairly distinctive crystallographic elongation in the C direction. In thin sections cut parallel to, or nearly parallel to, the plane of igneous lamination, this elongation is pronounced. The feldspar, in sections cut at right angles to this plane, exhibits nearly equi-dimensional outlines generally surrounded by pyroxene. It is immediately obvious to the naked eye in which of these two directions a slide was cut (Photos. 1 & 2, Slides VB43 & RP6/42).

All grains are subhedral and have an average composition of 60% An ± 5%.

No zoning was observed in the feldspar. Feldspar grains in contact with each other invariably show a sutured type of boundary. Contacts between grains of feldspar and pyroxene are frequently uneven, but smooth contacts exist. It appears as if the orthopyroxene has replaced feldspathic material to a small extent (Slide VB 44). Bent feldspar laths are common, and may be accompanied by fracturing.

(2) Orthopyroxene

The orthopyroxene, depending on the orientation of the section, shows either one or two sets of exsolution lamellae - a very coarse set and a much finer one. The coarse exsolved material is augite, which is coarse enough to be optically determined with the aid of a universal stage ($2V_{\gamma}$ about 60° & $\gamma \angle C$ about 42°). The augite occupies positions in the (001) plane of the original pigeonite. The fine lamellae are probably diopside exsolved parallel to (100) of the inverted pigeonite. These lamellae are too fine to be optically determined. These phenomena attest to the fact that all the orthopyroxene is inverted pigeonite, and that the temperature of the magma during crystallisation was above the inversion curve for clinopyroxene/orthopyroxene.

Twinning on (101) of the orthopyroxene (Slide VB43), which is also a relict plane from the monoclinic state, is common.

Measurements of $2V_{\alpha}$ range from 48 to 60 degrees, which puts the composition of the orthopyroxene in the hypersthene field, carrying from 35 to 50 molecular percent $FeSiO_3$ - after A. Poldervaart (1950, p.1076). The molecular composition of the orthopyroxene is corroborated by refractive index determinations ($Nx = 1.70$ & $Nz = 1.71$).

The size of the orthopyroxene grains varies widely and ranges from a fraction of a millimeter to several millimeters in diameter. The overall shape of the grains is anhedral, and they envelope, or partially envelope, feldspar laths. This is not a poikilitic or ophitic texture as a single pyroxene grain seldom envelopes more than one feldspar grain. The arrangement of the minerals is such that discrete and distinct pyroxene grains, interstitial to the feldspar laths, are more or less evenly disseminated throughout the rock. Only the larger grains of the pyroxene show a tendency towards elongation in the C crystallographic direction.

A phenomenal feature of the grains of orthopyroxene is that they possess in groups the same optical orientation. This is easily detected, as members of a group extinguish nearly simultaneously when rotated under crossed nicols. Occasionally an isolated randomly orientated grain is also encountered, which does not belong to a set. Careful plotting of the optical directions of the orthopyroxene grains belonging to one set on a stereonet, clearly indicates that they consist of individual grains with a closely aligned optical orientation, and are not portions of a single large crystal. Under high magnification boundaries can actually be seen. The Z and X optical directions of orthopyroxene grains in a single thin section have been plotted on a stereonet (Diagram 9). Two distinct sets, nearly at right angles to each other, can be recognised. The section, on which these determinations were made, was cut parallel to the lamination in the rock.

In J.J. van der Berg's (1946) work on the petrofabric analysis of the Bushveld gabbro from Bon Accord, this self-same texture was noted in virtually all thin sections. He found that nearly 70% of all the feldspar grains lie with (010) parallel, or approximately parallel, to the plane of igneous lamination (p.175). With regard to the orientation of the orthopyroxene, nearly all grains lie with their crystallographic C-axes (optically Z direction) in the plane of igneous lamination, whereas grains of clinopyroxene show no significant preferential orientation of optical direction (pp. 183 & 197).

(3) Clinopyroxene

The clinopyroxene grains exhibit a wide variety in size without any particular preference for a specific size. Their shape is anhedral. Crystal faces are virtually never developed, and mostly share common boundaries with feldspar and orthopyroxene. They wrap themselves around grains of feldspar and between orthopyroxene and feldspar.

Measurements of 2Vγ range from 56 to 66 degrees and average about 48 degrees, which corresponds with that of augite. Typically, they contain sets of exsolution lamellae, and simple twins (100) predominate. The clinopyroxene grains are randomly orientated.

(B). ANORTHOSITE-NORITE

The mineralogical composition of this rock differs somewhat from the previous one, as the feldspathic content is much higher (Slide B2). It averages about 78% plagioclase, 17% orthopyroxene and 4% clinopyroxene by volume. The anorthite content of the feldspar ranges from 55 to 65%, averaging about 60%.

The composition and mode of occurrence of the pyroxene is similar to that of the coarse-grained hyperite. A similar texture to that of the hyperite is developed.

Slight reduction in grain-size from the coarse hyperite may be ascribed to more rapid cooling of the magma. This would lead to a faster rate of nucleation of the feldspar, and may result in denser packing of the feldspar mesh. This would result in a reduction of interprecipital liquid from which ferromagnesian minerals could crystallise.

From field evidence the norite is estimated to be approximately 450 feet thick.

(C) ANORTHOSITE-GABBRO

The relevant constituents of this rock amount to 74% plagioclase feldspar, 5% orthopyroxene and 20% clinopyroxene by volume (Slide B3). The individual minerals have identical compositions to those of the coarse-grained hyperite.

The mode of occurrence of the hypersthene is different, as the grains are not optically similarly orientated. Separate large grains may, however, envelope one or more of the feldspar grains, indicating intercumulus growth (Slide B3). Probably insufficient orthopyroxene material was present in order to establish a similar texture to that found in the Bon Accord Hills.

It is reasonable to expect that an interstitial liquid, which would yield almost exclusively clinopyroxene after crystallisation, would establish a similar texture to that of the Bon Accord Hyperite. This was, however, never observed, although the present anorthosite-gabbro must have closely approximated a condition whereby clinopyroxene takes the place of orthopyroxene. The reason for the non-establishment of the texture of the Bon Accord Hyperite is not clear.

(D) ANORTHOSITE

The lower contact of the anorthosite is not exposed in the Bon Accord area, but is readily available from drill-hole cores from Rhenosterfontein. Here it is gradational in nature over about five feet with regard to the underlying anorthosite-gabbro. The pyroxene in the coarse-grained anorthosite-gabbro gradually gives way to feldspar to a point where a nearly pure anorthosite is found.

The anorthosite layer varies in thickness from about 30 to over 100 feet in the Rhenosterfontein area, and terminates abruptly upwards against the Lower Main Magnetitite Band. The contact is sharp and smooth. The smoothness of the contact suggests a certain amount of compaction of the topmost layer of the mesh of the feldspar crystals.

An astonishing feature of all the major anorthosite bands intersected in the bore-holes of Rhenosterfontein and Kopje Alleen, is their nearly complete hydrothermal alteration into a mass of secondary products. The feldspar is nearly completely saussuritised.

Where ferromagnesian minerals existed interstitial to the feldspar, hydrothermal alteration has produced pale green chlorite (Slide 13). This consists of a mass of radiating crystals with the mutual edge against altered feldspar laths (Photo. 3)

The selective deuteric alteration of the anorthosite points to instability and a hydrous magmatic condition. The abundant water content is shown by the presence of secondary amphibole and chlorite (Slide 7). Vague outlines of crystals yield evidence that the grain-size of the feldspar (up to 15 m.m. long) is larger than in any other rock type in this sequence.

Optical determinations made on a few partially preserved laths (Slide 17) yield an anorthite content of about 60%. The feldspar grains appear to be unzoned, but in the anorthosite of Unit I of the Upper Zone a single large feldspar crystal exhibits a zonal build. It was too badly weathered to be optically determined.

The anorthosite layer of the Bon Accord Unit could be an example of a monomineralic plagioclase cumulate with most of the intercumulus liquid squeeze out. It is impossible to see to what extent, if any, adcumulate growth has taken place.

V. UNIT 1 OF THE UPPER ZONE

(Diagram 7)

(A) LOWER MAIN MAGNETITITE BAND

This band averages about 4½ feet in thickness. The bottom one or two feet consist only of metallic oxides. This portion is frequently followed by a layer of plagioclase crystals, which is only a few inches thick. The upper portion of the band contains an increasing percentage of feldspar towards the top and grades into a magnetite anorthosite.

(B) MAGNETITE ANORTHOSITE

This rock contains 80% plagioclase, 13% magnetite, 2% biotite and about 5% secondary amphibole by volume (Slide 16).

Texturally the rock is an orthocumulate with only plagioclase as the primary precipitate. The intercumulus liquid precipitated some pyroxene (now altered to hornblende), then magnetite and lastly biotite. The band composed of this rock averages ten feet in thickness and is somewhat deuterically altered.

(C) FELDSPATHIC MAGNETITITE

The contact between the magnetite anorthosite and the feldspathic magnetitite is gradational over a few inches. The feldspathic magnetitite averages from 6 to 7 feet in thickness.

Several specimens of this rock, gathered from Rhenosterfontein bore-holes, were crushed to a fineness of 150 mesh. The magnetite was extracted by magnetic means, and assayed for it's V_2O_5 content. The results are given in Table X. Apart from the magnetite, the rest of the material is plagioclase feldspar.

TABLE X.

Magnetite Content (Weight Percentage) of the Feldspathic Magnetitite from Rhenosterfontein

Bore-hole No.	Thick-ness	% Magne-tite	% V_2O_5 in the Magnetite
P 4	83"	73.6	1.71
17	71"	80.0	1.65
19	63"	82.0	1.49
20	44"	80.0	1.23
21	65"	78.8	1.57

The relative proportion of feldspar to magnetite is evenly maintained throughout the total thickness of the band, apart from the sharply gradational upper and lower contacts. This distinguishes it from the "normal" magnetitite bands, where a higher concentration of magnetite is found at the bottom.

The rock consists texturally of an interlocking mosaic of anhedral magnetite grains. Outlines of the magnetite grains are difficult to discern (Polished section RP4/411), but measure about 5 to 6 millimeters in diameter. The plagioclase crystals are interstitial, but display a greater tendency than the magnetite towards crystal outlines. This can be seen macroscopically (Polished Section RP4/411). The feldspar appears to be floating in the magnetitite and may have become trapped as more magnetite was deposited on top of the feldspar.

(D) HYPERITE

The twenty feet of rock above the feldspathic magnetitite contains an average of about 47% plagioclase, 44% pyroxene, 6% magnetite and from 1 to 2% biotite by volume. The pyroxene content can be divided into 30% orthopyroxene and 14% clinopyroxene. The rock is therefore classified as a hyperite in accordance with Table I. The orthopyroxene is hypersthene inverted from pigeonite, and the clinopyroxene is augite.

The feldspar in the rock forms a feldspathic framework, whereas the rest of the minerals crystallised interstitially.

"The texture of the Bon Accord Hyperite" is well developed.

(E) MAGNETITE HYPERITE

Overlying the hyperite and extending up to the anorthosite of Unit 1 is about 150 feet of magnetite hyperite.

It contains less pyroxene and slightly more magnetite and feldspar than the underlying hyperite. The composition averages 64% feldspar, 16% magnetite, 1% biotite and 19% pyroxene by volume. As the ratio of clinopyroxene to orthopyroxene is approximately one, it is difficult to classify this rock according to Table I. For convenience it has been termed a "magnetite hyperite".

The orthopyroxene, inverted from pigeonite, has a $2V\alpha$ which ranges from 54 to 60 degrees, and falls therefore into the hypersthene field. Determinations of refractive index on orthopyroxene gave Ny= 1.715, which corresponds with that of hypersthene. All the clinopyroxene is augite ($2V\gamma$ about 56 degrees and $\gamma\angle C$= 42 to 54 degrees) (Slide 6).

Feldspar (about 60%An) was the first to crystallise and collected at the bottom to form a self-supporting mesh. Pyroxene formed next from an essentially interstitial liquid. Magnetite invariably envelopes grains of pyroxene, and is a later crystallisation product than the pyroxene. Biotite represents the ultimate stage of crystallisation.

It is not always conclusively established as to whether pigeonite or augite crystallised first. In this section, different slides yielded conflicting evidence. Where augite is more abundant than orthopyroxene, the augite was the first to crystallise and vice versa. This contrasts with the rocks of the Bon Accord Unit, where the pigeonite always separated first from the magma.

The biotite is nearly always in close association with magnetite and frequently rims it. This association may be explained by regarding the biotite and the magnetite as the last and next to last stages of crystallisation of the residual liquid.

Magnetite and feldspar frequently reacted to form intermediate products rimming the magnetite (Photo. 4 , Slides 11 & 12).

Where the magnetite has reacted with feldspar, the magnetite is surrounded by an inner zone of green chlorite and remnants of the magnetite (Slide 12). Surrounding the chlorite zone and radiating outwards is a feldspar matrix containing numerous worm-like bodies. These bodies have a high relief and are dark-coloured. X-ray diffraction patterns of the intergrowth show strong feldspar lines, and smaller lines that compare with clinopyroxene (Hiemstra and Liebenberg, 1964, p.11). A clinopyroxene, formed from ion-exchange between plagioclase and magnetite, would have a composition of hedenbergite.

The feldspar matrix surrounding these worm-like bodies on rotation under crossednicols extinguish differently from the parent feldspar. This denotes that the feldspathic material was formed in its own right. The width of the reaction zone may be as much as one millimeter.

(F) MAGNETITE TROCTOLITE

The magnetite troctolite froms a band which is about 20 feet thick. This band occurs within, and about, 35 feet from the top of the magnetite hyperite.

With experience the magnetite troctolite can be recognised in the field and resembles a spotted norite.

It consists of about 61% plagioclase, 16% magnetite and 19% olivine. The rest of the rock consists of alteration products, notably secondary amphibole and some serpentine (Slide 4).

The anorthite content of the plagioclase is about the same as that for the rocks above and below it, i.e. in the region of about 55 to 60%.

