THE BUSHVELD IGNEOUS COMPLEX IN THE STOFFBERG AREA, EASTERN TRANSVAAL, WITH SPECIAL REFERENCE TO THE MAGNETITITE SEAMS

by

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ABSTRACT

In the Stoffberg area a portion of the Main Zone, and the whole of the Upper Zone of the Bushveld Igneous Complex have been emplaced.

The floor of the Bushveld Complex consists of so-called Dullstroom andesite belonging to the Smelterskop Stage of the Pretoria Series.

The structure of the region is characterised by a gentle westward dip. A fault, referred to as the Laersdrif Fault, has displaced the sedimentary and the igneous rocks. The horizontal separation of the Main Magnetitite Seam of Subzone B is about 20,000 feet, and the vertical displacement about 3,700 feet. North of the fault the structural dip is from 0 to 12° W, and south of it the dip increases to about 25° W.

Impure quartzite of the Smelterskop Stage has been altered, in some places to such an extent that it may be termed a leptite. The gabbroic rocks of the Bushveld Complex were responsible for the metamorphism. The Dullstroom andesite was also metamorphosed, mainly along the top of the succession, into pyroxene hornfels which has a granulitic texture. Xenoliths of the hornfels settled within the gabbroic magma.

Layers of felsitic rocks have formed within the andesite; chemical analyses, Niggli values and norms of the andesite and the felsitic rocks are given.

The "roof" of the Bushveld Complex in the Stoffberg area is made up of various types of felsitic rocks (Rooiberg felsite). Based on the degree of metamorphism, textural relationship, volumetric mineral composition, analyses and grain-size, the Rooiberg Felsite has been subdivided into the following;

1. Basal felsite and altered quartzite.
2. Red granophyric felsite.
3. Spherulitic felsite.
4. Main felsite with bands of quartzite.

Granite and granophyre have been intruded mainly into the Basal felsite along its whole length of strike. A persistent sill of diabase was located within the felsitic rocks.

The gabbroic rocks of the Main Zone of the Bushveld Complex are composed of layers of hypersthene gabbro, hyperite and norite. A lens of magnetite gabbro is interlayered in the gabbroic rocks.

A peculiar/.....

A peculiar type of black gabbro was found to owe its colour to the presence of minute grains of magnetite in the plagioclase feldspar.

The magnetite gabbro of the Upper Zone follows on the gabbroic rocks of the Main Zone. In the southern part of the area the two zones are separated from each other by a large xenolith of pyroxene hornfels and by microgranite of uncertain derivation.

The contact between the Main and the Upper Zone is not clearly defined, the main difference being that magnetite is present in amounts exceeding 0.5 per cent in the latter.

Magnetitite seams have formed only in the magnetite gabbro suite which is made up of various rock types including hypersthene gabbro, hyperite, norite, olivine-hypersthene gabbro, olivine diorite, diorite and fayalite diorite. In all these rocks magnetite is present in amounts of from 0.5 to as much as 15 per cent.

Four subzones of magnetitite viz, A, B, C and D have formed in the magnetite gabbro of the Upper Zone. Subzone B is economically the most important in that it contains about 1.6 per cent V_2O_5. The so-called Main Seam of this Subzone is some 6 feet thick in the Stoffberg area. Northwards it becomes progressively thicker. In Sekhukhuneland it is 10 feet thick.

The magnetitite seams of Subzone A, B and C are associated with hypersthene gabbro, hyperite and norite whereas the seams of Subzone D are found in olivine diorite and diorite. The V_2O_5 content of the seams of Subzone C is about 0.6 per cent, and that of Subzone D about 0.3 per cent. The TiO_2-content of the different seams varies from 8 to 23 per cent.

Several magnetitite pipes of similar composition to that of the seams have been emplaced.

Quantitative spectrographic determinations for vanadium and titanium were done.

Unit cell determinations suggest that magnetite reached various stages of alteration to hematite.

Ore reserves of the Main Seam of Subzone B have been calculated.

Fractional/.....

Fractional crystallisation under the influence of gravity is considered to be the major cause of the rhythmic layering of the gabbroic rocks of the Bushveld Complex. However, with regard to the magnetitite seams, it is argued that partial separation of the Fe-Ti fraction of the magma took place before crystallisation commenced.

CONTENTS

	Page.
PART I - GENERAL	1
1 - INTRODUCTION	1
A - Locality	1
B - Previous Work	1
C - Present Investigation	2
D - Acknowledgments	4
2 - PHYSIOGRAPHY	4
A - Drainage	4
B - Relief and Climate	5
3 - GENERAL GEOLOGY	6
4 - GEOLOGICAL STRUCTURE	7
PART II - THE PRE-BUSHVELD ROCKS	11
5 - LEPTITE	11
A - Distribution and Origin	11
B - Mineralogical Compostion	13
C - Alteration of Quartzite to Leptite	14
6 - DULLSTROOM LAVA AND ASSOCIATED ROCKS	15
A - The Dullstroom Andesite	15
1 - Distribution	15
2 - Subdivision	16
3 - Petrography	16
4 - Metamorphism	19
(a) - Subdivision of Metamorphic Stages	23
B - The Felsite	24
1 - Distribution	24
2 - Mineral Composition	24
C - Chemical Composition of the Andesite and the Felsite	25
7 - XENOLITH OF METAMORPHOSED DULLSTROOM ANDESITE AND AGGLOMERATE WITH ASSOCIATED HORNBLENDE GRANITE	32
A - Distribution	32
B - Field Relationships	32
C - Rock types	33
1 - Pyroxene hornfels	33
(a) - Chemical Compostion	38
(b) - Origin	39
2 - Agglomerate	39
3 - Hornblende Microgranite	40
(a) - Description and Composition	40

Page.

(b) - Chemical Composition 42
(c) - Effects of the Micrigranite on the Gabbro 43
PART III - THE EARLY BUSHVELD ROCKS
8 - ROOIBERG FELSITE 45
A - General 45
B - Subdivision 45
C - The Basal Felsite 46
1 - Field Relationship 46
2 - Mineralogy 47
(a) - Megascopic Features 47
(b) - Microscopic Features 47
3 - Chemical Composition 48
4 - Quartz Content and Volumetric Composition 50
5 - Quartzite bands in the Basal Felsite 52
D - Red Granophyric Felsite 53
E - Spherulitic Felsite 54
1 - Distribution 54
2 - Mineralogical Composition 54
(a) - Megascopic Features 54
(b) - Microscopic Features 54
F - Main Felsite 55
1 - Description 55
2 - Quartzite bands in the Main Felsite 55
9 - INTRUSIVE ROCKS IN THE ROOIBERG FELSITE 56
A - Granite and Granophyre 56
1 - Distribution 56
2 - Field Relationships 56
3 - Mineralogical Description 57
(a) - Megascopic Features 57
(b) - Microscopic Features 57
4 - Composition 58
5 - Origin 58
B - Diabase Sill 59
10 - DIABASE IN THE PRETORIA SERIES 60
A - Distribution 60
B - Mineral Composition 60
PART IV - THE BUSHVELD IGNEOUS COMPLEX 62
11 - GABBROIC ROCKS OF THE MAIN ZONE 62
A - Distribution 62
B - Subdivision 63

Page.

1 - Hypersthene Gabbro 64
2 - Hyperite 64
3 - Norite 67

C - Anorthite contents of the Plagioclase 67
D - Mineralogy 67
E - Intergrowths in the Clino- and Orthopyroxenes of the Gabbroic Rocks 71
F - Zone of Magnetite-bearing Gabbro 76
G - Anorthosite 76
H - Emplacement of the Gabbro 77

12 - MAGNETITE GABBRO AND DIORITE 77
A - Distribution 77
B - Thickness 79
C - Meaning of the term Magnetite Gabbro 80
D - Subdivision 81
E - Megascopic Features 83
F - Microscopic Features 83
G - Textural Relationships 86
H - Refractive Index Determinations 87
I - Volumetric Composition of Random Specimens 87
J - Main Differences between Gabbro of the Main Zone and Magnetite Gabbro of the Upper Zone 88

13 - FAYALITE DIORITE 89
A - Distribution 89
B - Composition 90
C - Determination of Optical Constants 92

14 - ANORTHOSITE IN THE MAGNETITE GABBRO 94
A - Field Relationships 94
B - Composition 94
C - Weathering 94
D - Emplacement and Genesis of Anorthosite in the Magnetite Gabbro 95

PART V - THE MAGNETITITE SEAMS AND PIPES 96

15 - MAGNETITITE SEAMS IN THE MAGNETITE GABBRO 96
A - General 96
B - Distribution 96
C - Description 99
D - Weathering of the Seams 108
E - Mode of Emplacement of the Magnetitite Seams and the Magnetite Gabbro 111

Page.

16 - MAGNETITITE PIPES AND ASSOCIATED BRECCIA 115
A - Distribution 115
B - Mineralogy of the Breccia 116
1 - Megascopic Features 116
2 - Microscopic Features 119
C - Weathering 120
D - Origin of the Magnetitite Pipes 120
E - Origin of the Breccia 123

17 - MINERALOGY OF THE ORE 125
A - General 125
B - Megascopic Description 126
C - Microscopic Description 127

18 - DETERMINATION OF VANADIUM AND TITANIUM IN THE MAGNETITITE 135
A - Introduction 135
B - Quantitative Determination for Vanadium 136
C - Methods used in present Study 136
1 - Qualitative Tests 136
(a) - Drop-method of Vanadium Detection 136
(b) - Colorometric Test for Vanadium in the presence of Titanium 137
(c) - Semiquantitative test for Vanadium 137
(d) - Quantitative Spectrographic Determination 139
(e) - Presentation of Working Curves 141
(f) - Results Obtained 141
(g) - Interpretation of Spectrographic and Chemical Analysis 147

19 - UNIT CELL DETERMINATIONS 151

20 - EXPLOITATION OF THE MAGNETITITE SEAMS 155
A - Mining Activity 155
B - Prospecting 156
C - Railage 156
D - Production of Vanadium 157
E - Future Demand 158
F - Persistence of Ore with Depth 158
G - Mining Techniques 159
H - The Utilisation of the Iron and Titanium 159
I - Ore Reserves 161

Page.

PART VI- POST-BUSHVELD INTRUSIONS 164

21 - DOLERITE INTRUSIONS 164

A - Distribution 164

B - Mineralogical Description 165

22 - QUARTZ VEINS 165

SUMMARY AND CONCLUSIONS

REFERENCES

THE BUSHVELD IGNEOUS COMPLEX IN THE STOFFBERG AREA, EASTERN TRANSVAAL, WITH SPECIAL REFERENCE TO THE MAGNETITITE SEAMS

by

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PART 1 - GENERAL

1 - INTRODUCTION

A - Locality

The area lies within the 2529B degree sheet, which represents the western half of Geological Sheet 11, Lydenburg. It is bounded by latitudes 25°12' and 25°35' south and longitudes 29°45' and 30°02' east (folder 1).

By rail the area is reached via a line branching from the main railway-line between Pretoria and Lourenço Marques. This line starts at Derwent some five miles east of Middelburg, passes through Wonderhoek and Languitsig and terminates at Stoffberg. The railway-line is being extended from Stoffberg through Laersdrif to Roossenekal and a short distance beyond. Construction commenced in 1966. By car the area is accessible from different directions along fairly good gravel roads. The normal route from Pretoria is to Middelburg where a main tarred road branches off to Stoffberg. From Groblersdal a road passes up the Blood River Valley, and from Lydenburg and Belfast down the steep western slopes of the Steenkampsberg into the Steelpoort River Valley. From Pretoria to the centre of the area the distance is about 150 miles.

B - Previous Work

The area comprising Sheet 11, Lydenburg, was geologically surveyed in 1905, 1906, 1909, 1910 and 1911 by A.L. Hall. The map, on a scale of 1:148,750, together with the explanation, was published in 1913 by the Geological Survey, Department of Mines. Subsequently, between 1940 and 1945, three students of the University of Pretoria, viz. J.C. Boshoff, A.F. Lombaard and J.M. van der Westhuizen mapped portions of Tauteshoogte, the Blood River Valley area, and Bothasberg. Since then, this now economically important area has received little

attention/.....

attention until 1958 when the first effort to exploit the vanadium present in the magnetitite seams commenced. S.P. Malan, a geologist in the employ of Minerals Engineering Co., S.A. (Pty.), Ltd., proceeded with the geological investigation of the magnetitite seams, but his work has not been submitted for publication.

From 1961 to 1963 R.F. Bouwer did geological investigations south of Stoffberg, near Roossenekal, at Magnet Heights and in Sekhukhuneland. Bouwer's work was done on behalf of AMCOR who was interested in those magnetitite seams and pipes with a relatively high vanadium content. This did not include detailed mapping. AMCOR has since then lost interest in the possible extraction of vanadium. Several bore-holes were drilled to intersect the seams at depth. The logs of core from holes drilled on Ironstone 847 KS, and from a hole on the Consolidated Farm Mapochsgronde 500 JS, were kindly made available to the author by AMCOR.

During 1962, 1963 and 1964, R. Jacob, K. McQuillin and T.G. Molyneux, geologists of the Anglo American Corporation, mapped and prospected by means of pits and trenches along the magnetitite seams of Subzone B on those farms and portions of farms which the Corporation had under option and which extended from south of Stoffberg to Magnet Heights. Apart from determining the tonnages of ore available on surface, many analyses for the vanadium content were made, and a few bore-holes were drilled to intersect the magnetitite seams at depth. Molyneux's work, which covered mainly the Magnet Heights area, was submitted in 1964 in the form of a thesis for the M.Sc. (geology) degree at the University of Pretoria.

C - Present Investigation

During a short field-season in 1959 specimens were collected mainly for study in the laboratory. As a result of the many unsolved problems encountered it was decided to continue mapping at a later date. This work was resumed in 1962, continued in 1964, and completed in 1966. A total of some 275 square miles was mapped.

The main aim of the investigation was to establish whether the magnetitite seams continue southwards from Laersdrif past Stoffberg to join up with seams which were known to outcrop south of Stoffberg. On Geological

Sheet 11,/.....

Sheet 11, Lydenburg, very few magnetitite seams are shown in the Laersdrif—Stoffberg area. It was also desirable to prove conclusively whether any portion of the Critical Zone of the Bushveld Complex was developed in the area.

In order to solve the problems it was decided to undertake a detailed geological mapping programme of the area, and to make a comprehensive mineralogical study of the rock types. The tracking of the Laersdrif Fault proved to be a decisive factor in solving the structure of the area, and in the grouping of the layers of the Bushveld Complex.

As the mapping progressed, specimens of the rocks were collected and examined microscopically. The X-ray diffractometer was used mainly for determining the identity of some of the ore-minerals, and also for measuring the cell edge of the magnetite. Quantitative spectrographic work was undertaken in order to determine percentages of titanium and vanadium in some of the magnetitite seams.

The refractive indices of several minerals have been determined. It is worthy of note that few of the previous workers have utilised this useful and rapid method of identifying the different types of plagioclase, and pyroxene in the rocks of the Bushveld Igneous Complex.

The immersion method of Larsen and Berman (1934, p. 20) was used. The specimen is ground to a powder and immersed in a liquid of known refractive index. Grains with pronounced birefringence were selected for comparison with the liquid. In each grain mount several grains having pronounced birefringence were measured and the highest and lowest values were taken as values for γ and α respectively. Grains which display weak or no birefringence will give a value for β. In all the measurements a sodium light source was used. Liquids having a difference in refractive index of one digit in the second decimal were available. In those cases in which the refractive index was between that of two liquids, portions of each one were mixed in a small tube until the index of the mineral was equal to that of the mixture. The refractive index of the liquid was then measured on an Abbe Refractometer.

The drawback of the method is that for γ the highest value may be still below, and for α the lowest value above, the true value. However, by careful selection of the minerals the results obtained were found to be

quite/ ...

Plate 1 - View from south to north of a part of the area investigated. The Blood River Valley is visible in the central part of the composite plate. The Sekhukhune plateau extends towards the north, and Bothasberg to the south. The outcrops in the foreground and in the centre-right are gabbro.

quite satisfactory and it is assumed that an accuracy of ± 0.002 was maintained.

The refractive indices of minerals can be measured with greater precision (± 0.001) by using the dispersion method. Tsuboi (1923, p. 109) used this method to measure accurately the indices of refraction of cleavage flakes of plagioclase.

As the composition of the minerals in the plagioclase and pyroxene groups are best determined with the aid of several optical properties, the Fedorow universal stage was also employed.

D - Acknowledgments

The author wishes to express his indebtedness to the following:

The late Dr. F.C. Truter, Director of the Geological Survey from 1955 to 1963, for approving the project, and to Dr. O.R. van Eeden for allowing me to continue the work when he became Director in 1963;

The late Prof. J. Willemse, my original promotor, for his unfailing interest and for many suggestions;

Prof. D.J.L. Visser, who, under difficult conditions, took over the promotorship in 1968, after the death of Prof. Willemse;

Members of the staff of the Geological Survey who assisted in various ways.

2 - PHYSIOGRAPHY

A - Drainage

The main physical features of the area are: the Steelpoort River which flows due north, the Blood River Valley to the west, the Sekhukhune Plateau to the north-west, Bothasberg to the south-west, and the Steenkampsberg to the east of Stoffberg (plate 1).

Many small streams, some perennial and others intermittent, coalesce and eventually flow into the two main rivers viz. the Steelpoort and the Blood River: The watershed between the Steelpoort and the Blood River Valley stretches from the south-western corner of Tauteshoogte to the north-eastern corner of Bothasberg. The Blood River flows westwards into the Olifants River and the Steelpoort River also flows into it, but does so farther to the north. The confluences of both fall well

outside/.....

outside degree sheet 2529B. Several flood-plains with appreciable numbers of rounded pebbles in the gravel beds some distance away from the present position of the Steelpoort River prove that it has changed its course from time to time. These flood-plains are not indicated separately on the map.

B - Relief and Climate

Tauteshoogte is one of the highest points on the Sekhukhune Plateau: The latter rises about 1,000 feet above the surrounding valleys. The Sekhukhune Mountains are actually a chain of hills formed by the dissection of an escarpment. Bothasberg, a plateau of similar design to the Sekhukhune Mountains, also adjoins the two valleys but this chain of hills is more regularly dissected. It reaches some 900 feet above the valley. Trigonometrical beacon Tauteshoogte and Schietpad on Bothasberg are 5809 and 5974 feet above sea level respectively.

The elevated ground adjacent to the eastern border of the Steelpoort Valley is made up of an irregular chain of fairly rugged gabbro hills, which can be regarded as the southward continuation of the Leolo Mountains.

The plateau regions and the valleys owe their origin to the varying susceptibility of the different rock types to the agencies of erosion. Thus quartz-rich rocks are found along the slopes of the scarps. In some areas dissection has been irregular and relicts of the rocks building the plateau have been isolated in the valleys. The mafic components of the Bushveld Igneous Complex, especially the magnetite gabbro have yielded mostly to erosional agencies and in the whole area magnetite gabbro is found along both the Steelpoort and the Blood Rivers.

The area drained by the upper reaches of the Steelpoort River, which includes the area under discussion, is sparsely bush-clad with the exception of some gabbro ridges east of the Steelpoort River. Farther northwards the terrain descends and gradually but perceptibly changes from Middle Veld to typical Bushveld country. Although the nights are cold, the average temperature during the winter season is fairly mild in comparison with that of the Highveld. The average annual rainfall for the area, measured over a period of more than 20 years, is between 28 and 29 inches, i.e. between 710.0 and 735.0 mm.

There/.....

There are only a few alluvial flood-plains along the Steelpoort River. Away from the river the surface consists of an irregular pattern of rocky outcrops and weathered rock covered by a thin layer of soil.

Agriculture is the main source of income of the inhabitants, but has not been as successful as one would expect. Several farms are lying fallow and the homesteads are deserted. The farmers prefer to rely on mixed crops rather than to specialise in one particular type. Livestock farming is confined mainly to cattle and sheep.

3 - GENERAL GEOLOGY

The area comprises a diverse variety of rock types including altered sediments, volcanic rocks, gabbro and magnetite gabbro, diorite, felsite, granite and granophyre.

Along the eastern boundary of the area quartzite and reconstituted quartzite (leptite) of the Smelterskop Stage are found. The Dullstroom volcanic rocks of the Smelterskop Stage overlie the leptite and the quartzite. The Dullstroom volcanic rocks consist mainly of andesite with subordinate felsite and agglomerate. The uppermost portion of the andesite has been further metamorphosed into a pyroxene hornfels.

A suite of gabbroic rocks forms the lowest part of the Bushveld Complex in the area and varies in thickness from 4,800 feet in the north, to 2,600 feet south of Stoffberg. Layers of anorthosite, hypersthene gabbro a and magnetite gabbro are present within the gabbro.

In the southern part of the area gabbro of the Main Zone is separated from magnetite gabbro of the Upper Zone by a xenolith of pyroxene hornfels (metamorphosed Dullstroom andesite). Together with this xenolith, hornblende microgranite is also present. The hornblende microgranite is not present north of Laersdrif.

The magnetite gabbro is poorly exposed and badly weathered and is therefore not fully described. In this respect the work of Molyneux (1964) around Magnet Heights should also be consulted. Four separate subzones of magnetitite seams and several magnetitite pipes occur within the magnetite gabbro. The nomenclature for the subdivision of the four magnetitite subzones as used by Molyneux (1964, Map IV) namely, Subzones A, B, C and D, taken from the lowest to the highest zone, has been adopted. The Main Magnetitite Seam of Subzone B is

economically/.....

economically the most important one owing to its exploitable vanadium-content.

The magnetite gabbro suite varies in thickness from 9,500 feet in the north of the area to 5,700 feet south of Stoffberg.

Diorite, from 100 to 800 feet in thickness, overlies the magnetite gabbro and is the uppermost member of the Upper Zone of the Bushveld Complex.

Along the western part of the area Rooiberg felsite, with subordinate leptite, is the predominent rock type. A thin but persistent sill of diabase has been intruded into the lower part of the Rooiberg felsite. Intrusions of granite and granophyre into the Rooiberg felsite are common.

Several dolerite dykes have been emplaced, mostly within the magnetite gabbro.

4 - GEOLOGICAL STRUCTURE

The general structure of the area is characterised by a gentle westward dip of the igneous and metamorphosed sedimentary rocks. An exception to this regular feature is the anticlinal disposition of the Upper Magnetitite Seam of Subzone D on Enkeldoorn 214 JS. The anticline is local in extent only and may be due to slumping of the underlying, completely weathered magnetite gabbro or to original folding during the viscous stage of the gabbroic magma. It is not a major structural feature. Another notable structural feature is the thickening of the upper part of the magnetite gabbro suite including the Upper Magnetitite Seam of Subzone D in the Blood River Area. Here the rock formations above the mafic portions of the Complex must have been relatively weak and were therefore eroded away easily, leaving the intrusives well exposed in the valley so formed.

The igneous rocks in the area, represent a section of the eastern portion of the Bushveld Igneous Complex. A plan and sections of the Bushveld Igneous Complex which illustrate the original interpretation of the Bushveld Complex as a single lopolith, and a revised one in which three separate lopoliths with their inferred feeders are assumed, are provided by A. Holmes (1965, p. 259). The feeder of the lopolith in the Eastern Transvaal would lie several miles west of the Stoffberg Area and therefore well outside the mapped region.

North/.....

North of Stoffberg the various rock types dip westwards at angles of from 3^{o} to 15^{o}. The general dip can be taken as 10^{o} West. South of the Laersdrif Fault the dip increases gradually so that on Goedverwacht 354 JS it is about 25^{o} West.

One major fault, referred to as the Laersdrif fault, and several minor faults were located. The Laersdrif fault displaced quartzite, shale and diabase of the lower portion of the Smelterskop Stage, the Dullstroom andesite and associated rocks, gabbro, a xenolith consisting of metamorphosed Dullstroom andesite and agglomerate, magnetite gabbro and some of the magnetitite seams within it. From south-east to north-west it enters the area on Konterdanskloof 223 JS and follows a slightly wavy course through Witpoort 216 JS, Swartkoppies 217 JS, then passes through the southern part of the village of Laersdrif situated on De Lagersdrif 178 JS and leaves the area on Blaauwbank 179 JS.

Assuming a vertical dip for the fault (no dip measurements could be taken owing to poor exposures), it has caused a downthrow on its north side. According to Section C-D (folder 1) the vertical displacement of the magnetitite seams of Subzone B is of the order of 3,700 feet. The horizontal separation of the Magnetitite Seams of Subzone B along the fault, taken as a straight line, is about 20,000 feet.

On Witpoort 216 JS, the horizontal separation of the contact between the Dullstroom andesite and the overlying gabbro along the fault is about 9,000 feet, and on Konterdanskloof 223 JS the separation of the lower Smelterskop quartzite along it, is only 8,000 feet. It is therefore clear that the displacement along the fault decreases from the north-west towards the south-east. Little is known about the fault on Blaauwbank 179 JS.

Routine mapping by A. van Schalkwyk* to the south of Dullstroom in Area 2530A during 1962 also revealed the presence of the Laersdrif Fault, passing through Paardeplaats 125 JT, Uitvlugt 126 JT and Welgevonden 128 JT where he assumed it to terminate (fig. 1). Subsequently, in 1965, D.P. de Carcenac* did routine mapping in Area 2530C and located a very prominent fault east

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*Geological Survey, Department of Mines.

of Belfast. He was able to establish that the fault is present from the northern boundary of Elandsfontein 322 JT and strikes southwards through Grunvlei 353 JT and Hartbeestspruit 361 JT into De Goede Hoop 358 JT where it apparently ends (fig. 1). If it is taken that this fault is the south-eastern continuation of the Laersdrif Fault, it must have gradually changed strike south of Dullstroom. East of Belfast it strikes a few degrees east of south.

A Section through the fault, drawn by D.P. de Carcenac, reveals that in his area the fault has caused an upthrow on its east side. (De Carcenac also accepted a vertical dip for the fault.) Allowing for the change of strike, the east side of the fault, is comparable with the north side of the Laersdrif Fault at Laersdrif. However, at Laersdrif the Fault has caused a downthrow on its north side. In De Carcenac's section the vertical displacement amounts to 1,250 feet.

As already mentioned, the amount of displacement by the Laersdrif Fault diminishes towards the south-east. It is suggested that the Laersdrif Fault, and its south-eastward continuation into the area mapped by Van Schalkwyk, is the same fault as that mapped by De Carcenac. It must accordingly be accepted that the fault is of the pivotal type.

The imaginary pivot of the fault will be somewhere south of Dullstroom and in this area the displacement will be small and this may be the reason why the fault was not picked up by Van Schalkwyk in that area. In both directions away from the pivot, displacement will increase, a phenomenon well seen in the Laersdrif area.

A certain amount of translatory movement may have taken place, but this will be difficult to confirm with the available evidence.

The rocks which make up the structures outlined above are given in table 1.

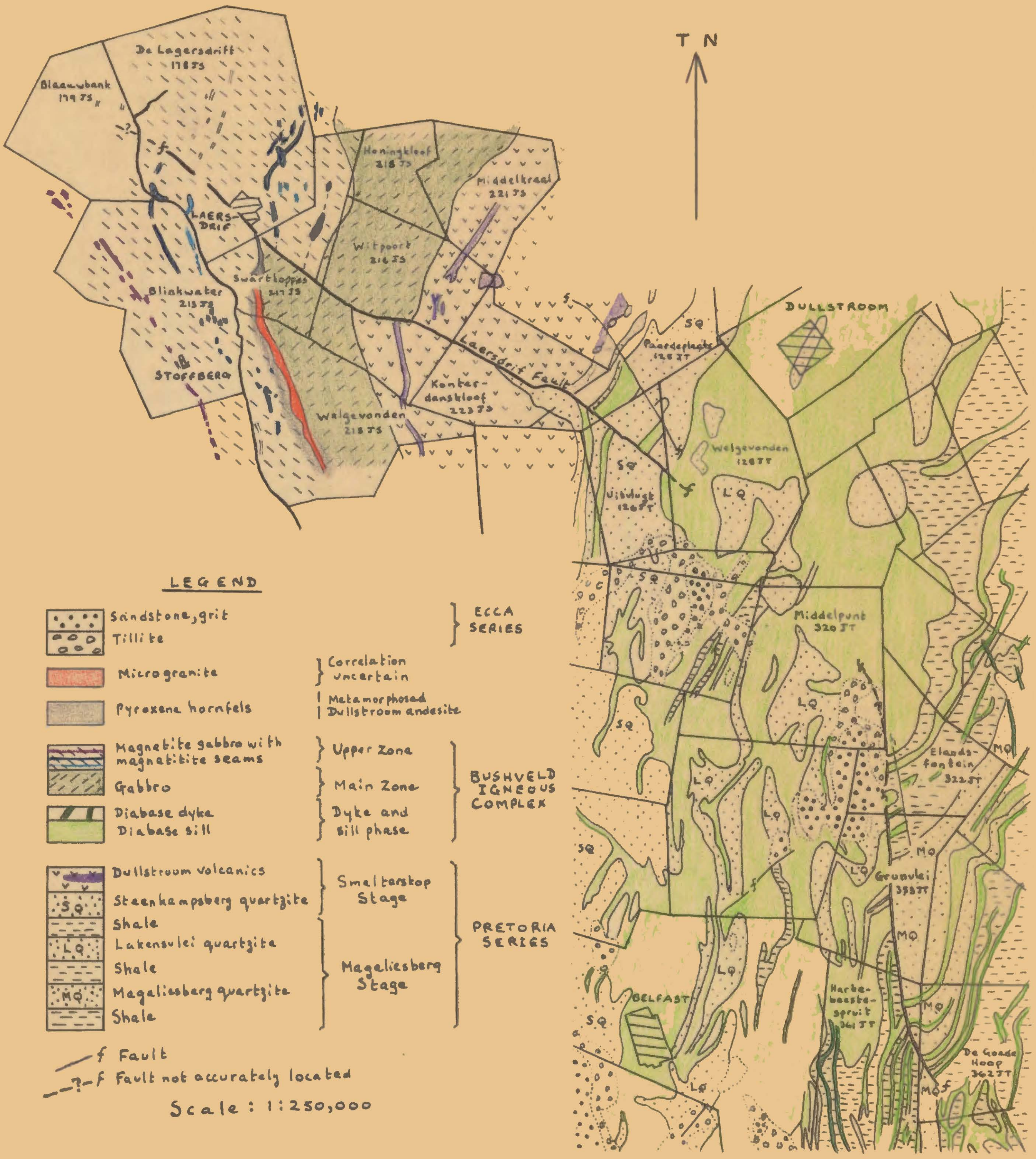


Fig. 1 - The Laersdrif Fault at Laersdrif, south-west of Dullstroom and east of Belfast.

PART II - THE PRE-BUSHVELD ROCKS

5 - LEPTITE

A - Distribution and Origin

Along the upper part of the Smelterskop Stage of the Pretoria Series, the quartzite has been transformed into leptite. The degree of transformation varies considerably from place to place but is usually found to diminish eastwards towards the more normal Smelterskop quartzite which in many outcrops merely exhibits very slight recrystallisation without any mineral change.

While mapping was in progress along the base of the Dullstroom andesite it was found that in many places the quartzite layers had been reconstituted to such an extent that they could be distinguished from the normal Smelterskop quartzite. The distribution of the leptite layers is irregular. On Witbooi 225 JS and Kwaggaskop 359 JS discontinuous lenses of leptite separate the Dullstroom andesite from the underlying unaltered Smelterskop quartzite. Several lenses of leptite lie wholly within the andesite. They may be fragments of original quartzite caught up in the andesite during the outflow period or they may denote periods of sedimentation which separate various lava flows.

The leptitic rocks attain their fullest development towards the north, on Windhoek 222 JS, Messchunfontein 98 and Houtenbek 97 JT. Several varieties, ranging from only slightly feldspathised quartzite to true leptite, can be distinguished. The quartzite becomes progressively less reconstituted eastwards, from just east of trigonometrical beacon Mid. 26 on Messchunfontein, and the contact between leptite and quartzite is arbitrary. In this area the quartzite is very impure and resembles an arkose. It is riddled with angular fragments consisting of quartz and fair amounts of kaolinite and sericite (determined by means of the X-ray technique).

Thin lenses of slate are found below the leptite, on the boundary between Witbooi and Ontevreden. Similar lenses, less than about 20 feet thick, but more persistent on strike than the lens on Witbooi and Kwaggaskop are present below the leptite on Windhoek 222 JS.

Table 1/.....

Table 1.

Rock types encountered in the Stoffberg area

Sequence number	Rock type	Phase, Stage or Zone	Series or Complex
13	Dolerite		Post-Karroo
12	Vein-quartz		Post-Bushveld
11	Fayalite diorite	Upper Zone	Bushveld Complex
10	Magnetite gabbro, consisting of magnetitite, anorthosite, olivine diorite and hypersthene-olivine gabbro	Upper Zone	Bushveld Complex
9	Gabbro, consisting of hypersthene gabbro, hyperite, norite, magnetite gabbro and anorthosite	Main Zone	Bushveld Complex
8	Quartz diabase	Sill phase	Bushveld Complex
7	Diabase	Sill phase	Bushveld Complex
6	Granite and granophyre	Rooiberg	Bushveld Complex
5	Felsite, spherulitic felsite and granophyric felsite	Rooiberg	Bushveld Complex
4	Hornblende micro-granite	?	
3	Pyroxene hornfels (metamorphosed andesite) and agglomerate	Xenolith of Dullstroom Volcanics	Pretoria Series
2	Andesite with agglomerate and felsite	Smelterskop Stage	Pretoria Series
1	Quartzite, in places altered to leptite	Smelterskop Stage	Pretoria Series

A notable feature regarding the distribution of the leptite is its absence along the contact between lava and the unaltered quartzite often for appreciable distances. For instance, north and south of the Laersdrif Fault on Konterdanskloof 223 JS slightly recrystallised Smelterskop quartzite is followed directly by Dullstroom andesite.

Some of the quartzite layers of the Smelterskop Stage are pure and consist mainly of quartz, for example those around the Laersdrif Fault, but others contain appreciable amounts of sericite, kaolinitic material and clayey material. Impure sandstone would readily yield a feld-spar-rich metamorphic product like leptite and the absence

of/.....

of leptite near the Laersdrif Fault could be explained in this way. Evidently the impure sandstone overlying the pure quartzite was eroded away prior to the outflow of lava or was not deposited in places.

It is presumed that the gabbro mass was mainly responsible for the transformation of the impure sandstone.* The most advanced stages of alteration may be observed on Houtenbek where leptite lies very close to gabbro.

B - Mineralogical Composition

Owing to the fine-grained texture of the rocks, the percentage of feldspar and sericite was not measured separately (table 2). The average grain-size of the constituents of the leptite is of the order of 0.1 mm.

Most of the leptites examined contain small amounts of magnetite, distributed throughout the thin section. They exhibit a great diversity in their composition (table 2), firstly, with respect to the relative amount of feldspar and quartz and, secondly, to the type and amount of the mafic minerals viz. amphibole, pyroxene, biotite and chlorite. Bearing in mind the diversified composition of the leptites, even over short distances, it is impossible to give a general mineralogical description which would pertain to the various leptite layers as a whole.

At several outcrops, especially on Windhoek 222 JS and Houtenbek 97 JT, pseudo-amygdales, consisting mostly of amphibole, have formed in the leptite. These rocks were at first taken to be amygdaloidal andesite. Close inspection soon led to the recognition of much quartz in the rock. The colour of the rock on fresh surfaces is gray or brown and the leptite has a glassy lustre. Weathered surfaces may be pitted or smooth, or the pseudo-amygdales may project.

Feldspar, usually slightly weathered, and sericite are present in all the leptites in amounts from 27 to 53 per cent. The percentage of feldspar increases with an increase in the degree of leptitisation, so that one can expect high percentages of feldspar in leptite which has undergone extensive alteration.

Quartz is also an ubiquitous constituent and a function of the degree of leptitisation. The percentage of quartz decreases with an increase in the degree of leptitisation.

* The Dullstroom andesite was probably also respon-

Table 2.

Volumetric composition of leptite and impure quartzite from the Smelterskop Stage

Specimen	DG 376	DG 307	DG 375	DG 306	DG 332	DG 379	DG 373	DG 350	DG 399
Pyroxene	-	-	-	-	-	-	-	2.35	
Amphibole	-	-	-	-	-	2.39	3.87		15.62
Biotite	-	-	-	-	2.00	-	-		-
Chlorite and muscovite	-	-	-	-	3.13	-	-	6.15	-
Total mafic minerals	-		-	-	5.13	2.39	3.87	8.50	15.62
Feldspar and sericite	35.10	41.46	42.48	53.70	37.11	30.34	27.05	36.28	43.84
Quartz	64.90	58.54	57.52	45.90	57.76	67.27	56.79	52.17	36.64
Amygdales		-	-	0,40	-	-	11.32	-	3.60
Magnetite		-	-	-	-	-	0.97	3.05	0.90
Total	100	100	100	100	100	100	100	100	100

DG 376, 307, 375 and 306 - Impure sandstone.

DG 332, 379, 373, 350 and 399 - Leptite.

DG 399, 373, 375, 376 and 379, Houtenbek 110 JS.

DG 306 and 307, Ontevreden 358 JS.

DG 332, Kwaggaskop 359 JS.

DG 399, Houtenbek 97 JT.

DG 350, Witbooi 225 JS.

The percentage of mafic constituents not only reflects the degree of leptitisation but also imparts a felsitic texture and appearance to the leptite. Amphibole, pyroxene and biotite are the main mafic minerals. Chlorite is an alteration product, mainly of amphibole.

C - Alteration of Quartzite to Leptite

The alteration of quartzite to the several varieties of leptite is not so much a function of the degree of metamorphic alteration as it is of the composition of the quartzite. Depending on the amounts of impurities in the original quartzite, roughly three varieties could be distinguished.

Variety 1./.....

Photomicrograph 1 - Normal impure quartzite consisting of rounded grains of quartz (white) in a matrix of clayey and sericitic material (dark) and fine quartz (white). Thin section 307, Ontevreden 358 JS. Transmitted light, X 30.

Variety 1. - The quartzite has merely changed colour from a typical light grey to a dark-grey rock in which rounded grains of quartz are cemented by sericitic and clayey material (photomicrograph 1). Tiny laths of plagioclase have usually developed at this stage.

Variety 2. - The leptite is now coloured dark grey or brown and often exhibits a slightly mottled appearance owing to the development of mafic minerals. A little chlorite and biotite are usually present as well as small amounts of microcline-perthite. In some varieties amphibole is present.

Variety 3. - The mafic minerals, especially amphibole, increase in amount and clinopyroxene and epidote may be present, the former sometimes in notable amounts. The rock is coloured reddish and often contains much microcline-perthite. It looks like a felsite or an aplite, especially on weathered surfaces. A certain degree of flowage may have taken place with the resultant formation of pseudo-vesicles. The vesicles have mostly been filled by quartz or amphibole.

6 - DULLSTROOM LAVA AND ASSOCIATED ROCKS

A - The Dullstroom Andesite

1 - Distribution

The Dullstroom lava follows conformably on the Smelterskop quartzite of the Pretoria Series and is therefore taken as a member of the Smelterskop Stage. In the Stoffberg area it is the highest recognizable member of this stage. The lava commences as a narrow strip on Houtenbek 97 JT from where the lower contact strikes south and the upper contact south-westwards so that on Konterdanskloof 223 JS and Witpoort 216 JS the lava thickens rapidly and attains a horizontal width of 4 miles from its base to the top, which is in contact with the gabbro. Taking the dip at 15^{o} to the west, the lava is here 5,200 feet thick. South of the Laersdrif Fault the upper contact gradually changes in strike to north-south whereas the lower contact continues directly southwards. This would account for the progressive thinning of the lava towards the north. On Doornkop 356 JS the horizontal distance from the base to the top is about 2.5 miles, which corresponds with a

thickness/.....

thickness of 4,400 feet at an average dip of 18° west. On the southern part of Kwaggaskop 359 JS the lava is 1.5 miles wide and, with a dip of 22° west, is 3,100 feet thick.

Outcrops of lava are generally plentiful but surfaces strewn with loose talus tend to obscure the successive zones, composed especially of amygdaloidal and nonamygdaloidal lava, lenses of leptite, felsite and granophyre as well as of other types due to variation in the composition of the lava and the degree of metamorphism.

Another troublesome aspect is that between the prominent ridges the ground is soil-covered which tends to obscure the succession and thereby renders the unravelling of the subdivision difficult.

The contact with the sediments of the Smelterskop Stage, mostly quartzite, can be readily followed in the field.

2 - Subdivision

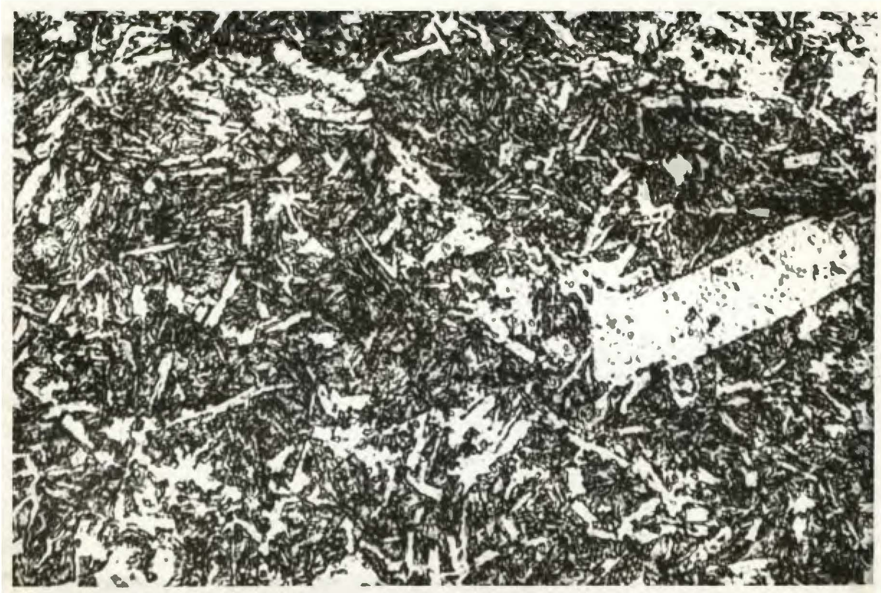
The lava consists of successive flows characterised by distinct mineralogical and textural variations. It would appear that a medium-grained lava, having mainly actinolite as the mafic constituent, is present at the base of the succession (photomicrograph 4) and can be distinguished from an upper, more fine-grained type (photomicrographs 3 and 2) which has mainly hornblende as the mafic mineral. It is not easy to notice the difference between the two types in the field owing to rapid local variations in the colour of the rocks and to the scattered distribution of amygdaloidal varieties. Outcrops are also not continuous over long distances.

Mineralogically the two varieties of andesite agree closely with Ongeluk Lava from Natalshoop 151 JT and Kranskloof 554 KT north of Lydenburg. On these farms drilling to test the foundation conditions for proposed dam-sites yielded fresh samples from depths exceeding 70 feet. One thin section indicated a medium-grained variety and the other a fine-grained amygdaloidal lava.

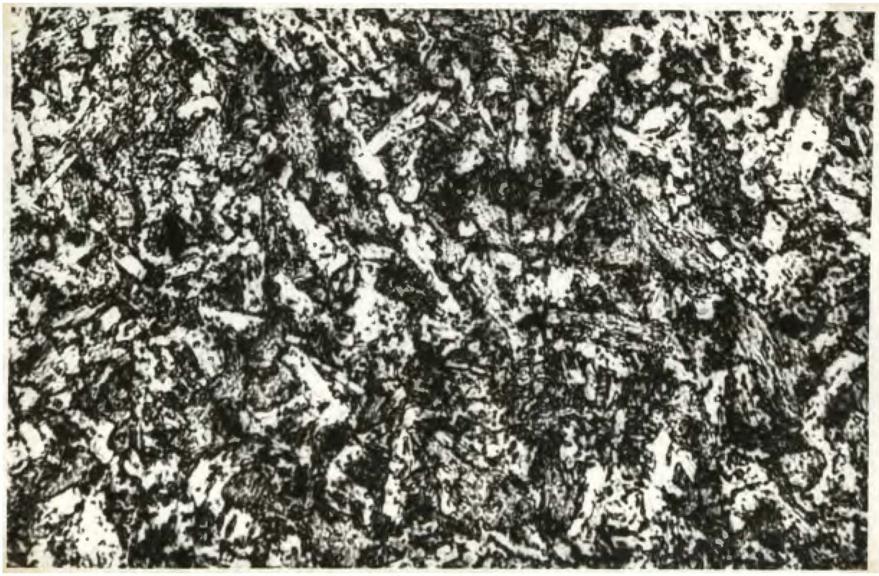
3 - Petrography

The northernmost occurrences of the Dullstroom lava were described first by A.L. Hall (1913, p. 28). Subsequently he also mapped and described the continuation

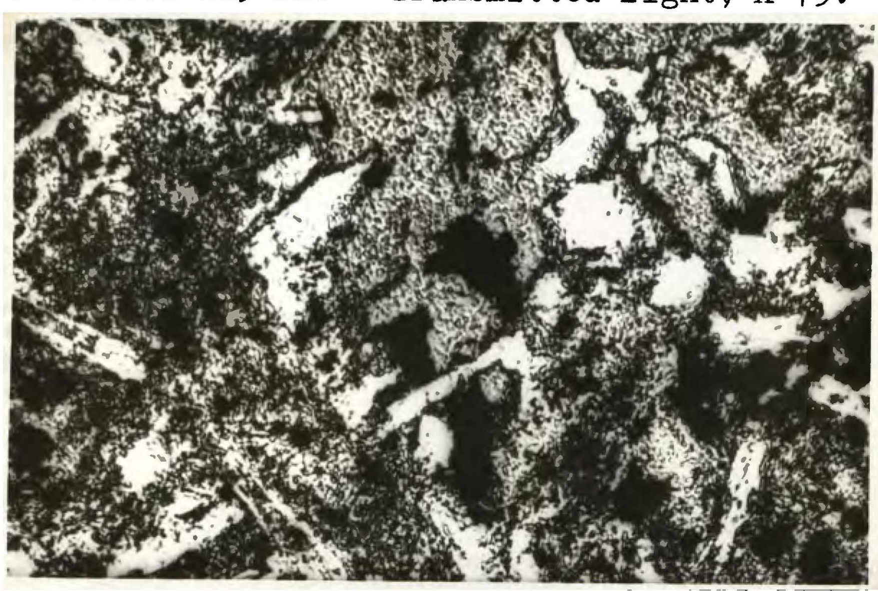
of/.....



Photomicrograph 2 - Fine grained andesite with laths of plagioclase feldspar (white) and amphibole (dark). A phenocryst of plagioclase may also be seen. Thin section 348, Doornkop 356 JS. Transmitted light, X 75.



Photomicrograph 3 - Fine- to medium grained andesite with plagioclase feldspar (white) and amphibole (dark). Thin section 301, Witbooi 225 JS. Transmitted light, X 75.



Photomicrograph 4 - Medium grained andesite with feldspar (white) and amphibole (dark). Thin section 323, Witbooi 225 JS. Transmitted light, X 75.

of the lava zone towards the south (1918, p. 44-45; 1932, p. 238-241).

The lava consists of typical fine- to medium-grained rocks which may range from grey through greenish grey to dark grey in colour.

Amygdaloidal varieties are confined mainly to the lower and central part of the zone. The amygdales often stand out on weathered surfaces. This phenomenon is not common to the Ongeluk lava of the Daspoort Stage in the Eastern Transvaal, owing to the very limited number of vesicles. Along the contact of the Dullstroom lava and the overlying Bushveld gabbro, amygdales are less numerous or completely absent. The amygdales consist of quartz, amphibole, epidote and chlorite. Often more than one of these minerals are haphazardly arranged in a vesicle. In others quartz forms the core and is then surrounded by amphibole. Clear-cut concentric banding of the amygdales is not developed. In those vesicles containing epidote, this mineral usually constitutes the core and is then surrounded by radiating grains of quartz. Chlorite, if present, also tends to occupy the cores of the vesicles. The lava is heavily jointed. The fractures have mostly been cemented by secondary chlorite.

Diameters of amygdales range from less than 1 mm to 30 mm and more but they are usually about 3 to 6 mm. The amygdales are commonly fairly spherical, but elongated, oval shapes were seen, suggesting flowage prior to solidification.

The ground-mass is made up of laths and microlites of plagioclase feldspar, and of microlites and corroded prisms of amphibole of about the same size, (Photomicrographs 2, 3 and 4). Phenocrysts of one or both of these minerals may be sparingly distributed in the ground-mass. The texture of the rock is pilotaxitic. Devitrification, due to the thermal-metamorphic effects of the Bushveld Igneous Complex, appears to have been complete. Magnetite forms very small crystals and is usually an accessory.

The optical properties of the constituent minerals are:

Plagioclase: Andesine with $n_{\gamma^1} = 1.558$ and $n_{\alpha} = 1.551$. The extinction angle on (010) is 17°.

Amphibole:/.....

Amphibole: In the lower part of the succession the amphibole is mainly actinolite with $n\gamma = 1.66$ and $n\alpha = 1.64$.

Higher up hornblende with $n\gamma = 1.685$ and $n\alpha = 1.663$ is commonly the main mafic constituent.

The pleochroism of the hornblende ranges from dark green (α) to yellowish green (γ) and of the actinolite from light green (α) to greenish yellow (γ).

The Dullstroom lava is mineralogically a typical andesite.

