

THE MARGIN OF THE BUSHVELD COMPLEX
IN THE VICINITY OF DE BERG,
NORTH OF DULLSTROOM

by

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Abstract

The sedimentary rocks of the Pretoria Series above the Magaliesberg quartzite consist mainly of quartzite and hornfels. The stratigraphical subdivision of these rocks is based on the principle that a cyclothem begins with coarse-grained material like sandstone which then passes into fine-grained sediments like shale. Accordingly the hornfels above the Magaliesberg quartzite should not be regarded as the start of a new cyclothem but should be grouped in the same zone as the Magaliesberg quartzite. Consequently the Magaliesberg Stage is subdivided into the Main Magaliesberg and the Lakensvlei zones, which consist of the Magaliesberg quartzite and hornfels and the Lakensvlei quartzite and hornfels respectively. The Smelterskop Stage is divided into the Steenkampsberg and the Dullstroom zones. The former consists of quartzite and the latter of andesite.

The Steenkampsberg quartzite, which forms the "floor" of the Bushveld Complex is considerably recrystallized, and has a sugary texture. Sillimanite, plagioclase and muscovite are usually present in this quartzite layer. The Magaliesberg and Lakensvlei quartzite is slightly recrystallized, and chlorite and epidote are prominent constituents. According to petrofabric analyses of the quartzite layers, it is evident that only the Steenkampsberg quartzite, having 9% concentration of the c-axes of the quartz grains, was affected by the thermal metamorphism which accompanied the emplacement of the Bushveld Complex.

Two layers of black sand in the Steenkampsberg quartzite represent a fossil beach sand, which was deposited in the littoral zone. The beach sand consisted originally of ilmeno-magnetite, zircor, magnetite and ilmenite, and during metamorphism the magnetite and ilmenite were altered to hematite and a mixture of ilmenite and rutile respectively.

The Dullstroom volcanics on Houtenbek contain many inclusions of quartzite and zonary amygdalae. Plagioclase and orthopyroxene are the main constituents of the lava and they indicate that the

Dullstroom lava was metamorphosed under conditions corresponding to the pyroxene hornfels facies.

Limestone layers, interlayered in the hornfels above the Magaliesberg quartzite, have been altered either to a diopside fels or to a marble.

Two types of aluminous metamorphic products could be distinguished, viz. cordierite hornfels and muscovite-biotite shale. Both formed in the hornblende hornfels facies and the difference in their mineral assemblages should be ascribed to the differences in chemical composition. The cordierite hornfels contains more Mg^{2+} and Al^{3+} , and relatively less K^{+} than the muscovite-biotite shale.

According to the sedimentology of the sediments of the Pretoria Series, the quartzite could have formed in a littoral environment, whereas the hornfels could have been deposited by the action of turbidity currents under neritic conditions.

Three new chemical analyses of the rocks intrusive into the Pretoria Series are supplied, and according to both the chemical and mineralogical composition these rocks can be grouped into an older undifferentiated and a younger differentiated group. The former usually consists of diorite and the latter comprises a glass-bearing margin and a differentiated central portion of the sills. The latter consists of harzburgite, dolerite, pyroxenite and quartz dolerite.

The rocks of the differentiated suite have been uralitised to a variable extent and can be called diabase. They belong to the hornblende hornfels facies. The diorite on the other hand was not affected, because hornblende and plagioclase are stable in the hornblende hornfels facies.

The composition of the glassy dolerite evidently represents the composition of the original magma which formed the differentiated sills. The chemical composition of the residual glass of the glassy dolerite indicates that iron enrichment characterizes an early stage of differentiation of a tholeiitic magma.

The rocks of the layered sequence of the Bushveld Complex consist of norite, hyperite, chromitite and a marginal zone. Three types of marginal rocks, viz. micro-norite, quartz norite and quartz micro-norite, could be distinguished. The micro-norite forms a continuous rim along the margin of the Bushveld Complex and it represents a chilled margin. The quartz norite is a hybrid rock, which has assimilated sedimentary material. The quartz micro-norite replaces the micro-norite where assimilation has preceded the rapid chilling of the layered sequence of the Bushveld Complex.

The two chromitite seams on De Kafferskraal and Sterkfontein belong to the Upper Group of chromitite seams. According to the petrography of the chromitite it is evident that the chromite grains settled from a magma rather than crystallized from a late magmatic residuum. On De Kafferskraal the chromitite seams end abruptly against the Steenkampsberg quartzite, without any evidence of faulting along the contact between the Bushveld Complex and the Pretoria Series.

The decrease in the width of outcrop of the Steenkampsberg quartzite on Kliprivier, Wanhoop, De Kafferskraal and Verloren Valei is explained by the transgression of the rocks of the layered sequence of the Bushveld Complex across the sedimentary rocks of the Pretoria Series. The slight folding on De Kafferskraal is insufficient to explain the decrease of 3,000 ft. in the width of outcrop of this quartzite layer and consequently this rather sudden and phenomenal change in width of igneous material is explained by transgression.

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I. INTRODUCTION

The area investigated covers approximately 180 sq. miles, and is defined by longitude $30^{\circ}3'$ and $30^{\circ}17'$, and latitude $25^{\circ}10'$ and $25^{\circ}25'$. It is situated 8 miles north of Dullstroom, along the Nederhorst-Draaikraal and Dullstroom-Lydenburg roads.

This area has previously been mapped by A.L. Hall (1913) on a regional scale, and has recently been remapped by the Geological Survey, with the view to publish a map of a large area on a scale of 1:250,000. Parts of De Kafferskraal 53-JT, Sterkfontein 52-JT, and Kliprivier 73-JT were recently mapped by P. Roux to round off his field-work on an area investigated for a thesis, farther to the north, but his work was not available to the author.

Three problems were involved which the present author had to try and solve. They were:

1. The sudden increase in the thickness of the "Upper Magaliesberg quartzite" south of the farm De Berg, as mapped by A.L. Hall (1913, sheet 11).

2. The nature of the metamorphism of the Pretoria Series compared with that farther north, especially in the vicinity of Burgersfort.

3. The considerable development of diabase in the area, and its relationship to the layered sequence of the Bushveld Complex.

During the investigation additional information was also obtained on:-

1. The nature of the contact of the chromitite seams and the sediments of the Pretoria Series.

2. The sedimentology and classification of the Smelterskop Stage of the Pretoria Series.

3. The nature of the contact of the layered sequence of the Bushveld Complex and the sedimentary rocks of the Pretoria Series.

The field-work commenced in July 1965, and the mapping was completed during the summer vacation of 1965-1966. Aerial photographs on a scale of 1:40,000 were obtained from the Trigonometrical Survey of South Africa, and were used as base maps in the field. From these photographs a map on a scale of 1:50,000 was compiled (map 1).

II. THE PRETORIA SERIES

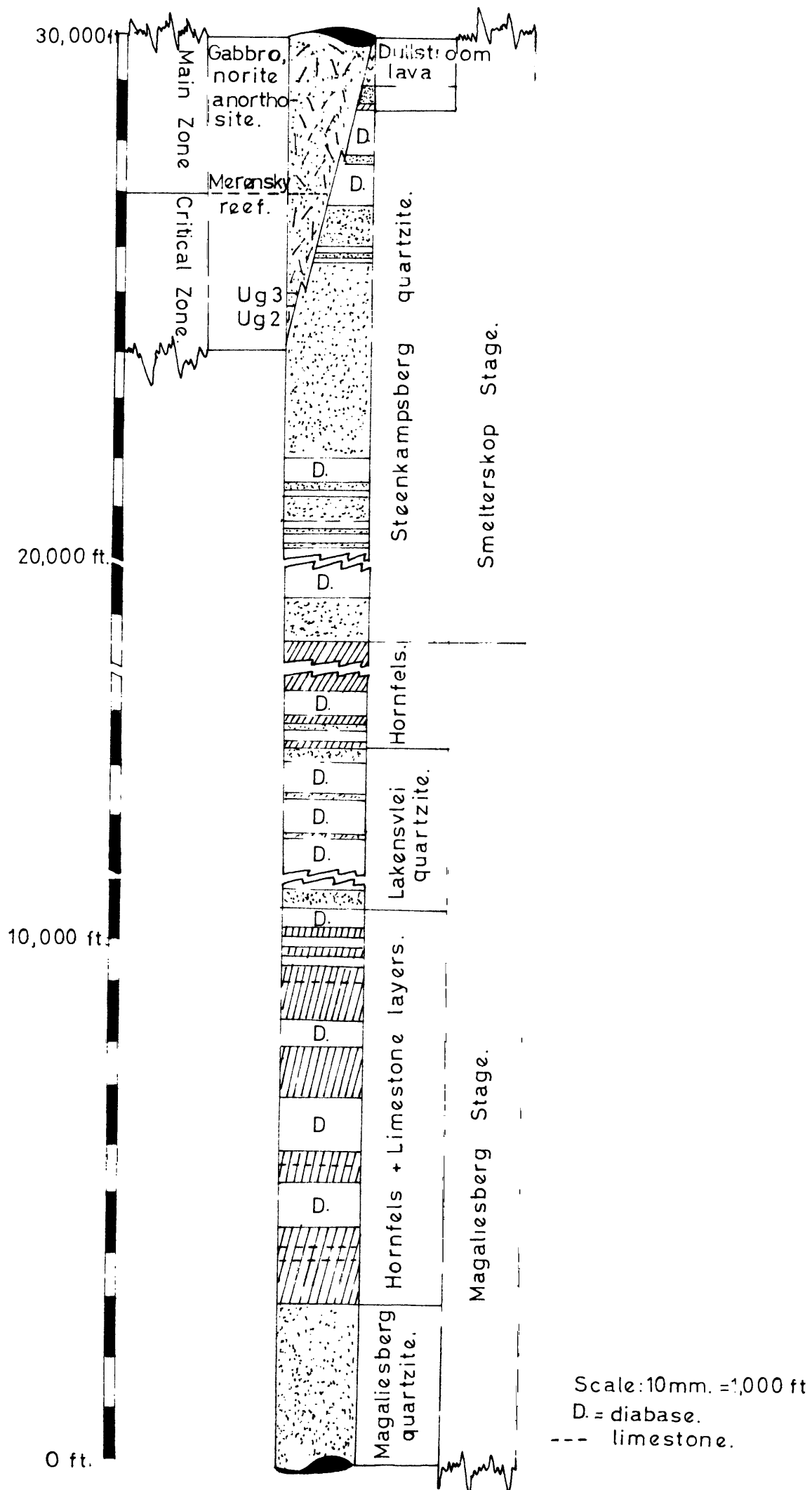
A. Introduction

The upper portion of the Magaliesberg Stage, and the whole succession of the Smelterskop Stage of the Pretoria Series falls within the area investigated (figure 1).

According to the classification of Coertze (1961, p.54-62), the hornfels succeeding the Magaliesberg quartzite should be assigned to the Smelterskop Stage, and the Magaliesberg quartzite should be regarded as the top of the Magaliesberg Stage. This grouping is not in agreement with the principles of stratigraphical classification based on normal sedimentation cycles, as proposed by Twenhofel (1950, p.23). According to Twenhofel sand and gravel are deposited at the start of a sedimentation cycle, whereas shale and limestone are formed during the closing stages. Genetically therefore the hornfels above the Magaliesberg quartzite should be regarded as part of the Magaliesberg Stage.

Since the Lakensvlei quartzite is interbedded with the hornfels above the Magaliesberg quartzite, it cannot be regarded as the beginning of a sedimentation cycle, but only represents a slight change in the depositional conditions in the geosyncline, in which the Pretoria Series was deposited. The base of the Steenkampsberg quartzite and that of the

FIG. 1. THE GEOLOGICAL SUCCESSION.



Magaliesberg quartzite represent the beginning of two cyclothem, and are consequently used as marker horizons in the grouping of the upper beds of the Pretoria Series (figure 3).

The sedimentary rocks of the Magaliesberg Stage consist of quartzite ($\pm 6,500$ ft), hornfels ($\pm 6,000$ ft) and several thin limestone layers (± 100 ft) towards the top of the succession. The Steenkampsberg quartzite is succeeded by the Dullstroom lava. At various horizons the Smelterskop Stage has been intruded by diabase sheets (figure 1).

The succession of the Smelterskop Stage in the vicinity of De Berg corresponds to that in the type locality at Rooiberg, and to that of the areas north-east of Pretoria and southeast of the Steelpoort Railway Station (figure 2).

It is clear from the information contained in figure 3, that the sedimentary rocks of the Pretoria Series above the Magaliesberg quartzite can be grouped into four zones, namely the Main Magaliesberg-, ^{the} Alakensvlei-, ^{the} Steenkampsberg- and ^{the} Dullstroom zones.

B. The Layers of Quartzite

1. Geological setting

A large part of the area mapped is taken up by a white to cream-white, fine- to coarse-grained quartzite, which forms prominent ridges, whereas diabase and hornfels which weather more easily underlie the valleys. The quartzite ridges cause a relief difference of $\pm 2,000$ ft in places, for example in the Steenkampsberg on De Berg 71-JT, but it is usually much less. The alteration of quartzite and shale in the succession of the Pretoria Series is easily detectable in the topography, mainly because of the development of white, linear, quartzite ridges.

Three quartzite layers, which belong to two stages of the Pretoria Series occur in the present area (figure 3 and map 1). The lowest quartzite, generally referred to as the Main Magaliesberg quartzite, outcrops on the farms Kwaggashoek, Klipsteen, Weimershoek and Knapdaar. The succeeding quartzite, which consists of several thin layers interbedded with hornfels,

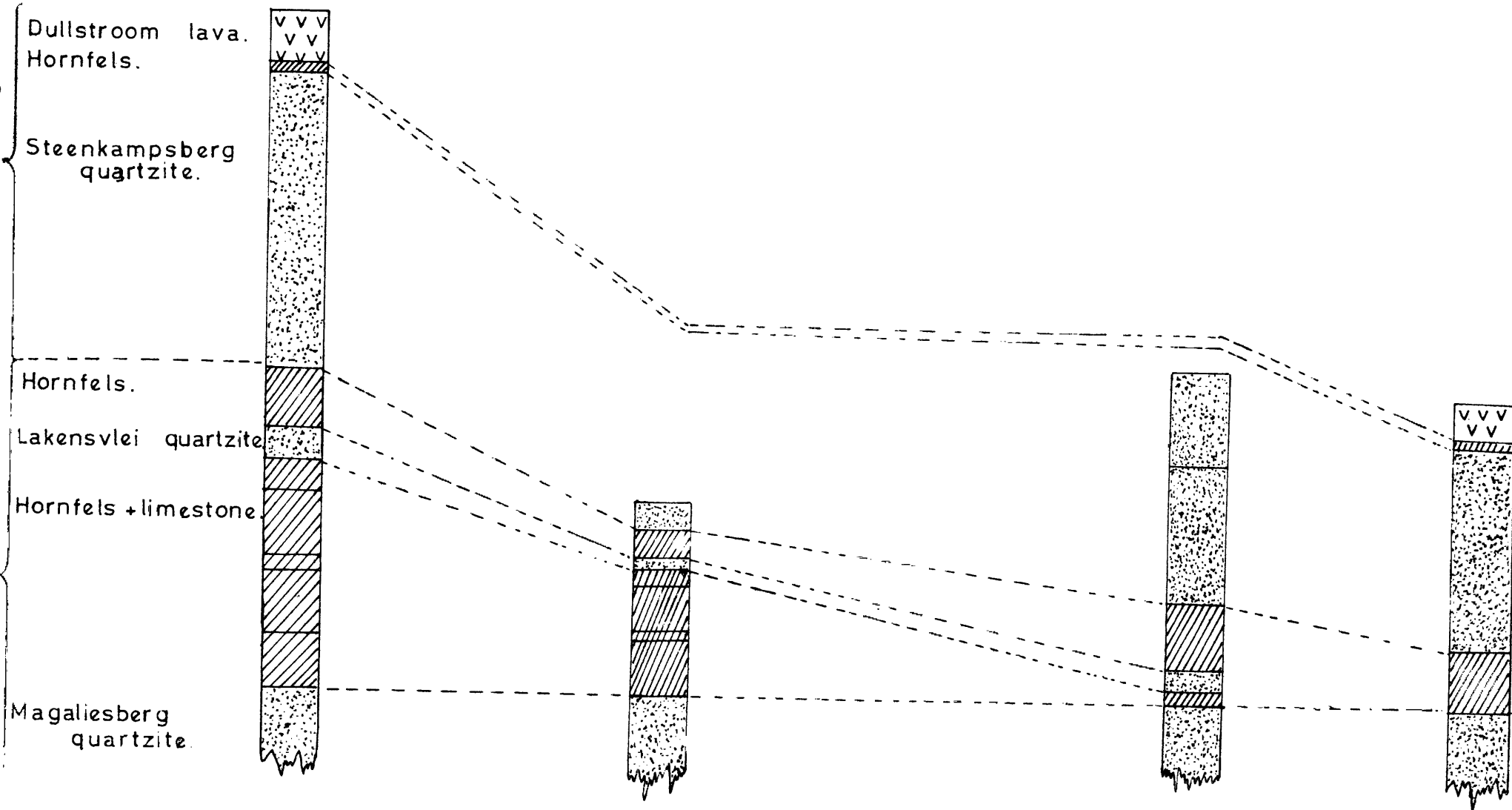
of Pretoria, southeast of Steelpoort station, and in the vicinity of De Berg.

De Berg

Southeast of Steelpoort
station (W. van Biljon,
1951).

Northeast of Pretoria
(Coertze, 1961, p59).

The type locality
Rooiberg.
(Boardman 1964, p.107).

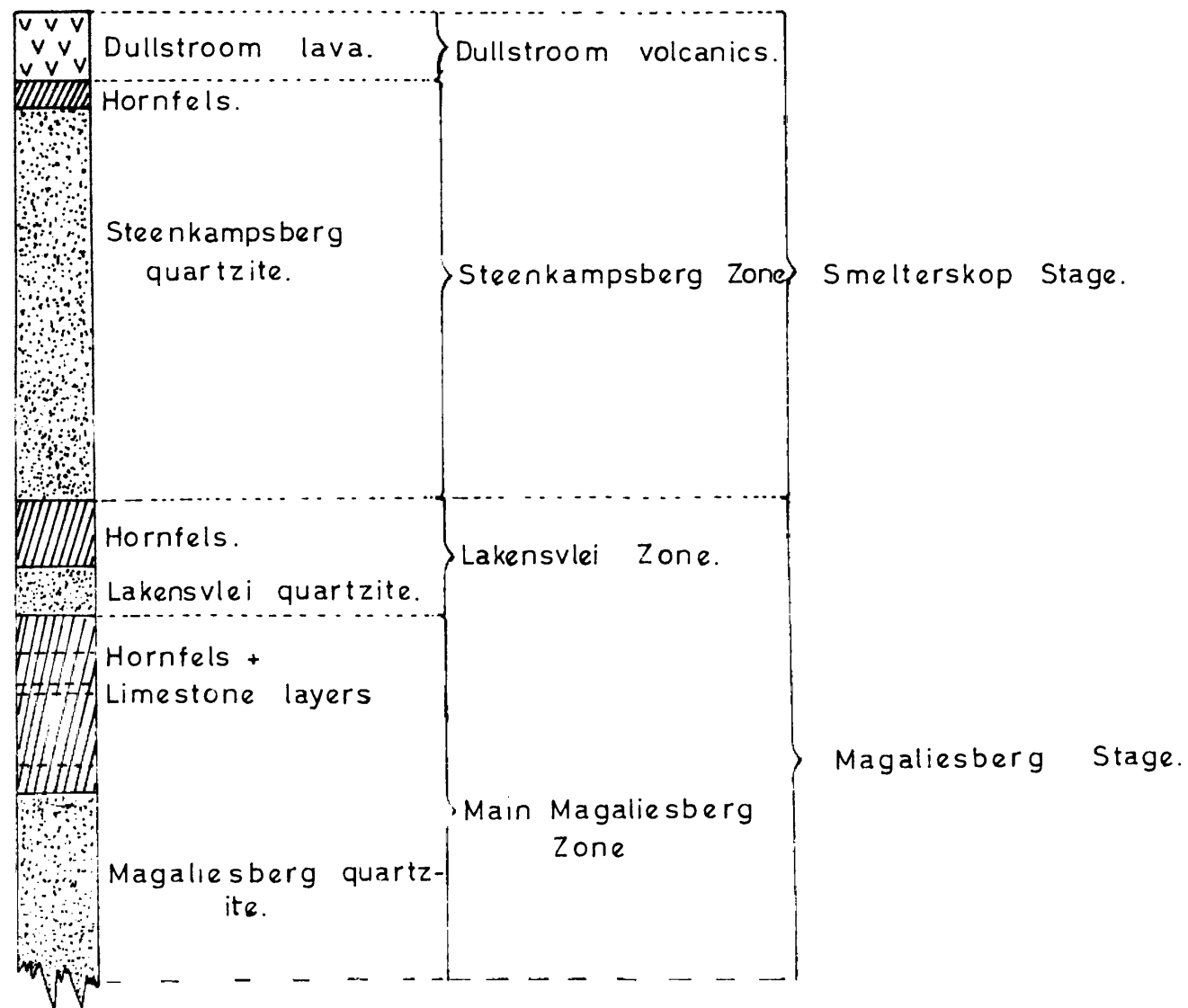


10,000 ft

5,000 ft.

— 9 —

FIG. 3. THE GROUPING OF THE UPPER BEDS OF THE PRETORIA SERIES.



has been mapped on the northern portion of Lunsklip 105-JT, Vrischgewaagd is Half Gewonnen 94-JT, and along the boundary lines between Suikerboschhoek 80-JT, Goedehoop 79-JT and Oshoek 69-JT and Schaapkraal 68-JT. S. van Biljon (1949, map 1) called this horizon the Lakensvlei quartzite. W.J. van Biljon (1951, p.7) and J. Willemse (1959, p.xxvi) evidently referred to the same horizon farther north as the quartzite between the Magaliesberg and the Lakensvlei quartzite. According to the information now available (fig. 2) it is clear that the quartzite layer which W.J. van Biljon called the Lakensvlei quartzite, should be correlated with the Steenkampsberg quartzite. In this thesis the name which S. van Biljon gave to this horizon has been retained. The uppermost quartzite, a thick layer, called the Steenkampsberg quartzite, outcrops on the farms Onvêrvalei, Verloren Valei, Wanhoop and Wicht, and in the eastern parts of Klipbankspruit and Kliprivier.

On the eastern part of the farm Goedehoop, and on Vrischgewaagd is Half Gewonnen, diabase sheets, which cut across the quartzite layers, have been mapped.

There is a considerable change in the thickness of the Steenkampsberg quartzite along the strike from north to south in the area investigated (table 1). Hall (1913) also indicated a variation in the thickness of the Steenkampsberg quartzite on his map of the Dullstroom-Lydenburg area (sheet 11). This difference in thickness is explained in a subsequent paragraph.

Table 1. The thickness of the Steenkampsberg quartzite in the north and the south

Profile, map 1	A.B.	C.D.
Thickness in feet	1,1000	4,700

The average dip of the Steenkampsberg quartzite ranges

between 18° and 22° West, but a tremendous variation exists at different localities, whereas the dip of the Lakensvlei and Magaliesberg quartzite ranges between 10° and 15° West, without much variation. To attain the maximum accuracy in the measurement of the dip, the method described by Phillips (1960, p.7) was used. It consists in measuring two apparent dips at each locality and then determining the real dip with the aid of a Wulff stereonet.

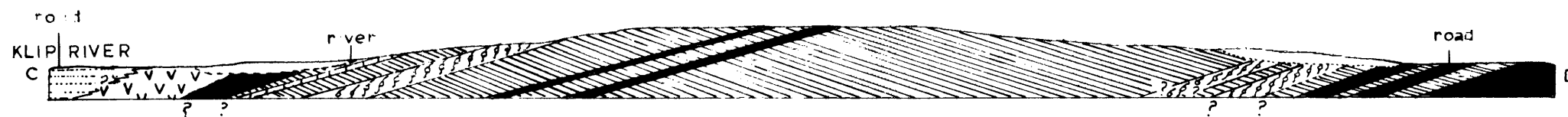
The variation in the thickness of the Steenkampsberg quartzite (table 1) can be explained by the transgressive relation of the layered sequence of the Bushveld Complex to the quartzite. Along profile AB (p.10) the Bushveld Complex rests against a quartzite layer which is 1,100 ft. thick, whereas along profile CD the layered sequence of the Bushveld Complex overlies the Dullstroom volcanics, which succeeds the Steenkampsberg quartzite. Consequently a thickness of $\pm 3,600$ ft. of quartzite was eliminated by the transgression of the Bushveld Complex across the quartzite on De Kafferskraal and farther to the north. Apart from this transgression of the Bushveld Complex, the width of outcrop of quartzite is accentuated by the topography. The slope of the mountains towards the Bushveld Complex corresponds nearly to the dip of the quartzite layers (profiles AB and CD) and in this way the width of outcrop is increased. Folding is present in the Steenkampsberg quartzite (map 2), but it is so limited in extent that it cannot explain the increase in the thickness of the quartzite.

Intersecting joint systems are common in the quartzite layers on De Berg, Wanhoop and Houtenbek. Thin layers of fine-grained argillaceous rocks are also characteristic of this zone.

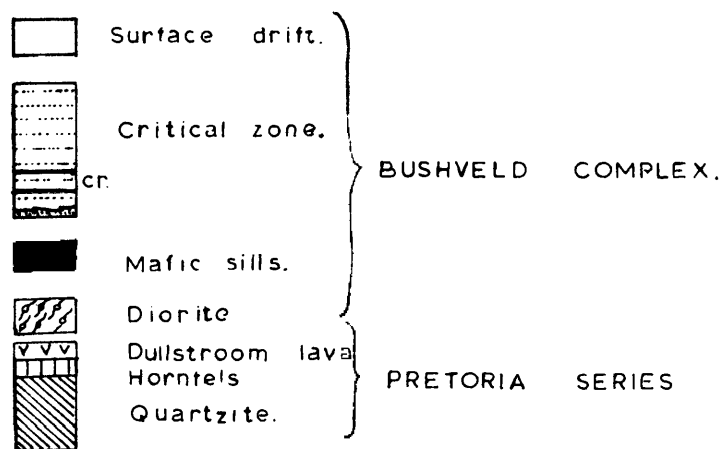
2. Petrology

Macroscopically there is very little difference between the quartzite of the different horizons. The upper layers of the Steenkampsberg quartzite, which forms the margin of the layered sequence of

PROFILES TO SHOW THE VARIATION IN THE THICKNESS OF THE STEENKAMPSBERG QUARTZITE IN THE NORTH (AB) AND THE SOUTH (CD)



LEGEND.



Scale 1:50,000.

the Bushveld Complex is recrystallized, coarse-grained, and has a sugary texture, without any cross-layering or ripple-marks visible. The Lakensvlei and Magaliesberg quartzite, and the base of the Steenkampsberg quartzite, were not much affected by the metamorphism. Cross-layering and ripple-marks still characterize these layers.

The average quartzite consisted of quartz, feldspar and a clay matrix, prior to metamorphism and during metamorphism sillimanite, hematite, epidote, biotite and muscovite formed (table 2). The Magaliesberg quartzite contains much more feldspar than the succeeding layers, but in places feldspar is absent and the original rounded feldspar grains are replaced by sericite and epidote (photo 4). Barth (1962, p.254) describes the alteration of plagioclase to sericite and epidote as the normal behaviour of plagioclase, during the early phases of thermal metamorphism. The Steenkampsberg quartzite on the farm Sterkfontein (CF 107) is feldspar-rich ($An_{45} \pm 5\%$), and this feldspar, which is xenomorphic and intergranular, is considered to have originated through metasomatism, rather than through recrystallization of original feldspar grains.

Zircons of various shapes, colours and displaying many growth phenomena are present as accessory minerals in the quartzite, but they are usually concentrated in laminae of black sand, that will be described subsequently. The opaque minerals present are either perfectly rounded and of sedimentary origin, for example ilmenite, magnetite and hematite or they are xenomorphic and of metamorphic origin like hematite and magnetite.

Petrographic analyses have been carried out on thin sections cut parallel to the strike and perpendicular to the dip of the Steenkampsberg, the Lakensvlei and the Magaliesberg quartzite. The petrofabric diagrams were constructed according to the

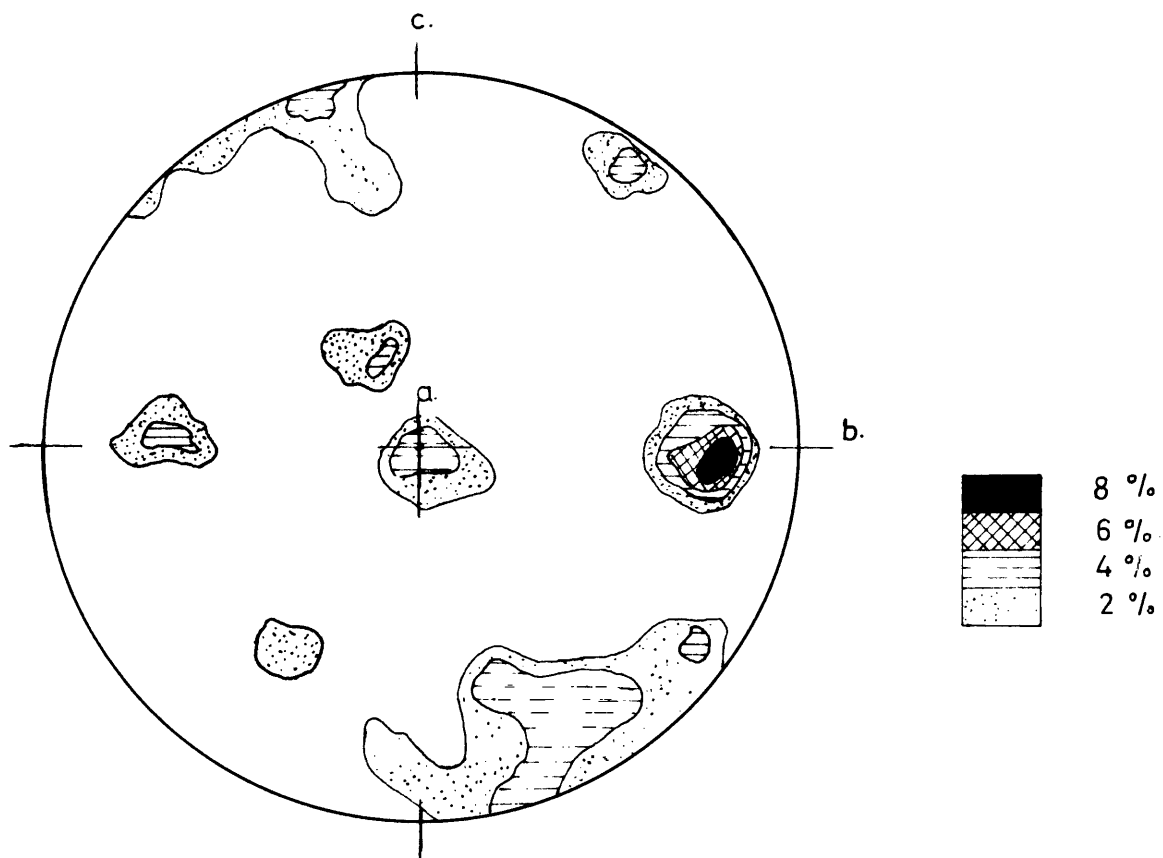


FIGURE 6 ORIENTATION OF THE C-AXES OF QUARTZ IN THE STEENKAMPSBERG QUARTZITE ON KLIPRIVIER 73-JT.
a = Direction of dip, b = direction of strike of the quartzite.
100 Measurements, CF 104.

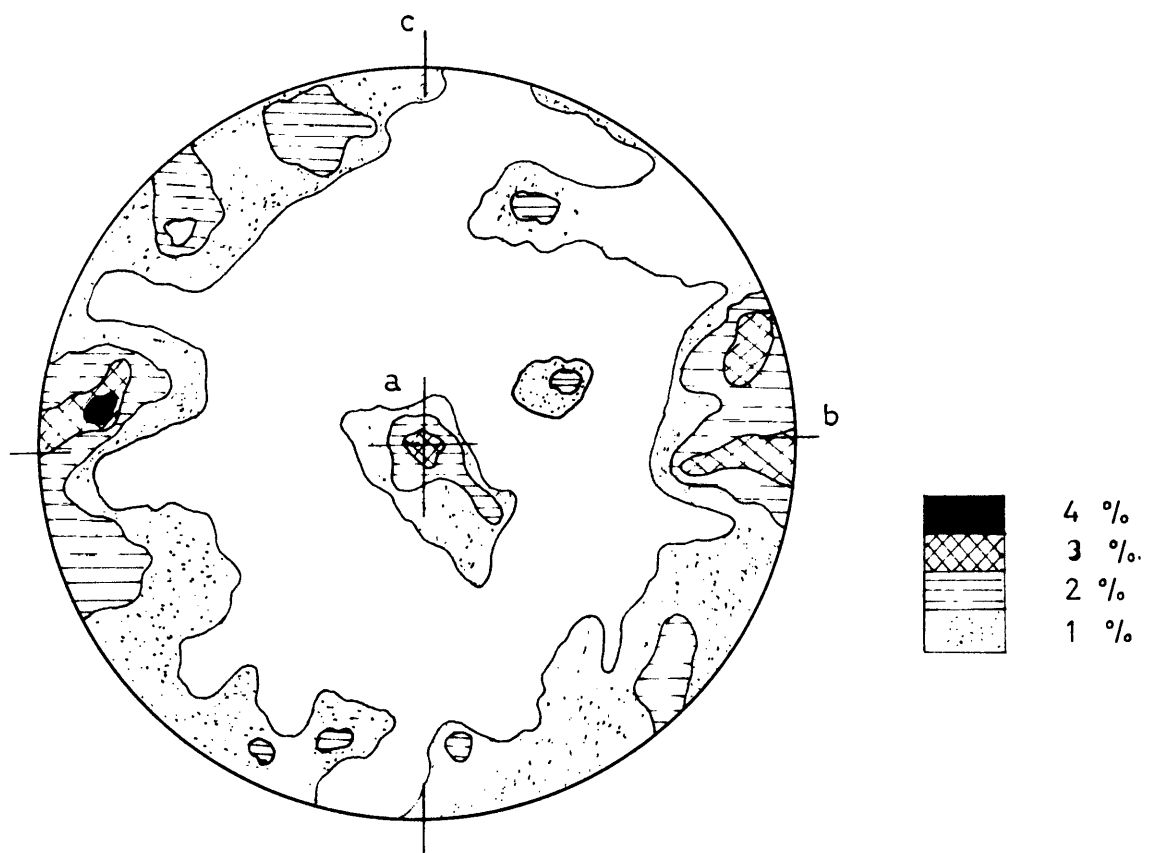


FIGURE 7 ORIENTATION OF THE C-AXES OF QUARTZ IN THE LAKENSVLEI QUARTZITE ON VRISCHGEWAAGD IS HALF GEWONNEN. 94. a = Direction of dip, b = direction of strike of the quartzite 200 Measurements, CF 103

methods of J.C. Haff (1938, p.543-574). All the c-axes of the quartz grains in each of the thin sections were measured. In the diagrams the a-axis is parallel to the dip, the b-axis is parallel to the strike, and the c-axis is perpendicular to the layering.