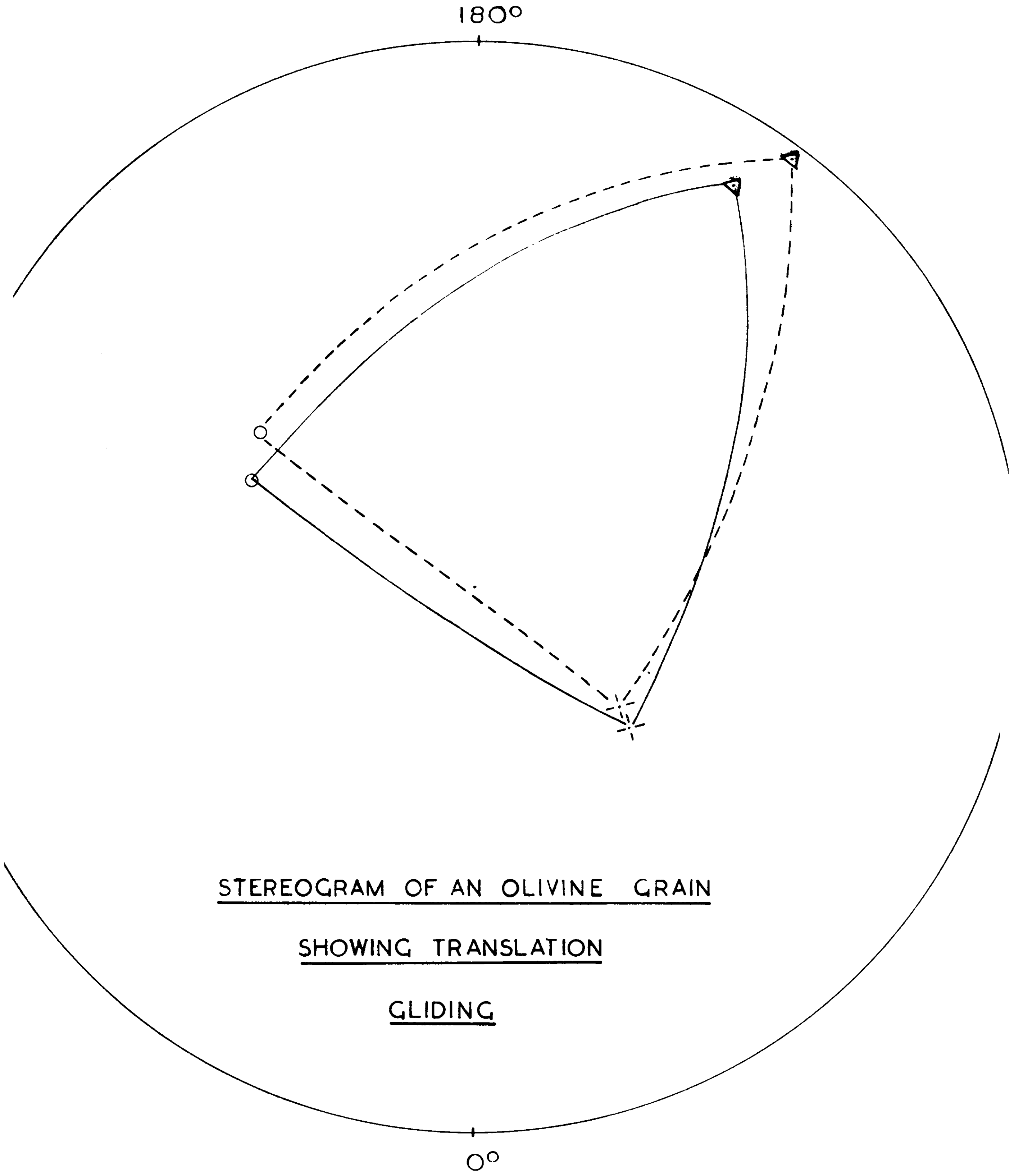
The olivine in the magnetite troctolite exhibits some very rare and interesting phenomena. $2V_\alpha$ measurements range from about 78 to 80 degrees, which yields a composition of about 40% fayalite, i.e. hyalosiderite. This is a surprisingly low iron content, as the bulk composition of the rock consists of about 16% magnetite.

A specimen of the rock was crushed, and after the magnetite was extracted with an electromagnet, the olivine was separated by means of heavy liquids. High-power magnification under a binocular microscope revealed the olivine as an amber-coloured mineral with numerous thin plates of magnetite cutting through it. This magnetite is believed to have originated through exsolution from the olivine itself, as it does not extend beyond the borders of the minerals grains.

Under crossed nicols the olivine appears to be twinned. This is, however, not the case. The individuals were measured with the aid of a universal stage, and the results were plotted on a stereonet (Diagram 10). It became immediately apparent that no twinning took place, as the pole positions of the optical directions were only slightly shifted in relation to one another. This is evidently an example of translation gliding under the influence of pressure.

The feldspar grains exhibit unique features, as frequently two distinct grains are found to be interpenetrated (Diagram 11, Photo. 5). This phenomenon only occurs in the magnetite troctolite. The feldspar does not extinguish in an undulose fashion, although some of the olivine does.

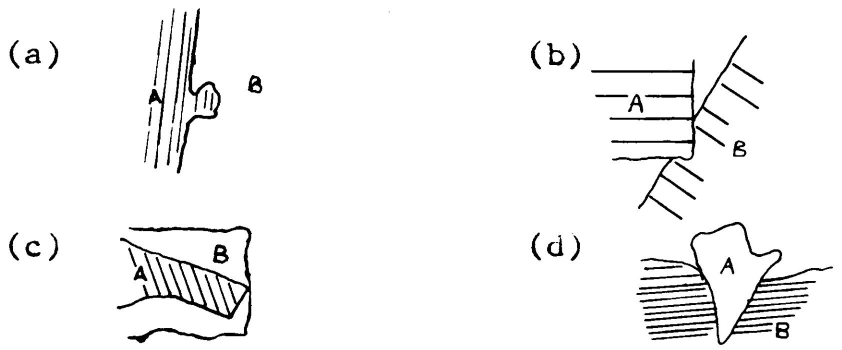
DIAGRAM 10



STEREOGRAM OF AN OLIVINE GRAIN SHOWING TRANSLATION GLIDING

DIAGRAM 11

Examples of feldspar interpenetration in the magnetite troctolite (Slide 4)



N.B. In each case feldspar A has "intruded" feldspar B. Stripes denote polysynthetic twinning (Photo. 5)

The following is a summary of the features relating to the magnetite troctolite:

(i) The average thickness of the magnetite troctolite is only ten to twenty feet.

(ii) It is underlain and overlain by magnetite hyperite. The relevant composition of the rock types is presented in Table XI.

TABLE XI

The mineral composition (volume percent) of the magnetite troctolite compared with that of the under- and overlying rocks

	Plagio-clase	Magne-tite	Ortho-pyroxene	Clino-pyroxene	Oli-vine	Horn-blende
Magnetite Hyperite	67	10	12	7	-	-
Magnetite Troctolite	61	16	-	-	19	3
Hyperite	70	2	8	6	-	13

(iii) The olivine contains 40% fayalite in a rock which carries 16% magnetite.

(iv) Exsolved magnetite is commonly found in the olivine.

(v) Translation gliding is often seen in the olivine.

(vi) The olivine crystallised later and interstitially to the plagioclase.

(vii) Plagioclase grains in the troctolite are often found interpenetrated and do not extinguish in an undulose fashion.

(viii) The composition of the plagioclase in the troctolite and in the under- and overlying hyperite is An 60% (± 5%).

(G) ANORTHOSITE

The uppermost member of Unit 1 of the Upper Zone is represented by about ninety feet of anorthosite. This anorthosite is in all respects identical to the anorthosite of the Bon Accord Unit, except that specks of sulphide are more commonly found in the anorthosite of Unit 1.

Deuteric alteration in the anorthosite is pronounced, resulting in saussuritization of the feldspar and development of secondary amphibole (hornblende) from pyroxene. Anorthosite occupying approximately a similar stratigraphic position in the Bushveld Complex in the Kruis River area near Middleburg, Transvaal, is similarly altered, although the rocks above and below it are fresh (Von Gruenewaldt - research in progress). Diagram 6 represents the composition of the various rock types of Unit 1.

VI. UNIT 2 OF THE UPPER ZONE

(Diagram 6)

(A) UPPER MAIN MAGNETITITE BAND

A five foot thick magnetite layer rests on a floor of anorthosite. The contact between the magnetite and the anorthosite is once again smooth and sharp (Specimens B1 & B2). This contact represents a definite break in crystal deposition and can be termed the "Unit 1/2 hiatus". This is analogous to the lower hiatus, which represents the boundary between the Main and the Upper Zone of the Bushveld Complex.

The lower third of the magnetitite band consists entirely of magnetite, after which feldspar becomes increasingly abundant towards the top. The upper contact of the magnetitite is gradational as feldspar becomes more abundant than magnetite. The texture of this rock is fully described under the heading "Magnetitite".

(B) MAGNETITE ANORTHOSITE

This rock is generally poor in pyroxene, but contains abundant feldspar and magnetite. It averages 74% feldspar, 17% magnetite, 9% pyroxene and just under 1% biotite by volume.

Clinopyroxene predominates slightly over orthopyroxene. The optical properties of the pyroxene in both the magnetite anorthosite and the hyperite is given in Table XII. The orthopyroxene in both rock types is hypersthene (inverted from pigeonite). The clinopyroxene is augite. The feldspar is plagioclase containing about 60% anorthite.

The grain-size of the rock is generally coarse, with plagioclase grains measuring on an average 4 millimeters in length. It is difficult to measure the magnetite in terms of individual grains, as it is opaque. Ortho- and clinopyroxene grains vary greatly in size, from a fraction of a millimeter to three millimeters.

The feldspar is euhedral to subhedral, whereas the rest of the minerals are anhedral.

Clino- and orthopyroxene are very clearly interstitial to the feldspar (Slides Ka 34 & 36). Orthopyroxene crystallised before clinopyroxene. Magnetitite occurs as clots around feldspar and pyroxene (Slide Ka36). Single isolated magnetite grains interstitial to the feldspar are common.

The feldspar grains tend to lie with their long dimension in the plane of igneous lamination, whereas the other minerals are randomly orientated. The total thickness of this rock type is about 300 feet.

TABLE XII

Optical Properties of Pyroxene from the Magnetite Anorthosite and Hyperite of Unit 2

	Slide No.	Mineral	$2V\alpha$	$2V\gamma$	$\gamma \angle C$
Ka HYPERITE	3	Hypersthene	48	-	-
	3	Augite	-	60	-
	3	Augite	-	60	43
	3	Augite	-	61	44
	4	Hypersthene	60	-	-
	4	Hypersthene	54	-	-
	4	Augite	-	48	-
	4	Augite	-	58	41
	4	Hypersthene	60	-	-
	5	Augite	-	60	53
	5	Augite	-	56	45
	5	Hypersthene	46	-	-
	5	Augite	-	60	53
	8	Augite	-	64	42
	8	Augite	-	62	50
MAGNETITE ANORTHOSITE	9	Augite	-	58	42
	9	Hypersthene	48	-	-
	13	Hypersthene	56	-	-
	16	Hypersthene	60	-	-
	24	Augite	-	50	44
	26	Augite	-	55	47
	31	Augite	-	60	42
	32	Hypersthene	46	-	-
	34	Augite	-	58	43
	36	Hypersthene	56	-	-

(C) HYPERITE

The contact between the hyperite and the underlying magnetite anorthosite is gradational. Pyroxene becomes more abundant, whereas the amount of feldspar decreases.

The bulk mineral composition varies considerably, but averages approximately plagioclase 55%, magnetite 9%, orthopyroxene 23% and clinopyroxene 13% by volume. In accordance with Diagram 6 this rock was called a hyperite and not a magnetite hyperite, although it contains more than 10% magnetite in some instances.

Individually the properties of the minerals, as well as the sequence of crystallisation, varies little if at all from that of the underlying magnetite anorthosite. The texture of the Bon Accord Hyperite is well developed, except in specimens taken in close proximity to the small magnetite bands. In the latter case the magnetite content increases substantially at the expense of the pyroxene. Diagram 12 represents th volumetric mineral composition of the various rock types of Unit 2.

VII. MAGNETITITE

(A) MODE OF OCCURRENCE

The most conspicuous mode of occurrence of magnetite in the Western Transvaal is the major magnetitite bands, which average several feet in thickness. Apart from the major magnetitite bands, numerous thinner magnetitite bands are also present and are termed the "minor bands". Magnetite is by far the dominant constituent in both the major and the minor magnetitite bands.

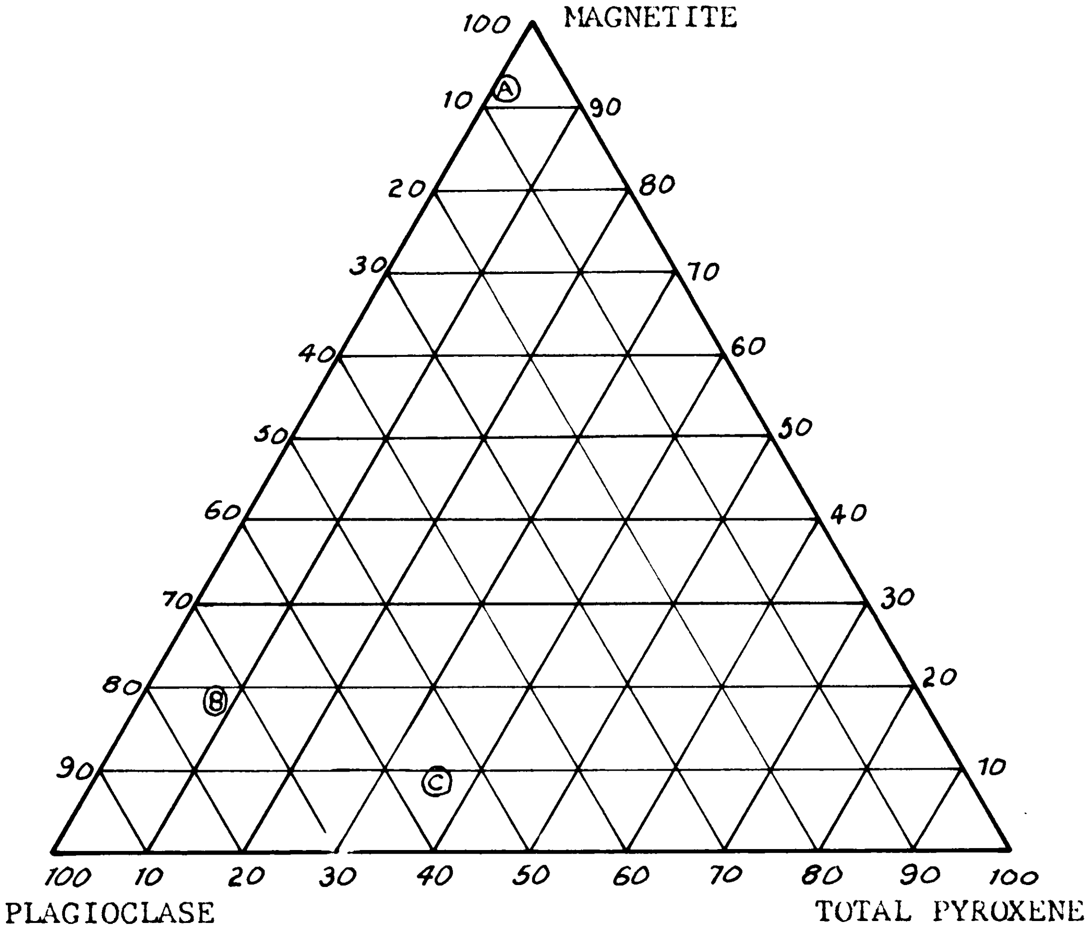
Except for the anorthosite bands, magnetite also occurs as a subordinate mineral in all the rock types of Units 1 and 2 of the Upper Zone of the Bushveld Igneous Complex.

Magnetite is also found in association with mafic pegmatoids.

A hand-specimen of magnetite from any of the bands appears as a dull-black to bluish-black

DIAGRAM 12

The Volumetric Mineral Composition of the Rock Types of Unit 2



C. Hyperite

B. Magnetite Anorthosite

A. Magnetitite

granular mass. White euhedral to subhedral feldspar grains as well as some sulphides are frequently visible. Rectangular jointing is universally developed in all outcrops, cutting the rock up into square blocks. The spacing of the joints is about 6 to 18 inches at right angles to each other. Jointing may also be repeated on a larger or smaller scale.

(1) The Major Bands

Magnetite makes its first appearance abruptly above the anorthosite of the Bon Accord Unit, where it builds the Lower Main Magnetitite Band. This band averages 50.9 inches in true thickness.