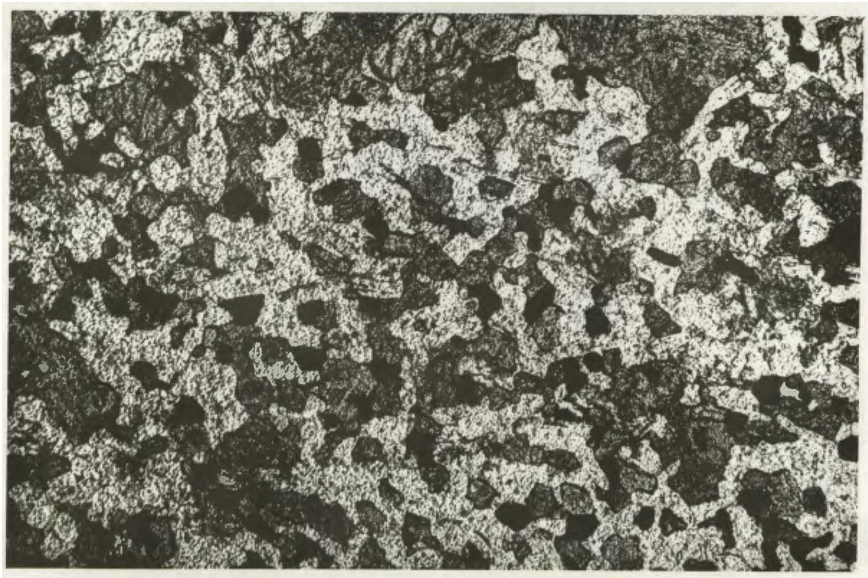
4 - Metamorphism

The upper part of the andesite has been thermally metamorphosed for as much as 200 feet from the contact by the overlying gabbro. The metamorphic product is a typical recrystallised, fine-grained, granoblastic rock which consists normally of microlites of plagioclase feldspar, pyroxene and magnetite (Photomicrograph 5). Generally the pyroxene crystallised after the feldspar as some feldspar microlites are included in pyroxene crystals. As pyroxene is always developed, these metamorphic rocks can best be described as pyroxene hornfels.

On Messchunfontein 98 JS and the surrounding farms the Dullstroom andesite thins rapidly and the whole succession has been metamorphosed. Just east of Trigonometrical beacon Mid. 26 amphibole-rocks have been formed (DG 372, table 4).

Plagioclase is the major felsic and pyroxene the major mafic constituent. Only one specimen, viz. DG 402, contains amphibole (very fresh and strongly pleochroic from green to yellow-green) in excess of pyroxene. Portions of the thin section are microcrystalline and were apparently not affected by the metamorphism. The amphibole is often accompanied by subordinate amounts of biotite. The quartz in specimen DG 343 was probably derived from amygdales. Specimens at the actual contact e.g. DG 328 and 317 have hypersthene in addition to the augite and these rocks must then be regarded as representative of the most advanced stage of thermal metamorphism of the Dullstroom andesite. As a result of the

smallness/.....



Photomicrograph 5 - Fine-grained pyroxene hornfels (metamorphosed andesite) with plagioclase (white) and pyroxene (dark). Thin section 317, Kwaggaskop 359 JS. Transmitted light, X 30.

Photomicrograph 6 - Medium-grained pyroxene hornfels (metamorphosed andesite) with plagioclase (white) and pyroxene (dark). Thin section 402, Middelkraal 221 JS. Transmitted light, X 30.

smallness of the pyroxene crystals, the amounts of the monoclinic and rhombic varieties could not be determined separately.

Table 3

Volumetric composition of pyroxene hornfels

Specimen No.	DG 403	DG 387	DG 328	DG 343	DG 317	DG 353	DG 354
Plagioclase	58.62	53.20	78.23	54.48	49.66	56.40	56.70
Pyroxene	x 27.34	x 36.20	y 21.34	x 33.43	y 39.87	x 42.50	x 40.10
Amphibole							
Biotite	4.80	8.90		2.28			
Quartz				2.56			
Magnetite	9.24	1.70	0.43	7.25	10.47	1.10	3.20
Total	100	100	100	100	100	100	100

Table 4

Volumetric composition of amphibolite

Specimen No.	DG 372	DG 402
Plagioclase	37.38	39.25
Pyroxene		x 6.93
Amphibole	58.60	50.82
Biotite	4.02	
Quartz		
Magnetite		3.00
Total	100	100

The specimens are listed from north to south over a distance of 15 miles.

DG 402 and 403 - Middelkraal 221 JS.

DG 387 - Witpoort 216 JS.

DG 328 and 343 - Doornkop 356 JS.

DG 317, 353 and 354 - Kwaggaskop 359 JS.

DG 372 - Houtenbek 97 JT.

x - Monoclinic pyroxene.

y - Monoclinic and rhombic pyroxene.

The rock is mostly fine-grained, equigranular, and grades into localised inequigranular, medium-grained varieties (Photomicrograph 6).

In the fine-grained pyroxene hornfels which is the dominant variety, the plagioclase grains form an interlocking mass of short, stout laths in which small irregular grains of both monoclinic and rhombic pyroxene and magnetite are evenly distributed (Photomicrograph 5). Where both rhombic and monoclinic pyroxene are developed, they occur separately or the monoclinic variety envelopes earlier-formed grains of rhombic pyroxene.

The clinopyroxene also envelopes plagioclase and was therefore one of the last minerals to crystallise.

Magnetite/.....

Magnetite surrounds the clinopyroxene and is therefore a product of late crystallisation. Biotite generally developed just after the plagioclse which it sometimes encloses. Amphibole, identified only in the medium-grained variety, is present as irregular prismatic grains which enclose plagioclase.

Sizes of individual minerals in the pyroxene hornfels

Table 5.

Fine-grained pyroxene hornfels

Mineral	Biotite	Magnetite	Augite	Hypersthene	Plagio-
Average diameter	0.2 mm	0.1 mm	0.15 mm	0.4 mm	
Average length					0.3 mm
Average width					0.07 mm

Table 6

Inequigranular, medium-grained pyroxene hornfels

Mineral	Hornblende	Magnetite	Augite	Hypersthene	Plagioclase
Average diameter	0.7 mm		0.2 to 0.3 mm	0.2 to 0.6 mm	
Length					0.3 to 1.5 mm
Width					0.1 to 1 mm

The feldspar ranges from labradorite ($Ab_{40}An_{60}$) having $n\gamma = 1.568$, $n\alpha = 1.560$ and the extinction angle on (010) of albite twins = 31^{o}, to andesine ($Ab_{60}Ab_{40}$) having $n\gamma = 1.558$, $n\alpha = 1.550$ and the extinction angle on (010) of albite twins = 22^{o}. Samples from near the contact with the gabbro commonly contain labradorite. Although the feldspar is usually clear, it is clouded by fine magnetic dust in some specimens. In the advanced stages of metamorphism the feldspar is very fresh.

The refractive indices of the hypersthene and the augite appear to be about the same and while doing determinations for hypersthene, difficulty was experienced in differentiating between the two minerals in grain-mounts.

The/.....

The augite has n γ' = 1.715 and n α = 1.690. The rhombic pyroxene has n γ' = 1.710 and n α = 1.697 and is therefore hypersthene with 28 per cent $FeSiO_3$ (Winchell, 1945, p. 218). The high tenor of iron is also indicated by the pleochroism which ranges from pink to greenish yellow.

(a) - Subdivision of Metamorphic Stages

First Stage. In the main andesite flow, away from the contact with the gabbro, thermal metamorphism has led to the formation of hornblende, quartz and epidote in the amygdales. The original pyroxene was converted to actinolite and hornblende. Some of the hornblende may represent products of uralitisation of the pyroxene. Devitrification of the glass has been completed and its place taken by small laths of dull feldspar. In the first stage of metamorphism the andesite still retains its original texture.

Second Stage. With advancing metamorphism, near the contact with the gabbro, the andesite assumes a crystalloblastic texture, with the formation of clear, individual grains of hornblende and plagioclase which displays noticeable polysynthetic twinning. Magnetite grains have also begun to crystallise. Original magnetite and ilmenite has furnished iron and titanium for the formation of biotite (Harker, 1956, p. 109).

Third Stage. In the highest stage of thermal metamorphism the original texture of the andesite is mostly obliterated and only the amygdales are retained. Augite reappears and although it may be found together with amphibole it is the only mafic constituent in the highest recorded stage of thermal metamorphism of the Dullstroom andesite. The augite has taken the place of the hornblende. The pyroxene is normally only augite but this mineral is also accompanied by appreciable amounts of pleochroic hypersthene. Olivine may also have formed in amounts of less than two per cent. The plagioclase in these rocks is very clear and possesses well developed polysynthetic twinning. The amygdales consist of coarse-grained quartz, monoclinic pyroxene and small amounts of plagioclase.

B - The/.....

B - The Felsite

1 - Distribution

At the base of the andesite on Windhoek 222 JS and Messchunfontein 98 JS, a grey-coloured felsite forms a fairly distinct ridge. On Houtenbek 97 JT it thins rapidly and is also intruded by quartz diabase. Outcrops in this area are discontinuous so that precise mapping of the various rock types could not be done.

Around the farm beacon common to Witpoort, Middelkraal, Windhoek and Konterdanskloof an outcrop of brick-red felsite, in places granophyric, is fairly well exposed on high ground. South of the Laersdrif Fault, on Witpoort 216 JS, similar material was found and followed southwards through Welgevonden 215 JS into Doornkop 356 JS where it apparently terminates just north of a perennial stream draining westwards. The felsite is interlayered with the andesite.

On Middelkraal 221 JS a lens consisting of fine- to medium-grained quartz-rich rock lies within andesite near the upper contact of the latter with gabbro and extends southwards into Witpoort 216 JS. It thins and peters out near the Laersdrif Fault. The layer was at first considered to be leptitised quartzite but a chemical analysis of the material revealed that it agrees closely with the felsite found around the farm beacon common to Witpoort, Middelkraal, Windhoek and Konterdanskloof (folder 1). On the strength of the analyses the layer is therefore also taken to be felsite.

2 - Mineral Composition

Generally the felsite from the base of the andesite, from the outcrops around the farm beacon common to Witpoort, Middelkraal, Windhoek and Konterdanskloof and from the layer south of the Laersdrif Fault is slightly medium-grained in the central portions of layered zones, each of which is about 200 feet thick. It becomes fine-grained along the upper and lower contacts. Although apparently fresh in the field the feldspar has been altered extensively to sericitic material. Micrographic intergrowths between quartz and feldspar are evident in the medium-grained varieties, but less so in the finer-grained rocks which then resemble felsite (photomicrograph 8). The felsite is slightly amygdaloidal in places and the vesicles are filled with quartz.

The/.....

The quartz is often needle-shaped (microphotograph 7). Although not so evident in the photo, this is especially the case where the quartz is graphically intergrown with feldspar.

In a few outcrops, especially at the small isolated felsite layer on Doornkop 356 JS, it was possible to recognise phenocrysts of twinned orthoclase and of plagioclase feldspar, and vague repeated twinning in some of the altered material suggests plagioclase as the original mineral. Although it is fairly certain that both plagioclase and K-feldspar are present the identity of the rocks could not be determined microscopically.

The granophyric felsite was probably extruded during an interval in the outflow of the andesitic lava. The limited distribution of the flow is in keeping with that of silica-rich lava.

The amount of feldspathic material in the felsite is high (table 7) but corresponds with that of a normal granite. The quartz content is fairly constant and the mineral can be taken to constitute from 25 to 30 per cent of the rock. Amphibole, as hornblende, ranges in amounts from 4 to 19 per cent.

In the felsite layer from Middelkraal to Witpoort the major constituent is andesine ($n\gamma = 1.560$, $n\alpha = 1.553$), which is intimately associated with quartz (photomicrograph 8). Amphibole is usually well represented and followed in quantity by pyroxene and biotite. Some samples contain mainly amphibole whereas in others only pyroxene and/or biotite are present.

The amphibole has $n\gamma = 1.685$ and $n\alpha = 1.658$, and is therefore hornblende. The marked variation in the type of mafic constituents is ascribed to metamorphism by the near-by gabbro.

C - Chemical Composition of the Andesite and the Felsite

Only one analysis of this andesite existed (Hall, 1932, p. 239), and to this two more have been added (folder 2). Three analyses of the felsite have also been done. The analyses, with the calculated Niggli values and norms are listed in folder 2. In the case of the andesite care was taken to select specimens practically free from amygdales.

The/.....

The andesite is a Si-gabbroidal rock derived from a gabbro-dioritic magma. The magma is a member of the calc-alkali series (Burri, p. 78).

The three analyses of felsite representing the felsite layer at the base of the andesite, the isolated outcrop around the farm beacon common to Witpoort, Middelkraal, Windhoek and Konterdanskloof and the layer near the top of the andesite, are, in contrast with the andesite, granitic rocks derived from a granitic magma (Burri, 1964, p. 78).

TABLE 7

Volumetric composition of felsite from layers in Dullstroom andesite on Middelkraal, Witpoort, Welgevonden and Doornkop

Specimen	DG 389	DG 390	DG 392	DG 405	DG 408	DG 409	DG 396	DG 364	DG 398	DG 400	DG 397
Feldspar and sericitic material	60.30	63.67	47.88	58.41	44.72	47.72	41.50	50.91	44.43	59.03	44.65
Quartz	24.10	23.33	29.55	40.27	38.43	36.32	38.59	33.06	32.16	32.69	32.50
Mafic minerals	a 11.50	a 8.14	b 18.97	–	a 12.32	c 15.46	d 18.91	c 14.08	e 21.42	d 7.25	e 20.39
Magnetite	4.10	4.86	3.60	1.32	4.53	0.50	1.00	1.95	1.99	0.93	2.46
Total	100	100	100	100	100	100	100	100	100	100	100

a - Hornblende

b - Mainly hornblende with a little biotite

c - Biotite and pyroxene

d - Hornblende and biotite

e - Hornblende, biotite and pyroxene

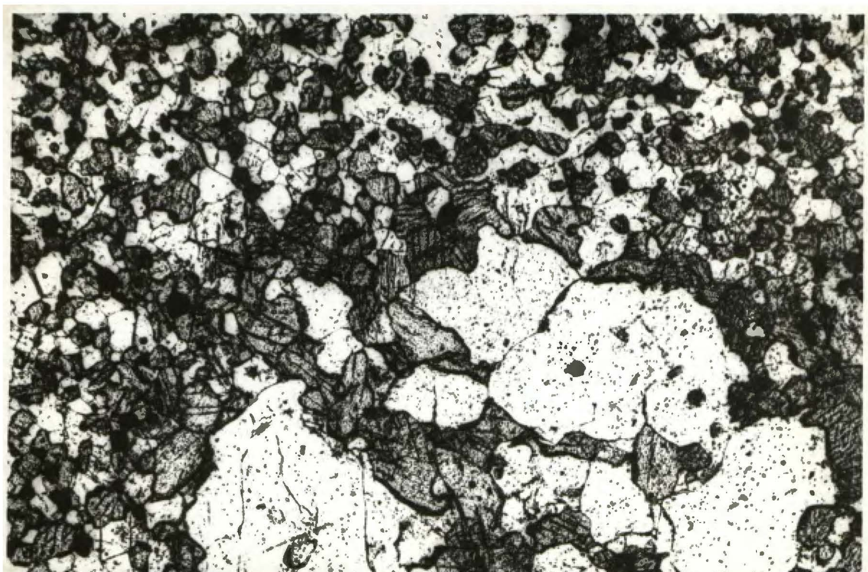
DG 389, 390, 392, 396 and 364 - Witpoort 216 JS

DG 405, 408 and 409 - Middelkraal 221 JS

DG 398, 400 and 397 - Messchunfontein 98 JS

In/.....

Photomicrograph 7 - Fine-grained felsite in which feldspar (dark) is intimately intergrown with quartz (white). Thin section 389, Witpoort 216 JS. Transmitted light, X 30.



Photomicrograph 8 - Quartz (white) intimately intergrown with feldspar (dark) in felsite from the layer on Middelkraal and Witpoort. Thin section 396, Witpoort 216 JS. Transmitted light, X 30.

In fig. 2 the Niggli values have been plotted, together with those of Rooiberg felsite and microgranite, on four diagrams. The variation of al, fm, c and alk relative to si are presented and compared with the interpolated values (solid lines) of lavas from Lassen Peak, California, U.S.A. (Burri, 1964, p. 70). The Lassen Peak lavas were selected for comparison purposes because they are of diverse composition, varying from basic to felsic varieties (Williams, 1932, p. 311). The two andesites fall along the more mafic portions, and the three felsites towards the more felsic portions of the variation curves. It is significant that the felsite from the lowest layer (DG 430) is the most mafic member of the three felsites.

The andesite and the felsite of the Dullstroom Volcanics have lower al- and c-contents and higher fm-contents than the Lassen Peak lavas, while the alk-content is about the same.

In the four diagrams of fig. 2 the felsic rocks of the Dullstroom volcanics and the Rooiberg felsites cluster rather close together and are therefore of similar composition. In figs. 4 and 5 they occupy a field of their own.

In the mg-k diagram (fig. 3) it is seen that the andesite and the felsite have a generally higher k-content and a lower mg-content than the lavas from Lassen Peak.

The analyses of the three felsites were also recalculated to atom percentages and the values plotted on the Fm-K, and ($K^+ + Na^+$) - Si^{4+} - ($Fe^{2+} + Fe^{3+} + Mg^{2+} + Mn^{2+}$) diagrams of Von Gruenewaldt (1966 pp. 45-46). In both cases they fall within the felsite field (figs. 4 and 5). In the former diagram K^+ is considerably lower and in the latter diagram ($Fe^{2+} + Fe^{3+} + Mg^{2+} + Mn^{2+}$) is much higher than Von Gruenewaldt's plotted values.

The variation diagram of oxide percentages against SiO_2 percentages (fig. 6) shows that Al_2O_3, FeO, CaO and MgO decrease, and Na_2O and K_2O increase from andesite to felsite. The alkali-lime index, that is, the silica value at which the curves for total alkalies and lime intersect is about 61.8. According to Peacock (1931, p. 62) indices from 56 to 61 belong to the calc-alkali series, and above 61 to the calcic series.

7 - XENOLITH/.....

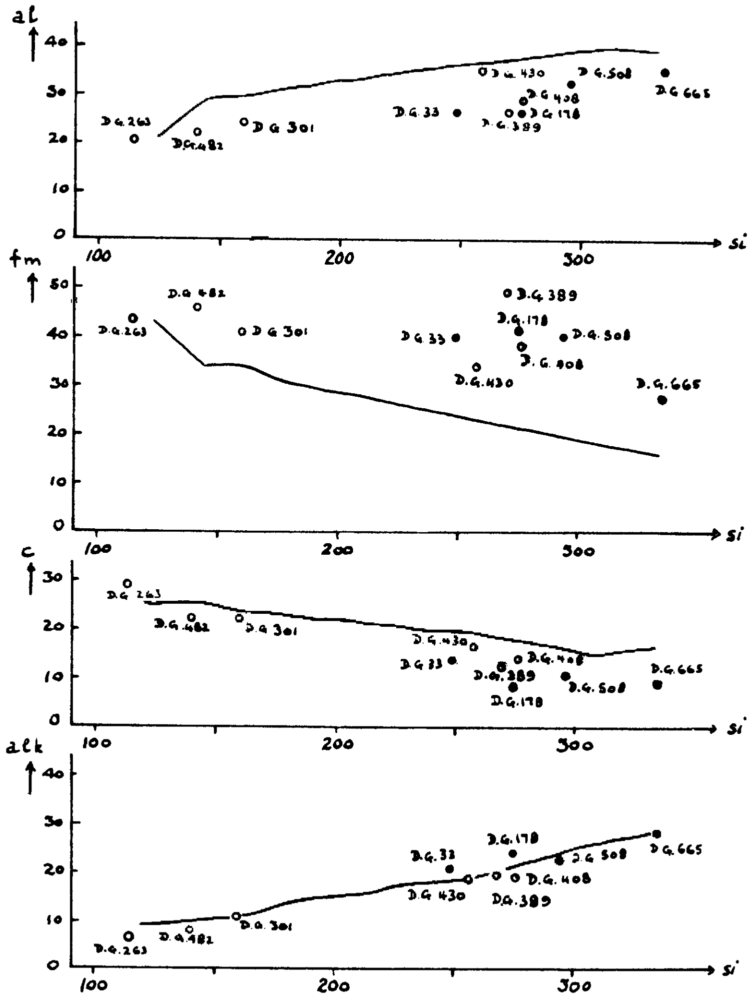


Fig. - Variation of al, fm, c and alk relative to si for the lavas from the Dullstroom Volcanics and Rooiberg felsite. Solid line represents interpolated vaives of the lavas from Lassen Peak, California (Burri, p.70).

o : Dullstroom volcanics
• : Micogranite and Rooiberg felsite

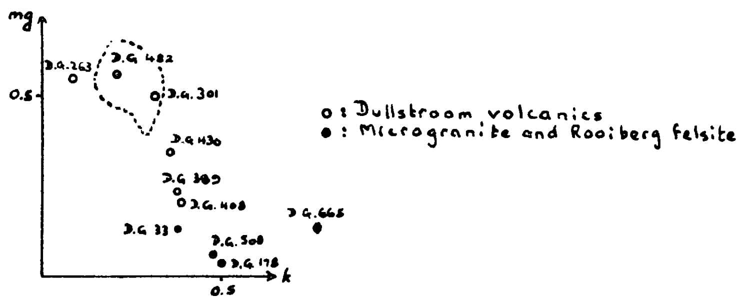


Fig. 3 - k-mg diagram for the lavas from the Dullstroom Volcanics and Rooiberg felsite. Lavas from Lassen Peak all fall within the area outlined by the broken line (Burri, p. 71).

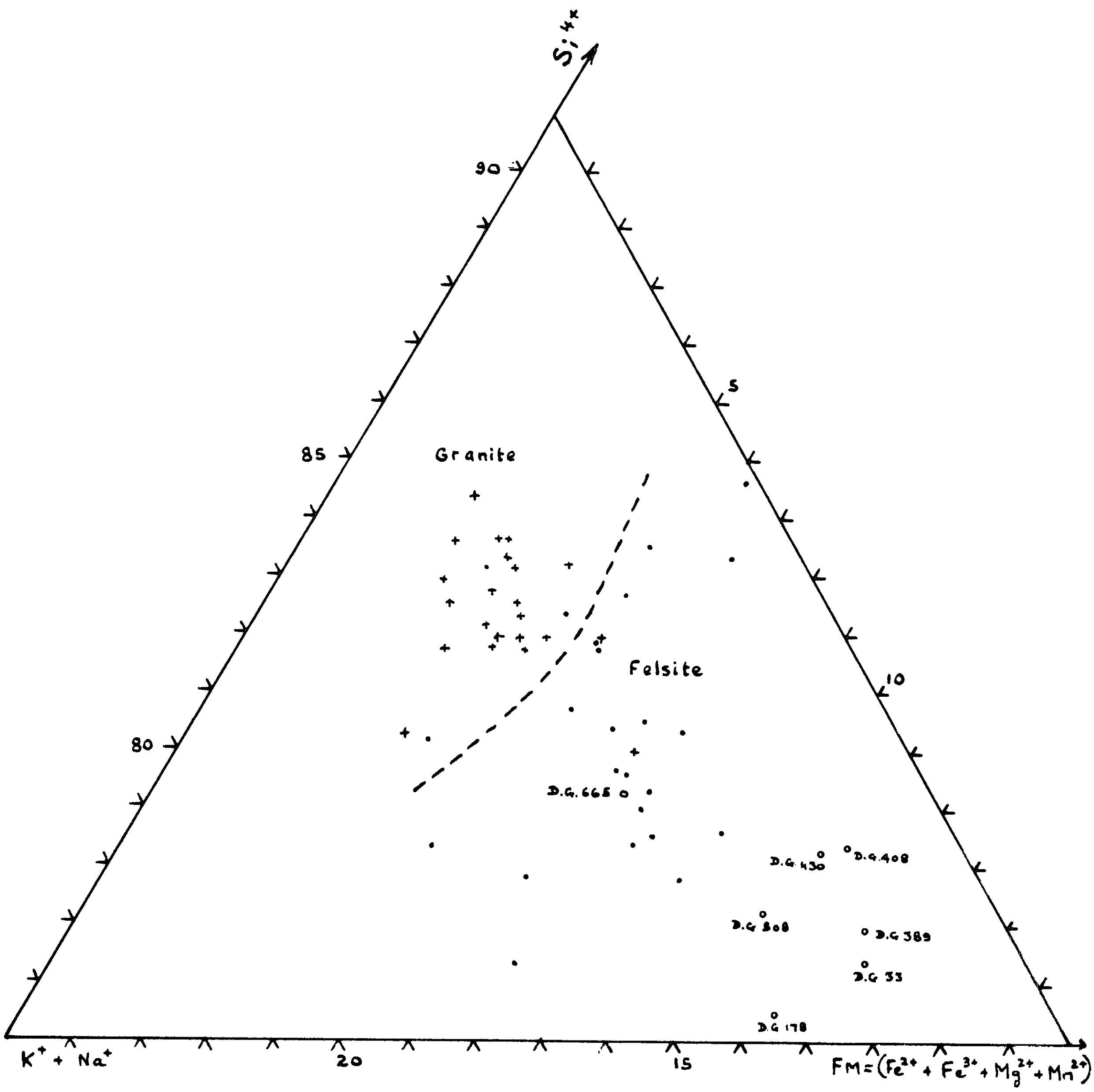


Fig. - Diagram for alkalis, femics and silicon (atom %) of Von Gruenewaldt (1966, p 46), with values of felsites from the Stoffberg area added.

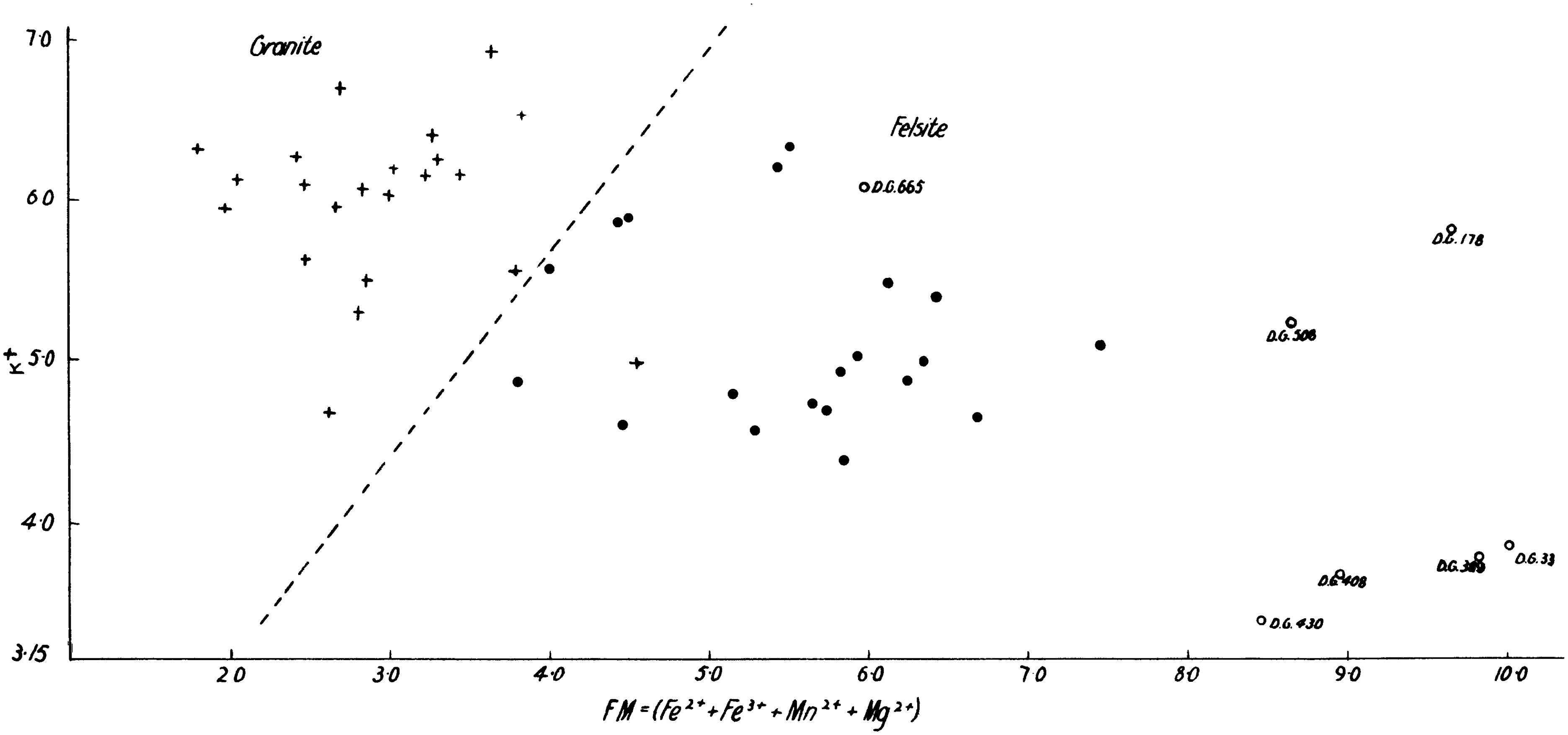


Fig.5:- K-FM diagram of Von Gruenewaldt (1966, p. 45) with values of felsites from the Stoffberg area added.

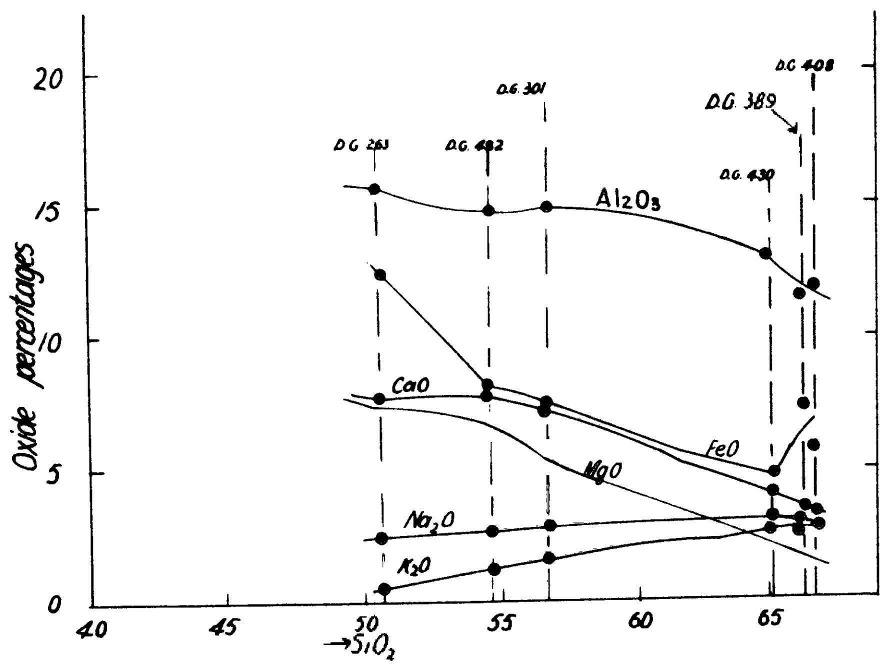


Fig.6:- Variation diagram of oxide percentages plotted against SiO_2 percentages (both by weight) for six analyses of the Dullstroom Volcanics.

7 - XENOLITH OF METAMORPHOSED DULLSTROOM ANDESITE AND AGGLOMERATE WITH ASSOCIATED HORNBLENDE GRANITE

A - Distribution

A concordant xenolith, situated between the gabbro of the Main Zone and the Magnetite gabbro of the Upper Zone was mapped on Swartkoppies 217 JS, Welgevonden 215 JS and Doornkop 356 JS. It measures from 200 to 250 feet across the outcrop and about 11 miles along the strike.

On Welgevonden, on the western side of the xenolith, a fragment of the main xenolith branches off towards the north-west. This fragment is therefore discordant with respect to the magnetite gabbro. It would appear that the magnetitite seams of Subzone B (see map for position of Subzone B) have been displaced along this fragment, which therefore probably lies along a fault-zone. North of this fragment, and on the same farm, smaller fragments also branch off from the main xenolith in a transgressive manner.

Farther south, on Kwaggaskop 359 JS are two further xenoliths lying in the same stratigraphical position within the magnetite gabbro.

North of the Laersdrif Fault small, scattered, but nonetheless concordant xenoliths of similar material, were mapped on Swartkoppies and along the eastern boundary of De Lagersdrift 178 JS.

The dip of the gabbroic rocks and of the xenolith on Swartkoppies is from 10° to 15° W but southwards on Welgevonden it increases to 20° and 25° W. The xenolith attains a maximum development on Doornkop and forms a prominent hill known as Vaalkop. It consists of two rock types viz, pyroxene hornfels and agglomerate (plates 2 and 3) and associated with them is hornblende granite (microgranite).

B - Field Relationships

Normally the microgranite underlies the pyroxene hornfels (metamorphosed andesite), e.g. on Welgevonden 215 JS, but on Vaalkop, in the western part of Doornkop 356 JS where the body is well developed a thin strip of pyroxene hornfels is present below the microgranite.

In many places small xenoliths of pyroxene hornfels were found in the gabbro; some outcrops were far away from the main xenolith. A few of the more prominent ones are indicated on the map, for instance in the northern part of Swartkoppies around Trigonometrical Beacon Mid 22. These smaller xenoliths still seem to follow the dip and the strike of the layering of the gabbro.

The stratigraphical position of the agglomerate is uncertain but it is closely associated with the pyroxene hornfels. It is well exposed in the bed of a stream in the southern part of Welgevonden (plate 3).

On Swartkoppies 217 JS near the Steelpoort River a large block of agglomerate is enclosed in magnetite gabbro, about ½ mile west of the main xenolith.

A few pegmatitic bodies were located, mainly above but also below the main xenolith. A few of the larger ones were mapped. They have approximately the same mineral composition as the granite and are lighter in colour, owing to a higher content of quartz.

In contrast with the concordant nature of the main xenolith with respect to the dip and strike of the layering of the gabbroic rocks, the pegmatitic bodies have much steeper dips than the magnetite gabbro (from 45° to vertical), and cut across the strike of the gabbroic rocks. One body consists mainly of quartz. Epidote is usually associated with the quartz-rich varieties. The pegmatite is probably a product of late-stage igneous activity.

C - Rock types

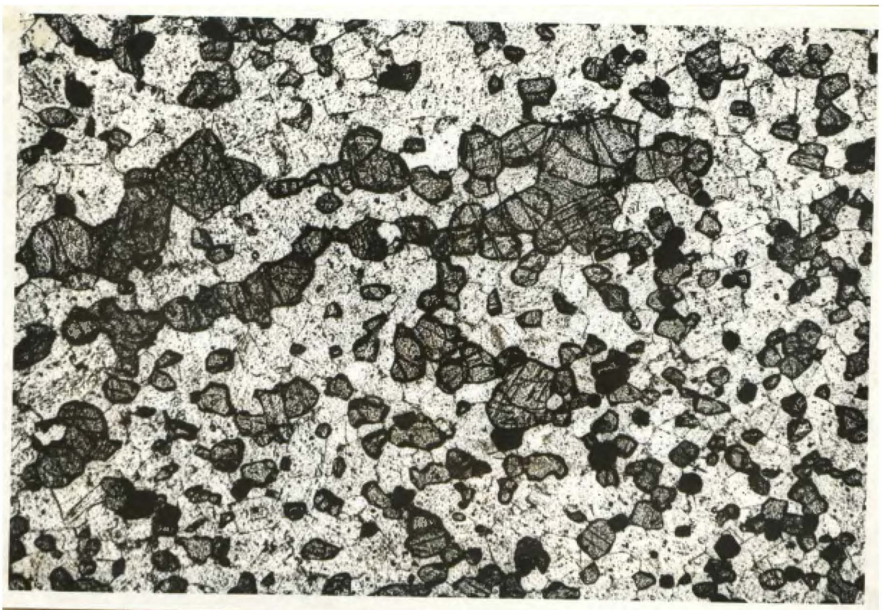
1 - Pyroxene hornfels

The rock is typically fine-grained, grey in colour and consists of interlocking laths of labradorite, small but also fairly large grains of augite (diallage), hypersthene and magnetite.

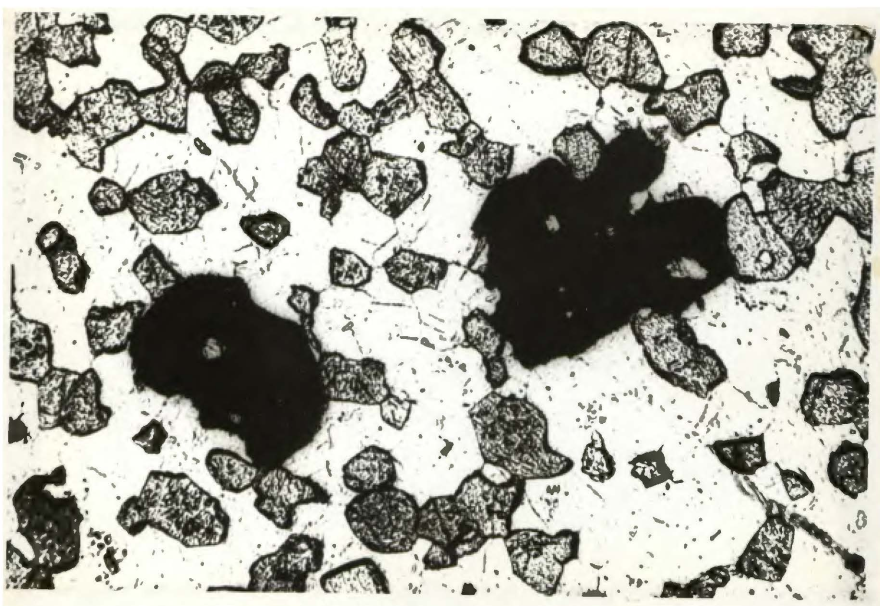
The clinopyroxene has the following indices of refraction: $n\gamma = 1.720\ (\pm 0.002)$; $n\alpha = 1.659\ (\pm 0.002)$. This mineral is therefore augite of the Diopside-Hedenbergite Series with $Diopside_{60}\ Hedenbergite_{40}$ (A.N. Winchell, 1945, p. 226).

The hypersthene is strongly pleochroic with α = clear and pink and γ = pale green, thus denoting a fairly high

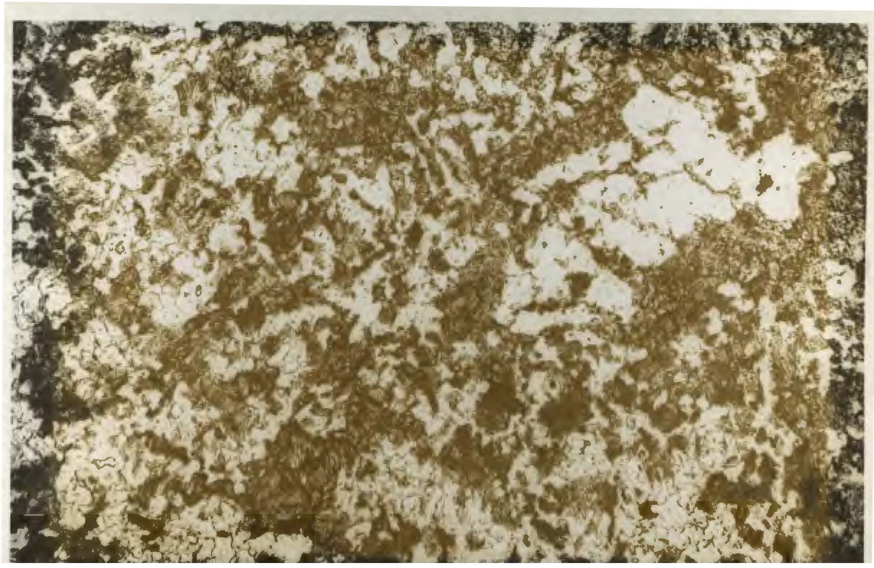
iron/.....



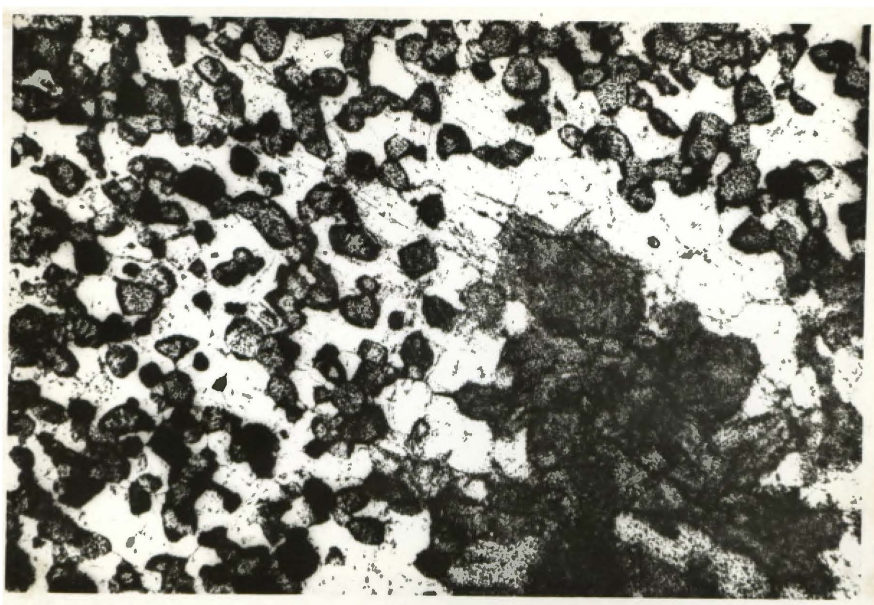
Photomicrograph 9 - Fine-grained pyroxene hornfels having pyroxene (dark grey) and plagioclase feldspar (white) in about equal amounts. Thin section 149, Swartkoppies 217 JS. Transmitted light, X 30.



Photomicrograph 10 - Pyroxene hornfels in which plagioclase feldspar (white) is the major constituent. The two magnetite grains (black) have inclusions of plagioclase. The grey mineral is pyroxene. Thin section 263, Welgevonden 215 JS. Transmitted light, X 30.



Photomicrograph 11 - Pyroxene hornfels with a quartz-filled vesicle. Pyroxene (grey) has proceeded to invade the quartz (white). Thin section 91A, Swartkoppies 217 JS. Transmitted light, X 30.



Photomicrograph 12 - Pyroxene hornfels with an amphibole-filled vesicle. Thin section 149, Swartkoppies 217 JS. Transmitted light, X 30.

Plate 2 - Metamorphosed amygdaloidal andesite (pyroxene hornfels) on Swartkoppies 217 JS. Some of the amygdales have been completely drawn out into lenses whereas others are oval or circular in outline.

Plate 3 - Agglomerate in a stream-bed on Welgevonden 215 JS. Diabase fragments are set in a base of metamorphosed Dullstroom andesite (pyroxene hornfels).

iron content. The hypersthene has the following refractive indices: $n\gamma = 1.713$ ($\pm$ 0.002) and $n\alpha = 1.679$ ($\pm$ 0.002).
Refractive index determinations point to a constant composition for the hypersthene.

In one thin section considerable amounts of a green pleochroic hornblende are present (table 8). It has $n\gamma = 1.658$ ($\pm$ 0.002) and $n\alpha = 1.6\ 8$ ($\pm$ 0.002). The hornblende varies from dark grey to black in colour and shows pleochroism from brown to yellowish.

The plagioclase which is not zoned, has $n\gamma = 1.568$ (0.002), $n\alpha = 1.559$ (0.002) and is therefore labradorite.

Chain textures are present and common to both the pyroxene (photomicrograph 9) and the hornblende. This texture points to mobilisation of the minerals during metamorphism.

In the following table (8), the modal compositions of nine specimens of pyroxene hornfels are given. Specimen DG 91A contains a fair amount of quartz as amygdales.

From table 8 it follows that either plagioclase or pyroxene is the major constituent (see also photomicrographs 9 and 10). In two samples viz, DG 143 and 262, hornblende has developed, apparently at the expense of plagioclase. This rock type may be regarded as an intermediate stage of metamorphism of the Dullstroom andesite.

The proportions of the monoclinic to the rhombic pyroxene vary considerably.

A mechanical separation of the minerals of the rock from Swartkoppies was done in order to determine the percentage of each mineral present and to establish conclusively whether any quartz is present. The labradorite was successfully separated from the pyroxene with the aid of a Frantz magnetic separator. Magnetite was removed with a hand magnet. The magnetite is partially altered to hematite. In some magnetite grains fine lamellae of ilmenite have formed, mainly along octahedral cleavage planes. The ilmenite has also formed separately.

The percentage (by weight) of the three main constituents are:

Pyroxene = 58%; labradorite = 36%; magnetite = 6%.
Accessory minerals include biotite, apatite, and olivine.

Although/.....

Table 8.

Modal Composition of pyroxene hornfels

Specimen No.	DG 91A	DG 149	DG 143	DG 140	DG 262	DG 263	DG 268	DG 269	DG 270
Plagioclase	37	38	20	51	27	49	54	55	54
Pyroxene	39[a]	54[b]	38[c]	47[d]	52[e]	50[f]	43[g]	44[h]	44[i]
Magnetite and ilmenite	11	7	8	2	6	1	3	1	2
Amphibole	-	1	34	-	15	-	-	-	-
Quartz	13	-	-	-	-	-	-	-	-
Total	100	100	100	100	100	100	100	100	100

a - Mainly augite; b - Mainly hypersthene; c - Augite;
d - Hypersthene; e - Augite;
f - Augite; g - Mainly hypersthene; h - Hypersthene;
i - Augite;
DG 91A and 149 - Swartkoppies 217 JS.
DG 143, 140, 262 and 269 - Welgevonden 215 JS.
DG 269 and 270 - De Lagersdrift 178 JS.

Although quartz was not specifically identified in the normal equigranular type of hornfels, at one outcrop near the northern extremity of the xenolith on Swartkoppies 217 JS the rock contains a large number of rounded, oval-shaped and drawn out amygdales which consist mainly of quartz (plate 2). They are original amygdales. In a few places pyroxene has entered the amygdale and has replaced the quartz (photomicrograph 11). DG 149 (table 8) contains a few vesicles filled with amphibole (photomicrograph 12).

(a) - Chemical Composition

The Niggli values and the norm in folder 2 reveal that the pyroxene hornfels (DG 263) is more basic than the original andesite (DG 301 and DG 482). On the variation-diagrams for al, fm, c and alk with respect to si in fig. 2, the pyroxene hornfels falls within the basic field demarcated by the curves. During metamorphism the available free silica was therefore taken up in the formation of the metamorphic minerals hypersthene, clinopyroxene, amphibole, biotite and olivine.

(b) - Origin/.....

(b) - Origin

The source-material of the pyroxene hornfels was the andesitic lava of the Dullstroom volcanic phase. A rock similar in composition is described by Harker (1956, p. 109) from Skye. He ascribed the existence of this rock type to the thermal metamorphism of a basalt lava.

The quartzitic pebbles and lenses are probably remnant amygdales. These inclusions did not take part in any reaction and are therefore relicts in the metamorphosed rock. The complete absence of quartz grains in the ground-mass makes it most unlikely that the source-material could have been a sandy shale. Their physical resemblance to, and comparable mineralogical composition with the upper metamorphosed Dullstroom andesite leaves no doubt that the pyroxene hornfels represents a metamorphosed andesite which became detached from the andesite layer during the intrusion of the gabbro.

2 - Agglomerate

A peculiar property of the agglomerate is that the fragments are often rounded and have smooth surfaces. The fragments vary in diameter from less than 1 inch up to 1 foot (plate 3).

Owing to the limited size of the outcrops of agglomerate and also to the erratic exposures, they were not mapped, but their positions have been marked on the map (Ag).

A similar agglomerate was found in the Dullstroom lava on Witpoort 216 JS. It is thus possible that the agglomerate outcrops within the gabbroic rocks are disrupted fragments of Dullstroom agglomerate.

The ground-mass of the agglomerate is similar to that of the metamorphosed lava (pyroxene hornfels) and consists mainly of rhombic pyroxene which displays the characteristic pink pleochroism. Plagioclase feldspar and fair amounts of quartz form the remainder of the matrix. The rounded and angular fragments contain plagioclase feldspar and fair amounts of quartz form the remainder of the matrix. The rounded and angular fragments contain plagioclase feldspar, largely altered to sericitic material, and fairly fresh monoclinic pyroxene. These fragments may represent diabase.

3 - Hornblende/.....

3 - Hornblende Microgranite

(a) - Description and Composition

The granite which mostly underlies the pyroxene hornfels (on Doornkop 356 JS it is found both below and above the pyroxene hornfels), consists of slightly rounded to serrated quartz grains, plagioclase feldspar, alkali feldspar, magnetite, pyroxene, hornblende, biotite, zircon and tourmaline. Quartz and feldspar are the two major constituents. Quantitive X-ray determinations of quartz on two samples gave values of 34 and 45 per cent.

The feldspar is invariably weathered but it could be established that both a plagioclase and K-feldspar are usually present. Plagioclase is in excess of the K-feldspar and in one sample very little K-feldspar was seen. The plagioclase has altered to a light brown mineral whereas the alkali feldspar has produced a more dark reddish-brown product of weathering.

The plagioclase feldspar has refractive indices $n\gamma^1$ = 1.547 and $n\alpha$ = 1.540 ($\pm$ 0.003) and is therefore oligoclase.