In the unmetamorphosed Magaliesberg and Lakensvlei quartzite a random orientation of the optical axes of the quartz grains prevail (fig. 7 and 8) whereas in the recrystallized Steenkampsberg quartzite, some orientation of quartz grains have been observed (table 4). This orientation of the quartz grains conforms to Riecke's principle (Billings 1959, p.32 and Turner and Verhoogen 1954, p.394-395), viz. that growth of a mineral grain, which is subjected to high pressure and heat, would occur in the direction of least stress. When pressure is applied perpendicular to the layering of a layered sequence of rocks, the directions of least stress would be in the plane of the layering. Consequently the recrystallized quartz grains would orientate themselves with their long axes parallel to the plane of the layering in the quartzite, and their optical axes would come to lie in the plane (ab) as in figures 4, 5 and 6.

According to the petrofabric diagrams of the Steenkampsberg quartzite (fig. 4, 5 and 6), the maximum concentration of the optical axes of the quartz grains, make an angle of $50^{\circ} \pm 10^{\circ}$ with the direction of dip of the quartzite. This distribution of the c-axes of the quartz grains corresponds to the results obtained by Mr. S. Zagt (personal communication) in a recent investigation of the Magaliesberg quartzite north of Pretoria. He ascribes this orientation of the c-axes in a zone $45 \pm 15^{\circ}$ around the direction of the dip of the quartzite layers to the original rounding and deposition of the quartz grains and he concludes that quartz is rounded off in the sedimentation cycle into ellipsoidal grains, of which the long axes are parallel to the presumed cleavage plane (10 $\bar{1}$ 1) of the mineral

Table 4. The orientation of the c-axes of the quartz grains in the Steenkampsberg, the Magaliesberg and the Lakensvlei quartzite

Quartzite zone	Thin section	Maximum concentration	Direction of maximum concentration	Figure	Recrystallisation	Symmetry planes
Steenkampsberg	CF 99	6%	$\pm 60^\circ$ from the a-axis in the (a-b) plane.	4		(ab)+(ac)
	CF 98	6%		5	Pronounced	(ab)+(ac)
	CF 104	8%		6		(ab)+(ac)
Lakensvlei	CF 103	4%	Parallel to a and b directions in the (a-b) plane.	7	Slight	(ab)
Magaliesberg	CF 100	3%	Randomly orientated.	8	Subordinate	No

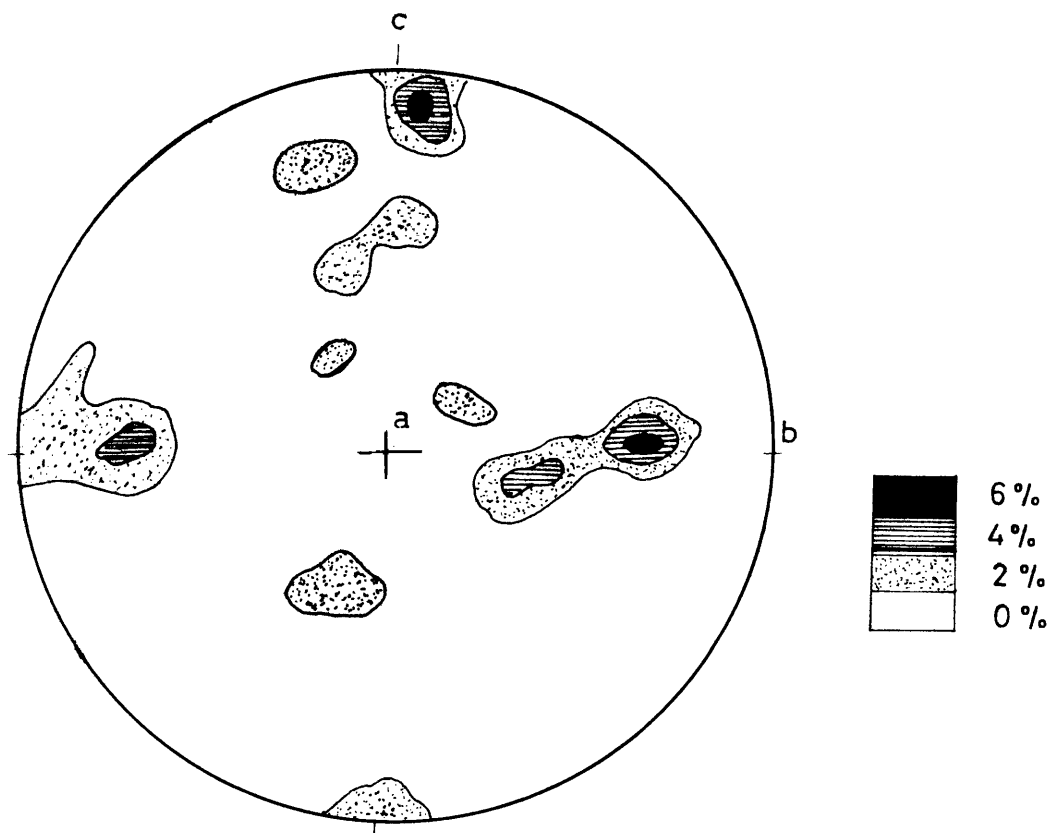


FIGURE 4 . ORIENTATION OF THE C-AXES OF QUARTZ IN THE STEENKAMPSBERG QUARTZITE ON DE KAFFERSKRAAL 53 JT. a = Direction of dip and b = direction of strike. of quartzite. 100 Measurements, C.F. 99.

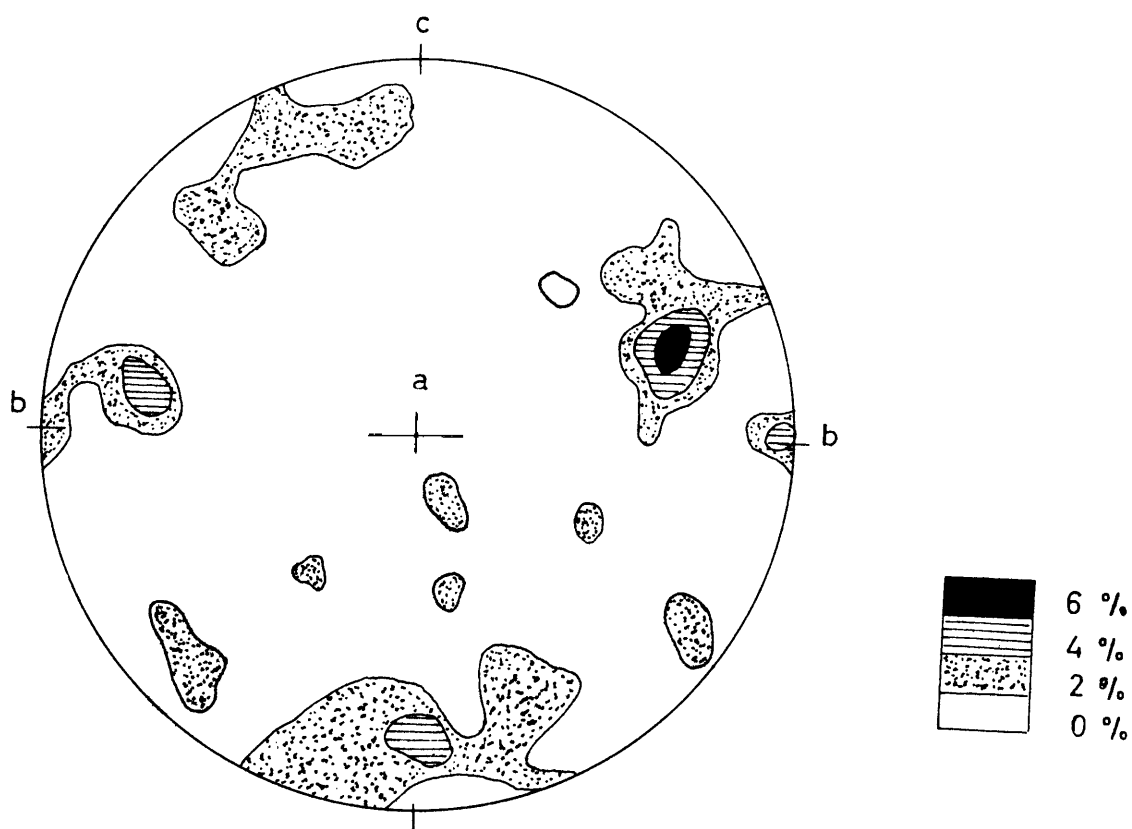


FIGURE 5. ORIENTATION OF THE C-AXES OF QUARTZ IN THE STEENKAMPSBERG QUARTZITE ON KLIPRIVIER 73 JT. a = Direction of dip and b = direction of strike of quartzite.

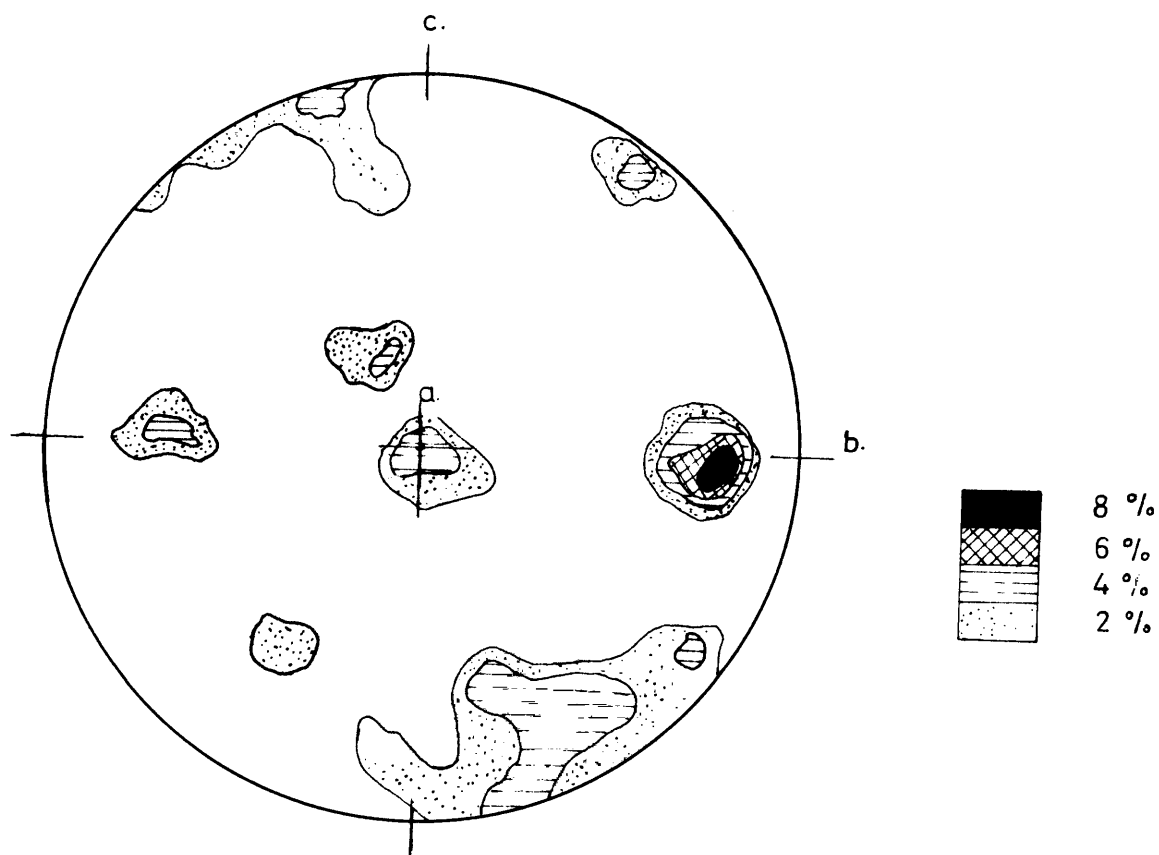


FIGURE 6 ORIENTATION OF THE C-AXES OF QUARTZ IN THE STEENKAMPSBERG QUARTZITE ON KLIPRIVIER 73-JT.

a = Direction of dip, b = direction of strike of the quartzite.
100 Measurements, C.F. 104.

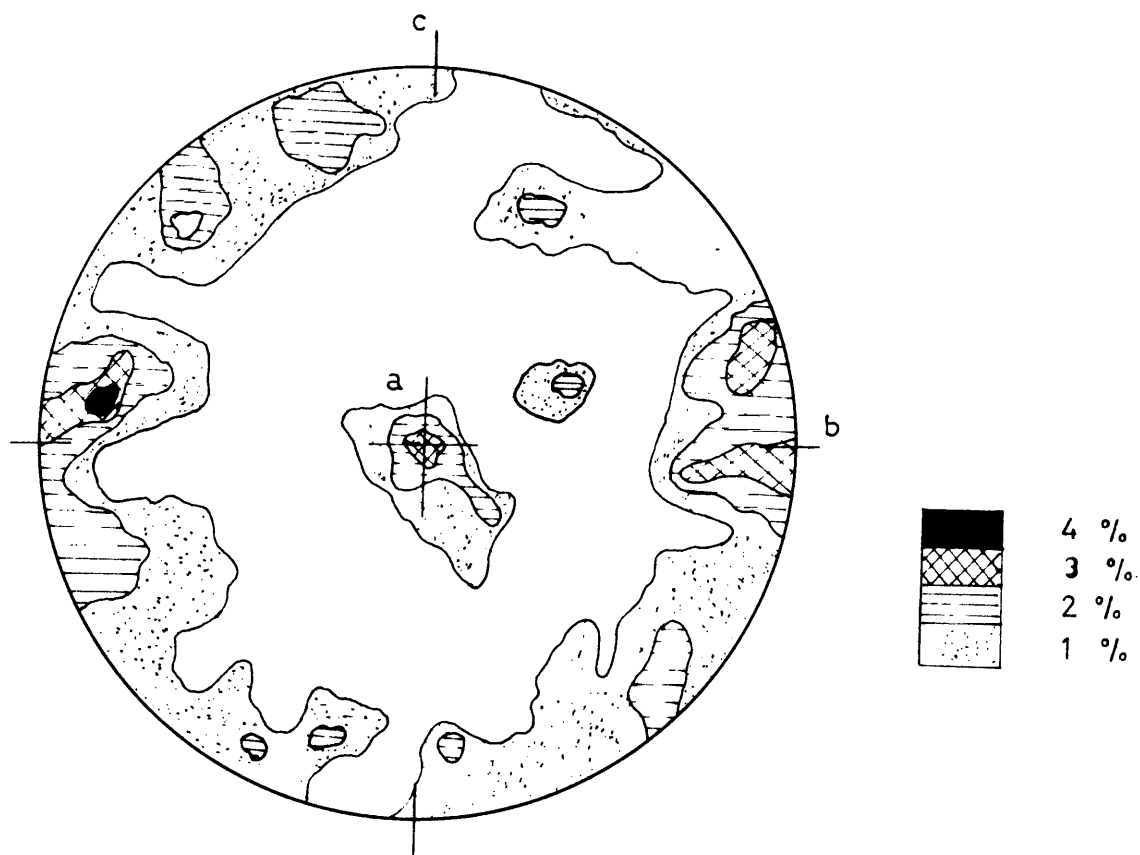


FIGURE 7 ORIENTATION OF THE C-AXES OF QUARTZ IN THE LAKENSVLEI QUARTZITE ON VRISCHGEWAAGD IS HALF GEWONNEN. 94. a = Direction of dip, b = direction of strike of the quartzite. 200 Measurements, C.F. 103

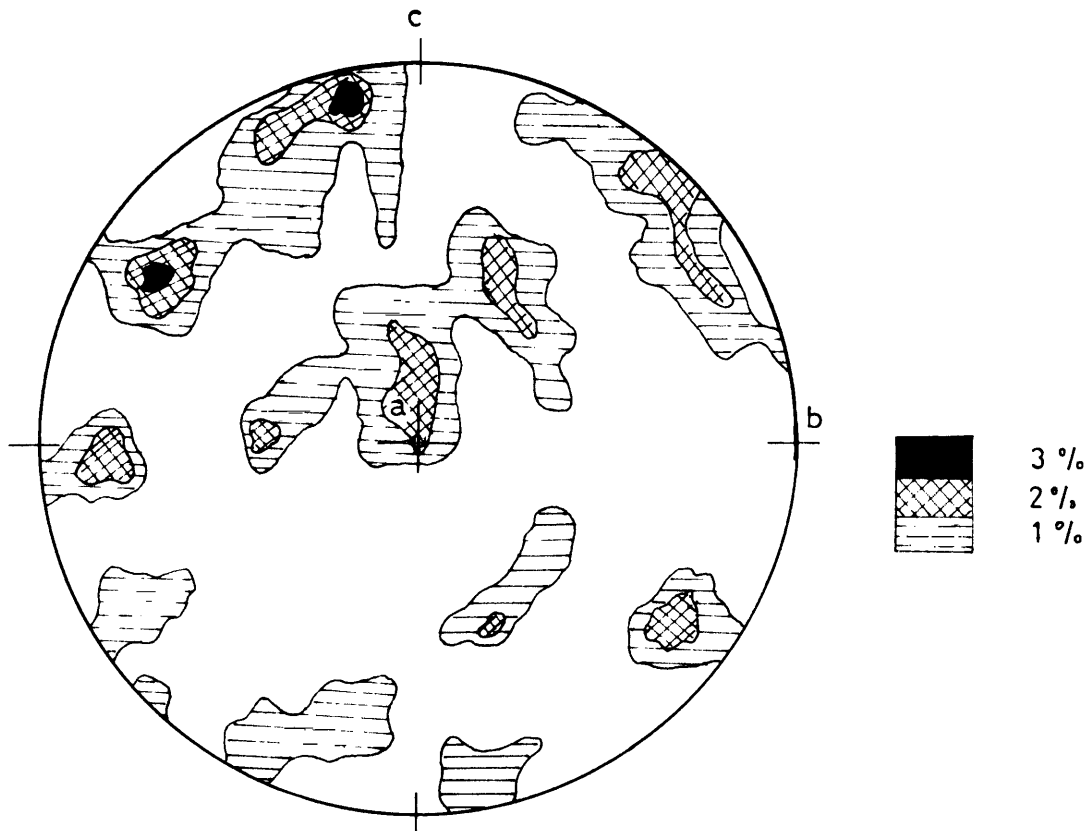


FIGURE 8 ORIENTATION OF THE C-AXES OF QUARTZ IN THE MAGALIESBERG QUARTZITE ON WEIMERSHOEK 81-JT
a=Direction of dip, b=direction of strike of quartzite. 170 Measurements. C.F. 100.

Since the ellipsoidal grains are orientated during deposition, the c-axes of the quartz grains will also be orientated.

It is conceivable that during the emplacement of the Bushveld Complex the weight of the intruding magma accompanied by the increase in temperature, caused growth of quartz grains mainly in the plane of the layering of the quartzite, and since many grains already had their c-axes in this plane, according to the conditions described above, most growth would have taken place along these directions. In the unmetamorphosed Magaliesberg and Lakensvlei quartzite, a random orientation of quartz grains has been observed, a phenomenon which is in conformity with the findings of Mr. Zagt for the Daspoort quartzite, which is not entirely metamorphosed,

The petrofabric diagrams, nevertheless, indicate that the Bushveld Complex did not exert much pressure on the bordering sediments, except for the increase in the weight of the overlying material. Since only the Steenkampsberg quartzite was subjected to an increase in temperature accompanied by an increase in overlying weight, it is the only quartzite layer which shows some orientation of the quartz grains.

In order to distinguish mineralogically between the three quartzite horizons, their heavy mineral content was also studied. The effect of the increasing grade of metamorphism on the zircon grains of the quartzite layers has also been investigated, and correlated with the mineralogical change in the quartzite.

One sample, taken from the middle of each of the Steenkampsberg quartzite (CF 105, Kliprivier 73-JT, 30°7' E. Long., 25°14' S. Lat.), the Lakensvlei quartzite (CF 103, Goedehoop 79-JT, 30°11' E. Long., 25°16' S. Lat.) and the Magaliesberg quartzite (CF 100, Weimershoek 81-JT, 30°17' E. Long., 25°14' S. Lat.) has been investigated. The samples were concentrated according to the usual method described by M.O.G. Schidlowski (1963, p.148), except that the Frantz isodynamic separator was not

used, because the author wanted a complete collection of all the heavy minerals in the quartzite, and not only the zircons.

Since the heavy mineral crop consisted largely of zircons (table 5), the author concentrated mainly on a study of this mineral. Only the frequency of the variation in mineralogical properties like colour, growth and shape of the zircon grains were recorded, and not the elongation statistics. A recent investigation by Saxema (1966, p.29) in Sweden, has proved that little significance could be attributed to elongation statistics. He (1966, p.19 and 29) provides data on the elongation of zircon grains, which contradict the findings of Poldervaart and Von Backström (1950), that an elongation smaller than 2 indicates a sedimentary origin, and larger than 2 an igneous origin. Also Schidlowski (1963, p.159) found that zircon grains of both sedimentary and igneous origin, according to the contentions of Poldervaart and Von Backström, occur in the norite of the Bushveld Complex.

The frequency of the variation in mineralogical properties of the zircons (fig. 9) corresponds closely to the results recorded by Schidlowski (1963, p.154). The Steenkampsberg quartzite contains more colourless, idiomorphic and overgrown zircon grains than the Magaliesberg and Lakensvlei quartzite.

Consequently the Steenkampsberg quartzite can be distinguished from the other two quartzite layers, by its comparatively highly recrystallized zircons. Although the general mineralogical changes in the quartzite indicate a low grade metamorphism, the zircon grains are considerably recrystallized. This proves the contention of Saxema, that zircons crystallize, and recrystallize at low temperatures, and not only during high grade metamorphic conditions. According to the variations in the zircon properties (fig. 9) combined with the relative proportions of the various heavy minerals (table 5) a distinction is possible between the quartzite layers in the present area.

A comparison of the data presented in figure 9, and the

FIGURE 9 Histogram of the characteristics of zircon grains in concentrates from quartzites.

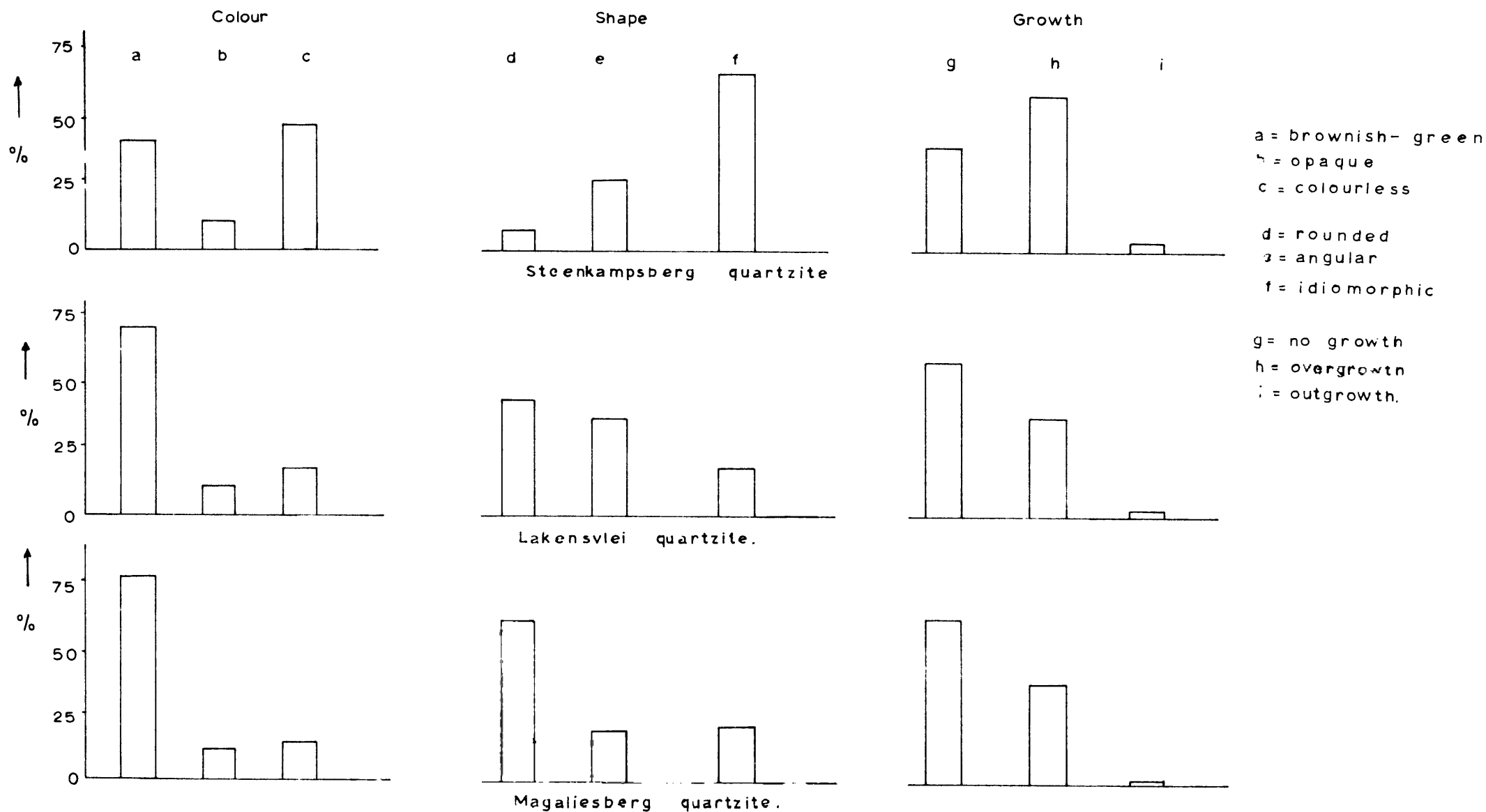


Table 5. Comparison of the heavy minerals of the Steenkampsberg, the Lakenvlei and the
Magaliesberg quartzite

Quartzite Zone	Steenkampsberg quartzite	Lakensvlei quartzite	Magaliesberg quartzite
% Zircon in the quartzite	0.50%	1.0%	1.0%
Volumetric composition of the concentrate of heavy minerals.			
Zircon (allogenic)	98..	92.0%	98.5%
Epidote (authigenic)	1.4%	1.0%	-
Apatite (allogenic)	-	2.0	1.5%
Beryl (allogenic)	-	2.0	-
Monazite (allogenic)	-	1.0	-
Rutile (allogenic)	-	2.0	-
Total	100.0%	100.0%	100.0%
Minerals present in the concentrate but not counted	Muscovite biotite	Biotite, muscovite, sericite and iron ore minerals	Muscovite and biotite

results obtained by Schidlowski (1963, p.154) indicates that zircon grains of the Steenkampsberg quartzite in the present area, and of the Magaliesberg quartzite north of Pretoria, are similar. Consequently it is clear that the zircon grains changed considerably during metamorphism, and a correlation of quartzite layers based on heavy minerals especially zircon is not very reliable.

3. The Metamorphism

The metamorphic grade of the various quartzite layers was determined on the mineral assemblages which formed from the clay matrix (10%) in the quartzite (table 6). The quartz grains (90%) recrystallized to a sugary texture without forming any new mineral phases.

Near the contact of the Bushveld Complex, plagioclase is always absent except when metamorphism has played a part. The clastic plagioclase is usually altered to ~~epidote~~ ^{epidote}. Since no chemical analysis of the matrix of the quartzite is available, it is impossible to indicate its composition on an A.C.F. diagram. The composition of the groundmass, however, has been indicated according to the volumetric composition of the altered matrix (figs. 10, 11, 12, 13).

C. Black Sand

1. Occurrence and Stratigraphy

Black sand forms a layer (0.1 to 2.0 cm thick) ^{at} ~~in~~ two horizons in the Steenkampsberg quartzite. The iron minerals consist mainly of magnetite and hematite, which alternate with thin layers of quartzite (photo 5). Both ripple-marks and cross-bedding are characteristic. The individual layers of this black sand are persistent, and could be followed for distances of 15 to 20 feet. It was found on Verloren Valei 95-JT at the base of the Steenkampsberg quartzite (CF 125 and 128), and on Wanhoop 78-JT towards the middle of the Steen-

Table 6. Facies classification of the quartzite of the
different layers

Stratigraphical Zone	Steenkampsberg quartzite		Lakensvlei quartzite	Magaliesberg quartzite
Thin sections	On the contact with the Bushveld Complex.	At the base of the quartzite layer.	CF 103	CF 100
	CF 104 CF 105 CF 107	CF 106 CF 108	CF 102	CF 101
Clastic minerals	quartz zircon feldspar	quartz zircon	quartz orthoclase plagioclase	quartz clay orthoclase plagioclase zircon
Metamorphic minerals	sillimanite hematite biotite magnetite muscovite calcite.... plagioclase (An 45% $\pm$ 5°)	epidote muscovite biotite sericite iron ore chlorite	sericite orthoclase muscovite	sericite hematite biotite epidote muscovite
Facies (According to Turner & Verhoogen 1960)	almandine amphibolite facies	hornblende hornfels facies	albite epidote hornfels facies	greenschist facies
Subfacies	sillimanite- almandine- muscovite- subfacies	none	none	
The field on the A.C.F. diagram	sillimanite biotite anorthosite field	muscovite biotite epidote field	epidote muscovite biotite field	biotite epidote sericite- field
Chemical nature of the matrix	Excess in SiO ₂ + K ₂ O			
Horizontal distance from the Bushveld Complex	$\pm$ 200 ft.	$\pm$ 4,000 ft.	$\pm$ 10,00 ft.	$\pm$ 14,000 ft.

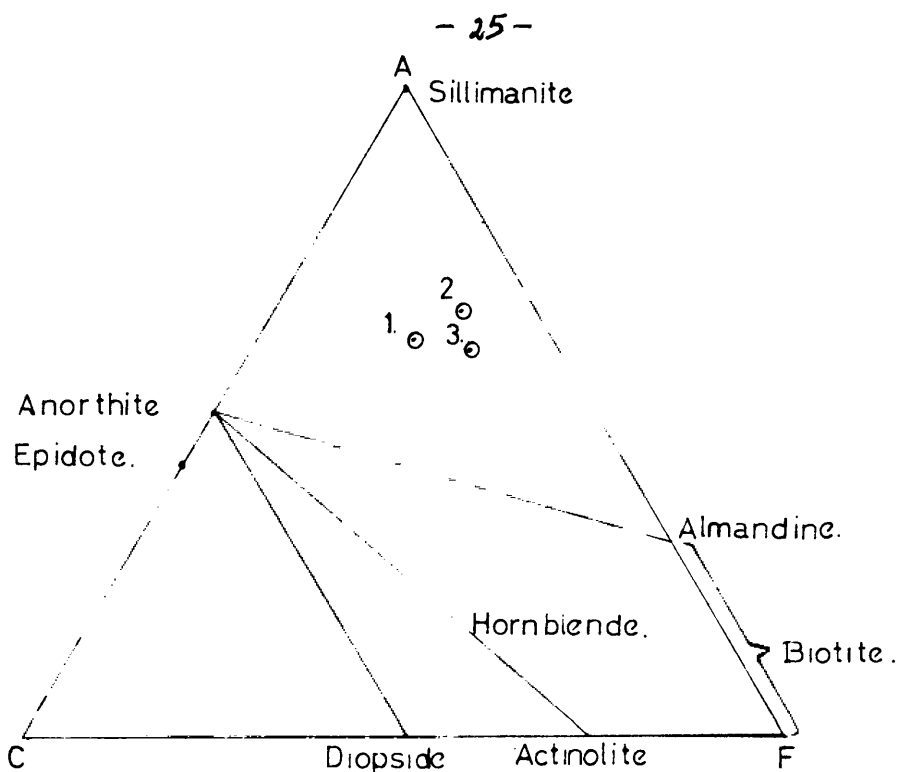


FIGURE 10. THE STEENKAMPSBERG QUARTZITE ON AN ACF DIAGRAM FOR ROCKS WITH EXCESS SiO_2 AND K_2O OF THE SILLIMANITE-ALMANDINE SUBFACIES OF THE ALMANDINE AMPHIBOLITE FACIES.

- 1 = CF 104 QUARTZITE FROM KLIPRIVIER 73 JT
 2 = CF 105 QUARTZITE FROM WANHOOP 78 JT
 3 = CF 107 QUARTZITE FROM WANHOOP 78 JT.

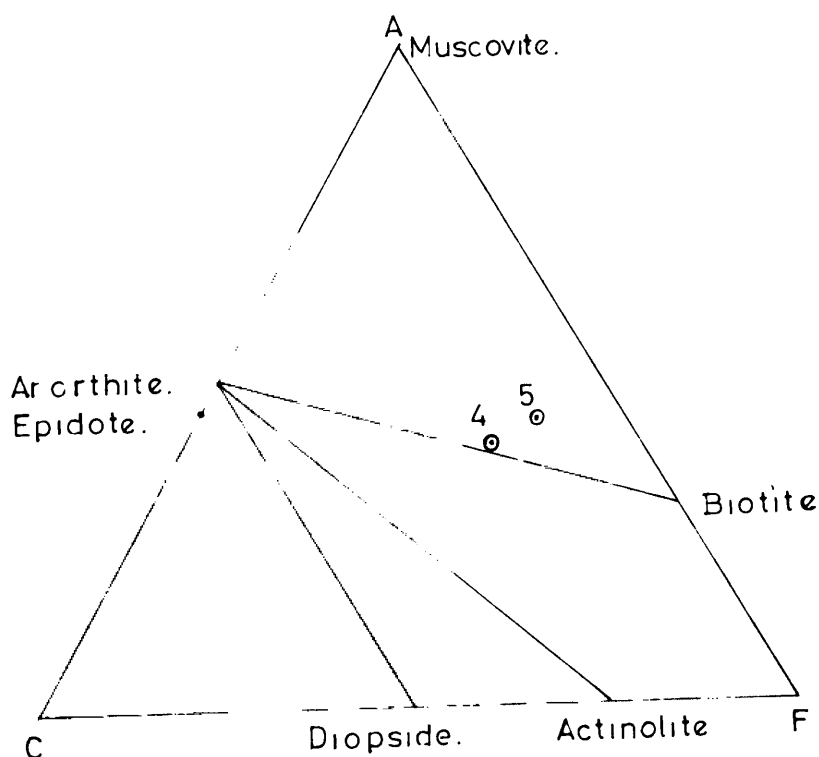


FIGURE 11. The matrix of the Steenkampsberg quartzite on an ACF diagram for rocks with excess SiO_2 and K_2O of the Hornblende Hornfels facies.