Once magnetite had made it appearance, it crystallised continuously. All the rocks of Units 1 and 2 of the Upper Zone of the Bushveld Complex contain some magnetite, except for the Upper Anorthosite and other small anorthosite bands.

The Upper Main Magnetitite Band is vertically separated from the Lower Main Magnetitite Band by 292 feet of host rock. The V_2O_5 content of the major bands and of the feldspathic magnetite is given in Diagram 12.

(2) The Minor Bands of Unit 1 (Diagram 7)

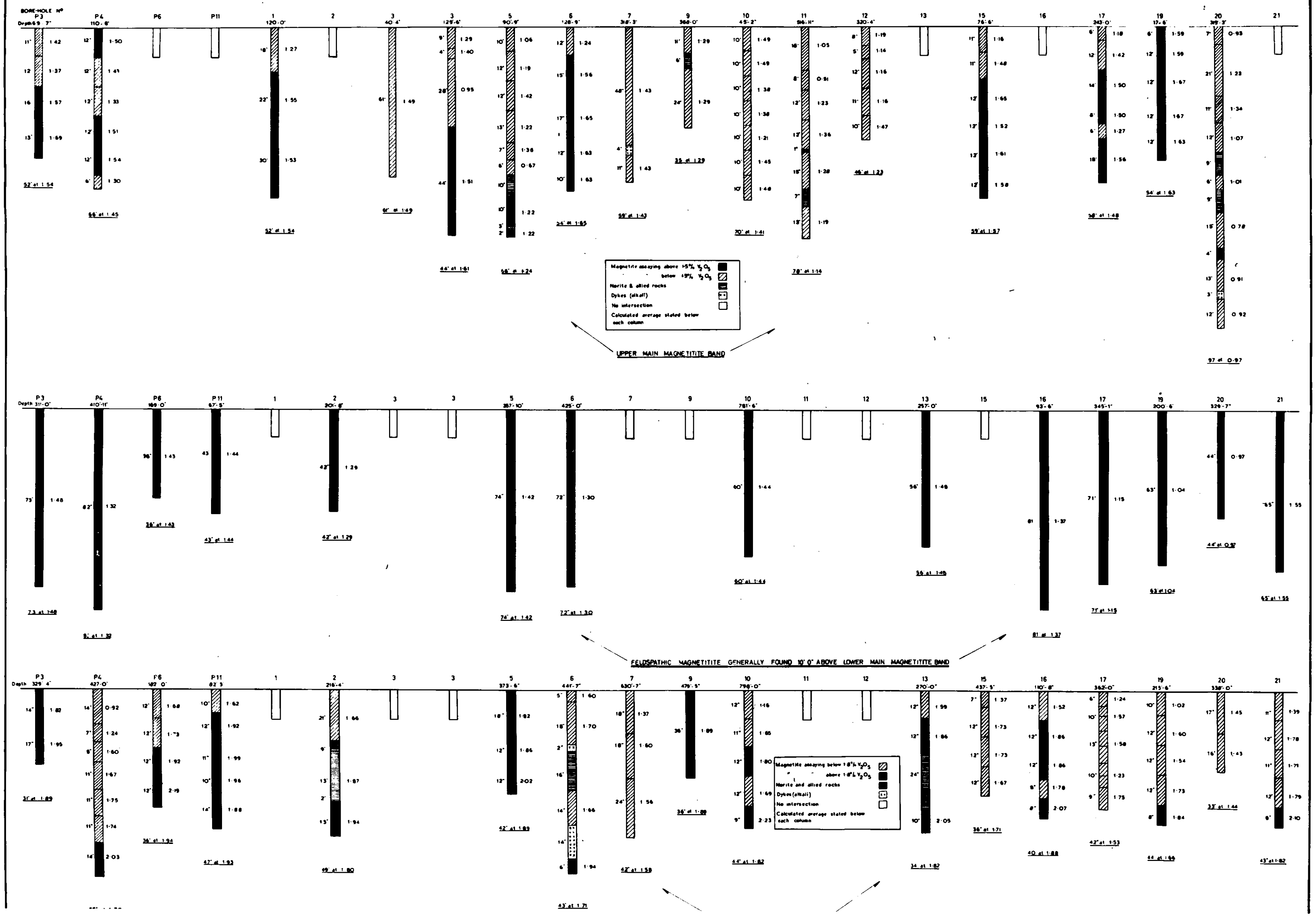
Three minor magnetite bands are commonly found interbedded in the rocks of Unit 1. The lowest band, which averages from 4 to 15 inches in thickness, generally occurs from 30 to 40 feet above the base of Unit 1. The other two minor bands are vertically separated by about 15 feet of rock. They are generally found from 100 to 120 feet below the top of the unit. The lowest of these two averages about ten inches in thickness, whereas the upper one is about thirty inches thick. The V_2O_5 content of these bands averages about 1.5%. The bands are on the whole feldspar-richer than the Lower Main Magnetitite Band.

DIAGRAM 15

RHENOSTERFONTEIN J.Q.86. RUSTENBURG DISTRICT.

DETAILED PLOT OF MAGNETITITE INTERSECTIONS SHOWING THICKNESS & ASSAY VALUES

SCALE: 1"= 1' 0"



(3) The Minor Bands of Unit 2

In Diagram 14 the minor magnetitite bands encountered above the Upper Main Magnetitite Band are plotted. The results were taken from four bore- holes on the farm "Rhenosterfontein", and one from the farm "Kopje Alleen".

Although individual bands cannot be traced with certainty from one bore -hole to another, a broad pattern is discernible. There are few, if any, individual characteristics whereby any particular minor bands can be recognised. Occasionally a few feet of anorthosite developed underneath some of the minor bands. This is a random development, as a band occupying approximately the same horizon elsewhere has no anorthosite developed beneath it.

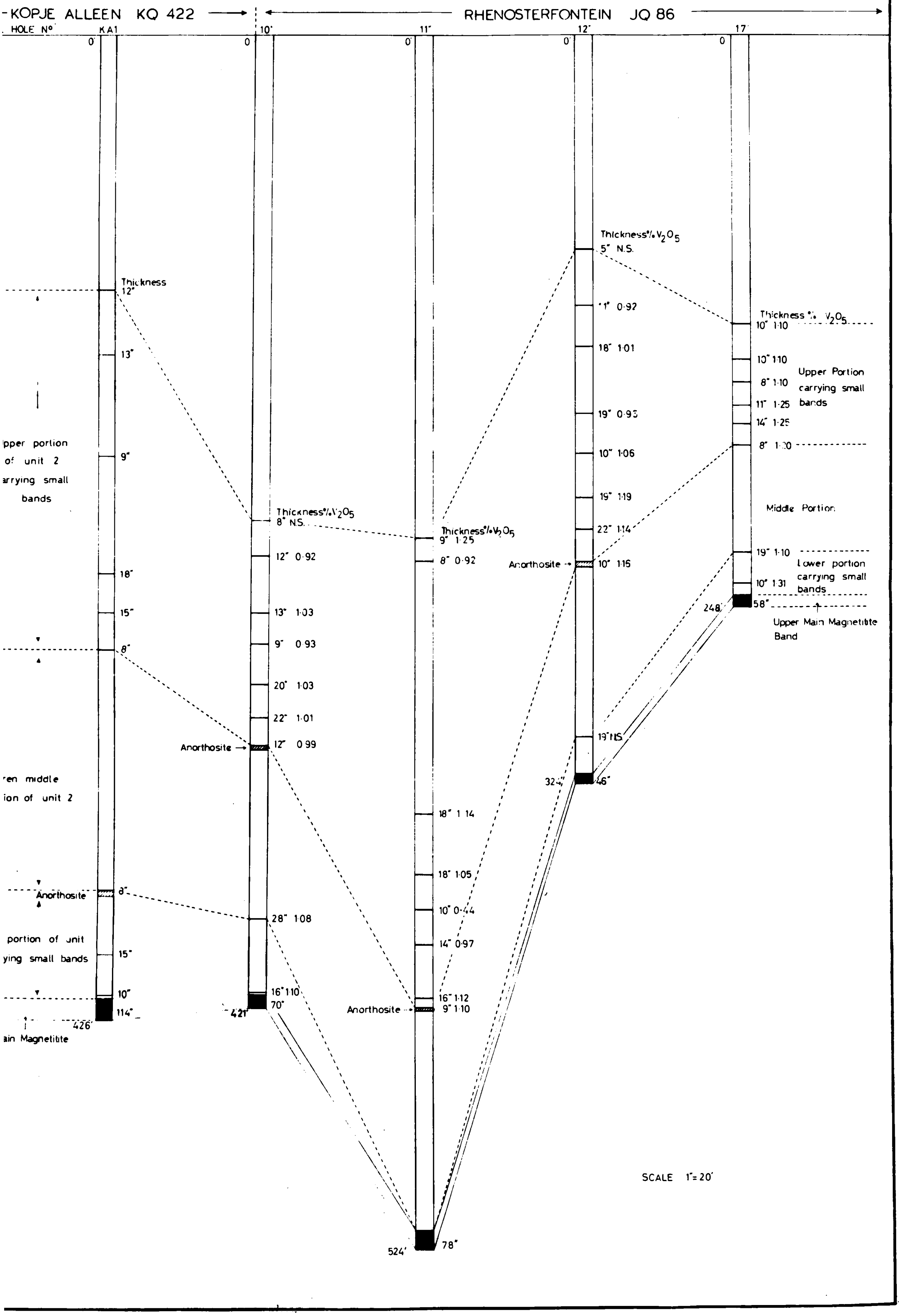
Upper contacts of minor bands are invariably gradational, whereas their lower contacts range from gradational to sharp. In the latter case, anorthosite is frequently developed beneath the minor band. These sharp contacts may, however, be "sutured" in contrast with the contacts of the Main Bands, which are usually smooth.

It can be seen from Diagram 14 that the minor bands above the Upper Main Band can be grouped into zones. The first twenty to forty feet of rock may contain from one to three minor magnetitite bands, although none are developed in Bore-hole 11.

The next 50 to 100 feet above this lower zone is generally barren of magnetitite bands. Superimposed upon the barren portion is a zone from 40 to 160 feet thick, carrying from 6 to 8 minor bands. These bands tend to be separated from each other by the same thickness of host rocks, irrespective of the total thickness over which they occur. This effect is particularly noticeable between Bore-holes 12 and 17.

DIAGRAM 14

THE MINOR MAGNETITITE BANDS ABOVE THE UPPER MAIN MAGNETITITE BAND



All available vanadium pentoxide assay results are given in Diagram 14. It is clear from these results that individual bands cannot be correlated by this method. The minor bands have thus no diagnostic characteristic by which to identify them.

(4) Pegmatoids

Several mafic pegmatoids were encountered in Bore-hole 7 on the farm "Rhenosterfontein". These pegmatoids have an intrusive relationship to the country rocks, and were intersected below the Lower Main Magnetitite Band. The thickness of the intersections varies from a few feet to fifty feet. As these pegmatoids are not layered it is difficult to determine the volumetric percentage of the magnetite found in them, especially as the magnetite is irregularly distributed.

(B) TOTAL MAGNETITE CONTENT OF UNITS 1 AND 2 OF THE UPPER ZONE

An effort was made, as shown in Tables XIII and XIV, to compute the total volumetric magnetite content of the 640 feet of rock which comprise Units 1 and 2, and which are represented in Diagrams 7 and 8.

Firstly, the magnetite content of all the magnetitite bands in Diagram 7 was calculated and distributed over the combined thickness of all the bands. By general observation and comparison with known magnetite contents, a figure of 85% magnetite was deduced for the main bands. A comparable figure of 70% magnetite by volume for the minor bands was similarly arrived at.

It was then necessary to determine the magnetite content of rocks other than the magnetitite bands. This was done by averaging the individual magnetite percentages of every thin section over the total thickness of the rock they represent. The volumetric percentage of magnetite in each slide was determined under the microscope using a special eye-piece, by counting the incidence of the various minerals.

TABLE XIII

The Magnetite Content of 300 feet of Rock
belonging to Unit 1

	Thickness	% Magnetite	Inch %
Lower Main Magnetitite Band	31"	85	2635
Total for Minor Bands	122"	70	8540
TOTAL	(12.7') 153"	73	11175
Average magnetite content in 197 feet of host rock, determined from 14 thin secions = 13%			
			Inch %
Total Magnetitite Bands	12.7'	73	11,125
Total Host Rocks	197.3'	13	30,732
Total Anorthosite	90.0'	-	-
TOTAL	300.0'	11.6	41,857
Unit 1 of the Upper Zone contains 11.6% magnetite by volume			

The magnetite content of the 325 feet of rock belonging to Unit 2 of the Upper Zone, encountered in Bore-hole KA1, was calculated as shown in Table XIV.

TABLE XIV

The Magnetite Content of 325 feet of Rock of
Unit 2 of the Upper Zone

	Thickness	% Magnetite	Inch %
Upper Main Magnetitite Band	104"	85	8840
Total Minor Bands	108"	70	7560
TOTAL	(17.7') 212"	77.3	16400
Average magnetite content in 307.3 feet of host rock determined from 34 thin sections = 16%			
			Inch %
Total Magnetitite	17.7'	77.3	16,418
Total Host Rock	307.3'	16.0	59,002
TOTAL	325.0'	19.3	75,420
The lower portion of Unit 2 represented by 325 feet of rock in bore-hole KA1 contains an average of 19.3% magnetite by volume.			

TABLE XV

Partial Chemical Analyses of Surface Samples
of Magnetitite from the farm "Rhenosterfontein"

Sample No.	% Fe	% TiO_2	% V_2O_5	% Mn	% Cr	% SiO_2
28	54.7	13.0	1.87	0.57	0.19	3.00
29	57.1	12.4	1.94	0.55	0.12	2.24
30	53.8	14.4	1.81	0.31	0.08	4.55
31	54.9	15.5	1.81	0.48	0.13	4.09
32	52.8	18.3	0.84	0.71	0.27	3.64
33	54.7	14.0	1.83	0.36	0.09	4.57
34	55.7	14.0	1.86	0.35	0.09	4.65
35	54.3	13.6	1.81	0.32	0.11	4.52
36	52.6	14.1	1.87	0.36	0.09	4.86
37	56.7	15.0	1.85	0.35	0.11	1.79
38	57.6	13.6	1.76	0.41	0.06	1.51
39	56.2	13.8	1.70	0.43	0.09	1.62
40	55.5	15.1	2.01	0.40	0.13	3.16
41	56.3	14.0	1.70	0.39	0.08	1.97
42	56.1	12.5	1.43	0.56	0.10	2.10
43	55.0	13.5	1.43	0.45	0.11	2.18
44	55.7	15.1	1.97	0.43	0.03	2.04
45	52.8	15.0	1.97	0.31	0.07	3.46
46	56.1	15.1	1.43	0.31	0.04	2.05
47	54.0	14.6	1.63	0.56	0.06	2.46
48	55.3	13.8	1.58	0.35	0.23	1.04
49	55.0	14.3	1.91	0.50	0.11	2.30
50	53.2	13.3	1.48	0.30	0.10	3.48
51	53.0	19.8	1.52	0.29	0.09	1.53
52	55.7	15.6	1.43	0.26	0.03	1.00
53	55.6	15.0	1.43	0.46	0.04	3.83
54	53.5	19.0	0.91	0.54	0.11	3.30
55	55.7	15.1	1.75	0.40	0.07	4.28
56	57.2	13.3	1.76	0.37	0.06	2.40
57	57.7	11.5	1.31	0.42	0.09	2.39
58	53.4	20.5	1.11	0.56	0.14	3.77
59	57.2	14.5	1.63	0.65	0.13	3.55
60	54.5	13.4	1.46	0.50	0.11	4.47
61	54.3	13.3	1.62	0.41	0.08	-
62	58.0	13.1	1.55	0.37	0.09	-
63	55.9	13.5	1.63	0.46	0.09	-
64	55.9	13.4	1.53	0.30	-	4.08
65	56.0	13.7	1.87	0.49	0.08	3.34
66	54.3	14.4	1.69	0.30	-	4.13
67	56.7	13.5	1.67	0.26	-	2.66
68	52.2	20.5	0.27	0.35	-	5.07
69	51.5	20.3	0.37	0.35	-	5.93
70	54.0	21.1	0.16	0.35	0.10	3.88
71	54.0	21.1	0.37	0.33	-	2.04
72	52.5	20.5	0.32	0.34	-	3.72
73	53.8	21.9	0.34	0.36	-	1.72
74	50.7	20.6	0.34	0.19	-	4.47
75	53.0	20.4	0.34	0.35	0.08	2.43
76	52.0	20.6	0.40	0.29	-	3.53
77	56.1	13.9	1.60	0.26	-	1.64
78	55.6	13.0	1.42	0.26	-	5.06
79	55.4	14.1	1.67	0.24	-	1.77
80	55.4	14.1	1.56	0.25	0.08	3.00
81	56.2	13.0	1.58	0.28	0.16	1.88
82	54.0	11.4	1.24	0.28	0.16	4.36
83	54.6	14.0	1.59	0.28	0.16	2.41

84/......