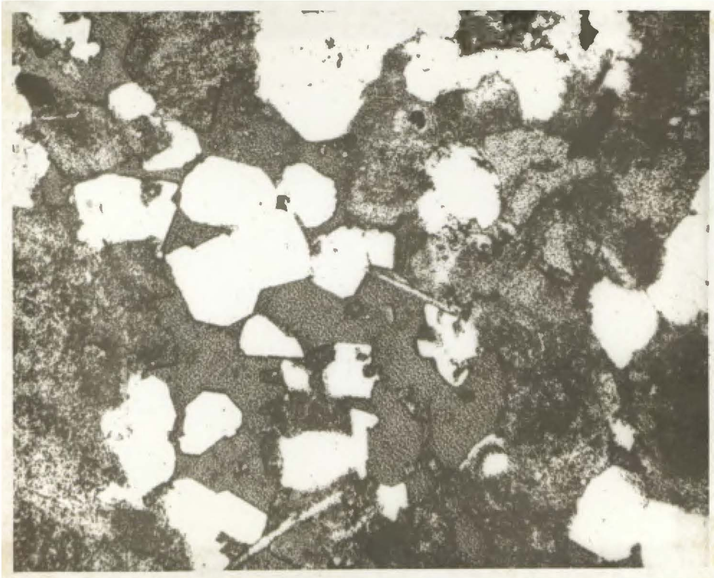
The K-feldspar has indices $n\gamma^1$ = 1.528 and $n\alpha$ = 1.520 ($\pm$ 0.003) and it shows the typical simple twinning of orthoclase.

The amphibole is hornblende with distinct pleochroism from green to light orange. It is a later product than quartz and has sometimes replaced the latter (photomicrograph 13). Where the replacement of quartz has reached an advanced stage the quartz grains are very irregular in outline. Magnetite is present as anhedral grains to subhedral crystals.

In table 9 the volumetric composition of the constituents of thirteen granite samples are given. Specimen 33 contains about 16 per cent K-feldspar as orthoclase.

It is more reddish-brown in colour than the other types which have a greyish colour. The sample was taken from the centre of the granite intrusive and it is therefore likely that plagioclase rapidly increases at the expense of K-feldspar towards the margins of the granite. The quartz content varies from 23.55 per cent to 38 per cent.

Photomicrograph/.....



Photomicrograph 13 - Hornblende granite with the hornblende as individual grains (stippled grey). Thin section 261, Doornkop 356 JS. Transmitted light, X 30.

TABLE 9

Modal composition of hornblende microgranite

Specimen	DG 33	DG 94	DG 141	DG 260	DG 337	DG 338	DG 339	DG 356	DG 261	DG 357	DG 358	DG 43 b	DG 34
Feldspar	56	48	46	58.70	53.62	53.60	61.71	68.98	54.25	52.96	48.71	57.46	63.28
Quartz	31	37	36	31.21	33.27	23.55	25.27	26.36	27.64	24.70	26.63	37.80	27.74
Amphibole	8	2	10	8.98	11.47	21.19	4.67	-	15.53	17.38	15.60	1.20	7.89
Clinopyroxene	-	3	-	-	-	-	5.20	4.00	-	-	6.26	2.00	-
Magnetite	5	4	5	1.11	1.64	1.66	2.17	0.66	2.58	4.96	2.90	1.54	1.09
Tourmaline and zircon	-	-	-	-	-	-	0.98	-	-	-	-	-	-
Biotite	-	6	3	-	-	-	-	-	-	-	-	-	-
Total	100	100	100	100	100	100	100	100	100	100	100	100	100

DG 33, 94 and 141 - Swartkoppies 217 JS

DG 260, 261, 337, 338 and 339 - Doornkop 356 JS

DG 43 b - Welgevonden 215 JS

In most of the samples amphibole is the major mafic constituent. In some, both amphibole and pyroxene are found and in some samples only pyroxene is present.

The magnetite content ranges from 0.66 to 4.96 per cent.

(b) - Chemical Composition

In order to compare the chemical composition of the hornblende microgranite with that of the other felsic igneous rocks in the Stoffberg area, a specimen from the centre of the granite body was submitted for analysis (folder 2).

The analysis showed that the composition of the granite agrees very closely with those of the other four felsic rock types analysed (folder 2).

Although it was at first presumed that the felsic rocks associated with the xenolith may represent leptites, the close agreement in chemical composition with, for example, those of the Rooiberg felsite and the granophyri felsite associated with the Dullstroom andesite, points to the probability that they too are of igneous origin.

From the Niggli values, the rock may be classified as granitic, belonging to the calc-alkali series, or as syenite-granitic, belonging to the potassic series.

The Niggli values were also plotted on the variation diagrams in figs. 2 and 3. The values for the hornblende microgranite (DG 33) fall close to those of the felsite from the Dullstroom Volcanic Phase (DG 389, 408 and 430), and to those of Rooiberg felsite (DG 178 and 508).

In figs. 4 and 5 the hornblende microgranite falls within the felsite field. This may indicate that the microgranite was originally a felsite rock which now looks more like a fine-grained granite as a result of alteration

The FM-value of the microgranite is considerably higher than the values plotted by Von Gruenewaldt (figs. 4 and 5).

It has not been possible to conclude from field evidence whether the hornblende microgranite is intrusive into the gabbroic rocks and the xenolith of pyroxene hornfels. Should the microgranite also be a xenolith, then it would seem logical to assume that it, and the pyroxene hornfels, which has already been shown to be a metamorphosed andesite, drifted away from the main

Dullstroom/.....

Dullstroom volcanic assemblage during the intrusion of the Bushveld Complex. On the basis of this assumption the microgranite could have been a felsitic layer associated with the andesite and therefore similar to those mapped on Witpoort, Middelkraal, Windhoek and Messchunfontein during the present survey (folder 1). The field relationships of the hornblende microgranite and the pyroxene hornfels certainly suggest that they are closely associated.

A factor which militates against this supposition is the several pegmatite intrusions which have been found both above and below it. On Doornkop 356 JS several pegmatite veins from less than one inch, to about 2 feet in thickness, cut the microgranite, the pyroxene hornfels and the gabbro. If the pegmatite is genetically related to the microgranite, the latter can be taken to be intrusive. It is however also possible that the pegmatite is of a much later age.

In the absence of conclusive evidence the mode of emplacement of the hornblende microgranite must remain open.

(c) - Effects of the Hornblende Micrograni te on the Gabbro

The granite has presumably been responsible for the sharp variation in composition of the magnetite gabbro above, and the gabbro below it along some parts of the contact. One sample which was taken about 50 feet below the granite on Swartkoppies 217 JS and which had the normal appearance in the field of gabbro was found by quantitive X-ray analysis to contain 10 per cent of quartz. Another sample, some 20 feet from the contact contained 25 per cent of quartz. The two samples mentioned last, do not on closer examination resemble normal gabbro. They are finer grained, have a more granoblastic texture and assume a different colour as well. A little northwards gabbro in contact with microgranite was found to be free from quartz. In table 10 the volumetric composition of five specimens of quartz gabbro is given. Samples DG Y and 355, both taken near the contact with the granite, contain the most quartz. In these specimens the plagioclase is fairly fresh in comparison with the altered state of the feldspar in the granite. Above the granite the same condition holds and in some places

quartz/.....

quartz grains stand out on weathered surfaces. Here, a modal analysis of a specimen (DG 34) proved its composition to be similar to that of the rocks immediately below the xenolith (table 10).

Farther away from the granite the presence of quartz in the gabbro, in amounts exceeding 1 per cent, is a rarity, excepting of course, near its upper contact with the felsite of Bothasberg. Here again the gabbro gives way to dioritic rocks. The altered gabbroic rocks near the granite consist of varying amounts of quartz, plagioclase feldspar, orthoclase, amphibole and magnetite. A few remnants of clinopyroxene, in different stages of alteration to amphibole, are often present. The plagioclase feldspar is altered to light- and the alkali feldspar to dark-brownish sericitic material. Plagioclase is in excess of alkali feldspar. Olivine, apatite and biotite are accessory minerals. The quartz replaces feldspar. According to the composition of the altered gabbroic rocks, they may be described as quartz gabbro. Owing to the paucity of good outcrops, its transitional nature and its limited thickness, the quartz gabbro was not mapped as a separate unit.

Table 10.

Volumetric modal composition of quartz gabbro

Specimen No.	DG W	DG Y	DG Z	DG 34	DG 355
Feldspar (mostly plagioclase	54	49	54	50	58.52
Pyroxene	15	14	31	16	9.30
Quartz	20	26	10	22	28.48
Magnetite	10	11	5	4	3.70
Biotite	-	-	-	8	-
Amphibole	1	-	-	-	-
Total	100	100	100	100	100

DG W, Y, Z and 34 - Swartkoppies 217 JS.

DG 355 - Kwaggaskop 359 JS.

8 - ROOIBERG/.....

PART III - THE EARLY BUSHVELD ROCKS

8 - ROOIBERG FELSITE

A - General

The felsitic rocks are found on the slopes and at the top of Bothasberg. Outcrops are conspicuous towards the base of the succession but higher up the felsite is covered by talus and soil. Although many different varieties are met with, they may collectively be termed felsitic rocks which have been metamorphosed.

B - Subdivision

The felsite succession has been subdivided into the following zones.

1. Main felsite with bands of quartzite.
2. Spherulitic felsite.
3. Red granophyric felsite.
4. Basal felsite with subordinate bands of leptitised quartzite.

Von Gruenewaldt (1966, p. 12) who has mapped and described the westward continuation of the Rooiberg felsitic rocks has subdivided them into a Lower felsite consisting of (a), micrographic and microcrystalline felsite and (b), fine-grained felsite which he terms leptite. The Lower felsite is followed by a variable felsite consisting of several types and these in turn, are followed by the Upper felsite.

Along the Bothasberg poor exposures made it very difficult to distinguish the various types mentioned by Von Gruenewaldt. In the present investigation the Basal felsite will correspond with Von Gruenewaldt's Lower felsite and leptite. Thin, impersistent bands of metamorphosed quartzite were located in the Basal felsite at a few localities. This altered quartzite is referred to as leptite in the sense used by C.A.Strauss (1954, p. 19). The Basal felsite gives no indication of being an altered feldspathic quartzite although in several places, especially near the base of the succession glassy types strongly resemble altered quartzite. On Sterkloop 352 JS a piece of Basal felsite contains a small piece of altered quartzite measuring 4 inches by about 1½ inches. The quartzite has not been altered and does not resemble the Basal felsite.

C - The/.....

C - The Basal Felsite

In the whole area the Basal felsite overlies the dioritic and granitic roof-phase of the magnetite gabbro. In most places the contact is at or near the crest of the hills forming Bothasberg. However east of the Schietpad Trigonometrical beacon the contact is at the foot of the hills.

The Basal felsite forms an unbroken succession along strike and extends from Rhenostershoek 180 JS to Sterkloop 352 JS. A discordant diabase sheet has been intruded into it (Chapter 9 - B).

The granite and the granophyre (Chapter 9 - A) are found mainly in the Basal felsite and form a very irregular discordant body within it.

The Basal felsite is mostly overlain by a dark coloured felsite which is spherulitic in places. Small but conspicuous xenoliths of Basal felsite are found in the diorite on Blinkwater 213 JS, on the slopes of Bothasberg.

1 - Field Relationships

Whereas the contact between the magnetite gabbro and the overlying diorite is ill-defined, gradational and variable, the contact between the fayalite diorite and the felsite is sharp. Small, localised apophyses of fayalite diorite extend into the felsite and the intrusive relationship of the former with respect to the latter is fairly obvious, especially if the xenoliths of felsite in fayalite diorite are also considered. One xenolith on Blinkwater 312 JS (about 1,300 yards east of the corner beacon of Rhenosterhoek, Schietpad and Blinkwater) dips at 85^{o} in the opposite direction to the general westward dip of the magnetite gabbro, the fayalite diorite and the main Basal felsite. Although Lombaard was unable to establish the intrusive relationships of the diorite with the counterparts of the felsite on Tauteshoogte he nevertheless noted the knife-sharp contact (1949, p. 365).

It appears that the intrusion of the Bushveld magma in the Bothasberg area was concordant with respect to the felsite layers which were therefore thermally metamorphosed. On Rhenosterhoek 180 JS and Blinkwater 213 JS the dip is about 10^{o} south-west.

The presence of reddish-coloured granophyric rocks in the felsite (not to be confused with the Bushveld granophyre) was noticed. The contact between the two rocks is sharp and the granophyric rocks have apparently intruded the felsite. Well exposed contacts between felsite and granophyric rocks were seen along the top of Bothasberg in the extreme western part of Blinkwater 213 JS. Texturally the granophyric rocks do not differ from the felsite except that they are more reddish-coloured. The quartz content on either side of a sharp contact between these rocks and the felsite (a random sample from the northern part of Schietpad) was 50 per cent for the felsite and 46 per cent for the granophyric intrusive rock. The granophyric rocks have not been mapped separately owing to their patchy and limited distribution.

2 - Mineralogy

(a) - Megascopic Features

The felsite displays a fairly wide range of colours but light- to dark-brown and light- to dark-grey colours on fresh surfaces are prevalent. On weathered surfaces the colour is usually light brown to light grey.

The felsites are mostly fine to medium grained and generally equigranular. Some varieties are slightly porphyritic, with recognizable phenocrysts of feldspar.

The medium-grained felsite is similar in appearance to microgranite (photomicrograph 14).

Layers of feldspathic quartzite which show incipient leptitisation, are distributed at random in the felsite. They are lighter coloured and usually medium grained.

(b) - Microscopic Features

Specimens taken on surface are seen to consist of quartz, altered alkali feldspar (some graphically intergrown with quartz), plagioclase feldspar, hornblende, clinopyroxene, chlorite as an alteration product of hornblende and pyroxene, biotite and magnetite. The dark minerals are subordinate in quantity to quartz and feldspar.

In the quartz-rich varieties of felsite the quartz grains are often subangular (photomicrograph 14) but in the highly feldspathic types the quartz is more irregular in outline owing to partial recrystallisation and replacement by feldspar. As a result of recrystallisation the crystals tend to coalesce and form larger aggregates with irregular outlines (photomicrograph 15). These patches always show undulatory extinction.

The quartz is also graphically intergrown with feldspar.

The alkali feldspar is turbid and in process of alteration to sericitic material; it is often present as small prismatic laths and is mainly interstitial to the quartz but in many places replaces it. The feldspar has formed around the quartz grains initially and then corroded and replaced them. The remaining quartz shows highly irregular outlines (photomicrographs 14 and 15).

The pyroxene crystallised as small anhedral grains which tended to cluster, and the hornblende is present as larger irregular grains (photomicrograph 15). The hornblende, and also the pyroxene, may be partially altered to chlorite.

Magnetite is present in all sections as fairly evenly distributed subhedral to anhedral grains.

3 - Chemical Composition

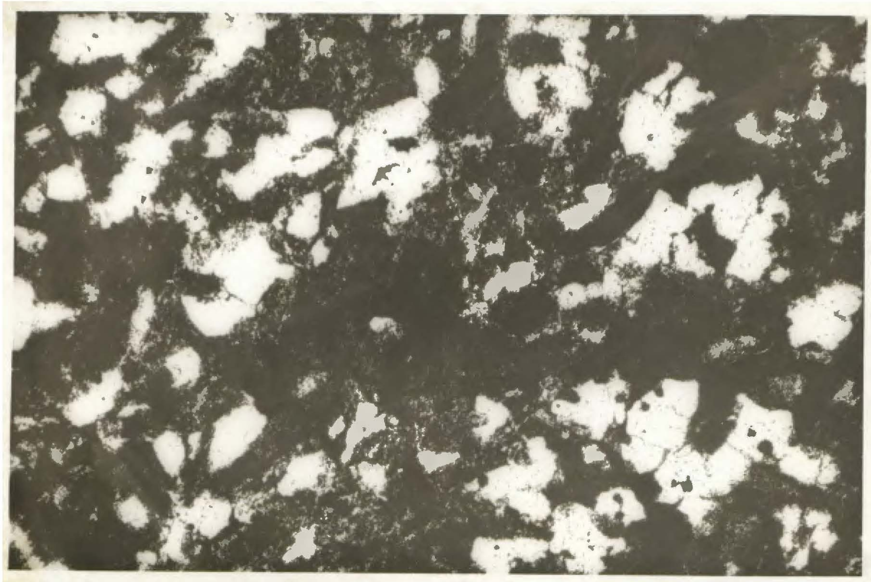
Two specimens of basal felsite were selected for chemical analysis. The one is from a felsite fragment at the base of the fayalite diorite belonging to the Bushveld Igneous Complex on Blinkwater 213 JS, and the other one was taken from the main mass of basal felsite on Enkeldoorn 214 JS.

According to the classification of Burri and Niggli (1964, p. 78) they are both derived from a granitic magma of the Calc-alkali Series and vary from alkali-intermediate to alkali-rich.

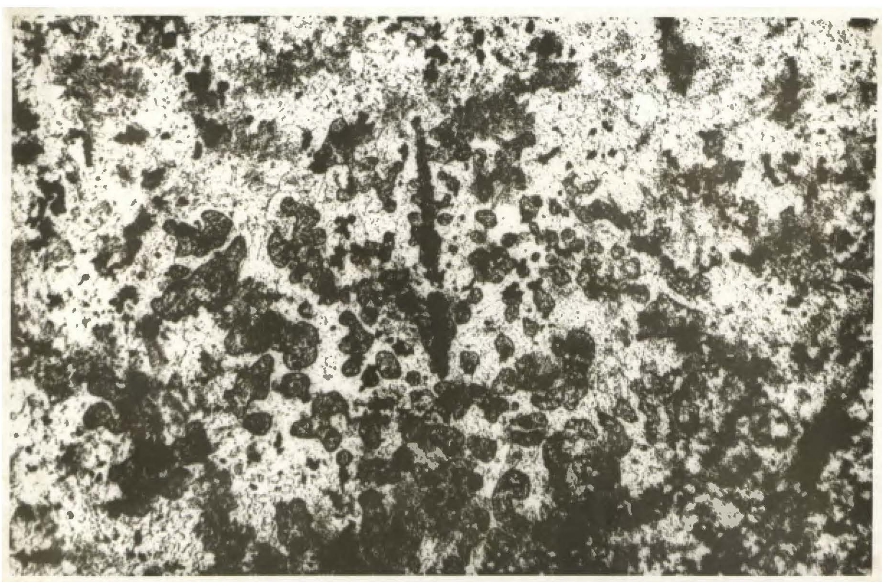
The two analyses (DG 508 and 178) were recalculated to atom percentages and the values plotted on the K - FM variation-diagram of Von Gruenewaldt (1966, p. 45), whereas the values Si^{4+}, K^{+} + Na^{+} and FM were plotted on his triangular diagram (1966, p. 46). Both analyses fall within the felsite field (figs. 4 and 5). In the case of the K^{+} - FM variation diagram, the K values a agree with those pertaining to the various felsites but FM is considerably higher.

For the triangular plot both analyses again fall within the felsite field and here Si^{4+} is somewhat lower than the other plotted values.

The/.....



Photomicrograph 14 - Medium-grained basal felsite having irregularly shaped quartz grains (white) set in feldspar and amphibole (dark area). Thin section 161, Rhenosterhoek 180 JS. Transmitted light, X 30.



Photomicrograph 15 - Basal felsite lying at the base of the quartz diorite. It has been metamorphosed with the resultant formation of amphibole grains. Dark material is feldspar and quartz is white in the photo. Thin section 178 from Blinkwater 213 JS. Transmitted light, X 30.

The two specimens of Basal felsite correspond with Von Gruenewaldt's leptite which he considers to be an altered felsite.

4 - Quartz Content and Volumetric Composition

The quartz content, determined by means of X-ray diffraction analysis (table 11), fluctuates between 36 and 49 per cent for the 6 samples examined.

Table 11.

Quantitative X-ray determinations of quartz in the felsite

Sample	Exact Locality	Percentage of quartz
DG 183	Just above the spherulitic felsite from western part of Schietpad 212 JS.	49
DG 158	Sample taken from small xenolith with dip of 85° E. on western extremity of Blinkwater 213 JS.	43
DG 171	Along eastern boundary of Rhenosterhoek 180 JS.	36
DG 130	In south-western corner of Blinkwater 213 JS.	40
DG 161A	Northern corner of Schietpad 212 JS.	36
DG 161B	Northern corner of Schietpad 212 JS.	39

The method of determining the quartz percentages with the aid of the X-ray Diffractometer is briefly as follows:

1. Run a few patterns of pure quartz pulverized to -325 mesh, and measure the intensities of the four strongest lines which are closely spaced.
2. Determine the average intensities.
3. Plot the intensity values of the four lines on a logarithmic scale. This plot serves as the standard pattern. Select an arbitrary index-point on the plot.
4. In the same way as in steps 1 to 3, a standard pattern for alumina (Al_2O_3) is made, and an arbitrary index-point selected. The alumina is the internal standard.

5. Mixtures/.....

5. Mixtures of quartz and alumina, in which the content of each varies with respect to the other are now prepared and patterns run as previously done for quartz and alumina alone. The line intensities for both quartz and alumina are measured and plotted on a logarithmic scale.

6. The quartz lines for each mixture are now compared with those forming the standard quartz pattern so that the lines of each of the four selected and measured, correspond most closely with those of the standard quartz plot. The index-point of the standard quartz plot is now marked on the new one.

7. The same procedure as in step 6 is followed for the alumina lines.

8. Two index-points are thus obtained on the plot of each mixture namely, one for the quartz and one for the alumina.

9. The distance between the two index-points depends on the proportion of quartz to alumina.

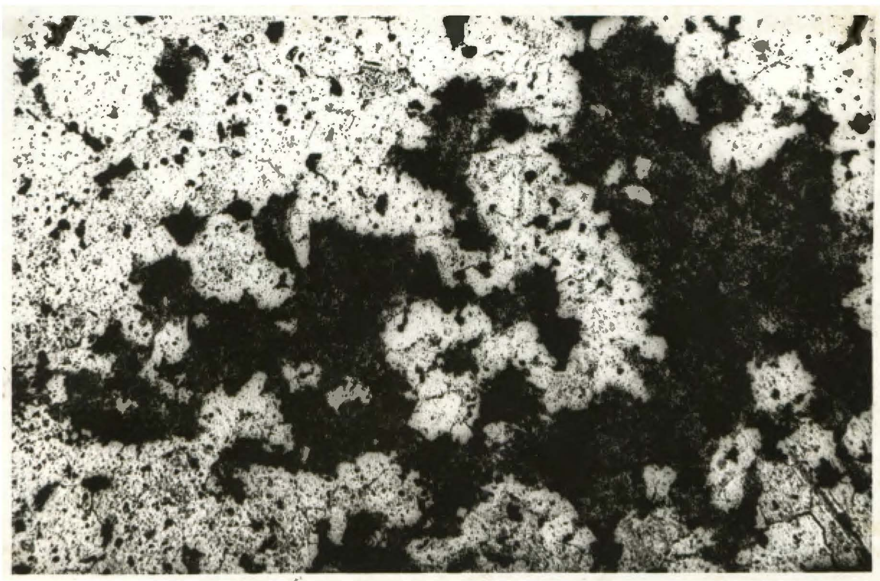
10. Now, by adding a known quantity of Al_2O_3 to a sample with an unknown percentage of quartz, the quantity of quartz can be found.

Volumetric modal analyses were done but only specimens possessing a minimum of fine textures and intergrowths were selected. The quartz content of specimens DG 158, 171, 130 and 161a was also determined by means of X-ray diffraction. These values are given in table 11 and can be compared with those in table 12. In all the determinations except one, viz. specimen DG 17 , the quartz percentage as determined by means of X-ray diffraction is higher.

Plagioclase is probably present in small quantities but owing to its fine grain (the feldspar often occurs as an irregular network between quartz grains) and to its weathered condition it has been counted together with the potash feldspar. In sample DG 158 it was possible to differentiate between the two minerals, and here the proportion of potash feldspar to plagioclase is about 3:1.

Although the percentages by volume of individual minerals vary considerably from place to place, the main constituents viz., feldspar, quartz, magnetite and amphibole are usually present.

Table 12/.....



Photomicrograph 16 - Leptitised quartzite in which feldspar, mostly very altered and unrecognisable, together with a little biotite (dark area), have begun to form and are replacing quartz (white). Thin section 135, Schietpad 212 JS. Transmitted light, X 30.

Table 12

Volumetric composition of the basal felsite

Specimen No.	DG 178	DG 158	DG 161a	DG 130	DG 137	DG 171
Plagioclase	n.d.	14	n.d.	n.d.	n.d.	n.d.
Alkali Feld-spar	n.d.	41	n.d.	n.d.	n.d.	n.d.
Plagioclase and K-feldspar	57	55	56	52	49	46
Monoclinic Pyroxene	-	-	-	10	-	-
Quartz	23	39	32	31	39	41
Amphibole	15	4	10	3	8	10
Magnetite	5	2	2	4	4	3
Total	100	100	100	100	100	100

DG 178 and 158 - Blinkwater 213 JS.
DG 161a and 171 - Rhenosterhoek 180 JS.
DG 130 and 137 - Schietpad 212 JS.

Of the remaining minerals potash feldspar predominates and the total dark minerals (pyroxene and amphibole) and magnetite do not average more than 13 per cent of the constituents (table 12).

5 - Quartzite Bands in the Basal Felsite

On Schietpad 212 JS a band of feldspathic quartzite, interlayered in the basal felsite, is exposed below a diabase sheet for a short distance. Northwards a similar outcrop was found near the Blinkwater boundary-fence. On Sterkloop, near its northern boundary, small loose fragments of feldspathic quartzite were noticed but no outcrop could be located. One boulder of Basal felsite encloses a small xenolith of quartzite measuring 5 inches by 1½ inches.

The feldspathic quartzite from near the northern boundary of Schietpad contains 90 per cent of quartz (quantitative X-ray determination), the remainder being mostly altered feldspar. A sample from the outcrop belo the diabase sheet, on the same farm, has a volumetric modal composition of 80 per cent of quartz, 15 per cent of feldspar, 4 per cent of magnetite and one per cent of biotite.

The rock is a slightly leptitised feldspathic quartzite.

D - Red Granophyric Felsite

On Enkeldoorn 214 JS and in the southern part of Schietpad 212 JS, a flow of red granophyric felsite overlies the basal felsite. The same rock type is present on Sterkloop 352 JS. Whereas the Basal felsite consists of multicoloured rocks, the red granophyric felsite is uniform in colour and granophyric textures, although not visible to the naked eye, are conspicuous in all the samples examined under the microscope.

The granophyric felsite is usually fine grained. Medium-grained varieties look more like granophyre than felsite. In this form it resembles the marginal phase of the red granite and granophyre (Chapter 9 - A).

The intergrowth between feldspar and quartz is very prominent and together they are the major constituents of the granophyric felsite (table 13). A little magnetite is usually present. The potash feldspar is always red and altered so that its identity could not be established. Small amounts of plagioclase, in an advanced state of alteration, but with polysynthetic twinning still faintly visible, are present and may also be intergrown with quartz.

According to the Niggli values (folder 2, DG 665) the rock is classified as granite (Tasna-granitic), and is derived from a magma of the calc-alkali series (Burri, 1964, p. 78). If it is permissible to judge from one analysis the red granophyric felsite appears to differ in chemical composition from the Basal felsite because the amount of FM is considerably lower than that of the latter.

Table 13.

Volumetric composition of red granophyric felsite

Specimen	DG 530	DG 541
Feldspar	54.40	52.31
Quartz	28.33	26.08
Amphibole	13.21	16.29
Magnetite	4.06	5.32
Total	100.00	100.00

DG 530 - Enkeldoorn 214 JS; DG 541 - Sterkloop 352 JS.

E - Spherulitic/.....

E - Spherulitic Felsite

1 - Distribution

The spherulitic felsite is developed on the plateau region of Bothasberg. The thickness of the sheet, on the average about 100 feet, varies from place to place and on Schietpad 212 JS it pinches out completely over a short distance.

On Rhenosterhoek, below the diabase sheet, the sheet is about 100 feet thick; on the boundary between Rhenosterhoek and Schietpad it is some 200 feet thick and farther southwards on Sterkloop it attains a thickness of some 500 feet. The spherulitic felsite mostly overlies the Basal felsite but in the southern part of the area it follows on the red granophyric felsite.

Small xenoliths of spherulitic felsite were found in the main Rooiberg felsite. They probably represent loose fragments taken up by the main Rooiberg felsite during its mobile stages of extrusion.

The spherulitic felsite does not show any affinities with the Basal felsite and can best be grouped separately as suggested by Van der Westhuizen (1945, p. 24).

2 - Mineralogical Description

(a) - Megascopic Features

In this felsite, spherulites may be plentiful, only sparsely and irregularly distributed, or they may even be absent. In the southern part of the area, on Enkeldoorn and Sterkloop, the upper part of the flow is practically devoid of spherulites and it is difficult to differentiate between it and the Main Rooiberg felsite. The spherulites rarely constitute as much as 10 to 15 per cent of the rock. Their shapes vary from oval to rounded.

The ground-mass is black and fine grained and none of the minerals can be identified or distinguished with the unaided eye.

(b) - Microscopic Features

The spherulites consist mainly of quartz. Each spherulite is made up of several interlocking grains of quartz and radiate textures are absent. The ground-mass consists of quartz, altered potash feldspar and chlorite. A quantitative X-ray determination on a sample, only

slightly/.....

slightly spherulitic, gave 29 per cent of quartz. Van der Westhuizen identified small plagioclase phenocrysts in samples he collected (1945, p. 24). The dark colour of the rock is probably due to finely disseminated iron oxide.

Flow-structures are conspicuous and the chloritic material tends to form separate bands.

Many of the perennial streams on Bothasberg have their source on the contact of the spherulitic felsite and the overlying Main felsite. The fine-grained, compact rock probably serves as an impermeable barrier for circulating water.

F - Main Felsite

1 - Description

The Main Rooiberg Felsite succeeds the spherulitic felsite and, where this rock is absent, the red granophyric felsite. On Rhenosterhoek 180 JS a diabase sheet separates the main felsite from the spherulitic felsite and on Schietpad 212 JS from Basal felsite.

The rocks of the Main Rooiberg Felsite were not examined microscopically. The succession consists mainly of fine-grained, grey- to reddish-coloured felsite with several separate flows of red granophyric felsite. Owing to their very irregular distribution and the paucity of continuous outcrops the red granophyric felsite is not shown on the geological map. Good exposures of this rock type may be seen between the two quartzite bands in the western part of Enkeldoorn 214 JS, and above the diabase sheet on Rhenosterhoek 180 JS.

2 - Quartzite Bands in the Main Felsite

Along the south-western part of Enkeldoorn two quartzite bands, interbedded in the main felsite, and dipping from 25° to 30° W, form fairly prominent outcrops. The westerly band apparently terminates on entering Sterkloop, but the easterly band continues, with breaks, for some distance. The quartzite is criss-crossed by numerous veins of white quartz.

9 - INTRUSIVE/.....

9 - INTRUSIVE ROCKS IN THE ROOIBERG FELSITE

A - Granite and Granophyre

1 - Distribution

These rocks are intimately associated with the felsite on top of Bothasberg. They are usually found completely within the felsite but numerous offshoots have been noted especially north of the boundary line between Schietpad 212 JS and Blinkwater 213 JS where they have apparently intruded diorite and magnetite gabbro below the felsite.* The intrusion generally "meanders" in the felsite but nevertheless follows its general strike.

Exposures of granitic rocks are continuous from Rhenosterhoek 180 JS in the north to Sterkloop 352 JS in the southern part of the area. On the eastern side of Rhenosterhoek 180 JS the contact between the granitic rocks and the felsite is very irregular and apophyses of granitic rocks into felsite are quite common.

2 - Field Relationships

On the map the granite intrusion shows a pinch-and-swell structure. Thus, on Rhenosterhoek 180 JS, the granite swells; southwards on the same farm it pinches considerably and bulges again along the boundary common to Schietpad 212 JS and Blinkwater 213 JS. From there southwards the granite thins and splits into two bodies. East of the Schietpad Trigonometrical beacon the body thickens once again.

In the field the granitic rocks can be distinguished from the Basal felsite by their coarser grain, more deep-red colour (although brownish varieties are also found) and their peculiar spheroidal mode of weathering. The granitic rocks tend to weather into rounded boulders which lie strewn about in soil. Solid outcrops are seldom seen. The felsite on the other hand breaks up into irregular fragments and, where solid outcrops are encountered, they tend to be slightly layered and jointed. Even so, it is still a difficult task to delineate clearly the contact where outcrops of felsite are absent and where the typical rounded boulders of granitic rocks are scarce.

It is very difficult to differentiate the granitic from the granophyric rocks.

*Relationships are still uncertain and subject to revision.

A road-cutting on Schietpad 212 JS, south of the Trigonometrical beacon, across felsite and granitic rocks exposes the contact-zone fairly well. In this cutting it was observed that the granitic rock becomes finer grained towards the contact and for this reason it is difficult to locate the exact position of the contact with the felsite, which is itself fine to medium grained. There may be a sharp contact-line visible below the zone of weathering but along the road-cutting the alteration of both rock types tends to mask it.

Owing to the peculiar effect of weathering of the intrusive granitic rocks it is difficult to determine their dip, but considering the general concordant strike with respect to that of the felsite it is likely that they follow the general structural dip of about 10° south-west. This finding is in agreement with that of Van der Westhuizen (1945, fig. 10).

3 - Mineralogical Description

(a) - Megascopic Features

The granitic rock is medium grained, equigranular (grain-size averages 0.7 mm diameter), but becomes finer grained towards the contact with the felsite. The characteristic red colour is due to the alkali feldspar. A fair amount of dark minerals impart a speckled appearance to the rock. In fresher samples, which are rather scarce, the weathering of the K-feldspar is less advanced and consequently the reddish colour is not so conspicuous.

(b) - Microscopic Features

A study of comparatively fresh samples taken along the road-cutting on Schietpad 212 JS and farther south revealed that granophyric textures between quartz and alkali feldspar are virtually absent and most samples are therefore decidely granitic. It seems however that the feldspar has in places corroded and replaced the quartz. Elsewhere clusters of rounded grains of quartz which have the typical granoblastic texture of quartzite, are evident. The distribution of the constituent minerals in the rocks is therefore by no means even although this property is not so apparent megascopically. In one specimen taken on Enkeldoorn 214 JS, granophyric textures are markedly developed.

Where/.....

Where feldspar and quartz are found together the outlines of the quartz are irregular, as a result of corrosion and replacement.

The feldspar, with $n\gamma = 1.530$ ($\pm$ 0.002) and $n\alpha = 1.525$ ($\pm$ 0.002), is mainly K-feldspar some of which is perthitic. It is invariably altered to a reddish colour and is therefore not very suitable for optical measurements. It is found mostly as fairly large prismatic laths with a conspicuous cleavage.

Plagioclase feldspar (albite) as smaller laths is a subordinate constituent.

Dark green, pleochroic hornblende is the major mafic mineral. It is usually somewhat altered to chlorite. Biotite and magnetite are interstitial to the major constituents and are present in small quantities.

4 - Composition

Quantitative volumetric determinations show that feldspar, both K-feldspar and plagioclase, is the major constituent (table 14). In specimens DG 128 the two feldspars were measured separately. In specimen DG 127 alkali feldspar accounts for 46 per cent, and plagioclase feldspar for 5 per cent of the constituents. In specimen DG 128 alkali feldspar totals 40 per cent and plagioclase feldspar 14 per cent.

In specimen DG 127 and DG 128 hornblende is in excess of quartz but in the other specimens it is subordinate to it.

5 - Origin

Although there is no doubt that the granitic rocks on Bothasberg are intrusive into the basal felsite, the possibility that they may represent granitised and mobilised sediments has been considered. The presence of patches of apparently unaltered quartzite noticed in thin sections of granites points towards a sedimentary origin although these patches may be quartzite assimilated by the granitic magma.

Strauss (1954) who described several different types of granophyric rocks in the Potgietersrus area suggested that the granophyre is a reconstituted quartzite. Strauss (1954, p. 14) found small inclusions of quartzite in what he termed reconstituted quartzite. Similar

small/.....

small inclusions of feldspatic quartzite as well as two fragments of quartzite, each measuring about 50 feet across, were located in the granitic rocks on Bothasberg. The two large fragments are in the most westerly corner of Blinkwater.

At present sufficient proof is lacking in order to determine the exact origin of the granitic rocks within the Basal felsite on Bothasberg.

Table 14.

Volumetric modal composition of the granite

Specimen No.	DG 127	DG 128	DG 250	DG 265	DG 251	DG 522
Feldspar	51	54	58.22	26.68	62.77	56.50
Quartz	15	12	25.02	32.04	31.34	28.26
Amphibole	31	34	15.19	10.43	5.06	15.24
Biotite	2	-	-	-	-	-
Magnetite	1	-	1.57	0.85	0.83	-
Total	100	100	100	100	100	100

DG 127, 128 and 250 - Schietpad 212 JS.
DG 265 - Sterkloop 352 JS.
DG 251 - Enkeldoorn 214 JS.
DG 522 - Blinkwater 213 JS.

B - Diabase Sill

A medium-grained grey-green diabase is intrusive into the basal felsite in the form of a sill; east of the Schietpad Trigonometrical beacon and in the southern part of Schietpad the sill is present in the granitic rocks as well.

On Rhenosterhoek the sill lies just above the fine-grained, black spherulitic felsite. The apparent change in the strike of the sill in the deep gullies along the slopes of Bothasberg affords evidence that its dip is conformable with that of the spherulitic felsite and the Basal felsite; its strike, with minor variations, likewise follows that of the felsite.

On/.....

On Enkeldoorn the sill passes from basal Rooiberg felsite into red granophyric Rooiberg felsite. Farther south no continuous outcrops of the diabase could be picked up. A small outcrop, probably of the same sill, was located along the contact of the spherulitic felsite and the main Rooiberg felsite on Sterkloop. The sill is not more than 15 feet thick.

Mineralogically the diabase is the normal type with the plagioclase feldspar much altered and therefore difficult to identify. The pyroxene, somewhat less weathered, has γ = 1.718 (± 0.003) and α = 1.695 (± 0.003). The pyroxene is monoclinic and non-pleochroic and is therefore augite. A notable accessory mineral in the sill is quartz. A sample of diabase from an outcrop on Schietpad 212 JS consists of 60 per cent plagioclase, 37 per cent pyroxene and three per cent magnetite by volume.

10 - DIABASE IN THE PRETORIA SERIES

A - Distribution

A sheet within the sediments of the Smelterskop Stage of the Pretoria Series on Houtenbek 97 JT consists of quartz diabase. A few dyke-like apophyses extend westwards from the main sheet and pass through the altered sediments of the Smelterskop Stage into the Dullstroom andesite. The central offshoot terminates near the western boundary of Houtenbek, but the other two continue westwards into The Consolidated Farm Mapochsgronde 500 JT and Messchunfontein 98 JS where they coalesce and the resulting body is again a sheet. Southwards the sheet splits into three separate ones which thin rapidly. The most easterly sheet was followed to the boundary between Messchunfontein and Windhoek. Scattered outcrops of the central sheet extend for some 200 feet into Windhoek 222 JS and the westerly sheet could be traced for 4000 feet into Windhoek.

B - Mineral Composition

The diabase from the main sheet on Houtenbek, from the three apophyses, and from the sheet on Mapochsgronde and Messchunfontein are all medium grained and have an average grain-size of 1.5 mm. In the southern part of

Messchunfontein/.....

Messchunfontein and on Windhoek the diabase becomes finer grained and diameters of individual grains are generally less than 1 mm.

The rock consists of plagioclase (α = 1.559 and γ = 1.568), green pleochroic hornblende (α = 1.659 and γ = 1.682) and quartz together with small amounts of monoclinic pyroxene, biotite and magnetite (table 15).

Table 15

Volumetric modal composition of uralitised diabase

Specimen No.	DG 436	DG 445	DG 447
Plag. feldspar	48.07	47.85	53.03
Hornblende (Uralite)	29.71	36.38	32.25
Quartz	13.65	9.32	4.49
Mon. pyroxene	2.65	1.25	1.92
Biotite	2.78	-	8.31
Magnetite	3.14	5.20	-
Total	100	100	100

DG 436 - central sheet on Messchunfontein 98 JS.

DG 445 - westerly sheet on Windhoek 222 JS.

DG 447 - main sheet in northern part of Messchunfontein 98 JS.

Just east of the road from Tonteldoos to Dullstroom and near the northern boundary of Messchunfontein 98 JS the diabase has a composition slightly different from those cited in table 15. Amphibole has formed but pyroxene is present in notable amounts and may even predominate over the amphibole. Potash feldspar is distributed at random and imparts a reddish colour to the rock owing to the alteration of this mineral. In the reddish-coloured variety quartz is present in amounts exceeding 10 per cent. In two examples epidote was noticed which replaces the feldspar. This local variation in the composition of the diabase amounts to only a very small percentage of the total diabase exposed in the area.

The monoclinic pyroxene is in various stages of alteration to uralite (hornblende). Some grains consist of monoclinic pyroxene with patches of hornblende. Under crossed nicols the difference in the extinction of the two minerals is evident. The hornblende is pleochroic from

green/.....

green to yellowish brown and the augite is colourless.

The hornblende has a fibrous texture, especially where urlitisation has not been complete. In any one thin section both fresh pyroxene, slightly uralitised pyroxene and grains of amphibole are present. It is possible that the hornblende grains are primary constituents of the diabase but the clear evidence of the various stages of alteration of the pyroxene points to a secondary origin for most of the hornblende. The rock is therefore considered to be a uralitised quartz diabase even though some of the hornblende may be of primary origin. Chloritisation of the hornblende has taken place to a small extent.

PART IV - THE BUSHVELD IGNEOUS COMPLEX

II - GABBROIC ROCKS OF THE MAIN ZONE

A - Distribution

In the Stoffberg area the Early Plutonic Phase of the Bushveld Igneous Complex, which includes the Merensky Reef and the chromitite seams, is not developed as in the areas to the north. The gabbro of the Main Zone therefore rests directly on the rocks of the Smelterskop Stage of the Pretoria Series. The contact between the base of the gabbro and the Dullstroom Andesite of the Smelterskop Stage is fairly clearly defined.

South of the Laersdrif Fault, on Swartkoppies 217 JS, Welgevonden 215 JS and Doornkop 256 JS, the top of the gabbro is in contact with a xenolith of metamorphosed andesite and associated microgranite.

On The Consolidated Farm Mapochsgronde 500 JS, the horizontal distance between the base of the gabbro (not shown on the geological map) and its top, that is the contact with magnetite gabbro, is about 6 miles, which represents a thickness of about 6,800 feet, taken at an average dip of 12^{o} W.

The gabbro succession thins rapidly from north to south. Along Section C-D (geological map and section) the thickness of the gabbro zone is about 4,800 feet (table 16). It is at its thinnest along section G-H where a value of 2,600 feet was measured. Still farther south the zone of gabbro widens slightly and along section I-H it is 3,600 feet thick.

Table/.....

Table 16.

Thickness of the gabbro along various sections

Section	Thickness	Dip
C- D)	4,800 Ft.	18°
) 4 miles		
G- H)	2,600 Ft.	19°
) 7 miles		
I- J)	3,600 Ft.	20°

The marked decrease in the width on surface of the gabbro as seen on the geological map is however not proportional to the actual reduction in the thickness of the gabbro. This is due to a steepening of the dip. In the area just south of Roossenekal it measures 12° and increases to a maximum of 25° W on Sterkloop 352 JS.

A dyke of medium-grained gabbro extends into the Dullstroom lava on the northern part of Kwaggaskop 359 JS. It is about 40 feet wide and slightly more than half a mile long. As shown on the geological map it trends north-eastward, about half a mile north of the road from Stoffberg to Belfast. It represents a special case in which the plagioclase is a comparatively sodic andesine ($Ab_{60}An_{40}$).

B - Subdivision

The volumetric compositions of 18 specimens taken from the base to the top along a profile on Mapochsgronde 500 JS, and of eleven specimens along a profile on Welgevonden 215 JS, indicate that the relative abundance of clino- and orthopyroxene varies considerably. By applying the classification set out by Frick (1967, p. 106)* the gabbroic rocks of the Main Zone of the Bushveld Complex along the profiles mentioned above have been subdivided into hypersthene gabbro, hyperite and norite (figs. 7 and 8). According to this classification, the ratio of orthopyroxene to total pyroxene expressed as a percentage is used as a basis. The orthopyroxene percentages fluctuate perceptibly along the Mapochsgronde profile, along which hypersthene gabbro and hyperite are the most common rock types.

*Classification adopted by Frick from a paper by J. Willemse which is to be published in the Encyclopedia of Earth Sciences.

Frick (1967, p. 107) found that just north of Draaikraal the Main Zone is composed of hyperite. Schwellnus (1956, p. 141) established that in Sekhukhuneland the Main Zone is composed mainly of normal gabbro. Along the Mapochsgronde profile hypersthene gabbro and hyperite predominate but norite is also developed. Still farther south, along the Welgevonden profile (fig. 8) hyperite is again strongly developed and hypersthene gabbro and norite are subordinate. It is therefore evident that the composition of the Main Zone changes from north to south with regard to its ortho- and clinopyroxene contents.

1 - Hypersthene Gabbro

On Mapochsgronde 500 JS hypersthene gabbro is developed from 0 to 1, at 750 feet, at 2750 feet, at 4,500 feet, at 5250 feet and from 5,500 to 6250 feet. The composition of the hypersthene remains fairly constant between En_{60} Fs_{40} and En_{63} Fs_{37}. No indication was found that the ferrosilite-content increases perceptibly upward in the layered sequence. At 4,550 and at 5300 feet where magnetite is an accessory mineral of the gabbroic rocks the composition of the hypersthene is slightly different (En_{58} Fs_{42}).

Along the Welgevonden profile hypersthene gabbro appears at 2,900 feet and the composition of the hypersthene is En_{59} Fs_{41}.

2 - Hyperite

Along the Mapochsgronde profile hyperite occurs at 3300 feet, from 4750 to 4900 feet and again at 6500 feet. The rocks along the Welgevonden profile are composed mainly of hyperite with a small break at 1,400 feet and at 2900 feet. On Mapochsgronde 500 JS the composition of the orthopyroxene varies from En_{60} Fs_{40} to En_{63} Fs_{37} except along the magnetite-rich zone where a sharp increase in the iron content is reflected in the variation of the composition of the orthopyroxene (En_{50} Fs_{50}).

On Welgevonden 215 JS the orthopyroxene at the base of the succession has the composition En_{67} Fs_{33}, and at 450 feet En_{61} Fs_{39}. Apart from a sudden change at 1400

feet/.....

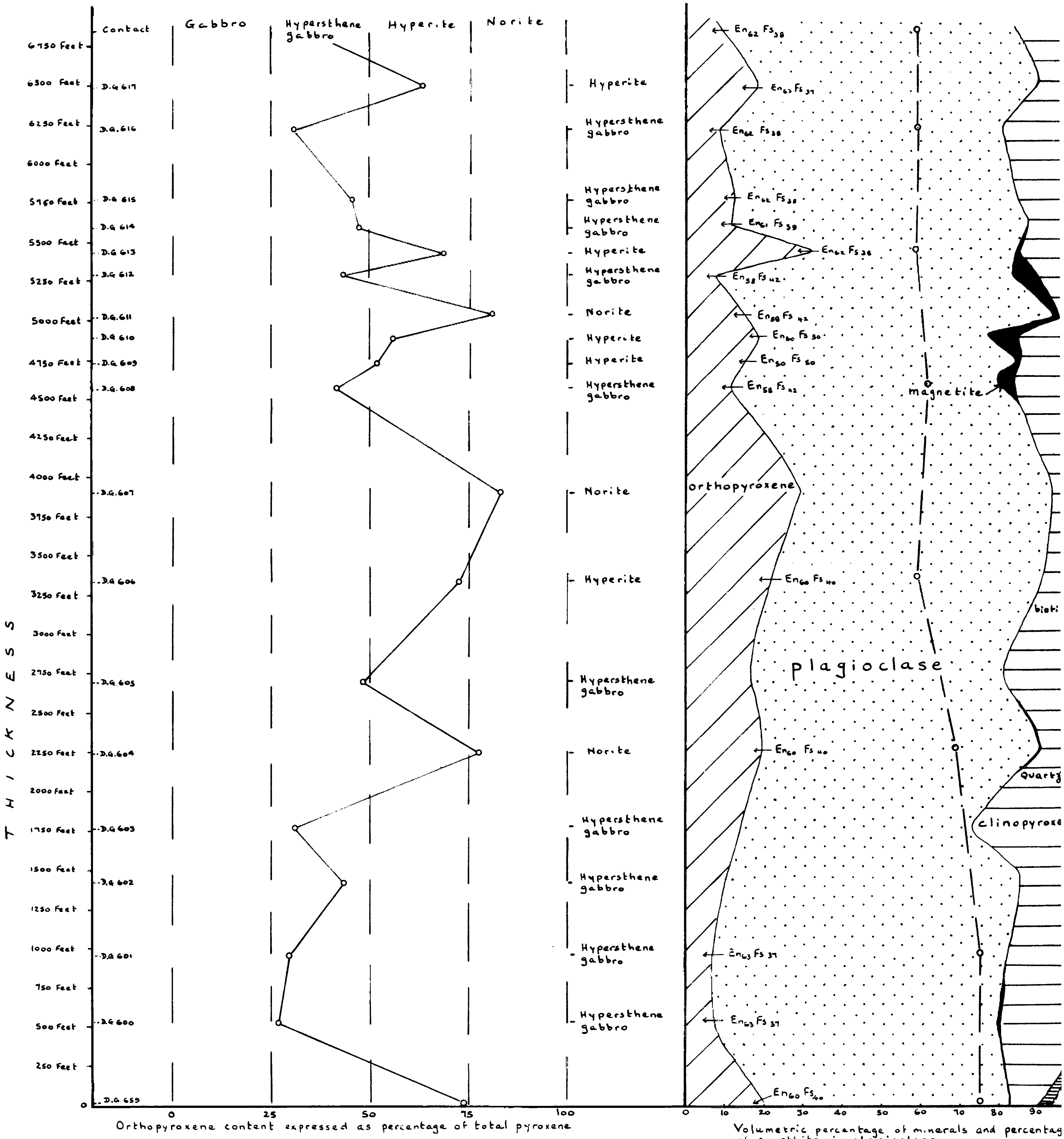


Fig. 7 - Rock types of the Main Zone of the Bushveld Complex based on the orthopyroxene content, expressed as a percentage of total pyroxene, and their mineral composition (both volumetric) along the Mapochsgronde profile. The mol composition of the orthopyroxene is also given.