- 4 = C.F. 106 From Wanhoop 78 -JT
 5 = CF 108 From Wanhoop 78 -JT.

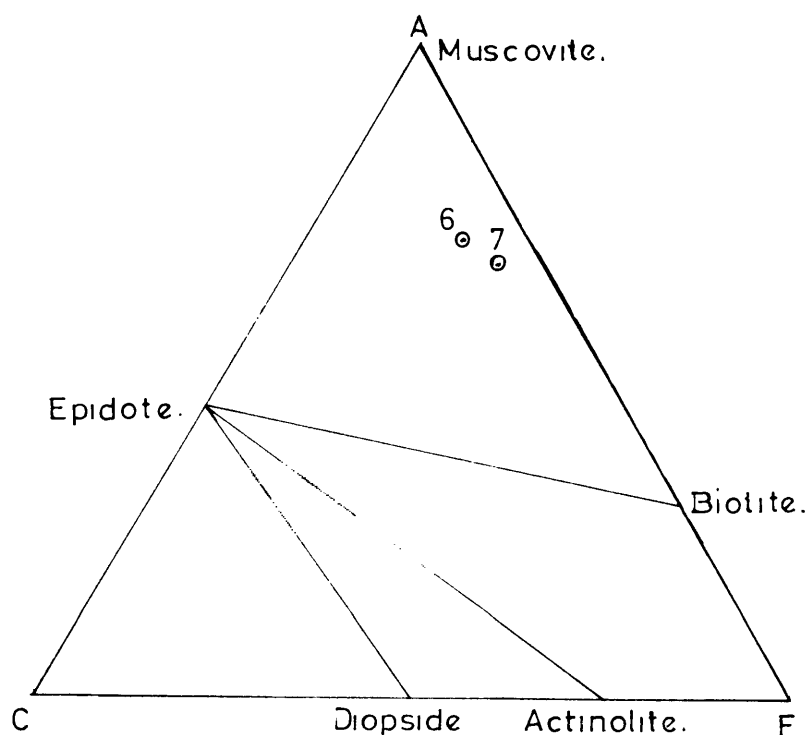


FIGURE 12. The matrix of the Lakensvlei quartzite on an ACF diagram for rocks with excess SiO_2 and K_2O of the **Albite-epidote hornfels facies**.

6 = C.F. 103 From Goederhoop 79-JT.

7 = C.F. 102 From Zuikerboschhoek 80-JT.

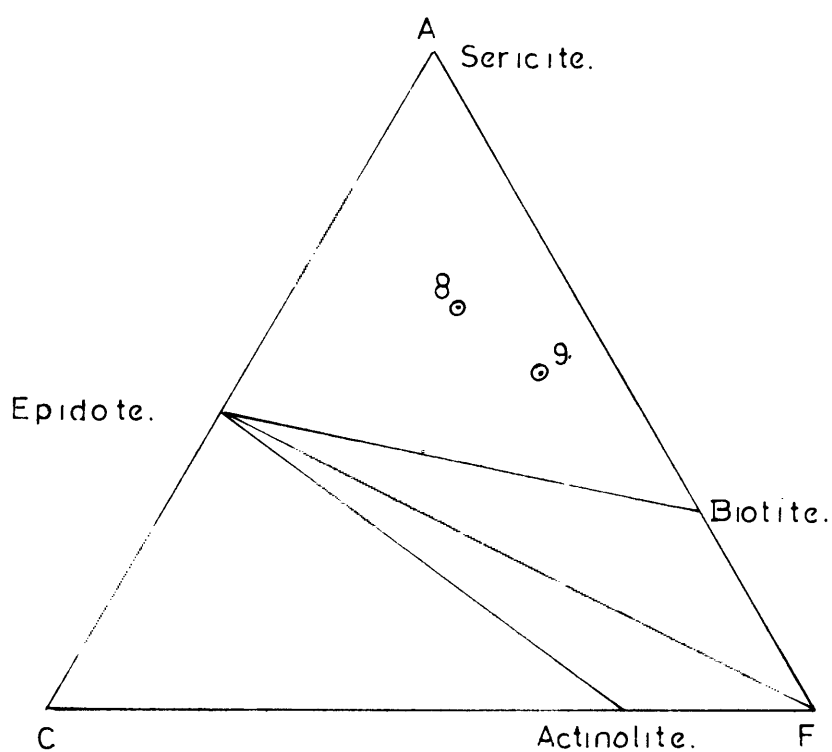


FIGURE 13 ACF DIAGRAM FOR ROCKS WITH EXCESS SiO_2 AND K_2O OF THE **QUARTZ-ALBITE-EPIDOTE-BIOTITE SUBFACIES OF THE GREENSCHIST FACIES**.

8. = Magaliesberg quartzite from Weimershoek 81 JT.

9. = Magaliesberg quartzite from Paardeplaats 91 JT.

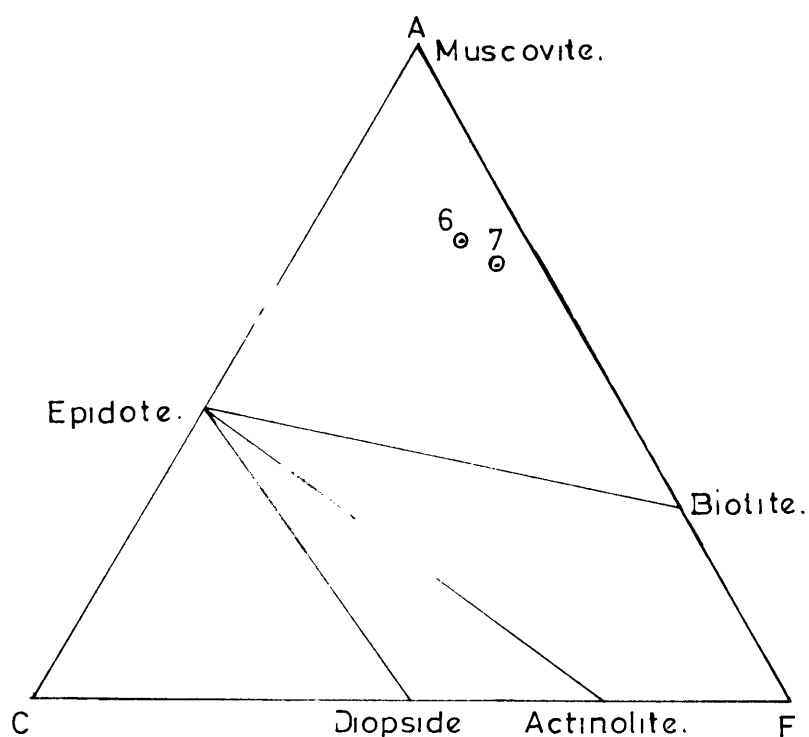


FIGURE 12. The matrix of the Lakensvlei quartzite on an ACF diagram for rocks with excess SiO_2 and K_2O of the **Albite-epidote hornfels facies**.

6 = C.F. 103 From Goederhoop 79-JT.

7 = C.F. 102 From Zuikerboschhoek 80-JT.

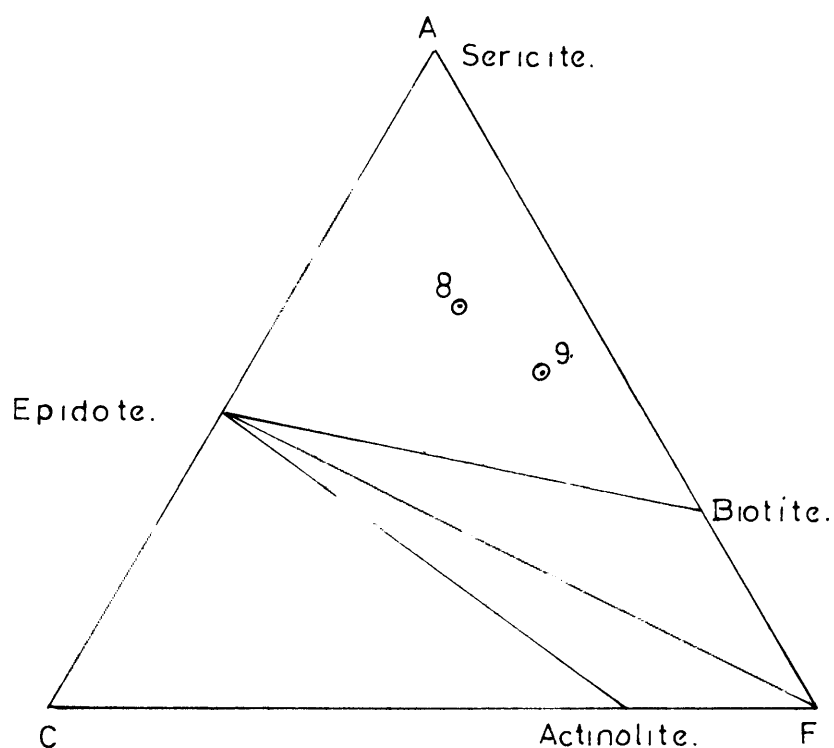


FIGURE 13 ACF DIAGRAM FOR ROCKS WITH EXCESS SiO_2 AND K_2O OF THE **QUARTS-ALBITE-EPIDOTE-BIOTITE SUBFACIES OF THE GREENSCHIST FACIES**.

8. = Magaliesberg quartzite from Weimershoek 81 JT.

9. = Magaliesberg quartzite from Paardeplaats 91 JT.

kampsberg quartzite (CF 126 and 127).

Iron-bearing minerals, like hematite, which presumably represents an altered iron-rich matrix is abundant in the Steenkampsberg quartzite on Wanhoop 78-JT and Kliprivier 73-JT.

The black sand from Verloren Valei forms separate hematite-rich layers without any admixed quartz grains, and has sharp contacts against quartzite. On the other hand the iron-rich sand from Wanhoop 78-JT is also hematite-rich, but is transitional into the normal quartzite.

2. Petrography

The mineralogical composition of the black sand from Wanhoop 78-JT corresponds to that from Verloren Valei, but texturally they differ significantly (tables 7 and 8). The black sand from the base of the Steenkampsberg quartzite is better sorted than that from the middle of the Steenkampsberg quartzite, and the hematite grains are also much more rounded.

The present mineral content of the black sand indicates that the original clastic minerals were magnetite, ilmenite, ilmeno-magnetite, zircon, monazite and quartz.

Since ilmenite exsolves parallel to (0001) in hematite, the exsolution lamellae of ilmenite should be orientated in only one and not in four directions in the hematite. The lamellae of ilmenite which are orientated in three directions in the hematite were consequently exsolved from magnetite, and this magnetite was changed to hematite during metamorphism (photo 10). The hematite also contains cores of unaltered magnetite (photo 7), which are relicts of the original ilmeno-magnetite.

Original magnetite is also represented by hematite, which contains cores of magnetite, without any lamellae of ilmenite,

Table 7. Microscopical features of the ore minerals
composing the black sand

Locality		Verloren Valei and Wanhoop	
Polished sections		CF 125 A,B; CF 126 A,B,C; CF 127 A,B; CF 128 A,B,C.	
Optical properties		Form of grains	Remarks
Main constituents	Magnetite	irregular relicts in hematite (photo 7).	Partially altered to hematite (photo 8).
	Ilmenite	An alteration product in a rounded grain.	1. Forms lamellae parallel to (111) in the original magnetite (photo 10) 2. Grains of ilmenite altered to rutile.
	Hematite	Rounded grains, or a cluster of idiomorphs of hematite in a rounded grain (photo 11).	1. Contains relicts of magnetite. 2. Contains lamellae of ilmenite parallel to (111) of the original magnetite (photo 7). 3. Forms ribbons in the altered ilmenite. (photo 11).
Subordinate minerals	Maghemite	Irregular rims around magnetite relicts	
	Limonite	Irregular inclusions in hematite	
	Zircon	Perfectly rounded	Zonary (photo 12) and unzoned
	Monazite	Perfectly rounded	

. Table 8. Petrographical data on the black sand

Locality	Verloren Valei 95-JT (CF 125 and 128)		Wanhooop 78-JT (CF 126 and 127)	
Stratigraphical horizon	Base of the Steenkampsberg quartzite		Middle of the Steenkampsberg quartzite	
Texture	Well-sorted and the grains well-rounded		Poorly sorted and grains poorly rounded	
Microscopical data	Form of grains	Remarks	Form of grains	Remarks
Opaque minerals of clastic origin	Rounded and corroded.	Densely packed hematite, magnetite and ilmenite grains.	Partly rounded and partly recrystallised.	Grains not densely packed.
Quartz	Rounded to angular.	Layers alternate with iron-rich layers.	Round to angular.	Not prominently layered.
Zircon	Rounded	Zonary and unzoned types with inclusions. Altered to malacon and hyacinth.	Rounded	Contains inclusions, and partially altered to malacon.
Biotite	Not present		Intergranular (photo 6)	Replaces the clay matrix $2V_{\alpha}=10^{\circ}+3^{\circ}$, Prominent (001) cleavage.
Opaque minerals of metamorphic origin	Xenomorphic	Replaces the chloritic matrix.	Xenomorphic	Replaces the chloritic matrix.
Cementing material	Intergranular	Recrystallized epidote and biotite.	Intergranular	Recrystallized to biotite and amphibole starts to form.
Metamorphic facies	Hornblende hornfels facies.		Hornblende hornfels facies.	

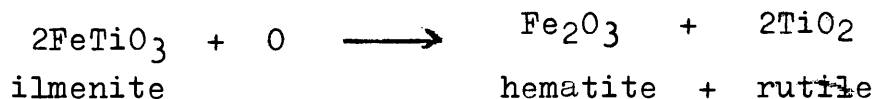
A large rounded grain, which consists of an aggregate of randomly orientated hematite idiomorphs, represents an original magnetite grain in which several nuclei of recrystallization developed during metamorphism (photo 11). A similar development of nuclei has been described by N. Rast (1905, p.73-102) from several localities in Scotland.

The original ilmenite is altered to a mixture of $\pm$ 20% hematite and 80% "altered ilmenite". The latter consists of ilmenite and rutile. The 20% hematite occurs as ribbons in the altered ilmenite, and they are usually orientated parallel to one another (photo 11).

The mineral composition of the present black sand corresponds to that of recent beach sands as defined by Twenhofel (1950, p.107) (table 9).

3. The metamorphism of the black sand

As the result of thermal metamorphism, various changes took place in the original minerals of the black sand. The ilmenite changed to hematite and a mixture of rutile and ilmenite, similar to the first phase in the breakdown of ilmenite during thermal metamorphism as described by Bailey, Cameron et al. (1956, p.263-279) from various localities. The alteration can take place according to the following equation (Stumpfl 1958, p.696).



The alteration of magnetite to hematite in detrital deposits during metamorphism has been described by Stumpfl (1958, p.693). In the present black sand the observed alteration resembles closely that described by Stumpfl. The hematite usually replaces the magnetite along certain crystallographical directions.

Oxidation obviously accompanied the temperature increase. The biotite, which changed to amphibole, indicates that the

Table 9. Comparison of the mineral composition of the black sand from Wanhoop 78-JT, and Verloren Valei 95-JT and of beach sand from other localities.

The minerals are arranged in order of abundance

Black sand Wanhoop 78-JT and Verloren Valei 95-JT	Several localities (Eugene Stumpf1) (Geol. Jb. 1958, p.685-724)	Van Rhynsdorp, (C.B. Coetzee, 1957, p.5)	Most beach sands, (H.W. Twenhofel, 1962, p.439)	Beach sand in the subalpine molasse trough (Zimmerle, 1963, p.452)
Magnetite ilmenite ilmeno-magnetite quartz zircon monazite clay	Magnetite ilmenite ilmeno-magnetite quartz zircon rutile titanite	Magnetite ilmenite ilmeno-magnetite quartz zircon rutile garnet pyroxene calcite	Magnetite ilmenite quartz zircon <u>The other minerals</u> <u>depend on the</u> <u>source-material,</u> <u>and may be:</u> rutile chromite garnet epidote pyroxene tourmaline	Magnetite ilmenite zircon monazite quartz

grade of metamorphism was that of the hornblende hornfels facies. This corresponds to the facies also identified in the Steenkampsberg quartzite (table 6).

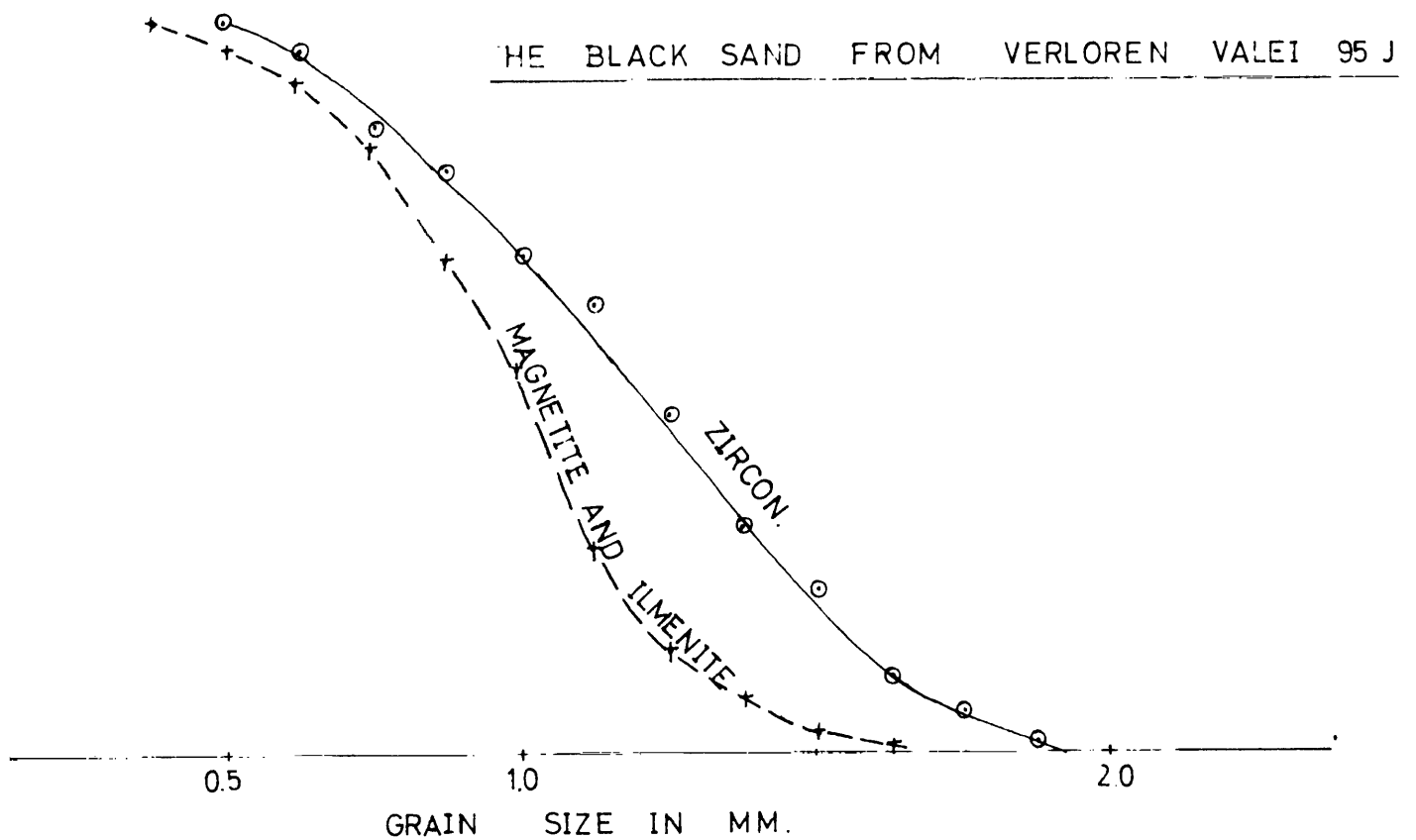
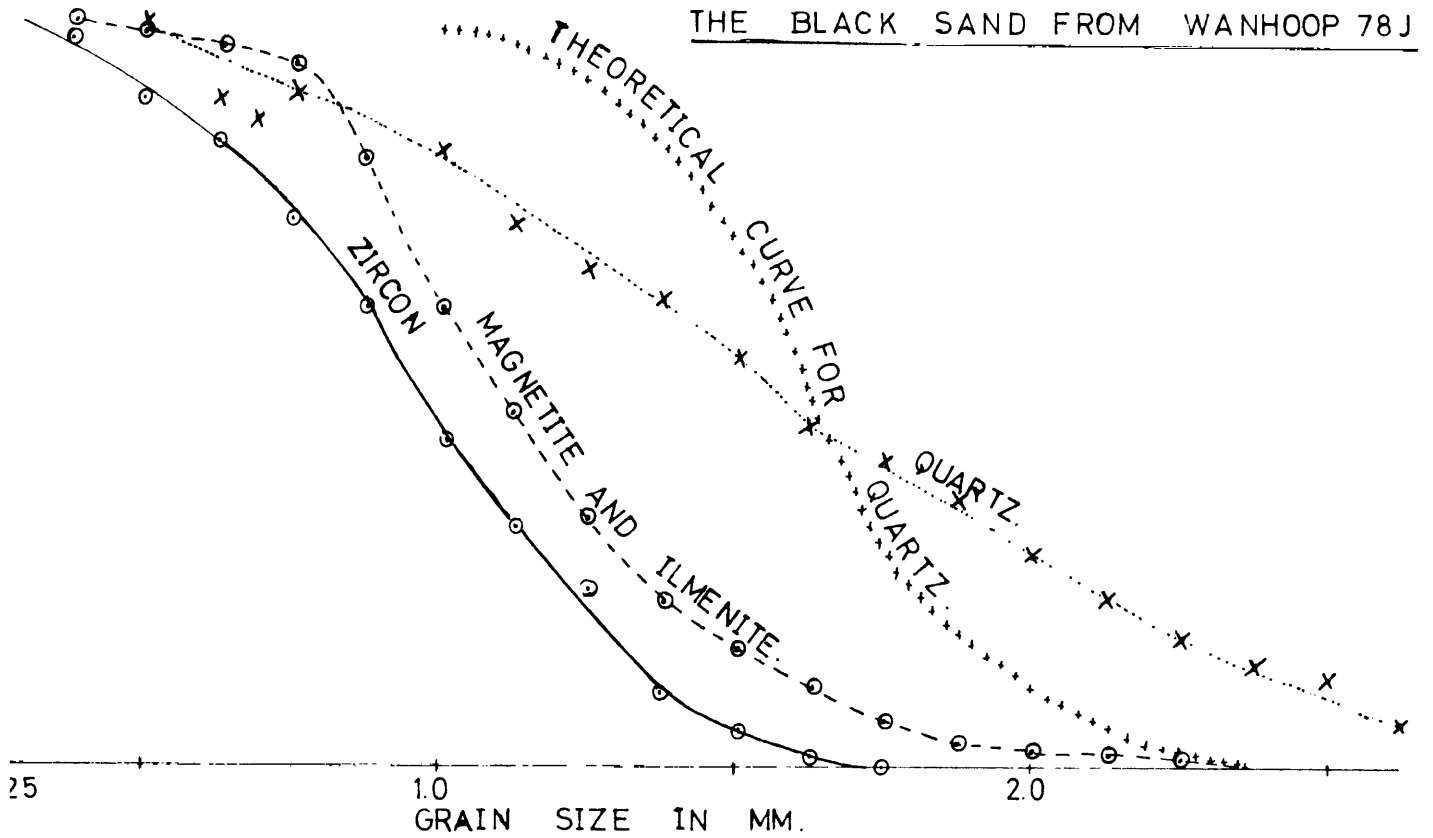
4. Discussion

According to the correspondence in mineralogical composition of the black sand and recent beach sands, a similar origin is indicated. The ripple-marks and the cross-bedding in the black sand also correspond to similar textures in recent beach sands. To determine whether the magnetite, ilmenite, zircon and quartz grains were deposited simultaneously, hydraulic equilibrium diagrams were drawn, according to the usual method outlined by Koen (1961, p.23-46). The length and breadth of the grains were measured in a thin section, and the median diameter calculated. The diameters were then plotted on a frequency diagram.

According to the results obtained, (fig. 14) the grains of quartz and zircon of the black sand from Wanhoop, which is poorly-sorted, were deposited simultaneously. Since the median diameter of the opaque minerals (1.1) exceed that of the zircon (0.9) and is not in agreement with their respective specific gravities, the opaque minerals and the zircon were evidently not deposited simultaneously. The median diameter of the zircon, the quartz and the opaque minerals in the black sand from Verloren Valei, which is well-sorted, are in agreement with their respective specific gravities, and were consequently deposited simultaneously.

Since the poorly-sorted black sand outcrops nearer to the margin of the Bushveld Complex. than the well-sorted black sand, the former is more intensely metamorphosed. Consequently the observed anomaly can be explained by the secondary enlargement and recrystallization of the ilmenite and magnetite in the poorly-sorted black sand.

FIGURE 14 CUMULATIVE SIZE DISTRIBUTION CURVES OF QUARTZ, ZIRCON, MAGNETITE AND ILMENITE IN SAMPLES OF "BLACK SANDS"



The hematite was not deposited originally, but it originated from the metamorphism of magnetite, ilmeno-magnetite and ilmenite. Hematite is also absent in most beach sands, as an original constituent. According to Stumpfl (1959, p.698) clastic hematite "kommt in den Sanden nur in geringem ausmass vor", whereas magnetite "Steht in sehr vielen quantitativ an erster stellen unter dem opaken Gemengteilen".

According to P.W. Guild (1953, p.639-679) two types of sedimentary iron ores can be distinguished, namely black sands, which consist of magnetite and ilmenite, and itaberrite. The latter forms the iron deposits of Minas Geraes, Brazil, where hematite, which was precipitated chemically, is the major constituent. The evidence from the investigation of the black sand from the Steenkampsberg quartzite, is in full accordance with the ideas of Guild and Stumpfl, and the hematite is authigenic.

D. The Dullstroom Volcanics

1. Distribution and field characteristics

The Dullstroom lava outcrops along the Dullstroom Draaikraal road, at the south-western border of Klipbankspruit 76-JT. Farther south, this wedge-like layer becomes more extensive until it reaches a considerable thickness on the farms Konterdanskloof 915, Welgevonden 40, and Witpoort 26 (Hall 1915, p.29). This wedge-like appearance of the Dullstroom lava is due to the transgressive relationship of the layered sequence of the Bushveld Complex to the surrounding sedimentary rocks. The Dullstroom lava succeeds the Steenkampsberg quartzite concordantly and is intruded discordantly by the Main Zone of the Bushveld Complex.

Most of the lava textures, like flow-lines, a glassy mesostasis and a fine-grained texture, have been destroyed by the high grade metamorphism to which the Dullstroom lava has been subjected. A volcanic origin is, nevertheless, indicated by the orientation of the drawn out vesicles filled with

quartz and by the fine-grained equigranular texture of the rocks.

The Dullstroom lava has a dirty-greenish colour on the fresh fractures and it weathers into rounded brown boulders, which contain white amygdales, or quartzite inclusions.

2. The microscopical features

Plagioclase, clinopyroxene and orthopyroxene are the major constituents of the Dullstroom lava, whereas biotite, quartz and opaque minerals are accessory (table 10).

3. Amygdales and inclusions in the Dullstroom volcanics

Amygdales are almost invariably present in the Dullstroom lava and have been studied on Houtenbek 97-JT, and Klipbankspruit 76-JT. Their mineralogical composition corresponds in many respects to that of the lava, except that quartz is abundant and augite absent in the amygdales, whereas augite is abundant and quartz absent in the lava.

In the amygdales, which are 2.0 to 5.0 mm in diameter, the plagioclase and the orthopyroxene are subhedral, whereas the quartz grains are either rounded or recrystallized. The presence of hypersthene and plagioclase places the Dullstroom volcanics in the pyroxene hornfels facies.

The amygdales display a zonary distribution of the metamorphic minerals, a fact which was also mentioned by Truter (1949, p.1xv). The outer zone consists of hypersthene grains, succeeded by a second zone of plagioclase, and a core of quartz (photo 13).

Inclusions of quartzite (4.0 to 12.0 mm in diameter) are ubiquitous in the area investigated and consist of rounded quartz grains, a biotite-rich cementing material and

Table 10. The macroscopical and microscopical properties of
the Dullstroom volcanics

Locality	Klipbankspruit 76-JT, CF 80, (30°3' E. Long., 25°18' S. Lat.)			
Occurrence	Above the Steenkampsberg quartzite			
Macroscopical features	Extremely fine-grained and contains amygdales and lenticular inclusions of quartzite (± 5 mm in diameter).			
Constituents (volumetric proportions in brackets).	The form of the grains	Optical properties	Composition	Remarks
Plagioclase (52.0%)	Xenoblastic 0.15 to 0.50 mm	$2V_x = 78^\circ \pm 3^\circ$	Ab ₅₄ An ₄₆ to Ab ₆₀ An ₄₀	Individual grains, and as inclusions in orthopyroxene.
Orthopyroxene (15.5%)	Xenoblastic	$2V_x = 48^\circ \pm 1^\circ$ $\delta \wedge C = 0^\circ$	Hypersthene En ₄₆ Fs ₅₄	Contains inclusions of plagioclase.
Clinopyroxene (24.5%)	Xenoblastic 0.15 to 0.40 mm.	$2V_x = 54^\circ$ $\delta \wedge C = 40^\circ$	Augite	Equidimensional grains
Biotite (4.3%)	Xenoblastic	-	-	Contains inclusions of plagioclase
Opaque minerals (3.4%)	Idiomorphic	-	-	Disseminated through the rock and enclosed by all the other minerals
Quartz (0.3%)	In the amygdales the quartz grains are xenomorphic and have outlines which are intergrown.			
	In the quartzite inclusions, the quartz grains are usually rounded.			
Texture	Equigranular and fine-grained. The minerals in the amygdales display a zonary distribution.			

hypersthene. The inclusions are usually lenticular (photo 14).

4. Metamorphism of the Dullstroom lava

According to A.L. Hall (1913, p.29) and A.L. du Toit (1954, p.123), hornblende and "acid labradorite" are the major constituents of the Dullstroom lava. The Dullstroom volcanics in the area mapped consist of hypersthene, augite and andesine (An₄₀₋₄₆). A chemical analysis, the only one available, falls within the anorthite-hypersthene-augite field of the pyroxene hornfels facies (fig. 15). The original hornblende, which was evidently unstable at the temperature of the metamorphism formed augite and hypersthene, whereas the andesine only recrystallized.

E. The Argillaceous Rocks

1. General geology

The argillaceous rocks are recrystallized to green and black hornfels, which outcrop mainly above the Magaliesberg quartzite (fig. 1) on Kwaggashoek 66-JT, Schaapkraal 68-JT, Weimershoek 31-JT, Kleinzuikerboschkop 93-JT, Elandspruit 107-JT, the western portion of Knapdaar 92-JT and the eastern portion of Suikerboschoek 80-JT. Hornfels has also been mapped above the Lakensvlei quartzite on the farms Oshoek. and Vrischgewaagd is Half Gewonnen, and above the Steenkampsberg quartzite on Houtenbek 97-JT, and the eastern part of Klipbankspruit 76-JT. The hornfels zones contain several limestone layers on many horizons (fig. 1). Numerous diabase sheets are intrusive into, and have distinct transgressive relationships to the hornfels in many places, for example on the farm Uitspanning 106-JT (map 3).

The argillaceous rocks are usually well bedded, and consist of alternating pelitic and psammitic layers similar to

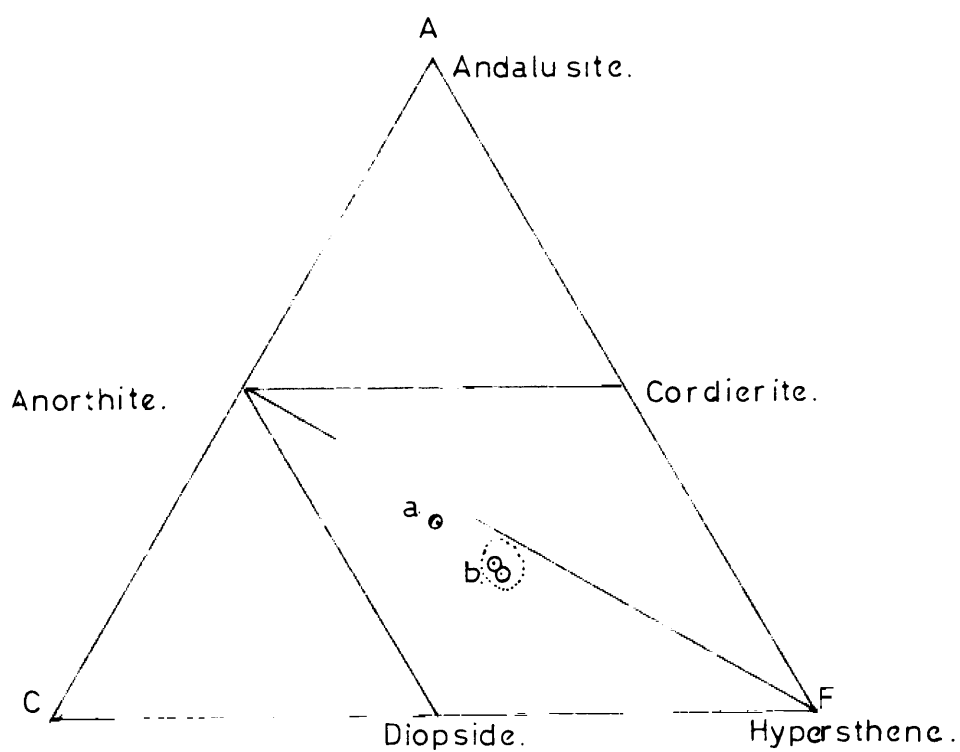


FIGURE 15. ACF DIAGRAM FOR ROCKS WITH EXCESS SiO₂ OF THE PYROXENE HORNFELS FACIES.

a = Dullstroom lava (Hull 1932;p 240.)

b = Chilled Norite (Visser 1964;p 75& 77.)

the products of turbidity currents described by Kuenen (1964, p.3-30) from the Maritime Alps. Despite the small mineralogical variation in the argillaceous rocks, a muscovite-biotite-rich shale could be distinguished from the cordierite hornfels. The former outcrops along the western boundary of Kwaggashoek, whereas cordierite hornfels outcrops are very common throughout the area.