TABLE XV (Cont.)

Sample No.	% Fe	% TiO_2	% V_2O_5	% Mn	% Cr	% SiO_2
84	53.2	13.4	1.49	0.28	0.16	2.30
85	56.7	13.4	1.58	0.28	0.16	1.17
86	56.2	14.1	1.63	0.28	0.16	1.04
87	56.2	13.8	1.62	0.28	0.16	1.59
88	55.4	12.9	1.55	0.28	0.16	2.30
89	55.1	13.9	1.56	0.28	0.16	1.92
90	54.8	12.9	1.74	0.28	0.16	2.17
91	54.0	14.4	1.66	0.28	0.16	2.00
92	54.0	14.1	1.87	0.33	0.13	3.18
93	47.5	12.6	1.56	0.33	0.13	10.40
94	54.3	13.4	1.92	0.33	0.13	3.04
95	51.6	13.8	1.89	0.33	0.13	5.15
96	54.0	13.6	1.89	0.33	0.13	3.58
97	53.9	13.9	1.89	0.33	0.13	3.67
98	53.5	14.1	1.94	0.33	0.13	3.24
99	55.6	14.1	1.94	0.33	0.13	1.42
100	54.8	12.5	1.63	0.33	0.13	2.98
101	55.4	15.0	1.99	0.33	0.13	1.90
102	54.1	15.3	1.94	0.33	0.13	3.00
103	55.4	14.5	1.96	0.33	0.13	1.90
104	53.2	13.9	1.86	0.38	0.13	5.16
105	55.0	13.6	1.61	0.38	0.13	2.43
106	55.0	14.0	1.58	0.38	0.13	1.92
107	57.1	14.8	1.46	0.38	0.13	1.19
108	54.8	13.5	1.64	0.38	0.13	1.91
109	55.9	13.0	1.58	0.38	0.13	1.73
110	56.0	13.0	1.56	0.38	0.13	1.19
111	56.9	14.5	1.44	0.38	0.13	1.55
112	56.2	14.1	1.77	0.38	0.13	1.29
113	54.8	13.9	1.63	0.38	0.13	1.45
114	55.4	13.1	1.56	0.38	0.13	1.71
115	53.5	13.9	1.65	0.38	0.13	2.85
116	51.9	21.9	0.39	0.28	0.11	2.65
117	54.9	17.0	1.12	0.28	0.11	0.75
118	55.4	12.9	1.46	0.28	0.11	2.06
119	54.9	14.3	1.35	0.28	0.11	3.05
120	55.7	13.6	1.67	0.28	0.11	2.15
121	55.7	14.9	1.76	0.28	0.11	0.81
122	56.5	13.3	1.52	0.28	0.11	2.34
123	54.3	21.0	0.96	0.28	0.11	1.61
124	56.2	19.6	1.03	0.28	0.11	0.74
125	55.4	13.1	1.78	0.28	0.11	1.79
126	55.7	14.3	1.96	0.28	0.11	2.68
127	55.4	15.1	1.69	0.28	0.11	1.25
128	56.2	13.3	1.78	0.35	0.16	1.25
129	53.5	12.9	1.55	0.35	0.16	3.31
130	55.1	14.8	1.48	0.35	0.16	2.21
131	55.1	13.9	1.46	0.35	0.16	2.48
132	55.9	15.6	1.51	0.35	0.16	1.50
133	55.4	13.1	1.71	0.35	0.16	1.95
134	57.4	10.9	1.96	0.35	0.16	2.75
135	56.5	13.4	1.86	0.35	0.16	2.37
136	56.5	15.1	1.72	0.35	0.16	1.12
137	52.1	19.4	1.21	0.35	0.16	2.05
138	55.1	14.9	1.82	0.35	0.16	1.96
139	56.0	14.2	1.93	0.30	0.19	2.00
140	56.0	14.2	1.88	0.38	0.10	1.12
141	52.5	13.7	1.75	0.46	0.18	5.00

(C) CHEMICAL COMPOSITION

Partial chemical analyses of 114 surface samples collected from the farm "Rhenosterfontein" are given in Table XV.. Diagram 13 was prepared from these tabled results - the titanium dioxide is plotted against the vanadium pentoxide content. A principal trend is revealed indicating the antipathetic relationship between these two constituents. This confirms the work of many previous authors.

The principal economic interest in the magnetite is its content of vanadium pentoxide. Therefore detailed plots of all intersections of the two major magnetite bands encountered in bore-holes on the farm "Rhenosterfontein" were made (Diagram 14). For each bore-hole intersection the weighted average of vanadium pentoxide was calculated according to the thicknes and the value. Internal and external waste (dykes) was ignored for this calculation.

Scrutiny of these results reveals that the content of vanadium pentoxide at the bottom of a band is remarkably higher than that at the top of a band. The poorer tops can be partially ascribed to a higher feldspathic content, but not entirely. Frequently the lower of two bottom samples adjacent to each other, both having equal amounts of silicate waste, has a higher vanadium content. This indicates that for some unaccountable reason the vanadium is more concentrated towards the bottom of the bands, and the titanium towards the top.

(D) ORE MINERALOGY

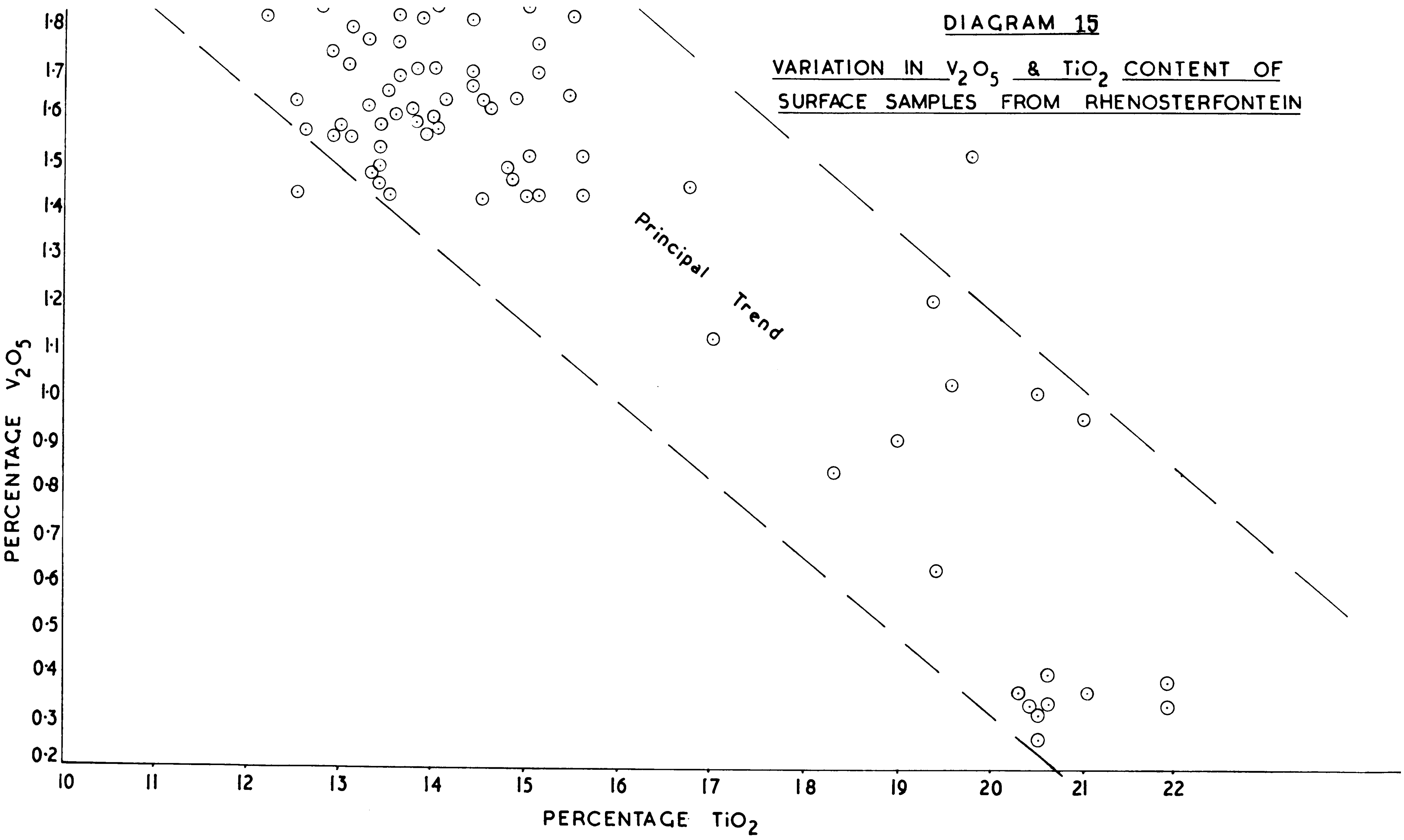
An effort was made to collect samples of magnetite ore showing a minimum of alteration. Polished sections were prepared from drill-hole cores recovered from depths down to 930 feet below the surface (Bore-hole RF7).

Three distinct types of magnetite ore can be distinguished, namely:

(1) Deep-seated ore forming regular bands

DIAGRAM 15

VARIATION IN V_2O_5 & TiO_2 CONTENT OF SURFACE SAMPLES FROM RHENOSTERFONTEIN



(2) Ore associated with pegmatoid intrusions
(3) Ore from outcropping bands.

(1) Deep-seated Ore forming Regular Bands

A complete sequence of polished sections were prepared from a magnetite band 76 inches thick, intersected by a bore-hole at a depth of 427 feet below the surface.

The microscope reveals the magnetite as a mass of interlocking anhedral grains of magnetite and ilmenite. The accessories include spinel and sulphide (Polished Section 1886).

(a) Magnetite

In polished section the magnetite appears as light-brown anhedral grains. Individual grains cannot always be distinguished from each other, but where boundaries are visible, they are irregular. The boundaries between the grains can sometimes be inferred as optical directions in the magnetite. They manifest themselves in exsolution and other phenomena. It is known for example that magnetite exsolves ilmenite parallel to (111) and spinel parallel to (100) (Polished Sections R7/930 & R7/937).

The size of individual grains varies considerably as their shape is irregular, but large grains which measure about 6 millimeters across predominate.

Frequently yellowish-brown patches can be seen, especially in the vicinity of cracks in the magnetite. These patches disappear eventually with careful polishing (Section 1886).

Lamellae of primary exsolved ilmenite in magnetite (Photo. 6) occur somewhat infrequently, whereas exsolved spinel is common. The more frequent exsolution phenomenon found in magnetite is, however, a fine network of ulvite exsolved parallel to (100) of the magnetite. This network is extremely fine and can only be seen clearly under the microscope at high magnification. Exsolution of titanium-bearing material in magnetite is sometimes solely represented by the network of ulvite in conjunction with discrete grains of ilmenite. Some of the ulvite is invariably oxidized to ilmenite and secondary magnetite. The latter mineral is indistinguishable from the parent magnetite.

In some sections the network of ulvite is absent, and in its place a coarse network of primary exsolved ilmenite lamellae is developed (Section RFP3). Generally this phenomenon is more noticeable in magnetite ore associated with pegmatoid intrusions, and in ore from seams above the Lower Main Magnetitite Band. The latter Band, which contains the least amount of titanium dioxide, also has fewer primary lamellae of exsolved ilmenite.

Under crossed nicols the magnetite displays a number of interesting features. Some measure of anisotropism is universally present.

Whole magnetite grains are rarely anisotropic, but rather exhibit anisotropism in several different patterns. Anisotropism as seen in magnetite can only be ascribed to the formation, or incipient formation, of ilmenite.

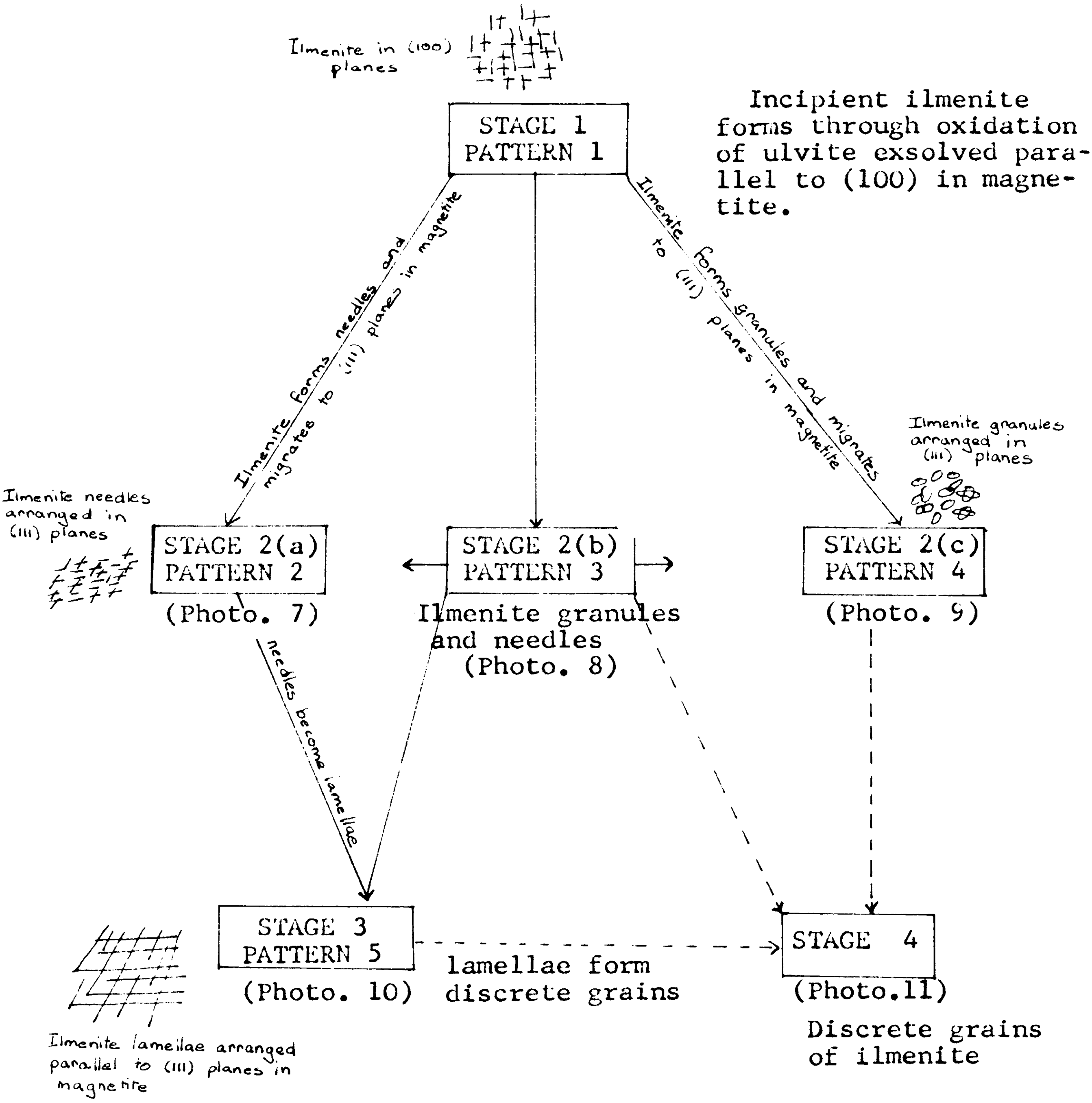
The several different patterns of anisotropism displayed in the magnetite are directly attributed to different stages of formation and behaviour in the magnetite (Diagram 16).