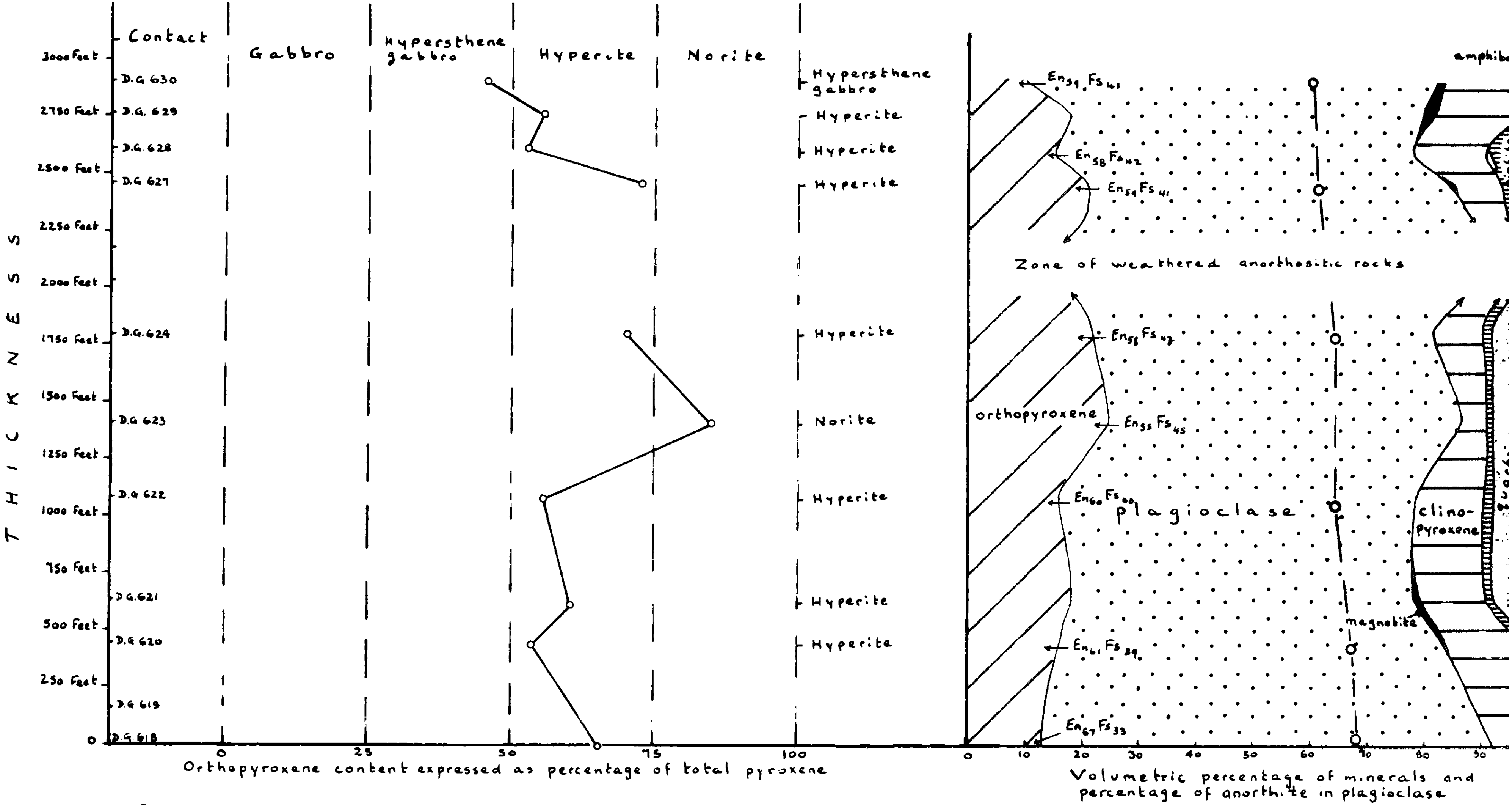


Fig. 8 - Rock types of the Main Zone of the Bushveld Complex based on the orthopyroxene content, expressed as a perce of the total pyroxene, and their mineral composition (both volumetric) along the Welgevonden profile. The mol. composition of the orthopyroxene is also given

feet (En_{55} Fs_{45}) the composition of the orthopyroxene remains fairly constant up to the roof of the succession.

3 - Norite

At three levels along the Mapochsgronde profile, viz. at 2250, 3900 and at 5000 feet norite is found, and along the Welgevonden profile at 1400 feet. The orthopyroxene in the norite on Mapochsgronde 500 JS has the composition En_{58-60} Fs_{42-40}. The orthopyroxene from the Welgevonden norite has the composition En_{55} Fs_{45}. This orthopyroxene is found at the level where magnetite is disseminated in the plagioclase of the norite.

C - Anorthite Content of the Plagioclase

Measurements on the universal stage, and application of the stereograms of Reinhard (1931) and of Van der Kaaden (in Tröger, 1959), showed that the anorthite content of the plagioclase decreases from An_{75} at the base to about An_{58} at the top of the gabbroic rocks.

From Fig. 7, a decrease in the An-content along the Mapochsgronde profile is apparent from 0 to about 3000 feet from where, apart from minor fluctuations, it remains practically constant at An_{60}. Along the Welgevonden profile (Fig. 8) the plagioclase ranges in composition from An_{68} to An_{60} from the base to the top.

Determinations of the refractive indices of the plagioclase (only γ was measured) were also done as a check on the universal stage measurements. In most determinations the An-contents were slightly higher according to this method. Owing to the increasing use of the universal stage in determining the composition of plagioclase in the rocks of the Bushveld Complex only the results obtained by the universal stage measurements have been plotted in figs. 7 and 8.

D- Mineralogy

Megascopically the gabbroic rocks vary in grain size from fine and medium grained to medium grained. The plagioclase is present as dirty white to light-grey laths and the clino- and the orthopyroxene as grey to dark-grey, prismatic crystals.

A/.....

A notable deviation from the general appearance of the gabbroic rocks is a well-defined zone about half way up in the succession and well exposed on the farms Doornkop 356 JS and Kwaggaskop 359 JS. In this zone the rocks resemble a pyroxenite, their colour being almost uniformly dark-grey. Closer inspection reveals the plagioclase laths to have a dark-grey colour. The plagioclase has tiny inclusions of magnetite. A few quarries have been established on prominent outcrops of this peculiar type of gabbro both on Doornkop and on Kwaggaskop. The blocks are exported mostly to Germany, where they are cut and polished for use as decorative stone in buildings. Similar material, but of finer grain, was noticed north of the Laersdrif Fault on Witpoort 216 JS, near the contact with overlying magnetite gabbro.

Along its contact with the Dullstroom andesite the gabbro has in many places a grain-size equal to that higher up (0.65 mm diameter) and in some places even slightly coarser, so as to become pegmatitic (1.3 mm diameter). In other places again, fine-grained varieties (0.45 mm diameter) would suggest chill-zones along the already solidified and cooled andesite. The presence of coarser-grained material along this contact would then represent slightly younger intrusions. It was not possible to establish any intrusive relationships, owing to the presence of an extensive cover of debris along the contact-zone.

Microscopically the gabbroic rocks do not offer any great diversity in mineral composition, as shown in table 17.

The modal composition of the gabbroic rocks sampled at random shows that the content of plagioclase, the major component, ranges from 63 to 72 per cent, and that of pyroxene from 20 to 36 per cent. The first four samples are from the base of the gabbro, on or near its contact with underlying Dullstroom andesite. In them no or very little magnetite was seen. Higher up in the succession magnetite is present as an accessory mineral only, and does not exceed 0.5 per cent. Surprisingly enough quartz is present in all the specimens examined. In specimen 360, which is a typical fresh gabbro as much as 7 per cent of quartz was recorded.

Table/.....

Table 17.

Modal composition by volume of gabbroic rocks sampled at random

Specimen Locality	DG 344	DG 325	DG 365	DG 366	DG 351	DG 401	DG 315	DG 360
Plagioclase	72	63	64	64	63	66	65	70
Ortho- and clinopyroxene	24	33	32	30	36	33	30	20
Biotite	1.5	1	1	3.5	0.4	-	1.5	2.5
Quartz	2.5	3	3	2.5	0.3	0.5	3	7
Magnetite	-	-	-	-	0.3	0.5	0.5	0.5
Total	100	100	100	100	100	100	100	100

DG 344 - Uitval 357 JS.
DG 325 and 315, Doornkop 356 JS.
DG 365, 366 and 401 - Middelkraal 221 JS.
DG 351 and 360 - Kwaggaskop 359 JS.

Plagioclase is always the major constituent around which the other minerals are distributed, and the rock is therefore a good example of a plagioclase orthocumulate (Wager, Brown and Wadsworth, 1960, p. 75). The plagioclase crystals show strong polysynthetic twinning.

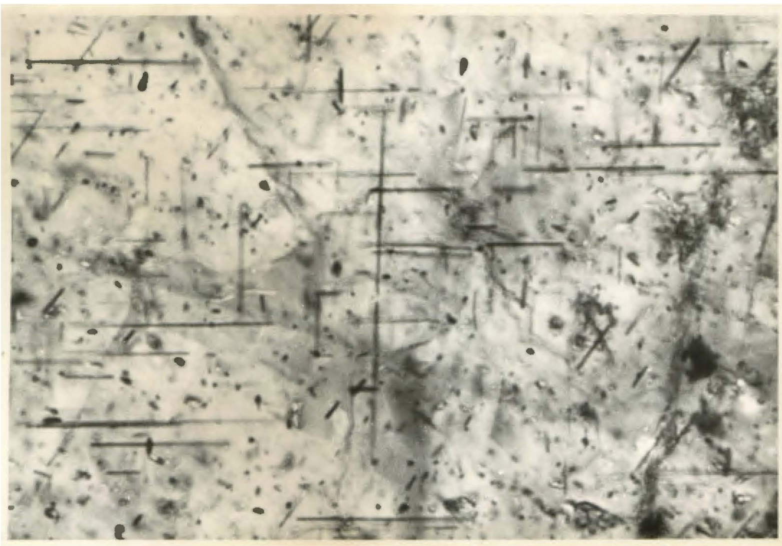
Magnetite and biotite, both sparingly present in the gabbro, generally crystallized last. They followed plagioclase and pyroxene but this is not invariably the case.

The monoclinic pyroxenes tend to form clusters and several crystals often surround, and may even partially replace plagioclase.

Small plagioclase crystals (and also fairly large ones) may be poikilitically enclosed in oikocrysts of pyroxene which themselves lie in larger plagioclase grains. In one example an inclusion of plagioclase in pyroxene is continuous with the plagioclase surrounding the pyroxene so that both are therefore of about the same age and older than the pyroxene.

The quartz may be graphically intergrown with orthoclase. This phenomenon was not recorded along the Mapochsgronde profile. Along the Welgevonden profile, from 0 to 1,500 feet, most specimens display the intergrowths, although the quartz may crystallise separately as well. The presence of the granophyric textures in the basal portion of the sequence can be ascribed to the

assimilation/.....



Photomicrograph 17 - Magnetite rods and fine "dust" in a plagioclase grain. The rods and the "dust" are considered to cause the dark colour of the gabbro. Thin section DG 155, Witpoort 216 JS. Transmitted light, X 400.

assimilation of sedimentary material by the gabbro with with resultant hybridization to a small degree of the latter. Magnetite is rarely graphically intergrown with biotite, pyroxene and plagioclase.

The plagioclase is usually fairly fresh but may give way to a fine-grained mass of sericitic material which on further alteration leads to the formation of kaolinite.

The almost uniformly dark-grey gabbroic rock referred to in the megascopic description, differs little from the others as regards mineral assemblage and the relative percentage of each mineral present (table 17, DG 315 and 360). The difference in colour is due to the presence of tiny grains of magnetite scattered mainly along three crystallographic directions of each plagioclase grain. The grains are considered to comprise from two to five per cent of the total volume of the rock. Collectively the schillerisation of the plagioclase by these grains imparts the dark colour to it. In some examples there is a greater concentration of grains along the rims of the plagioclase crystals so that an effect of zoning is produced.

Under high magnification the magnetite appears as tiny specks when the section is at right angles to the longest axes of the needles and as tiny rods when the section is at an angle to their longest axes (photomicrograph 17). Tiny, irregular magnetite grains, with random orientation, have also formed in the plagioclase.

The clinopyroxene is augite which, owing to a parting parallel to (100), is referred to as diallage. Small crystals of magnetite lie haphazardly in the clinopyroxene. Herringbone textures are quite common. The pyroxene alters to amphibole (hornblende). The alteration commences as specks at various points in a pyroxene crystal. With increased alteration the specks grow larger and coalesce to form larger patches until the whole crystal is altered.

The orthopyroxene, usually present in considerable amounts and always in excess of clinopyroxene, is hypersthene with distinct pleochroism from light pink to very light green. The orthopyroxene is usually associated with the monoclinic pyroxene and small hypersthene crystals are often replaced by augite. The hypersthene therefore crystallised first.

The/.....

The index of refraction of the clinopyroxene was determined in several specimens extending from the lower to the upper part of the gabbro. In all the measurements the refractive index varied only slightly. Using sodium light, the value most often measured was γ = 1.719, α = 1.693. In each grain-mount several grains having a high birifringence were measured and the highest and lowest values were taken as γ and α respectively. Accordingly, the mineral is augite, which by virtue of the abundant partings on (100) is diallage-augite.

E - Intergrowths in the Clino- and Orthopyroxenes of the Gabbroic Rocks

The development of exsolution-intergrowths of clinopyroxene in orthopyroxene of the gabbroic rocks were examined in order to ascertain, amongst others, at which height in the Main Zone the orthopyroxenes are free of exsolution-lamellae. The presence of exsolution-lamellae in orthopyroxene has been used to determine the temperatures of crystallisation of magmas (Hess, 1941, p. 583).

Thin sections from a profile on Mapochsgronde 500 JS, which represents a thickness of some 6,840 feet, revealed that in all cases the orthopyroxene have lamellae of exsolved clinopyroxene, and that the clinopyroxene contains lamellae of orthopyroxene.

The base of the Mapochsgronde profile is the lowest horizon of the gabbroic rocks developed in the area shown on the geological map. The orthopyroxene along the Mapochsgronde profile contains from 50 to 63 molecular per cent $MgSiO_3$ and from Hess's figure (1941, p. 583) the temperature of the Bushveld magma must have varied between 1095 and 1080° C.

The molecular ratios of $MgSiO_3$ and $FeSiO_3$ of some orthopyroxenes in the magnetite-rich portion of the gabbroic rocks of the Mapochsgronde profile are En_{50} Fs_{50}, indicating that the temperature of crystallisation at this height (about 4750 feet) was 1080° C.

It was noticed that in some of the thin sections, notably from 5500 to 6250 feet both orthopyroxene free of clinopyroxene lamellae and orthopyroxene with exsolved clinopyroxene coexist. This peculiarity may be explained on the assumption that at the heights mentioned above the magma attained the inversion temperature on Hess's figure (1941, p. 583).

The/.....

The molecular percentage of $MgSiO_3$ of the orthopyroxene in the gabbroic rocks from 5,500 to 6,250 feet along the Mapochsgronde profile varies from 60 to 63 per cent; from Hess's figure (1941, p. 583) this corresponds to a crystallisation temperature of about 1090° to 1095° C. However, the inversion temperature shown on Hess's curve is about 1,105° C. In the case of the magma of the Main Zone of the Bushveld Complex, the inversion temperature may have been of the order of 1095° C.

Exsolution-Lamellae in Orthopyroxene Hosts.

The actual exsolution-phenomena, recorded along the Mapochsgronde profile, with orthopyroxene as the host, remained fairly constant. The preponderance of either clino- or orthopyroxene does not have any influence on the degree of formation of lamellae. The type of lamellae most commonly observed are:

(1) Orthopyroxene hosts with broad exsolution-lamellae of augite.

(2) Orthopyroxene hosts with fine, continuous or broken lamellae of augite.

(3) Fine striae developed parallel to one another in the orthopyroxene host.

In the first type some of the augite lamellae are often continuous with contiguous grains or rims of augite. Generally, however, they do not extend to the edges of the orthopyroxene host. They may terminate without changing shape or they may thicken slightly. The augite has also separated from the original orthopyroxene as irregular blebs and even as grains which display no orderly orientation. Somewhat thinner lamellae of augite, similar to those cited by Brown (1957, plate XVI, fig. 5) are fairly common.

In the second type the fine lamellae in the orthopyroxene host are present as continuous or interrupted lamellae which are parallel to one another (photomicrograph 18). More than one set is often developed in an orthopyroxene host (photomicrograph 19). The thin lamellae are often continuous with an augite grain alongside the orthopyroxene and are therefore considered to be clinopyroxene (photomicrograph 20, point d). Quite irregularly shaped lamellae with no sign of parallel

orientation/.....

orientation have formed but tend to be subordinate to the lamellae with parallellism.

The third type, in which the orthopyroxene host is intergrown with very fine laths of clinopyroxene, is regarded by Maske (1966, p. 58) as due to pseudo-twinning. These laths are present in the orhopyroxenes from 5,500 feet upwards in the succession across the Mapochsgronde profile (photomicrograph 20 A). This texture has also been attributed to translation-gliding and to twinning. As found by Maske irregular platelets of augite are arranged parallel to the fine laths.

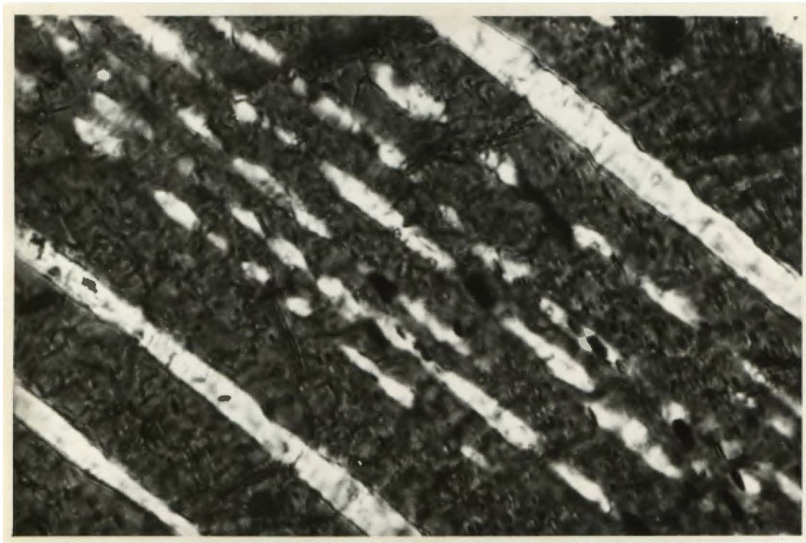
Exsolution-lamellae in Clinopyroxene Hosts

Along the whole length of the Mapochsgronde profile, the clinopyroxenes contain orientated lamellar intergrowths. In his study of the Ingeli Mountain Range Maske (1966, p. 57) found that one set of lamellae in the clinopyroxene is composed of orthopyroxene and another set of clinopyroxene.

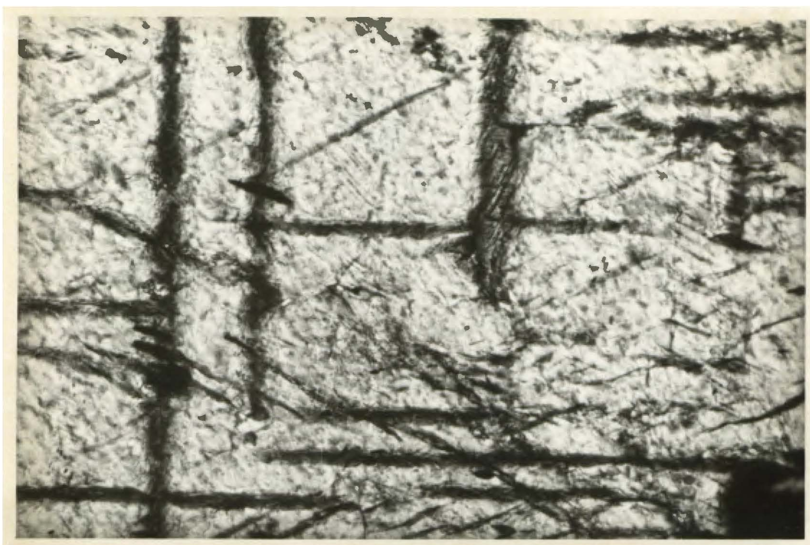
What is considered to be conclusive evidence that all the lamellae in the clinopyroxene of the gabbroic rocks of the Main Zone of the Bushveld layered suite, as exposed along the Mapochsgronde profile, are orthopyroxene was provided by the relationships between orthopyroxene and clinopyroxene grains. In thin section DG 605 (photomicrograph 20) taken at a height of 2700 feet above the base of the suite (fig. 7), two thin lamellae at point a in the augite host (dark grey) are continuous with an orthopyroxene grain (white). These lamellae and the orthopyroxene grain have the same position of extinction. The broad somewhat irregularly shaped lamellae in the augite host, which are aligned at approximately right angles to the thin lamellae in the observed plane of the thin section, also extinguish in the same position as the orthopyroxene grain and the thin lamellae. At points b and c in photomicrograph 20 broad lamellae are continuous with the contiguous orthopyroxene grain.

On the basis of the interrelationships mentioned above, both sets of lamellae in the clinopyroxene are therefore taken to be exsolved orthopyroxene.

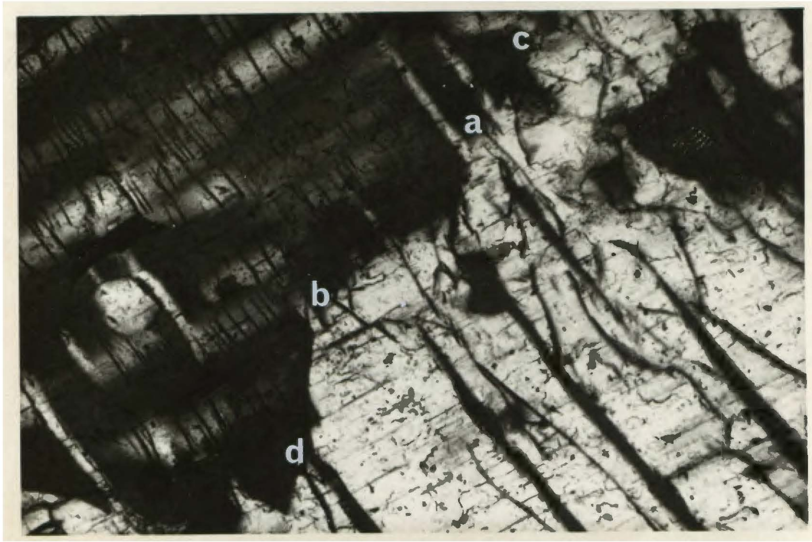
F - Zone/.....



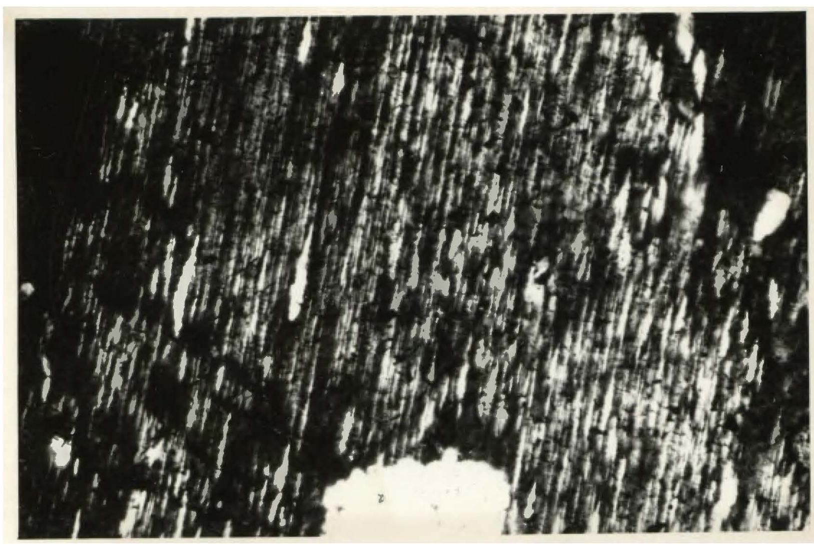
Photomicrograph 18 - Parallel orientation of continuous and interrupted lamellae of clinopyroxene in an orthopyroxene host. Thin section 315, Doornkop 356 JS. Crossed nicols , X 400.



Photomicrograph 19 - Two major, and two minor sets of clinopyroxene lamellae in an orthopyroxene host. Thin section 614, The Consolidated Farm Mapochsgronde 500 JS. Crossed nicols , X 160.



Photomicrograph 20 - Two lamellae (point a) in augite host (dark grey) are continuous with a contiguous orthopyroxene grain (white). The clinopyroxene lamella in orthopyroxene at point d is continuous with the clinopyroxene grain. The broad irregular lamellae in the clinopyroxene grain have the same optical orientation as the orthopyroxene grain and the thin lamellae at point a and b. At point c the broad lamella is continuous with the orthopyroxene grain. Thin section 605 from The Consolidated farm Mapochsgronde 500 JS. Crossed nicols , X 100.



Photomicrograph 20A - Fine laths of clinopyroxene (light) in an orthopyroxene host (dark). The laths are very irregular and discontinuous but nonetheless exhibit marked parallellism. Thin section 616 from The Consolidated Farm Mapochsgronde 500 JS. Crossed nicols, X 160.

F - Zone of Magnetite-bearing Gabbro

In the central part of Honingkloof 218 JS, and Mapochsgronde 500 JS, a layer containing much magnetite (folder 1 and fig. 7) was followed northwards past Trigonometrical beacon Mapoch I. It is within this layer that a magnetite pipe has formed. East of the pipe a magnetitite seam, a few feet thick and dipping about 10° W, is exposed in a prospecting-trench. The seam also crops out in a few places. The zone of magnetite gabbro appears to lie conformably in the gabbro of the Main Zone.

Apart from the magnetite, orthopyroxene is present and in excess of clinopyroxene. In the magnetite gabbro of the Upper Zone (Chapter 12) orthopyroxene is usually subordinate to clinopyroxene.

By virtue of the presence of magnetite in this layered zone (from 4,500 to 5,500 feet along the Mapochsgronde profile) the hypersthene gabbro, hyperite and norite comprising it can be referred to as magnetite-hypersthene gabbro, magnetite hyperite and magnetite norite.

South of the Laersdrif Fault this zone was not encountered but it is possible that in this area it is represented by the zone having tiny rods, grains and "dust" of magnetite within the plagioclase (folder 1).

G - Anorthosite

South of the Laersdrif Fault a few layers of anorthosite are found on Witpoort 216 JS, and Welgevonden 215 JS. The layers are near the contact between the gabbro and the Dullstroom andesite. They always contain a fair amount of pyroxene and it is difficult to trace them in the field. They also weather at about the same rate as the gabbro and do not form prominent outcrops. Although no actual contact with the under- and the overlying gabbro was encountered the anorthosite appears, if one may judge from loose blocks, to grade into gabbro over a few feet, and it is assumed that they are differentiates of the gabbro magma. The thickness of the layers range from a few feet to about 5 feet; the thickest and most prominent one strikes N-S and persists for more than a mile near the western boundary of Witpoort.

H - Emplacement/.....

H - Emplacement of the Gabbro

From the geological map it is clear that the Dullstroom andesite thins rapidly from the Laersdrif Fault northwards to Houtenbek 97 JT, whereas the gabbro thins about equally rapidly from Houtenbek southwards. The original gabbroic magma was intruded into the Dullstroom andesite and the impure quartzite of the Smelterskop Stage on Houtenbek 97 JT. Evidence on this farm, for example the presence of dioritic rocks (folder 1), which probably represent a separate magma, points to the likelihood that the gabbro has cut across the andesite and assimilated large parts of it. The various xenoliths of altered andesite which were buoyed up in the molten gabbro and the large xenolith along the top of the gabbroic rocks of the Main Zone indicate that the gabbro was injected with considerable force and that the andesite was in consequence thereof disrupted and displaced. It is therefore reasonable to assume that a considerable portion of the Dullstroom andesite was assimilated north of Houtenbek and that its position was taken up by the mafic members of the Bushveld Complex the most important being the gabbro and, farther north, norite and allied rocks.

The failure of the gabbro and the more mafic rocks of the Bushveld Complex to disrupt and displace the andesite completely from Houtenbek southwards would explain the rapid thinning of the gabbro and the absence of the more mafic members of the Bushveld Complex in this direction.

12 - MAGNETITE GABBRO AND DIORITE

A - Distribution

In the layered sequence of Bushveld rocks the magnetite gabbro follows on the gabbro. The magnetite gabbro occupies the low-lying ground between the foothills of the Steenkampsberg and the Sekhukhune - Bothasberg plateaux. Especially towards the upper portion of the suite, outcrops are scarce and the ground is soil-covered. Here exposures of weathered magnetite gabbro can usually be seen only in gullies and in streambeds. The areas of outcrop are shown on the geological map. From this map it is clear that the number and size of the outcrops increase to the east and very good examples are available for studying the variation in the magnetite content in the sequence. Still farther east, beyond the Steelpoort Valley, the prominent hills represent common gabbroic layers. As yet there is no clear explanation for the rapid rate of weathering of the magnetite gabbro compared with that of the common gabbroic rocks. The possibility that the effect is due to the rapid decomposition of magnetite was disregarded when it was found that in completely weathered rock the magnetite grains are fairly solid and intact, although microscopically they showed incipient alteration to hematite, etc. A possible general explanation is that the magnetite gabbro is better layered than the common gabbro, especially where magnetitite seams have formed, thereby facilititating the action of agencies of erosion. It is accordingly not surprising that in only one instance a magnetitite seam outcrops on a small ridge of magnetite gabbro and even then the material above and below the seam is partially soil-covered. The task of following and mapping magnetitite seams was therefore confined to the flats and this proved to be no easy one as they are difficult to locate amongst the grass. Some outcrops appear as prominent ridges, but as a rule the seams protrude as strips only a few feet wide and seldom more than 3 feet above the soil. In some areas the soil is reddish in colour whereas in others, especially towards the base of the magnetite gabbro, the soil is black, sometimes admixed with round and oval pebbles of grey limestone.

At Bothasberg and Tautesberg the upper contact of the magnetite gabbro with fayalite diorite runs approximately parallel to the base of the chain of hills, the overlying diorite making up the higher and more resistant ground. The contact is not clearly defined and is gradational although the transition is over a short distance and very variable and may therefore be regarded as arbitrary.

The contact between the magnetite gabbro and the underlying common gabbro which strikes north-south, is not clearly defined either. The percentage of magnetite in the magnetite gabbro immediately above and below the lowermost magnetitite seam of Subzone A is well over 10 per cent. Eastwards the percentage drops rapidly to values of between 3 and 10 per cent. The normal gabbro seldom contains more than 0.5 per cent of magnetite

(table/.....

(table 17). In the field it is difficult to determine a distinct contact as a result of poor outcrops, and owing to the slight visual difference between the two rock types. In general the area west of the prominent xenolith of metamorphosed Dullstroom andesite is underlain by magnetite gabbro and that east of it by common gabbroic rocks.

B - Thickness

From Roossenekal southwards a gradual thinning of the magnetite gabbro takes place from more than 9000 feet to about 6000 feet.

Table 18.

Thickness (in feet) of the magnetite gabbro, and the thickness from its base to the various magnetite seams, along different sections (map and sections, folder 1).

Distance between profiles	50,000	5,000	18,000	35,000	
Section	A - B	C - D	E - F	G - H	I - J
Dip	12°	17°	17°	18°	22°
	Top of magnetite gabbro				
Thickness from base to roof of magnetite gabbro and diorite	9500	7200	7000	5750	6500
	Seams of Subzone D				
Thickness from base to seams of Subzone D	8400	5500	5000	4200	4800
	Seams of Subzone C				
Thickness from base to seams of Subzone C	3000	3250	2900	1500	?
	Seams of Subzone B				
Thickness from base to seams of Subzone B	1000	3000	2900	500	1900
	Base of magnetite gabbro				

As in the case of the gabbroic layers, the decrease in the width on surface of the magnetite gabbro, from north to south in the Stoffberg area is in excess of the actual decrease in its thickness. The same explanation, namely the increase in the dip of the layering from 10° W to

22° W/.....

22^{o} W and more, may be offered to account for the apparent limited development of the magnetite gabbro to the south of Stoffberg.

In order to obtain conformity with regard to the various magnetitite seams occurring within the magnetite gabbro of the Eastern Transvaal, the nomenclature of Molyneux (1964, map IV) has been adopted. The magnetitite seams of Subzone C are but poorly developed on Blaauwbank 179 JS but where outcrops of them were seen, there is no indication that they extend into the Blood River area. The magnetite seam of Subzone D on the other hand, together with the surrounding magnetite gabbro, continues with interruptions, westwards around Bothasberg and Tautesberg into the Blood River flats.

Along Bothasberg, on Sterkloop 352 JS, there are two outcrops of magnetite gabbro which are considered to represent separate layers not connected with the main magnetite gabbro. The one lies within the basal Rooiberg felsite, and the other within the main Rooiberg felsite.

C - Meaning of the term Magnetite Gabbro

The term ferrogabbro has been applied by Coertze (1958, p. 90) to those mafic rocks in which magnetite crystals are disseminated. Wager and Deer (1939, p. 98) first applied the name ferrogabbro to rocks in the Skaergaard intrusion in Greenland, which contain pyroxene and olivine rich in iron so that the orthopyroxene may contain ferrosilite up to 74 per cent and the olivine is almost pure fayalite. The meaning of the term ferrogabbro as applied by Coertze to the Bushveld Igneous Complex does not therefore correspond to the original usage of Wager and Deer. Accordingly the designation magnetite gabbro is preferred.

It is often difficult to differentiate between some pyroxene and magnetite with the naked eye or even with a hand lens. However a simple field method of differentiating between gabbro containing magnetite and gabbro without magnetite has been found to work quite well. The pointed end of the geologist's pick readily pulverizes the dark-coloured minerals on weathered surfaces. A white powder indicates that the dark mineral is a mafic silicate whereas if the powder, which may reveal magnetic orientation, is black, the mineral is invariably magnetite.

In/.....

In this way it has been possible to map the gabbro separately from the magnatite gabbro. This subdivision proved very useful to Coertze in his mapping of the Bushveld Igneous Complex north of Pilanesberg (1958, p. 390), although he preferred the name ferrogabbro for those gabbros containing free magnetite. Actually other differences in the composition of normal gabbro and magnetite gabbro are also evident but the orthopyroxene of the latter, as we shall subsequently see, is not abnormally rich in iron. As can be seen from Table 20 (page 89), the main differences between gabbro and magnetite gabbro, apart from the presence of magnetite, are in the lower percentage of orthopyroxene, the virtual absence of quartz in the magnetite gabbro and the differences in the optical properties of the plagioclase and the orthopyroxene. The fayalite diorite which represents the roof of the suite shows a variation in composition which could be, as will be discussed later, due partly to assimilation.

D - Subdivision

A knowledge of the volumetric modal percentages of the various constituents of the suite, coupled with the determination of the oomposition of the plagioclase, the orthopyroxene and the olivine made it possible to subdivide the magnetite gabbro on a mineralogical basis.

Owing to generally poor and impersistent outcrops it was found inadvisable to attempt mapping the separate subdivisions of the magnetite gabbro suite. Only the fayalite diorite is shown as a separate subdivision.

A property common to all the rocks of the magnetite gabbro suite is the presence of magnetite. This mineral, although present in the gabbro suite as well, appears in notable quantities some distance below the magnetitite seam of Subzone A and persists to the roof of the Bushveld Complex.

On the basis of the percentage of orthopyroxene in the total amount of pyroxene (Chapter 11 - B) the magnetite gabbro varies from hyperite at the base to hypersthene gabbro and gabbro higher up in the succession (figs. 9 and 10). Actually there are other differences which also have to be considered, e.g. the appearance of olivine and the composition of the plagioclase.

The/.....

The anorthite content of the plagioclase was found to decrease from about An_{60} at the base of the layered rocks to An_{50} in the vicinity of the magnetitite seams of Subzone D (fig. 9), corresponding to a thickness of some 4000 feet. Above the magnetitite seams of Subzone D the anorthite content of the plagioclase is less than 50 per cent.

Norite, Hyperite and Hypersthene Gabbro. From the base up to 2,100 feet and probably continuing to about 2,750 feet, olivine has not crystallised in amounts exceeding one per cent and the hyperite, norite and hypersthene gabbro varieties are found. Above the magnetitite seams of Subzone B, clinopyroxene is always in excess of orthopyroxene. The composition of the orthopyroxene varies from En_{55} Fs_{45} at the base to En_{51} Fs_{49} at 2,200 feet along the Enkeldoorn profile.

Along the De Lagersdrift profile (fig. 10), where the magnetite gabbro below the magnetitite seams of Subzone B is much thicker than along the Enkeldoorn profile, and where the magnetitite seams of Subzone A are exposed, the orthopyroxene varies from En_{55} Fs_{45} at the base to En_{52} Fs_{48} at the 2,500 feet level.

The anorthite content of the plagioclase remains fairly to constant, varying from An_{56} to An_{55} (from 0 to 2,200 feet) along the Enkeldoorn profile and from An_{61} to An_{56} along the De Lagersdrift profile (0 to 2,500 feet).

Olivine-hypersthene gabbro and olivine diorite. Olivine was found in quantity in specimen DG 638 at a height of 3250 feet, and from there onwards it is present almost without exception to the top of the Bushveld Complex. It is probably also present below the 3250 feet level but outcrops are virtually absent. According to Boshoff (1942, p. 12) olivine appears abruptly about 1,000 feet above the magnetitite seams of Subzone B, to the south of Roossenekal. Scattered grains of olivine are present in rocks from the base of the magnetite gabbro. The zone in which olivine is present in amounts exceeding 15 per cent continues to just below the magnetitite seams of Subzone D, that is at the 4000 feet level. The zone of olivine-rich rocks has been termed troctolite by Molyneux (1964, p. 19) and olivine diorite by Hammerbeck (1965, p. 31). Molyneux found that as much as 30 per cent of olivine is present, which justifies the term troctolite.

Hammerbeck does not give volumetric percentages of olivine. The amount of olivine most commonly found in these rocks as they occur north and south of Stoffberg is about 20 per cent. As both ortho- and clinopyroxene are present in noticeable quantities the rock is not a true troctolite. The olivine has crystallised instead of both clino- and orthopyroxene. The anorthite content within this portion of the layered sequence is from An_{48} to An_{53}, corresponding to both andesine and labradorite. Along the Enkeldoorn profile the rock can therefore be called an olivine diorite or an olivine-hypersthene gabbro, depending on the composition of the plagioclase.

Diorite and Olivine Diorite. Above the magnetitite seams of Subzone D the anorthite content of the plagioclase is less than 50 per cent. From 4700 to 5750 feet there are no outcrops but the composition of the plagioclase is presumably still between An_{40} and An_{50}. Considering the anorthite content of the plagioclase, which corresponds to andesine, these rocks are therefore dioritic. As both olivine and magnetite are present they can be termed olivine-magnetite diorite or just olivine diorite as suggested by Boshoff (1942, p. 24). The olivine is ferrohortonolite with $Fa_{79 \text{ to } 87}$. From 4000 feet to 4450 feet very little olivine is present and this zone is therefore composed of more normal diorite.

E - Megascopic Features

The fresh rock is grey-green but it weathers to a brown or grey colour. It is medium grained and grain-sizes range from 0.2 mm to 2.5 mm. Pyroxene and plagioclase feldspar can be distinguished macroscopically and magnetite with difficulty.

F - Microscopic Features

Plagioclase feldspar, clinopyroxene, orthopyroxene and magnetite are the minerals normally present. The amounts of plagioclase and total pyroxene remain fairly constant at a ratio of 3.7:2, but the amount of magnetite is very variable. It was found that the highest concentration of disseminated magnetite is directly above the massive magnetitite seams. The magnetite gabbro between successive seams may also

contain/.....

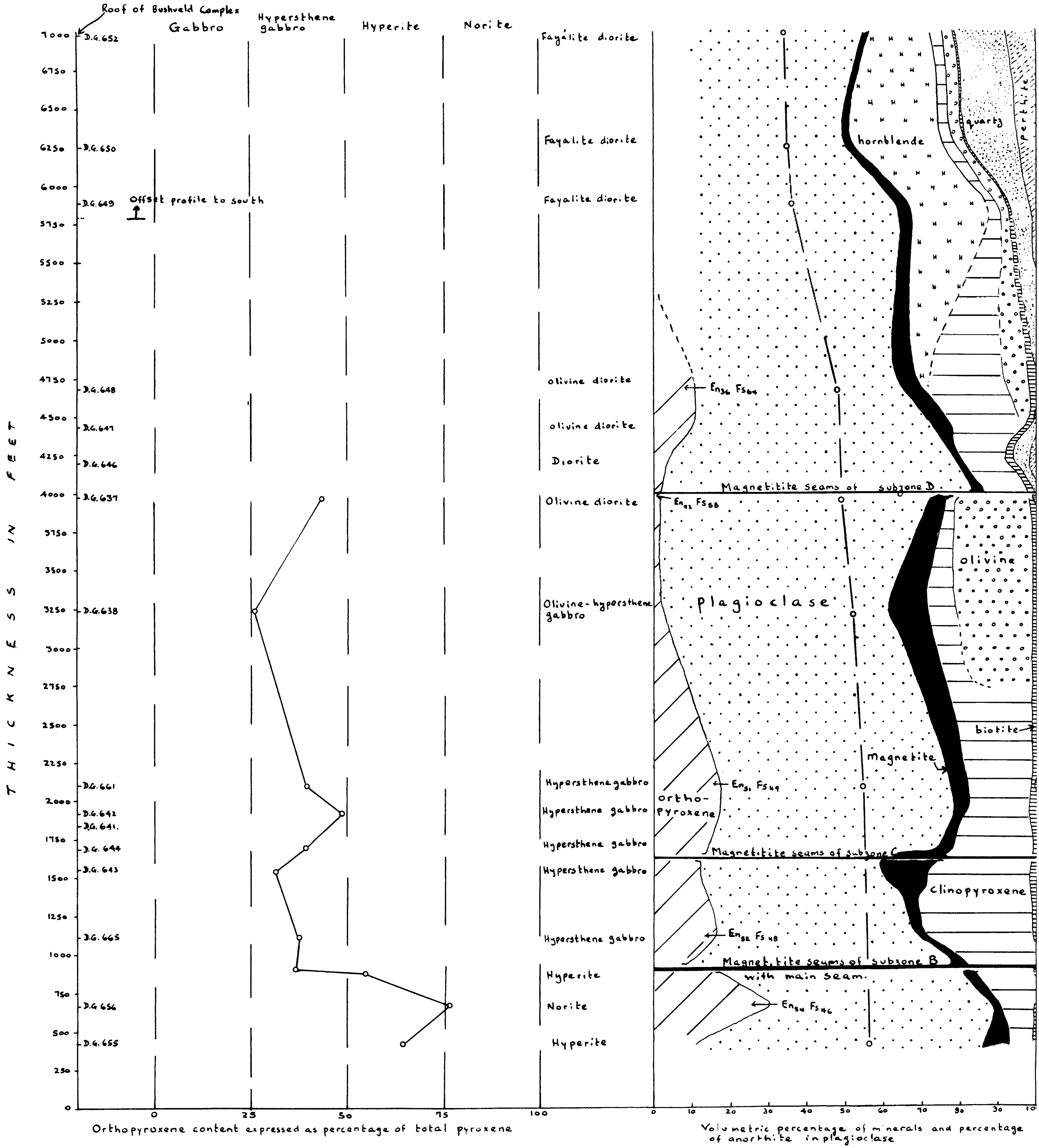


Fig. 9 - Rock types of the Upper Zone of the Bushveld Complex based on the orthopyroxene content, expressed as a percentage of the total pyroxene, and their mineral composition (both volumetric) along the Enkeldoorn profile. The molecular composition of the orthopyroxene is also given

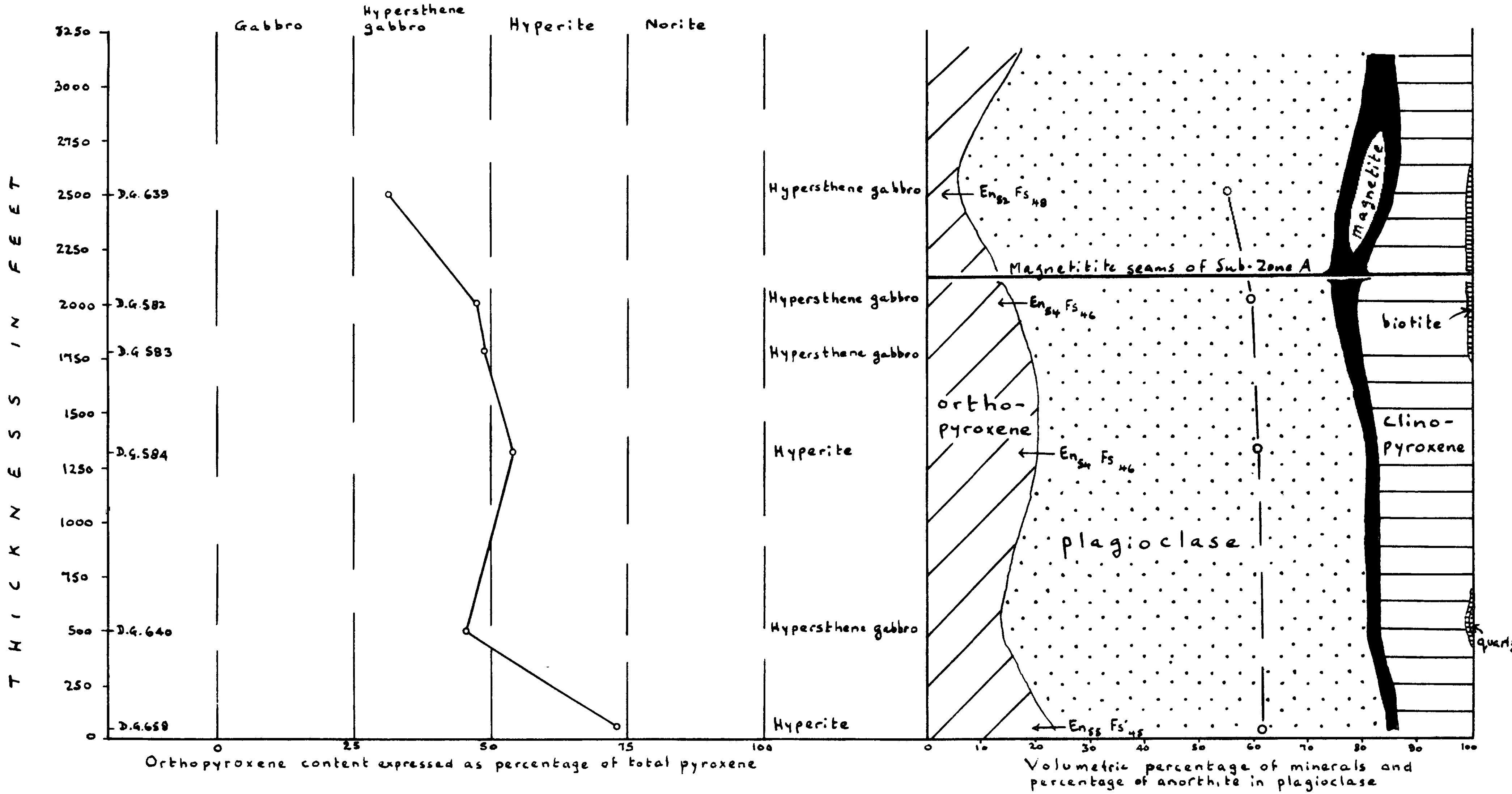


Fig. 10 - Rock types of the lower portion of the Upper Zone of the Bushveld Complex based on the orthopyroxene content, expressed as a % of the total pyroxene, and their mineral composition (both volumetric) along the De Lagersdrift profile. The molecular composition of the orthopyroxene is also given.

contain considerable amounts of magnetite: This is especially so in the vicinity of the Main Seam of Subzone B and C.

Other constituents which may be present in variable amounts include quartz, biotite, apatite, olivine and amphibole. The amphibole is an alteration product of pyroxene. Olivine is usually present. This mineral has not been found in amounts exceeding 22 per cent.

Molyneux (1964, map IV) was able to distinguish several separate troctolite layers in the Magnet Heights area, where the rocks are generally better exposed.

Quartz is usually more abundant in the vicinity of granitic and felsitic rocks, and there its presence is ascribed to assimilation.