The cordierite hornfels displays a pitted surface due to the differential weathering of the alternating layers of pelitic and psammitic material, and to the weathering of the cordierite. The muscovite-biotite shale is a dark, homogeneous rock. The cordierite hornfels is very abundant, and constitutes nearly the whole succession of argillaceous rocks. The argillaceous rocks are less resistant to weathering than the quartzite and consequently ~~is~~ forms the valleys, where outcrops are rare.

2. Microscopical description

Cordierite, muscovite, biotite, epidote and hematite are the most important metamorphic minerals, which formed from the clay minerals of the argillaceous rocks, whereas quartz, feldspar and zircon are the typical clastic constituents. According to the mineral assemblages, and the relative amounts of the constituents, the various hornfelses have been divided into two groups viz. the cordierite hornfels and the muscovite-biotite shale (tables, 11, 12 and 13).

The mesonorms of each of the two types correspond closely to their respective volumetric composition. In both groups, the composition of the fine-grained matrix corresponds to that of albite and orthoclase. The major chemical differences between the two types are discussed in a subsequent

On an A.C.F. diagram (fig. 16) both groups of hornfels fall in the hornblende hornfels facies and the composition

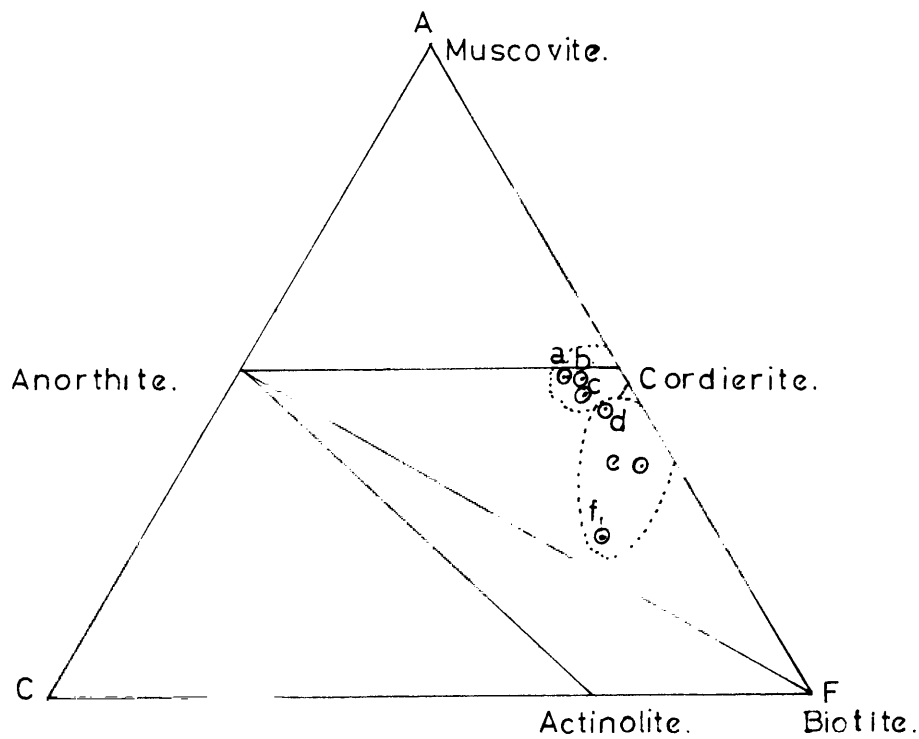


FIGURE 16 VARIOUS TYPES OF HORNFELS
ON AN ACF DIAGRAM FOR ROCKS WITH EXCESS SiO_2 AND
DEFICIENT IN K_2O OF THE HORNBLende HORNFELS FACIES.

- | | |
|-------------------------------------|---|
| a = Cordierite hornfels | } (Table 14 numbers 4 9 10 11 8
and 2 respectively) |
| b = Cordierite hornfels | |
| c = Cordierite hornfels | |
| d = Cordierite-biotite
hornfels. | |
| e = Muscovite-biotite shale | |
| f = Biotite-rich shale. | |

Table 11. The petrography of the metamorphosed argillaceous rocks

(The minerals are in alphabetical Order)

Rock types and Specimen No	Minerals	Grain shape	Optical properties	Remarks
Muscovite-biotite shale Cordierite hornfels CF 4 CF 5, 135, 136, 137, 138, 139, 140, 142, 143	Clastic minerals			
	Orthoclase plagioclase quartz zircon	Rounded to angular grains		Mostly confined to the psammitic layers.
	Chlorite sericite	fine-grained		Confined to the pelitic layers, but also intergranular in the psammitic portions.
	Metamorphic minerals			
	Cordierite	idioblastic to xenoblastic also diablastic	$2V_{\lambda} = 50^{\circ} \pm 10^{\circ}$ low refractive index.	1. Contains inclusions of sericite, quartz, feldspar and opaque minerals (photos 15 and 16). 2. Inclusions are zonally arranged, and the cores are clear from inclusions (photo 16).
	Hematite and magnetite	Idioblastic	opaque	1. Replace the iron-rich matrix. 2. Ore inclusions in cordierite 3. Forms a "Knotter-schiller" (table 11).
	Sericite	fine-grained	-	1. Replaces the clay-rich matrix. 2. Changes to feldspar. 3. Forms inclusions in cordierite (photo 15).
	Biotite	Xenoblastic to idioblastic	$2V_{\lambda} = 15^{\circ} \pm 5^{\circ}$	1. Replaces the chlorite matrix. 2. Contains inclusions of quartz.
	Muscovite	Xenoblastic to idioblastic	$2V_{\lambda} = 20^{\circ} \pm 5^{\circ}$	1. Has a decussate texture 2. Contains inclusions of quartz and sericite.
	Epidote	Xenoblastic	$2V_{\lambda} = 65^{\circ} \pm 10^{\circ}$ $N_f = 1.700$ (± 0.005)	1. Replaces the clay matrix. 2. Changes to feldspar.

of the cordierite hornfels (analyses a, b and c) occupies a field close to the composition of cordierite, near the cordierite-anorthite tie-line, whereas the biotite-rich rocks (analyses d, e and f) tend to fall farther away from the composition of cordierite, but also in the biotite-cordierite-anorthite field. According to the A.C.F. diagram for rocks with excess silicon and deficient potassium (fig. 16), muscovite, biotite and anorthite constitute an unstable association. However, in the A.C.F. diagram for rocks with excess silicon and potassium (fig. 17), muscovite, biotite and anorthite do represent a stable assemblage. Accordingly the amount of potassium in the original chemical composition of the hornfels controls to some extent the formation of cordierite.

Idioblastic plates of hematite replace the iron-rich matrix of the hornfels during the initial stages of metamorphism. During more advanced metamorphism the hematite was replaced pseudomorphously by magnetite (photo 17 and 18).

3. Chemistry

The andalusite-rich rocks (table 14, no 3 and 6) tends to (fall near the Al^{3+} corner of the Mg^{++} , Fe^{++} , Al^{3+} and $K^+ + Na^+$ triangle (fig. 18), whereas the biotite-rich hornfels (no. 2) is the farthest away from the Al^{3+} corner. The cordierite hornfels occupies an area intermediate between the $Mg^{2+} + Fe^{2+}$ and the Al^{3+} corners of the triangle. According to the facies diagrams of the hornblende hornfels facies, cordierite, biotite and andalusite form under similar thermal conditions. The distribution of these minerals are consequently mainly controlled by the chemical composition of the sediments. The Al^{3+} -rich shale yields andalusite hornfels, the Al^{3+} -poor and Mg^{2+} -rich sediments form cordierite, and the Al^{3+} -poor and K^+ -rich sediments biotite.

In the area mapped, which comprises also the hornfels above the Magaliesberg quartzite, andalusite is absent, and

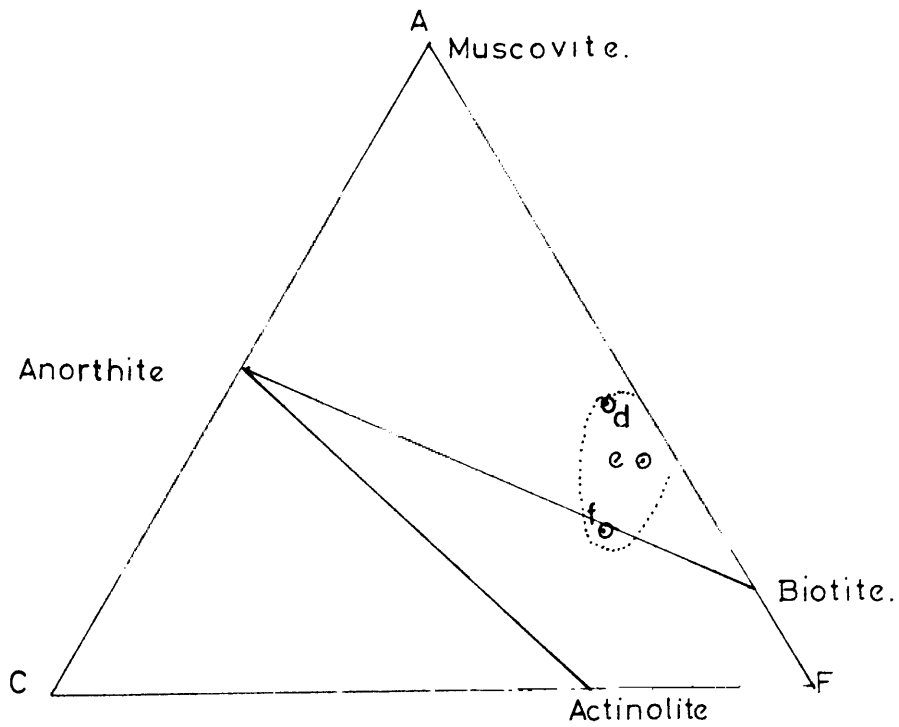
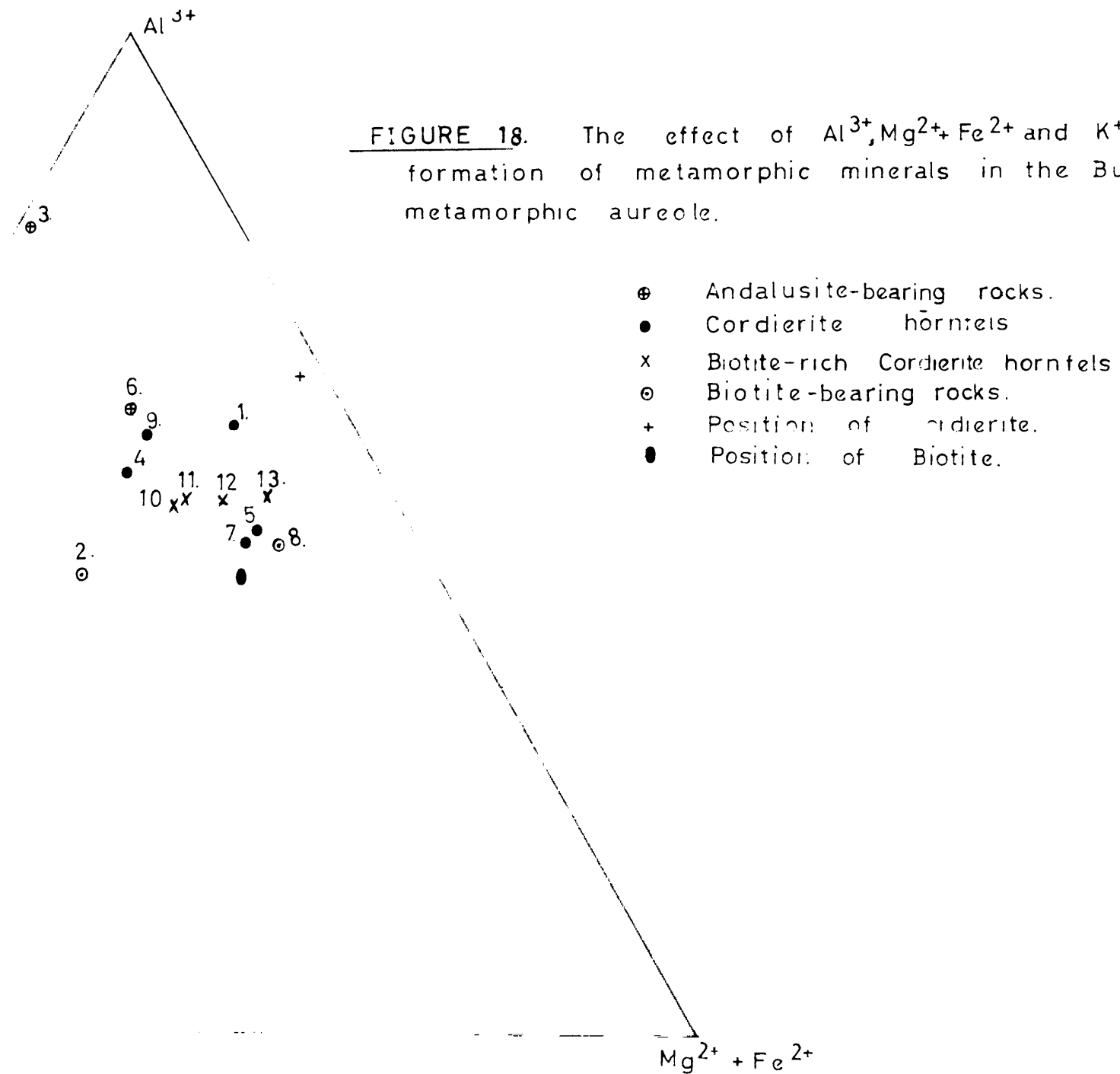


FIGURE 17. VARIOUS TYPES OF HORNFELS
ON AN ACF DIAGRAM FOR ROCKS WITH EXCESS SiO_2 AND
OF THE HORNBLende HORNFELS FACIES.

d, e and f = Cordierite and Biotite-bearing rocks. (Table 14 numbers 11, 8 and 2 respectively)

FIGURE 18. The effect of Al^{3+} , $\text{Mg}^{2+} + \text{Fe}^{2+}$ and $\text{K}^{+} + \text{Na}^{+}$ on the formation of metamorphic minerals in the Bushveld metamorphic aureole.

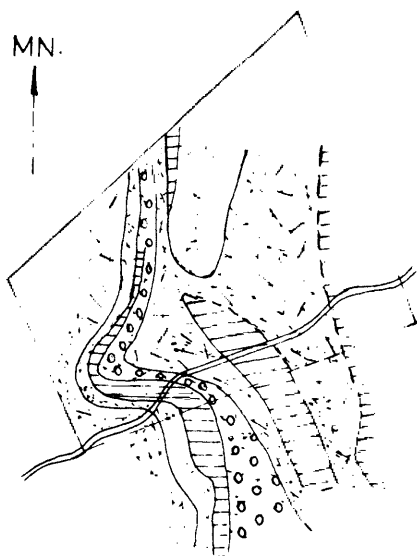


MAP. 3.

THE RELATIONSHIP BETWEEN THE DIFFERENTIATED
MAFIC SILLS AND THE DIORITE ON UITSPANNING 106 JT

Scale 1:40,000

Page 45

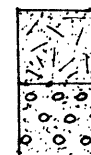


Legend



Quartzite

Hornfels



Differentiated sill

Diorite



Dullstroom - Lydenburg
road

cordierite abundant. J. Willemse (1959, p.lvi) similarly noticed in the north-eastern rim of the Bushveld Complex that "above the Daspoort quartzite the rocks form a series of andalusite-bearing hornfelses up to the cordierite hornfels above the main Magaliesberg quartzite". This distribution of metamorphic minerals can be ascribed to either differences in the original chemical composition of the argillaceous rocks, or to magnesium metasomatism during metamorphism.

Since chemical analyses of the unmetamorphosed shales of the Pretoria Series are lacking, the original composition of the hornfels is unknown. However, according to H. Kano (1961, p.12-13) a lava of andesitic composition usually forms cordierite when it is subjected to magnesium metasomatism during the hornblende hornfels facies. Moreover, according to Turner and Verhoogen (1960, p.528) cordierite is still stable in the sanidinite facies and consequently also in the pyroxene hornfels facies. If magnesium metasomatism accompanied the intrusion of the Bushveld Complex, and caused the large scale development of cordierite in the argillaceous rocks which are $\pm$ 10,000 feet away from the contact, then cordierite must have developed in the Dullstroom lava, which is not the case.

No evidence of magnesium metasomatism has been observed in the Steenkampsberg quartzite, nor in the limestone layer, which is interbedded in the cordierite hornfels. Two limestone layers, which consist mainly of calcite are interbedded in cordierite hornfels. Since no magnesium was present, no metamorphic change except recrystallization could occur in these limestone layers. Hence the presence of these limestone layers also militate against any magnesium metasomatism.

From the evidence submitted above, it is clear that the development of cordierite in the present area should be ascribed to the original composition of the argillaceous rocks.

Table 14. Argillaceous rocks of which the chemical composition was available

No.	Hornfels	Locality	Author
1.	Cordierite hornfels	Syferfontein 24, Hartbeespoortdam area, (Magaliesberg Stage)	J. Willemse (1959, Table 10, No. 13)
2.	Biotite-rich arenaceous shale.	Bothashoek 775; Steelpoort River area, (Magaliesberg Stage)	J. Willemse (1959, Table 10, No. 4)
3.	Andalusite shist	Mount Maré are possible Figtree Series, (Zandrivier 139)	J. Willemse (1959, Table 10, No.10)
4.	Cordierite hornfels	Above Magaliesberg Stage. (Groothoek 171)	J. Willemse (1959, Table 10, No. 8)
5.	Cordierite hornfels	Practiseer 110; Steelpoort River area (Magaliesberg stage)	J. Willemse (1959, Table 10, No. 7)
6.	Andalusite shale	Naboomkoppies 574, Steelpoort River area (Magaliesberg Stage)	J. Willemse (1959, Table 10, No. 6)
7.	Chloritoid-andalusite shist	Zandrivier 139, Mount Maré area, (possible Figtree Series)	J. Willemse (1959, Table 10, No.11)
8.	Muscovite-biotite rich arenaceous shale	Kwaggashoek 66-JT; Lydenburg district, above the Magaliesberg quartzite.	C. Frick (New analysis)
9.	Cordierite hornfels	Kwaggashoek 66-JT; Lydenburg district, above the Magaliesberg quartzite	C. Frick (New analysis)
10.	Cordierite hornfels	Vraaiuitzicht; along the Spekboon River	L. Liebenberg (1964, p. 52)
11.	Cordierite-biotite hornfels	Bakoven; Cape Town	J.N.J. Visser (1964, No. 1446)
12.	Cordierite-biotite hornfels	Campsbay; Cape Town	J.N.J. Visser (1964, No. 1445)
13.	Cordierite-biotite hornfels	Llandudno; Cape Town	J.N.J. Visser (1964, No. 1444)
14.	Cordierite-biotite hornfels	Froggy Pond; Simonstown	J.N.J. Visser (1964, No. 1443)

The shale above the Magaliesberg quartzite was evidently more magnesium-rich than the shale below the Magaliesberg quartzite.

F. The Limestone

1. Occurrence and stratigraphy

Four thin layers of carbonate-bearing sedimentary rocks, the width of which range from 10 to 15 feet, are interlayered in the cordierite hornfels above the Magaliesberg quartzite. These limestone layers are either a diopside fels or a recrystallized marble without any calc-silicate minerals. Two layers of marble have been found on Weimershoek 81-JT, and Kleinzuikerboschkop 93-JT. The outcrops of the marble are rare, and consequently samples which were studied were mainly collected from a prospecting pit on Kleinzuikerboschkop 93-JT (map 1 and table 15).

Table 15. The Occurrence, the Stratigraphy and the Mineralogical Composition of the Limestone layers

Rock type	Marble		Diopsidefels	
Locality and Thin sections	Weimershoek 81-JT. (CF 110)	Klein-zuikerboschkop 93-JT. (CF 118)	Klein-zuikerboschkop 93-JT. (CF 117)	Suikerboschkop 80-JT. (CF 114)
Distance above the Magaliesberg quartzite.	600 ft.	800 ft.	2,400 ft.	2,300 ft.
Mineralogical composition	Mainly calcite		diopside 48.1% *olivine 17.0% wollastonite 16.9% vesuvianite 12.3% grossularite 4.9% calcite 0.8%	100.0%

A.L. Hall (1931, p.27) mentions a serpentinized limestone

* Serpentine was counted as olivine.

50/ ..

in the area mapped, which the present author failed to find. A soft, green limestone has, however, been observed (CF 110) which resembles a serpentized limestone in a hand-specimen, but it only contains calcite and chert, and no serpentine, when studied in thin sections.

The diopside fels appears either as a banded or as a homogeneous green rock, which has a spotted appearance whenever garnet is developed (CF 111). The banded nature, displayed on weathered surfaces, is due to the differential weathering of alternating hard and soft layers of calc-silicate minerals and calcite respectively (CF 112). The marble is homogeneous and contains lenses of blue and white chert (CF 110).

2. The mineralogy of the limestone

The marble consists essentially of calcite, although etching, according to the method of Mitchell (1956, p.181), shows occasional dolomite grains. Occasional grains of diopside and lenses of chert are also present. The diopside fels consists of diopside, wollastonite, olivine and vesuvianite (table 15).

The minerals in the diopside fels and ^{the} marble are now discussed in alphabetic order.

(a) Calcite

In the diopside fels calcite is present as xenoblasts in subordinate amounts, whereas in the marble it forms subhedral grains.

The grain-size of the calcite in the diopside fels is ±1.0 mm and in the marble it ranges between 0.2 mm and 0.05 mm. Extremely fine-grained lamellae of chert cause the banded texture in the marble.

(b) Diopside

This mineral is the major constituent of the diopside fels, and is also present in subordinate amounts in the marble. The diopside grains are usually confined to certain original sedimentary layers (photo 22). The grain-size of the diopside in the diopside fels ranges between 2.0 and 0.1 mm, whereas in

the marbles it ranges from 0.5 to 0.1 mm. $2V_X$ of the diopside = $58^\circ \pm 1^\circ$, $\chi_c = 35 \pm 2^\circ$, and $N_c = 1.675$, $N_X = 1.673$ and $1.683 > N_X > 1.675$. According to Muir 1951 (Tröger 1959, p.62) these properties indicate a composition $En_{47}Fs_3Wo_{50}$. The diopside is enclosed by wollastonite (photo 19), vesuvianite (CF 111) and serpentine CF 111. Inclusions of olivine in diopside indicate that olivine formed before diopside (CF 111, 113 and 114). The diopside grains are both idiomorphic and xenomorphic..

(c) Garnet

This mineral is represented by green and brown xenoblasts, which contain inclusions of diopside (photo 21) (CF 111 and 114), wollastonite (photo 24), olivine and serpentine (CF 111). The wollastonite inclusions are usually idiomorphic, whereas the diopside and olivine are rounded. The garnet was probably the last mineral to form during the progressive metamorphism, because it contains inclusions of all the other constituents. In the banded diopside hornfels, CF 112, the garnet replaces certain sedimentary layers.

A vesuvianite grain, which changes to garnet has also been encountered (photo 23). The replacement of garnet by vesuvianite under retrograde metamorphism is described by Harker (1950, p.82), but the reverse has not previously been recorded. Since garnet can change to vesuvianite during retrograde metamorphism it is conceivable that the reverse may also take place during progressive metamorphism.

The garnet is isotropic, $N = 1.727 \pm (0.003)$ and $A^\circ = 11.89^\circ$. Both the optical properties and the x-ray data indicate that the garnet is grossularite (table 16).

(d) Hematite

Xenomorphic crystalloblasts of hematite replace the iron-rich cementing material in the diopside fels. The hematite crystalloblasts have a tendency to form between the wollastonite fibres

Table 16. X-ray data on grossularite from a carbonate layer above
Magaliesberg quartzite

CF 111		A.S.T.M. 3-0826	
d(Å)	I ₀	d(Å)	I/I ₁
3.01	80	2.96	80
2.71	100	2.65	100
2.45	70	2.44	60
2.34	50	2.33	50
2.17	30	2.16	60
1.96	60	1.92	70
1.806	10	-	-
1.74	40	1.71	60
1.66	50	1.65	80
1.58	90	1.58	90
1.46	30	1.46	10
1.35	20	1.33	50
1.31	20	1.30	60
1.26	20	1.27	20
1.208	10	1.21	20
1.11	40	1.11	50
1.09	30	1.08	40

I₀ = Relative Intensity estimated visually

Cu K_α radiation and a Debye-Scherrer camera
(57.3 mm diameter) on a Seifert machine were used.

or along cleavage directions in the wollastonite (CF 114).

(e) Olivine

The olivine is xenomorphic and rounded, indicating that it has been resorbed (photo 25). $2V_{\omega} = 82^{\circ} \pm 1^{\circ}$, $N_g = 1.652 (\pm 0.003)$

The composition of this olivine is $Fo_{98}Fa_2$, according to the curves of Winchell (1956, p.500), and Kennedy 1947 (Tröger 1959, p.37), and $Fo_{97}Fe_3$ according to the curves of Poldervaart (1950, p. 1073).

Since the olivine is included in all the calc-silicate minerals it is regarded as the first mineral which formed during the progressive metamorphism. The olivine is always replaced by serpentine, which represents a product of retro-grade metamorphism. In the banded diopside fels, the olivine is confined to certain layers of the original sediment.

(f) Serpentine

Serpentine replaces both olivine and diopside.

(g) Vesuvianite

The vesuvianite is colourless, has a low birefringence and a high relief, $N = 1.706 (\pm 0.002)$ and $N = 1.702 (\pm 0.002)$. The x-ray data of the vesuvianite corresponds to the data given on the ASTM-cards (table 17).

The vesuvianite usually replaces the diopside in the same way as discussed by J. Willemse and J.J. Bensch (1966, p.25) in the carbonate inclusions in the Bushveld Complex (photo 20), and is replaced in its turn by grossularite (photo 23).

(h) Wollastonite

The wollastonite grains are usually elongated along the b-axis. The wollastonite has cleavage planes parallel to (100), (001) and (101) and $\gamma \wedge b = 3^{\circ}$. $2V_{\omega} = 37^{\circ} \pm 1^{\circ}$.

Table 18. X-ray data on fine-grained, altered wollastonite from a carbonate horizon above the Magaliesberg quartzite

CF 111		A.S.T.M. 10-487	
d(Å)	I _o	d(Å)	I/I ₁
3.52	80	3.52	80
3.44	10	3.40	5
3.31	60	3.31	80
3.05	40	3.09	30
2.97	90	2.97	100
2.57	30	2.55	30
2.476	40	2.47	60
2.35	30	2.33	40
2.31	60	2.29	40
2.15	20	2.18	60
		2.01	20
		1.98	20
1.92	30	1.91	20
1.846	40	1.83	60
1.766	10	1.75	40
1.719	40	1.72	60
		1.602	40
1.532	10	1.531	10
1.473	30	1.478	20
1.459	10	1.455	30
1.353	40	1.358	30
1.331	10	1.332	10
1.313	5	1.312	5

I_o = Relative intensity estimated visually

Cu K_α radiation and a Debye-Scherrer camera (57.3 mm diameter) on a Seifert machine were used.

but later than diopside and vesuvianite. Grains of vesuvianite which replace diopside and alter to grossularite bear witness of the late formation of grossularite. The temperature at which this metamorphism took place is difficult to determine, since both the pressure and the original composition of these carbonate rocks are unknown. The absence of monticellite and akermanite is according to Bowen (1940) an indication that wollastonite was the last mineral to crystallize. The presence of grossularite and the absence of plagioclase indicate that the sanidinite facies was not yet reached, according to Turner and Verhoogen (1951, p.443). The reaction between calcite and quartz to form wollastonite is the last reaction to take place at an estimated temperature of 600°C to 680°C according to Bowen (1940); 680°C to 720°C according to Harker and Tuttle (1956), and 620°C to 670°C according to Danielson (Hanekom 1962). However, Barth (1951, p.287-289) points out that most rocks are semi-permeable to carbon dioxide gas and consequently the pressure influence on the temperature is insignificant. Barth concludes that the temperature which causes this reaction need not have exceeded 450°C.

The three available chemical analyses of carbonate rocks from the limestone layers, above the Magaliesberg quartzite in the north-eastern aureol of the Bushveld Complex (Visser, 1964, p.153) fall near two corners of the wollastonite-grossularite-diopside field of the hornblende hornfels facies. (figure 19). The diopside fels (analyses b) falls near the diopside corner of the diopside-calcite-anorthite field indicating that the original rock consisted mainly of dolomite and consequently reacted more easily during metamorphism, whereas the analyses of the marble fall near the calcite corner (analyses a). This rock obviously consisted mainly of calcite and did not *change readily* during metamorphism.

The grade of metamorphism in the limestone viz. the

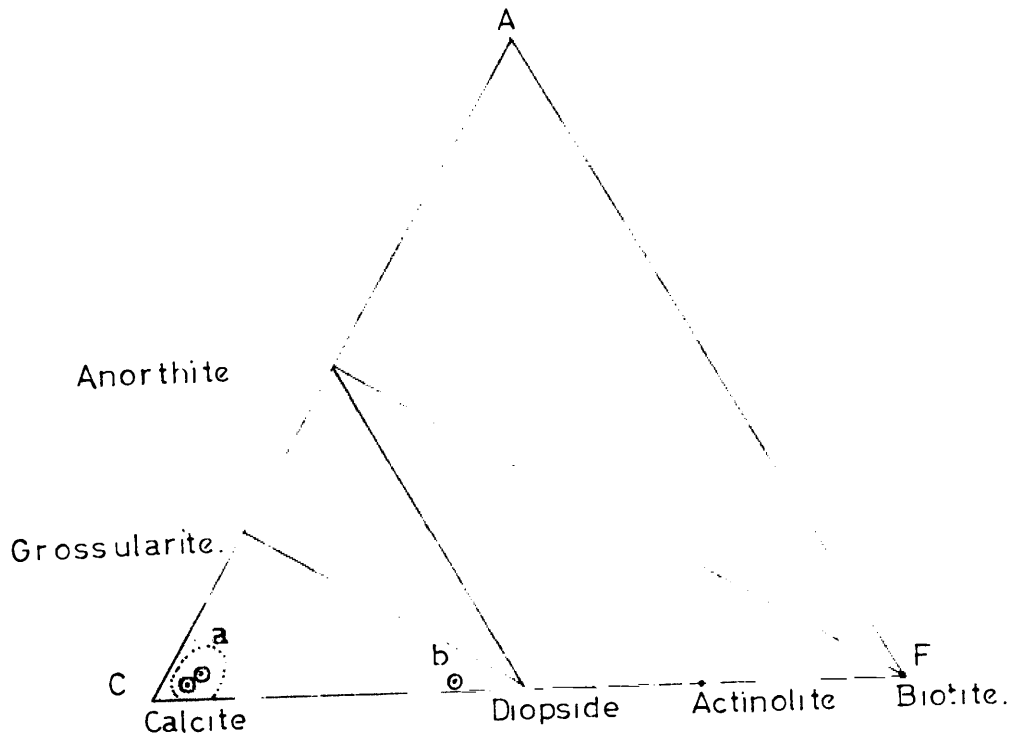


FIGURE 19 ORIGINAL CARBONATE ROCKS FROM ABOVE THE
MAGALIESBERG QUARTZITE ON AN AC-DIAGRAM FOR CAR-
BONATE ROCKS OF THE HORNBLende HORNfels FACIES.

a = Calcium-rich limestone. } (VISSER 1964, p 153)
b = Magnesium-rich limestone.

hornblende hornfels facies corresponds to that in the adjoining hornfels and quartzite.

G. The Sedimentology

A.L. du Toit (1954, p.555) considers the sedimentary rocks of the Pretoria Series to have been deposited in shallow water conditions. D.J.L. Visser (1957, p.xxxii) agrees about the shallow water conditions, but added that it must have been a lacustrine environment. Because the sediments are uniformly developed over a large area, J. Willemse (1959, p. xxxi) regards them to be deposited under marine conditions. He also added that the shale and limestone could have been deposited under neritic conditions, and during the interruption of littoral conditions the arenaceous beds could have formed.

Since the quartzite is recrystallized, it is difficult to reconstruct its original environmental conditions. Twenhofel (1950) attributes very little significance to the estimation of roundness, sorting and size-frequency-distribution as a key to the conditions of sedimentation. Moss (1962, p.341) on the other hand indicates that size-frequency-distribution curves can be of great significance, provided that the mineral grains have not been broken during the crushing of the samples. The recrystallized quartzite did not furnish material suitable for a detailed investigation of this nature.

The frequent development of cross-bedding (photo 5), black sand and ripple-marks indicate that the origin of the quartzite is similar to that of beach sand.

The fine-grained shale and limestone were formed in the deeper parts of the sedimentary basin, under neritic conditions. The poorly-sorted shale, which contains many angular fragments of feldspar and quartz did not settle under the

same neritic conditions as the other shales did, but could have originated by the action of turbidity currents. The observed alternation of the thin psammitic and pelitic layers are also characteristic of turbidites. The thin psammitic layers could have formed during the action of the turbidity current, whereas the pelitic layers could have been deposited during the quiet period alternating with the current.

The alternation of the arenaceous and argillaceous beds, indicates major changes in the sedimentary environment from littoral to neritic conditions.

H. The Metamorphism in the Pretoria Series

In 1959 J. Willemse proposed a facies classification of the metamorphic rocks in the north-eastern part of the Bushveld Complex (p.lxi). A similar classification is now provided for the present area (table 19).

Compared with the classification of Willemse, the almandine-amphibolite facies is added, which Willemse did not distinguish. Because the rocks belonging to this facies contain sillimanite, plagioclase, muscovite and biotite in equilibrium, this facies belongs neither to the pyroxene hornfels facies, nor to the hornblende hornfels facies, according to the facies classification of Turner and Verhoogen (1960, p.502-560).

The hornfelsic rocks on Klipbankspruit 76-JT, and Kliprivier 73-JT do not shed much light on the grade of metamorphism on the immediate contact of the sedimentary rocks and the layered sequence of the Bushveld Complex, because they are too highly altered by metasomatism. This hybridised shale consists of feldspar, orthopyroxene, cordierite and quartz, and will be discussed as quartz micro-norite, in a subsequent chapter.