Stage 1

This stage represents the formation of ilmenite in the (100) planes of the magnetite as a result of the oxidation of primary exsolved ulvite. In unweathered magnetite from Rhenosterfontein, the primary exsolved ulvite occurs on too small a scale to be photographed. Anisotropic pattern no. 1 was hardly ever seen in the unweathered magnetite from Rhenosterfontein.

DIAGRAM 16

Formation and Behaviour of Ilmenite in Magnetite and resultant Anisotropic Patterns



Stage 2

The transition from Stage 1 to Stage 2 is the migration of ilmenite from the (100) into (111) planes of the magnetite.The ilmenite formed in Stage 1 presents itself in Stage 2 as either needles (Stage 2a, Pattern 2), as granules (Stage 2c, Pattern 4), or as a combination of both granules and needles (Stage 2b, Pattern 3).

Stage 3

The ilmenite needles of Stage 2 appear to "grow" together to form incipient lamellae (Pattern 5)(Photo.10). It is interesting to note in the photograph that there are two ages of ilmenite lamellae. The first or earlier set represents primary exsolved ilmenite, whereas the later set of incipient lamellae formed in the manner described above.

Stage 4

Ilmenite which formed through the oxidation of ulvite, tends ultimately to form discrete grains. It remains doubtful whether Stage 2(c) could yield discrete grains directly. Photograph 11 provides fairly convincing evidence that ilmenite lamellae, whether of primary or secondary origin, tend to form discrete grains.

In nearly all the polished sections examined, the spinel hercynite can be seen as an exsolution product in the magnetite, arranged parallel to (100)(Photo.12). This spinel occurs generally as fine slender plates and also as very fine veinlets composed of individual grains (Photo. 12).

Frequently the interior of a magnetite grain contains numerous spinel plates, whereas the border areas may be spinel free. This is probably due to the migration of the spinel to the edges (Photo. 12).

The small size of the spinel plates (1 or 2 microns thick and up to 10 microns long) defies absolute identification.

(b) Ilmenite

Ilmenite may occur firstly as discrete grains measuring from a fraction to several millimeters across. These discrete grains are interstitial to the magnetite and must have crystallised later. The ilmenite may also occur as coarse, primary exsolved lamellae in the magnetite, or as secondary products from the oxidation of the ulvite (Photo 6).

The titanium content in the magnetitite varies from 12 to 22% TiO_2. Calculations indicate that, should all the titanium in a sample of magnetitite containing 15% TiO_2 be used to build ilmenite, the rock would contain about 28½% ilmenite.

(c) Feldspar

Apart from the exsolution bodies in the magnetite, the only silicate present in magnetitite is plagioclase, which has an anorthosite content of 60%. Under the microscope it is apparent that the feldspar invariably crystallised later than the magnetite. The feldspar frequently occupies irregular spaces between magnetite grains (Section 1884).

Contacts between feldspar and magnetite are mostly uneven and curvilinear.

Some of the feldspar reacted with the magnetite to form secondary products. These products are identical to those formed by the interaction of magnetite and feldspar in the magnetite hyperite of Unit 1.

There is fairly abundant evidence of the replacement of magnetite by silicate. It appears that gangue preferentially replaces magnetite rather than ilmenite. This tendency is illustrated in Photograph 13. In the center of this photograph a magnetite grain (dark-grey) is flanked by ilmenite on both sides (light). The magnetite is preferentially replaced by silicates leaving ilmenite lamellae as relict structures.

(d) Sulphides

Sulphides in small quantities are present as discrete grains, as tiny veinlets cutting across magnetite, and as bodies in the silicates (Sections R7/929, R7/321, Photo. 13).

The most commonly found sulphides are pyrite, pyrrhotite, chalcopyrite and marcasite (Sections R7/929 & R7/321).

Chemical analyses of the magnetite (Table XV) indicate that the average manganese content is about 0.35%. Manganese is known to have the highest affinity of all metals for sulphur (Rankama & Sahama 1949, p.646). It is therefore strange to find no trace of the manganese sulphide alabandite in the magnetite.

Magnetite in rare cases has been known to contain up to 1.5% manganese oxide (Rankama & Sahama 1949, p.646). This could be a possible solution as to where the manganese is, but not as to the reason why it is there. Rankama and Sahama give no explanation regarding the absence of manganese in primary magmatic sulphides and only suggest that their absence may be ascribed to the high solubility of manganese sulphide in a sulphide melt.

(2) Ore Associated with Pegmatoid Intrustions

W.J. van Rensburg (1962) dealt exhaustively with titaniferous magnetite in association with an ultramafic pegmatoid on the farm Kennedy's Vale in the Eastern Transvaal.

Small differences do exist between pegmatoid ore and ore from the magnetitite bands, as pegmatoid ore tends to contain more sulphide than the magnetitite bands (visual observation).

Magnetite in the pegmatoid has a greater propensity of exsolving coarse lamellae of primary ilmenite (Section R7/929, Photo 6) than magnetite of the magnetitite bands.

(3) Ore from Outcropping Bands

Polished sections of magnetite collected on the surface are markedly different from the fresh samples found at depth. The differences are detectible with the naked eye. The surface samples reveal the presence of a reddish-brown mineral which is never found at depth.

Under the microscope the brownish colour of unweathered magnetite is absent and has been replaced by the typical bluish-grey colour of the maghemite. This has been recognised by Frankel and Grainger (1940, p.103), Schwellnus and Willemse (1943, p.29) and Strauss (1946, p.38)

The typically blue-grey maghemite is seldom in direct contact with the reddish-brown surface mineral, as an intermediate stage is usually developed which has a purplish sheen. This colour gradation is attributed to admixture of the blue-grey maghemite and the reddish-brown mineral. The latter mineral is irregularly developed in a moth-eaten pattern (Photo 14)

An error in polishing using a Durener Polishing Machine yielded startling results. It is not clear as to what went wrong in the polishing process. By means of scratches it was revealed that the blue-grey maghemite is substantially softer than the darker-coloured mineral (Photo 15)

Micro-hardness tests were conducted on "fresh" magnetite, on blue-grey maghemite and on the reddish-brown mineral (Table XVI).

TABLE XVI

Micro-Hardness Data on Various Magnetite Ores

Ore	Vicker's Hardness	Average
"Fresh" Magnetite Section 1886 Rhenosterfontein	660 644 639 660 639 639	647
Reddish-Brown Mineral Section JW 380 Groenfontein	1007 1017 996 927 900 985 918	964
Blue-Grey Maghemite Section JW 380 Groenfontein	857 780 857 909 927 857	865

B.B. Young and A.P. Millman (1963/64, p.45) give the Vicker's Micro-hardness of magnetite as 490 - 660. Van Rensburg (1962, p.62) determined the Vicker's Micro-hardness of blue-grey maghemite and fresh reddish-brown magnetite as 869 and 538 respectively. The high micro-hardness of the reddish-brown mineral in the weathered samples precludes it from being magnetite. The blue-grey mineral is without doubt maghemite.

It has been noted by many authors that martitization in surface ores is common.

The anisotropic patterns in surface ores are similar to those of fresh magnetite and cut across all colour gradations.

Magnetite is resistant to most etch reagents. Experiments indicate that HF readily etches fresh magnetite, leaving ilmenite virtually untouched. Incipient ilmenite bodies (after ulvite) become visible in lightly etched (30 seconds with undiluted HF) fresh magnetite.

Surface samples of magnetite are far more resistant to etching with HF than the unweathered magnetite samples from Rhenosterfontein. The maghemite gives an essentially negative reaction to undiluted HF after 60 seconds, whereas the unknown reddish-brown mineral reacts more slowly and less intensively than the fresh magnetite (60 seconds with undiluted HF).

Some of the reddish-brown material was drilled out of polished section 143, and x-rayed by using a powder diffraction method. The measured d -values of the reddish-brown mineral are given in Table XVII. This table also provides the d-values of magnetite, ilmenite and maghemite which correspond with that of the reddish-brown mineral.

TABLE XVII

X-ray Diffraction Data on Reddish-Brown Mineral

Line No.	Intensity	d-values			
		Reddish-Brown Mineral	Magnetite	Ilmenite	Maghemite
1	6	6.051	-	-	-
2	6	4.983	-	-	-
3	6	4.215	-	-	-
4	3	3.739	-	3.73	-
5	5	2.990	-	-	-
6	4	2.933	-	-	2.94
7	7	2.741	-	2.74	-
8	10	2.529	2.53	2.54	-
9	2	2.221	-	2.23	2.22
10	4	2.101	2.096	-	2.08
11	3	1.869	-	1.86	-
12	4	1.728	1.712	1.72	-
13	5	1.606	1.614	1.63	1.60
14	6	1.474	1.483	1.47	1.47
Lines 1 to 3 are very thick and of doubtful value.					

Results of the x-ray study were inconclusive, as some of the lines obtained on the x-ray films correspond with magnetite, others with ilmenite and maghemite, whereas line 5 has no equivalent in the latter three minerals.

It is regretted that the reddish-brown mineral common in the surface ore, has not been identified definitely.

Some doubt prevails as to whether the reddish-brown mineral represents remnants of "magnetite" which is being replaced by maghemite. The latter relationship is advocated by Schwellnus and Willemse (1943, p.29), and van Rensburg (1962, p.61).

Strauss (1946, p.39) advocates the opposite. He regards the blue-grey maghemite as a first development, and the reddish-brown mineral as a later product.

The author favours the latter concept as it is fairly clear that the reddish-brown mineral is absent in unweathered ore. It is admitted that from textural relationships, it is not easy to decide which developed first. There is a slight preponderance of evidence in favour of the reddish-brown mineral being a later product than the maghemite (Photo 14)

VIII. PETROGENESIS

(A) THE BON ACCORD UNIT

In the Bon Accord Hyperite, which is the lowest member of the Bon Accord Unit, the plagioclase feldspar was first to separate from the magma. There is a great deal of textural evidence to support this.

Ortho- and clinopyroxene grains invariably occupy triangular, or other irregular shapes between the feldspar laths. They frequently envelope feldspar grains. Thin tongues of pyroxene occupy narrow and elongated spaces between feldspar laths. The wide range in size of both the clino- and the orthopyroxene grains, as well as the absence of crystalline outlines, yields corroborative evidence that they crystallised interstitially (Photos. 1,2&16) Only the feldspar grains exhibit crystal faces, mostly (010), which means that at the time of crystallisation they were surrounded by a liquid medium which allowed free growth. Once separated from the magma, they sank rapidly to the bottom coming to rest with the major axes of elongation predominently orientated parallel to the floor of the magma chamber. It must be appreciated that not all the feldspar crystals lie flat, as a large number are inclined as the opposite ends come to rest on different elevations. Any bottom currents operating in the magma would enhance the process of pushing the feldspars flat and arranging them in a more orderly fashion.

It is almost certain that crystallisation took place near to the surface of the magma where the greatest heat-loss could be expected.

Heat-loss from the sides of the magma chamber is feasible, and would yield more or less comparable results to heat-loss at the surface.

The earliest preserved feldspar crystals have a composition of An$_{60}$. It is obvious that feldspar of a more calcic composition should have separated earlier and at a higher temperature. In order to account for the anorthite content in the preserved crystals, the precipitating liquid might have reached a measure of super-cooling before crystallisation of the feldspar commenced.

The probable answer is that the first formed plagioclase of high calcium content (>60% An), while lying at the bottom, reacted perfectly with the liquid on cooling until the temperature remained constant, i.e. a fine balance between heat-loss and heat-gained existed. This process continued with the constant accumulation of new crystals, while the older crystals grew adcumulatively.

The rate of feldspar deposition at the bottom of the chamber was not excessively fast since relatively few, if any, pockets of completely trapped liquid are evident. The liquids in such pockets, should they have existed, would have left pore spaces upon crystallisation as a result of a reduction in volume. Pressure due to the weight of the overlying material would tend to eliminate any such spaces, which might account for the bent feldspar laths.

It was established that the orthopyroxene grains crystallised later and interstitially to the plagioclase. Although the orthopyroxene commenced to crystallise after the feldspar network was established, some overlap of the periods of crystallisation of these two constituents is feasible. This is attested by the non-linear interfaces which are frequently developed between feldspar and orthopyroxene. This type of situation is well illustrated by A.K. Wells (1952, fig. 2, p.914).

Immediately the problem arises as to the reason why the orthopyroxene did not crystallise at the top of the liquid and did not form bottom cumulates.

In fact, a complete feldspathic crystalline mesh must have existed at the bottom, and was enveloped by a liquid that contained a great deal of pyroxenite material. Further slow cooling of this mesh and the interprecipitate liquid caused relatively few nuclei of pigeonite to separate from the magma.

It is quite possible for a single crystal structure propagating itself in a three dimensional way, to reach a certain point from three different directions after some time. Should this process of propagation be somewhat imperfect, it might result in three slightly different optical orientations at this point. In a thin section this would appear as three different grains.

The feldspar framework might also have become slightly unstable as the overlying weight increased. Should some of the feldspar grains have shifted slightly at the time of crystallisation of the calcium-poor pyroxene, such a movement would have contributed towards severing the thin connections of the pigeonite framework. Crystallisation would continue, i.e. the original material would again propagate itself, but such a break would contribute towards a slight disorientation of the pyroxene grains.

At the time of crystallisation of the clinopyroxene, a condition existed in which a small amount of liquid co-existed with a large amount of crystalline material. Cooling through convection or turbidity currents would be very inefficient, and small temperature inequalities would be likely. Consequently, the clinopyroxene represents individual points of crystal nucleation and growth.