G - Textural Relationships

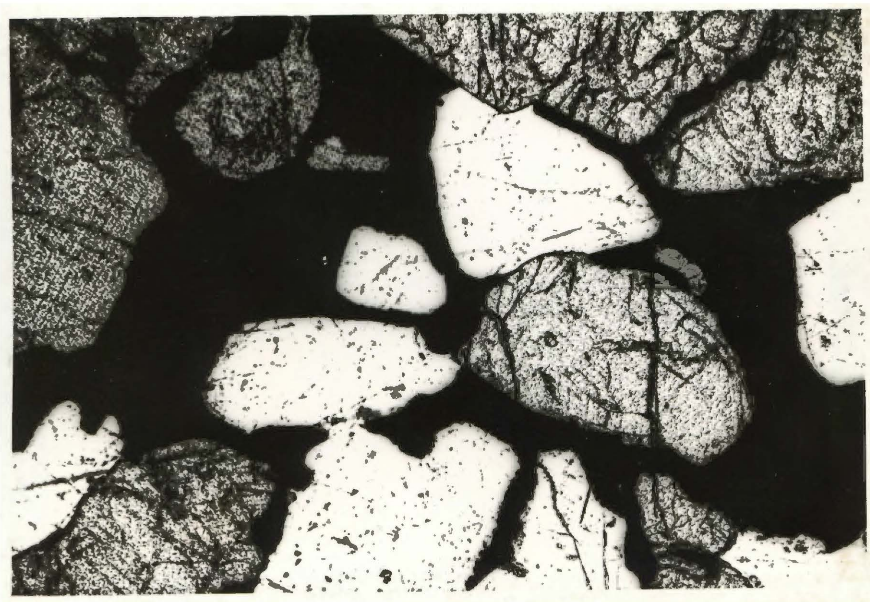
With regard to the magnetite there is abundant evidence that it has formed mostly around the plagioclase and the pyroxene and that it is therefore one of the last products of crystallisation (photomicroggraph 21).

The rocks are all hypidiomorphic granular. Plagioclase and pyroxene are subhedral. The magnetite varies from euhedral to anhedral. The magnetite gabbro is mostly medium-grained but certain areas contain coarser-grained material which approaches and sometimes even attains pegmatitic dimensions.

The labradorite is always twinned. Growth textures along crystal planes of the plagioclase (schillerisation) are quite commonly caused by minute inclusions of magnetite and pyroxene.

The myrmekitic and symplectic textures in rocks from Magnet Heights described by Hatch <u>et al</u> (1951, p. 282) were noticed and can best be seen in polished section under high magnification (X400), but here the titaniferous and vanadiferous magnetite is usually intergrown with feldspar and/or pyroxene. These intergrowths are very similar to the graphic, zebra or eutectic intergrowths often found in ores, for example between chalcocite and bornite and denote contemporaneous crystallisation, exsolution, reaction or replacement. Present opinion is that the intergrowths are exsolution phenomena.

H - Refractive/.....



Photomicrograph 21 - Magnetite gabbro consisting of : plagioclase feldspar (white), monoclinic pyroxene (grey) and magnetite (black). The magnetite surrounds earlier-formed plagioclase and pyroxene and also fills cracks in them. Thin section from De Lagersdrift 178 JS. Transmitted light, X 30.

H - Refractive Index Determinations

Along the base of the magnetite gabbro the refractive indices of the clinopyroxene are: $n\gamma = 1.724$, $n\alpha = 1.699$ ($\pm$ 0.002). The composition of the augite falls within the diopside-hedenbergite series, i.e. $diopside_{56}$ $hedenbergite_{44}$ (Winchell, 1945, p. 226). It will be noted that the indices of refraction of the clinopyroxene in the magnetite gabbro are somewhat higher than those of the pyroxene in the gabbro (Chap. 11 - D; p. 71).

The different anorthosite layers, especially those below the magnetitite seams also contain labradorite (Ab_{40} An_{60}) and where augite (diallage) is present it is $diopside_{56}$ $hedenbergite_{44}$. This fact is significant and probably implies that these anorthosite layers are differentiates of the magma in the position where they occur.

I - Volumetric Composition of Random Specimens

Apart from the two profiles in figs. 9 and 10, ten specimens were selected at random and the percentages of the constituent minerals determined (table 19). None of the specimens listed was taken from the transitional zones overlying the magnetitite seams; they would give very high percentages of magnetite and therefore create an erroneous impression of the composition of the magnetite gabbro (a sample taken just above seam No. 8 of Subzone C, at the boundary between The Consolidated Farm Mapochsgronde 500 JS and Onverwacht 148 JS, contains 61.95 per cent of plagioclase, 30.17 per cent of magnetite and 7.88 per cent of clino- and orthopyroxene by volume.

Specimen DG 568 taken just below seam No. 21 of Subzone D contains 21.82 per cent of olivine and only 5.63 per cent of clino- and orthopyroxene. This rock is therefore a troctolite, which is a variety of gabbro consisting of labradorite and olivine with little or no pyroxene.

Table/.....

Table 19.

Volumetric composition of magnetite gabbro

Specimen No.	DG 122	DG 11	DG 19	DG 89	DG 145	DG 123	DG 186	DG 412	DG 187C	DG 568
Plagioclase	73	60	75	56	53	62	61	51	61	46.94
Clino- and orthopyroxene	21	30	14	35	42	26	26	26	29	5.63
Olivine	-	-	-	-	-	-	-	16	-	21.82
Magnetite	2	8	11	7	4	7	10	6	6	12.16
Amphibole	-	-	-	-	-	2	2	-	-	
Apatite, biotite and chlorite	-	2	-	-	1	3	1	a 1	b 4	c 13.45
Quartz	4	-	-	2	-	-	-			
Total	100	100	100	100	100	100	100	100	100	100.00

a. Apatite only.

b. Apatite: 1.6 per cent.

c. Apatite: 6.44 per cent.

DG 122 - Welgevonden 215 JS.

DG 11, 19, 123 and 145 - De Lagersdrift 178 JS.

DG 89 - Swartkoppies 217 JS.

DG 186 - Blinkwater 213 JS.

DG 412 and 568 - Duikerskrans 173 JS.

DG 187C - Rhenosterhoek 180 JS.

Magnetite is the third or fourth most prevalent mineral and serves to differentiate the magnetite gabbro from the normal gabbro. Specimens DG 122 and DG 89 contain small amounts of quartz but both were taken in close proximity of granite.

J - Main Differences between Gabbro of the Main Zone and Magnetite Gabbro of the Upper Zone

Some of the main differences between the gabbroic rocks of the Main Zone and the various types of magnetite gabbro of the Upper Zone of the Bushveld Complex are given in table 20.

Table/.....

Table 20.

Comparison between gabbro (Main Zone) and magnetite gabbro (Upper Zone)

Diagnostic minerals	Gabbro	Magnetite gabbro
Plagioclase : content	63 to 72 per cent	53 to 75 per cent
composition	Labradorite to bytownite	Andesine to labradorite
Clinopyroxene : content	4 to 27 per cent	20 to 36 per cent
Orthopyroxene : content	6 to 30 per cent	2 to 17 per cent
composition	En_{67-59} Fs_{33-41}	En_{55-36} Fs_{45-64}
Magnetite : content	0 to 0.5 per cent	0.5 to 15 per cent, and more
Olivine : content	Not present	Present from less than 1 per cent to 25 per cent
Perthite : content	Not present	Present along upper part of succession
Amphibole : content	Rare; as alteration product of pyroxene	0 to 20 per cent

Generally, the most important factor which serves to distinguish between the two types of gabbro is the fact that seams of layered magnetite are not found in the gabbro of the Main Zone but are plentiful in the magnetite gabbro.

13 - FAYALITE DIORITE

A - Distribution

The fayalite diorite follows on the olivine diorite and is the uppermost member in the layered succession of the Bushveld Igneous Complex.

From Rhenosterhoek 180 JS, the diorite layer strikes southwards through Blinkwater 213 JS, Schietpad 212 JS, and Enkeldoorn 214 JS to Sterkloop 352 JS. The thickness of the diorite layer together with its granophyric upper part varies from 100 feet to 800 feet.

The contact between the olivine diorite and the overlying fayalite diorite is not sharply defined. To

complicate/.....

complicate matters further, outcrops are scarce, firstly, as a result of weathering, and secondly, owing to the extensive covering of talus in some parts, especially in the Blood River area. It would appear that the contact which is gradational in character runs parallel to the line of hills which make up Bothasberg. The upper contact is sharp and the diorite has an intrusive relationship with the overlying felsite. Xenoliths of felsitic rocks in the diorite are present on Blinkwater 213 JS and Rhenosterhoek 180 JS, and occupy such extensive areas that they could be indicated on the map.

The terrain rises sharply from the base of the diorite to its top so that the resistance of the diorite to erosion in contrast with the magnetite gabbro is conspicuous; and yet, although samples of diorite collected appeared to be quite fresh, the constituent minerals are in fact highly altered even though the rock itself is still massive. Along the old road up Tautesberg, on Paardekloof 176 JS, two layers of quartz diorite occur within the felsite. The one is separated from the main quartz diorite by a thin zone of felsite, and the second one is much higher up in the felsite succession.

B - Composition

On surface the rock is medium-grained, dark grey with much plagioclase feldspar, mostly in an advanced stage of decomposition. A few remnants of clinopyroxene are usually retained but this mineral is mostly in various stages of alteration to amphibole. Some amphiboles (hornblende) are primary constituents of the rock. Quartz is well represented and can be easily differentiated from the feldspar by its fresh appearance against the brownish colour of the weathered feldspar. Magnetite is fairly plentiful and secondary magnetite is found intimately associated with olivine from which it has separated through alteration. Olivine is present in most samples. Lower down in the succession, a little K-feldspar is usually present but then only in subordinate amounts. Other minerals, variably present, include biotite and apatite.

From about 5800 to 7000 feet along the Enkeldoorn profile (fig. 9) the composition of the diorite changes, in this respect that microperthite and quartz percentages

increase;/.....

increase; magnetite, olivine and clinopyroxene percentages vary only slightly and the amphibole content is somewhat variable with a tendency to decrease near the roof of the Bushveld Complex.

A notable feature of the diorite succession is that clinopyroxene has become a subordinate constituent and orthopyroxene, although present along the base is practically absent along the roof of the diorite.

Near its contact with the felsite, the fayalite diorite changes to a reddish-coloured rock in which much alkali feldspar is present, and is closely associated with quartz. In one of these samples the percentage of quartz was determined quantitatively, by means of X-ray diffraction, at 21 per cent. This type of rock has been termed melagranophyre, granophyre and alkali granophyre by A.F. Lombaard (1949, p. 358) depending on its mineralogical composition. The samples examined on Bothasberg along the contact are probably melagranites as much plagioclase is still present. A volumetric determination of a sample near the western boundary of Blinkwater gave the following results: Feldspar = 60.61 per cent, hornblende = 19.92 per cent, quartz = 17.83 per cent and magnetite = 1.64 per cent. This specimen (and others) showed no granophyric textures and is more like the normal red granite.

Table 21.

Volumetric composition of fayalite diorite (random specimens)

Specimen No.	DG 187A	DG 187D	DG 192	DG 157
Plagioclase	53	50	63	32
Alkali feldspar	-	-	-	22
Clinopyroxene	8	6	-	33
Amphibole	30	25	15	1
Magnetite	5	6	9	3
Olivine (fayalite)	2	2	2	1
Quartz	1	5	11	3
Apatite	1	3	-	5
Biotite	-	3	-	-
Total	100	100	100	100

DG 187A,/.....

DG 187A, 187D: Rhenosterhoek 180 JS.
DG 192: Schietpad 212 JS.
DG 157: Blinkwater 213 JS.

The additional modal determinations of specimens taken at random (table 21) clearly show the wide diversity in the composition of the diorite succession. The specimens, which are listed from the base of the diorite upwards in the sequence show a fairly regular variation in composition, but it is apparent that, along the contact with the magnetite gabbro i.e. at the base, plagioclase prevails and near the contact with felsite i.e. at the top, K-feldspar is also conspicuous.

Apatite is a constituent of all but one of the specimens and magnetite is always present. Olivine was found as large separate crystals in only one specimen (DG 187D); in others it is associated with magnetite as very tiny, irregular clusters. Quartz is a regular constituent of most samples, attaining the highest percentage (11 per cent) just below the contact with the felsite (DG 192).

Owing to the weathered state of most samples it was thought advisable not to attempt giving names to the various types of diorite found in the area mapped.

Although microperthite is present in variable amounts it is always subordinate to plagioclase so that the rock is not a monzonite. Quartz percentages also fluctuate. The olivine, always present in subordinate amounts, is fayalite and the collective name of fayalite diorite is perhaps the best to describe these widely diverse rocks. Boshoff referred to these rocks as fayalite-bearing syenodiorite (1942, p. 29).

C - Determination of Optical Constants

Along the contact with the magnetite gabbro, below the diabase dyke on Rhenosterhoek 180 JS, the fayalite diorite still contains labradorite, on which the following refractive indices were determined:

$$n\gamma = 1.566 \ (\pm\ 0.002)$$
$$n\alpha = 1.558 \ (\pm\ 0.002)$$

This corresponds with a composition of $Ab_{40}\ An_{60}$.

Farther up in the layered sequence (see localities of samples cited in table 21) labradorite gives way to

andesine/.....

andesine and oligoclase. The refractive indices most frequently obtained for the plagioclase were:

$$n\alpha = 1.546\ (\pm\ 0.002)$$
$$n\gamma = 1.553\ (\pm\ 0.002)$$

This corresponds with a composition of $Ab_{62}\ An_{38}$.

A.F. Lombaard (1949, p. 351) gives a value of An_{42-48} for diorite across the Blood River Valley, and Van der Westhuizen values of An_{40-49} for olivine diorite on Bothasberg. The albite content of the plagioclase therefore increases in the dioritic rocks.

The K-feldspar is difficult to measure owing to its advanced stage of alteration but in one comparatively fresh specimen the following refractive indices were measured:

$$n\gamma = 1.532\ (\pm\ 0.002)$$
$$n\alpha = 1.525\ (\pm\ 0.002)$$

These indices corresponds with those of microcline and, from the appearance of the K-feldspar under the microscope it is perthite as found by Van der Westhuizen (1945, p. 17).

A.F. Lombaard (1949, p. 362) was able to establish that the percentage of fayalite in the olivine increases from 80 to 100 per cent from the bottom to the top of the diorite layer. Van der Westhuizen's findings regarding the olivine were similar to those of Lombaard's, namely, Fa_{85} to Fa_{98}. Along the Enkeldoorn profile (fig. 9) the olivine is fayalite with Fa_{91} to Fa_{94}.

D - Origin

Previous workers, e.g. Boshoff, A.F. Lombaard and Van der Westhuizen believed that the magnetite gabbro, the diorites and the granophyric rocks were products of differentiation. There can be little doubt that these findings, amply corroborated by evidence from variations in the composition of the feldspar, pyroxene and olivine, are true but after careful mapping and examination of the diorite along Bothasberg, where it was found that numerous xenoliths of felsite lie in the diorite, it seems quite likely that the overlying rocks, now termed Basal felsite, were to a certain extent assimilated by the intrusive magma. This will account for the rather abrupt and

marked/.....

marked change from magnetite gabbro and olivine diorite, where quartz is a mineral seldom seen, to fayalite diorite containing up to 20 per cent of quartz. The coexistence of quartz and olivine can also be explained in this way.

On Bothasberg the presence of felsite xenoliths in the layer of fayalite diorite is proof that large blocks settled in the magma during intrusion.

14 - ANORTHOSITE IN THE MAGNETITE GABBRO

A - Field Relationships

The majority of the anorthosite layers are found directly underneath the magnetitite seams. Their position in the layered sequence will again be discussed in the chapter on the Magnetitite Seams (p. 96).

Away from the magnetitite seams anorthosite was also encountered, but owing to the weathered and impersistent nature of the layers they were not mapped separately.

The anorthosites associated with the magnetitite seams are generally quite weathered and consequently fresh specimens suitable for microscopic study were difficult to obtain.

B - Composition

Generally the anorthosite is coarse grained and consists of more than 95 per cent plagioclase with very little pyroxene, mostly in different stages of alteration to amphibole and chloritic material. Where still fresh the pyroxene is usually clinopyroxene. The only other mineral present is magnetite and then in only very small amounts.

C - Weathering

The anorthosite below the magnetitite seams is usually in an advanced stage of alteration. One prospecting pit, just below the Main Magnetitite Seam of Subzone B on Blinkwater 213 JS, had reached a depth of 5 feet and was still in loose, weathered material, mainly kaolinite, and feldspar in different stages of alteration to kaolinite.

A significant and important factor is that boreholes for water often meet with success in anorthositic areas. Weathering is often deep enough to render the anorthosite permeable with resultant concentration of underground water (figure 11).

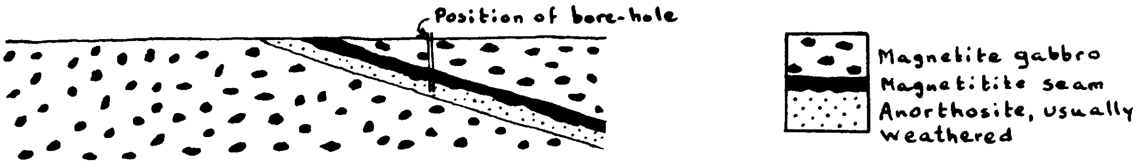


Fig. 11 - Sketch to indicate the correct siting of bore-holes for water in the vicinity of magnetitite seams which are underlain by anorthosite.

The susceptibility of the anorthosite to weathering also explains the fact that magnetitite seams are seldom found on high ground.

D - Emplacement and Genesis of Anorthosite in the Magnetite Gabbro

An important fact to bear in mind is that the anorthosite layers, which are concordantly emplaced in relation to the magnetite gabbro in this area, are the roof-facies of differentiated magmas. The roof of the anorthosite served as a floor for the succeeding unit. The postulation that anorthosite represents the roof-facies of each unit is acceptable as its main constituent, plagioclase, is the lightest of the minerals which crystallised and would therefore tend to concentrate at the top and decrease in amount downwards.

The plagioclase adcumulate (anorthosite) is usually found along the upper portions or at the top of the rhythmic units of magnetite gabbro. Wager, Brown and Wadsworth (1960, p. 77) use the term "adcumulus growth" in describing the formation of igneous layers which contain crystals of the same composition and which are unzoned. They state that the adcumulus process, which gradually reduces the intercumulus liquid by mechanically pushing it out, may sometimes reduce the amount of intercumulus liquid to vanishing point. Any trapped liquid will crystallize and have the composition of the contemporary magma.

In/.....

In the case of the anorthosite, monoclinic pyroxene and magnetite, in amounts of much less than 5 per cent, are usually disseminated in the anorthosite and as such will represent the crystallised and trapped liquid which is known as porematerial.

In describing the reason for the presence of the adcumulus growth of the anorthosite Wager, Brown and Wadsworth state that they expect that enlargement of the crystals at the top of the pile would take place before those at the bottom and that such growth would eliminate the intercumulus liquid in the layer at the top and so prevent diffusion of material to lower levels.

The anorthosite which formed at the top of a magma unit will show a transitional contact with the underlying magnetite gabbro, whereas its contact with the overlying layers will be sharp. It can also be assumed that anorthosite layers formed below, but usually near the top, of a rhythmic layer, will possess gradational contacts above and below it.

PART V - THE MAGNETITITE SEAMS AND PIPES

15 - MAGNETITITE SEAMS IN THE MAGNETITE GABBRO

A - General

The vast deposits of magnetitite in the magnetite gabbro of the Bushveld Igneous Complex have in the past received scant attention from geologists but fortunately some have made interesting studies on them and deductions therefrom. Since 1958 when the ore became of potential economic importance the findings increased in value both scientifically and commercially.

It may also be added that the Geological Survey, Department of Mines, had accumulated a wealth of information by means of routine mapping, reports, analyses and laboratory investigation, which has been eagerly sought and used by members of the mining houses interested in the exploitation of the vanadium, titanium and iron in the ore.

B - Distribution

Four separate subzones, each with one or more magnetitite seams are found in the magnetite gabbro. In

order/.....

order to attain conformity with regard to the designation of the various subzones in the different parts of the Bushveld Igneous Complex of the Eastern Transvaal, the seams as located around Stoffberg, have been given the same subzone letters as those that Molyneux (1964, map IV) used. In this way confusion is mostly avoided.

Of all the subzones, the lowest, viz. Subzone A is poorly distributed; Subzone B, which contains the Main Seam, is prominent; Subzone C is fairly conspicuous north of the Laersdrift Fault but crops out only sporadically south of it, and Subzone D is quite consistent.

Only actual magnetitite outcrops are shown on the geological map. Where the seam could not be seen on surface, as a result of a soil cover, blank spaces were left. It is not known whether magnetitite seams are present underneath those blank spaces. Drilling by AMCOR and the prospecting by the Anglo American Corporation by means of pits and trenches revealed that, as far as the Main Seam of Subzone B is concerned, it is continuous for mile upon mile with very few barren areas. On the geological map the outcrops of magnetite gabbro and those portions of it which are soil-covered are shown separately. Even in the soil-covered areas the seams are seen to protrude above the soil cover. Thus the inferrence is made that in many places the seams are masked by a soil cover and that drilling, pitting or trenching will reveal the seam below it. In such areas the soil is usually heavily charged with magnetite grains and assumes a dark-brown colour.

Seams of Subzone A are present north-east and east of Laersdrif as very scattered and small outcrops on The Consolidated Farm Mapochsgronde 500 JS, Swartkoppies 217 JS and De Lagersdrift 178 JS. South of the Laersdrif Fault, on De Lagersdrift the subzone is fairly well exposed and was followed southwards across the Steelpoort River and the Stoffberg-Roossenekal road, where it presumably terminates, as no further outcrops of it were seen over a distance of more than 10 miles southwards.

Subzone B extends southwards with minor displacements and breaks in the outcrop, from the junction of the road from Roossenekal to Steelpoort and the road from Roossenekal to Stoffberg on The Consolidated Farm Mapochsgronde 500 JS. The road from Roossenekal to Stoffberg crosses

the/.....

the zone twice and then runs approximately parallel to it to just north of Laersdrift. From here the zone continues southwards, crosses the Swartspruit and can then be followed for a short distance before dissappearing underneath a soil cover up to the Laersdrif Fault. South of the Fault it is present on De Lagersdrift 178 JS. The Steelpoort River crosses it and the zone continues into Blinkwater 213 JS, where the road from Roossenekal to Stoffberg crosses it. South of the road the outcrops were followed for a short distance before disappearing under a cover of soil. Further outcrops were again located north-east of Stoffberg but they are very scattered. On Welgevonden 215 JS good outcrops are found east and west of the road from Stoffberg to Belfast. The zone is apparently displaced by a fault-zone running along a xenolith of pyroxene hornfels. South of the xenolith the zone extends into Lang Maar Smal 353 JS and farther south into Goedverwacht 354 JS, but outcrops are not continuous.

The seams of Subzone C are the best seen along stream-beds and gullies on The Consolidated Farm Mapochsgronde 500 JS and Onverwacht 148 JS (plate 4). From here southwards a large area is covered by soil but on De Lagersdrift seams of the subzone are again seen north of Modderspruit, and south of it but here the outcrops are sporadic up to the Laersdrif Fault. At the position where the seam of Subzone C can be expected to crop out south of the Laersdrif Fault only one narrow seam was seen on Blaauwbank 179 JS. From there southwards no further outcrops of the subzone are found for several miles. On the east side of the Steelpoort River on Welgevonden 215 JS, a single seam is again developed and on Sterkloop 352 JS, scattered magnetite rubble in river gravel could mark the position of magnetitite seams below. On the same farm, in the southernmost part of the area, an outcrop of a seam from Subzone C was located.

The main seam of Subzone D is exposed continuously below Tautesberg on Duikerskrans 173 JS and the Wedge 175 JS and strikes into Paardekloof 176 JS to a point east of Trigonometrical Beacon Tauteshoogte from where it could not be located southwards in spite of continuous outcrops of magnetite gabbro. Across the Blood River Valley on Rhenosterhoek 180 JS, several magnetite outcrops and much

slump-material/.....

slump-material are present on either side of the road from Stoffberg to Groblersdal. The upper seam continues from here southwards through Blinkwater 213 JS and Enkeldoorn 214 JS into Sterkloop 352 JS.

C - Description

Although, when describing the magnetite in the ore the compound term titaniferous and vanadiferous magnetite is used, even this rather lengthy term does not describe the ore adequately owing to the complex nature of its individual components, particularly when weathered. When discussing the seams in general, their rock-name, viz, magnetitite will be used.

Normally the ore has formed as stratiform seams, the hanging wall being magnetite gabbro or magnetite anorthosite and the foot-wall magnetite gabbro or anorthosite. The individual seams vary in thickness from less than one inch to well over 6 feet.

In the Stoffberg area four separate subzones were located.

Subzone A, as exposed in a gully just west of the old bridge spanning the Steelpoort River on Blinkwater 213 JS contains three seams, each one between 10 and 15 inches thick. They are separated from one another by magnetite gabbro and are underlain by seams of anorthosite. Lower contacts at the base of the individual seams are fairly sharp but the topmost parts of the seams grade rapidly into magnetite gabbro. The thickness of the succession comprising this subzone could not be established but is probably between 50 and 100 feet. The V_2O_5-content of the seams is about 2.3 per cent, this value representing the highest values of any subzone. Owing to their thinness and impersistent distribution they are of no immediate economic significance.

Subzone B is the most important one from an economical point of view, owing to the relatively high vanadium content of the magnetitite seams. They contain up to 2.47 per cent V_2O_5 and average about 1.86 per cent (table 26, specimens 65 to 70 and table 25, specimens S1 and S2). Three seams have generally been found. The lowest is the thickest and is followed upwards by two comparatively thin seams. Where typically developed, the Main Seam is composite and is made up of two separate seams, with interlayered magnetite gabbro.

The/.....

The thickness of the Main Seam is, on the average, of the order of six feet. The parting of magnetite gabbro is heavily charged with magnetite and is usually from 8 to 12 inches thick (plate 5). The two parts of the Main Seam seldom coalesce to form one continuous unit of magnetitite, as the core from one of the bore-holes drilled by AMCOR at Magnet Heights indicates. The bore-hole was drilled on Ironstone 847 KS, some 50 miles north of the mapped area. The Main Seam was here found to be only 45 inches thick; normally it is more than 90 inches thick in the Magnet Heights area. Another bore-hole on the same farm revealed that, apart from the central parting another had developed locally in the upper portion of the Main Seam. This parting is 3 inches thick. For descriptive purposes the composite seam is referred to as the Main Seam.

On The Consolidated Farm Mapochsgronde 500 JS, Seam No. 1, above the Main Seam is 14 inches, and Seam No. 2, 18 inches thick. Seam No. 1 appears 6 feet and Seam No. 2, some 23 feet above the Main Seam.

In all cases where outcrops are visible the contact at the base of the Main Magnetitite Seam is sharp, the foot wall being anorthosite. The anorthosite grades downwards into magnetite gabbro. The contact at the top of the seam is gradational, the magnetitite passing rapidly into normal magnetite gabbro. This is also the case with Seams Nos. 1 and 2 but here no anorthosite is usually present. The feldspar grains in the transition-zone are well orientated and sometimes display a remarkable parallellism. This parallellism can be ascribed to fluid-flow during crystallisation and/or to normal preferred orientation during crystallisation.

Subzone C as developed on Onverwacht 148 JS consists of five, and possibly six magnetitite seams. Taken from the base, the second seam is overlain by an anorthosite layer of about 12 inches thick. The other seams as far as could be ascertained, are not associated with anorthosite. The contacts at their bases are sharp but gradational at the top. The intervening material is again magnetite gabbro. The whole succession is about 750 feet thick. Thicknesses of individual seams vary from 1 to 2 feet. The second seam follows closely on the first, whereas the others are about

equally/.....

Plate 4 - A magnetitite seam (No. 12) of Subzone C, with seam No. 13 visible below the skyline to the right of the plate, outcropping on Onverwacht 148 JS.

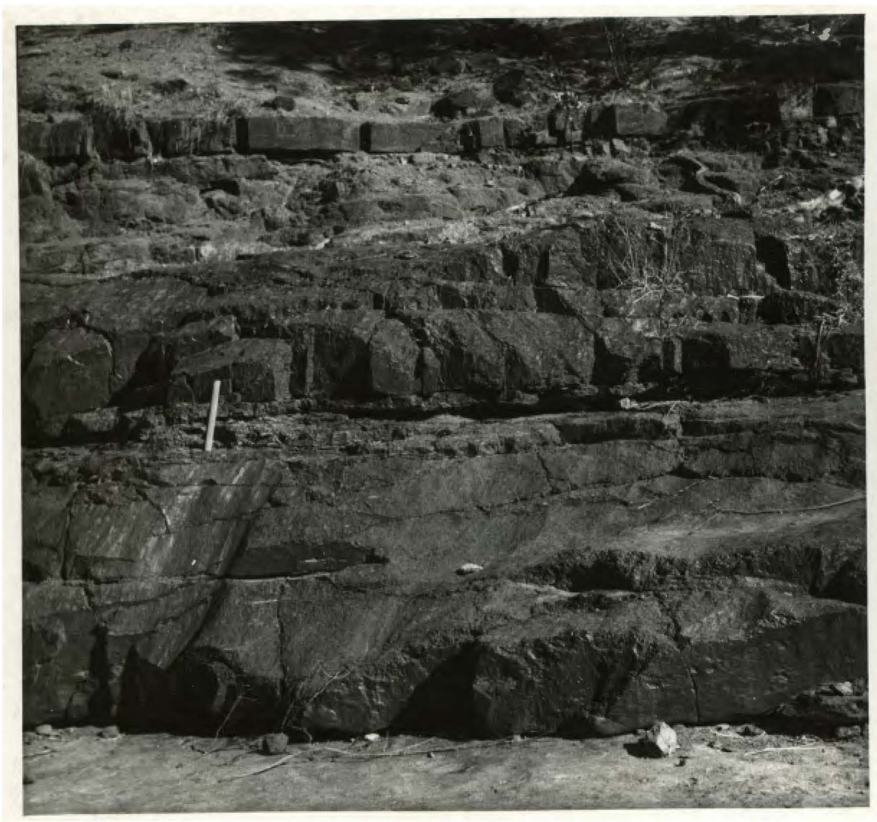


Plate 5 - The Main magnetitite Seam and Seam No. 1 of Subzone B exposed in a stream near Magnet Heights some 40 miles north of the mapped area. The parting of magnetite gabbro can be clearly seen at the ruled scale of one foot. The Main magnetitite Seam rests with a sharp contact on anorthosite.

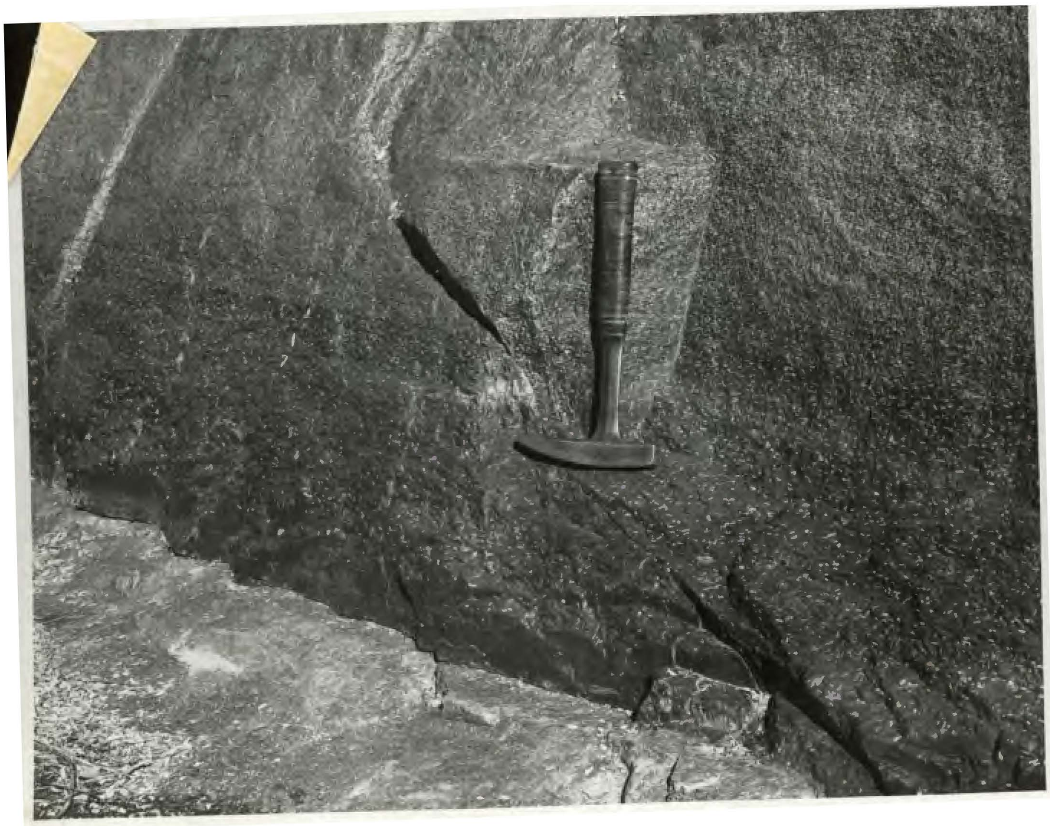


Plate 6 - Magnetitite Seam No. 1 of Subzone B near Magnet Heights, some 40 miles north of the mapped area. The seam rests with a sharp contact on anorthosite. From the hammer head upwards the seam grades rapidly into magnetite gabbro. The layering of the transition phase is clearly visible.

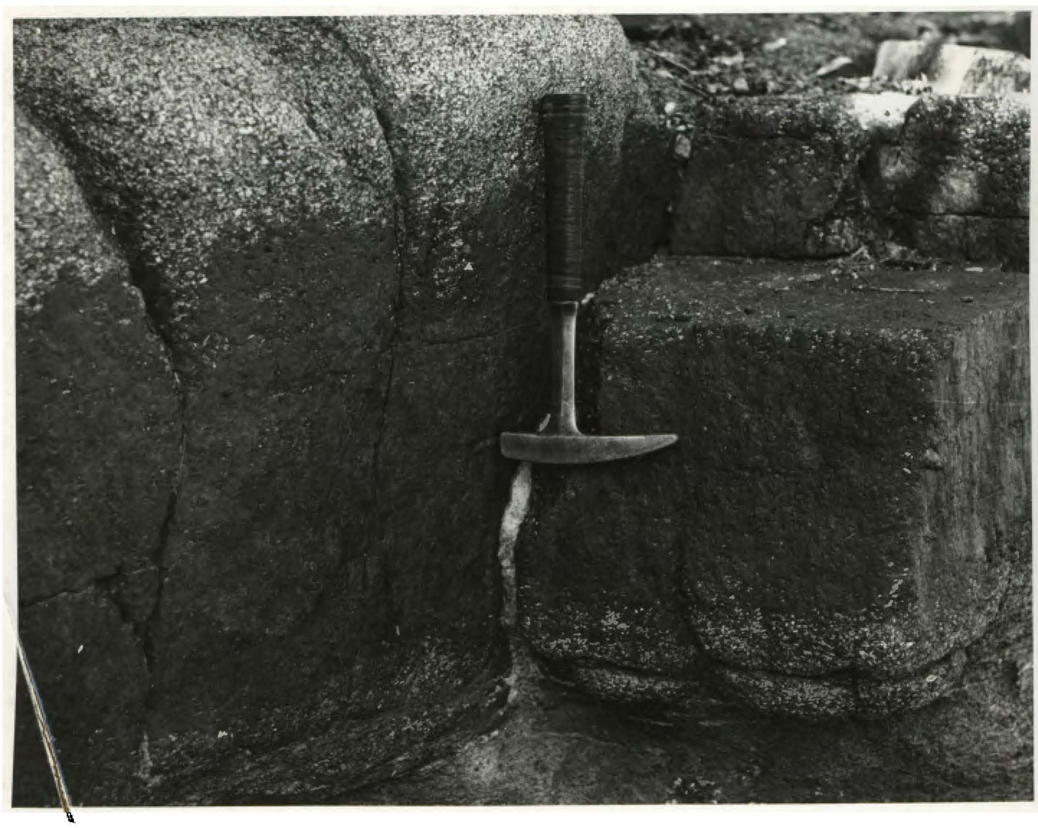


Plate 7 - Seam No. 4 of Subzone B near Magnet Heights, some 40 miles north of the mapped area. Both at the base and at the top the magnetitite grades into magnetite gabbro.

equally spaced. The fourth seam is well exposed in a gully and could be carefully examined. It actually consists of a basal seam, two inches thick, separated from the main part of the seam by a parting of magnetite gabbro 2-3 inches thick. This parting is heavily charged with magnetite and can be compared with the parting in the Main Seam of the Subzone B. The main portion of the seam is 12 inches thick and the upper part of it is transitional into magnetite gabbro. The V_2O_5-content of the seams of Subzone C, ranges from 0.6 to 0.8 per cent. The values were obtained for seams north of the Laersdrif Fault on De Lagersdrift 178 JS, and were done by the Anglo American Corporation during their investigation of the seams of Subzone B. The main seam of Subzone D, below Bothasberg in the south of the area, has a consistent thickness of 2½ feet. The contact at the base is sharp against an anorthosite layer and gradational at the top into magnetite gabbro. Below Tautesberg, however, the seam assumes an entirely different appearance. Here it is actually a whole succession of layered rocks some 30 to 40 feet thick and consists of many poorly differentiated seams with intervening magnetite gabbro rich in magnetite. The most prominent seam, about 18 inches thick, is developed at the base of the succession. The contacts between individual seams and magnetite gabbro may be gradational or fairly sharp. The V_2O_5 content of the seam is from 0.2 to 0.3 per cent.

The positions of the various seams relative to magnetite gabbro are depicted in the sections accompanying the map.

In the Stoffberg area idealised sections of the magnetite gabbro with the magnetite seams of the various subzones, and of the upper seam of Subzone D below Bothasberg and its composite counterpart below Tautesberg will be more or less as follows:

Fig. 12/.....

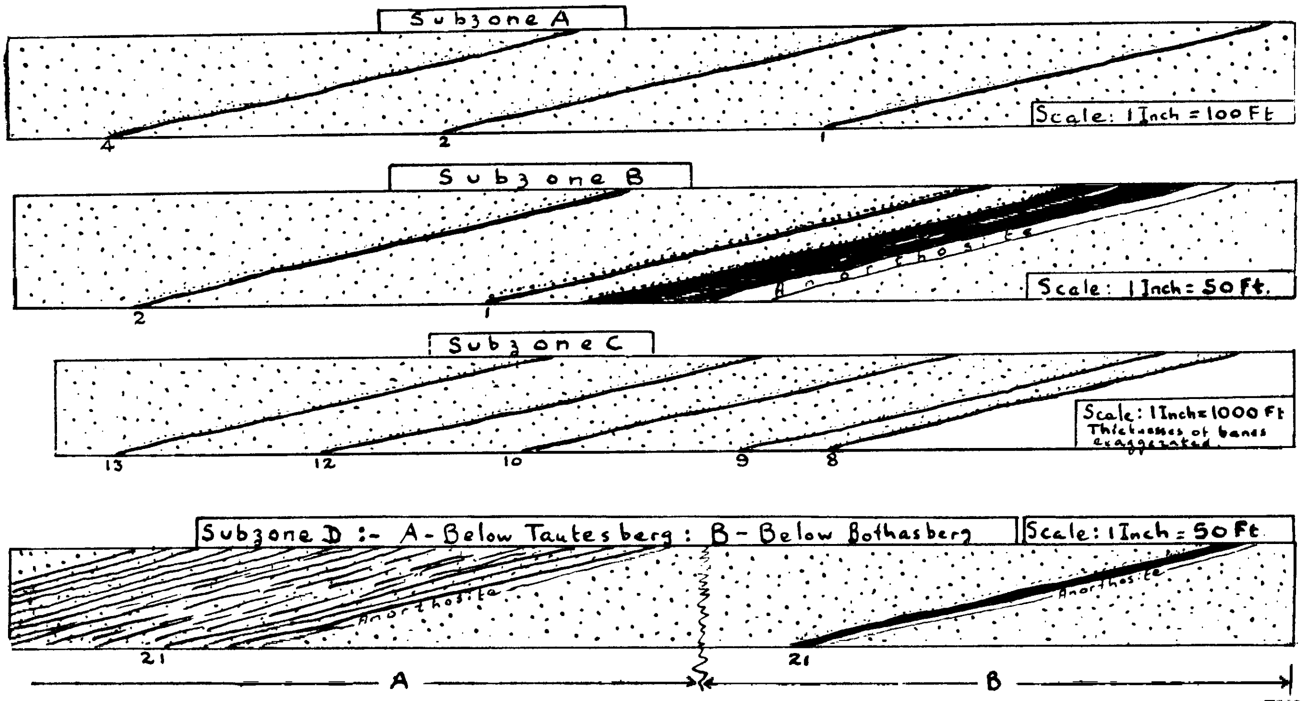


Fig. 12 - Idealised profiles of the various subzones of magnetitite seams in the Stoffberg area. Below Bothasberg only one seam of Subzone D has developed, while under Tautesberg there are many ill-defined and poorly differentiated seams.

At Magnet Heights Hall (1932, p. 342) originally established that two almost identical sets of seams had been emplaced. They are separated by some 60 feet of magnetite gabbro.

Detailed geological mapping by Molyneux in the same area (1964) also revealed the presence of two sets of seams. In this stratigraphical column Molyneux (1964, map IV) called the lower set Subzone A and the upper set Subzone B.

In Subzone A Molyneux located four separate magnetitite seams whereas Subzone B comprises the Main Seam and seven of the other magnetitite seams.

Drilling undertaken by AMCOR on Ironstone 847 KS, just south of Magnet Heights revealed additional seams in Subzone B but unfortunately not one of the bore-holes penetrated Subzone A (tables 22 and 23 and fig. 3). The logs of the bore-holes, kindly made available by AMCOR, showed that in Subzone B, the Main Seam, eight subordinate

magnetitite/.....

magnetitite seams and eight layers of magnetite gabbro rich in magnetite are developed, although as shown in table 22, only the main seam and solid seams 1, 2, 3 and 4 are more or less consistent. Seams 10, 12, 14 and 16 are still solid magnetitite seams and were located in only two of the holes drilled. The other bore-holes were drilled too low in the succession. In the one bore-hole, in the southern part of Ironstone, seams 10, 12, 14 and 16 have been logged as solid seams while in the other bore-hole, in the northern part of Ironstone, they have been logged as layers of magnetite gabbro rich in magnetite (fig. 13).

According to the bore-hole logs, seams 1, 2, 3, 10, 12, 14 and 16 grade upwards into magnetite gabbro but are in sharp contact with underlying magnetite gabbro or anorthosite. The bore-hole logs showed that seam 2, and rarely seam 3, may in places be underlain by anorthosite. Seam 4 is underlain by anorthosite in four of the bore-holes while in three of the bore-holes it is separated from the anorthosite layer by about 5 feet of magnetite gabbro. In several places it is anomalous and grades into magnetite gabbro above and below it, as shown in plate 7.

In comparing the magnetitite seams mapped by Molyneux at Magnet Heights (and the bore-holes evidence from the same area), with the magnetitite seams exposed around Stoffberg, the great number of magnetitite seams exposed on surface at Magnet Heights compared with the meagre exposures around Stoffberg must be considered. At Magnet Heights the whole gabbroic succession together with the magnetitite seams is very well exposed. Southwards exposures gradually become less and south of Roossenekal the magnetitite seams are mostly only seen to protrude through a cover of soil. As the bore-holes on Ironstone 847 KS revealed seams additional to those located by Molyneux in such a well exposed area, it is likely that in the Stoffberg area drilling would reveal many more seams than those exposed on surface. This is especially the case with Subzone B. As shown in Fig. 12, Subzone A consists of three seams on Blinkwater 213 JS which is one less than the four found by Molyneux. It is possible that the poorly differentiated seam of

the/.....

the Magnet Heights area, is either absent or, more likely, not properly exposed at Stoffberg.

Subzone B is shown by Molyneux to consist of the Main Seam and seven other thinner seams, while the bore-holes results on Ironstone indicate several more. At Stoffberg only the Main Seam is fairly continuously exposed. Seams 1 and 2 are only exposed in trenches and along road-cuttings. Elsewhere scattered magnetite rubble above the main seam points to the presence of seams below the soil cover.

In Subzone C, Molyneux mapped seven seams at Magnet Heights. At Stoffberg, on De Lagersdrif 178 JS, The Consolidated Farm Mapochsgronde 500 JS and Onverwacht 148 JS, the seams of Subzone C are well exposed. Six separate seams were distinguished.

In Subzone D Molyneux found that the number of seams varies from four to seven. The highest seam is by far the thickest. North-west of Stoffberg, along the foot-hills of Tautesberg, the highest seam is well exposed over long distances but the other six seams located by Molyneux are not continuously exposed and some have probably not been emplaced around Stoffberg. It was only on Duikerskrans that a few seams, probably corresponding to Nos. 19 and 20 found at Magnet Heights (Molyneux, 1964, map IV), were noted below the thick seam. Below Bothasberg, and west and south-west of Stoffberg, only one seam appears to have been formed. On Blinkwater 213 JS the presence of three seams of Subzone D is suggested to be present according to the outcrops, but a little further south local folding points to the development of a single seam. Still farther south on Sterkloop 352 JS no folding was noticed and here Subzone D is marked by only one visible magnetitite seam about two feet six inches thick. On Rhenosterhoek 180 JS several scattered out-crops of magnetitite from Subzone D are shown but most of them probably represent slump-material from the same seam.

From the foregoing account it is therefore clear that in the Stoffberg area the presence of several of the seams located at Magnet Heights could not be established, mainly owing to the paucity of outcrops, although it is likely that some of them have not been formed in this area.

D - Weathering/.....

TABLE 22

Distance, in feet, between hanging-wall of Main magnetitite seam of Subzone B and foot-wall of successive seams and phases upward in the column as revealed by bore-holes on Ironstone 847 KS, Lydenburg District. A dip of 10° is taken as average. Blank spaces denote that the seam is not developed.

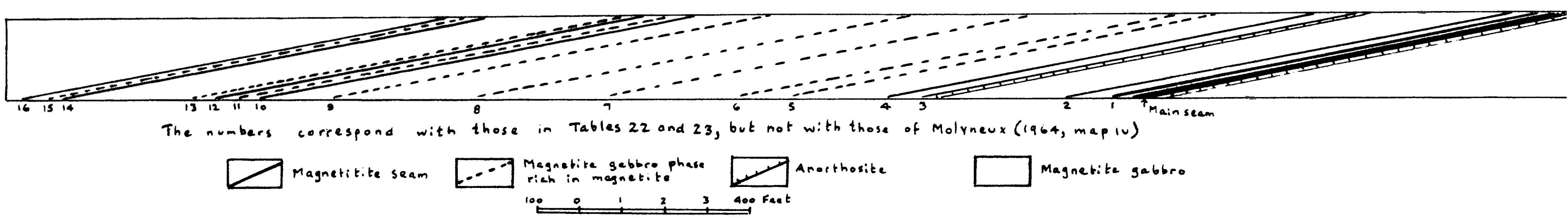
Number of seam or phase	Main Seam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bore-hole 1	Datum	8	22	84	98												
Bore-hole 2	Datum	7	26	86	98		146										
Bore-hole 3	Datum	8	25	84	97												
Bore-hole 4	Datum	7	24	84	97		151										
Bore-hole 7	Datum	11	29	92	106	123			175	337	369	372	383	391	452	455	461
Bore-hole 10 ...	Datum	13	26	92	106												
Bore-hole 11 ...	Datum	8	28	96	108		145	164			371		390		452		460
Bore-hole 13 ..	Datum	13	23	80, 84, 90 (phases)													
Average distance	Datum	9	25	87	101	123	147	164	175	337	370	372	386	391	452	455	460

TABLE 23

Average thickness, in inches, of the magnetitite seams and magnetite rich gabbro phases on Ironstone 847 KS, Lydenburg District, together with average V_2O_5 - percentages

Number of seam or phase	Main seam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Average thickness	82	14	24	18	16						48		31		17		30
Average % V_2O_5	1.59	1.35	1.21	1.84	1.25		1.03				1.05	1.02	1.30	1.28	1.19	1.25	1.19

Fig. 13 - Ideal geological section across the magnetitite seams on Ironstone 847 KS, about 40 miles north of the mapped area. Average distances between the main and successive seams, as given in Table 22, have been taken and the seams projected to an imaginary horizontal plane. Average dip is 10°.



D - Weathering of the Seams

The magnetitite seams are more resistant to erosion than the magnetite gabbro but tend to break up easily into larger and smaller angular fragments as a result of prominent open jointing (fig. 14 and plate 8).

The granular nature of the ore also tends to facilitate weathering. The jointing is more or less as given in the following diagram:

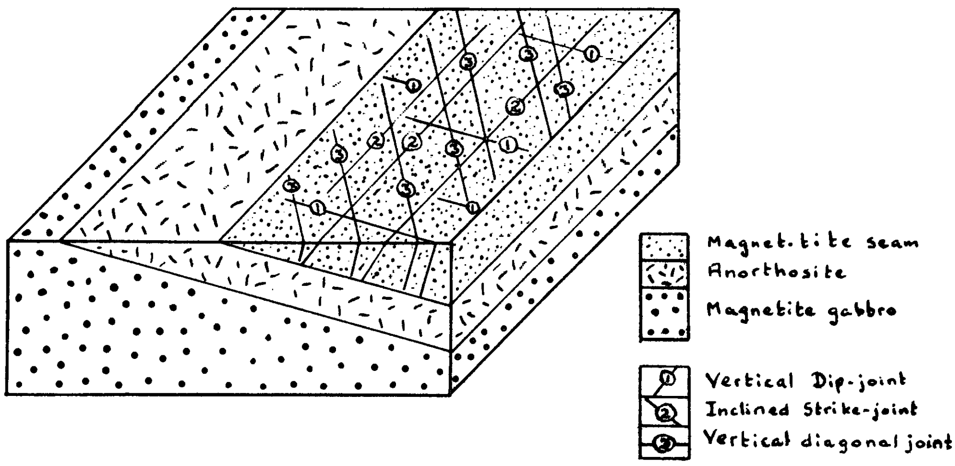


Fig. 14 - Block-diagram showing the joint pattern in the main magnetitite seam of Subzone B.