On map 4, the distribution of the various facies has been indicated. Since the quartzite does not show the effects

Table 19. The metamorphic types, facies and zones in the metamorphic aureole of the Bushveld Complex,
north of Dullstroom

Type	Facies	Subfacies	Rock types	Distance from the Bushveld Complex
Groothoek type	Pyroxene hornfels facies		Hypersthene, diopside and anorthite in the Dullstroom lava.	Close to the contact
	Almandine amphibolite facies	Sillimanite almandine muscovite subfacies	Sillimanite-biotite-muscovite-bearing quartzite	± 200 ft.
	Hornblende hornfels facies		Biotite-muscovite-epidote-bearing quartzite	$\pm 4,000$ ft.
			Cordierite hornfels	$\pm 10,000$
			Muscovite-biotite-bearing shale.	$\pm 10,000$ ft.
			Grossularite-diopside-wollastonite-bearing diopside fels.	$\pm 10,000$ ft.
Longsight type	Albite-epidote hornfels facies		Epидote-muscovite-biotite chlorite-bearing quartzite.	$\pm 10,000$ ft.

of metamorphism as clearly as the hornfels, the position of the boundary line between the pyroxene hornfels facies and the almandine-amphibolite facies is doubtful.

Not much variation in the grade of metamorphism is evident, when the various facies from the north-eastern part of the Bushveld aureol ~~are~~ compared with those in the present area. The cause of the metamorphism can only be attributed to the intrusion of the layered sequence of the Bushveld Complex.

III. THE INTRUSIVE SHEETS

A. Introduction

Both A.L. Hall (1913, p.28) and J. Willemse (1959, p.xlii) mentioned the considerable development of diabase south of the Steelpoort River, and west of Dullstroom. This diabase is intrusive into the Pretoria Series between the Magaliesberg and the Steenkampsberg quartzite, *where* it is so abundantly developed that it almost forms a complex on its own.

The present study is an attempt at obtaining more petrographical information about this diabase. This gap in our knowledge was mentioned by J. Willemse (1959, p.xliii). In the present study the thin sections of previous investigators on diabase were also used. Mainly slides of diabase of which the chemical composition is known, were studied. These thin sections were taken from the collections of J. Willemse, C.P. Snyman, B.V. Lombaard and L. Liebenberg at the University of Pretoria.

The American Geological Institution (1960; p.80) defines a diabase as "a rock of basaltic composition, consisting essentially of labradorite and pyroxene, characterized by an ophitic texture". W.W. Moorehouse (1959, p.164), A. Johannsen (1937, p.317) and E.E. Wahlström (1960, p.298) describe "a basaltic rock with an ophitic texture as a dolerite, and the

term diabase is restricted to an altered dolerite". F.H. Hatch, A.K. Wells and M.K. Wells contend that the term dolerite should be used for all gabbroic rocks, regardless of textural features, and a diabase should be an altered dolerite.

J. Willemse (1959, p.xxxii) defines a diabase in South Africa as any hypabyssal rock of vaguely andesitic to basaltic composition of Pre-Karoo age, and in which one or more of the primary minerals, plagioclase and pyroxene are considerably altered. The author accepted the last three definitions as applicable to the rocks investigated.

B. Previous work on Diabase

A.L. Hall (1913, p.28) observed a diversity among the diabasic rocks and mentioned the occurrence of olivine. He also concluded that the norite of the layered sequence of the Bushveld Complex and the diabase sheets were derived from the same parent magma. This conclusion was based on the fact that the diabase sills became more abundant near the margin of the main body, and that the diabase possesses a close petrographical correspondence to the norite.

B.V. Lombaard (1934) distinguished between the normal diabase and the noritic diabase. He regarded the latter to be genetically related to the Bushveld norite. H.J. Nel (1940) described a noritic diabase, and mentioned that it consists mainly of hypersthene and plagioclase, and displays an ophitic texture. He supported the views of Hall and Lombaard that the noritic diabase is in some way related to the Bushveld norite.

J. Willemse divided the diabase on mineralogical and chemical grounds into the Lydenburg and Maruleng types. He considered the Lydenburg type to be older than the noritic diabase (Maruleng type). He stressed the idea that the diabase is a "sill-phase", "leading up to the actual emplacement of the Bushveld Complex".

Recently C.A. Cousins (1962) described the diabase sills

as extrusions of lava. His evidence for this contention is the presence of amygdales in the fine-grained rock in places, the absence of metamorphism in the overlying sediments, and the concordant nature of the sheets compared with the Karroo dolerite.

A hypodiorite defined as a noritic diabase which had assimilated sedimentary material, was recognized by B.N. Temperly (1964) in the Western Transvaal, as a type of diabase which may be younger than the Bushveld norite.

C. Geological Setting

The sills, which are intrusive into the sediments of the Pretoria Series can be grouped into an older undifferentiated group which consists of diorite and a differentiated group. The latter consists of harzburgite, pyroxenite, dolerite and quartz dolerite. The diorite consists mainly of green hornblende, andesine and quartz, whereas the major constituents of the differentiated suite are labradorite, orthopyroxene, clinopyroxene, olivine and magnetite in varying proportions. When the differentiated rocks are metamorphosed, they contain either urallite or sericite.

In the investigated area, the total thickness of all the intrusive sheets adds up to $\pm$ 14,000 ft., compared with the 6,000 ft. of hornfels and the 6,500 ft. of quartzite ^{excluding the} Magaliesberg quartzite. The diabase sheets are intrusive into all the zones of the Smelterskop Stage, but preferably along the contacts between hornfels and quartzite. These sheets are usually transgressive towards both the hornfels and the quartzite (map 3).

In the composite sheets, consisting of both types of diabase, the differentiated sill usually cuts across the undifferentiated ones. North-east of Santa Railway Station on Uitspanning, a composite sill mapped in detail, displays this feature markedly (map 3). Inclusions of diorite in a differentiated sill has also been found on Uitspanning 106-JT (photo 27).

In the area investigated only the sheets, which are intrusive into the sedimentary rocks above the Main Magaliesberg quartzite are dealt with. There are of course also many sheets which are intrusive into lower zones of the Pretoria Series beyond the boundaries of the present area.

Karoo dolerite is readily distinguished from these intrusive sills, since the Karroo dolerite forms dykes, and weathers more easily (photo 28). The distribution of the two types of intrusive sheets are dealt with in a subsequent paragraph.

D. Petrography

1. The grouping of the intrusive sheets

As already mentioned, in the area mapped two groups of sheets intrusive into the Pretoria Series could be distinguished, namely an older undifferentiated diorite and a younger differentiated group. In a profile across a differentiated suite, a variety of rock types like glassy dolerite, harzburgite, pyroxenite, dolerite and quartz dolerite are present. In addition these differentiated rocks can be metamorphosed to a variable extent, and in this way a third group can be distinguished, namely diabase.

2. The undifferentiated sills of diorite

Three sheets of diorite have been mapped in the area investigated:

(1) A diorite sill, ± 10 feet thick, below the Lakenvlei quartzite on Elandspruit 107-JT and Uitspanning 106-JT. (map 1). This sill thins out on Uitspanning 106-JT (map 3), but farther to the north it has again been picked up on Schaapkraal.

(2) A sill ± 450 feet thick, and interlayered in the Steenkampsberg quartzite on Houtenbek. This sill also wedges

out towards the north on Kliprivier 73-JT (map 1).

(3) A 400 feet thick sill along the base of the Steenkampsberg quartzite on Wanhoop and Verloren Valei (map 1). It contains three, and in places four lenses of quartzite which were wedged off from the thick Steenkampsberg quartzite. Towards the south, on Verloren Valei, this sill breaks up into a number of branches which terminate in quartzite.

At many other localities towards the east, outcrops of diorite have been found. Owing to poor outcrops and the similar appearance of the metamorphosed mafic rocks and of the diorite in hand-specimens, the individual sills could not be mapped separately.

The diorite consists of amphibole, plagioclase, quartz and biotite (table 20), and its volumetric composition differs significantly from that of the diabase (table 21).

2. The differentiated sills

The holocrystalline mafic sills are usually characterized by a glass-bearing chilled margin. The holocrystalline centre of the sills is usually differentiated into several rock types, whereas the chilled margin is more homogeneous.

(i) The chilled margin

The chilled margin of the differentiated sills usually consists of a glassy dolerite, which forms the upper and lower contacts of these sills, and it is succeeded by a devitrified glass-bearing dolerite towards the centre of the sill. Since the sheets are mostly composite, and outcrops are poor, the chilled margin of the differentiated sills could not be mapped in detail. On Schaapkraal 68-JT, however, a sill $\pm$ 100 ft. thick, contains a chilled margin which is $\pm$ 10 ft. thick on both contacts.

An intrusive sill of glassy dolerite also occurs on Kwaggashoek 66-JT. This sill is near the base of the Magaliesberg quartzite.

Table 20. The petrographical features of the diorite

Thin sections and localities	CF 3 Onverwacht 99-JT (30°4' E. Long; 25°22' S. Lat.) CF 25 Houtenbek 97-JT (30°3' E. Long; 25°22' S. Lat.) CF 26 Elandspruit 107-JT (30°13' E. Long; 25°23' S. Lat.)			
	Grain shape	Optical properties	Composition	Remarks
Amphibole	Subhedral	$2V_f = 65^\circ + 2^\circ$ $\gamma \wedge C = 17^\circ + 1^\circ$ $N_\beta = 1.660$ $N_\alpha = 1.655-1.660$ $\bar{N}_f = 1.670-1.660$ Pleochroic in green, yellow and blue-green.	Horn-blende	Contains inclusions of quartz and plagioclase.
Plagioclase	Idiomorphic to xenomorphic	$2V_\alpha = 88^\circ$ to $2V_f = 80^\circ$	Ar 36% to An 63%	1. Enclosed in amphibole. 2. Zonary
Quartz	Xenomorphic			1. Worm-like inclusions in amphibole. 2. Intergranular
Biotite	Xenomorphic	Pleochroic		1. Intergranular
Texture	1. Hipidiomorphic 2. Coarse-grained			

Table 21. Volumetric composition of diorite, hybrid
dolerite, and diabase

Rock type	Diorite		Hybrid dolerite	Diabase
Locality	Onverwacht Houtenbek Elandspruit	Wolwekraal 13-JS Groblersdal	De Kaffers- kraal	Wanhoop 78-JT. and Kwaggashoek 66-JT
Thin section	CF ₃ , CF ₂₅ , CF ₂₆	S72	CF ₂₄	CF ₁₀ , 21, 36
Uralite	-	-	-	43.6
Hornblende	38.6	44.5	20.2	-
Plagioclase	39.5	54.0	44.6	42.1
Pyroxene	-	-	13.3	0.6
Quartz	12.6	2.5	12.6	6.6
Biotite	8.9	-	9.0	3.2
Opaque minerals	0.5	-	0.3	2.5
Total %	100.1	100.0	100.0	100.6

On Weimershoek 81-JT, Kleinzuikerboschkop 93-JT, and Knapdaar 92-JT, a differentiated sill contains a 3 ft. thick chilled basal zone of glassy dolerite. This chilled margin is followed by a devitrified glass-bearing dolerite, which is again succeeded by a harzburgite zone.

Farther west, towards the outcrops of the Lakensvlei quartzite, and above it, these chilled margins have never been observed. The inflow of heat during the emplacement of the Bushveld Complex, probably caused devitrification or recrystallization of the glassy mesostasis, nearer towards the contact of the Bushveld Complex.

In hand-specimens the glassy dolerite is a hard, fresh and dark rock, which contains many needle-like phenocrysts. The pyroxene phenocrysts weathers more easily than the glassy mesostasis, and consequently the weathered surface also shows the needle-like character of the rock.

Microscopically the chilled margin consists of a glass-bearing rock, in which phenocrysts of orthopyroxene are scattered. In some places the glass is devitrified, and even recrystallized. In the recrystallized rocks plagioclase and augite usually formed from the glass. The volumetric composition of the glassy dolerite and the devitrified dolerite of the chilled margin of the sills compares favourably with that of similarly chilled dolerite from other localities (table 22).

The orthopyroxene phenocrysts were resorbed by the magma, and reacted with it to form a light-coloured glass, which surrounds the unresorbed phenocrysts (photo 29). This glass, which can be distinguished from the darker glassy mesostasis, recrystallized to augite (photo 30). In some examples, nearly the whole orthopyroxene grain has been melted, so that only a relict of the orthopyroxene phenocryst remains (photo 32).

The composition of the orthopyroxene phenocrysts in the glassy dolerite and the devitrified dolerite differs slightly

Table 22. Volumetric composition of glassy dolerite from
the present area compared with chilled dolerite
from various localities

	Glassy dolerite				
	Devitrified dolerite	Glass- bearing	G.Joplin (1957, p. 54)	F. Walker (1935, p. 150)	E.A.Vincent (1950, p. 56)
	Weimershoek 81-JT (CF26)	Schaapkraal 68-JT (CF6)	Tasmania	Scotland	Kap Daussey, Greenland
Orthopyroxene	35.1	44.8	46.8	7.0	-
Glass	-	55.1	19.0	31.5	20.3
Opaque minerals	3.4	0.1	5.6	10.8	6.5
Olivine	-	-	-	-	3.3
Plagioclase	42.2	-	28.4	28.3	38.2
Clinopyroxene	14.5	-	-	22.4	31.7
Biotite	4.1	-	-	-	-
Total in %	99.3	100.0	99.8	100.0	100.0

Table 23. Optical properties of orthopyroxene phenocrysts
in the glassy dolerite of the chilled margin of
the mafic sills

Thin sections	Glassy dolerite	Devitrified dolerite
	CF 6, 27	CF 17, 38
2V _x	69° ± 1°	78° ± 2°
N _d	1.670	1.657
Length	Variable	0.2 mm to 7.0 mm
Composition	En ₇₅ Fs ₂₅	En ₈₂ Fs ₁₈

in composition (table 23).

The phenocrysts are sometimes bent (photo 31) in the same way as those from a quartz dolerite near Potgietersrus discussed by Strauss (1947). He concluded that the bent phenocrysts can only be explained by distortion of the grains either during or after their crystallization. If they were distorted after they had formed, they must have been subjected to stress, prior to the solidification of the intergranular material. The orthopyroxene phenocrysts are intratelluric in origin, and were evidently partially melted by the increase in heat during the emplacement. Winkler (1962, p.222-231) determined experimentally that the temperature of a basaltic magma increases when the pressure decreases. During the emplacement of the mafic sills, the phenocrysts were also bent and arranged parallel to the flow-lines in the magma.

The glassy mesostasis is isotropic, and contains numerous small microlites of opaque minerals, which cause the glass to have a high relative density, namely 3.25 for the glass from Schaapkraal (CF 6) as determined with the aid of a pycnometer. The refractive index of this glass is 1.568. The microlites of opaque minerals and the phenocrysts of orthopyroxene are arranged parallel to the flow-lines, but spherulites are absent. In the devitrified dolerite and also in the Maruleng norite (as defined by J. Willemse 1959) a parallel orientation of plagioclase and clinopyroxene is very prominent (photo 30). J. Willemse (1959, p.xxxviii) called this a trachytoidal texture, and attributed its origin to the recrystallization of "spherulites formed in a viscous environment" (after Colony and Howard 1934, p.517). This explanation appears reasonable.

The glassy mesostasis was separated from the phenocrysts of orthopyroxene, according to the technique described by E.A. Vincent (1950, p.49) and the chemical composition of the glass (CF 6) is discussed subsequently.

Intergranular clinopyroxene is moulded onto the laths of plagioclase, like the texture in dolerite from Australia discussed by Joplin (1957, p.48) and McDoughil (1961, p.58). This texture indicates that plagioclase was the first mineral to form during the crystallization of the glassy matrix, and clinopyroxene the last

(ii) The differentiated central portion

This zone succeeds the devitrified dolerite in a profile across a mafic sheet from the lower contact to the upper one, and it is differentiated into four zones, which consist of harzburgite, pyroxenite, dolerite and quartz dolerite.

(a) The Harzburgite zone

Harzburgite usually succeeds the devitrified dolerite in the differentiated sills. The harzburgite zone has a thickness which ranges from 10 to 100 ft., and this zone is well exposed above the Lakensvlei quartzite on Oshoek 69-JT, Goedehoop 79-JT (CF 1), Lunsklip 105-JT and Suikerboschhoek 80-JT.

The harzburgite is usually very fresh in hand-specimens, it has a green colour and is fine-grained.

The volumetric composition and the mineralogy of the harzburgite differs very markedly from that of the devitrified chilled dolerite (table 24, 25 and 23).

Idiomorphic grains of orthopyroxene are in places partly replaced along their rims by clinopyroxene, which contains more magnetite inclusions than the orthopyroxene. Muir (1953, p.386) also mentions the increase of magnetite inclusions in clinopyroxene, whenever it replaces orthopyroxene. Wells (1952, p.913-924) explained the augite rims as reaction rims between Ca-rich intercumulus liquid, and orthopyroxene cumulus crystals in the case of the Bushveld norite.

(b) The Pyroxenite zone

Pyroxenite usually succeeds the harzburgite in the

Table 24. Average volumetric composition of the different zones in a differentiated sill, on Goedehoop 79-JT and Suikerboschhoek 80-JT

Rock type	Glassy dolerite	Devitrified dolerite	Harzburgite	Pyroxenite	Dolerite	Quartz-dolerite
Orthopyroxene	44.8	35.1	60.1	61.5	32.8	18.0
Clinopyroxene	-	14.5	5.2	4.6	17.1	14.4
Olivine	-	-	12.0	-	-	-
Feldspar	-	42.2	20.4	20.4	45.8	50.0
Amphibole	-	-	-	7.8	-	7.6
Opaque minerals	0.1	3.4	1.2	0.5	2.6	3.1
Biotite	-	4.1	0.8	-	1.7	-
Glass	55.1	-	-	-	-	-
Quartz	-	-	4.1	4.1	-	7.0
Total	100.0%	99.3%	99.9%	98.9%	100.0%	100.1%

Table 25. Petrographical data on the harzburgite of the
differentiated mafic sheets

Thin sections and localities	CF 1	Goedehoop 79-JT		
	CF 34	(Map 1) Suikerboschhoek 80-JT		
	Form of grain	Optical properties	Composition	Remarks
Orthopyroxene	Idiomorphic length: $\pm 2.0\text{mm.}$	$2V_x = 70^\circ \pm 2^\circ$ $\chi_c = 0^\circ$ $N_x = 1.665$	Bronzite En ₇₀ Fs ₃₀	1. Encloses both olivine and magnetite. 2. Contains exsolution bodies of augite.
Clinopyroxene	Xenomorphic	$2V_x = 51^\circ \pm 1^\circ$ $\chi_c = 43^\circ \pm 1^\circ$ $N_x = 1.675$ (± 0.005)	Augite Wo ₄₀ En ₅₅ Fs ₅	1. Reaction rims of clinopyroxene around orthopyroxene. 2. Contains magnetite inclusions.
Olivine	Rounded grains, resorbed by orthopyroxene	$2V_x = 87^\circ \pm 2^\circ$ $N_x = 1.682$	Fe ₈₀ Fay ₂₀	Alters to serpentine.
Plagioclase	Intergranular and xenomorphic	$2V_x = 85^\circ$ to $2V_x = 89^\circ$ zonary	An 65% to An 70%	-
Magnetite	Idiomorphic	Opaque	-	Enclosed in olivine and augite
Serpentine	Pseudomorphous after olivine.	-	-	Replaces olivine
Biotite	Xenomorphic			Late magmatic alteration product
Texture	The orthopyroxene is a cumulus product and the plagioclase is intercumulus.			
Type of cumulate	Orthopyroxene-olivine cumulates.			

sequence across a differentiated sill. The pyroxenite zone has a width which ranges from 10 to 70 ft. There is no sharp contact between the pyroxenite and the harzburgite, but the harzburgite becomes poorer in olivine towards the top of the harzburgite zone, and the pyroxenite richer in olivine towards the bottom of the pyroxenite zone. The pyroxenite forms the largest portion of the differentiated sills, and good outcrops are to be found on Oshoek, Suikerboschhoek, Schaapkraal and Vrischgewaagd is Half Gewonnen.

Orthopyroxene, clinopyroxene, uralite and plagioclase are the major constituents of the pyroxenite (table 24), and the composition of the orthopyroxene and plagioclase in the pyroxenite (En₇₇Fs₂₃, and Ar₆₅₋₇₀ respectively) corresponds closely to that in the harzburgite (En₇₀Fs₃₀ and An₆₅₋₇₀ respectively) (table 26).

Small grains of augite in large orthopyroxenes are usually rounded or drawn out parallel to the c-axis of the orthopyroxene, and the augite grains have the same optical orientation. In Karroo dolerite from South Africa Walker and Poldervaart (1949) found similar grains of augite in orthopyroxene. They called this texture a "graphic intergrowth". Poldervaart and Walker (1949) ascribed the origin of this texture to the rapid exsolution of augite from pigeonite during its early inversion to enstatite. According to Poldervaart and Hess (1951, p.482) the orthopyroxene was erroneously interpreted as inverted pigeonite. These augite grains are arranged parallel to (100) of the orthopyroxene (CF 10).

If the sections are cut parallel to the (100) plane of the orthopyroxene, that is parallel to the direction of the exsolution of augite, the augite could appear as rounded grains, similar to those discussed above. Consequently the "graphic intergrowth" could also be explained by a special section of the orthopyroxene.

Lamellae of augite parallel to (100) in orthopyroxene

Table 26. The petrography of the pyroxenite from the
differentiated sills

Thin sections and localities	CF 2 Kleinzuikerboschkop 93-JT (CF 35 Suikerboschhoek 80-JT.			
	CF 12 Oshoek 69-JT			
	CF 13 Goedehoop 79-JT			
	CF 32 Suikerboshoek 80-JT.			
	Form and size of grains	Optical properties	Composition	Remarks
Orthopyroxene	Idiomorphic. Length 0.5 mm. to 2.5 mm.	$2V_x = 70^\circ$ to 85° $\Delta C = 0^\circ$ $N_F = 1.666$	Bronzite En77 Fs23	1. Translation twins characteristic (photo 35). 2. Alters to uralite (photo 34). 3. Contains exsolution lamellae of augite (photo 35).
Clinopyroxene		$2V_x = 55^\circ + 2^\circ$ $\Delta C = 43^\circ - 35^\circ$ $N_F = 1.671$	Diallage Wo44 En52 Fs4	1. Replaces orthopyroxene. 2. Forms exsolution lamellae in orthopyroxene. 3. (110) twinning and (100) parting. 4. Herring bone twins.
Plagioclase	Xenomorphic	$2V_x = 82^\circ$ to 88° zonary	Rims An 35% and the cores An 65-70%	Intercumulus material. Cores more sericitized than rims.
Quartz	Xenomorphic	-		Forms granophyric intergrowths with orthoclase. Represents intercumulus liquid.
Amphibole	Fibrous and xenomorphic	Light green. Low birefringence	Replaces orthopyroxene sieve-like (photo 34).	
Accessory minerals	Biotite			
	Opaque minerals			
Type of cumulate	Orthopyroxene-cumulates			

(CF 1, 10) indicate that the augite has exsolved from orthopyroxene during cooling.

Thin lamellae in the orthopyroxene, similar to those described by S. Maske (1966, p.53-54) from the Ingeli mountain range, by D.L. Scholtz (1936, p.112) from East Griqualand and Pondoland, and by other authors from various localities, are common. According to Scholtz they are translation twins.

Granophyric intergrowths of K-feldspar and quartz fill the intergranular spaces of the pyroxenite (CF 10) and obviously represents a late eutectic crystallization product.

(c) The dolerite zone

In the succession from the lower contact to the upper contact of the differentiated sills the dolerite usually succeeds the pyroxenite. The contact between the pyroxenite and the dolerite is marked by a gradual increase in plagioclase towards the dolerite. The width of this zone ranges from 10 to 40 feet. Outcrops of dolerite are common on Oshoek, Goedehoop, Schaapkraal, Vrischgewaagd is Half Gewonnen, and Suikerboschhoek.

In hand-specimen the dolerite is usually fine-grained, fresh and melanocratic, although coarse-grained varieties also occur frequently. The coarse-grained variety may be classified as a norite.

Plagioclase and orthopyroxene are the major constituents (table 24), and the dolerite is characterized by the typical ophitic texture (table 27).

(d) The quartz dolerite zone

The quartz dolerite zone forms the uppermost part of the differentiated sills, and succeeds the dolerite. This rock contains more quartz than the dolerite (table 24), and is characterized by granophyric intergrowths between quartz and k-feldspar. This granophyric intergrowth also represents a late eutectic crystallization product, rather

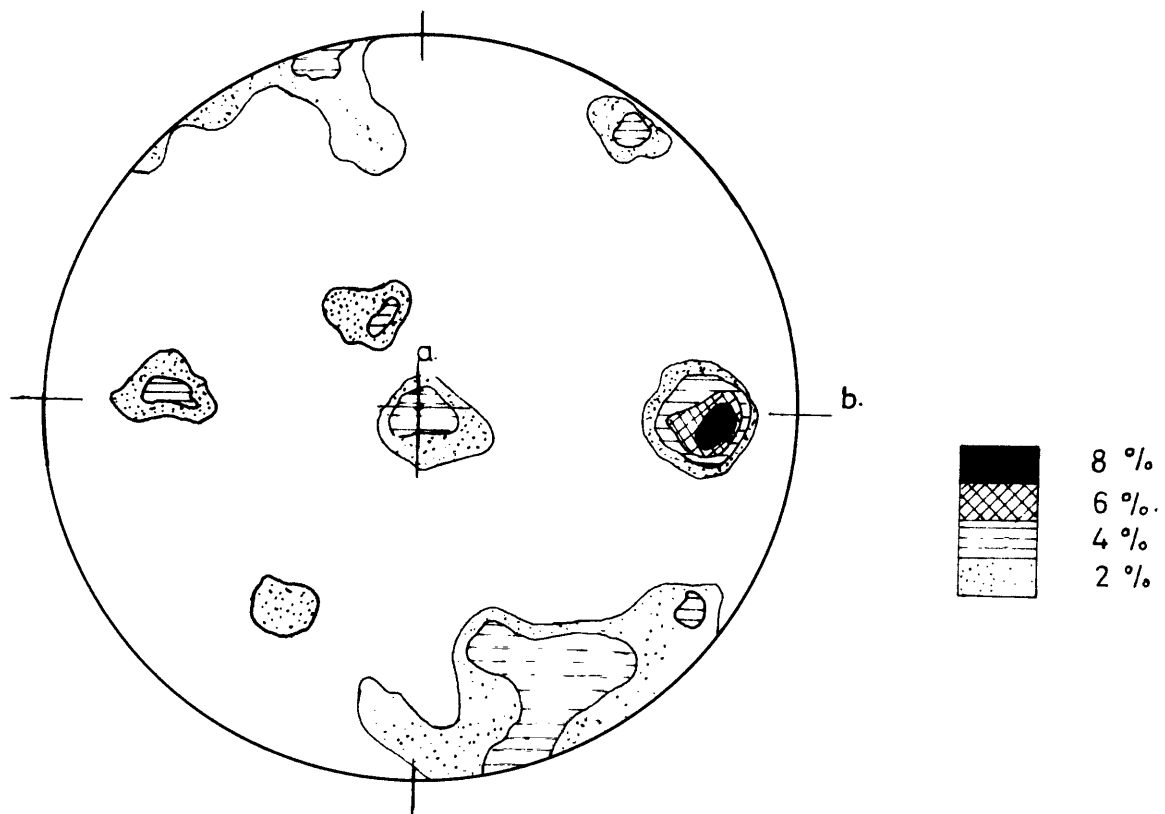


FIGURE 6 ORIENTATION OF THE C-AXES OF QUARTZ IN THE STEENKAMPSBERG QUARTZITE ON KLIPRIVIER 73-JT.

a = Direction of dip, b = direction of strike of the quartzite.
100 Measurements, C.F. 104.

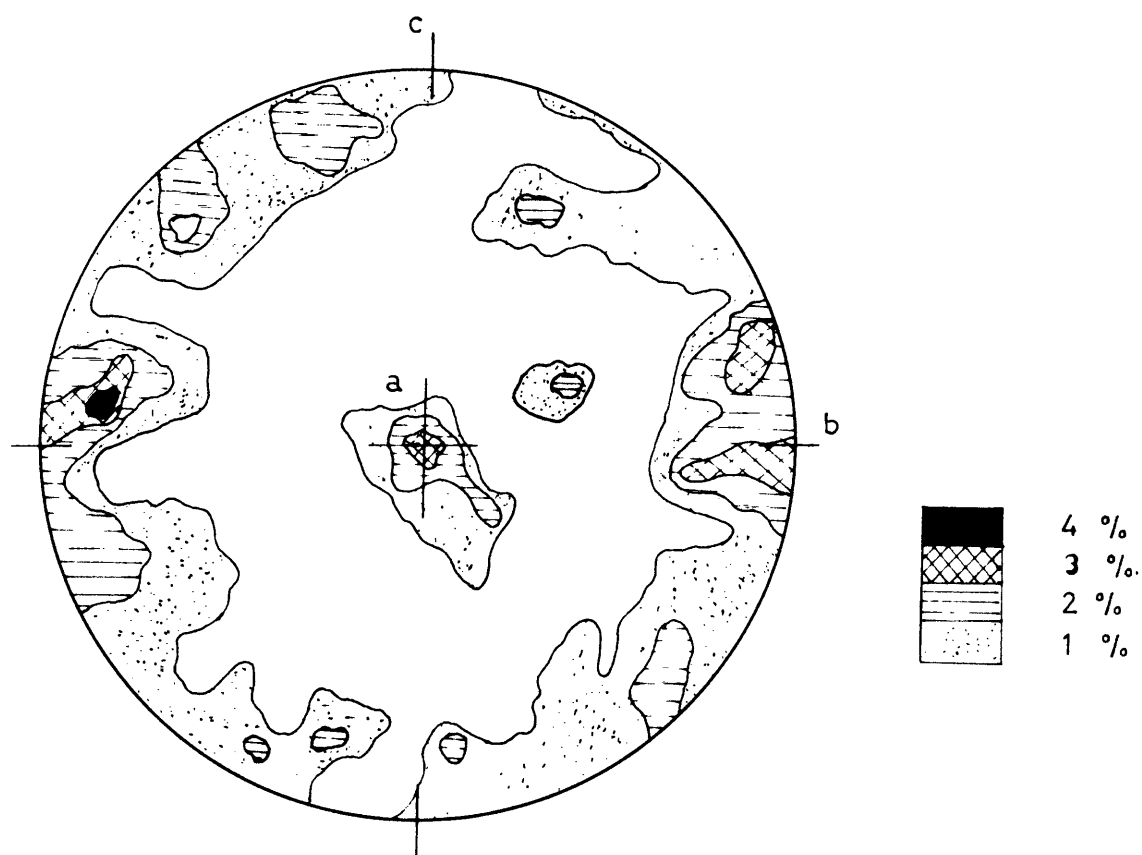


FIGURE 7 ORIENTATION OF THE C-AXES OF QUARTZ IN THE LAKENSVLEI QUARTZITE ON VRISCHGEWAAGD IS HALF GEWONNEN. 94-1. a = Direction of dip, b = direction of strike of the quartzite. 200 Measurements, C.F. 103

Table 27. Petrography of the dolerite in a differentiated sill

Thin sections and localities	CF 18 Kleinzuikerboschkop 93-JT CF 37 Wanhoop 78-JT CF 39 Goedehoop 79-JT CF 41 Wanhoop 78-JT (Map 1.)			
	Form of grains	Optical properties	Composition	Remarks
Orthopyroxene	Xenomorphic and intergranular	$2V_x = 60^\circ \pm 1^\circ$ $\chi_c = 0^\circ$ $N_x = 1.682$	Hypersthene En ₆₇ Fs ₃₃	Replaced along rims by clinopyroxene. Contains idiomorphic plagioclase inclusions.
Clinopyroxene	Xenomorphic	$2V_x = 54^\circ \pm 2^\circ$ $\chi_c = 33^\circ \pm 1^\circ$ $N_x = 1.680$	Wo ₄₄ En ₄₈ Fs ₈	Contains inclusions of magnetite and plagioclase.
Plagioclase	Idiomorphic and lath-shaped	$2V_x = 90^\circ$ to $2V_x = 82^\circ$	An 70% to An 63%	Zonary. Represents cumulus crystals.
Accessory minerals	Biotite, Magnetite and K-feldspar			
Texture	Ophitic			

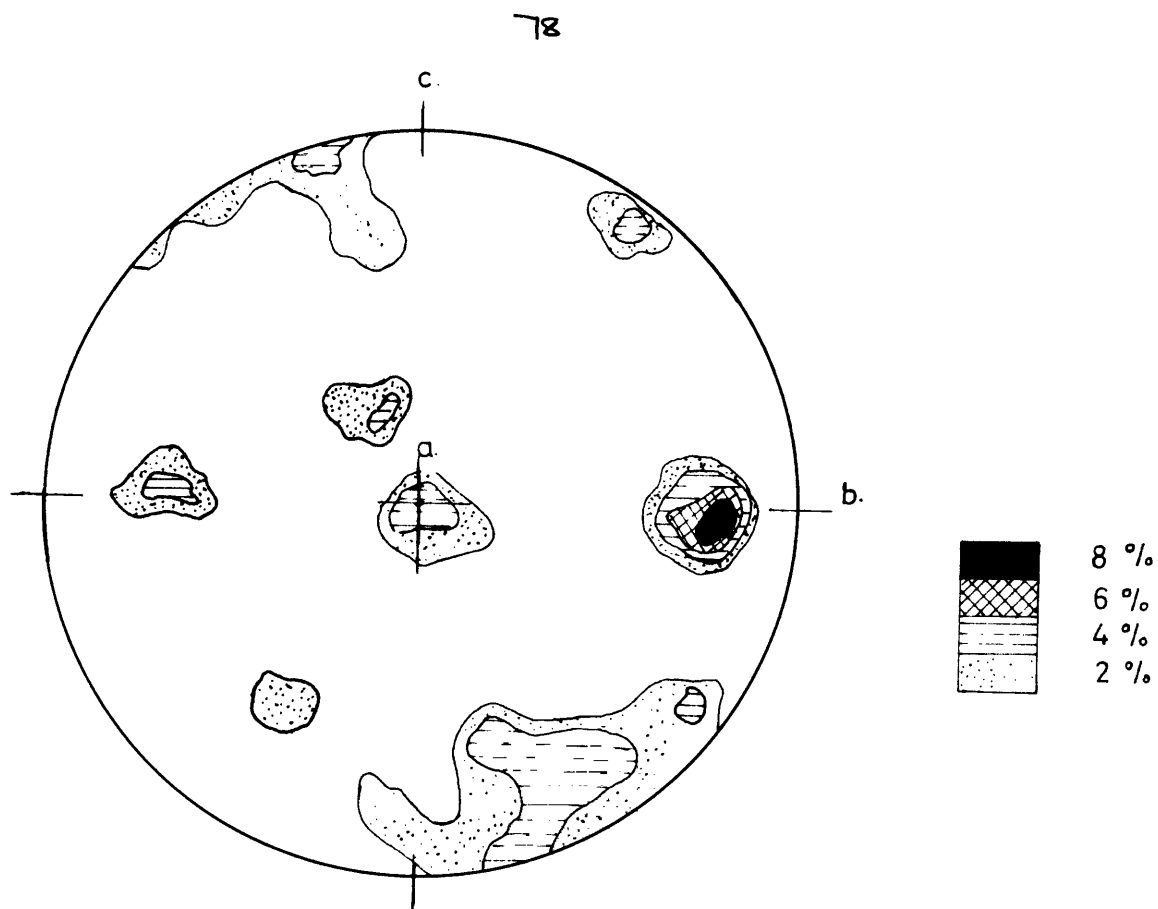


FIGURE 6 ORIENTATION OF THE C-AXES OF QUARTZ IN THE STEENKAMPKOPBERG QUARTZITE ON KLIPRIVIER 73-JT.

a = Direction of dip, b = direction of strike of the quartzite.
100 Measurements, C.F. 104.