In J.J. van der Berg's (1946, p.199) summary and conclusions regarding the orientation of the constituents, he states "crystal settling under the action of gravity is a perfect example of such a force and is hence regarded as the most probable cause of the orientation". Continuing his reasoning he concludes that the force of gravity was unable to orientate the clinopyroxene, as it crystallised late from an interstitital liquid.

Close microscopic examination of his Bon Accord sections reveals abundant evidence that the orthopyroxene crystallised interstitially (Slide VB43 of present thesis). This texture is not in evidence in the pyroxenites found elsewhere in the Bushveld, where they are clearly bottom cumulates.

The texture of the Bon Accord Hyperite occurs repeatedly at higher horizons in the Bushveld Complex but nowhere has its occurrence been noted where a previously formed feldspathic network did not exist prior to the crystallisation of the pyroxene.

Walter Wahl (1963, p.17) discusses hypidiomorphic granular textures in plutonic rocks. He finds that crystals of a solid solution series are of uniform structure and have arisen at a uniform temperature. Then he concludes that the hypidiomorphic granular texture of a rock was formed by growth of the crystal components at a constant temperature, and that the crystallisation of the rock took place as a result of a rise in pressure in the magma chamber, and not due to a drop in temperature.

It is well-known that isothermic crystallisation can occur due to an increase or decrease in pressure. Tuttle and Bowen (1958, p.67) state, however, that "crystallisation in 'dry' systems takes place in response to heat-loss from the system with consequent temperature drop - if the heat is not lost crystallisation will not proceed". This implies that pressure plays a small role in the crystallisation of "dry" systems. In comparison to a hydrous granite liquid, the mafic plutonic phase of the Bushveld Complex must have been relatively "dry".

An adiabatic rise in temperature will result when a closed magmatic system undergoes confining pressure. Should crystallisation commence, even more heat would be released. All heat thus gained by the system must be dissipated for crystallisation to proceed isothermally. It is therefore reasonable to assume that before confining pressure was applied, a heat-loss occurred. This must have eventually resulted in a lowered temperature. Accordingly, it is unnecessary to invoke polybaric isothermal crystallisation in order to explain unzoned plagioclase crystals.

Although the volumetric mineral composition of the Bon Accord hyperite is different from that of the overlying anorthosite-norite and anorthosite-gabbro, the sequence in which the various minerals crystallised remained the same. The petrogenic history of these three rock types is essentially similar, and textural differences are attributed to differences in mineral composition.

The uppermost rock-type of the Bon Accord Unit is anorthosite, which reveals the tendency for the Unit to become richer in feldspar towards the top (Table XVIII).

TABLE XVIII

Volumetric Feldspar Content of the Bon Accord Unit

Rock Type	Percentage Feldspar
Anorthosite	90
Anorthosite-Gabbro	74
Anorthosite-Norite	78
Hyperite	62

In a broad sense this type of sequence is analogous to the layered mafic rocks of Rhum, Inner Hebrides, where an olivine-rich rock gradually passes upwards into a rock rich in feldspar.

This is suggestive of density layering, but the actual mechanism by which this is accomplished remains an enigma, especially as all the heavier minerals (pyroxene) are interstitial to, and crystallised later than the lighter one, namely feldspar.

(B) UNIT 1 OF THE UPPER ZONE

Magnetite first appears at the beginning of Unit 1 of the Upper Zone of the Bushveld. It constitutes 11% of the whole unit including 90 feet of anorthosite.

In order to understand the iron-rich nature of these rocks, the general layered sequence of the Bushveld Complex has to be studied.

It has been convincingly illustrated that the iron content of ferromagnesian minerals, notably olivine and pyroxene, increases at the expense of magnesium in successive stages of crystallisation of a basaltic magma. To explain the enormous quantities of iron in the Upper Zone, vast amounts of magnesium-rich ferromagnesian minerals must have been present in the lower regions. Osborn (1962, pp.211-225) has adequately demonstrated the importance of sufficient oxygen vapour pressure before magnetite will crystallise. At an oxygen vapour pressure of 0.21 atmospheres, magnetite crystallises instead of fayalitic olivine and iron-rich pyroxene. Osborn (p.218) states that this process requires a constant oxygen pressure, and that the magmatic liquid becomes progressively enriched in SiO_2.

Since its first appearance at the beginning of Unit 1, the magnetite crystallised continuously with only minor interruptions when the anorthosite bands were formed. This implies a sufficient and constant oxygen pressure.

The Bon Accord sequence of rocks is essentially magnetite free. It is probable that, irrespective of the oxygen pressure, magnetite could not have crystallised. The composition of the magma which yielded the Bon Accord Unit was not sufficiently iron-rich to precipitate magnetite at the expense of pyroxene.

The Bon Accord Unit was terminated by anorthosite, and as previously stated, this signifies an end of a magmatic cycle.

The magma which was then emplaced and gave rise to Unit 1 of the Upper Zone differed substantially from the previous one, and allowed magnetite to crystallise in appreciable, to very large quantities.

Assuming a constant high oxygen pressure and a magmatic liquid, which is compositionally capable of precipitating magnetite at a high oxygen pressure, it is necessary to invoke other agencies to explain the intermittently heavy concentrations of magnetite in the magnetitite bands.

Accordingly, it is postulated that the degree of supersaturation of the various constituents in relation to each other plays a vital role.

At the commencement of crystallisation, after emplacement of the magma of Unit 1 of the Upper Zone, a degree of iron supersaturation existed, probably as a result of differentiation in depth. The crystallisation of the magnetite, which builds the Lower Main Magnetitite Band, forced the remaining liquid in the direction of feldspathic and pyroxenitic enrichment. Towards the top of the Lower Main Magnetitite Band feldspar started to crystallise.

It is inconceivable that magnetite should crystallise before the feldspar in the magnetitite bands, and later than feldspar in the host rocks between the bands, unless a degree of supersaturation of iron in the magma is invoked.

The exact mode of crystallisation of the magnetite is complex, as it so rarely exhibits crystal faces. Interstitial trapped liquid must have existed if the magnetitites are bottom cumulates. As such, crystal faces would surely develop in the direction of the pore liquid, since the intercumulate liquid must crystallise later.

A degree of liquid immiscibility may be inferred, whereby at a temperature above the freezing point of the liquid, droplets of the heavier magnetite separate from the magma. These droplets would collect at the bottom, and on subsequent crystallisation, would assume a cubic framework within the confines of the outline of the droplet. There are numerous objections to this theory, the most important being that no degree of liquid immiscibility has been proved experimentally. A further criticism is that the overall rate of cooling was very slow, and such a droplet would most probably assume some crystal outline, which was not observed under the microscope.

The most probable answer is that the original crystals precipitated and had an essentially cubic nature, but that they carried such a large excess of titanium dioxide, that some of it was exsolved as irregular blebs of ilmenite. This process destroyed the crystal outlines, and eventually resulted in the anhedral granular texture which is almost universally developed in the magnetitites. This theory was also advanced by Vaasjoki Heikkinen (1962, p.154).

In this connection, heating experiments carried out by Wright (1961, pp.32-37) are interesting in that they reveal that a specimen of magnetite carrying a fine network of ilmenite lamellae, upon heating up to 1300°C under oxidising conditions, forms large masses of ilmenite and magnetite cutting across cracks which represent the original grain boundaries.

In a convincing article supported by abundant experimental data, Buddington and Lindsley (1964, p.317) come to the general conclusion that a magnetite-ulvite solid solution is more feasible at high and intermediate temperatures than a magnetite-ilmenite one.

The deposition of the Lower Main Magnetitite Band alleviated the supersaturation of the magma with regard to iron, and allowed other minerals to crystallise.

It is difficult to account for a magnetitite layer that gradually becomes feldspar-rich towards the top if a degree of iron supersaturation is not invoked.

An alternate theory is that a nearly pure iron-rich liquid displaced previously formed feldspar and pyroxene grains. This is at variance with the chemistry of the magnetitite. It does not explain the relative abundance of vanadium towards the bottom and of titanium towards the top of the magnetitite band.

The magnetite anorthosite and the feldspathic magnetitite overlie the Lower Main Magnetitite Band. The essential minerals in both rocks are plagioclase feldspar and magnetite.

In the magnetite anorthosite, the feldspar grains are cumulates and the magnetite is intercumulate, whereas in the feldspathic magnetite the reverse is true.

The hyperite, which overlies the feldspathic magnetitite, is very similar to the Bon Accord hyperite. It has the same texture and petrogenic history.

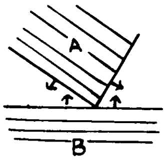
Above the hyperite is the magnetite hyperite, in which the feldspars are cumulates and the rest of the minerals are intercumulates.

The petrogenic history of the magnetite troctolite is unique. The magnetite hyperite, which over- and underlies the magnetite troctolite, crystallised at approximately the same temperature, as the anorthite content of the plagioclase of both is the same. The primary cumulus phase in the magnetite troctolite was plagioclase feldspar. Olivine, probably of fayalitic composition, crystallised later from an intercumulus liquid.

At this stage in the crystallisation history of the rock, an increase in confining pressure could have caused the fayalite to become unstable. As a consequence of this, the olivine exsolved some magnetite and translation gliding occurred. The exsolution of magnetite caused the olivine to become richer in magnesium. The fayalitic olivine most likely crystallised under high pressure conditions, as application of pressure tends to shift the olivine towards the forsterite field (T.C. Davies and J.L. England, 1964, p.1116).

The author is unable to find a satisfactory explanation for the interpenetration phenomena of the feldspar. It is suggested that when two feldspars grow towards each other and the corner of one meets a plane surface of the other, the first will exert a pressure on the other (Diagram 17).

DIAGRAM 17



The resultant two forces of growth of feldspar A could be greater than the single force exerted by feldspar B. It is possible that partial "melting" of feldspar B took place at the point of contact, if the temperature of both feldspars approximated the temperature of crystallisation and an increase in pressure occurred. It is most unusual for the atoms of one feldspar to actually rearrange themselves in order to suit those of an intruding one. A metamorphic solution of this problem is untenable, as neither the rocks above or below it are in the least metamorphosed.

It is significant that the magnetite troctolite occurs near the top of Unit 1. It may be that at this stage in the consolidation of the unit, an increase in pressure occurred prior to the emplacement of a new pulse of magma.

Unit 1 is terminated by an anorthosite which is similar to the anorthosite of the Bon Accord Unit.

(C) UNIT 2 OF THE UPPER ZONE

It is considered that after consolidation of Unit 1, a new pulse of magma was emplaced over the feldspathic rock. This new wave of igneous material was even richer in iron than the previous one. This resulted in a thicker magnetitite band being deposited over the upper anorthosite.

The magnetitite anorthosite, which follows the Upper Main Magnetitite Band, is an orthocumulate. The feldspar established a cumulate framework, whereas the other minerals crystallised interstitially.

The petrogenic history of the hyperite, which overlies the gabbro, would be the same as that of the Bon Accord hyperite.

The rhythmic occurrence of minor magnetitite bands in Unit 2 of the Upper Zone was caused by the periodic iron-supersaturation of the magma, and represents a classic example of differentiation *in situ*.

BIBLIOGRAPHY

Brown, G.M. (1958) : "The Layered Ultrabasic Rocks of Rhum, Inner Hebrides". Phil. Trans. Vol. 240, Series B, pp. 1 - 53.

Bruynzeel, D. (1957) : "A Petrographic Study of the Waterfall Gorge Profile at Insizwa". Ann. Univ. Stellenbosch. Vol.33, Sec.A, pp. 481 - 531.

Buddington, A.F. and Lindsley, D.H. (1964) : "Iron-Titanium Oxide Minerals and Synthetic Equivalents". J.Petr., Vol.5 No. 2, pp. 310 - 335.

Cameron, E. (1959) : "The Origin of Certain Chromite Deposits of the Eastern Part of the Bushveld Complex". Econ.Geol., Vol. 54, no. 7, pp. 1151 - 1213.

Davies, T.C. and England, J.L. (1964) : "The melting of Forsterite up to 50 Kilobars". J.Geophys. Res., Vol. 69, no.6, pp. 1113 - 1116.

Frankel, J.J. and Grainger, G.W. (1940) : "Notes on Bushveld Titaniferous-Iron Ore". S.Afr. J. Sci., Vol. 37, pp. 101 - 110.

Fourie G.P. et al (1960) : "Die Geologië van Rustenburg en die Omliggende Gebied". Geol. surv. S.Afr. An explanation of sheet 4.

Hall, A.L. (1932) : "The Bushveld Igneous Complex of the Central Transvaal". Mem. Geol. surv. S.Afr. 28.

Hess H.H. (1960) : "The Stillwater Igneous Complex". Mem. Geol. Soc. Amer. 80.

Lombaard, B.V. (1934) ; "On the Differentiation and Relationship of the Rocks of the Bushveld Complex". Trans. geol. Soc. S.Afr., Vol. 37, pp. 5 - 55.

Molyneux, T.G. (1964) : "The Geology and the Structure of the Area in the Vicinity of Magnet Heights in the Eastern Transvaal with special reference to Magnetic Iron Ore". MSc. Thesis - University Pretoria.

Nel, H.J. (1941) : "The Basal Rocks of the Bushveld Igneous Complex North of Pretoria". Trans. geol. Soc. S.Afr., Vol. 43, pp. 37 - 60.

Osborn, E.F. (1962) : "Reaction Series". American Min., Vol.47, No. 3, pp.211-225

Poldervaart, A.(1950) : "Correlation of Physical Properties and Chemical Composition in the Plagioclase, Olivine and Orthopyroxene Series". Amer. Min. Vol.35, pp. 1067-1079.

Ramkama and Sahama (1949) : "Geochemistry". pp. 643, 646.

Schwellnus, C.M(1956) : "The Basal Portion of the Bushveld Igneous Complex and the Adjoining Metamorphosed Sediments in the North-eastern Transvaal". DSc. Thesis, Univ. Pretoria.

Schwellnus, C.M(1943) and Willemse, J. : "Titanium and Vanadium in the Magnetic Iron-Ore of the Bushveld Complex". Trans. geol. Soc. S.Afr.,Vol46, pp. 23-38.

Strauss, C.A. (1946) : "Notes on the Microscopic Features of the Magnetic Iron-Ores of the Bushveld Complex". Trans. geol. Soc. S.Afr., Vol. 49, pp. 35 - 50.

Streckeisen, A.(1964) : "Zur Klassifikation der Eruptingesteine". Neues Jb. Miner. Heft 7, pp. 195 - 222.

Truter, F.C. (1955) : "Modern Concepts of the Bushveld Igneous Complex". C.C.T.A. Reg. Com. Geol. pp. 77 - 92.

Tuttle, O.F. (1958) and Bowen, N.L. : "Origin of Granite in Light of Experimental Studies". Mem. geol. Soc. Amer. 74.

Vaasjoki, O. (1962) and Heikkinen, A. : "On the Significance of some Texural and Compositional Properties of the Magnetites of Titaniferous Iron Ores". Bull. Comm. geol. Finl. 34. pp. 155 - 204.

Van der Berg, J.J.(1946): "Petrofabric Analysis of the Bushveld Gabbro from Bon . Accord". Trans. Geol. Soc. S.Afr., Vol.49, pp. 155-204.