Three main sets may therefore be recognised viz:

(1) Dip-joints which are vertically disposed.

(2) Strike-joints dipping at 70° in a direction opposite to the dip of the seams.

(3) Diagonal joints, vertically disposed.

The surfaces of the joints often show quite prominent slickensides. Samples of core, consisting of magnetitite from drill-holes did not reveal any jointing, so it is likely that the joints are surface- and near-surface features only.

A common occurrence above the seams is the presence of irregular cappings of ferricrete which resemble gossan material. This was observed particularly at the Upper Seam of Subzone D.

The weathering of the magnetitite seams is also affected by that of the magnetite gabbro. In several

places/.....

Plate 8 - The main magnetitite seam of Subzone B, with prominent cross- and strike-joints, dipping 12°W on Ironstone 847 KS some 40 miles north of the mapped area.

Plate 9 - Seam No. 1 of Subzone A which has been folded anticlinally. The photo was taken near the old Steelpoort bridge on Blinkwater 213 JS. Folding is presumed to be due to slumping of the highly weathered underlying anorthosite and the magnetite gabbro.

places weathering of magnetite gabbro below, and even between the seams of one subzone, has given rise to slumping of the seams. This may be lead to erroneous structural interpretations especially as regards dip measurements. The fold in plate 9 has formed as a result of the slumping of the underlying magnetite gabbro and anorthosite. Near Roossenekal prospecting excavations have revealed that slumping of Seam No. 1 of Subzone B, due to the decomposition of magnetite gabbro, has brought it almost in contact with the main seam at the surface.

Down dip the distance between the two seams increases rapidly (fig. 15).

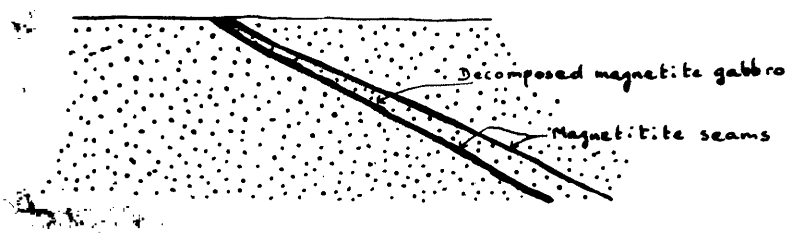


Fig. 15 - Sketch showing the effect of slumping on the magnetitite seams.

The overburden is usually composed of reddish soil which contains magnetitite fragments of varying sizes so that magnetometric surveys are often unreliable; this type of overburden gives high anomalies which can easily be misinterpreted. The fine surface-sand usually averages less than 1 mm in grain size and is invariably heavily charged with rounded grains of titaniferous and vanadiferous magnetite. This type of surface-soil is present even on the magnetite gabbro. In gullies and stream-beds titaniferous and vanadiferous magnetite is often found almost pure as a result of natural concentration by gravity.

E - Mode/.....

E - Mode of Emplacement of the Magnetitite Seams and the Magnetite Gabbro

The result of the drilling on Ironstone (see p. 104) proved conclusively that the lower magnetitite seam is practically always underlain by anorthosite. The core logs show that, with the exception of the Main Seam of Subzone B, in most places the tops of the seams are gradational into the overlying magnetite-gabbro (plate 6), whereas the contact with the underlying rocks is sharp.

In a few seams, however, the contact at the top and at the bottom are gradational (plate 7), for example seam No. 4, and seam No. 2 (in bore-hole 13, table 22). Several zones of magnetite gabbro which have a high magnetite content were logged and here no clear contacts are delineated.

It seems clear that the solid seams which exhibit gradational contacts at the top and at the base must have originated by; (i) a process of partial separation of magnetite and ilmenite from the gabbroic magma before and during emplacement; (ii) by gravity-settling during crystallisation or; (iii) by a combination of both these processes.

One gains the impression that the mode of formation of the seams with gradational contacts at the top and at the base is somewhat different from that of the Main Seam with its footwall of anorthosite. The fact that no clear contacts are present argues in favour of the second explanation, i.e. that the seams were formed by a process of gravity-settling during crystallisation. The seams with gradational contact at the top and at the base are never underlain by anorthosite. Partial liquid separation of an iron-titanium fraction of the magma may have taken place before and after emplacement but this possibility cannot be substantiated.

The other seams with sharp basal and gradational contacts at the top have probably been formed partly by liquid separation before and during emplacement and mainly by gravity accumulation, especially along the upper contacts.

The investigation of the associations between anorthosite layers, magnetitite seams and magnetite gabbro, and the possibility that the Fe-Ti magma

separated/.....

separated partially before intrusion, or afterwards, but before crystallisation commenced, must be considered. This is especially the case with the magnetitite seams of Subzone B, where the Main Seam rests with a sharp contact on anorthosite and has a gradational contact at the top (plates 5 and 6).

The possibility that the Fe-, Ti-, and V-minerals settled as a result of gravity-differentiation during crystallisation has been carefully studied but here it becomes most difficult to explain the fact that the magnetite gabbro between successive subzones of magnetitite seams contains up to 15 per cent of magnetite disseminated amongst the pyroxene and plagioclase. In these rocks careful examination showed no sign of magnetite crystals in stratiform layers as a result of gravity-differentiation, although it can be assumed that they were in the process of settling. On the eastern side of the bridge crossing the Steelpoort River on De Lagersdrift 178 JS, the magnetite gabbro assumes a mottled appearance due to clusters of magnetite (an example of an heteradcumulate) but with no visible banding.

Undoubtedly differentiation _in situ_ took place as it would appear that the magnetite content of the magnetite gabbro increases downwards towards the magnetitite seams. However, it is difficult to attribute the practically complete separation between seams and magnetite gabbro to this phenomenon alone, while so much magnetite (see modal determinations, figs. 9 and 10 and table 12) remained disseminated at random in the magnetite gabbro between the four subzones of magnetitite seams. In this respect the same applies to liquid immiscibility.

With regard to gravitational layering, about which so much has been written, especially with respect to the Bushveld Igneous Complex, Hatch _et al_ (1951, p. 290) state, "The process is easy to visualize, and there is no doubt that differential sinking of crystals in a liquid environment is the fundamental cause of layering. If the crystals are heavier they will tend to sink, if lighter to float upwards". But they emphatically state that gravitational sorting alone does not explain the clear-out contacts between contiguous bands.

Hatch/.....

Hatch <u>et al</u> assume that periodic agitation of the magma during crystallisation would aid crystal sorting by dislodging the heavy crystals temporarily held up in the crystal mesh, and by tending to keep the plagioclase suspended. This may be so and probably applies to the Bushveld Igneous Complex but does not explain the presence of magnetitite seams above the lighter plagioclase-rich anorthosite. This phenomenon can best be clarified by accepting the fact that separate successive phases of the magnetite gabbro crystallised separately, each one coming to rest on the anorthosite roof of the former. Each magma phase will then keep plagioclase suspended as explained by Hatch <u>et al</u> and the roof-phase will therefore be anorthositic. It is possible that a previous magma phase had not solidified completely before the next one commenced.

Steyn (1950, p. 47) who favoured gravity-differentiation, postulated that crystallising magnetite separated and settled on a more solid bottom to form seams. Molyneux, who also favours the crystal-settling mechanism for the formation of the monomineralic rocks of the Bushveld Complex which he examined at Magnet Heights, draws particular attention to Steyn's remarks. As mentioned by Molyneux (1964, p. 103) magmatic currents were not turbulent and therefore not strongly erosive so that contacts between seams and the floor are normally not very irregular.

With regard to partial separation of the Fe-Ti-magma before emplacement it has been said that this liquid is miscible with the rest of the gabbroic magma (Hatch). This postulation cannot be discredited and may be true. However, the fractions could have separated nonetheless in order to satisfy equilibrium conditions in the magma before crystallisation actually commenced.

An explanation similar to the one presented herewith, is that offered by Stephenson for the origin of the titaniferous iron ores of the Lake Stanford Area, New York (1945, p. 72). He notes that contacts between ore and underlying anorthosite are sharp and that ore grades upwards into gabbro. With regard to the contacts between ore and anorthosite Stephenson states that ore moving along the floor encountered consolidated anorthosite which it penetrated and displaced to form discordant bodies. It is of course not a necessity that the magnetitite seams must rest on anorthosite. Where this rock is not developed the ore will rest on the magnetite gabbro of the previous magma phase. This latter phenomenon was also recorded by Stephenson.

Coertze (1958, p. 390) found that magnetite gabbro of the Upper Zone shows intrusive and transgressive relationships with respect to the common gabbro of the Main Zone. This interesting finding could not be substantiated in the Stoffberg area.

A possible explanation for the formation of the magnetitite seams is by means of late gravitative liquid accumulation as described by Bateman (1951, p. 407). According to Bateman heavy residual liquid trickles down through the interstices of already crystallised silicates to form a late gravitative liquid accumulation, which rests upon the floor of early crystallised silicates. Bateman states that, if the liquid accumulation crystallised under quiescent conditions, stratiform deposits may result and cites the Bushveld Igneous Complex as an example. Broadly speaking his method of concentration will produce results similar to that obtained by partial liquid separation.

Another explanation for the emplacement of some of the seams is that the Fe- and Ti-rich liquid intruded as pipes and that sheet-like offshoots from these pipes were formed due to hydrostatic pressure (Coertze, 1967). In this connection it must be pointed out that the existence of intrusive pipes and fissures of magnetitite in the Bushveld Igneous Complex is now confirmed but the gradational contact of the seams with the overlying magnetite gabbro does not suggest intrusive relationships. It is, however, possible that some seams are connected with pipes but then it will probably be found that contacts of the seams with the overlying magnetite gabbro and the underlying anorthosite are sharp and that the seams have only a limited distribution.

Another fact which mitigates heavily against the intrusive theory is that the disseminated magnetite of the magnetite gabbro which overlies the seams of Subzone B contains as much V_2O_5 as that of the seams (see table 25, sample M.G.). Also difficult to explain according to this theory is the fact that two of the pipes on

Blinkwater/.....

Blinkwater 215 JS contain less V_2O_5 than the magnetitite seams in the immediate vicinity, whereas the TiO_2-content of the pipes is also usually higher than that of the seams.

A few examples of small veins and irregular bodies of magnetite in the magnetite gabbro were seen in gullies but each of these occurrences were close to underlying seams. Veins below the seams were not seen (but may have formed by infiltration of cracks in the anorthosite and the magnetite gabbro). The explanation of these veins and irregular bodies is therefore that pressure was exerted on the magma before its final consolidation and that the liquid was forced upward into the surrounding rocks along cracks, joints and planes of layering.

A very revolutionary theory on the origin of the magnetitite seams is mentioned by Van Biljon (1949, p. 120). He believes that with the transformation of the sediments of the Pretoria Series into the different rock types of the Bushveld certain limestone bands were transformed to seams of magnetitite. The presence of thin bands of limestone in shale of the Pretoria Series north of Pretoria led him to this conclusion. Van Biljon suggested that these limestone bands are on the same horizon as the magnetitite seams in the Bushveld Igneous Complex and that some at least have remained unaltered.

Coertze who mapped a portion of the area around the new Pienaars River Dam on behalf of the Geological Survey found that the limestone bands swing away from the line of strike of the magnetitite seams. The complete selective replacement of the different sedimentary rocks by injected igneous matter to form the gabbros, norites, etc., is still a very interesting but speculative theory. Evidence of replacement can be found in leptites along the base of the Bushveld Igneous Complex, but in them sufficient proof was obtained that they are of sedimentary origin.

16 - MAGNETITITE PIPES AND ASSOCIATED BRECCIA

A - Distribution

Nine pipes were located on The Consolidated Farm Mapochsgronde 500 JS. Of these, two are between the

seams/.....

seams of Subzones B and C, four are in close proximity of the lowest magnetitite seam of Subzone C, two are near the seams of Subzones A, and one is in gabbro well below the contact with the magnetite gabbro. The last-named pipe is in the nature of a ring-intrusion with pegmatoid material in the centre of the intrusion. This ring-intrusion lies north of Trigonometrical beacon Mapoch 1. In addition, one body which may be a short fissure was encountered along the third magnetitite seam of Subzone C. It appears to displace this magnetitite seam.

On De Lagersdrif 178 JS three pipes were located close to the main seam. Two of them (plates 10 and 11) have breccia material associated with them. Just north of the Laersdrif Fault on the same farm a small pipe lies close to scattered outcrops of the seams of Subzone C.

On Blinkwater 213 JS north-east of Stoffberg a pipe was located and here again it is present near the Main Seam of Subzone B. It also has associated breccia material.

The largest pipe in the area has formed on Welgevonden 215 JS, near the Main Seam of Subzone B just east of the Steelpoort River.

The fourteen pipes and the possible fissure are all shown on the geological map.

B - Mineralogy of the Breccia

1 - Megascopic Features

With the unaided eye very few minerals can be identified with ease. Even the quartz was not noticed until microscopic work was done. This is due to the fact that a very fine matrix with colours varying from white to grey and various shades of brown cloud the other minerals. In fact, the only minerals recognizable visually are magnetite and goethite.

The rock varies from fairly compact to very porous varieties. Fragments, mostly of magnetite, may be small, but larger pieces measure several inches across. They are embedded in the matrix. The magnetite fragments are angular and of all shapes.

2 - Microscopic/.....

Plate 10 - A typical magnetitite pipe. The koppie which is about 35 feet high also contains some breccia material. The pipe is present on De Lagersdrift 178 JS.

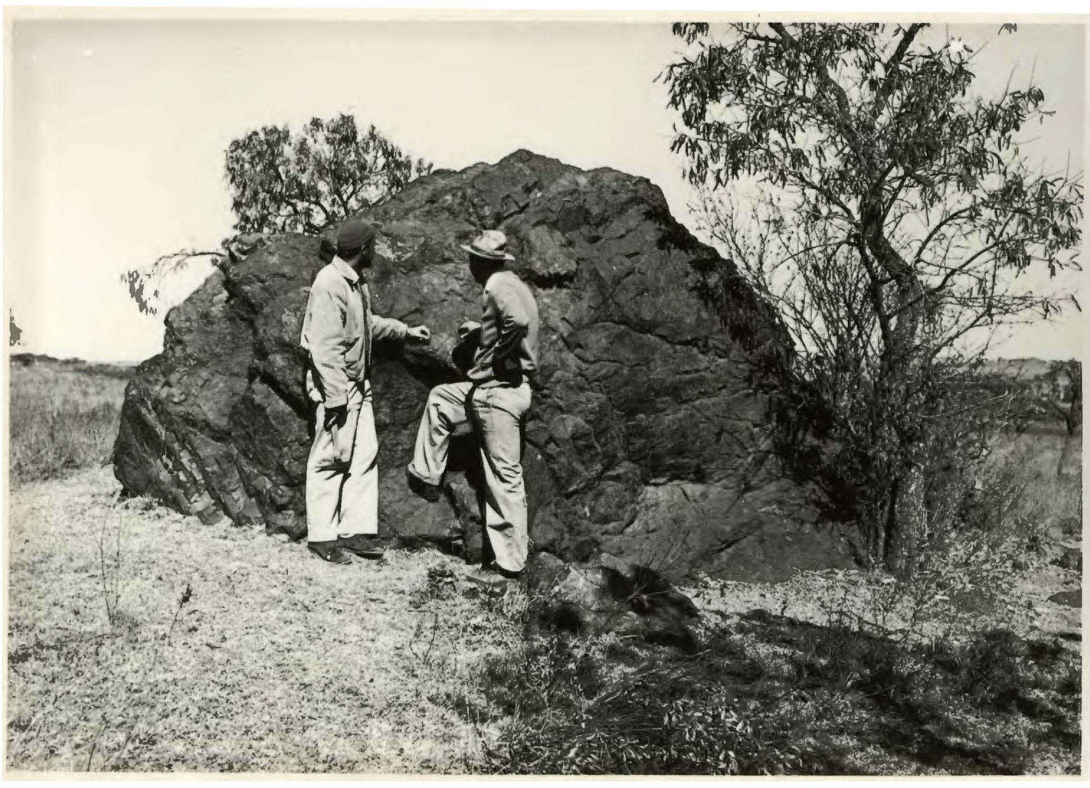
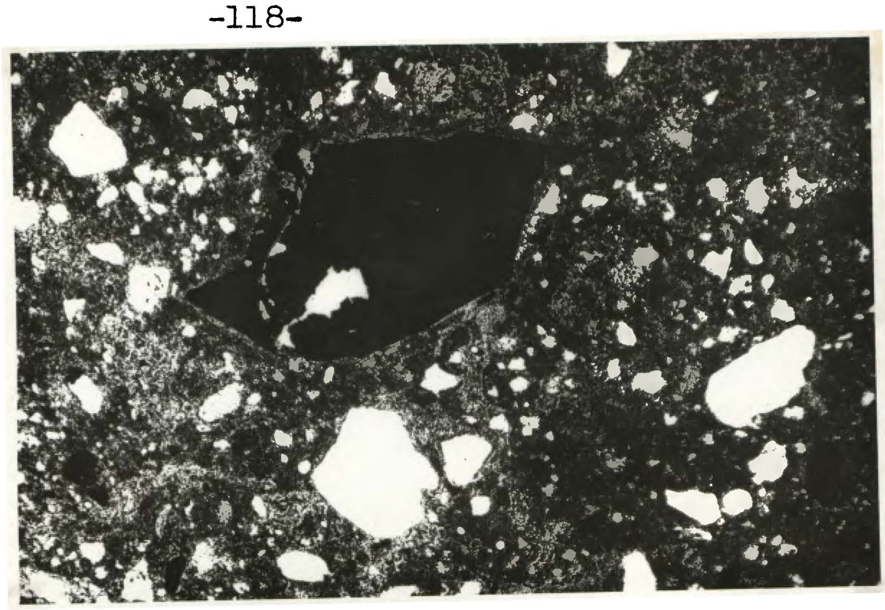
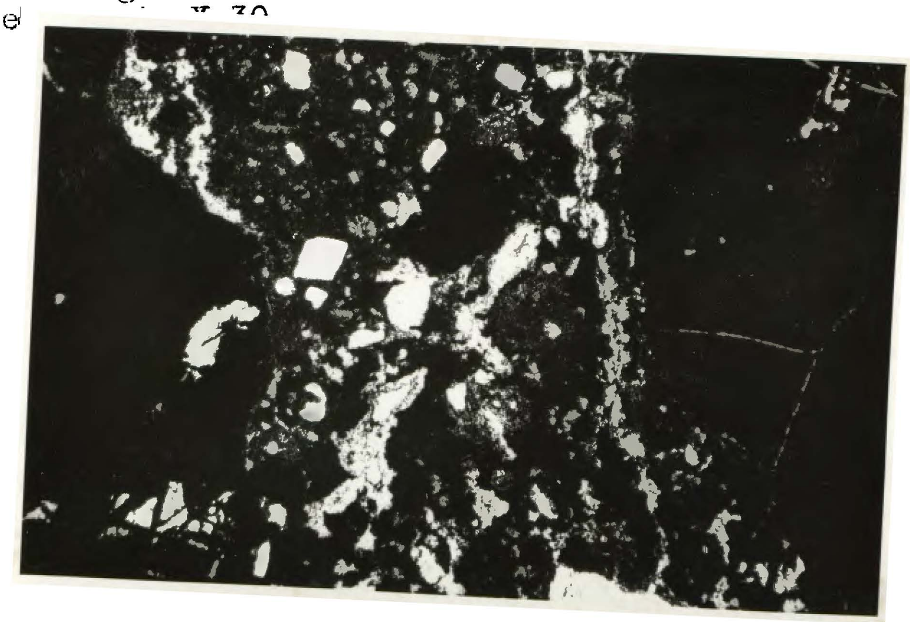


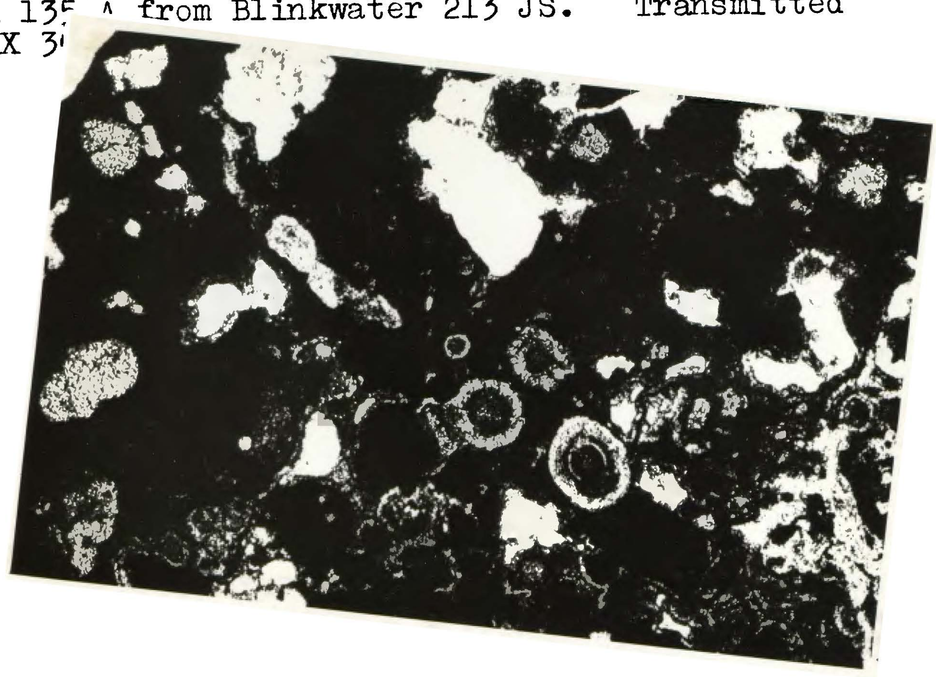
Plate 11 - The smallest magnetitite pipe found. It also has breccia associated with it. The pipe is present on De Lagersdrift 178 JS.



Photomicrograph 22 - Breccia from a magnetitite pipe on Blinkwater 213 JS, showing quartz (white) of different dimensions and one magnetite grain (pitch black) lying in a matrix of goethite (black). Thin section 135. Transmitte[illegible]



Photomicrograph 23 - Quartz-goethite breccia material flanked by goethite with very little quartz. Thin section 135 A from Blinkwater 213 JS. Transmitted light, X 3[illegible]



Photomicrograph 24 - Spherulites lying in quartz-goethite breccia material. Thin section 805 from Blinkwater 213 JS. Transmitted light, X 30.

2 - Microscopic Features

In transmitted light not much can be seen as the matrix is dark coloured. Flow-structures and banding are common.

In the matrix the following minerals are very irregularly scattered:

Quartz is seen in all shapes and sizes from less than 0.006 mm diameter to 1.15 mm along the longest axis (photomicrographs 22 to 24).

Goethite may be observed as irregular veins and also bands and as part of the matrix (photomicrographs 22 to 24).

Spherulites have formed in some parts of the breccia and may surround quartz grains. The material which constitutes the spherulites has the following refractive index:

$$n\gamma' = 1.720\ (\pm\ 0.003).$$

Its true identity could not be established. The spherulites are nearly spherical although some are deformed. They are further characterised by an imperfect black cross between crossed nicols. Their diameters vary from 0.04 mm to 0.24 mm. An imperfectly shaped one measured 0.50 mm by 0.59 mm. The centres of some spherulites consist of quartz and in one of them a small grain of magnetite is included.

Phosphate occurs as irregular veins. The material was investigated by means of X-ray analysis and was found to give weak lines which compared with some of the apatite lines. The identity of the mineral was however, not conclusively proved. At least some of the phosphate is not visible under the microscope, as in sections cut from specimens which gave phosphate-positive tests no phosphate could be observed.

Generally the material has no recognizable shape or crystal habit.

Magnetite is clearly visible as opaque grains and smaller fragments in the breccia stand out.

A complete mineralogical study of the breccia material associated with the magnetitite pipes will probably reveal the identity of minerals additional to those listed above. Similar pipes with breccia material have formed south of the area investigated. They were not examined.

Volumetric/.....

Volumetric determinations were done to give a rough idea of the proportion of matrix and other minerals to quartz and magnetite. The results are given in the following table:

Table 24.

Volumetric composition of three breccia specimens

Specimen No.	135	135A	138
Matrix, Phosphate	87	84	96
Quartz	10	12	3
Magnetite	3	4	1
Total	100	100	100

C - Weathering

The pipes are resistant to erosion and stand out boldly above the magnetite gabbro. Jointing is prominent and this no doubt assists in the breaking up of the material. The ground surrounding the larger pipes is strewn with magnetitite rubble of different sizes.

D - Origin of the Magnetitite Pipes

The magnetitite pipes mapped in the Stoffberg area furnished sufficient evidence to assign to them an intrusive mode of emplacement. Their circular and plug-like shape, typical of intrusive material, can be seen clearly in the field and on aerial photographs. On Malekskraal 509 KS in Sekhukhuneland, a magnetitite pipe in contact with magnetite gabbro was examined. The magnetite gabbro is conspicuously sheared along the contact.

According to surveys by Coertze, Morgan and Dürr (Geol. Survey) a magnetitite occurrence of Goedgedacht 114 JQ in the Rustenburg District lies in normal gabbro well below the lowest group of magnetitite seams. Dürr's magnetic survey around the "magnetite kop" showed that the anomalies decreased away from the Kop and that the magnetitite therefore does not extend in any direction. The body is therefore taken to be a pipe. The TiO_2-content of the ore is also much higher (about 20 per cent TiO_2) than that normally found in the seams.

Owing to the poor exposures away from the actual magnetite cores, the rocks surrounding them could not be examined, but Coertze mentions magnetite-rich dunite associated with pipes in Sekhukhuneland. It is doubtful whether this relationship holds around the Stoffberg pipes. The impression gained is that at most of the pipes magnetite gabbro surrounds them. At the pipe near the Steelpoort River in the southern part of Welgevonden 215 JS coarse-grained pegmatoid material consisting of amphibole and plagioclase was found around the main magnetitite body. Drilling by AMCOR at the pipe north of Trigonometrical beacon Mapoch 1 on The Consolidated Farm Mapochsgronde 500 JS revealed the presence of pegmatoid material.

Irregular bodies similar to the unique occurrence on Kennedy's Vale have not been located in the Stoffberg area. The body on Kennedy's Vale dips at $70^{\circ}N$, is 150 feet thick and has a proved distance on strike of 1,200 feet. Whereas other intrusive bodies of magnetitite usually have fairly low V_2O_5 contents, the Kennedy's Vale material contains 2.06 per cent V_2O_5 on the average. The highest value obtained was about 4.5 per cent. Its position in the Bushveld Igneous Complex is well below that of the seams of Subzone A.

Apart from a drilling programme by the Anglo American Corporation of South Africa Ltd. at the Kennedy's Vale occurrence very little is known about the persistence of the pipes with increasing depth. The drilling at Kennedy's Vale revealed that the body thins and splits at depths below 300 feet. (Information supplied by the Resident Geologist, Mr. Marais, in 1961).

In the Stoffberg area, a fairly large pipe, near the Main Seam of Subzone B on De Lagersdrift 178 JS (Plate 10) rises some 35 feet above ground-level. A still larger pipe on Welgevonden 215 JS, also near the Main Seam of the Subzone B, reaches about 50 feet above ground-level. Farther south, and outside the area mapped, a pipe, near the Main Seam of Subzone B, was seen and judged to attain a height of well over 50 feet.

As/.....

As the pipes mentioned above are near a magnetitite seam, it may be argued that they are connected with it. Taking all the pipes near the Main magnetitite Seam of Subzone B shown on the map into consideration it is seen that some are above and others below the Main Seam. Although those pipes above the seam could be connected with it, the pipes below must have been fed from a still lower source. The pipes are related to, but independent of the seams.

There are pipes which have formed some distance away from the seams, notably those in the gabbro of the Main Zone, for example the pipe north of Trigonometrical Beacon Mapoch 1 on The Consolidated Farm Mapochsgronde 500 JS. The pipe shown in Section A-B on the geological map is another example. These pipes must have been fed from a pegmatoid pool and it is obvious that the Fe-Ti-V-melt had already separated from the silicates. These pools must have been present at various levels in the magnetite gabbro and, to a lesser extent, in the gabbro of the Main Zone. Most of them formed in place. In order to ease the pressure exerted on those pegmatoid pools by the congealing gabbroic magma, the magnetite melt was injected upwards. In this way the pipes are depicted as bodies which do not extend to great depths.

A peculiar phenomenon of the pipes relative to seams near by is their similarity as regards the vanadium content. Those pipes near the Main magnetitite Seam of Subzone B all have a V_2O_5 content of more than one per cent. The average V_2O_5 content of the main seam is taken as 1.6 per cent. The magnetitite pipes near the seams of Subzone C on Onverwacht 148 JS have about 0.5 per cent V_2O_5. The seams here contain about 0.6 per cent V_2O_5. North of the area mapped a pipe near the Upper Seam of Subzone D which contains 0.3 per cent V_2O_5 is reported to have less than 0.3 per cent V_2O_5.

The pipes in the gabbro of the Main Zone have V_2O_5 contents exceeding 1 per cent.

The conclusion to be drawn from the comparisons made above is that the material constituting each pipe is more or less the same as that of the particular seam near-by. The magnetite pipes will therefore not extend to depths much greater than the height on surface of the near-by

seam./.....

seam. This is of course not the case with the pipes in the gabbro of the Main Zone where no seams of magnetitite exist owing to the limited amount of iron and titanium available.

E - Origin of the Breccia

The four magnetitite pipes with which breccia is associated are all, at their present exposed level, close to the Main magnetitite Seam of Subzone B. The magnetitite outcrops have breccia material as cappings here and there, and in some pipes the breccia follows open joints and large cracks in the magnetitite. The two men in Plate 11 are looking at a small patch of capping-breccia.

One of the significant constituents of the breccias is phosphate as earthy material. Qualitative tests for phosphate on all the breccia samples proved to be positive. Schwellnus and Willemse (1943, p. 34) reported 6.96 per cent of P_2O_5 in a sample taken from a crush-zone passing through a magnetitite pipe on Goedgedacht 114 JQ (old registration No. 409) in the Rustenburg District. This breccia-zone was regarded by the authors to be of secondary origin.

Apart from the equally surprising presence of the spherulites, the presence of quartz in amounts of as much as 21 per cent is also very interesting.

Neither the quartz nor the spherulites are ubiquitous constituents. Some sections show no quartz and the spherulites were noticed in only one section. The development of quartz in some parts of the breccias strongly suggests that it is of secondary origin. Quartz is never found within the main magnetite mass comprising the pipes. The presence of the quartz will therefore be ascribed to subsequent supergene contamination.

The goethite present in the matrix and as veinlets further points to secondary precipitation of material from percolating solutions.

Breccia, similar in appearance to that associated with the four pipes, was seen in open joints in the poorly differentiated seams of Subzone D below Tautesberg on Duikerkrans 173 JS. In these breccias angular fragments of magnetite, of varying size, lie embedded in a matrix which consists mainly of the completely altered constituents of the surrounding magnetite gabbro. Fairly fresh plagioclase, in subordinate amounts, was all that could be identified. The matrix is loose and powdery in contrast with the fairly hard and consolidated matrix of the pipe-breccias. The breccia associated with the seams of Subzone D is clearly of secondary origin. The fact therefore emerges that breccias consisting of angular fragments of magnetite in a fine-grained matrix can form in the magnetitite seams in the same way as gossan. In the case of the breccias associated with magnetitite seams it appears that no precipitation of foreign minerals from mineralising solutions has yet taken place.

If the breccias associated with the pipes are due to solution and oxidation they will appear as superficial and near-surface features only. Owing to the fact that none of the pipes which has associated breccias has been tested at depth by drilling, it is not known whether it persists well below ground level.

If the breccias are of volcanic origin, and therefore primary, they must be referred to as pyroclastic breccias. The quartz will then be an original constituent and the breccia will be rhyolitic in composition. Spherulites are typical of some rhyolitic magmas (Hatch et al, 1951, o. 224).

The ubiquitous presence of phosphate in varying amounts, as earthy material, is difficult to account for. Phosphate is not a common constituent of rhyolitic magmas. If the breccias are gossan the phosphate must either have crystallised from the mineralising solutions or must have formed from organic deposits taken up by the porous breccia.

Considering all the available evidence, the most likely explanation for the association of the breccia with some of the pipes, is that the breccia represents gossan material formed by percolating mineralising solutions moving upwards along the pipes and that the goethite, quartz, spherulites and other products crystallised from these solutions. No outward migration of the solutions appears to have taken place as no breccias were seen away from the pipes.

17 - MINERALOGY/.....

17 - MINERALOGY OF THE ORE

A - General

Before proceeding with the actual microfacial description of the ores it must be stressed that an infinite number of textural relationships have been observed. It was noted for instance that in one and the same sample, the nature of mineral distribution varied markedly from one part to the other.

Of prime importance in the ore-microscopic study of the Bushveld titaniferous and vanadiferous ores is that, as far as surface and near-surface material is concerned, the majority of the so-called different types of Ti-V-magnetite are merely stages in its alteration to maghemite and hematite. It was found that magnetitite core at more than 1,000 feet in a bore-hole on Vlakfontein 207 JP, Rustenburg District, showed none of the oxidation minerals and the same held for core from Kennedy's Vale. Ortlepp (1959, p. 44) who examined core from depths of over 1,000 feet in an igneous pluton, found that the minerals were not altered to the extent of surface material, such as that examined by Strauss (1946, p. 46). Fortunately many samples from surface still retain the original textures even though parts of the sample show signs of incipient alteration.

A rather disconcerting factor in the examination of the ores is that the visual identification of minute intergrowths cannot be fully substantiated by chemical or by X-ray analyses.

Before commencing with a study of the ores relevant publications were carefully studied. Ramdohr favours the name ulvite (1960, p. 486) for a mineral of the spinel group and gives its composition as Fe_2TiO_4. Previously he referred to this mineral as ulvöspinel (1953, p. 677). Basta refers to this mineral as titanomagnetite (1959, p. 698) and gives its composition as Fe_3O_4- γ - $FeTiO_3$. In the present work the name ulvite is favoured and hematite and maghemite is taken to be altered, opaque material while the titaniferous, vanadiferous magnetite is primary grey and/or pink-coloured material.

The primary constituents of the magnetite ore are ilmenite, titaniferous and vanadiferous magnetite, ulvite, spinel (pleonaste), sulphide ore-minerals and gangue material.

The/.....

The secondary minerals are maghemite, titanomaghemite, hematite and goethite. It is suspected (from microscopic study) that the grey-coloured Ti-V-magnetite (i.e. with little Ti) altered to hematite, and the more light pink-coloured Ti-V-magnetite (i.e. with more Ti) to titanomaghemite.

B - Megascopic Description

On a weathered surface the ore is dull brownish black but fresh surfaces have a bright black to greyish-black, metallic lustre. Fresh samples produce a brownish-black powder on pulverisation but when weathered the powder is often brownish and even red, thereby indicating the degree of hematitisation. The ore is veined in places by secondary goethite. The goethite has also settled on joint-planes where botryoidal structure may be developed.

Many varieties of ore have formed - even in one single seam all types may be developed. They include massive, hard lumpy, compact, coarse- and fine-grained, and friable coarse- and fine-grained varieties. The friable granular types are the result of the agencies of weathering. The thin films of gangue-material between grains weather to kaolinitic and chloritic material, thereby destroying the cohesive bond between grains. It was noticed that in the friable granular ore the crystals are coated mostly with white powdery kaolinitic material, which is a product of alteration of plagioclase. In the massive type of ore, grain-boundaries are irregular (anhedral), but in the granular types grains are euhedral, octahedron and dodecahedron faces being recognizable. The largest single crystal measured 12 mm in diameter. From this size they may grade downward to as small as 1 mm and less.

Ilmenite with its brighter lustre is usually visible on fresh surfaces.

The magnetism of the seams and pipes is very variable, depending mainly on the degree of alteration. Some ores act as natural magnets and are known as lodestone. This lodestone which is more common to the pipes, is used quite extensively on office desks, but as far as is known, it is not sold commercially for this purpose.

C - Microscopic/.....

C - Microscopic Description

A wealth of mineragraphic information on the Bushveld ores has been made available through official publications and unpublished reports. The main workers in this field include Frankel and Grainger (1941), Schwellnus and Willemse (1943), Strauss (1946), Ramdohr (1953; 1960), Coertze (1958; 1967), Basta (1957) and Hiemstra and Liebenberg (1964). For the purpose of this study the work by Ramdohr on ulvite is adopted as standard. It must however be mentioned that Mogenson (1946, p. 578) was the first to identify this mineral from the Grundhamn Mine on one of the Ulvö Islands, Sweden. He identified it as ferro-ortho-titanate with a spinel structure viz. Fe_2TiO_4, i.e. FeO + $FeTiO_3$. He found this mineral intimately associated with magnetite.

Ilmenite (photomicrographs 25 to 32) is readily recognized in the magnetite ore from the Bushveld Complex. Its reflection-pleochroism and strong anisotropism are diagnostic properties. Commonly the ilmenite may be observed as anhedral grains which vary in size from much less than 1 mm to 1 mm and larger. In this form it has crystallised before the titaniferous, vanadiferous magnetite and complete unmixing and segregation of the ilmenite-magnetite solute has resulted. The ilmenite is always fresh and no alteration to leucoxene, brookite, or anatase was ever seen. Von Gruenewaldt (1966, p. 77) noted alteration products of ilmenite and concluded that they are leucoxene. Photomicrograph 26 is an example of separate grains of ilmenite in the ore.

Ilmenite has also formed as lamellae intergrown with titaniferous, vanadiferous magnetite, which in the zone of weathering is often altered to hematite. A parallellism with octahedral crystallographic directions is often noticeable. Visually the ilmenite lamellae can be distinguished from the ulvite by their darker pink colour.

Very fine lamellae of ilmenite can easily be mistaken for ulvite, but their pleochroism and anisotropism confirm their identity.

Ore with the typical exsolution-lamellae of ilmenite is usually found in the Upper Seam of Subzone D. This is not the rule, however, because the lamellae also

occur/.....

occur in the magnetite gabbro below the seams of Subzone B. The lengths of the ilmenite lamellae vary from less than 0.1 mm to 2 mm and more.

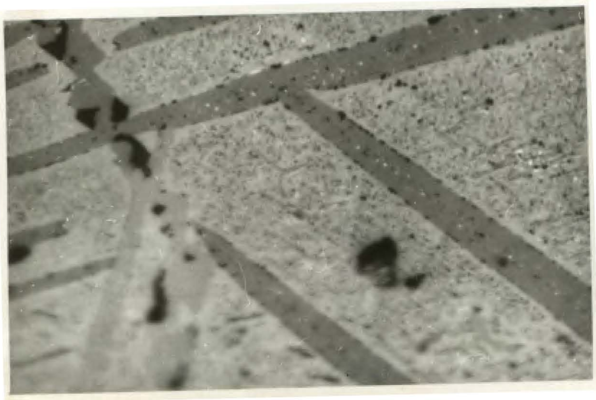
Magnetite and ulvite. Magnetite is one of the "scarce" minerals in the seams, as exposed at or near the surface. This fact was proved by exhaustive unit cell determinations with the aid of X-ray analysis. In one determination the cell edge almost agreed with that of pure magnetite. The material examined was taken from a piece of core from a depth of more than 1,000 feet on Vlakfontein 207 JP, Rustenburg District, where a drill-hole was put down to test the downward extent of the nickel deposits in that area. This magnetite is considered to be in solid solution with TiO_2, V_2O_5 and γ -Fe_2O_3 (maghemite). For the purpose of this study it is referred to as titaniferous, vanadiferous magnetite. When this material oxidises the unit cell decreases.

Some veins and cracks have been filled by material consisting of intergrowths of magnetite and hematite. This magnetite may be free from titanium, vanadium and other impurities. Its time of formation post-dates that of the principal minerals comprising the seams. Unfortunately the veins are too small to allow sufficient uncontaminated material to be drilled out for X-ray study. The colour of this magnetite is more clear light pink in comparison with the other varieties of magnetite. It takes a much better polish than the other minerals in the section.

On all polished surfaces titaniferous, vanadiferous magnetite is intimately associated with ulvite (photomicrographs 32, 33, 34, 35, 36 and 37), the two minerals having unmixed at more or less constant temperature. In general the two minerals have occupied the cubic lattice, but often the eutectic intergrowth is irregular and not aligned parallel to any particular crystallographic direction.

The colour of the titaniferous, vanadiferous magnetite varies from light grey to grey and different shades of pink. This material is isotropic in fresh samples but variably anisotropic when weathered. The pinkish magnetite is fresh and the light grey material is practically completely altered to hematite.

Where/.....



Photomicrograph 25 - Ilmenite lamellae in a fine intergrowth of ulvite and magnetite. Polished section 287 from Subzone D, Blinkwater 213 JS. Oil immersion, X 1540.

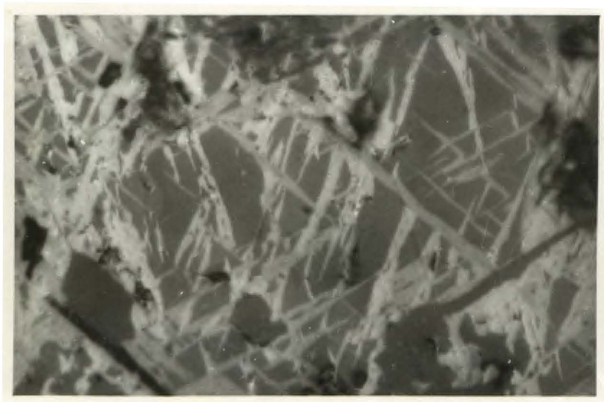
Photomicrograph 26 - Irregular patches of ilmenite in magnetite. Polished section 287 from Subzone B on Blinkwater 213 JS. Oil immersion, X 1540.

Photomicrograph 27 - An ilmenite lamella in an irregular intergrowth of magnetite (light grey). The magnetite has been altered to hematite (white). Polished section 70 from Subzone D on Enkeldoorn 214 JS. Oil immersion, X 1540.

Photomicrograph 28 - Prominent irregular intergrowth of ilmenite (grey) and magnetite in process of alteration to hematite (white). Polished section 70 from Subzone D, Enkeldoorn 214 JS. Oil immersion, X 1540.

Photomicrograph 29 - Parallel intergrowth of ilmenite (grey) and hematite (white). Polished section 193A from Subzone B, Blinkwater 213 JS. Oil immersion, X 1540.

Photomicrograph 30 - Four directions of parallel intergrowth between ilmenite (grey) and hematite (white). Polished section 70 from Subzone D, Enkeldoorn 214 JS. Oil immersion, X 1540.



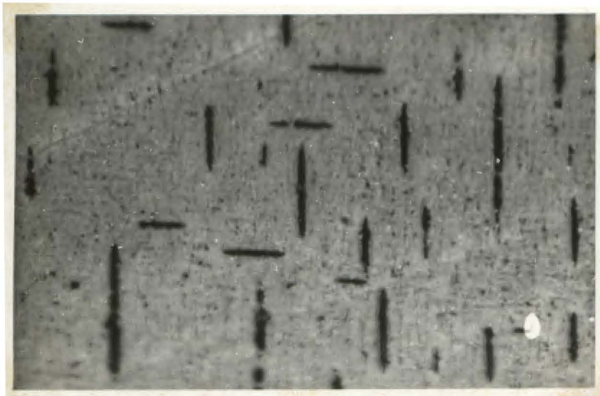
Photomicrograph 31 - Fairly coarse octahedral intergrowth of ilmenite (grey) and hematite (white). Polished section 70 from Subzone D on Enkeldoorn 214 JS. Oil immersion, X 1540.

Photomicrograph 32 - Part of an ilmenite grain (dark grey) in contact with an intergrowth of magnetite (light grey) and ulvite (grey). Along the border of the ilmenite only magnetite crystallised. Polished section 287 from Subzone D, Blinkwater 213 JS. Oil immersion, X 1540.

Photomicrograph 33 - Parallel intergrowth of magnetite (light grey) and ulvite (grey). Polished section 280 from drill-hole core at 900 feet on Vlakfontein 207 JP, Rustenburg District. Oil immersion, X 1540.

Photomicrograph 34 - Very fine parallel intergrowth of ulvite and magnetite (light grey). Polished section 280A from drill-hole core at about 1,000 feet on Vlakfontein 207 JP, Rustenburg District. Oil immersion, X 1540.

Photomicrograph 35 - Cubic pattern of intergrowth of ulvite (grey) and hematite (white). Polished section 148 from Subzone B, on Blinkwater 213 JS. Oil immersion, X 1540.



Photomicrograph 36 - Cubic orientation of spinel needles in an intergrowth of ulvite (grey) and magnetite (light grey) of the same orientation. Polished section 280 from drill-hole core at 900 feet on Vlakfontein 207 JP, Rustenburg District. Oil immersion, X 1540.

Photomicrograph 37 - Spinel needles prominently bordered by magnetite (light grey) which in turn is bounded by ulvite. Polished section 280 drill-hole core at 900 feet on Vlakfontein 207 JP. Oil immersion, X 1540.

Photomicrograph 38 - Light- and dark grey goethite cut by a later vein of dark grey goethite. Polished section of ore from Main Seam; Blinkwater 213 JS. Parallel nicols, X 22.

Where the titaniferous, vanadiferous magnetite shows alteration, the ulvite stands out clearly and has apparently not been altered. Oxidised ulvite may be slightly pleochroic from light grey-brown to darker chocolate brown.

The alteration of the titaniferous, vanadiferous magnetite may be patchy (photomicrograph 35) or regular (photomicrograph 29). The patchy type of alteration may give rise to as many as 3 or 4 differently coloured zones. This has been admirably illustrated by Strauss (1946, p. 46). Typically the alteration proceeds from grain boundaries and cracks. Where these are numerous hematite is plentiful.

Maghemite, hematite (photomicrographs 27 to 31).

Although some workers believe that maghemite is not developed in Bushveld ores, evidence was found to suggest the possible presence of maghemite. This is especially the case where titaniferous magnetite has altered to show light blue material which is associated with white hematite. This material has also been recognised by Basta (1959, p. 711) who refers to it as titanomaghemite. X-ray patterns of fresh ore containing pink and blue material yield variations of the magnetite structure.

Little doubt can exist that the white anistropic, weathered products are all hematite. Furthermore, ore with much white anistropic material invariably yields a red powder, which is also typical of hematite.

Therefore, whereas hematite is a product of secondary oxidation the different types of maghemite are only partially secondary and possibly also primary.

Spinel needles are dark coloured under parallel nicols and are probably pleonaste. They stand out prominently on polished surfaces owing to their hardness. They can be seen under fairly high magnification but are invisible to the naked eye.

Some samples are riddled with cubic gratings formed by tiny needles of pleonaste. These pleonaste needles are characteristic of samples from seams of Subzone C. The other zones also contain pleonaste but not to the same extent. A characteristic feature of the pleonaste is that the spaces around them usually

consist/ .....

consist of titaniferous magnetite which may be altered to maghemite or hematite (photomicrograph 37).

The pleonaste forms but a small percentage of the ore but could account for most of the magnesium in the analyses.

Goethite: Goethite is of secondary origin and occupies veins, cracks, fractures, minute joints and bedding planes. The vein- and fracture-fillings can readily be identified in most weathered samples. Fresh material is practically devoid of this mineral. The veins are usually occupied by alternations of light-grey and darker grey goethite (photomicrograph 30). A later phase of goethite traverses an earlier one. Secondary magnetite, intergrown, with hematite may be associated with the goethite and has probably formed simultaneously with the latter.

Sulphide Minerals (Chalcopyrite, Pentlandite, Pyrrhotite)

Chalcopyrite is the most common sulphide and careful study reveals that most sections contain very fine-grained chalcopyrite. In this form it is enclosed in titaniferous magnetite. More rarely it is found as large grains visible in hand-specimens. The pentlandite is present as tiny grains around chalcopyrite although it has crystallized separately; rarely it is found within or around pyrrhotite. The more coarse-grained development of sulphides has only been found in the Main Seam of Subzone B and in the magnetite gabbro well below it. An anorthosite layer below the thick seam of Subzone D, on Duikerskrans 173 JS (folder 1), is riddled with sulphides.

In the magnetite gabbro, chalcopyrite, pyrrhotite and possibly also pentlandite, are present as tiny grains within plagioclase, and are therefore amongst the first minerals to have crystallized from the magma.

All these minerals account for copper and nickel in the analyses.

Gangue-minerals: In solid ore, silicate gangue is seldom seen. Very finely disseminated silicates have probably been leached out but larger crystals are occasionally admixed with solid ore. In the transition-zone silicates increase, and here the ore is often finely

intergrown/.....

intergrown with silicates. An exceptional type of intergrowth is where the intergrowths have occupied the cubic lattice. More commonly however, irregular graphic intergrowths between gangue-minerals and titaniferous magnetite prevail. It would thus appear that as far as the transition-zone is concerned crystallisation of ore and gangue was more or less contemporaneous, the silicates tending to crystallize first.

The same minerals and the same textural relationships are found in ore from the intrusive pipes, but the main difference is that titanium is generally more plentiful in the pipes. Some samples have as much as 25 per cent of pure ilmenite. Another property of the pipes is the advanced stages of weathering which give the polished surfaces a typically mottled appearance. This property is not a diagnostic feature of the pipes as it is also common to the seams. As in the case of the seams the vanadium content of the ore from the pipes varies from less than 0.5 per cent to about 1.5 per cent.