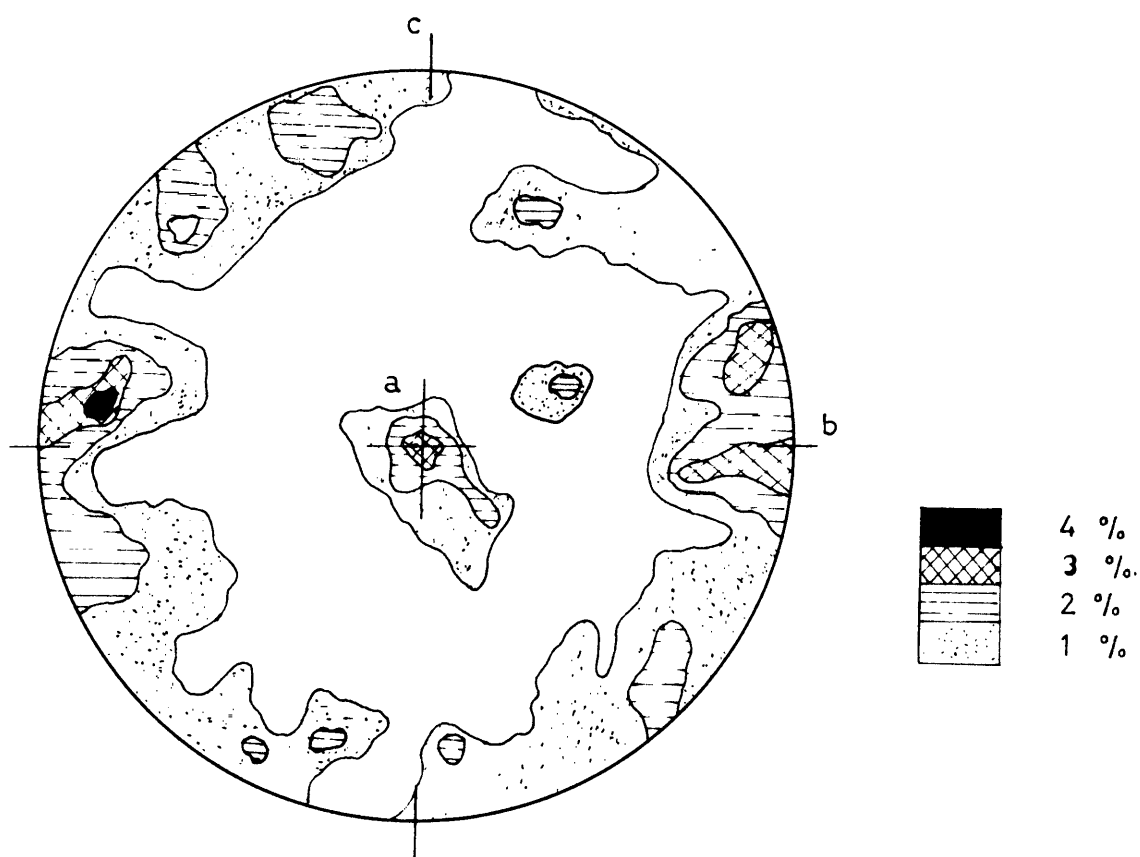


FIGURE 7 ORIENTATION OF THE C-AXES OF QUARTZ IN THE LAKENSVLEI QUARTZITE ON VRISCHGEWAAGD IS HALF GEWONNEN. 94-JT. a = Direction of dip, b = direction of strike of the quartzite. 200 Measurements, C.F. 103

than a replacement of plagioclase by quartz. An ophitic texture, similar to that of dolerite, is also characteristic of the quartz diorite (table 28).

3. The hybrid dolerite

In addition to a prominent outcrop (CF 15) on Houtenbek, hybrid dolerite is extremely well exposed near the corner beacon of Wanhoop, Goedehoop and Suikerboschhoek. A dolerite sill, which contains many angular fragments of hornfels and quartzite, is exposed at the latter ^{two} localities. This sill has a thickness of approximately 10 feet. Towards the top of the sill, the number of inclusions becomes less, and at the upper contact they are absent.

The hybrid dolerite consists of plagioclase, pyroxene, hornblende, biotite, and quartz (table 29). The labradorite and pyroxene are characteristic of the dolerite zone of the differentiated sills, whereas the hornblende, andesine and quartz characterize the diorite of the undifferentiated sills. In the hybrid-dolerite two types of amphibole can be distinguished easily (CF 24), namely hornblende, which is pleochroic, has a high birefringence and forms large grains and has straight boundaries, and urallite, which is not pleochroic, has a low birefringence, is developed along cleavage planes and fractures in orthopyroxene (photo 34) and clinopyroxene, and is fibrous.

Relicts of orthopyroxene and clinopyroxene, surrounded by rims of green hornblende, are characteristic of the hybrid dolerite. These relicts of pyroxene have been partly metamorphosed to urallite, whereas the hornblende remains unaltered.

The high percentage of quartz in the hybrid dolerite (table 21) and the association of hornblende, orthopyroxene, clinopyroxene, labradorite and andesine (table 29) indicate that the normal course of differentiation of a basaltic magma, was suddenly changed from a saturated to an over-

Table 28. Petrographical data on the quartz dolerite in the differentiated sheets

Thin sections	CF 14, CF 16 and CF 33 from Oshoek 69-JT, Uitspanning 106-JT and Knapdaar 92-JT respectively.			
	Form of grain	Optical properties	Composition	Remarks
Orthopyroxene	Xenomorphic and rounded	$2V_{\gamma} = 58^{\circ}$ $\gamma \wedge C = 0^{\circ}$	En 63% Fs 37% Hypersthene	Alters to uralite. Contains inclusions of plagioclase.
Clinopyroxene	Xenomorphic	$2V_{\delta} = 50^{\circ}$ $\delta \wedge C = 32^{\circ}$	Augite	Alters to uralite Encloses plagioclase.
Plagioclase	Idiomorphic	$2V_{\gamma} = 78^{\circ} \pm 2^{\circ}$ $2V_{\delta} = 83^{\circ} \pm 2^{\circ}$	An 45% to An 63%	Included in fimoic crystals. Zonary (core An ₄₅ - rim An ₆₃).
Amphibole	Fibrous	Low birefringence, light green	Uralite	Cuts across grain boundaries.
Quartz	Xenomorphic	-		Intergrown with orthoclase.
Opaque minerals	Xenomorphic	Opaque		Enclosed in pyroxene and plagioclase.
Texture	Ophitic and also a eutectic intergrowth of quartz and K-feldspar.			

saturated magma. The sedimentary material, which was assimilated by the tholeiitic magma, pushed the mother liquid along its normal differentiation course (Bowen 1927, p.221) and a diorite formed.

4. The diabase

The designation Lydenburg type of diabase was proposed by J. Willemse (1959, p.xlviii) to include the diabase which consists mainly of amphibole, plagioclase and augite. It has been mentioned before that both the orthopyroxene and the clinopyroxene of the differentiated sills alter to uraltite during thermal metamorphism, giving rise to diabase, according to the definitions discussed previously. Consequently the designation Lydenburg type of diabase should only be used to describe the metamorphosed sills. Since the composition of these metamorphic rocks corresponds to that required by the definition of diabase, the term diabase is preferred.

Hall and Molengraaff (1925, p.48) called a similarly metamorphosed gabbro from the Vredefort-Parys area an epidiorite. They discussed seven phases in the process of epidioritisation, all of which could be traced in the thin sections investigated. Both Harker (1956 p.272-286) and Moorehouse (1959, p.179-184) points out that orthopyroxene and clinopyroxene alter to uraltite during the thermal metamorphism of mafic igneous rocks. Harker, Moorehouse and Wahlström (1955, p.175-180) also distinguish between green hornblende, which is a constituent of diorite, granite and amphibolite and uraltite which forms in metamorphosed mafic rocks.

It is also evident from the volumetric composition (table 21) and the petrography (table 30) that the diabase intrusive into the Pretoria Series differs significantly from the diorite.

E. The Metamorphism

Table 30. Petrographical data on diabase

Thin sections and localities	CF 10 Wanhoop 78-JT CF 21 Wanhoop 78-JT CF 36 Wanhoop 78-JT Map 1. CF 11 Kwaggashoek 66-JT CF 22 Wanhoop 78-JT			
	Form of grains	Optical properties	Composition	Remarks
Uralite	Fibrous and xenomorphic	$2V_x = 74^{\circ} \pm 2^{\circ}$ $\chi \wedge C = 16^{\circ} \pm 2^{\circ}$ Not pleochroic Low birefringence	Uralite	1. Replaces ortho- and clino-pyroxene.(CF10) 2. Has inclusions of opaque minerals.(CF10)
Plagioclase	Xenomorphic	$2V_x = 86\%$ δ to $2V_x = 76\%$ zonary	An 65% (cores) to An 47% (rims)	Sericite replaces the plagioclase.(CF 11).
Quartz	Xenomorphic	-		1. Eutectic intergrowths with K-feldspar 2. Intergranular.
Accessory minerals	Opaque minerals, biotite and chlorite.			
Texture	A fine-grained fibrous uralite mass.			

The differentiated sills nearest to the **Bushveld** Complex are intensely metamorphosed, whereas the sills farther away, are hardly affected. The dolerite which underlies the Lakensvlei quartzite is not much altered and even contains glass. The dolerite which overlies the Lakensvlei quartzite is metamorphosed partly but still contains unaltered parts. The differentiated sills were consequently emplaced before the Bushveld Complex was formed.

According to their chemical composition the differentiated sills fall within the anorthite-biotite-actinoliet field of an A.C.F diagram of the hornblende hornfels facies (fig.

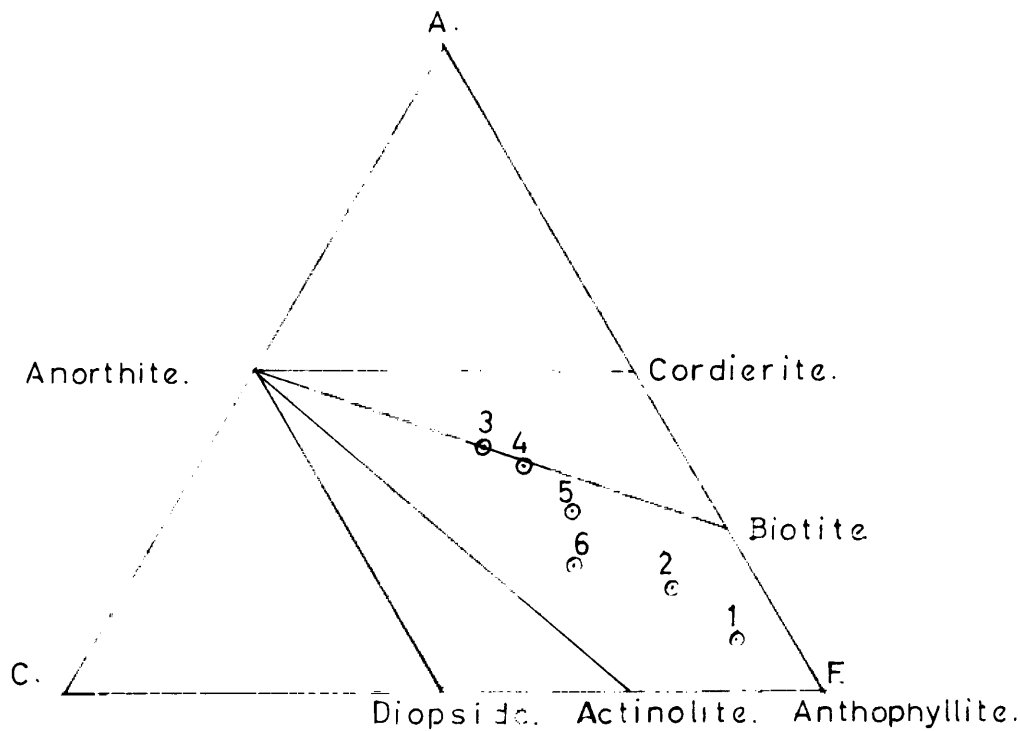


FIGURE 20 MAFIC ROCKS INTRUSIVE INTO THE PRETORIA SERIES ON AN ACF-DIAGRAM OF THE **HORNBLende HORNfels FACIES**.

1 & 2 = Differentiated rocks. C.F. 1 & 2 } (New analyses)
 3 = Undifferentiated rocks. C.F. 3. }
 4, 5 & 6 = Diabase (Lombaard 1934; p 39)

20). indicating that the rocks of these sills could contain urallite and sericite. According to the A.C.F. diagram of the hornblende hornfels facies, it is evident that green hornblende could also form under these conditions. Consequently an amphibolite can result, which may consist of green hornblende. Diorite on the other hand would also be stable under these conditions, since green hornblende and plagioclase represent a stable association in the hornblende hornfels facies.

Both the volumetric composition and the mineralogy of the diorite and the diabase (metamorphosed differentiated rocks) differ significantly. The diabase consists of urallite, which replaces pyroxene and destroys the original textures, whereas the green hornblende in the diorite does not replace any mineral and is hypidiomorphic. The plagioclase in the diorite is andesine and was not affected by metamorphism, whereas the labradorite in the diabase is intensely sericitized. Furthermore the hornblende in the diorite corresponds in physical properties to the hornblende described by Johannsen (1937, p.152) in diorite from various localities. The urallite resembles the metamorphic amphibole which develops in metamorphosed mafic rocks (Moorehouse 1959, p.178-184). It could be maintained, however, that the diorite originated by advanced metamorphism of the diabase. According to Harker, hornblende replaces pyroxene at a much higher temperature than urallite. Consequently the diorite must have been subjected to a higher grade of metamorphism than the bordering diabase on Houtenbek 97-JT if it had formed through metamorphism. All the evidence indicate that this diorite is magmatic in origin and not metamorphic.

F. The Chemistry

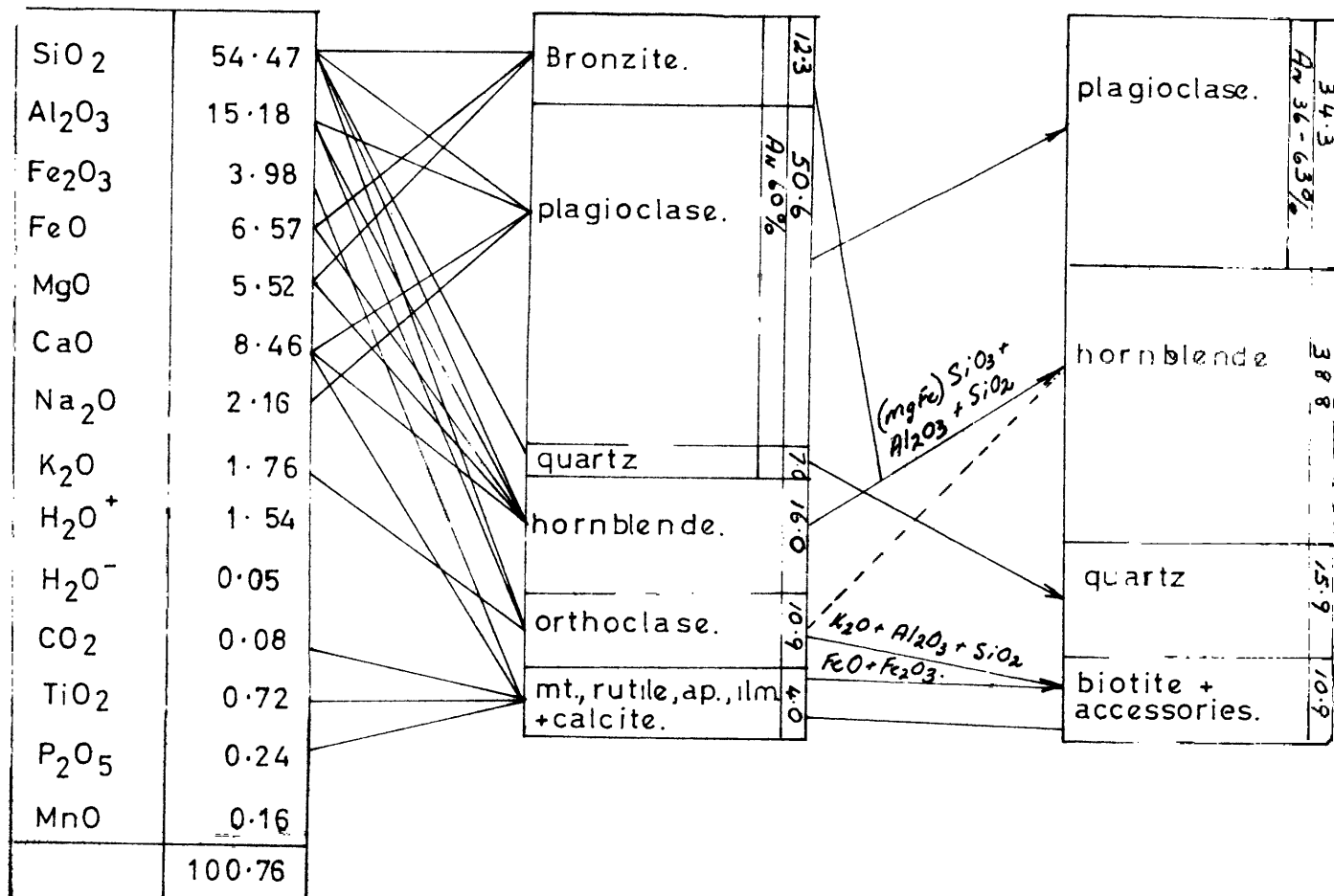
According to the katamolecular norm of the diorite (table 31), bronzite and orthoclase could form in this rock, but

TABLE 31. Chemical composition of diorite from Houtenbek 97JT, CF 3.

Chemical analysis.

Katamolucular norm.

Volumetric compositio



Scale: 1 mm = 1 %

the mode reflects hornblende and biotite.

The harzburgite (CF 1) (table 32) from a differentiated mafic sill on Goedehoop contains more orthopyroxene and less olivine than that revealed by the katamolecular norm. Biotite has also been recorded in the volumetric composition but in the katamolecular norm its place is taken up by orthoclase (table 32). These differences could be explained by the distribution of SiO_2 between the norm minerals. Silica allotted to orthoclase and olivine would yield biotite and orthopyroxene.

The pyroxenite from the differentiated sheet on Kleinzuikerboschkop does not display much difference between the volumetric composition and the katamolecular norm. The latter, however, reflects much more bronzite and less uraalite than the volumetric composition. Since bronzite alters to uraalite during thermal metamorphism, this difference is readily explained (table 33).

The chemical composition of the harzburgite (CF 1), the pyroxenite (CF 2) and the diorite (CF 3) from the sills on Goedehoop, Kleinzuikerboschkop and Houtenbek respectively, together with that of 13 other mafic rocks (table 34) were plotted on a diagram after J. Willemse (1967). The variables of this diagram are Mg^{2+} , $\text{K}^+ + \text{Na}^+$, $\text{Fe}^{2+} + \text{Fe}^{3+}$ (fig. 21). The harzburgite (No. 6) and the pyroxenite (No. 7) of the differentiated sill fall along the general trend of differentiation of the layered rocks, indicating that the harzburgite could represent an early crystal cumulate close to the lower contact of the sill, whereas the pyroxenite formed later. The diorite (No. 8) falls within the diorite field, farther along the line of differentiation. However, it originated evidently from a separate magma, because it is older than the differentiated rocks.

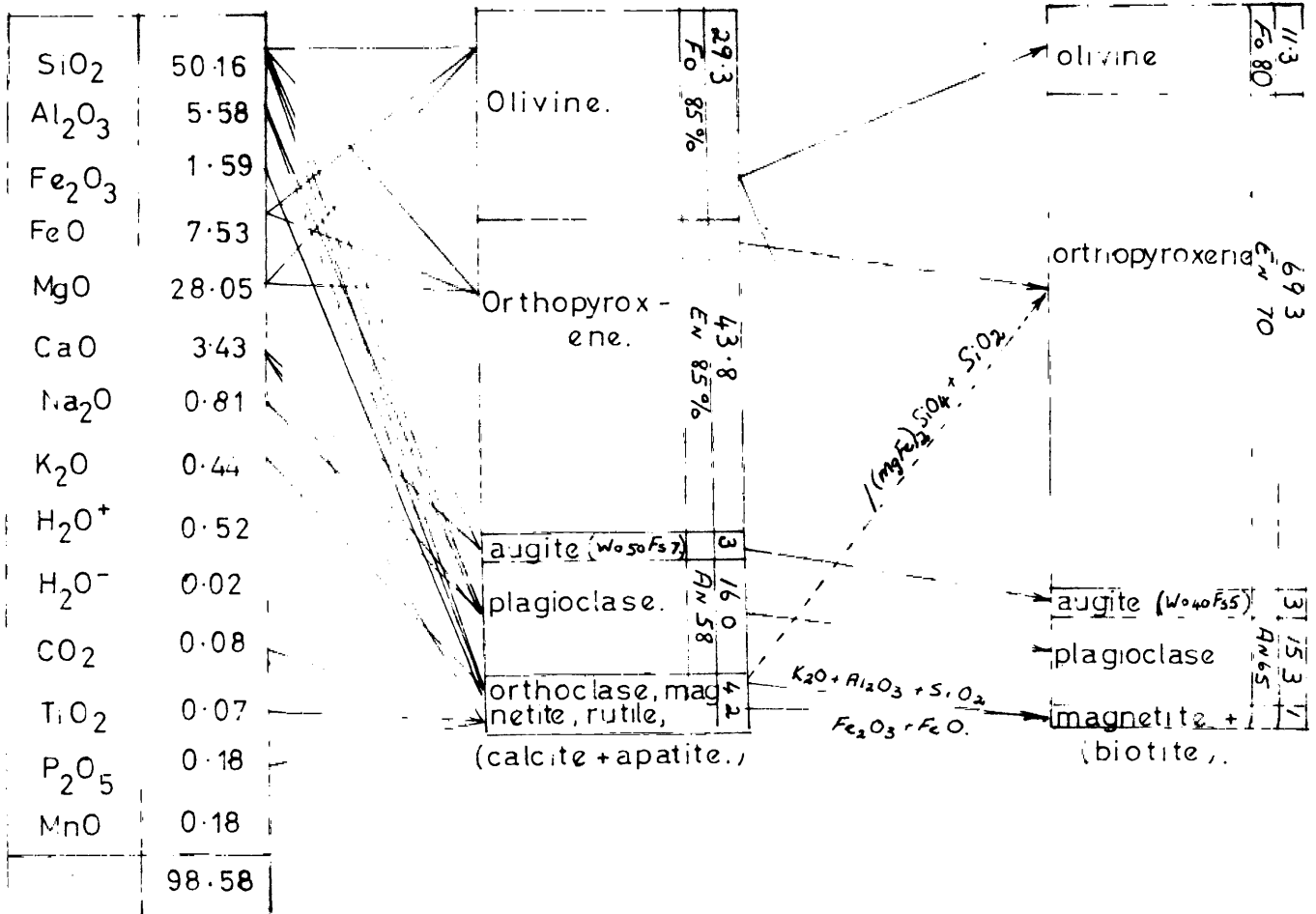
The analyses of the examples of hornblende-bearing diorite (13, 4, 8, 3, 9) all fall within the diorite field, whereas the diabase (No. 10, 11, 12, 16) and the other mafic rocks (No. 5, 1, 7, 15, 6) form a complete differentiation series

TABLE 32 Chemical composition of harzburgite of the differentiated sil. on Goedehoop 78 JT, C.F. 1.

Chemical analysis.

Katamolucular norm

Volumetric composition



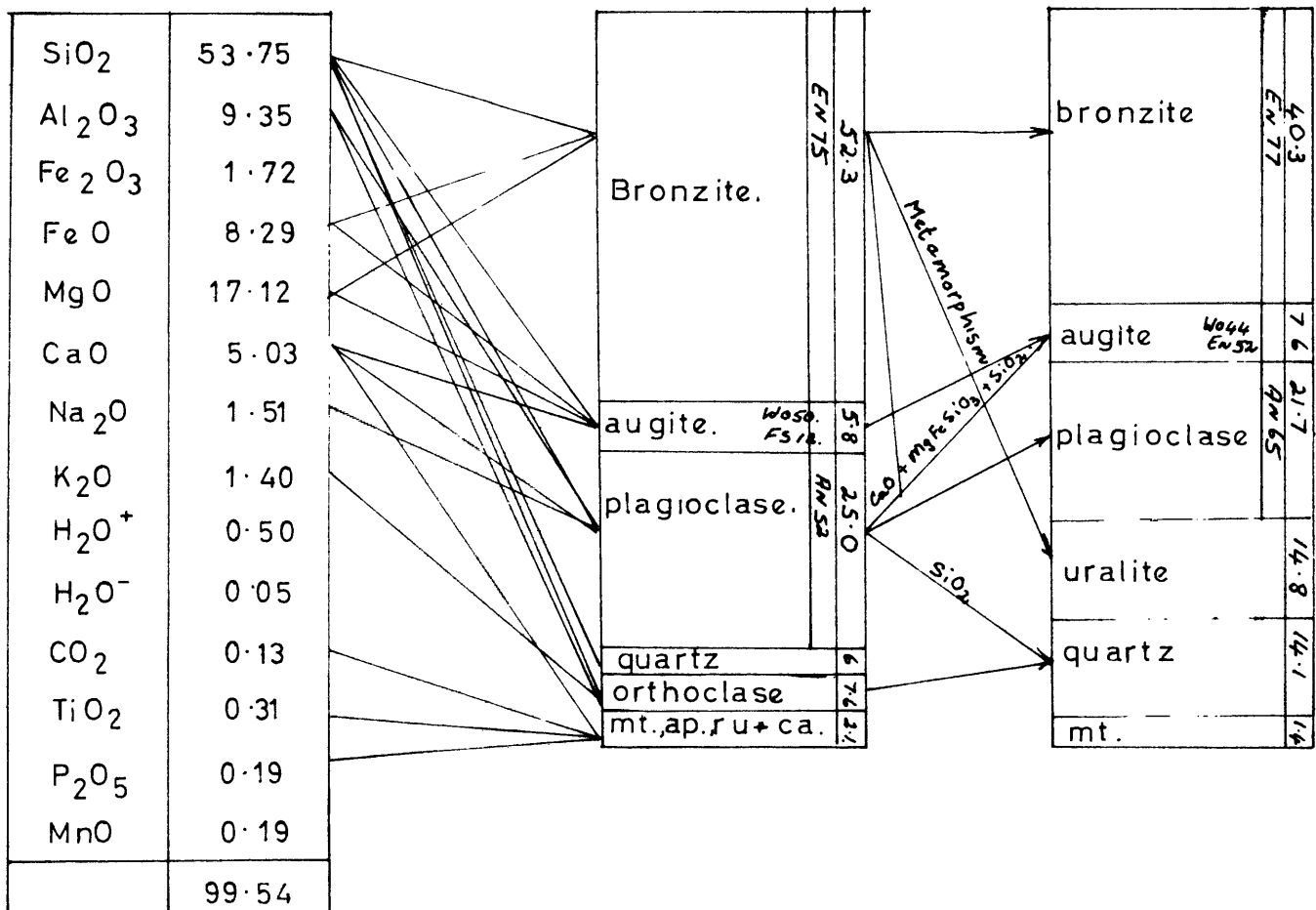
Scale 1mm = 1 %.

TABLE 33. Chemical composition of pyroxenite of a differentiated sill on Kleinzuikerboshkop. 93 JT, CF 2.

Chemical analysis

Katamolucular norm

Volumetric composition



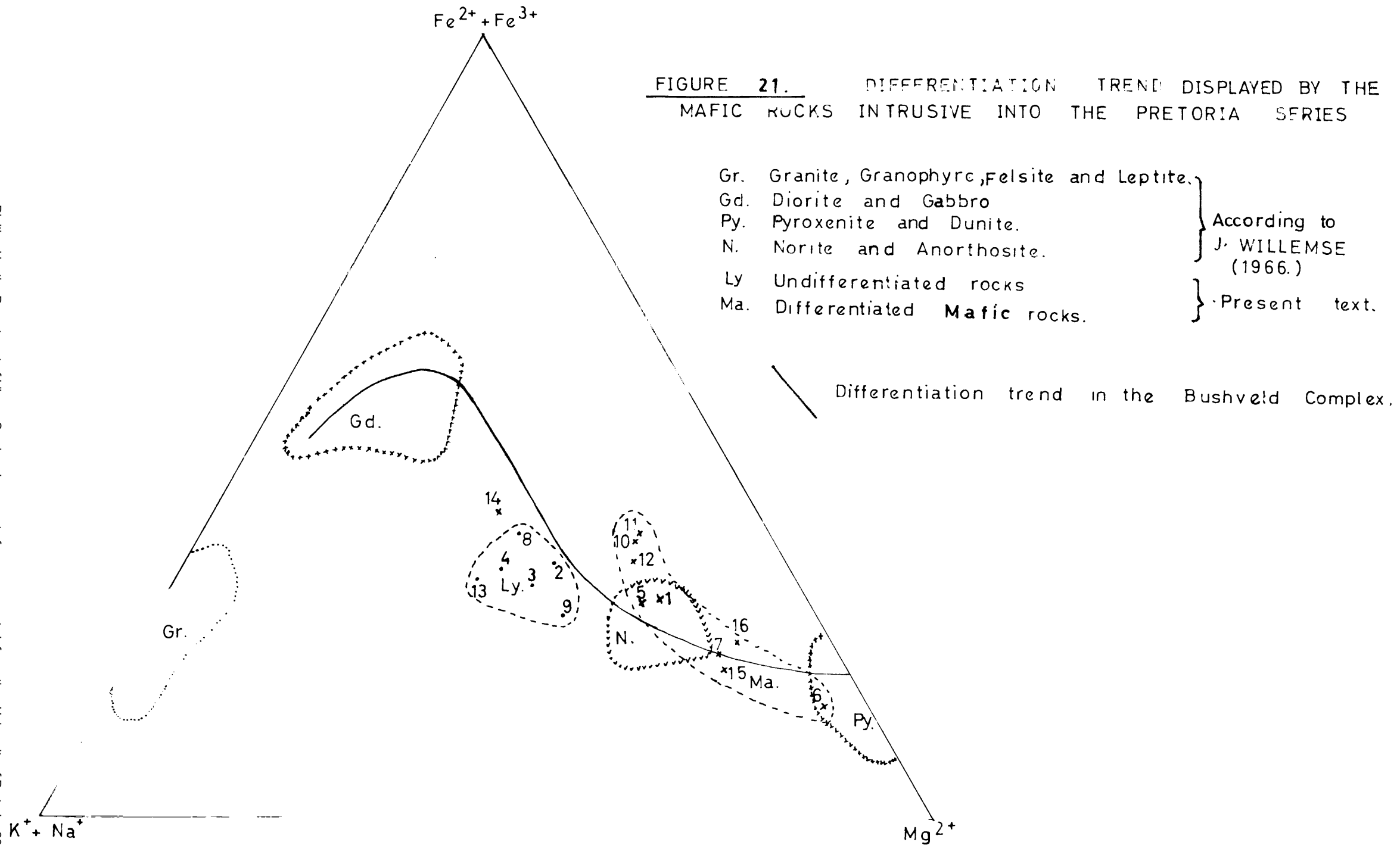
Scale: 1 mm.=1%

Table 34. Rocks from the intrusive sills of which chemical analyses are available

No.	Diabase	Locality	Source
1.	Quartz norite	Schlickmannskloof 12, Lydenburg	J. Willemse (1959, Table 10, No. 1)
2.	Diabase	A bore hole near Penge	J. Willemse (1959, Table 10, No. 2)
3.	Diabase (diorite)	Union Buildings, Pretoria	J. Willemse (1959, Table 10, No. 3)
4.	Diorite	Average composition	T. Barth (1962, pp. 58)
5.	Norite	Average composition	T. Barth (1962, pp. 59)
6.	(haraburgite)	Goedehoop 79-JT, Belfast	C. Frick (New analysis)
7.	(pyroxenite)	Zuikerboschhoek 93-JT, Belfast	C. Frick (New analysis)
8.	Diorite	Houtenbek 97-JT. Belfast	C. Frick (New analysis)
9.	Diabase	Wolwekraal 13-JS, Groblersdal	C.P. Snyman (1958, p. 253)
10.	Diabase - fine-grained	Zwagershoek 82-JT, Lydenburg	B.V. Lombaard (1934, p. 38)
11.	Diabase - fine-grained	Lydenburg	B.V. Lombaard (1934, p. 38)
12.	Diabase	De Kafferskraal 53-JT, Lydenburg	B.V. Lombaard (1934, p. 38)
13.	Granophyric diabase (diorite)	Kraaibosch 55-JT, Lydenburg	B.V. Lombaard (1934, p. 38)
14.	Noritic diabase	Schaapkraal 42-JT, Lydenburg	B.V. Lombaard (1934, p. 34)
15.	Diabase	Wildebeesthoek 310-JR, Pretoria	Nel (1940, p. 45)
16.	Diabase	Wonderboom, Pretoria	Nel. (1940, p. 45)

New names are given in brackets where the names have been changed.