Van Rensburg, W.(1962) : "The Geology of the Dwars River Fragment and the Ore-minerals of the Magnetite-Deposit on Kennedy's Vale 361 KT, E.Tvl." M.Sc. Thesis -Univers. Pretoria

Van Zyl, J.P. (1960) : "Die Petrologie van die Merensky rif". M.Sc. Thesis -University Pretoria.

Von Gruenewaldt, G. (1965) : Research in progress - personal communication.

Wadsworth, W.J. (1961): "The layered Ultrabasic Rocks of South-West Rhum, Inner Hebrides" Phil. Trans., Ser. B., Vol. 244, pp. 21-64.

Wager, L.R. (1959): "Differing Power of Crystal Nucleation as a Factor Producing Diversity in Layered Igneous Intrusions". Geol. Mag. xcvi. pp. 75 - 80.

Wager, L.R. (1960): "The Major Element Variation of the Layered Series of the Skaergaard Intrusion and a re-estimation of the Average Composition of the Hidden Layered Series and of Successive Residual Magmas". Jnl. Petrol., Vol. 1, pp. 364-398.

Wager, L.R. and Deer, W.A. (1939): "Geological Investigations in East Greenland : The Petrology of the Skaergaard Intrusion, Kanquerllugssuag, East Greenland". Medd. Greenland.

Wahl, W. (1965): Geochim et cosmoch Acta, Vol. 29, no. 1, pp. 17 - 20.

Wells, A.K. (1952): "Textural features of some Bushveld Norites". Miner. Mag., Vol. XXIX, pp. 913 - 924.

Willemse, J. (1964): Geology of Some Ore Deposits of South Africa, Vol. 11, pp. 91 - 128.

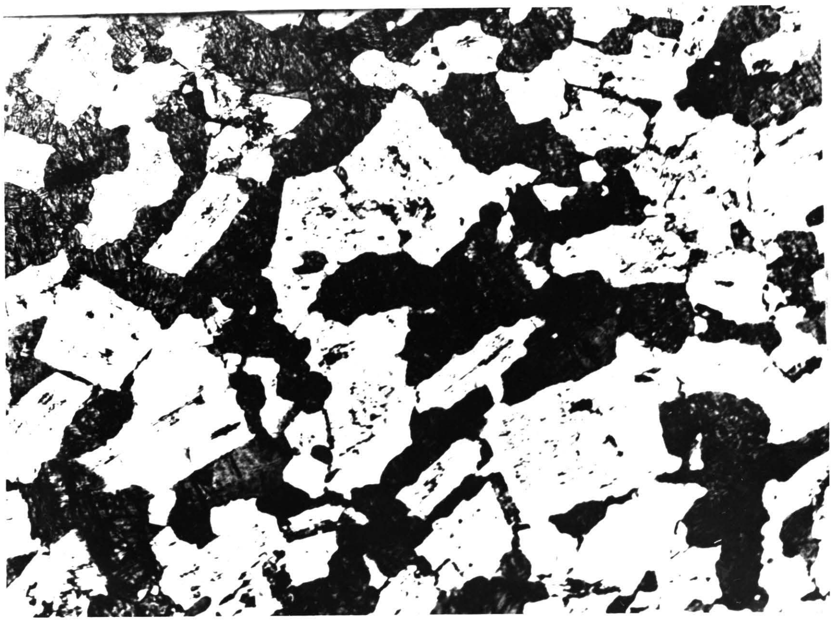
Willemse, J. (1965): Encyclopedia of Earth Sciences - for publication.

Worst, B.G. (1958): "The Differentiation and Structures of the Great Dyke of S. Rhodesia". Trans. geol. Soc. S.Afr., Vol. 61, pp. 283-358.

Wright, J.B. (1961): "Some Further Heating Experiments on Natural Titaniferous Magnetitites". Miner. Mag., Vol. 32, no. 244, pp. 32 - 37.

Young, B.B. and Millman, A.P. (1963): "Microhardness and Deformation Characteristics of Ore Minerals". Trans. Instn., Min. Metall., Lond., Vol. 73, Part 7, pp. 437 - 465.

PHOTOGRAPH 1

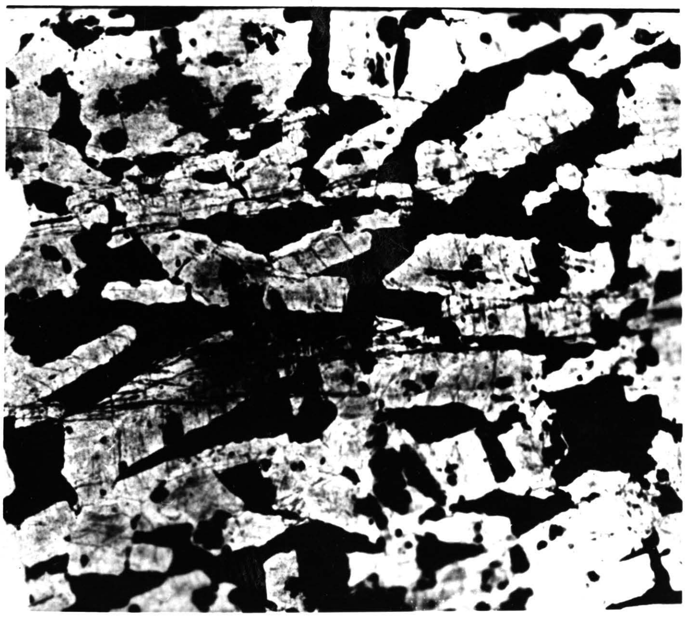


Slide VB 43 x 7 Ordinary Light

Texture of the Bon Accord Hyperite. Plagioclase (white) surrounded by a mixture of ortho- and clinopyroxene. Section cut at right angles to plane of lamination.

Hyperite - Bon Accord

PHOTOGRAPH 2



Slide RP 6/42/E-F x 4 Ordinary Light

Texture of the Bon Accord Hyperite. Ortho- and clinopyroxene (dark) envelope feldspar (grey) grains. Section cut in plane of igenous lamination.

Hyperite - Unit 1 - Rhenosterfontein

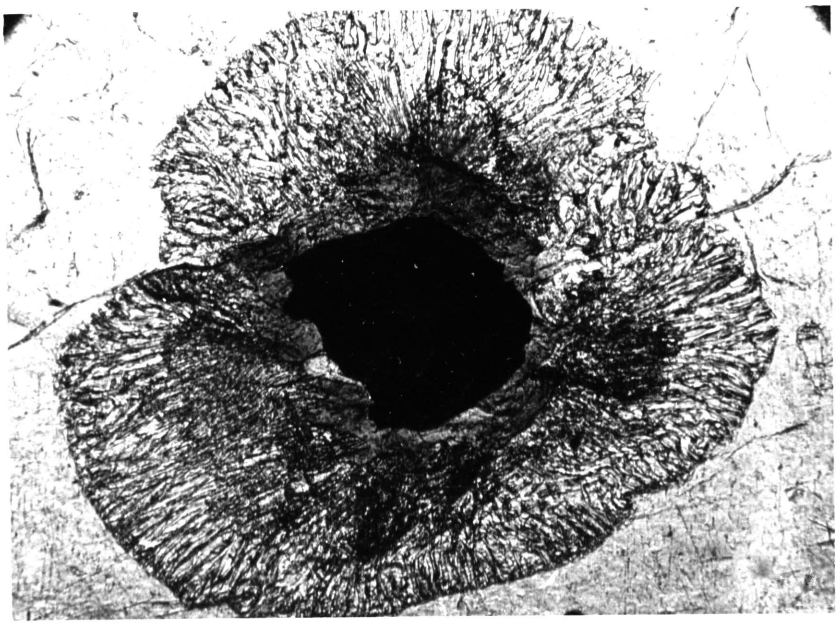
PHOTOGRAPH 3

Slide 13 x 20 Crossed Nicols

Mass of green chlorite (in centre of photograph) shares smooth common boundary with highly altered feldspar crystals.

Anorthosite - Bon Accord Unit.

PHOTOGRAPH 4



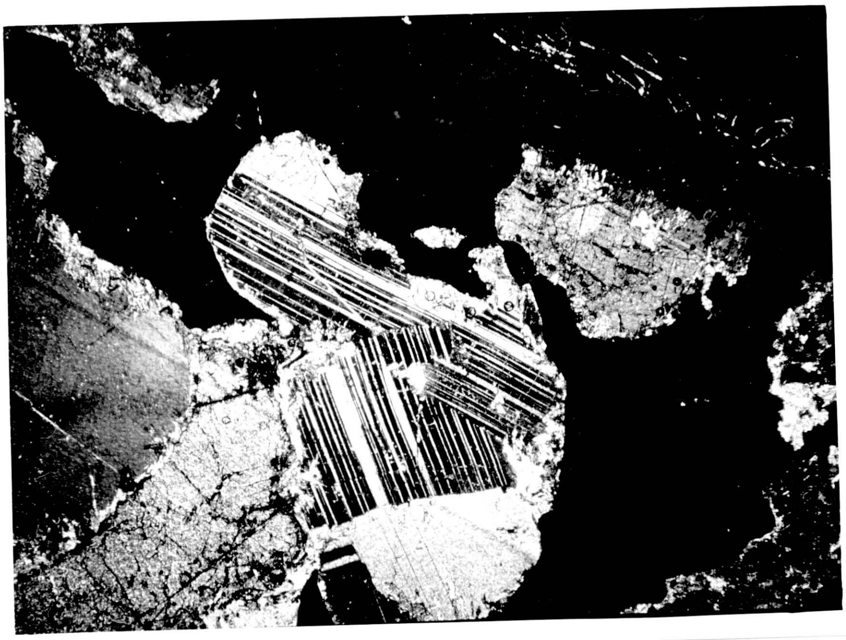
Slide KA 12 x 20 Ordinary Light

Dark core of magnetite surrounded by

(a) an inner zone of biotite (dark-grey),
(b) an intermediate zone of chlorite and magnetite, and
(c) an outer zone of feldspar and pyroxene

Hyperite of Unit 1 - Rhenosterfontein

PHOTOGRAPH 5

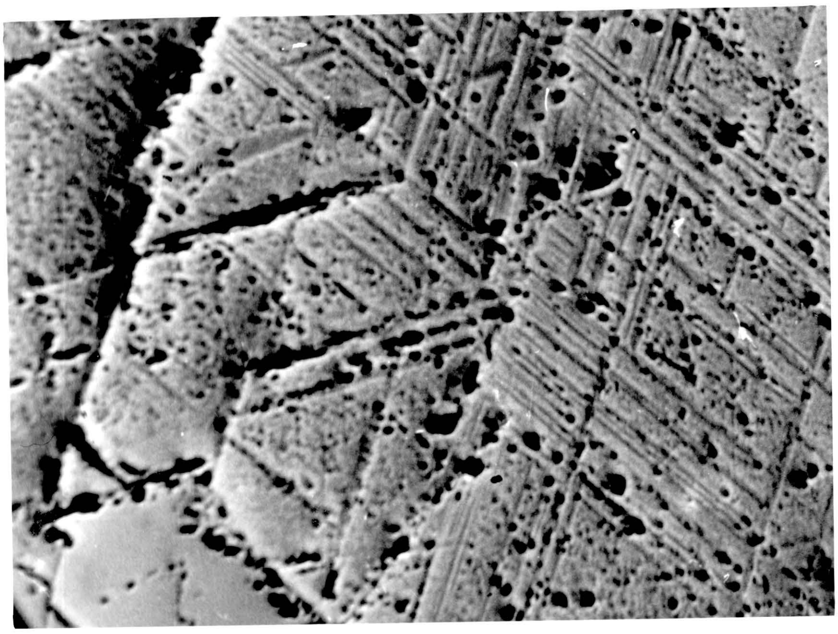


Slide 4 x 20 Crossed Nicols

Interpenetration of two twinned feldspar grains in part surrounded by olivine (dark). Olivine contains small plates of magnetite.

Magnetite troctolite, Unit 1 - Rhenosterfontein.

PHOTOGRAPH 6

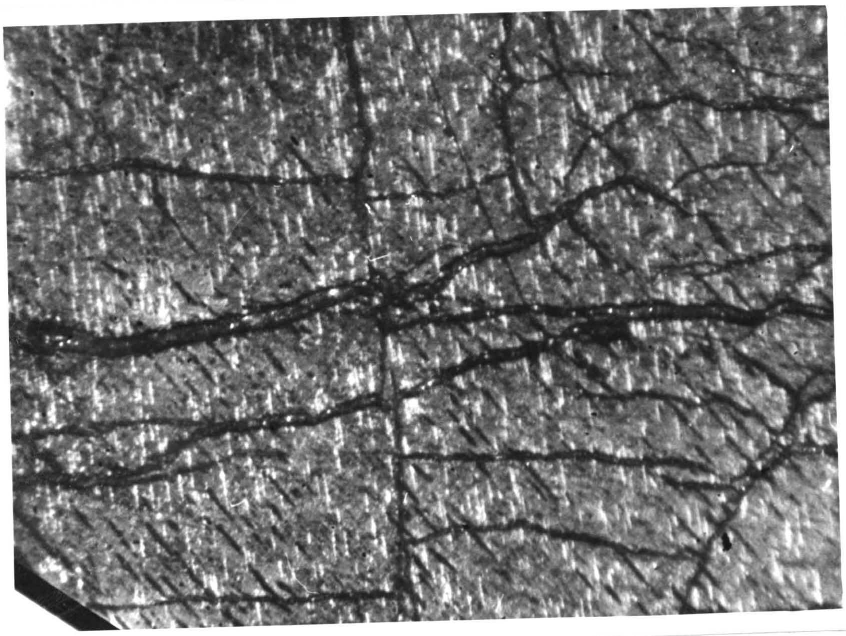


Polished Section R7/930 x 250 Reflected Light

Primary exsolved ilmenite lamellae arranged parallel to (111) in magnetite.

Pegmatoid Ore - Rhenosterfontein.

PHOTOGRAPH 7

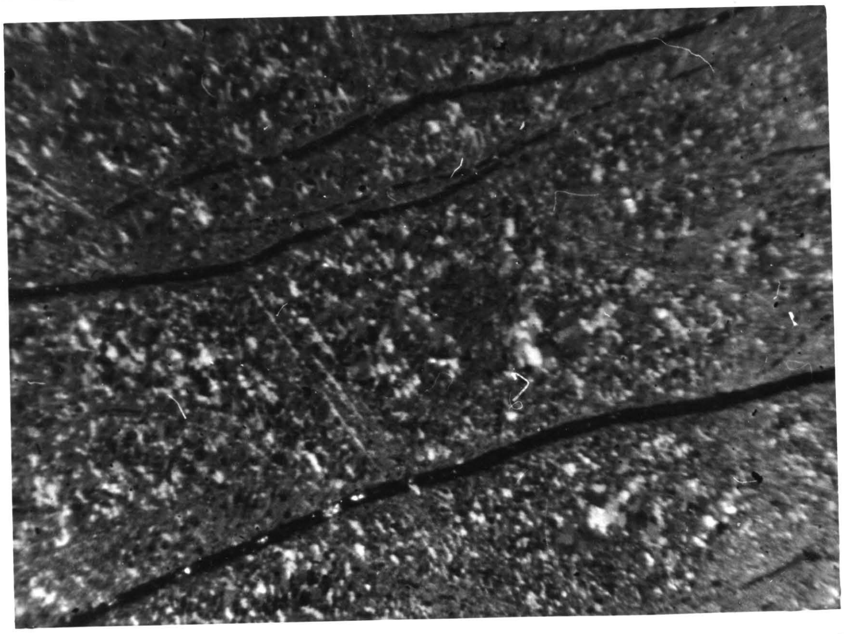


Polished Section 1884 x 650 Reflected Light
Crossed Nicols

Anisotropic needles (white) in magnetite caused by incipient development of ilmenite (Pattern 2). Anisotropic needles have cross-cutting relationship with spinel needles arranged parallel to (100) of the magnetite.