The magnetite in the magnetite gabbro shows a surprising similarity to that of the seams. It is therefore taken as possible that the magnetite from the magnetite gabbro and the magnetite from the seams emanated from the same magma. The V_2O_5 present in pure ore, separated by physical processes from the magnetite gabbro was 1.45 per cent while that of the underlying seam was about 1.6 per cent.

18 - DETERMINATION OF VANADIUM AND TITANIUM IN THE MAGNETITITE

A - Introduction

The detection of vanadium and titanium in the ore can be achieved either qualitatively, semi-quantitatively or quantitatively. Wet chemical analyses were not attempted as they fall outside the scope of the geologist. Several laboratories have adopted new, more exacting and precise techniques, similar to those used for the detection of vanadium in steel.

B - Quantitative/.....

B - Quantitative Determination for Vanadium

Toerien (1959, pp. 1-5) has successfully determined vanadium and molybdenum quantitatively and simultaneously by ion-exchange chromatography. He states that the older methods for determining small amounts of vanadium in samples containing Fe, Cu, Mn, Cr, Ni, etc., in relatively large quantities were found to be unsatisfactory, probably as a result of co-precipitation and absorption of these metals. According to Toerien the method owes its accuracy and rapidity to the following:

(1) Both molybdenum and vanadium are completely separated from interfering elements and from each other.

(2) Only a small quantity of the sample need be taken. Hence, decomposition of the sample is greatly facilitated.

(3) No lengthy precipitation and extraction procedures are involved.

There are apparently many pitfalls in the quantitative chemical determination of vanadium. Groves (1957, p. 131) mentions:- "In the quantitative analysis for vanadium the solution must be filtered carefully through a 7 mm No. 40 paper to remove traces of ferric oxide. A No. 41 paper is apt to pass iron which renders colorimetric comparison inaccurate and on acidification gives a high value for vanadium". Toerien states:- "Small amounts (0.5% or less) of vanadium cannot be successfully determined volumetrically by means of potassium permanganate. The end point of the oxidation-reduction filtration is uncertain since the titrating solution is necessarily very dilute (0.01n)".

C - Methods used in present Study

1 - Qualitative Tests

(a) - Drop-method of Vanadium Detection

The solution under examination is oxidised by concentrated nitric acid . A drop is placed on a filter paper previously wetted with analine hydrochloride, when a greenish ring forms in the presence of vanadium. This reaction indicates the presence of vanadium up to limiting concentrations of not less than 0.3 mg per cc.

Cations/.....

Cations do not interfere with this test which cannot, however, be made in the presence of chromate, chlorate, hypochlorite and permanganate of iron; should those be present, the solution must first be boiled with concentrated hydrochloric acid.

This method was tried in the hope of locating vanadium-enriched areas on polished surfaces, but it was found that most areas drilled out with a dental drill gave positive results and no idea as to the possibly enriched areas could be established. The method is not applicable to semi-quantitative tests but can serve as a quick, inexpensive and effective method of establishing the presence of vanadium.

(b) - Colorimetric Test for Vanadium in the presence of Titanium

The method is briefly as follows:

Fuse a small quantity of the material (about 0.1 gram) with potassium bisulphate. Dissolve the melt in dilute sulphuric acid. The solute is usually coloured yellow due to the formation of ferric sulphate. Add some phosphoric acid until the solution becomes clear (the phosphoric acid changes the iron sulphate to iron phosphate which has a much weaker colour).

Now add a little hydrogen peroxide. The colour of the liquid will be brown if titanium or vanadium is present. If, as in the case of Bushveld ore, titanium is present, crystals of sodium fluoride must be added to remove the titanium colour while that of vanadium (more yellowish-brown) remains.

It was found that the presence of quantities less than 0.4 per cent, V_2O_5 could not be conclusively established.

The method is very useful in routine laboratory identification.

(c) - Semi-Quantitative test for Vanadium

The colorimetric test just described was used as a standard method and was extended to determine vanadium semi-quantitatively.

The following procedure was adopted:

A sample of which the percentage of vanadium has been accurately determined, is taken as a standard. The

percentage/.....

percentage V_2O_5 present in the standard sample is therefore the highest percentage which can be determined colorimetrically. In the present study a standard sample containing 2.5 per cent of V_2O_5 was used. This sample is used as follows to make up standards for colorimetric comparison:

Fuse 0.05 g of standard sample, with 3 g potassium bisulphate. Add 1 cc concentrated sulphuric acid and 5 cc H_2O to the melt and dissolve. Then add 2 cc phosphoric acid.

Make up the solution to 10 cc with distilled water. This is the first standard solution.

Add 2 drops of hydrogen peroxide to 2½ cc of the first standard solution. The resultant brown colour due to titanium is removed and the intensity of the resultant yellowish brown colour represents ± 2.5 per cent V_2O_5.

By taking a further 2½ cc of the standard solution and diluting it to 5 cc, half of the V_2O_5 percentage viz. 1.25 per cent is obtained, and so on.

The unknown material is now subjected to identical treatment i.e. up to the first standard solution stage, when it is colorimetrically compared with the different standard solutions ranging from 2.5, 1.25 and 0.625 to 0.312 per cent.

By taking less than 0.05 grams of material the colouring is weakened below effective perceptible comparison, and by taking more, the titanium colouring interferes unduly. In each case the colour of the unknown solution was compared visually with that of the standard solution.

It was noticed that, after a while, the titanium colour returns and further sodium fluoride must be added. The V_2O_5-colouring in the standard solutions weakens after a week or two and fresh standards have then to be prepared. This is the only drawback of the method, which can be regarded as a cheap and effective way of doing preliminary tests in order to indicate ore of possible economic grade. After this has been done expensive but accurate determinative methods can be proceeded with on selected samples.

(d) - Quantitative/.....

(d) - Quantitative Spectrographic Determination

Procedure -

In preparing a standard, pure magnetite from Allanwood, U.S.A., was tested spectrographically for the presence of vanadium and titanium as well as for some other possible deleterious elements. This magnetite, which was used by SASOL as a catalyst (in 1959), was found to be exceptionally pure. It was therefore selected for the preparation of samples containing known percentages of vanadium and titanium. Spectrographically pure V_2O_5 and TiO_2 were mixed with the magnetite to obtain the different percentages.

To obtain a standard containing 3.16 per cent of vanadium 0.05641 g of V_2O_5 was added to 0.94359 g of pure magnetite from Allanwood. (The same procedure was adopted in preparing titanium standards but here percentages ranging from 1 to 25 per cent were used.)

During the experimental stage it was found that for quantities of vanadium and titanium exceeding 0.5 per cent the spectral lines were too strong when this material was arced after mixing with the internal standard and graphite. It was therefore decided to dilute the material with pure quartz which is readily available. The most suitable ratio arrived at was 1 part of standard : 9 parts of quartz. The silica lines do not interfere with the selected spectral lines of vanadium and titanium.

Both the Allanwood magnetite and the diluent was pulverized to -325 mesh Tyler. Copper, mixed with graphite in the ratio of 9:20 was used as an internal standard. The ratio of base material (i.e. material to be analysed) to internal standard was 1:1. In this way arcing was complete and lines were generally clear for the range of percentages required.

In all the determinations mixing was done in unmarked agate mortars with chemically pure methanol or ethanol, and then oven-dried at 80^oC for half an hour.

All the determinations were done in triplicate. It was found that by weighing 0.05 g of the prepared unknown samples and 0.45 g of quartz (ratio 1:9) enough of the material is available for these determinations. Further, by taking 0.07 grs of the prepared

base/.....

base material against 0.07 g of internal standard enough material is available to load three electrodes.

The samples were arced in hollowed graphite anodes using pointed cathodes on a large Hilger Littrow spectrograph. The following spectrographic conditions were adhered to throughout the examination:

Arcing time: from 1½ to 2 minutes.
Current: Constant at 8 amps.
Film: Ilford Thin Film, half tone, Plate N. 50.
Slit width: 0.03 mm.
Gap: 10 mm.
Spectrographic carbons: The batch of carbons originally available contained impurities in the form of Cu, Si, V and Ti, among others. For this reason they were first purified by boiling in concentrated sulphuric acid and then washing in water distilled in glassware. The type of carbon used in later determinations was practically free from the above-mentioned impurities and was therefore used without prior treatment. It was sold under the trade name Ringsdorff Spektralkohlen.
Development: For 10 minutes at 24°C in ID_2 (1 part diluted with 4 parts of water).
Care was taken to ensure equal development by gently rubbing over the emulsion surface with cotton wool. Later a Jarrel-Ash type of developing tank was made available and this proved ideal for even development.
Stop bath: 15 secs.
Washing: For from 30 minutes to one hour with tap-water and then splashed evenly with distilled water.
Lines Used: V, 3185.396; Cu, 3307.948; Ti, 3371.0.

The general method adopted was therefore by means of comparing the vanadium and titanium in the magnetite with copper oxide. This procedure is known as the internal standard method (Twyman, 1941, p. 166 and Ahrens and Taylor, 1961, p. 90). The measurements of the intensities of the spectral lines were made with a Steinheil Photometric Comparator, and the calculation of the percentages by means of the Respectra Calculator for spectrochemical analysis.

(e) - Presentation/.....

(e) - Presentation of Working Curves

The values log $\frac{IV}{ICu}$ were plotted against the corresponding known percentages of vanadium on logarithmic x 12ths (3 cycle) data sheets; the same procedure was followed for the titanium percentages.

In fig. 16 the different percentages of vanadium prepared artificially to draw up the working curve, have been plotted against log $\frac{IV}{ICu}$. The working curve in fig. 16 is a straight line which is a very satisfactory condition as it shows that interference from other elements, and the possibility of self reversal for percentages up to 3 per cent of vanadium is at a minimum and therefore negligible. This curve was used throughout the present study to determine the percentages of vanadium in samples of magnetite from the area investigated.

The working curve for titanium is given in fig. 17. This is also a favourable working curve.

(f) - Results Obtained

In each sample the average of three values was taken. The results are presented in table 25 together with, in some determinations the value obtained by wet analysis and/or ion-exchange chromatrography.

By applying qualitative and semi-quantitive methods for preliminary determinations, and the quantitative methods to ore which falls within the limits of payability the geologist and the chemist who seek payable vanadium ore can save a good deal of time in the field and in the laboratory.

The choice of samples for spectrographic analysis was not confined to any one area. Samples were taken more or less at random in order to obtain a general picture of the distribution of vanadium and titanium and it was therefore considered advisable to give all the results.

In the Western part of the Bushveld Complex the magnetitite seams commence north-east of Pretoria and stretch westwards intermittently to a point south of Brits where they are displaced by two prominent faults. They continue west of the faults towards the north of Rustenburg where the intrusion of the Pilanesberg Igneous Complex has caused the disappearance of the seams.

North-east/.....

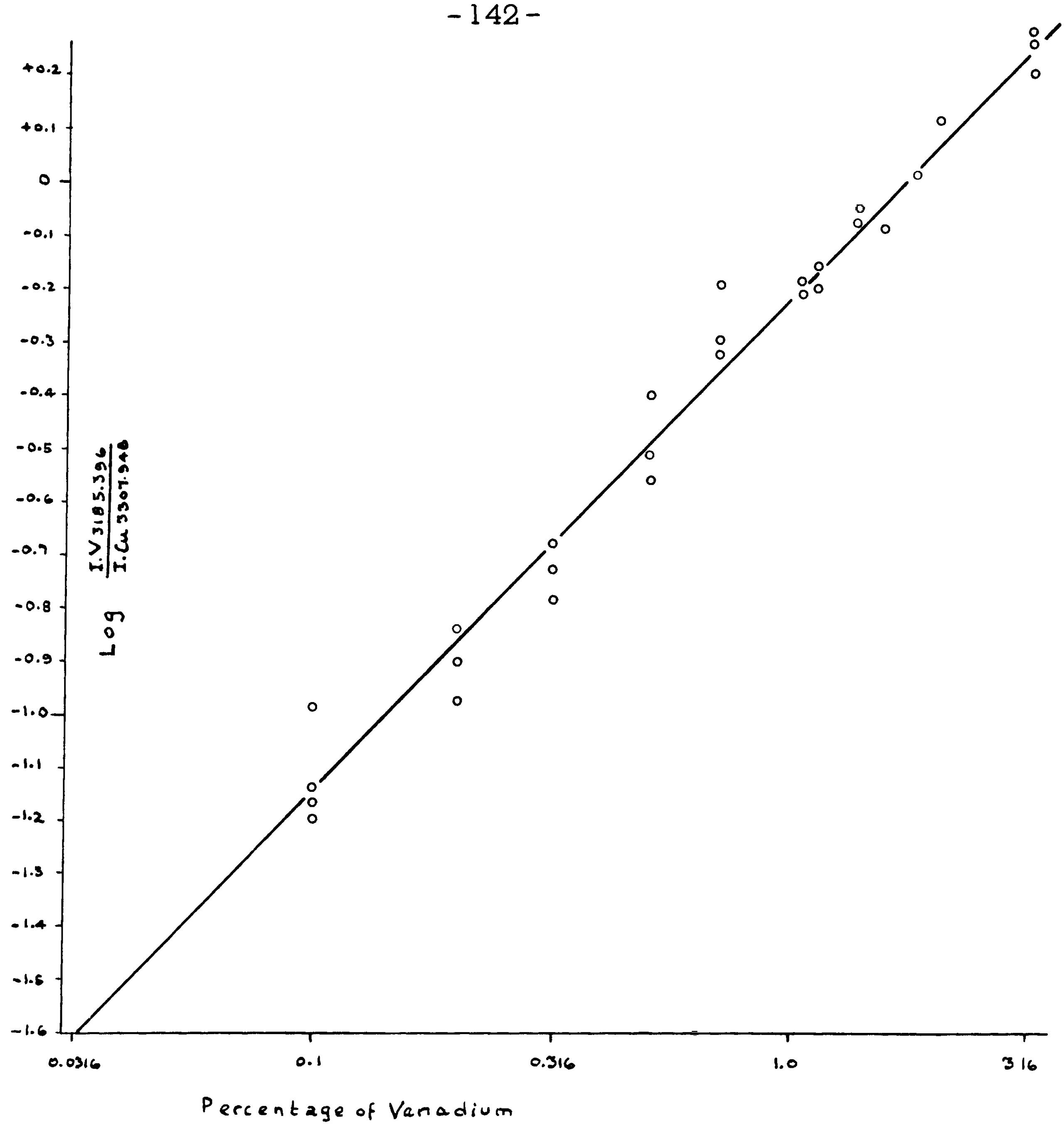


Fig 16 - Working curve for the spectrographic determination between 0.0316 and 3.16 % V_2O_5

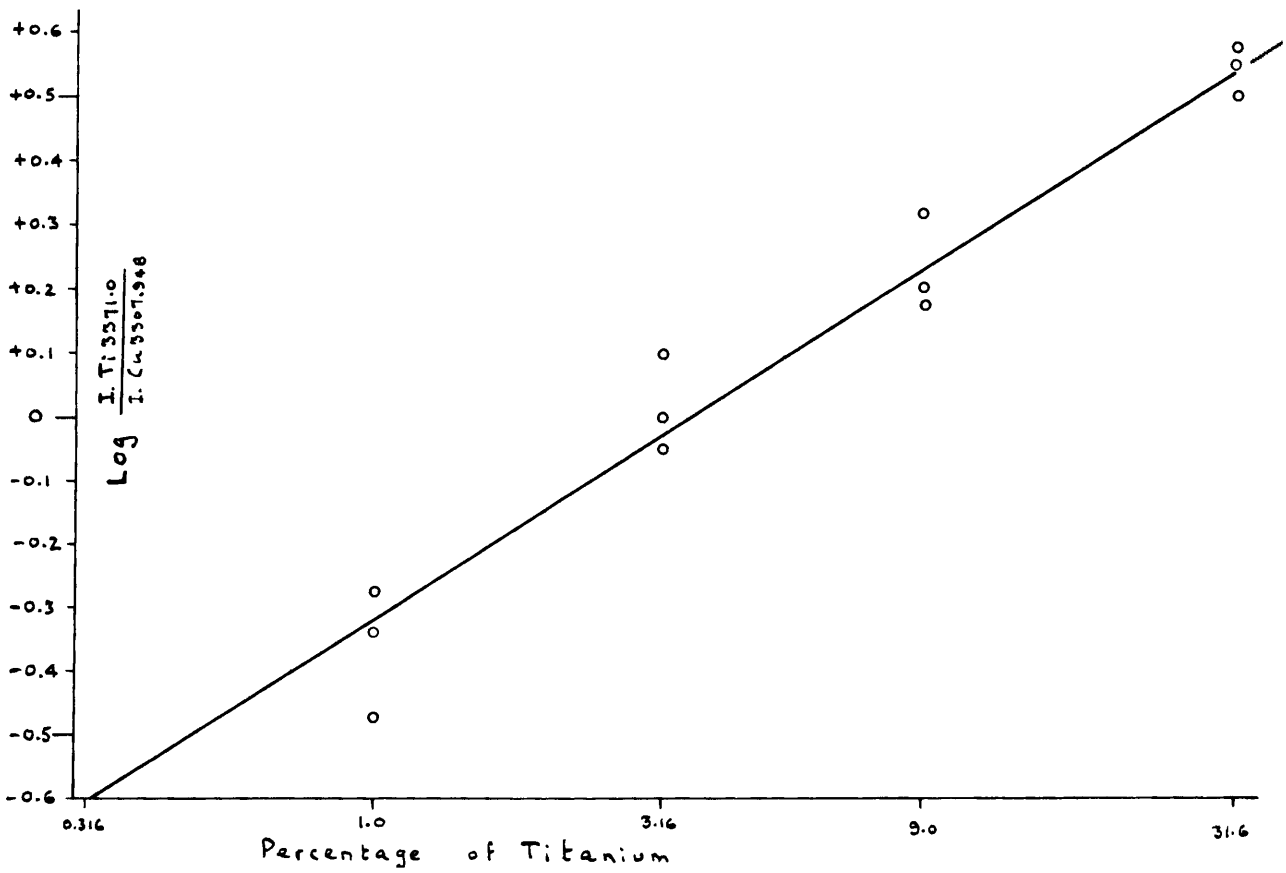


Fig. 17 - Working curve for the spectrographic determination between 0.316 and 31.6 % TiO_2

TABLE

Results of spectrographic analyses compared with some values obtained by chemical analyses

Sample	Geological	Position in reef	Locality	District	Percentages: Spectrographic V_2O_5	Spectrographic TiO_2	Chemical V_2O_5	Chemical TiO_2	Part of Bushveld Complex
P1	Subzone B	Channel sample	Syferkuil 9 JQ	Rustenburg	2.00	10.3			Western
P2	Subzone B	At bottom of seam	Syferkuil 9 JQ	Rustenburg	2.32	12.2			Western
P3	Subzone B	Centre of seam	Syferkuil 9 JQ	Rustenburg	3.24	17.4			Western
P4	Subzone B	At top of seam	Syferkuil 9 JQ	Rustenburg	2.32	15.2			Western
P5	Subzone B	Channel sample	Syferkuil 9 JQ	Rustenburg	2.17	16.3			Western
P6	Subzone B	At bottom of seam	Syferkuil 9 JQ	Rustenburg	1.73	12.8			Western
P7	Subzone B	Centre of seam	Syferkuil 9 JQ	Rustenburg	2.35	11.6			Western
P8	Subzone B	At top of seam	Syferkuil 9 JQ	Rustenburg	2.67	14.7			Western
Tr 1	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	2.10		2.0; 1.64^x		Western
Tr 2	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.69		1.65		Western
Tr 3	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.40		1.69		Western
Tr 4	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.81		1.24		Western
Tr 5	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	2.10		2.0; 1.58^x		Western
Tr 6 A	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	2.50		2.7; 1.48^x		Western
Tr 6 B	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	2.00		3.0; 1.55^x		Western
Tr 6 D	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.49		1.18		Western
Tr 7	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.33		1.13		Western
Tr 8 A	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.75				Western
Tr 8 M	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	2.54				Western
Tr 11	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	1.94		1.56		Western
Tr 12	Subzone B	Trench sample	Syferkuil 9 JQ	Rustenburg	2.42		1.63		Western
K 1	Subzone C	Trench sample	Kameelhoek 408 KQ	Rustenburg	0.46				Western
D 1	Pipe	Grab sample	Goedgedacht 114 JQ	Rustenburg	0.67				Western
FSM 1	Subzone D	Channel sample	Grootkuil 409 KQ	Rustenburg	0.18	22.9			Western
FSM 2	Pipe	Grab sample	Leeuwkopje 415 KQ	Rustenburg	0.15	19.8			Western
FSM 3	Subzone D(?)	Channel sample	Leeuwkopje 415 KQ	Rustenburg	0.32	14.9			Western
FSM 4	Subzone D(?)	Channel sample	Leeuwkopje 415 KQ	Rustenburg	0.22	15.4			Western
FSM 5	Pipe	Grab sample	Leeuwkopje 415 KQ	Rustenburg	0.16	15.6			Western
FSM 6	Subzone D	Channel sample	Grootkuil 409 KQ	Rustenburg	0.17	16.9			Western
FSM 7	Subzone C	Channel sample	Nooitgedacht 11 JQ	Rustenburg	0.48	13.3			Western
FSM 8	Subzone D	Channel sample	Wachteenbeetjeslaagte 4 JQ	Rustenburg	0.15	17.4			Western
FSM 9	Subzone B	Channel sample	Rhenosterfontein 86 JQ	Rustenburg	1.60	8.2			Western
FSM 10	Subzone B	Channel sample	Wachteenbeetjeslaagte 4 JQ	Rustenburg	1.94	14.5			Western
FSM 11	Subzone D	Channel sample	Kaalvlakte 416 KQ	Rustenburg	0.27	13.7			Western
FSM 12	Subzone D	Channel sample	Haakdoorn 6 JQ	Rustenburg	0.18	17.4			Western
FSM 13	Subzone D(?)	Channel sample	Kaalvlakte 416 KQ	Rustenburg	0.28	12.9			Western
FSM 14	Subzone D(?)	Channel sample	Haakdoorn 6 JQ	Rustenburg	0.25	15.9			Western
FSM 15	Subzone D(?)	Channel sample	Middelkuil 8 JQ	Rustenburg	0.27	19.3			Western
FSM 16	Pipe	Grab sample	Kruidfontein 40 JQ	Rustenburg	0.12	3.2			Western
FSM 17	Subzone D(?)	Channel sample	Cyferkuil 1 JQ	Rusteburg	0.19	17.0			Western
D 5	Subzone B	At bottom of seam	De Onderstepoort 300 JR	Pretoria	1.57	9.0	1.3	12.0	hestern
D 9	Subzone C(?)	Centre of seam	De Onderstepoort 300 JR	Pretoria	0.17	19.5	0.2		Western
D 10	Subzone B	Grab sample	Sjambok Zyn Oude Kraal 258 JR	Pretoria	1.66	7.8	0.7	9.43	Western
D 13	Subzone D	Grab sample	Sjambok Zyn Oude Kraal 258 JR	Pretoria	0.25	13.3	0.3	12.2	Western
D 14	Subzone C	Grab sample	Sjambok Zyn Oude Kraal 258 JR	Pretoria	0.55	10.5			Western
D 15	Subzone D	Grab sample	Sjambok Zyn Oude Kraal 258 JR	Pretoria	0.15	15.0			Western
D 16	Subzone D	Grab sample	Sjambok Zyn Oude Kraal 258 JR	Pretoria	0.31	10.7	0.3^{.:.}	18.5	Western
WV 1	Fissure	Grab sample	Kennedy's Vale 361 KT	Lydenburg	1.64	12.5	1.61^{.:.}		Eastern
WV 2	Fissure	Grab sample	Kennedy's Vale 361 KT	Lydenburg	2.21	13.0	2.13^{.:.}		Eastern
KV 1	Fissure	Grab sample	Kennedy's Vale 361 KT	Lydenburg	2.14	1.92	1.92^{.:.}		Eastern
KV 2	Fissure	Grab sample	Kennedy's Vale 361 KT	Lydenburg	2.24	25.5	1.87^{.:.}		Eastern
KV 3	Fissure	Grab sample	Kennedy's Vale 361 KT	Lydenburg	2.13	20.0	2.05^{.:.}		Eastern
KV 4	Fissure	Grab sample	Kennedy's Vale 361 KT	Lydenburg	1.64	25.0			Eastern
S 1	Subzone B	Grab sample	Mapochsgronde 500 JS	Middelburg	1.74	9.5			Eastern
S 2	Subzone B	Grab sample	Mapochsgronde 500 JS	Middelburg	1.98	12.2			Eastern
S 3	Subzone B	Grab sample	Mapochsgronde 500 JS	Middelburg	1.87	11.6			Eastern
S 4	Subzone C	Grab sample	Sterkloop 352 JS	Middelburg	0.39	16.3			Eastern
MD	Mill dump residue	Grab sample	Plant at Witbank		0.60	10.8			
MG	Magnetite in gabbro	Separated from gangue	De Lagersdrift 178 JS	Middelburg	1.45				Eastern
SF	Surface ferricrete	Grab sample	Blinkwater 213 JS	Middelburg	0.39	3.3			Eastern
PB	Breccia from pipe	Grab sample	Blinkwater 213 JS	Middelburg	0.39	3.3			Eastern

x : Check [illegible]

.:. Analysis by ion-exchange chromatography (see p. 136).

North-east of Pilanesberg they outcrop again and follow a course towards Swartklip, Northam and Swartkop. In this area the seams are conspicuously folded (Coertze, 1958, plate LXVI). The seams peter out near the Crocodile River. Their total strike distance in this area measures some 150 miles.

Forty seven samples were taken in the Western area and the vanadium and, in some of them, the titanium percentages determined (table 25).

In the Eastern part of the Bushveld Complex the seams stretch from near Wonderfontein northwards past Stoffberg and Roossenekal to Magnet Heights and into Sekhukhuneland where they curve north-westwards and terminate near the Olifants River. The total distance is about 100 miles. Thirteen samples were taken in this area and analysed for vanadium and titanium (table 25). In addition, twelve samples were submitted for partial analysis (table 26, Nos. 59 to 70).

Some intrusive pipes, fissures and magnetite-rich dunite bodies are found among, and well below the magnetitite seams in magnetite gabbro and gabbro. They are represented along the entire strike distance in both the Western and the Eastern parts of the Bushveld Complex. Seven samples were taken from deposits of this type and analysed for vanadium and titanium (table 25), and five samples were submitted for partial analysis (table 26, Nos. 66 to 70).

The results are listed in table 25 and show that the conclusion arrived at by Schwellnus and Willemse (1943, p. 33) is substantiated, namely, that of the seams only those of Subzones A and B carry vanadium in excess of 1 per cent (expressed as V_2O_5). Those pipes which lie near the seams of Subzones A and B, and those in the gabbro, also contain more than 1 per cent of V_2O_5. The richest bodies encountered so far have been that of Kennedy's Vale and the thin impersistent seams of Subzone A. These deposits are not related to one another in any way.

A comparison between the spectrographic, the chemical and the ion-exchange chromatographical analyses (table 25) shows that in most determinations the percentage obtained by spectrographic analysis is higher than that obtained by chemical analysis. It must, however, be pointed out that the chemical analyses

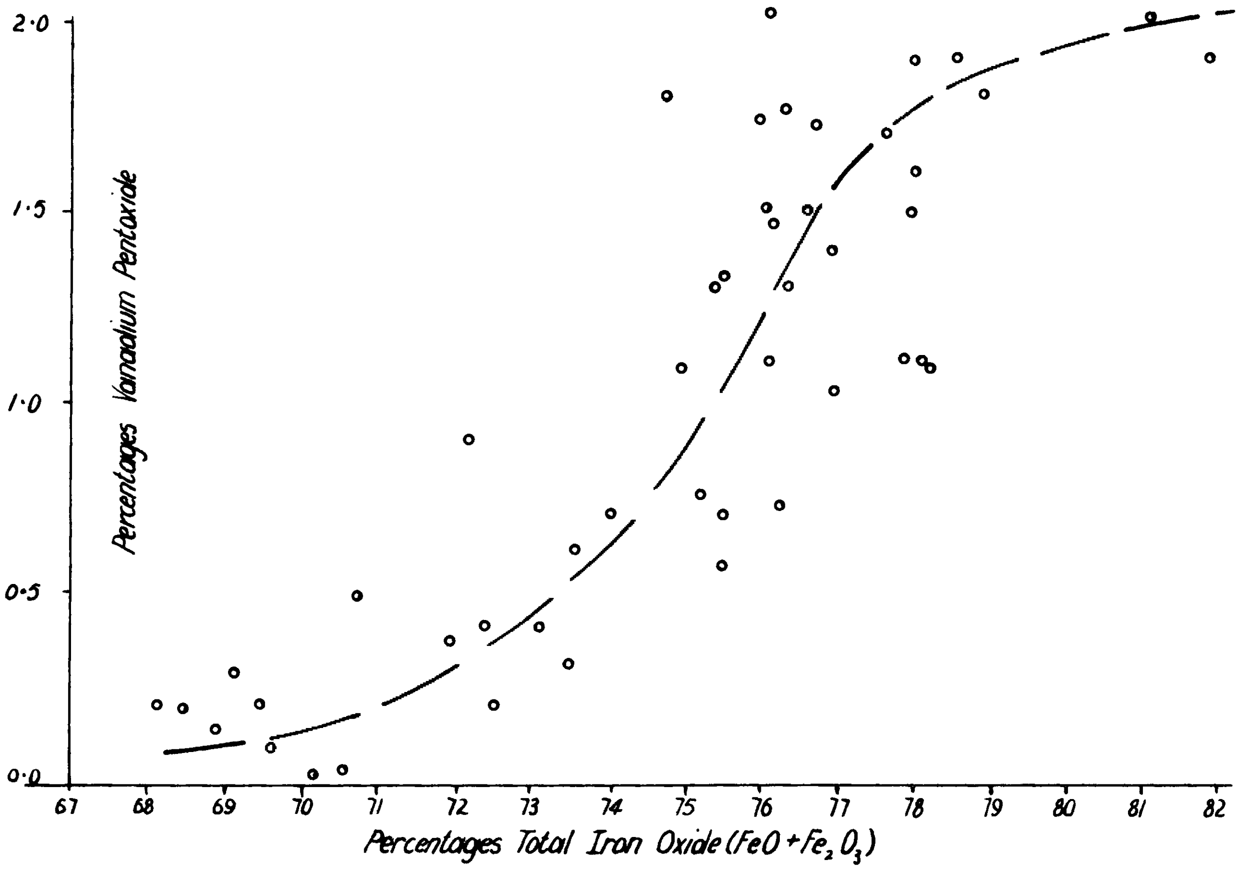


Fig.18 - Values of V_2O_5 plotted against total iron ($FeO + Fe_2O_3$) in 47 chemical analyses of magnetitite.

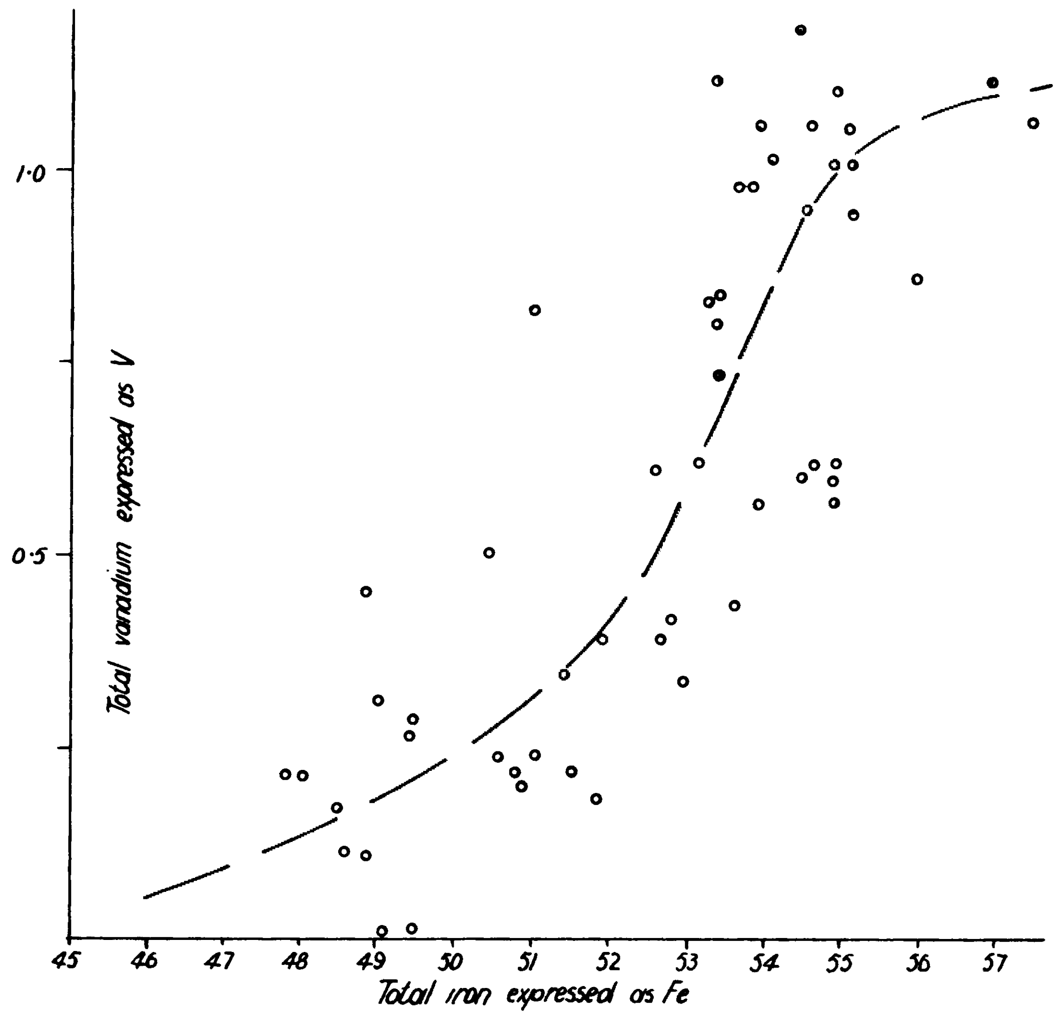


Fig.19 - Values of Vanadium (V) plotted against total iron (Fe) in 51 chemical analyses of magnetitite.

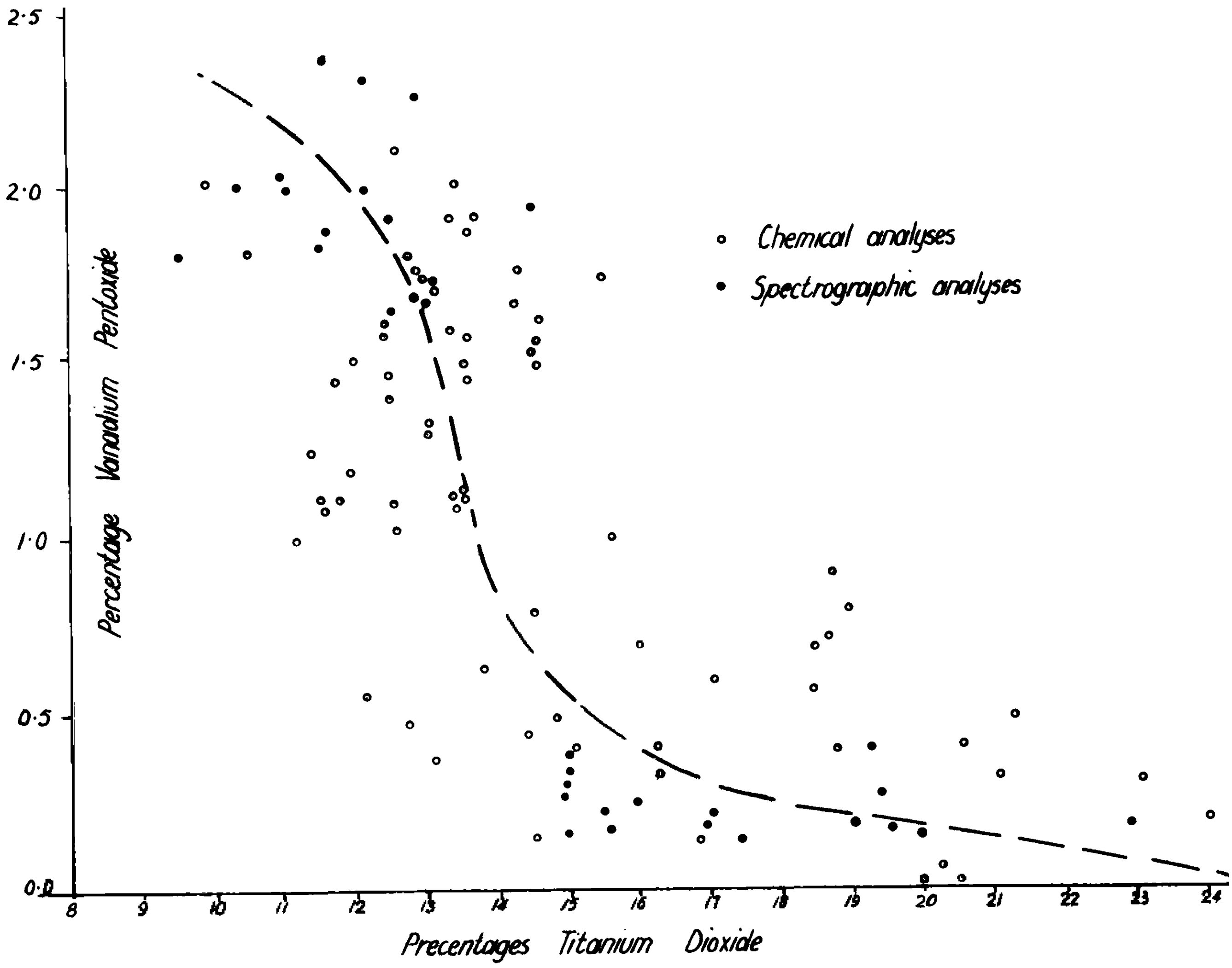


Fig. 20-Values of V_2O_5 plotted against TiO_2 in 74 chemical and 30 spectrographic analyses of magnetitite.

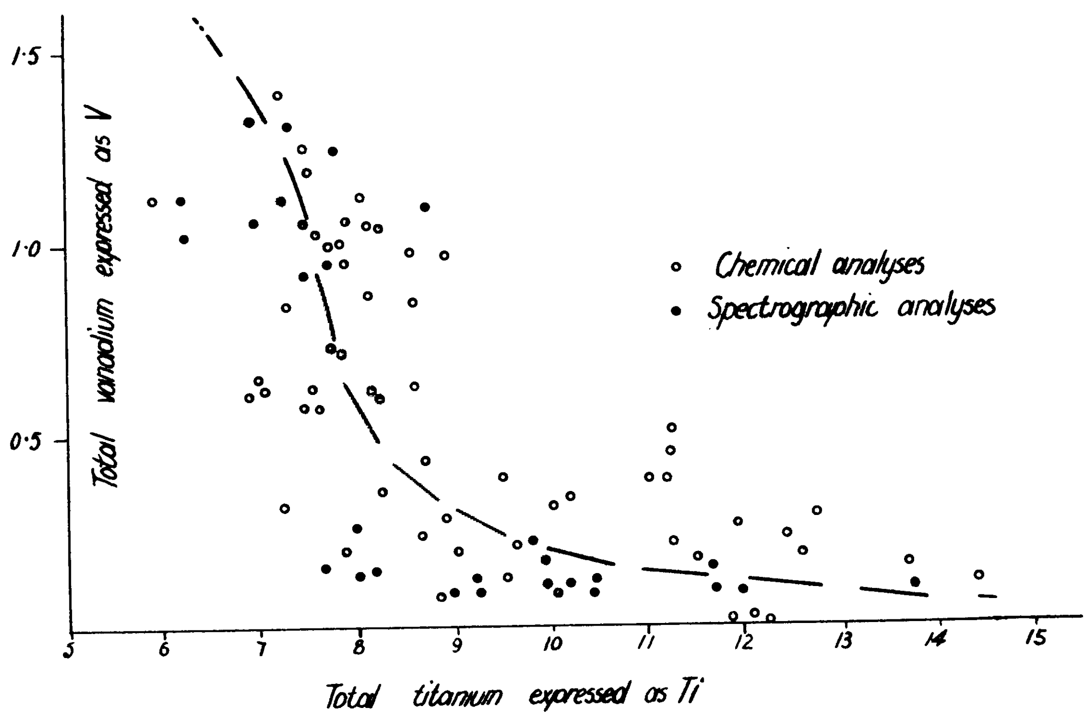


Fig. 21-Values of V (metal) plotted against Ti (metal) in 59 chemical and 26 spectrographic analyses of magnetitite.

are mostly old ones and were therefore not done according to the more precise methods used at present. The values obtained by spectrographic and ion-exchange chromatography agree admirably (Specimens D16, W.V.1, W.V.2, K.V.1, K.V.2 and K.V.3 in table 25).

The spectrographic technique, although not rapid as used in the present study, appears to be ideal for this type of determination. Although spectrographs are expensive, running costs are extremely low.

(g) - Interpretation of Spectrographic and Chemical Analyses

Schwellnus and Willemse (1943, p. 34) have shown that the relationship between vanadium and iron is sympathetic but that between vanadium and titanium is antipathetic. These relationships are not a straight-line function as is illustrated graphically in figures 18 and 20.

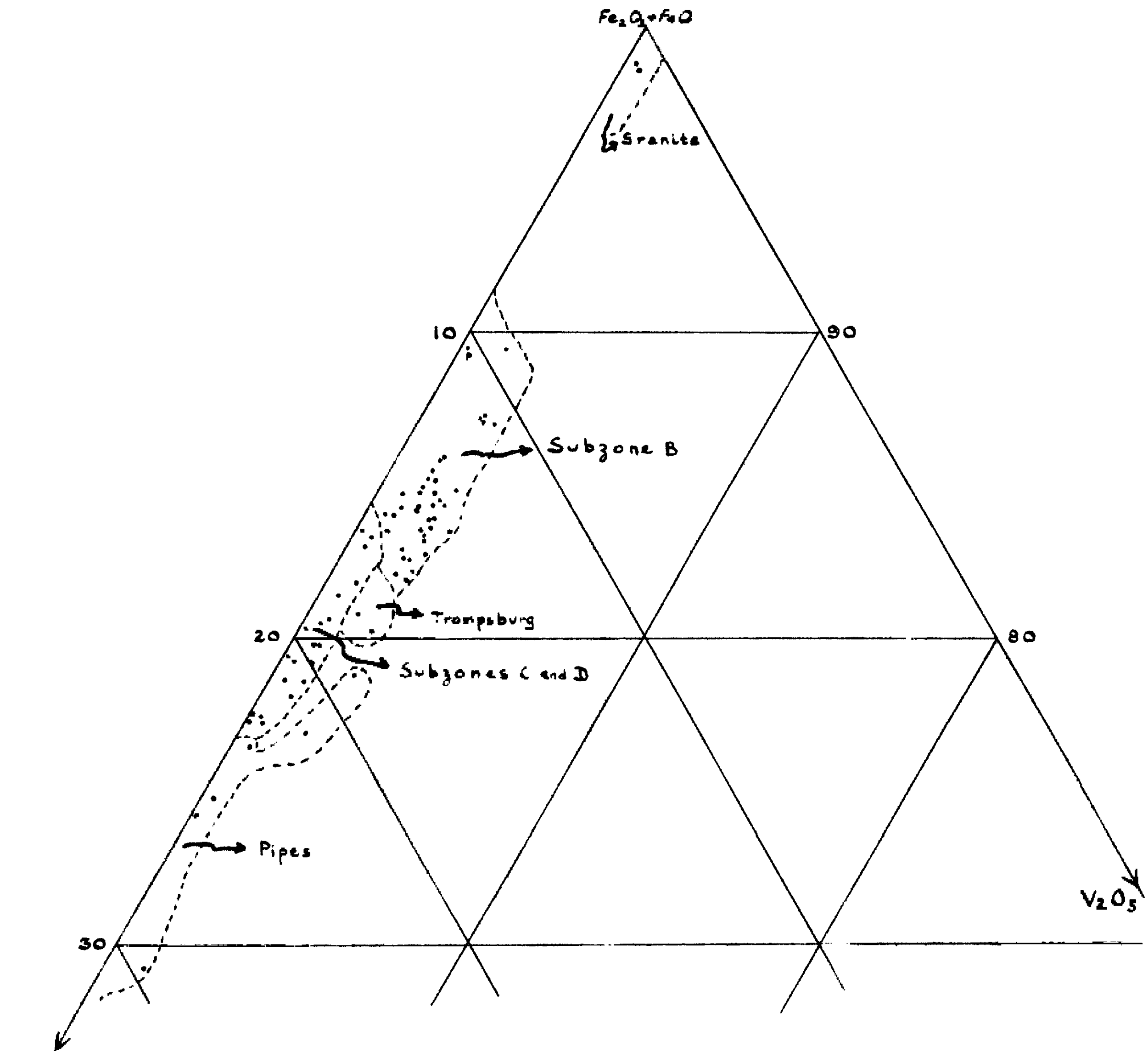


Fig.22 - Plot of values for TiO_2, V_2O_5 and Fe_2O_3+FeO in chemical analyses (see table 26).