FIGURE 21. DIFFERENTIATION TREND DISPLAYED BY THE
MAFIC ROCKS INTRUSIVE INTO THE PRETORIA SERIES



along the curve of J. Willemse (No. 6, 15, 16, 7, 1, 5, 12, 20, 11). A diabase of a sill near Penge (No. 2) which consists of clinopyroxene and plagioclase falls within the diorite field, which is difficult to explain. The quartz dolerite of the differentiated sills (No. 14) lies still farther along the line of differentiation.

The intrusive rocks in the Pretoria Series can be divided chemically into diorite and differentiated mafic rocks. The latter display a complete differentiation sequence (fig. 21), and alters to urallite-bearing diabase. The variation in the quantitative mineralogical composition and in the composition of the orthopyroxene and the plagioclase also reveals the differentiation in an individual sill (fig. 22 and 23).

A comparison of the chemical composition (table 35) of a number of glassy rocks from which the residual glass was separated, indicates that the glassy dolerite from Schaapkraal contains more magnesium and less sodium, calcium and iron than the tholeiite of Kinkell (Walker, 1935, p.150) and of Kap Daussy (Vincent 1950, p.56). The glassy dolerite from Schaapkraal has also a tholeiitic composition, according to the definition of a tholeiitic magma given by F. Walker (1961, p.3-4).

According to the katamolecular norm the glassy dolerite from Schaapkraal contains also more anorthosite and hypersthene, but much less albite and diopside than the tholeiites of Kinkell and Kap Daussy. As the composition of the glassy dolerite differs noticeably from that of the tholeiites from Kinkell and Kap Daussy the course of differentiation which magmas of these rocks would follow, would also be different. Furthermore the magma of the glassy dolerite had only started to crystallize when it was chilled and contains 55% glass, whereas the tholeiites of Kinkell and Kap Daussy contains $25 \pm 5\%$ glass and its magma obviously had more time to differentiate.

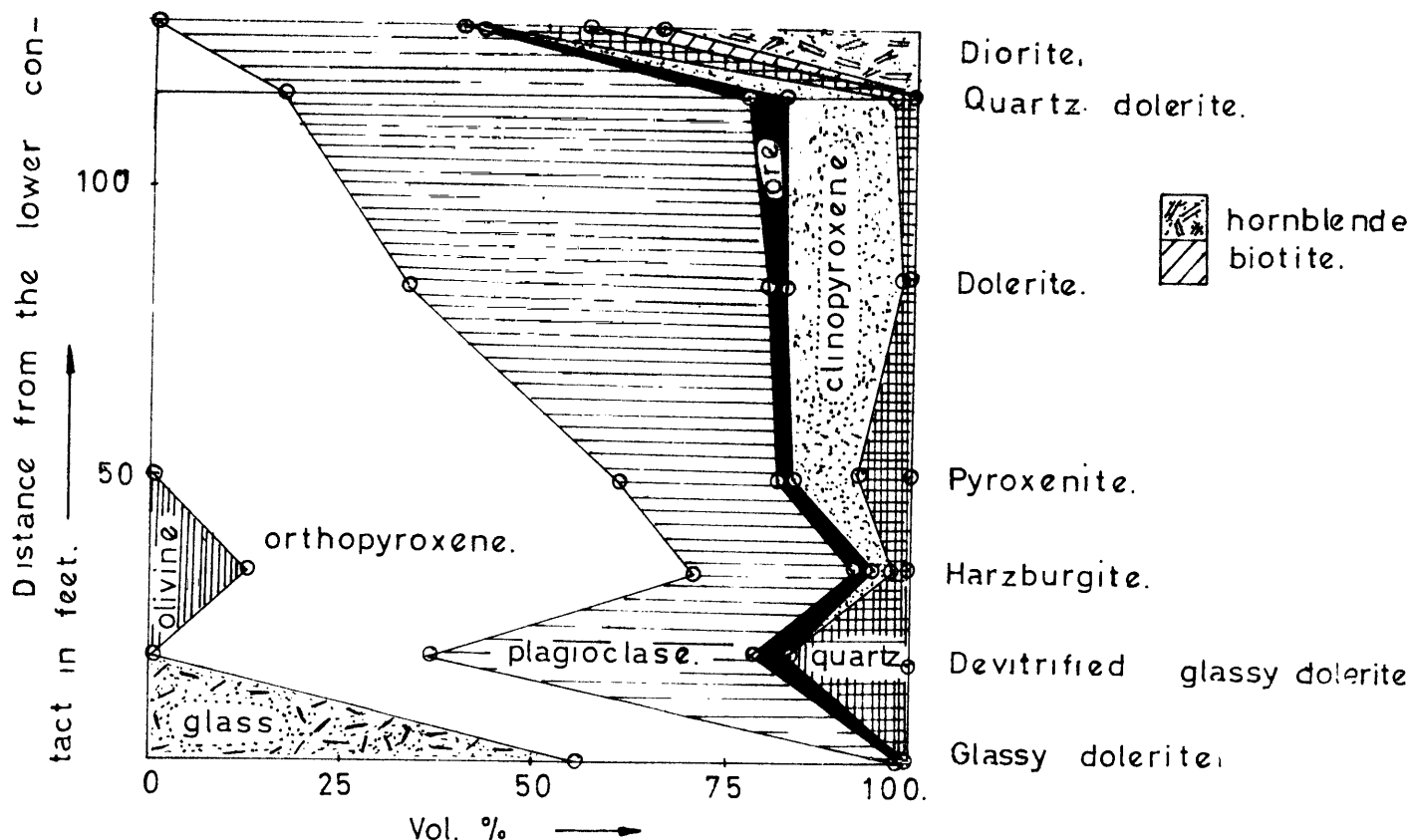


FIGURE 22 VARIATION IN THE VOLUMETRIC COMPOSITION OF THE DIFFERENTIATED MAFIC SILL ON VRISCHGEWAAGD IS HALF GEWONNEN 94 JT, COMPARED WITH THE COMPOSITION OF DIORITE.

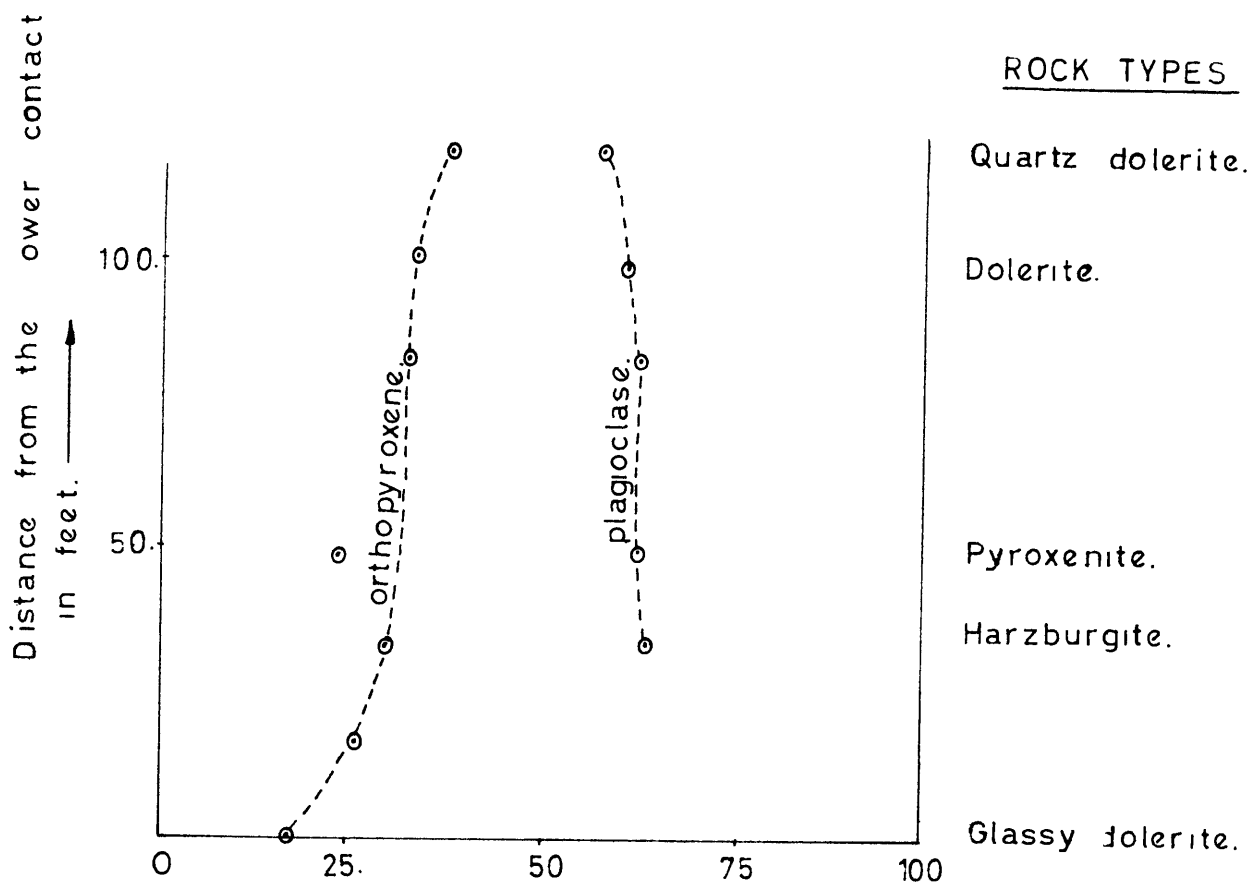


FIGURE 23. FeSiO₃ (mol per cent) IN ORTHOPYROXENE, AND An (per cent) IN PLAGIOCLASE, IN A PROFILE ACROSS A DIFFERENTIATED MAFIC SILL ON VRISCHGEWAAGD IS HALF GEWONNEN 94-JT.

Table 35. The chemical composition of rocks from which glass has been separated

	A	B	C
SiO ₂	47.42	49.10	56.91
Al ₂ O ₃	11.75	12.13	12.68
Fe ₂ O ₃	3.39	4.61	2.51
FeO	12.79	8.92	6.71
MgO	5.35	4.50	9.77
CaO	10.83	8.20	7.14
Na ₂ O	2.36	2.14	1.46
K ₂ O	0.55	2.10	0.62
H ₂ O ⁺	0.95	2.50	0.98
H ₂ O ⁻	0.30	1.02	0.04
TiO ₂	3.98	4.02	0.38
P ₂ O ₅	0.54	0.51	0.09
MnO	0.10	0.15	0.19
Others	-	0.03	0.36
Total	100.31%	99.93%	99.84%

Katamolecular norm

qu.	1.82	7.6	13.3
or	3.22	12.2	3.5
ab	19.96	17.8	13.1
An	19.79	17.5	25.7
diop.	25.19	15.8	6.04
hy.	10.1	6.2	12.4
En.	4.99	3.5	19.3
mt.	4.92	6.7	3.5
ilm.	7.55	7.6	0.2
Ap.	1.28	1.3	0.1
Water.	1.25	3.6	2.0
	100.04%	99.8%	100.14%

Volumetric composition

plagioclase	38.2	28.3	-
augite	31.7	22.4	-
hypersthene	-	7.0	44.8
olivine	3.3	-	-
magnetite	6.5	10.8	0.1
glass	20.3	31.5	55.1
	100.0%	100.0%	100.0%

- A. Tholeiite from Kap Daussy, East Greenland; Vincent (1950, p.56). Analyst: E.A. Vincent
- B. Tholeiite from Kinkell, North Scotland; Walker (1935, p.150) Analyst: F. Herdsman
- C. Glassy dolerite from Schaapkraal 68-JT, Lydenburg district (New analysis) Analyst: National Institute for Mining and Metallurgy.)

The composition of the residual glass from Schaapkraal is tholeiitic and the glasses from Kap Daussy and Kinkell are granitic in composition (table 36). According to the composition of the residual glass from Schaapkraal. it is evident that an increase in calcium and iron and a decrease in magnesium in the residual magma took place during the early stages of crystallization of the glassy dolerite. This decrease in magnesium can easily be explained by the crystallization of enstatite. The glasses from Kinkell and Kap Daussy on the other hand represent a later product of differentiation and during this phase an enrichment of silica, water and alkali takes place in the residual magma. During this late stage of differentiation anorthite-rich plagioclase crystallized and an increase in albite, orthoclase and quartz occurred in the residual magma.

According to Walker and Poldervaart (1949, p.650-665) the normal course of differentiation in a basaltic magma leads to iron enrichment in the early and middle stages and the enrichment of silica and alkalis towards the end stages. According to the chemical analyses of the residual glasses by Walker from Kinkell and Vincent from Kap Daussy the enrichment in alkalis and silica is obvious. The residual glass from the glassy dolerite from Kwaggashoek however indicates an earlier stage of crystallization and is characterized by iron enrichment (fig. 24) in the residual magma.

V. THE LAYERED SEQUENCE OF THE BUSHVELD COMPLEX

The Critical and Main Zones of the Bushveld Complex were studied on Kliprivier 73-JT, and the southern portion of Sterkfontein 52-JT, and De Kafferskraal 53-JT. The contact between the Pretoria Series and the Bushveld Complex received most attention.

Table 36. The chemical composition of residual glass

	1	2	3
SiO ₂	64.03	66.80	58.52
Al ₂ O ₃	11.27	12.10	15.07
Fe ₂ O ₃	2.98	0.97	2.48
FeO	2.81	1.50	5.74
MgO	1.18	0.50	5.99
CaO	5.57	2.62	7.65
Na ₂ O	1.82	2.40	1.89
K ₂ O	1.56	4.20	0.66
H ₂ O ⁺	6.23	5.75	0.99
H ₂ O ⁻	0.73	3.00	0.02
TiO ₂	0.79	0.18	0.41
P ₂ O ₅	0.98	0.39	0.11
MnO	0.05	-	0.14
Others	-	-	0.27
	<u>100.00%</u>	<u>100.41%</u>	<u>99.84%</u>

Katamolecular norm

qu	36.3	30.7	17.4
or	9.2	25.0	3.9
ab	15.4	20.4	16.9
an	17.9	10.0	30.5
diop	2.7	0.3	4.4
hy.	2.2	1.8	9.0
En.	.9	0.7	9.1
mt	4.3	1.4	3.5
ilm.	1.5	0.5	0.6
ap.	2.3	1.0	0.1
calcite	-	-	0.6
water	<u>7.0</u>	<u>8.7</u>	<u>4.1</u>
	<u>99.7%</u>	<u>100.5%</u>	<u>100.1%</u>

1. Residual glass from tholeiite from Kap Daussy.
(Analyst E.A. Vincent) (Vincent 1950, p. 56)
2. Residual glass from tholeiite from Kinkell
(Analyst F. Herdsman) (Walker 1935, p. 150)
3. Residual glass from the glassy dolerite from Schaapkraal.
(New analysis) (Analyst: National Institute for Mining and Metallurgy).

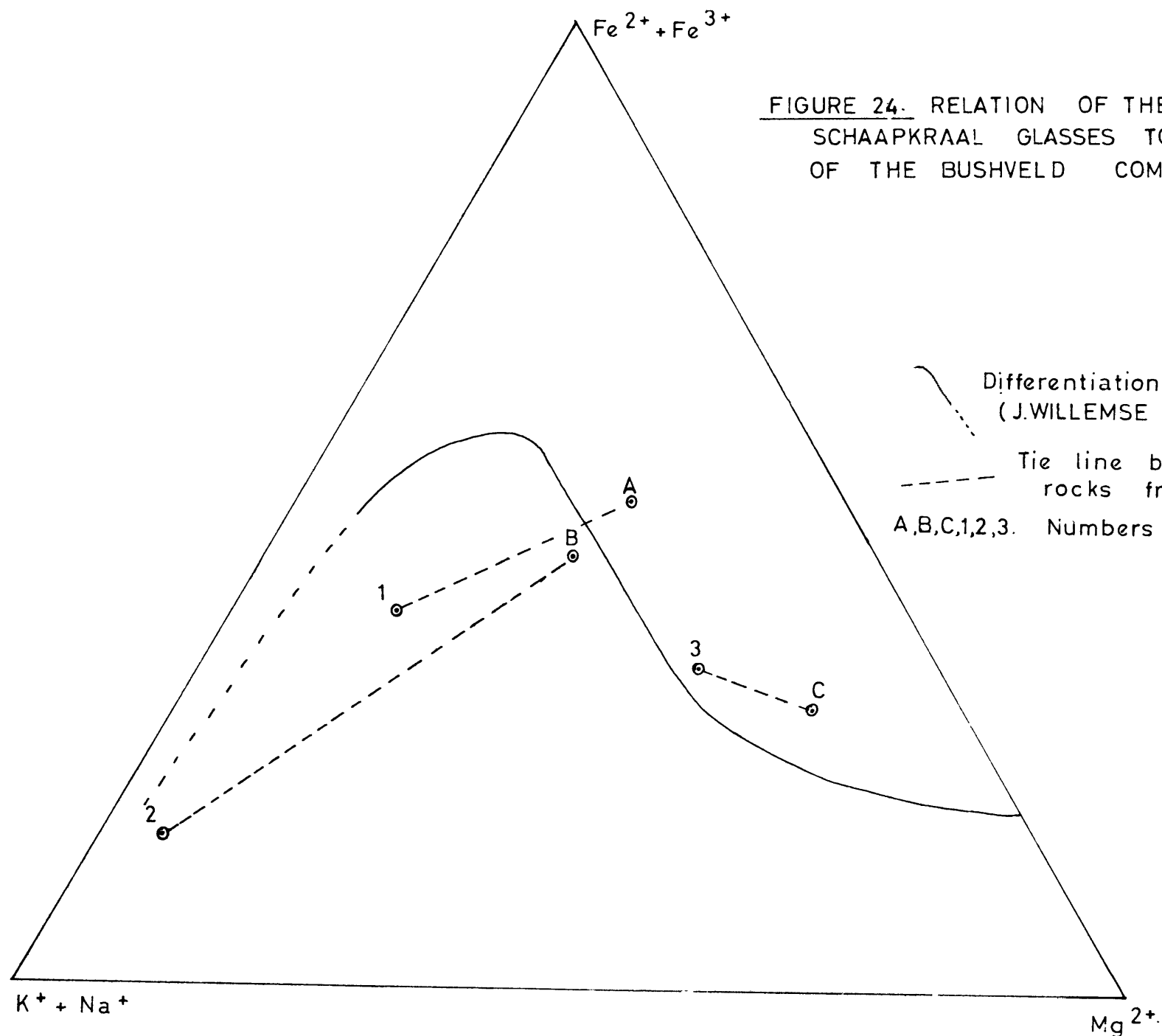


FIGURE 24. RELATION OF THE KAP DAUSSY, KINKELL AND SCHAAPKRAAL GLASSES TO THE DIFFERENTIATION TREND OF THE BUSHVELD COMPLEX.

Differentiation trend of the Bushveld Complex
(J.WILLEMSE 1967.)

Tie line between the glasses and the
rocks from which they were separated.
A,B,C,1,2,3. Numbers of the analyses (text)

The Pretoria Series, which consists essentially of quartzite near the contact, gives rise to the prominent Steenkampberg, $\pm$ 7,200 ft. above sea-level, whereas the norite and anorthosite of the Bushveld Complex forms the adjoining lower-lying areas, $\pm$ 5,400 ft. above sea-level. The main constituents of the Critical Zone in this area are norite, hyperite and anorthosite, but include also subordinate and mottled anorthosite and chromitite seams. The composition of the rocks of the Main Zone does not differ significantly from that of the Critical Zone, except that gabbro and hypersthene gabbro are more plentiful. These igneous rocks weather into rounded koppies, which stand out like islands in a local peneplain.

A. Geological Setting

The zonal classification originally proposed by Wagner and amended by Hall has been followed (table 37). The chromitite seams, which are studied, belong to the upper group of chromitite seams according to the grouping by Cousins (1964, p.174-176). Cameron, 1963, p.97) places them in the "anorthosite zone", which succeeds the "pyroxenite zone" of the Critical Zone.

The chilled norite is confined to a narrow zone, $\pm$ 10 ft. thick, along the margin of the Bushveld Complex. In places it is absent, whereas in other places it is more abundant. Near the Dullstroom-Draaikraal road, on Kliprivier 73-JT an outcrop of chilled norite was found which is completely surrounded by quartzite. This outcrop indicates the transgressive nature of the Bushveld Complex towards the Pretoria Series.

The prominent layering which characterizes the Bushveld Complex is accentuated in the Critical Zone by both the layered norite (photo 36) and the distribution of the chromitite seams. The dips of the chromitite seams are indicated

Table 37. A profile across the Critical and Main Zone of the Layered Sequence

Zone	Rock types	Thickness
MAIN ZONE	Gabbro and norite	± 700 ft.
	Merensky Reef	
CRITICAL ZONE	Norite, anorthosite and spotted and mottled anorthosite	$\pm 1,000$ ft.
	<u>Ug3</u> Chromitite Seam	1-2 ft.
	Norite and anorthosite	
	<u>Ug2</u> Chromitite Seam	1-2 ft.
	Norite and spotted norite	± 400 ft.
	Chilled norite	± 10 ft.

on map 1. It is noteworthy that the average dip of the quartzite exceeds the dip of the chromitite seams, which is $\pm 2^\circ$ West. This strengthens the contention that the Bushveld Complex does not follow the Pretoria Series concordantly.

B. The Chilled Margin of the Bushveld Complex

Most authors refer to the marginal diabase, which represents the sill phase of the emplacement of the Bushveld Complex, as the Chill Zone of the Complex (J. Willemse 1964, p.103). In the area investigated, however, a Chill Zone, which differs from the sill phase of the Bushveld Complex was encountered.

This chilled margin of the main noritic body consists essentially of a fine-grained norite. Apart from this micro-

norite, both quartz norite and quartz micro-norite outcrops along the outer margin of the norite body of the Bushveld Complex,

The micro-norite forms a narrow zone ± 10 ft. wide along the margin of the Bushveld Complex. Excellent outcrops of micro-norite have been found on Kliprivier (CF 70b and CF 55), Sterkfontein (CF 40) and De Kafferskraal (CF 70). It has not been indicated separately on map 1.

The quartz norite occurs only at one locality in the area mapped and that is on De Kafferskraal (CF 24). One good exposure is ± 10 yards away from the contact between the quartzite of the Pretoria Series and the Bushveld Complex. The quartz norite does not form a continuous zone in the layered sequence, but is only developed locally and is characterized by many quartzite inclusions.

A quartz micro-norite replaces the micro-norite rim along the margin of the Bushveld Complex where the rocks of the Complex overlies hornfels and Dullstroom lava. Excellent outcrops are available on Klipbankspruit (CF 78).

1. Micro-norite

The micro-norite can easily be distinguished from the quartz norite, since the latter contains quartz and hornblende, which is absent in the former.

The micro-norite resembles hornfels in hand-specimen and is usually a dark rock, which contains inclusions of coarse-grained norite (CF 70b). The former usually weathers into rounded, brown boulders which have fractures filled with quartz and amphibole (CF 55).

According to the volumetric composition and the mineralogy, there is a remarkable correspondence between the micro-norite from the chilled margin of the Main Zone and that from the Critical Zone. The mineralogy of the micro-norite, however, differs from that of the norite of the layered sequence of the

Table 38. Petrographical data on micro-norite of the chilled margin of the Bushveld Complex

Specimens and localities	CF 28 Klipbankspruit 76-JT. (Main Zone) CF 55 Kliprivier 73-JT. (Main Zone) CF 56 Kliprivier 73-JT. (Main Zone) CF 70b Kliprivier 73-JT. (Critical Zone)			
	Form of the grains	Optical properties	Composition	Remarks
Plagioclase	Xenomorphic and intergranular 0.05 to 0.5 mm. long	$2V_{\beta} = 78^{\circ} \pm 2^{\circ}(\text{rim})$ $2V_{\beta} = 86^{\circ} \pm 1^{\circ}(\text{core})$ zonary	An 54% An 68% (Determined on federof)	Mutually parallel (CF 28)
Clinopyroxene	Subhedral 0.06 mm to 0.25 mm long	$2V_{\beta} = 56^{\circ}$ $\beta \wedge \gamma = 43^{\circ}$ $N_{\beta} = 1.674$ $N_{\gamma} = 1.680$ $N_{\alpha} = 1.670-1.674$	Augite Wo46 En47 Fs7	-
Orthopyroxene	Idiomorphic to subhedral length range from 0.06 to 0.4 mm.	$2V_{\alpha} = 64^{\circ} \pm 1^{\circ}$ $\beta \wedge \gamma = 0^{\circ}$	Bronzite En72 Fs28	1. Contains exsolution lamellae of augite. 2. Encloses plagioclase grains. (CF 55)
Quartz	Xenomorphic	-	-	-
Magnetite	Subhedral to xenomorphic		-	-
Texture	Equigranular Ophitic inclusions of plagioclase in Orthopyroxene. Radiating			

Bushveld Complex (tables 38 and 42). The opaque minerals of the micro-norite are similar to those observed in the norite of the layered sequence, except that pyrite is present in the micro-norite, (table 39) and not in the norite.

A fine-grained equigranular texture. and a radial orientation of the plagioclase, the pyroxene and the magnetite

Table 39. Ore minerals of the micro-norite of the chilled margin
of the Bushveld Complex

Specimens	CF 55A, 56A, 70 A.b.		
	Shape of grains	Texture	Remarks
Magnetite	Idiomorphic to xenomorphic	1. Disseminated through the rock. 2. Contains exsolution lamellae of ilmenite // (111).	1. Inclusions of magnetite in plagioclase and pyroxene occurs. 2. Magnetite is also inter-granular (CF 55)
Ilmenite	Rounded	-	Occurs as lamellae in magnetite (CF 55)
Pyrite	Xenomorphic to intergranular	-	-

grains are prominent features of the micro-norite

The latter texture resembles a recrystallized spherulite (CF28).

2. Quartz norite

Quartz norite outcrops along the outer margin of the layered sequence of the Bushveld Complex, on De Kafferskraal (CF 24), $\pm$ 10 yards from the actual contact. This rock resembles the norite of the Critical Zone in hand-specimen, except that quartz and hornblende are abundant in the quartz norite, and not in the other norite. Both mineralogically and petrographically the quartz norite (hybrid norite) differs from the micro-norite.

Table 40. The petrography of the micro-norite inclusions in the Main Zone of the Bushveld Complex

Specimens and localities	CF 60 Klipbankspruit 76-JT. CF 59 Klipbankspruit 76-JT.				
	Shape of grain	Optical properties	Compo- sition	Vol %	Remarks
Plagioclase	Idiomorphic 0.25 mm. to 1.5 mm.	$2V_{\gamma} = 80^{\circ}$	An 60%	65.9	Displays a parallel ori- entation of grains.(CF 60)
Orthopyroxene	Xenomorphic and idiomorphic 0.05 to 1.0 mm.	$2V_{\alpha} = 72^{\circ} \pm 2^{\circ}$ $\gamma_{AC} = 0^{\circ}$	Branzite En75 Fs25	16.1	-
Clinopyroxene	Xenomorphic and idiomorphic 0.05 to 1.0 mm.	$2V_{\gamma} = 56^{\circ}$ $\gamma_{AC} = 35^{\circ} \pm 1^{\circ}$	Augite	13.9	-
Opaque minerals	Xenomorphic	-	-	3.1	-
Biotite	Xenomorphic	-	-	0.7	-
Texture	Equigranular. Fine-grained. Alternating layers of plagioclase and pyroxene is present.				

The mineralogy of the quartz norite, however, corresponds approximately to that of the Hendriksplaats norite (J. Willemse 1959, p.xl), the hybrid marginal norite (J.S.I. Schwellnus 1956, p.89) and to the rocks on the contact of the differentiated mafic sills which have assimilated sedimentary material.

In places on De Kafferskraal large inclusions of quart-

zite are present both in the quartz norite and in the norite of the Layered Sequence of the Bushveld Complex (photo 40). This assimilation of sedimentary material probably caused the hornblende and quartz to crystallize in the quartz norite, in addition to plagioclase, pyroxene, magnetite and ilmenite.

3. The Quartz micro-norite

On Houtenbek 97-JT and Klipbankspruit 76-JT, the chilled margin of the Layered Sequence of the Bushveld Complex succeeds hornfels and Dullstroom lava, and not quartzite. At these localities the hornfels, the lava and the micro-norite are hybridized. These hybrid rocks are designated quartz micro-norite.

There is a close correspondence between this quartz micro-norite and a hybrid rock from the vicinity of Hartbeespoortdam described by H.J. Nel (1940, p.57). He called it a magmatic diabase. He also mentions the presence of cordierite, which is lacking in the quartz micro-norite.

Subhedral quartz, which contains liquid inclusions is a prominent constituent of the quartz micro-norite. Plagioclase, altered to sericite, and orthopyroxene are the major constituents. The orthopyroxene gives rise usually to short euhedral grains. Biotite is also present, which contains inclusions of zircon surrounded by pleochroic halos. In addition there are intergranular grains of muscovite, chlorite and magnetite in the quartz micro-norite.

C. Inclusions in the Layered Rocks

The inclusions in the gabbroic rocks in the area mapped consist either of micro-norite similar to that described by Wells (1951, p.729) from the Ardnamurchan intrusion in Argyllshire, or of quartzite. The quartzite inclusions can be referred to the quartzite margin of the Bushveld Complex, whereas the origin of the micro-norite is uncertain.

The mineralogy and petrography of the quartzite inclusions, which were found in the norite of the Critical Zone, about 10 to 50 ft. above the chilled margin on De Kafferskraal 53-JT., correspond to that of the Steenkampsberg quartzite. These inclusions range in diameter from 1 to 10 feet and they show very little orientation.

The micro-norite inclusions correspond in mineralogy and volumetric composition to the micro-norite of the chilled margin of the Bushveld Complex, but differ from that of the Dullstroom lava (table 40).

These inclusions of micro-norite could represent fragments of sedimentary material or of Dullstroom lava, or of disrupted micro-norite of the Chill Zone, which became engulfed in the layered body of the Bushveld Complex. The latter mode of origin is favoured, because:-

1. The mineralogy of the inclusions corresponds to that of the micro-norite and differs from that of the Dullstroom lava. The composition of the plagioclase in the micro-norite is An_{60} , whereas in the Dullstroom lava it is An_{40} to An_{50} . The orthopyroxene in the former is bronzite (En_{75}), and in the latter it is hypersthene (En_{46}). Had these inclusions been sedimentary material, they must have had a special chemical composition to form this mineral assemblage.

2. The texture of the inclusions resembles that of the micro-norite and of the metamorphosed Dullstroom lava, except that amygdales are absent.

3. The chemical analyses of the chilled norite occupy a completely different position on an A.C.F. diagram for rocks with excess SiO_2 of the pyroxene hornfels facies from those of the Dullstroom lava, indicating a difference in the original chemical composition (fig. 16).

D. The Layered Rocks of the Bushveld Complex

1. Introduction

A. Hall (1932, p.299) defined norite as a rock consisting of "plagioclase (labradorite) and pyroxene, the latter dominantly or exclusively rhombic". Esmark (Lombaard, 1934) gave a more exact definition, according to which norite consists of plagioclase (An 50-70%) and $\pm$ 40% bronzite.

According to Schwellnus (1956, p.114) the rocks of the Main and Critical Zones fall within two groups, those containing plagioclase and orthopyroxene (norite) and those consisting of clinopyroxene and plagioclase (gabbro). Depending on the percentage rhombic pyroxene, in the total amount of pyroxene, the following classification has been used:-

Norite	100-75% of orthopyroxene
Hyperite	75-50% " "
Hypersthene gabbro	50-25% of orthopyroxene
Gabbro	25-0% of orthopyroxene

A.L. Hall (1932, p.299) applied the designations spotted and mottled norite to norite which contains single grains or clusters of ~~rhombic~~ pyroxene respectively. A rock composed wholly or nearly wholly of plagioclase (labradorite) is an anorthosite. In this thesis these definitions by Hall have been followed. A zone of rounded inclusions, $\pm$ 2 to 3 inches in diameter, which consists essentially of orthopyroxene, has been called the Tennis-ball marker after G. von Gruenewaldt (1966) who described a similar zone from the area east of the Moos River fragment.

2. Distribution

The rocks of the layered body of the Bushveld Complex which were mapped belong to the upper part of the Critical Zone and the lower part of the Main Zone. To the south the whole Critical Zone is eliminated. Consequently the Main Zone succeeds the Dullstroom volcanics, whereas in the north the Critical Zone adjoins the middle portion of the Steenkampsberg quartzite.

In the present area the layered body of the Bushveld Complex has been mapped on Klipbankspruit 67-JT, Kliprivier 73-JT, the southern portions of Sheeprun 53-JT, Buttons Hope 51-JT, De Kafferskraal 53-JT and Sterkfontein 52-JT. In this area norite forms the base of the succession in the Bushveld Complex and contains two chromitite seams. The lowest seam (Ug_2) is $\pm$ 10 ft. to 400 ft. above the contact with the Steenkampsberg quartzite. About 20 ft. below this chromitite seam on De Kafferskraal a spotted norite is developed, but it could not be followed for a long distance owing to poor outcrops. About 500 ft. above the Merensky Reef an exposure of mottled norite was mapped. It could also not be traced for a long distance, owing to poor outcrops. About 500 ft. above this horizon the tennis-ball marker is exposed. The outcrop of the tennis-ball marker is extremely poor, and the author failed to locate it on a second visit.

3. Petrography

According to the volumetric composition of the rocks of the different zones, it is evident that the Critical Zone consists essentially of norite, whereas the Main Zone consists of hyperite (table 41). The variation diagram of the mineralogical composition along a profile xy' across the Bushveld Complex however indicates a decrease in clinopyroxene and an increase in orthopyroxene (fig. 26) *in an upward direction*. The variation diagram of the mineralogical composition along a profile xy' from the chilled margin into the layered series indicates that quartz and plagioclase reach their maximum, whereas pyroxene reaches its minimum (fig. 25) at a distance of 2,5000 ft. from the contact.

The mineralogy of the different rock types in the Layered Sequence (table 42) and the composition of the plagioclase and the pyroxene in a profile across the Bushveld Complex does not vary much (fig. 27).