Lower Main Magnetitite Band - Rhenosterfontein.

PHOTOGRAPH 8

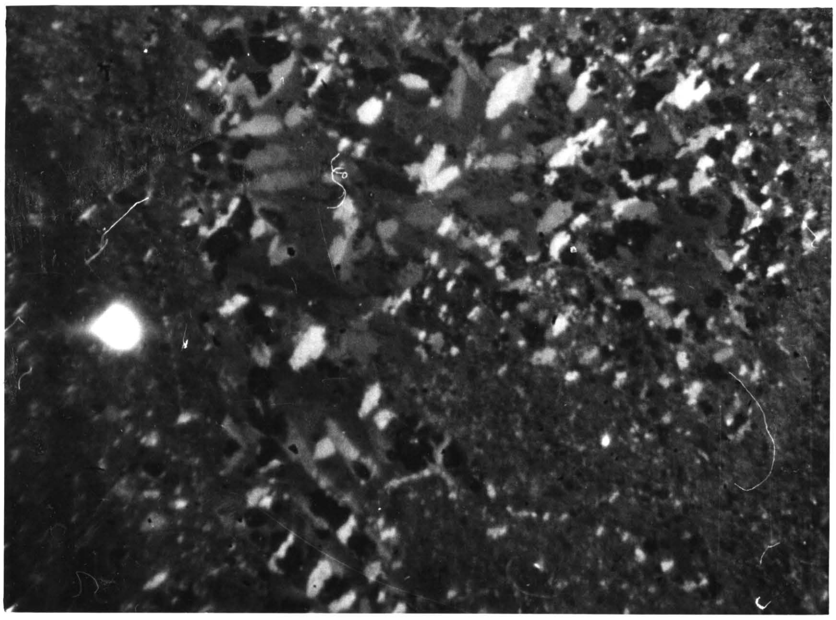


Section 1886 x 650 Reflected Light
Crossed Nicols

Anisotropism in magnetite (Pattern 3). Needles and anisotropic grains occur together. Some needles grown together to form incipient lamellae.

Lower Main Magnetitite Band - Rhenosterfontein.

PHOTOGRAPH 9

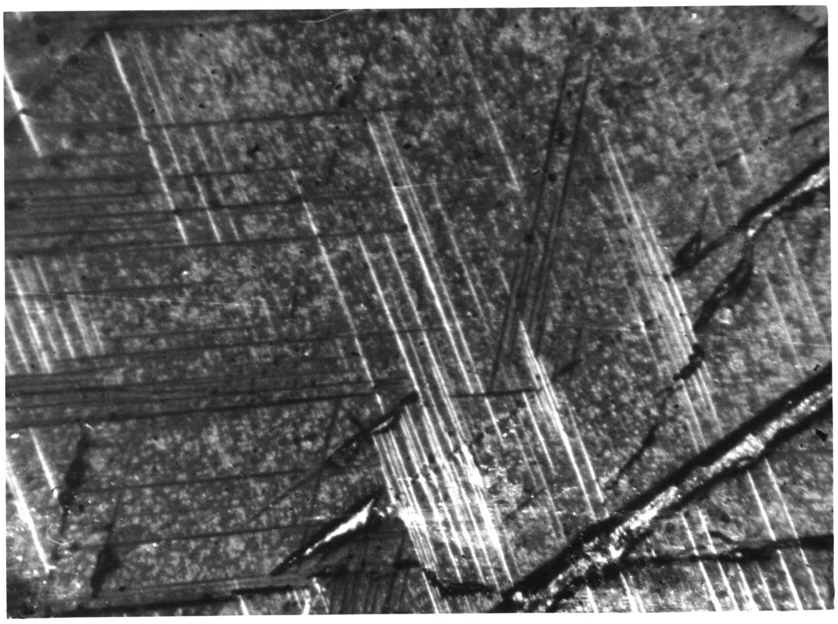


Polished Section 1886 x 650 Reflected Light
Crossed Nicols

Anisotropism in magnetite (Pattern 4). Grains displaying anisotropism arranged in sets, which are grouped together to form a patch. Material surrounding the patch is more isotropic. Rounded white spot on the left is sulphide.

Lower Main Magnetitite Band - Rhenosterfontein.

PHOTOGRAPH 10

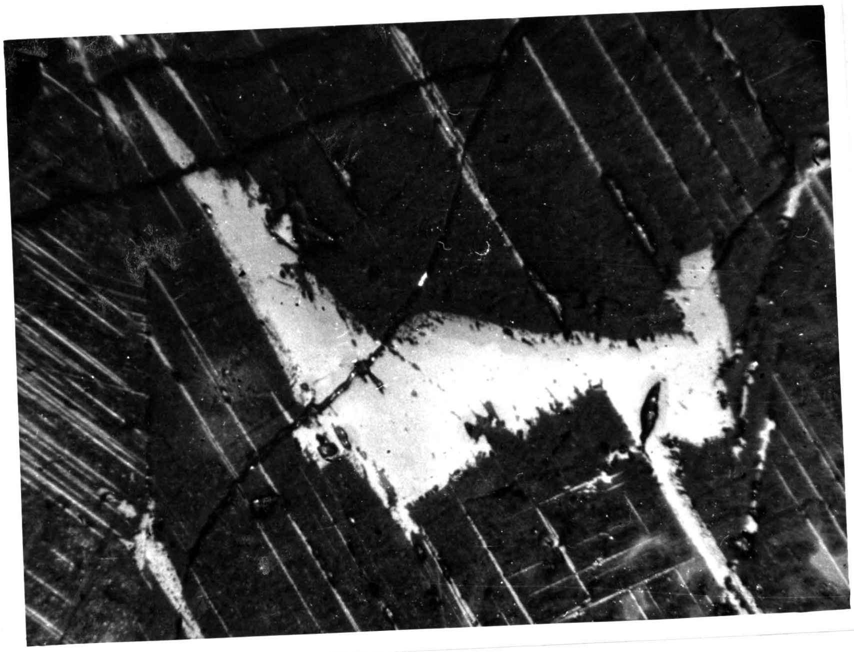


Section R7/929 x 650 Reflected Light
Crossed Nicols

Anisotropism in magnetite (Pattern 5). Distinct anisotropic lamellae as well as incipient lamellae of a later age.

Pegmatoid Ore - Rhenosterfontein.

PHOTOGRAPH 11

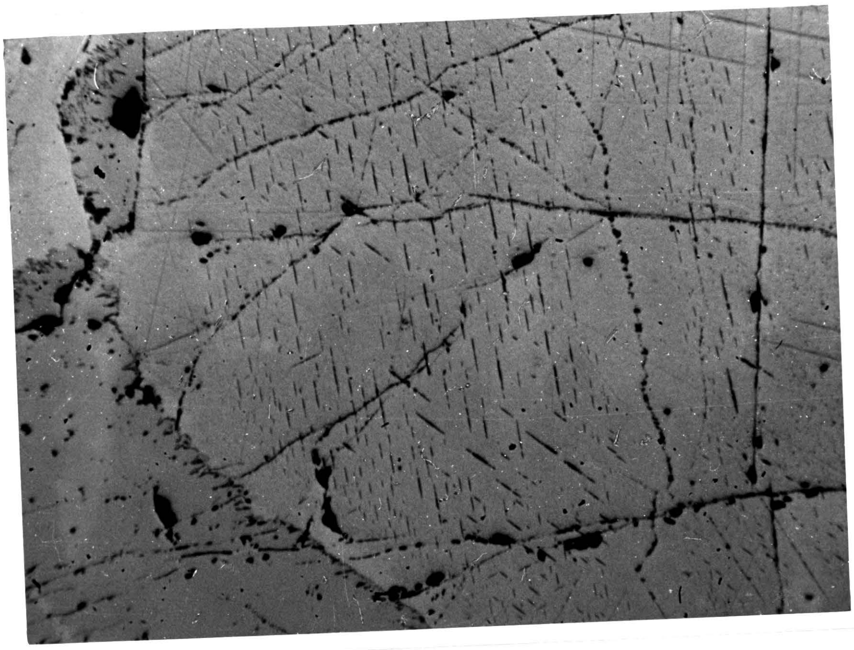


Section R7/929 x 450 Reflected Light
Crossed Nicols

Ilmenite grain, surrounded by magnetite, is ringed by ilmenite of a later growth.

Pegmatoid Ore - Rhenosterfontein.

PHOTOGRAPH 12

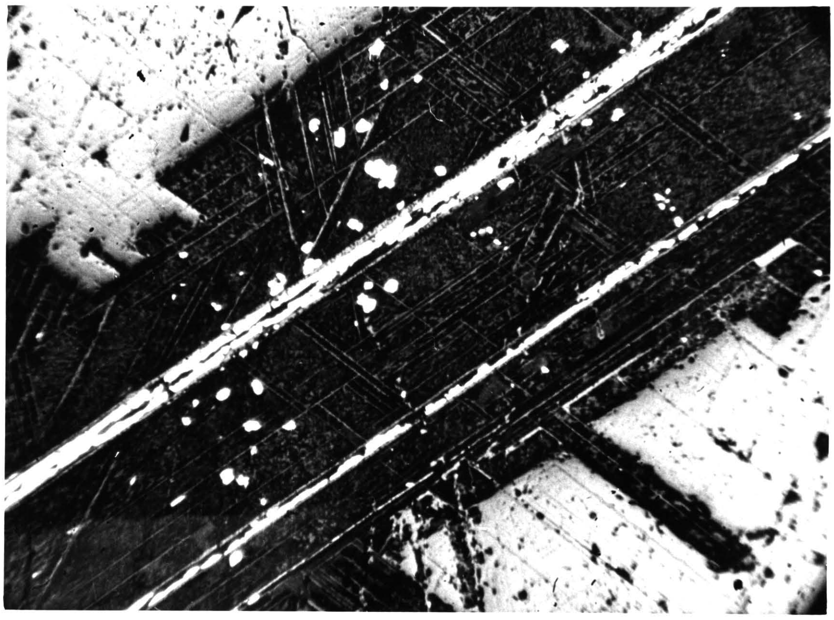


Section R7/937 x 450 Reflected Light

Exsolved plates of spinel orientated parallel to (100) in magnetite. Edges of grain are spinel free. A tiny veinlet of spinel, composed of individual grains near centre is surrounded by magnetite which is spinel free.

Pegmatoid Ore - Rhenosterfontein.

PHOTOGRAPH 13



Polished Section R7/930 x 400 Reflected Light

Preferential replacement of magnetite by silicate (dark-grey) in centre of photograph, leaving ilmenite lamellae as relict structures. Large white areas are ilmenite and the circular white spots are sulphides.

Pegmatoid Ore- Rhenosterfontein.

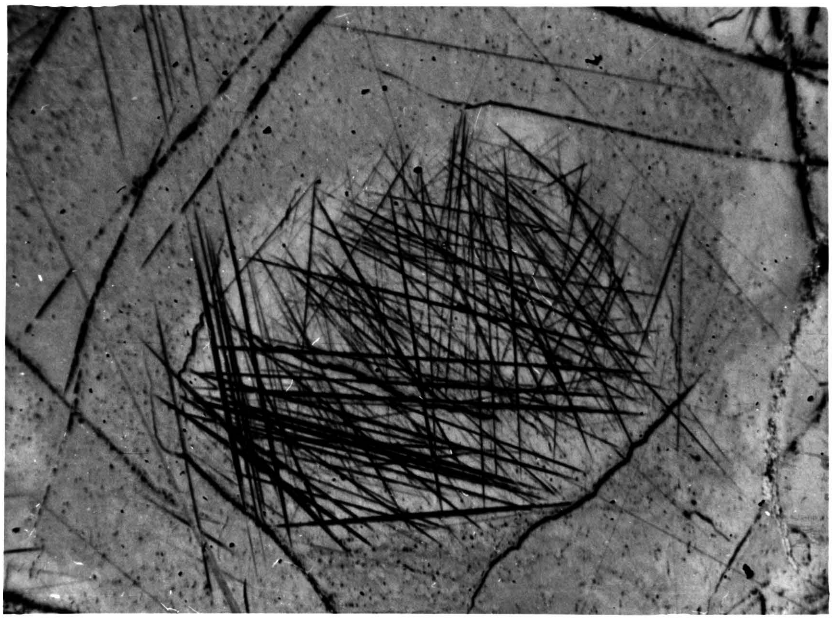
PHOTOGRAPH 14

Section JW 380 x 450 Reflected Light

Light-grey areas represent maghemite. Darker areas represent unknown reddish-brown mineral. Alteration of maghemite to darker-coloured mineral along cracks.

Surface Magnetite Ore - Bon Accord.

PHOTOGRAPH 15

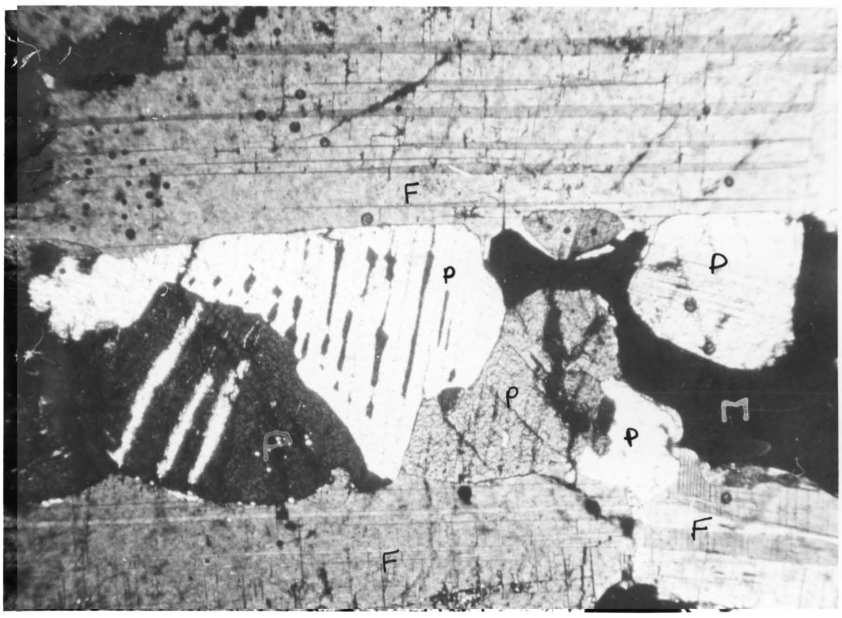


Section JW 143 x 450 Reflected Light

Central part of photograph (white background) represents maghemite which is heavily scratched. Surrounding maghemite is unknown reddish-brown mineral, which is only lightly scratched - denoting its superior hardness.

Magnetite Ore - Groenfontein

PHOTOGRAPH 16



Slide 14 x 100 Crossed Nicols

Texture of the Bon Accord Hyperite. Interstitial to large feldspar laths are orthopyroxene grains, containing exsolution bodies and magnetite. The crystallisation sequence is

(a) Feldspar (F)
(b) orthopyroxene (P)
(c) magnetite (M)

Hyperite - Rhenosterfontein.