Fig. 20/

TABLE 26

Chemical analyses of magnetites taken from publications and reports

No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2																	
Al_2O_3																	
Fe_2O_3	71.2	71.3	67.7	66.8	67.1	62.0	69.3	44.6	51.1	76.5	69.9	75.9	62.8	72.8	55.7	68.7	89.9
FeO	9.9	6.3	9.1	11.7	8.9	7.1	4.7	15.5	18.1	5.6	4.8	2.9	6.8	5.1	12.9	4.8	3.5
MgO																	
CaO																	
Na_2O																	
K_2O																	
H_2O^+																	
H_2O^-																	
TiO_2	9.9	13.2	12.5	13.3	13.4	23.0	18.7	25.9	12.6	13.6	12.7	12.8	18.8	13.6	10.4	17.1	0.8
P_2O_5																	
S																	
Cr_2O_3																	
V_2O_5	2.0	1.7	1.9	1.9	2.0	0.3	0.7	1.1	2.1	1.9	1.8	1.8	0.8	1.9	1.8	0.6	0.4
MnO																	
NiO																	
Total																	
Total Fe	57.5	54.7	54.2	55.4	53.8	48.7	52.0	43.0	49.6	57.7	52.45	55.2	49.05	54.65	47.6	51.6	

No	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SiO_2	4.00	0.33	1.25	5.24	2.77	3.02	5.12	1.82	0.83	2.47	1.46	2.26	1.47	9.2	2.01	1.63	1.42	22.21
Al_2O_3	6.25	7.13	2.72	3.35	1.40	2.84	3.99	2.6	4.1	3.14	2.88	3.84	4.92	8.91	3.41	0.74	3.85	16.41
Fe_2O_3	35.02	36.46	66.70	59.25	58.46	61.49	56.69	63.4	67.23	69.47	55.58	70.27	67.24	61.0	73.78	68.67	65.8	37.53
FeO	29.99	32.87	8.77	9.9	12.07	8.62	11.5	9.05	9.19	5.75	17.53	5.75	10.63	4.31	2.59	9.48	10.34	2.87
MgO	5.96	4.54	1.07	0.59	0.7	0.58	0.8	0.84	0.66	0.67	0.93	0.8	1.33	0.8	0.78	1.04	1.23	0.07
CaO	1.16	0.56		0.28	0.56	0.5	0.56	0.56	0.16	0.44	0.5	0.36	0.07	0.34	0.39	0.45	0.22	0.81
Na_2O	0.20	0.20	0.0					0.0						0.03				0.2
K_2O	0.25	0.35	0.0					0.0						0.0				0.07
H_2O^+	2.40	2.66		4.14	2.61	2.32	4.16	1.45	1.55	1.69	1.46	2.25	1.51	4.46	1.89	2.11	1.53	10.21
H_2O^-	0.0	0.0		0.50	0.22	0.24	0.4	0.04	0.08	0.13	0.05	0.03	0.1	0.63	0.23	0.05	0.04	1.66
TiO_2	14.4	15.32	18.4	16.21	20.41	19.93	15.17	19.26	14.85	16.0	18.82	12.6	11.69	8.23	13.0	13.69	2.17	4.24
P_2O_5	0.17	0.09	0.0															
S			0.0															
Cr_2O_3				0.02	0.04	0.02	0.02	0.02		0.05	0.19	0.23	0.31	0.22	0.33	0.23	1.0	0.23
V_2O_5	1.1	1.82	0.57	0.4	0.0	0.0	0.4	0.4	0.5	0.7	0.4	1.1	1.1	1.3	1.3	1.1	1.5	0.6
MnO	0.41	0.31	0.23	0.24	0.43	0.38	0.4	0.38	0.2	0.23	0.33	0.2	0.07	0.25	0.15	0.3	0.3	0.09
NiO				0.03	0.0	0.0	0.0	0.0			0.0	0.02	0.07	0.05	0.07	0.08	0.06	0.07
Total	100.24	100.52	100.00	99.44	99.67	99.94	99.21	99.32	99.35	100.51	100.09	99.96	100.51	99.73	99.94	99.61	99.46	98.27
Total Fe	47.6	50.6	53.2	48.35	50.15	49.5	48.4	51.25	54.0	52.9	52.25	53.4	55.4	45.8	53.8	55.1	53.9	27.9

No	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
SiO_2	0.3	1.75	1.16	1.5	1.25	0.92	0.16	6.14	0.7	3.03	1.66			9.94	10.72	7.08	1.73
Al_2O_3	2.85	1.35	3.99	3.12	2.72	1.49	3.45	3.79	0.0	2.91	7.07			4.72	2.66	3.27	2.97
Fe_2O_3	55.1	62.92	46.31	60.68	66.7	44.72	43.86	52.30	68.8	67.34	62.25	47.78	39.46	64.35	63.55	64.36	75.89
FeO	14.37	6.61	24.41	11.5	8.77	28.74	23.57	30.18	8.9	9.59	12.62	27.67	29.42	5.6	7.04	7.76	1.72
MgO	1.24	0.43	0.64	1.49	1.07	1.54	1.85	8.30	0.2	0.72	1.07			0.8	1.34	0.87	0.12
CaO	0.16	0.44	0.16	0.16				0.0		0.5				0.3	0.3	0.3	0.37
Na_2O	0.0				0.0									0.35	0.24	0.22	0.24
K_2O	0.0				0.0									0.15	0.2	0.44	0.2
H_2O^+	1.52	9.85	1.83	1.01	0.14	1.1	0.65	0.7	1.0		1.36			0.22	0.68	1.17	2.09
H_2O^-	0.07	0.89	0.08	0.08	0.15	0.05	0.06	0.13	0.7		0.10			0.38	0.2	0.15	0.23
TiO_2	24.09	8.01	21.32	18.76	18.4	21.05	20.75	0.66	20.01		11.68	14.72	16.83	12.06	19.92	14.5	13.8
P_2O_5														0.05	0.05	0.05	0.05
S									0.1	0.07	0.16			0.05	0.05	0.05	0.22
Cr_2O_3	0.02		0.05	0.32		0.03	0.16		0.2		0.70	1.20	1.88	0.07	0.03	0.01	0.15
V_2O_5	0.2	0.2	0.5	0.9	0.68	0.32	0.41	0.27		1.02	1.08	0.15	0.14	0.56	0.48	0.43	0.62
MnO	0.27	0.2	0.2	0.2	0.23	0.30	0.20	0.16	0.15	0.52	0.27			0.27	0.32	0.26	0.15
NiO				0.07						0.38							
Total	100.57	99.61	100.69	99.79	100.11	100.27	100.11	99.63	100.85	98.68	53.3	54.5	50.3	99.87	100.78	100.88	100.55
Total Fe	49.6	48.9	51.15	51.2	53.2	53.1	52.2	49.8	54.9	54.4	53.3	54.5	50.3	49.2	49.7	50.9	54.3

No	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
SiO_2	3.71	0.8	0.50	2.91	0.7	0.09		0.16							1.20			
Al_2O_3	8.14	4.93	5.01	6.34	5.31	5.39		2.59							1.27			
Fe_2O_3	38.64	60.84	53.55	46.2	42.99	74.89	42.47	51.70	68.38	47.06	58.29	67.08	44.90	66.88	61.27	61.68	68.87	71.86
FeO	33.19	15.45	22.63	25.57	29.38	1.72	26.43	24.78	5.82	28.60	24.78	9.70	27.67	12.57	14.73	10.42	4.67	7.54
MgO	1.26	0.69	0.12	0.74	1.05	0.13		0.98							1.05			
CaO	0.6	1.37	1.12	2.23	1.74	0.5												
Na_2O	0.4	0.24	0.18	0.35	0.18	0.18												
K_2O	0.2	0.15	0.2	0.2	0.2	0.3												
H_2O^+	0.13	0.37	1.26	0.03	0.41	1.58												
H_2O^-	0.1	0.05	0.14	0.09	0.11	0.26												
TiO_2	13.2	14.3	14.6	13.6	15.8	13.0	18.58	14.83	16.0	14.85	7.25	14.75	12.46	12.05	17.00	20.0	18.65	14.40
P_2O_5	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.10	0.32	0.40	0.64	0.03	0.06	0.07	0.94	0.94	1.52	0.24
S	0.1	0.22	0.22	0.41	0.16	0.22		0.40							0.23			
Cr_2O_3	0.36	0.06	0.03	0.12	0.35	0.01	0.21	0.04	0.04	0.33	0.03	0.05	0.15	0.05	0.06	0.005	0.02	0.05
V_2O_5	0.36	1.75	0.76	1.56	1.74	1.74	1.05	2.11	2.01	1.65	1.46	2.11	2.23	2.47	1.83	1.46	1.83	1.51
MnO	0.17	0.27	0.29	0.3	0.15	0.08	0.37	0.18		0.32	0.15	0.25	0.28	0.13	0.26	0.35	0.26	0.14
NiO																		
Total	100.62	100.44	100.66	100.70	100.32	100.14												
Total Fe	52.8	54.4	54.7	51.9	52.7	53.8												

The chemical analyses are from the following publications and reports:

Nos. 1 to 17 ; (Unpubl. Rep. Soils Research Institute, Pretoria, 1955. Analysts: C.E.G Schutte and C. Lessing)

Nos. 18 and 19 ; (ORTLEPP, R.J., 1959, p.45)

Nos. 20 to 40 ; (SCHWELLNUS, C.M. and WILLEMSE, J., 1943, Table 1)

Nos 41 to 43 ; (STRAUSS, C.A., 1946, p. 44)

Nos. 44 and 45 ; (VAN ZYL, J.S., 1950, p. 57)

Nos. 46 to 48 ; (FRANKEL, I.J and GRAINGER, G.W., 1941, p. 101 and 106)

Nos. 49 to 58 ; (COERTZE, F.J, 1967, p.32)

Nos. 59 to 70 ; (Unpubl. Rep. Soils Recearch Institute, Pretoria, 1960. Analysts: P.J. Fourie and S.J.J. Geldenhuis)

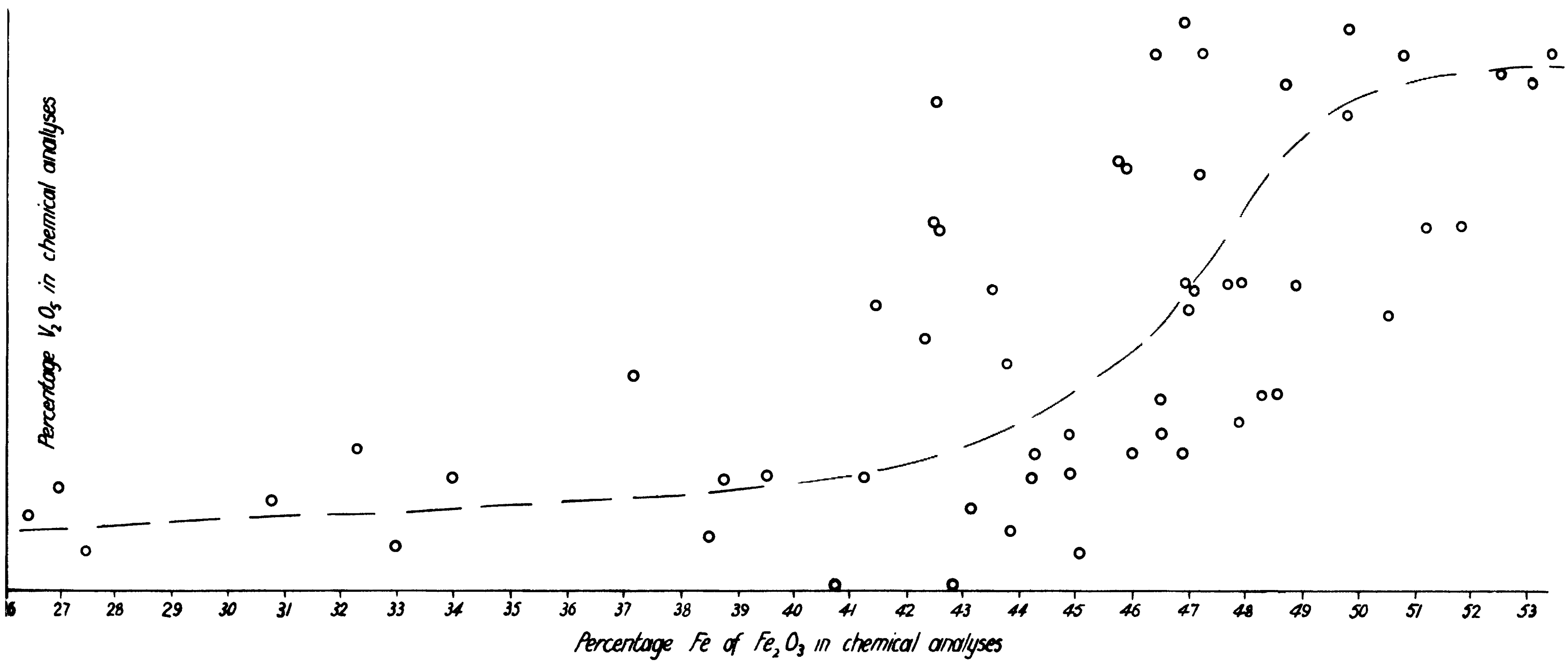


Fig. 23- Graph showing the sympathetic relation between Fe of Fe_2O_3 and V_2O_5

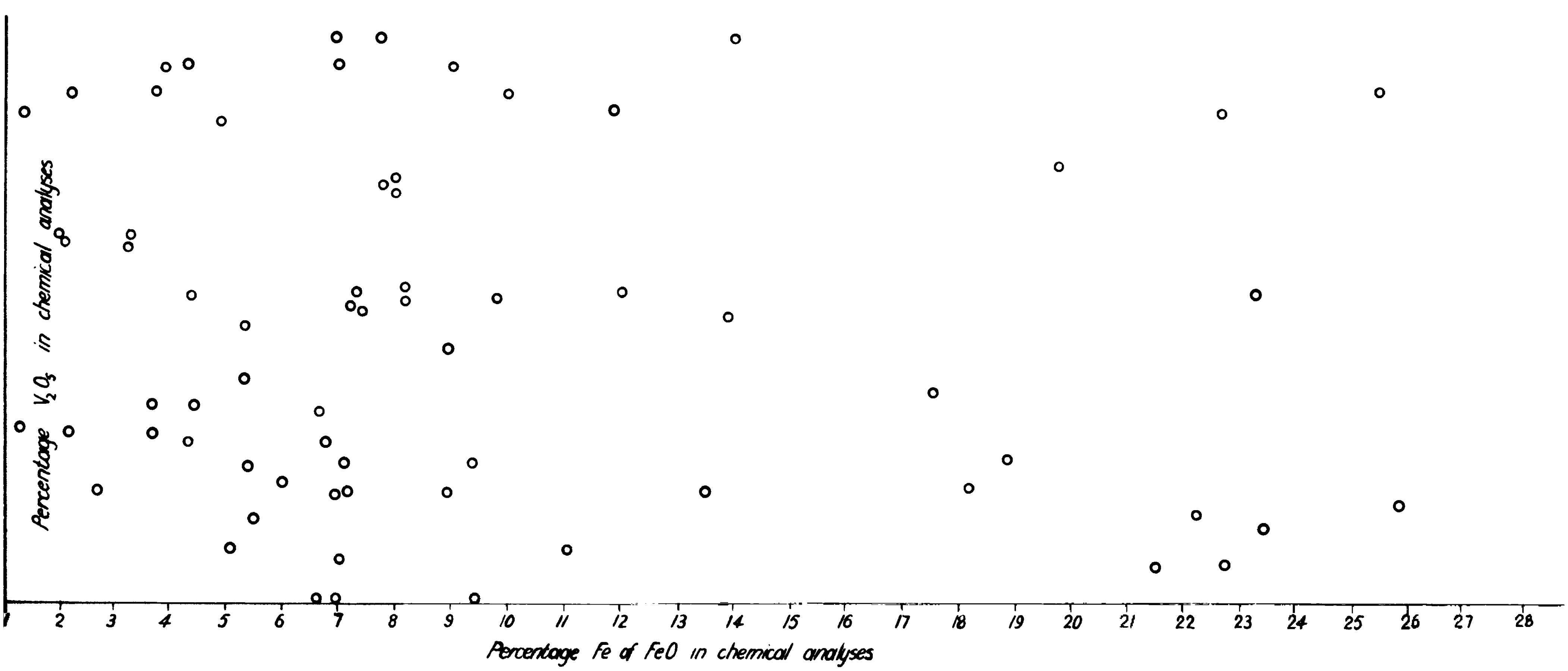


Fig. 24- Plot to show the absence of any relation between Fe of FeO and V_2O_5

Fig. 20 also serves to illustrate the more or less equal accuracy of spectrographic values (dots) compared with those obtained by chemical analysis (circles). The relationships vary considerably, even allowing for possible discrepencies in the analyses. In the case of the iron-vanadium graph, the curve shows a rapid increase in iron compared with a small increase in vanadium for the lower V_2O_5 percentages (up to about 0.5 per cent V_2O_5). From this point the curve steepens and V_2O_5 increases rapidly for a relatively small increase in iron. At the higher percentages of vanadium, a rapid increase in iron once again leads to only a small increase in vanadium.

In the case of the V_2O_5 - TiO_2 curve (fig. 20) the same holds true, except that here for a decrease in titanium, vanadium increases.

In order to ascertain whether reduction of the magnetite to hematite has affected the relation between iron and vanadium, values of vanadium (V) were plotted against total iron (Fe) in Fig. 19. The relationships were found to be the same as shown in Fig. 18.

Likewise, the values of vanadium (V) were plotted against titanium (Ti) in Fig. 21. The relationships remained the same as in Fig. 20.

In Fig. 22 the values for TiO_2, V_2O_5 and Fe_2O_3 + FeO have been calculated to 100 and plotted on a triangular diagram. These values, together with values for the chemical analyses in figs. 18 to 21 have all been taken from analyses of samples from the Bushveld Igneous Complex and from elsewhere in various publications and unpublished reports (table 26). The points plotted on the triangular diagram can be grouped into 4 separate fields viz:

A. Pipes: Low or high vanadium, high titanium and low iron percentages.

B. Seams of Subzones B and C and magnetite from the Rooiwater Complex: Low to medium vanadium, medium titanium and medium iron percentages.

C. Magnetite from the Trompsburg Pluton: High vanadium, medium titanium and medium iron percentages.

D. Seams of Subzone B: High vanadium, low titanium and high iron percentages.

For/.....

For comparative purposes two magnetite samples from granite were also plotted. They are typified by low vanadium, very high iron and very low titanium contents.

A further attempt at determining the interrelationships between elements was made by plotting the percentage of Fe in the Fe_2O_3 against the percentage of V_2O_5 of the chemical analyses (table 26). The resultant curve (fig. 23) is similar to that in Figs. 18 and 19 even though oxidation played a role in the relationship.

Likewise, the values of Fe in FeO were plotted against the percentage of V_2O_5 of the chemical analyses (table 26) but in this case the points fall haphazardly and no curve could be drawn in (see fig. 24).

19 - UNIT CELL DETERMINATIONS

A complete set of determinations of the size of the unit cell of magnetite from different seams and pipes was not made owing to the limited time available for this phase of the study but a few unit cell dimensions were nonetheless accurately determined and should serve as a comparison with the findings of Basta (1957, p. 437) and with those of Hiemstra and Liebenberg (1964, p. 7 and 13).

The results obtained are used in an effort to explain, account for, and possibly prove phenomena observed under the ore-microscope. X-ray work, undertaken mainly in conjunction with the chemical properties of the ore, has been fully dealt with by Basta.

X-ray photographs were taken and used to calculate the lattice parameters and the unit cell dimensions of the magnetite. Films were mounted in 57.3 mm cameras and iron-filtered cobalt radiation was employed. The choice of the most suitable filter caused some difficulty. Although magnetite gives a fair pattern with normal unfiltered radiation, the important back-reflections, which are necessary for unit cell calculations, are usually not very clear. Furthermore, it was found that the Bushveld magnetites give patterns inferior to that of pure magnetite from Allanwood, U.S.A. By slightly annealing the samples before subjecting them to X-rays, the quality of the patterns improved somewhat but not sufficiently for accurate unit cell determination.

A very/.....

A very thin iron foil was subsequently cut to the size of the film and mounted inside the camera (fig. 25). With the camera so equipped the quality of the photographs improved to such an extent that all the back-reflections could be measured.

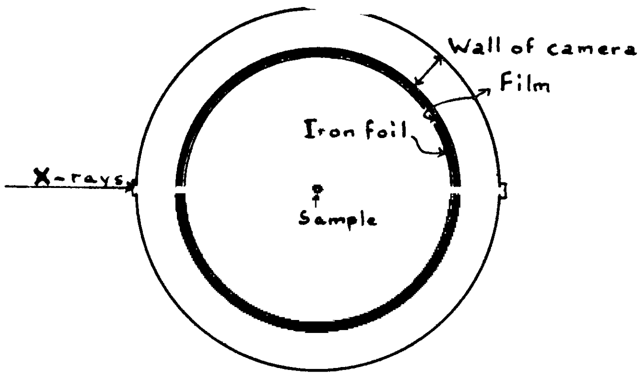


Fig. 25 - Cross section of camera to show the position of iron foil in relation to the film.

With the iron filter placed outside the camera diffraction lines were very weak. Before the iron foil was acquired tape used for tape-recorders was employed but the widest available measured only 12 mm whereas the width of the exposed portion of the film is 24 mm. However, by placing the tape along the centre of the film a sufficient portion of the diffraction lines were accentuated.

Calculation of unit cells were made after correction for shrinkage or expansion of films. The calculated unit cells were plotted against the value

$$\frac{1}{2}\left(\frac{\mathrm{Cos}_2\theta}{\mathrm{Sin}\ \theta} + \frac{\mathrm{Cos}_2\theta}{\theta}\right)$$

and the unit cell dimension taken where the value of the formula equals zero.

The values obtained together with the relevant determinations by Basta for the De Onderstepoort material are presented in table 27.

In Basta's table (1953, p. 707) values determined by Newhouse and Glass are listed and Basta states that they are much lower than his values. It was immediately suspected that Newhouse and Glass gave their values in K units and not in Ångstrom units. The three unit cell values were converted to Ångstrom units (multiply by 1.00202) and the values so obtained agree tolerably with those of Basta.

In/.....

In the following table all values are listed in Ångstrom units.

Table 27.

Unit cells of titaniferous vanadiferous magnetites from various localities in the Bushveld Igneous Complex, and the unit cell of pure magnetite from Allanwood, U.S.A.

Specimen Locality	a in Å	a in Å by Basta	Subzone of seams
1) Allanwood, U.S.A.	8.395 (± 0.002)	-	-
2) Sjambok Zyn Oude Kraal 258 JR Pretoria District	8.342 (± 0.002)	-	Subzone D
3) De Onderstepoort 300 JR, Pretoria District	8.358 (± 0.002)	8.342 (± 0.002)	Subzone B
4) Vlakfontein 207 JP, Rustenburg District	8.394 (± 0.002)	-	? (bore-hole over 1000 ft.

The values given in table 27 are significant especially in that the unit cell of material from Vlakfontein 207 JP approaches that of normal magnetite, which can be taken arbitrarily at Å 8.395 (± 0.002) for the purpose of this report. The size of the unit cells, omitting the Allanwood sample, decreases from 8.394 to 8.342. Thus, bearing in mind that the Vlakfontein ore is not, or practically not, affected by oxidation, it seems safe to accept the fact that on oxidation the unit cell of the titaniferous, vanadiferous magnetite will decrease.

The role of small amounts of vanadium in the lattice of magnetite cannot have much influence on the size of its cell edge. The ionic radius of V^{3+} is 0.65 Å and that of Fe^{3+} is 0.67 Å, so that the tendency would be towards a decrease in cell-size. The presence of titanium will tend to increase the size of the cell edge but it is unlikely that much titanium is present. The pinkish colour of some polished surfaces definitely suggests the presence of titanium in variable amounts but most of the TiO_2 given in analyses is attributable to ulvite and ilmenite.

Absolutely/.....

Absolutely pure magnetite from Allanwood, U.S.A., was used to check the accuracy of the other determinations. Basta (1957, p. 435) gives a value of 8.396 for pure magnetite from Bisperg, Sweden.

A feature of the spinels is their capacity to take up in solid solution indefinite quantities of the oxides Al_2O_3 and Fe_2O_3. The explamation of this phenomenon was provided by the investigation of the structure of Al_2O_3 and γ - Fe_2O_3. As normally prepared, these oxides have the corundum structure but by the careful oxidation of Fe_3O_4, which is a spinel, γ - Fe_2O_3, with an entirely different structure is obtained.

With regard to the Bushveld ore, the presence of γ - Fe_2O_3, in solid solution with the magnetite, as postulated by Basta, is regarded as a distinct possibility in the present report as a result of the sympathetic relation between vanadium and Fe_2O_3 (fig. 23). Basta (1957) examined magnetites which give a value of the unit cell somewhat lower than that of pure magnetite. He assumes that this may be due to partial oxidation of the magnetite to maghemite.

Weathered samples with a pronounced degree of anisotropism were selected for X-ray work, but these gave hematite patterns. No lines were identified which could be ascribed to the presence of maghemite. These samples pulverize to a reddish powder. It therefore follows from X-ray study as well that hematite is the prevalent final product of alteration and that dissociated free maghemite is confined to the bluish isotropic patches lying within the white anisotropic hematite.

The maghemite is therefore mostly confined as an intergrowth with original magnetite. It is now in different stages of dissociation and the dissociated γ - Fe_2O_3 will tend to revert to stable Fe_2O_3. Basta is therefore justified in calling this type of material titano-maghemo-magnetite or titano-maghemite if more than 50 per cent of γ - Fe_2O_3 is present. For the purpose of this report the term titaniferous, vanadiferous magnetite is used, even though some maghemite (γ - Fe_2O_3) may be associated.

20 - EXPLOITATION/ .....

20 - EXPLOITATION OF THE MAGNETITITE SEAMS

A - Mining Activity

Ever since their discovery and identification, probably even before the turn of this century, the magnetitite seams have been correctly labelled enigmatic deposits. Fortunately geologists and mineralogists, although admitting at the time that they were not of immediate economic importance, nevertheless examined them and several publications and reports were made available.

Today the picture has changed and the quest for unclaimed ground is over. Rather surprisingly, vanadium was at first the only metal which was recovered from the ore.

The vanadium project was started in 1957 by an American firm registered as "Minerals Engineering Company, S.A. (Pty.) Ltd.", with its Head Office in Johannesburg. Shares were held by High Speed Alloys Ltd., England; Minerals Engineering Co., Grand Junction, Calorado, U.S.A. (Technical Knowledge) and Rockefeller Centre Inc., New York, U.S.A. (Finance). Lately the Anglo American Corporation of South Africa Limited, has acquired a leading interest.

Mining rights were originally held on farms in the Middelburg and Belfast districts and also near Brits. Most of the ore which came from near Roossenekal was transported by road and rail to the processing plant at Witbank. They mined eluvial and surface-ore, and planned to strip eventually to a depth of about 30 feet. At that stage it was reckoned that underground mining would be commenced with.

The original method of reduction is briefly as follows:

$$\text{pulverized ore} + NaCl \xrightarrow[\text{at } 800^{\circ}C]{\text{roasting}} NaVO_4 \xrightarrow{\text{Leach}} \text{solution} \xrightarrow{\text{electro-lysis}} V_2O_5$$

The remainder is iron plus about 15 per cent TiO_2. In 1959 the ore mined was considered to carry on the average 1.75 per cent V_2O_5; recovery was about 70 per cent.

At present (1968) the Anglo American Corporation is mining the Kennedy's Vale ore which assays on the

average/.....

average 2.06 per cent of V_2O_5 (400 samples). The ore from the Roossenekal area although considered to be payable ore (magnetite containing less than 1.5 per cent V_2O_5 is regarded as unpayable) has the disadvantage of having to be transported by road for up to 20 miles to the nearest railhead at Stoffberg. For this reason the railway is being extended from Stoffberg to Roossenekal.

The Kennedy's Vale deposit is lensshaped, being 150 feet thick with a proved length along strike of 1,200 feet. It dips northwards at 70°. The eluvial ore has been mostly removed and at present the strip of solid outcrop is being mined by means of open-cast work. In this way another 5 million tons of ore can be mined before underground mining commences.

B - Prospecting

Prospecting has been confined mostly to areas favourably situated with respect to a railway line and the western part of the Bushveld Complex has in this respect received much attention especially the area around Northam where some drilling and trenching has been carried out. African Metals Corporation did drilling near Magnet Heights, on Malekskraal 509 KS and on The Consolidated Farm Mapochsgronde 500 JS. Drilling is the best method of determining the percentage of V_2O_5 at depth. It is considered that surface-material is enriched as a result of leaching of silicates, but not in the solid gangue-free portions of the seams.

The Western and the Eastern parts of the Bushveld Complex differ mainly in this respect that the seams in the latter have produced more eluvial ore and outcrops are generally more plentiful and stand out more prominently so that more ore can be mined cheaply before resorting to blasting as the only means of recovering the ore.

C - Railage

The seams in the Western part of the Bushveld Complex are particularly well situated with regard to railage. In the Eastern part this is not the case.

Except/.....

Except for the Kennedy's Vale ore which is transported for 10 miles to Steelpoort Station, and ore from near Stoffberg and Roossenekal, the outcrops are far removed from the railheads. From Magnet Heights and farther north into Sekhukhuneland the ore will have to be carted by road for distances of 20 miles and more.

D - Production of Vanadium

The first production figures appeared in 1957 when 6 tons of vanadium metal with a F.O.B.-value of R9,584 were produced. The exports since then, together with the countries of destination are reflected in the following table:

Table 28.

Annual exports of fused vanadium oxide

Year	Long Ton	F.O.B. Value	Country
1958	428	660,312	England
	81	129,598	France
	61	95,194	Austria
	11	18,272	Holland
	400 lb.	344	Germany
Total (1958)	581	903, 720	
1959	516	816,506	England
	56	85,106	France
	9	14,506	Holland
	3	6,128	Germany
Total (1959)	584	922,246	
1960	540	846,030	England
	219	321,420	Austria
	101	147,494	Germany
	105	156,680	France
	81	122,970	Japan
	52	80,346	Czechoslovakia
	60	89,946	Holland
Total (1960	1,158	1,764,886	
1961	2,529	3,668,403	
1962	1,587	2,283,760	
1963	1,900	2,274,295	
1964	3,575	4,118,728	
1965	2,368	3,090,247	
1966	2,982	5,141,286	
1967	3,039	5,447,329	

In/.....

In addition to the exports, local sales of fused vanadium oxide accounted for 145.82 tons with a F.O.B. value of R41,931 (1961 to 1967). Ammonium Vanadate with a minimum V_2O_5-content of 75 per cent was also exported from 1962 onwards and until 1967 exports of this material amounted to 309 tons at a F.O.B. value of R504,204.

Thus, from 1957 to 1967 some 20,317 tons of fused vanadium oxide (with a V_2O_5-content of 99.9 per cent) and with a F.O.B. value of R29,624,464 was exported. According to these figures the average price of fused vanadium oxide as exported was R0.68 per pound weight.

E - Future Demand

Further demand for vanadium metal hinges on steel production, the opening up of new deposits elsewhere, and the extraction of vanadium as a by-product in some overseas uranium mines. New uses of vanadium may also be found, for example the present increased demand for vanadium in the production of vanadium salts for use in an apparatus which is installed in the exhaust systems of petrol-driven vehicles. The apparatus serves to remove harmful carbon gases. It is reported that in some states in America the installation of this apparatus is compulsory (Mining Commissioner's Monthly Report, Barberton, Oct. 1960).

F - Persistence of Ore with Depth

It can be expected with confidence that the ore of the seams will persist in depth, just as the chromitite seams do. The presence of solid ore at a depth of 1300 feet in the bore-hole on Vlakfontein 207 JP, Rustenburg District, is sufficient proof that downward continuation is assured even though local discontinuation and variation in thickness may be encountered. Intrusive bodies apparently thin out with increasing depth. The Kennedy's Vale fissure-vein already shown signs of changing shape at a depth below 300 feet, where bore-hole evidence points to a thinning and splitting of the main ore-body.

G - Mining/.....

G - Mining Techniques

At all the deposits the tendency is to remove the eluvial and the outcropping material only. As yet, underground mining has not commenced, but when it does, a few points should be borne in mind.

1) Jointing of Seams. The joints which run in several directions (fig. 14) will in a way assist mining by facilitating the breaking process but in another will have to be considered a danger hazard in that blocks in the hangingwall will tend to break away at any time during mining operations.
2) Above the zone of weathering the anorthosite underlying the seams will in many areas be altered to kaolonitic material, and must in this state be regarded as an unsatisfactory footwall.
3) The overlying magnetite gabbro is practically always weathered and will be an unstable hangingwall. Preliminary determinations of the electrical resistivity by Mr. Oasson, Technical Assistant, Geological Survey, during 1962 suggested weathering to depths of about 130 feet (on De Hoop 886 KS, Lydenburg District).
4) The presence of much water can be expected in the zone of weathering.
5) Layering and fracturing will, even at depth, be a disadvantage as movement down dip along the planes, especially between the seams and the anorthosite may result. This has happened in one of the platinum mines near Rustenburg, and precautionary measures had to be adopted.

Fortunately most of the points referred to are confined to the zone of weathering where quarrying in weathered material and stripping of ore can solve most problems. In the mining of the chromitite seams weathering is not a troublesome factor but in the Upper Zone of the Bushveld Igneous Complex, especially in the magnetite gabbro, weathering has been much more severe.

H - The Utilisation of the Iron and the Titanium

In the United States of America ore containing 34.8 per cent TiO_2, 40.3 per cent iron ~~(as Fe)~~ and 0.16

per cent/.....

per cent vanadium was beneficiated on a large scale in the Lake Sanford area, New York. The final product contained 98.51 per cent iron. The slag contained 71.9 per cent TiO_2 and 0.52 per cent V_2O_5. This project was started to offset the dwindling reserves of iron ore of that Country and to assure sufficient reserves of TiO_2 for use as a pigment.

The Anglo American Corporation is at present (1968) setting up a new plant near Witbank. At this plant ore, mainly from the magnetite seams of Subzone B will be treated. Vanadium steel will be the main product, with titanium dioxide as a by-product. The following figures (tables 29 and 30) should serve to show the distribution of iron ~~(as Fe)~~ and TiO_2 in the different seams:

Table 29

Percentage of iron in various magnetite seams of the Western and Eastern parts of the Bushveld Complex

	Western part of Bushveld Complex	
Analysis	Main Seam of Subzone B (Average of 25 samples	Seams of Subzones C and D (Average of 6 samples
Chemical	52.95	50.63
	Eastern part of Bushveld Complex	
Analysis	Main Seam of Subzone B (Average of 5 samples)	Seams of Subzone C and D (Average of 6 samples)
Chemical	53.56	51.77

The average percentage of iron in the Eastern and Western parts is 52.43 per cent.

Table 30/.....

Table 30.

Percentage of titanium, expressed as TiO_2, in various magnetitite seams of the Western and Eastern parts of the Bushveld Complex.

Analysis	Western part of Bushveld Complex	
	Main Seam of Subzone B (Average of 25 samples)	Seams of Subzones C and D (Average of 6 samples
Chemical	12.25	17.40
Spectrographic	12.73	15.66

Analysis	Eastern part of Bushveld Complex	
	Main Seam of Subzone B (Average of 5 samples)	Seams of Subzones C and D (Average of 5 samples
Chemical	14.26	13.30
Spectrographic	11.10	16.35

The average percentage of titanium in the Eastern and Western parts is 14.14 per cent.

The Main Seam of Subzone B contains an average of 53.25 per cent of iron and 12.58 per cent of TiO_2. Taking the Main Seam only, the Bushveld magnetite contains about 13 per cent more iron and 22 per cent less TiO_2 than the magnetite from Lake Sanford, America. In addition, the Main Seam contains on the average about 1.6 per cent V_2O_5.

I - Ore Reserves

Eastern part of Bushveld Complex:

For one mile of unbroken distance along the strike of the Main Seam of Subzone B, with an average thickness of 6 feet and persisting for 100 feet down dip, and with a specific gravity of 4.5, the ore reserve is 1,800,000 tons (to nearest 100,000 tons). At an average content of 1.62 per cent V_2O_5 the seam will yield 29,000 tons of V_2O_5 (table 31 a).

If it is assumed that along a strike of 110 miles in the Eastern part of the Bushveld Complex the Main Seam is developed over a total distance of 80 miles, it will yield 144,000,000 tons of ore to a depth of 100 feet down dip. The recoverable amount of V_2O_5 will be 2,320,000 tons (table 32 a).

Western part of Bushveld Complex:

For one mile of unbroken distance along strike of the Main Seam, with an average thickness of 5 feet and persisting for 100 feet down dip, and with a specific gravity of 4.5, the ore reserve is 1,500,000 tons (to nearest 100,000

tons)./...

tons). At an average content of 1.70 per cent V_2O_5 the seam will yield 25,000 tons V_2O_5 (table 31 b).

In the Western part of the Bushveld Complex the Main Seam is assumed to be developed over a total distance of 90 miles. Along this distance the Main Seam will yield 135,000,000 tons of ore and the recoverable amount of V_2O_5 will be 2,200,000 tons (table 32 b).

Table 31 a.

Eastern part of Bushveld Complex	
Tonnage of ore per 100' down dip and 1 mile along strike	Tonnage of V_2O_5 per 100' down dip and 1 mile along strike
1,800,000	29,000

Table 31 b.

Western part of Bushveld Complex	
Tonnage of ore per 100' down dip and 1 mile along strike	Tonnage of V_2O_5 per 100' down dip and 1 mile along strike
1,500,000	25,000

Table 31 c.

Total for Eastern and Western parts.	
Tonnage of ore per 100' dip and 1 mile along strike	Tonnage of V_2O_5 per 100' down dip and 1 mile along strike
3,300,000	54,000

Table/.....

Table 32 a.

Eastern part of Bushveld Complex	
Tonnage of ore per 100' down dip over 80 miles along strike	Tonnage of V_2O_5 per 100' down dip over 80 miles along strike
144,000,000	2,320,000

Table 32 b.

Western part of Bushveld Complex	
Tonnage of ore per 100' down dip over 90 miles along strike	Tonnage of V_2O_5 per 100' down dip over 90 miles along strike
135,000,000	2,200,000

Table 32 c.

Total for the Eastern and Western parts	
Tonnage of ore per 100' down dip	Tonnage of V_2O_5 per 100' down dip
279,000,000	4,520,000

The total distance along which the Main Seam is developed in the Eastern and Western parts of the Bushveld Complex is unknown and difficult to determine at this stage. The figures in the table above are therefore estimates only as they are based on assumed distances of 80 and 90 miles along strike for the Eastern and Western parts respectively.

The reserves of ore at grass are also considerable. This includes solid outcrops and eluvial material. At Kennedy's Vale alone several million tons of ore were available. Assuming therefore that mining of vanadiferous ore in the Bushveld Igneous Complex will continue and that in the near future the magnetite seams will be further exploited for their iron and titanium contents, it will be many years before the resources below surface are tapped. In spite of this, it is still believed by some that if payable ore is mined underground near a railhead it may be cheaper than ore mined from outcrops some distance from rail.

The largest tonnages of ore on surface are available south and north of Roossenekal and at Magnet Heights. With the railway line extended from Stoffberg to

Roossenekal,/.....

Roossenekal, ore along the line and from north of Roossenekal will be removed first and will be sufficient for several years.

PART V1- POST-BUSHVELD INTRUSIONS

21 - DOLERITE INTRUSIONS

Several dolerite dykes of sufficient persistence to warrant mapping were located. All have intruded the magnetite gabbro.

In the field they can be differentiated from the magnetite gabbro by their finer grain-size and by the difference in the weathering of the dolerite and the magnetite gabbro. The dolerite tends to form smaller and more numerous blocks on surface than the magnetite gabbro. The dolerite outcrops can also be recognised by their narrow ridge-like protruberances above the surrounding magnetite gabbro.

Along some of the dykes chilled contacts were observed.

A - Distribution

The most prominent dyke, 10 miles long, passes from Paardekloof 176 JS through the De Lagersdrift 178 JS and Swartkoppies 217 JS into Witpoort 216 JS. Its strike is south-east to north-west and it cuts across the general north-south strike of the magnetite gabbro at an angle of about 20°.

In the bed of the Steelpoort River on De Lagersdrift the dip was seen to be steeply south-west. The dyke was not picked up south of the Laersdrif Fault.

Another dolerite dyke strikes approximately parallel to the previous one. It crops out prominently on Welgevonden 215 JS along the road between Stoffberg and Belfast, but owing to a thick soil cover its north-westward and south-eastward continuation is uncertain. Its length along strike is about 2 miles.

A dolerite dyke, followed for 1.3 miles, strikes about north-south and peters out north of the De Lagersdrift Trigonometrical beacon. Southwards it was followed to the banks of the Steelpoort River on Swartkoppies 217 JS. Beyond this point it could not be followed owing to a soil cover. This dyke differs from

the/.....

the others in that it is porphyritic; the phenocrysts, some of which measure up to 20 mm in diameter, consist of fibrous serpentine, which may be an alteration product of original olivine. A dyke striking westwards on P Paardekloof, passes through the Wedge 175 JS and splits into two separate dykes on Duikerskrans; it is 2½ miles long.

A dolerite outcrop was noticed in the Swartspruit near the western boundary of Konterdanskloof, and also near the northern boundary of Witbooi. These outcrops are not shown on the map.

The two larger dykes cut the magnetitite seams. No displacement has taken place along the seams at these points.

B - Mineralogical Description

Mineralogically the dykes are medium-grained dolerite. Plagioclase crystals are long and slender. The pyroxene is in process of alteration to chloritic material. The refractive indices of the plagioclase are:- $n\gamma = 1.566\ (\pm\ 0.002)$ and $n\alpha = 1.558\ (\pm\ 0.002)$. It is therefore labradorite. The pyroxene is monoclinic and non-pleochroic with $n\gamma = 1.720\ (\pm\ 0.002)$, and is therefore augite. A comparatively fresh dolerite specimen on Welgevonden 215 JS contains 55 per cent of plagioclase, 40 per cent of monoclinic pyroxene and 5 per cent of magnetite by volume.

22 - QUARTZ VEINS

A number of quartz veins were observed and some of them are large enough to be shown on the geological map (folder 1). Good exposures of quartz veins are found on Rhenosterhoek 180 JS, Laersdrif 178 JS, Windhoek 222 JS and Doornkop 356 JS. Much loose vein-quartz was noticed along the direction of strike of the Laersdrif Fault on Swartkoppies 217 JS and Witpoort 216 JS.

SUMMARY AND CONCLUSIONS

Geological mapping of an area around Stoffberg, in which mainly rocks of the Bushveld Igneous Complex are exposed, and a laboratory investigation of the various rock types encountered has revealed the following major features:

1. It has been established that the Critical Zone of the Bushveld Complex is not developed in the area.
2. Both the Main and the Upper Zone are present. They are separated from each other by a xenolith of metamorphosed andesite and micrugranite of uncertain derivation.
3. The Main Zone consists of hypersthene gabbro, hyperite and subordinate norite. Collectively the rocks of the Main Zone are referred to as gabbroic rocks. They contain less than 0.5 per cent magnetite.
4. The Main Zone rests on the Dullstroom andesite of the Smelterskop Stage whereas the "roof" of the Complex consists of various types of felsite. The basal portion of the Rooiberg felsite has been metamorphosed and xenoliths of it lie within the fayalite diorite.
5. Based on the ubiquitous presence of magnetite (more than 0.5 per cent) in the rocks of the Upper Zone, the term magnetite gabbro is proposed for them. Along the base of the Upper Zone hypersthene gabbro, hyperite and norite have formed.
6. Along the top of the Upper Zone diorite, olivine diorite and olivine-hypersthene diorite are developed. Owing to poor outcrops the different layers are not shown separately on the map.
7. The top of the Bushveld Complex is made up of fayalite diorite which could be mapped separately.
8. Four zones of magnetitite seams have been distinguished in the rocks of the Upper Zone and they can be correlated with the seams from Magnet Heights, some 40 miles north of Stoffberg.
9. A fault, for which the name Laersdrif Fault is suggested and which has displaced the rocks of the Bushveld Complex and of the Pretoria Series, has been recognised and mapped. The maximum vertical displacement along the fault is about 3,700 feet.

10. North/.....

10. North of the Laersdrif Fault the various layers of the Bushveld Complex dip from 0^{o} to 10^{o} westwards. South of the fault the dip increases to as much as 25^{o} W.

11. Only the Main Seam of Subzone B and two thinner seams of the zone (Nos. 1 and 2) are of immediate economic significance. They contain about 1.7 per cent of V_2O_5, 53 per cent of iron and 10 per cent of TiO_2.

12. Vast tonnages of titaniferous and vanadiferous magnetite ore are available. Along one mile of strike, and 100 feet down dip, the Main Magnetite Seam with an average thickness of 6 feet contains 1,8000,000 tons of titaniferous and vanadiferous magnetite. From this quantity some 29,000 tons of V_2O_5 may be extracted.

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FOLDER 1


GEOLOGICAL MAP OF THE
STOFFBERG AREA
1:50,000
LEGEND
Alluvium, sand and soil
Recent
Dolerite
Post Karroo
Sandstone
Ecca Series
KARROO SYSTEM
Fayalite diorite
Soil-covered magnetite gabbro
Magnetite-bearing hypersthene gabbro, -hyperite, -norite, -olivine hypersthene gabbro, -diorite and -olivine diorite. Anorthosite
Magnetitite seams: Seams of Subzone A; Seams of subzone B; Seams of subzone C; Seams of subzone D
Magnetitite pipe:
The various rock types were not mapped in owing to poor exposures
Magnetite gabbro (Ferrogabbro)
Upper Zone
Hypersthene gabbro, hyperite, norite, a layered zone of magnetite gabbro containing a magnetitite seam and a pipe, and a layer of black gabbro having finely disseminated magnetite
Anorthosite layer
Leolo Mountains Gabbro
Main Zone
Bushveld Igneous Complex
Uralitised diabase
Diabase
Sill Phase
Diabase
Granite and granophyre
Rooiberg felsite and quartzite layers
Black felsite, spherulitic in places
Granophyric red felsite
Basal felsite and leptite layers
Rooiberg Felsite
Hornblende microgranite associated with the xenolith
Xenolith of metamorphosed Dullstroom andesite (pyroxene hornfels) and agglomerate
Dullstroom andesite (its upper part metamorphosed to pyroxene hornfels); Agglomerate (Ag); felsite ( ) and leptite ( )
Quartzite, feldspathic quartzite, arkose, breccia and overlying leptite ( )
Smelterskop Stage
Pretoria Series
TRANSVAAL SYSTEM
OTHER FEATURES
Quartz vein or blow
Fault
Fault not accurately located
Strike and dip of strata
Dip of layering in igneous rocks
Cu : Copper
Quarry
Main road
Secondary road
Homestead
Railway line
Approximate trace of Stoffberg-Erts Railway line
25°15
25°30
25°45
THE CONSOLIDATED FARM MAPOCHSGRONDE 500JS
BLAAUWBANK 173 JS
RHENOSTERHOEK
SCHIETPAD
STOFFBERG
LAERSDRIF
SWARTKOPPIES
WITPOORT
WINDHOEK
RIETPOORT
WELGEVONDEN
KONTERDANSKLOOF
ZOORNKOP
ONTEVREDEN
UITVAL
STERKLOOP
LEEUWVLIP
KWAGGASKOP
NAUWHOEK
PAARDEPLAATS
KOUTENBEK
SECTIONS A-B, C-D, E-F, G-H, I-J
Horizontal and vertical scale; 1:50,000
Steelpoortrivier
Laersdrif Fault
Subzone A
Subzone B
Subzone C
Subzone D

Folder 2 | **Analyses of specimens**

Specimen	DG 430	DG 389	DG 408	DG 301	DG 482	DG 263	DG 33	DG 178	DG 508	DG 665
Locality	Messchunfontein 98 JS	Witpoort 216 JS	Middelkraal 221 JS	Witbooi 225 JS	Windhoek 221 JS	Welgevonden 215 JS	Welgevonden 215 JS	Blinkwater 213 JS	Enkeldoorn 214 JS	Enkeldoorn 214 JS
SiO_2	65.17	66.36	66.75	56.78	54.78	50.52	65.11	66.13	67.93	69.20
Al_2O_3	13.18	11.43	11.82	14.81	14.61	15.60	11.00	10.69	10.73	11.79
Fe_2O_3	2.15	2.20	2.54	1.73	1.59	2.70	2.37	2.52	3.01	2.35
FeO	4.63	7.33	6.38	7.35	7.90	7.73	8.24	8.96	7.09	3.79
MgO	2.17	1.53	1.29	5.09	6.88	7.41	1.06	0.35	0.45	0.71
CaO	4.00	2.88	3.26	7.29	8.17	12.41	3.79	2.10	2.20	1.71
Na_2O	3.02	3.00	2.84	2.77	2.70	2.41	3.05	2.92	2.97	2.94
K_2O	2.64	2.94	2.88	1.88	1.05	0.28	3.00	4.58	4.14	4.95
H_2O^-	0.11	1.44	1.21	0.069	0.19	0.075	1.09	0.69	0.60	0.15
H_2O^+	1.89	0.02	< 0.01	1.60	1.67	0.41	0.03	< 0.01	< 0.01	1.25
TiO_2	0.65	0.64	0.80	0.57	0.63	0.42	0.92	0.60	0.62	0.60
P_2O_5	0.12	0.19	0.19	0.13	0.11	0.024	0.29	0.18	0.19	0.14
MnO	0.14	0.06	0.06	0.16	0.15	0.22	0.08	0.09	0.09	0.18
Li_2O	nd	0.09	0.09	nd	nd	nd	0.09	0.10	0.10	nd
SnO_2	nd	< 0.10	< 0.10	nd	nd	nd	< 0.10	< 0.10	< 0.10	< 0.01
Total	99.87	100.19	100.22	100.229	100.42	100.425	100.22	100.02	100.23	99.78

Analyses by the National Institute for Metallurgy, Johannesburg

Specimen particulars:

DG 430, DG 389, DG 408 } Felsite from Dullstroom volcanics

DG 301, DG 482 } Andesite from Dullstroom volcanics

DG 263 Pyroxene hornfels; metamorphosed andesite from Dullstroom volcanics

DG 33 Hornblende microgranite (Uncertain derivation)

DG 178, DG 508, DG 665 } Felsite from Rooiberg Felsites

Niggli values:

	DG 430	DG 389	DG 408	DG 301	DG 482	DG 263	DG 33	DG 178	DG 508	DG 665
si	257.20	268.41	275.03	160.20	141.50	113.40	252.98	272.25	293.52	333.70
al	30.53	27.25	28.70	24.58	22.20	20.63	25.19	25.94	27.32	33.57
fm	34.45	40.92	37.99	42.49	46.61	43.92	40.11	41.12	38.64	28.74
c	16.83	12.48	14.39	22.00	22.56	29.82	15.78	9.26	10.19	8.75
alk	18.20	19.35	18.91	10.92	8.61	5.65	18.92	23.68	23.85	28.94
k	0.37	0.39	0.40	0.31	0.21	0.07	0.39	0.51	0.48	0.53
mg	0.37	0.22	0.21	0.50	0.57	0.56	0.15	0.05	0.07	0.17
c/fm	0.49	0.30	0.38	0.52	0.48	0.68	0.39	0.22	0.26	0.30
Magma type	Granitic (Normal granitic)	Granitic (Normal granitic)	Granitic (Normal granitic)	Gabbro dioritic (Si-gabbroidal)	Gabbro dioritic (Normal gabbrodioritic)	Gabbroidal (Pyroxene gabbroidal)	Granitic (Normal granitic)	Granitic (Normal granitic)	Granitic (Normal granitic)	Granitic (Tasna-granitic)

Norms:

	DG 430	DG 389	DG 408	DG 301	DG 482	DG 263	DG 33	DG 178	DG 508	DG 665
Q	23.82	25.31	28.78	11.25	4.84	–	22.59	21.55	24.73	26.48
or	15.83	18.28	17.95	11.64	6.35	1.57	18.67	28.49	25.55	30.45
ab	28.30	28.62	26.80	26.26	24.65	21.66	28.75	27.60	27.86	27.60
an	15.26	9.44	9.27	23.75	25.03	31.21	7.81	1.57	4.82	4
hy	4.91	8.31	8.23	9.94	10.40	4.87	8.60	9.48	6.56	3.50
di	4.27	4.29	4.21	11.54	12.94	24.56	6.12	1.99	2.56	3.33
hed	–	–	–	–	–	–	3.47	4.60	3.36	–
en	4.14	2.27	1.61	2.68	12.96	10.49	–	–	–	0.33
ol	–	–	–	–	–	1.92	–	–	–	–
ilm	0.99	0.98	0.33	0.88	0.94	0.58	1.33	0.94	0.92	0.92
mt	2.35	2.45	2.76	1.88	1.69	2.86	2.60	2.74	3.57	2.57
Total	99.87	99.95	99.94	99.82	99.83	99.72	99.94	98.96	99.93	99.77
Normative plagioclase	$Ab_{65}An_{35}$	$Ab_{75}An_{25}$	$Ab_{74}An_{26}$	$Ab_{52}An_{48}$	$Ab_{50}An_{50}$	$Ab_{41}An_{59}$	$Ab_{79}An_{21}$	$Ab_{95}An_{5}$	$Ab_{85}An_{15}$	$Ab_{86}An_{14}$

CIPW classification:

	DG 430	DG 389	DG 408	DG 301	DG 482	DG 263	DG 33	DG 178	DG 508	DG 665
Class	2	2	2	2	3	3	2	2	1	1
Order	4	4	4	4	5	5	4	4	4	4
Rang	2	2	2	4	5	4	4	2	2	2
Subrang	4	4	4	4	4	5	4	3	3	2