Table 41. The volumetric composition of the rocks of the different zones in the area mapped

Samples	Micro-norite of the chilled margin	Inclusion of hyperite in the Main Zone	Hypersthene gabbro near base of Critical Zone	Chromitite Seam Ug ₂	Average norite of the Critical Zone	Average hyperite of the Main Zone	Mottled hyperite	Tennis ball marker (hyperite)
	CF 56 + 55	CF 60	CF 61 + 63	CF 51	CF 65 + 57	CF67+68	CF64+66	CF 69
Localities	Kliprivier 73-JT	Klipbankspruit 76-JT	De Kafferskraal 53-JT	De Kafferskraal 53-JT	Sterkfontein and De Kafferskraal	Kliprivier 73-JT	Kliprivier 73-JT	Houtenbek 97-JT
Plagioclase	56.7	66.0	61.1	36.0	65.0	60.3	68.6	30.2
Orthopyroxene	31.1	16.2	11.3	19.	23.5	22.9	17.2	28.8
Clinopyroxene	11.6	14.0	25.6	-	6.8	14.4	9.9	13.5
Biotite	-	0.8	-	-	1.2	0.1	0.2	10.7
Opaque minerals	0.8	3.2	0.1	45.0	0.9	0.4	0.3	2.3
Quartz	-	-	2.1	-	2.7	1.8	3.7	14.4
Total	100.2%	99.9%	100.2%	100.0%	100.1%	99.9%	99.9%	99.9%

Table 42. Mineralogical and petrographical data on various gabbroic rocks of the Layered Sequence

Horizon	Chilled Main Zone Kliprivier 73-JT	Critical Zone near the contact of the Bushveld Complex	Critical Zone	Main Zone	Mottled hyperite 400' above the Merensky Reef	Tennis ball marker +700' above the Merensky Reef	Porphyritic norite +100' above the contact of the Bushveld Complex
Rock type	Hyperite	Hypersthene gabbro	Norite	Hyperite	Hyperite	Hyperite	Norite
Thin sections	CF 55, 56, 57	CF 61, 63	CF 65	CF 67, 68	CF 64, 66	CF 69	CF 62
Composition	An 60-70%	An 68-78%	An 67%	An 68%	An 64-68%	An 67-74%	An 56-70%
Form of grains	Idiomorphic to xenomorphic	Idiomorphic	Idiomorphic	Idiomorphic	Idiomorphic	Xenomorphic	Idiomorphic
Remarks	Mutually parallel	Cumulus crystals and inclusions	Cumulus crystals and inclusions	Cumulus crystals and inclusions	Inclusions in clinopyroxene	Intergranular	Inclusions in orthopyroxene
Optical properties	$2V_{\alpha} = 49^{\circ}-54^{\circ}$	$2V_{\alpha} = 66^{\circ}$	$2V_{\alpha} = 70^{\circ}$	$2V_{\alpha} = 65^{\circ}$	$2V_{\alpha} = 70^{\circ}$	$2V_{\alpha} = 62^{\circ}$	$2V_{\alpha} = 56^{\circ}$
Composition	Hypersthene Fs 44%	Bronzite Fs 27%	Bronzite Fs 25%	Bronzite Fs 28%	Bronzite Fs 25%	Hypersthene	Hypersthene
Remarks	Idiomorphic to xenomorphic	Altered to hornblende	Intercumulus. Has inclusions of plagioclase	Intercumulus. Has inclusions of plagioclase	Coronophitic inclusions in clinopyroxene	Idiomorphic to xenomorphic	Large grains with small plagioclase inclusions.
Optical properties	$2V_{\alpha} = 55^{\circ}+1^{\circ}$ $\gamma \wedge C = 43^{\circ}$	$2V_{\alpha} = 56^{\circ}$ $\gamma \wedge C = 41^{\circ}$	$2V_{\alpha} = 54^{\circ}$ $\gamma \wedge C = 41^{\circ}$	$2V_{\alpha} = 48^{\circ}$ $\gamma \wedge C = 40^{\circ}$	$2V_{\alpha} = 50^{\circ}-56^{\circ}$ $\gamma \wedge C = 41^{\circ}$	$\gamma \wedge C = 36^{\circ}$	$2V_{\alpha} = 54^{\circ}+3^{\circ}$ $\gamma \wedge C = 42^{\circ}$
Composition	Augite	Augite	Augite (diallage)	Augite (diallage)	Augite	Augite (diallage)	Augite
Remarks	Granular	Altered to hornblende	Intergranular, forms around orthopyroxene	Intergranular, forms around orthopyroxene	Intergranular, forms around orthopyroxene	Intergranular forms around orthopyroxene	Very rare
Accessories	Biotite and opaque minerals	Biotite + quartz + opaque minerals	Quartz + opaque minerals	Quartz + opaque minerals	Quartz + opaque minerals	Quartz + opaque minerals	Quartz + opaque minerals
Texture	Equigranular	Ophitic	Ophitic	Ophitic	Ophitic	-	Ophitic
Type of cumulate	-	Plagioclase orthocumulate	Plagioclase orthocumulate	Plagioclase orthocumulate	Plagioclase adcumulate	?	Plagioclase and orthopyroxene heteradcumulate

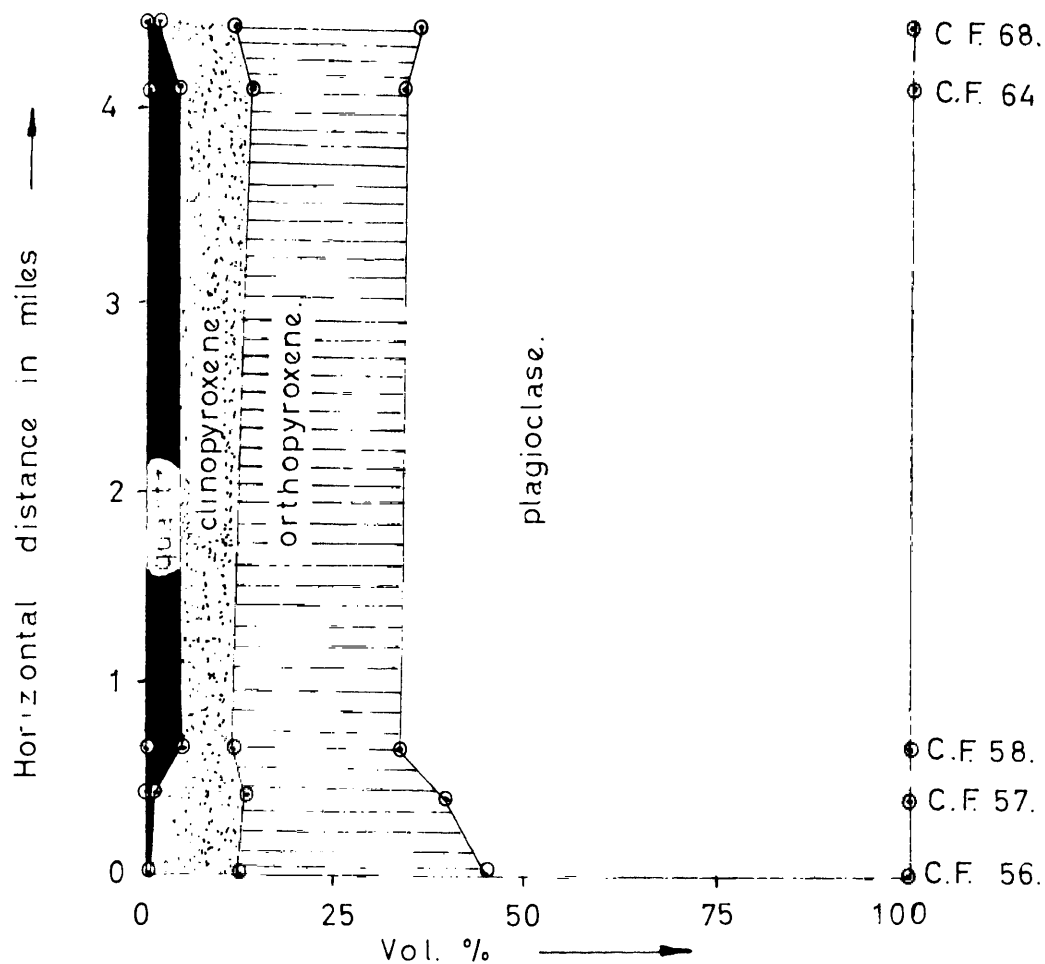


FIGURE 25. Variation in mineralogical composition along XY' on map 1

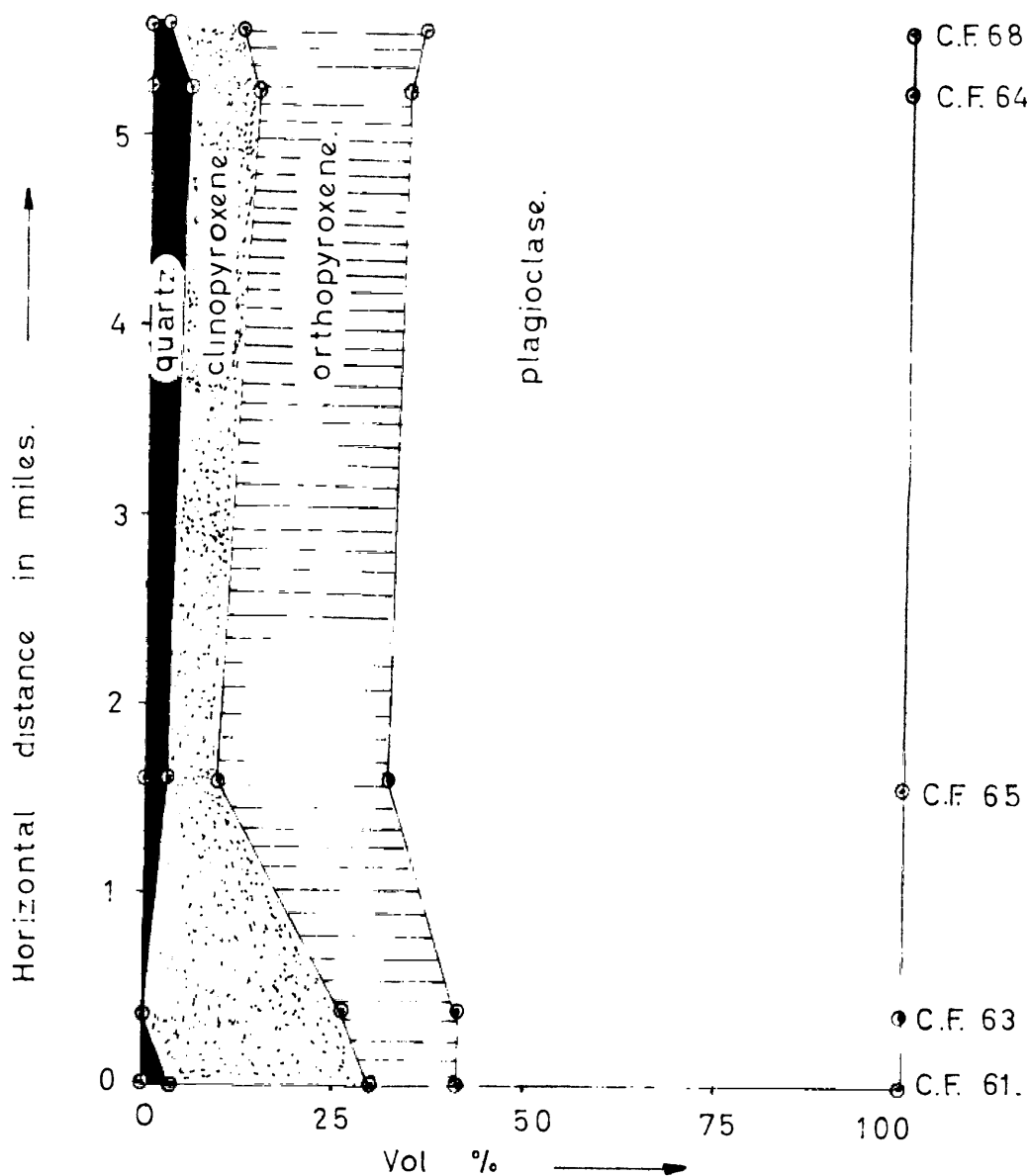


FIGURE 26. Variation in mineralogical composition along YI' on map 1.

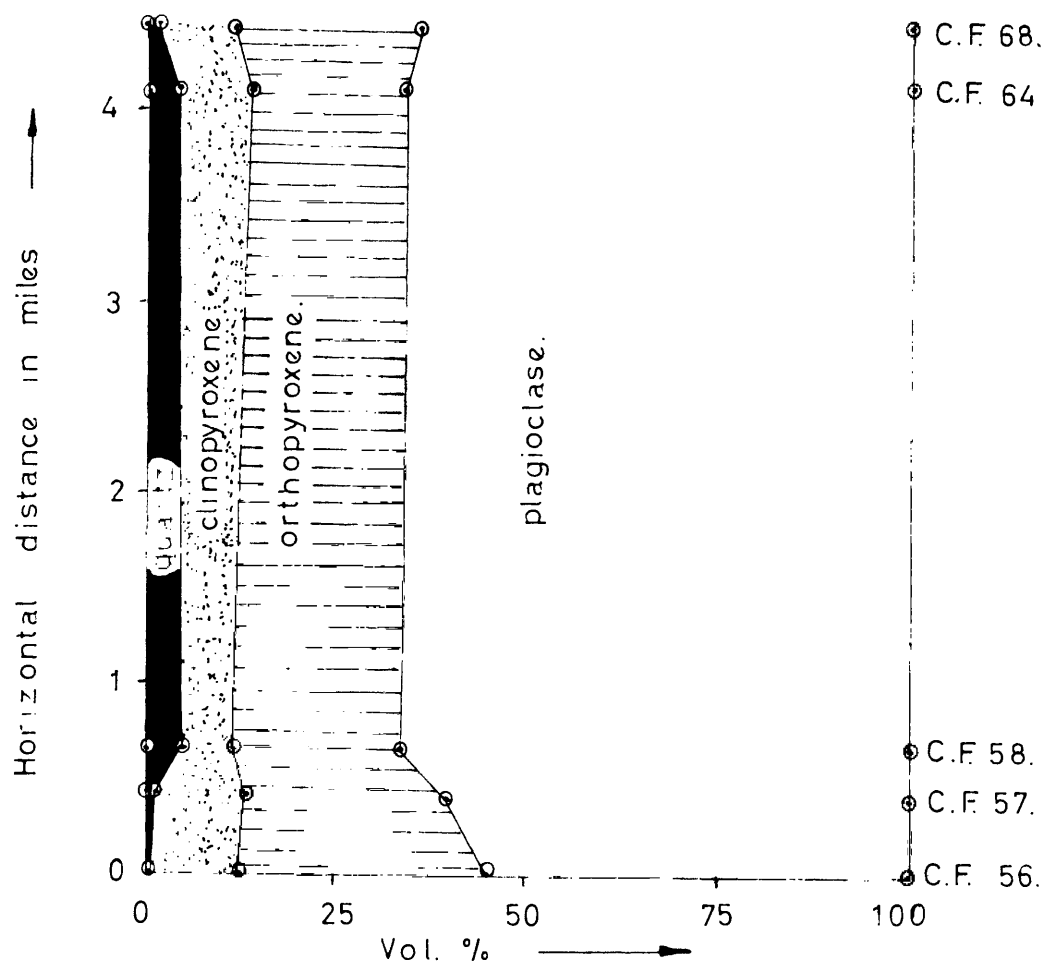


FIGURE 25. Variation in mineralogical composition along XY' on map 1

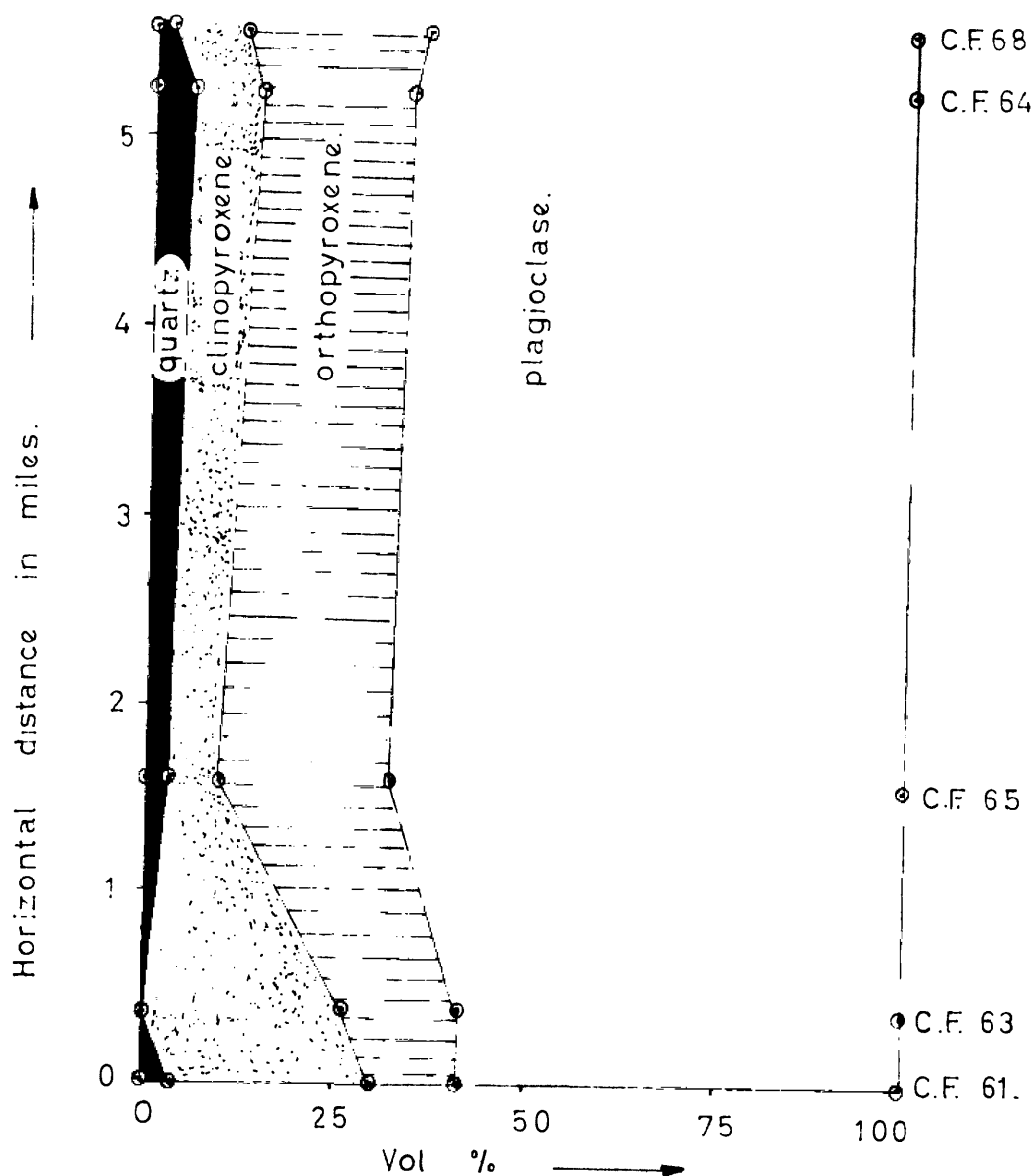


FIGURE 26. Variation in mineralogical composition along XY' on map 1

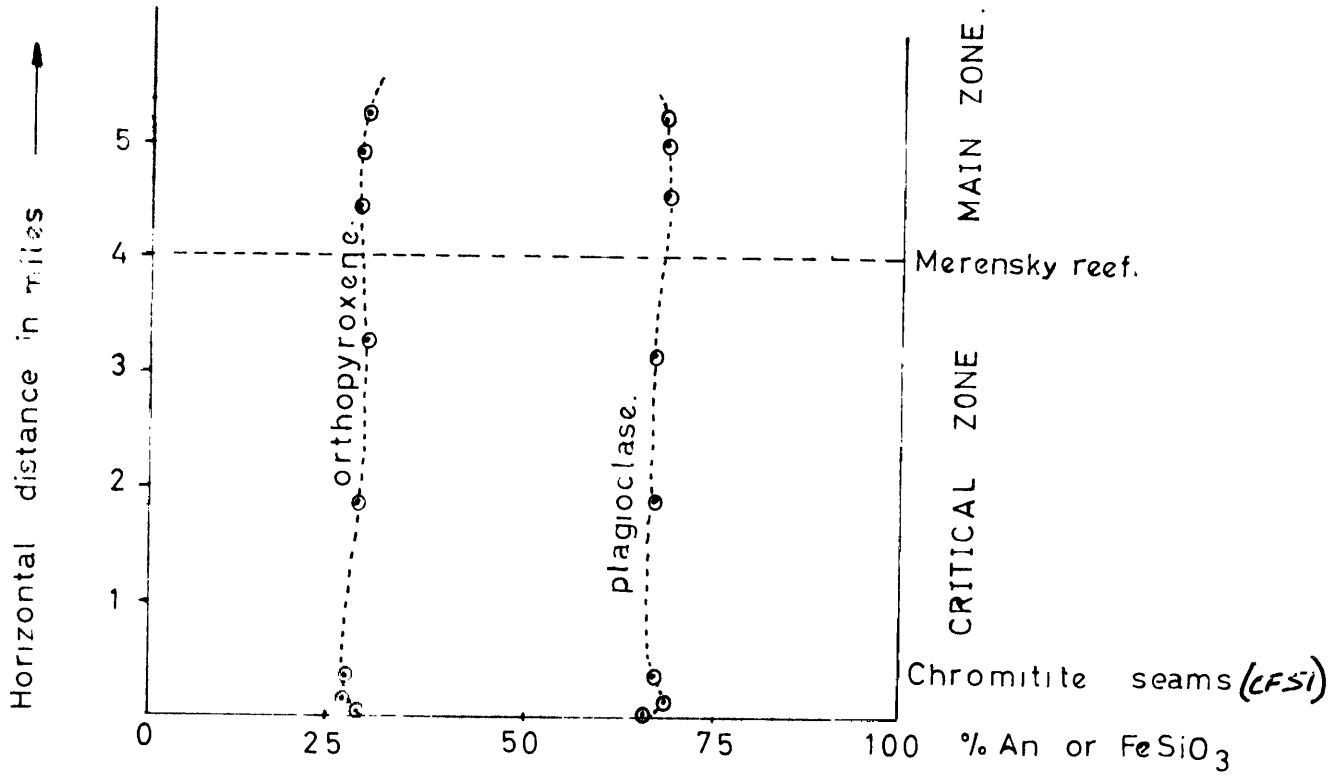


FIGURE 27 FeSiO_3 (mol per cent) in orthopyroxene and An (per cent), in plagioclase of the rocks in a profile YY' across the Main and Critical zones of the Bushveld Complex (map 1)

Table 43. The ore minerals in the hyperite of the upper
Critical Zone and the Main Zone

Specimens	CF 65A, 68A		
Minerals	Crystal form	Textures	Remarks
Magnetite	1. Idiomorphic inclusions in pyroxene and plagioclase. 2. Intergranular xenomorphic grains.	1. Exsolution lamellae of ilmenite // (111) (photo 38). 2. Schiller exsolutions in orthopyroxene (photo 37).	Alters to goethite
Ilmenite	Idiomorphic and xenomorphic	1. Contains filmy exsolution-bodies of hematite (photo 41). 2. Exsolution in magnetite.	More abundant than magnetite.
Pyrite	Xenomorphic and intergranular	Inclusions in pyroxene and intergranular.	-

In the norite and hyperite, the plagioclase crystallized either before or simultaneously with the orthopyroxene. The simultaneous crystallization of plagioclase and orthopyroxene is suggested by their irregular boundaries, whereas the ophitic texture indicates that plagioclase crystallized first.

The coronophitic texture described by Wells (1952, p.919) from the Bushveld norite has been encountered (photo 42) and consists of large clinopyroxene grains which contain several orthopyroxene grains and lath-shaped plagioclase. The relicts of orthopyroxene have the same optical orientation

Wells (1952, p. 919) ascribes this texture to the transfusion of Al^{3+} , Fe^{2+} , Ca^{2+} and Mg^{2+} ions to and from the intercumulus liquid. The orthopyroxene was replaced by the augite, which formed during the transfusion of the ions.

The norite and hyperite investigated are plagioclase orthocumulates in terms of the nomenclature of Wager et al. (1960, p.74). The anorthosite represents an adcumulate (table 42).

Both magnetite and ilmenite are present in the rocks of the Critical and the Main Zone (table 43). Since the magnetite and the ilmenite are both idiomorphic and intergranular, it is concluded that they crystallized before the plagioclase and pyroxene, and also afterwards.

4. Textural features of the layered rocks

(a) The tennis-ball marker

This marker consists of spheroids of pyroxenite (CF 60) scattered through the hyperite. The pyroxenite contains 42.2% pyroxene and 14.4% quartz, against 36.0% pyroxene and 1.8% quartz in the adjoining hyperite. The composition of the minerals in the pyroxenite spheroids compares favourably with that of the hyperite of the Main Zone (table 42). These spheroids may represent inclusions of a lower pyroxenite layer, but the 14.4% quartz is then unexplained.

(b) Porphyritic norite

Large grains of orthopyroxene are usually scattered at random through the hyperite, and contain idiomorphic plagioclase grains (An_{56-60}). A rim of coarse-grained plagioclase ($\text{An}_{65-70\%}$) has developed around the orthopyroxene in a similar way to that described by Heckroodt from Driekop (photo 43). The difference in the composition of the plagioclase indicates that the orthopyroxene and the enclosed plagioclase oikocrysts were formed in an albite-richer environment than the one in which they settled.

C. Mottled Anorthosite

Large grains of clinopyroxene, which contain ophitic inclusions of plagioclase and resorbed grains of orthopyroxene, form the mottled texture in the anorthosite. The clinopyroxene is coronophitic in these examples (photo 42).

The composition of the enclosed plagioclase corresponds to that of the rest of the rock (table 41). These grains therefore evidently formed in the same environment in which they settled.

E. The Chromitite Seams

Two chromitite seams outcrop on Sterkfontein 52-JT and De Kafferskraal 53-JT. G. Trevor (P. Wagner 1923, p.225) also mentions a chromitite seam on Kliprivier 1314, and farther to the west. The present author has traversed this farm on several occasions, but failed to locate the seam.

The lowest chromitite seam (Ug₂) could be followed until it was $\pm$ 10 ft. from the contact of the quartzite. However, here it is no longer continuous and its position is only revealed by angular inclusions of chromitite in the norite. These inclusions range from 4 inches to 1 foot in diameter. No chromite has been found in the chilled margin of the Critical Zone. Another chromitite seam (Ug₃) according to the classification of Cousins (1964, p.174-176) is $\pm$ 100 ft. above seam Ug₂, and could be followed readily in the area mapped.

Since the outcrops are poor, the dips could not always be determined accurately. The double outcrop of both chromitite seams, indicated on map 2, could be due either to a synclinal structure, or to the low dip of the chromitite seams in conjunction with the topography.

The chromitite seams, which consist essentially of labradorite, bronzite and chromite, form lenticular layers in the Critical Zone (photo 45). These lenticular layers are

seldom continuous over long distances, since they branch and join together frequently, but the chromitite seams which are built up of several of these lenticular layers are continuous over long distances.

Lense-like inclusions of adjoining norite and anorthosite are abundant in the chromitite seams (photo 46). Inclusions of chromitite are also present in the adjoining rocks. Both the top and bottom contacts of the chromitite seams may be either sharp or transitional towards the anorthosite and the norite.

1. The petrography of the chromitite seams

According to Fockema and Mendelsohn (1954, p.79) one can distinguish euhedral inclusions of chromite in bronzite from anhedral grains, which are moulded on the bronzite and the olivine, as described by Kuschke. The latter texture indicates that the anhedral chromite crystallized from a late magmatic liquid. Many chromite grains are obviously fused together and are moulded on bronzite (photo 50), but they do not represent a crystallization product of an intercumulus liquid, because they are idiomorphic and enclosed in pyroxene and plagioclase (photo 49).

It is conceivable that during settling of the chromite crystals, they landed in a part of the magma with a comparatively higher temperature, where they became fused together.

Sampson (1932, p.128) observed that the chromite grains which are enclosed by bronzite are much smaller than those in the plagioclase. The same phenomenon is displayed by the chromite from the area investigated.

Chromite grains form continuous rims around bronzite in places similar to the characteristic chain texture, which consists of

a series of chromite grains joined together along their apices, (photo 50 and 47). These chains usually ramify and are in places enclosed by the bronzite and the plagioclase. They may also give the impression of a late magmatic residuum but they are euhedral. The origin of this chain texture is ascribed by Sampson (1932, p.128) to remelting of the cumulus chromite during settling.

Both Sampson (1929, 1932) and Fockema and Mendelsohn (1954, p.81) ascribed the origin of the chromite grains, which are partly enclosed in bronzite, to the replacement of bronzite by chromite. The chromite grains are usually surrounded by a thin film of plagioclase, which is also included in the bronzite. According to McDonald (1963, p.26) this film of plagioclase indicates that bronzite was not replaced by chromite. The contention of Cameron and Emerson (1954, p.1191) that this texture originated during the growth of pyroxene around chromite grains is favoured also by the present author.

Kuschke (1939, p.80) ascertained that the optical axial angle of orthopyroxene below the main group of chromitite seams always exceeds 80° , whereas above the main group it never reaches 80° . Apart from the stratigraphical correlation, the seams investigated can be regarded as being above the main group, because the optical axial angle of the orthopyroxene is $\pm 70^{\circ}$ (tables 44 and 45).

III. The "floor" contact of the Bushveld Complex

Several interesting structural features are evident at the "floor" contact of the layered body of the Bushveld Complex in the area investigated.

1. The transgressive nature of the layered body of the Bushveld Complex to the sediments of the Pretoria Series is excellently displayed in the area mapped. As already pointed out the Main Zone of the Bushveld Complex in the southern

Table 44. Microscopical data on the Chromitite Seams

Specimens and localities	De Kafferskraal (Map 1)			
	Grain shape	Optical properties	Compo- sition	Remarks
Chromite	Idiomorphic and rounded grains 0.25 - 0.05 mm. diameter	-	-	1. Disseminated in plagioclase and pyroxene. 2. Chains of grains typical
Bronzite	Idiomorphic to xenomorphic 2.5 - 0.5 mm. diameter	$2V_x = 70^\circ + 2^\circ$ $N_x = 1.671$	Bron- zite En72 Fs28	1. Exsolution lamellae of augite present. 2. Cores have less chromite inclusions.
Plagioclase	Xenomorphic	$2V_y = 85^\circ$ to $2V_y = 89^\circ$ zonary	An ₆₅ (cores) to An ₇₀ (rims) Labra- dorite	1. Intercumulus material. 2. Plagioclase encloses chromite and bronzite grains. (CF 52)
Texture	Poikilitic			

Table 45. The opaque minerals of the Chromitite Seams on

De Kafferskraal 53-JT

Specimens	CF 49A, 51A, 50A.	
Minerals	Form of grains	Remarks
Chromite	1. Idiomorphic 2. Equidimensional 3. Sometimes rounded	Encloses pyroxene and plagioclase grains (photo 44).
Rutile (?)	Small xenomorphic grains	Inclusions in chromite, and in the gangue material.

part of the area follows on the Dullstroom lava, whereas in the northern part the central portion of the Critical Zone succeeds the central Steenkampsberg quartzite (photos 57).

2. No conformable contact has been observed between the Steenkampsberg quartzite and the Bushveld norite. The Bushveld norite usually forms inlets into the Steenkampsberg quartzite (map 2, photo 51).

3. The ending of the chromitite seams against the Pretoria Series proves the discordant character of the Bushveld Complex. A similar relationship has been described by Cameron and Abendroth (1957, p.1065) from south of the Steelpoort River. They, however, ascribe the abrupt ending of the chromitite seams to faulting along the margin of the Bushveld Complex. The chilling of the layered body against the sedimentary rocks, the absence of any evidence of faulting and the wavy nature of the contact between the Bushveld Complex and the sediments in the present area exclude the possibility of faulting.

4. Slight folding of the Steenkampsberg quartzite is present on De Kafferskraal. 53-JT. As depicted on map 2 the Steenkampsberg quartzite has been folded into a syncline succeeded by an anticline. The increase in the width of the outcrop of the Steenkampsberg quartzite mentioned by Hall (sheet 11, 1913) cannot be accounted for by the folding, because the latter is too insignificant. The layered body of the Bushveld Complex transgresses obviously across the folded sediments of the Pretoria Series. The folding is ascribed to stress, which operated during the emplacement of the Bushveld Complex.

For many years geologists have regarded the Bushveld Complex as a lopolith, applying a genetic significance to the definition of Grout (1918). Since the layered body of the Bushveld Complex has a transgressive contact with respect to

the sedimentary rocks of the Pretoria Series, and the chromite seams end abruptly against the Pretoria Series, the present author prefers to agree with Wilson (1957, p.298-300) that the Bushveld Complex is not a concordant intrusive body but is rather funnel shaped.

V. KARROO DOLERITE

Six dolerite dykes have been mapped in the area. The most prominent outcrops are found on Sterkfontein 52-JT, Kleinzuikerboschkop 93-JT and Lunsklip 105-JT. They cut across the diabase, the quartzite, the hornfels and the rocks of the Bushveld Complex and have a trend which ranges mainly from N 30° East to N 50° East. Their thickness ranges from 2 to 25 ft. The dolerite weathers more easily than the diabase and norite, and consequently the dykes could be followed readily in the field (photo 28). Only samples from a dyke on Sterkfontein have been investigated, since it is the thickest dyke in the area mapped.

Along their contacts, all the dolerite dykes have a chilled margin which consists mainly of orthopyroxene and glass, followed by a fine-grained and a coarse-grained central zone, form the central part. The length of the plagioclase grains in the three zones varies considerably and range between 0.005 to 0.5 mm. in the chill zone, between 0.5 and 1.0 mm. in the fine-grained zone, and 1.25 to 2.0 mm. in the coarse-grained zone.

The plagioclase ($An_{65+2\%}$) is usually subhedral and lath-shaped, the $2V_A = 83^\circ \pm 2^\circ$ and it is ophitically enclosed by pyroxene. In the fine- and coarse-grained zones, plagioclase is more abundant than in the chill zone.

The clinopyroxene is generally xenomorphic and intergranular, $2V_Z = 60^\circ$; $\angle C = 58^\circ$. It replaces the orthopyroxene, and has a prominent (001) parting, which characterizes diallage.

Xenomorphic and intergranular grains of orthopyroxene, which have $2V_p = 87^\circ \pm 3^\circ$ and $\chi^c = 0^\circ$ enclose plagioclase ophitically. In the chill zone the orthopyroxene is idiomorphic and plagioclase is occasionally absent.

The opaque minerals consist mainly of disseminated magnetite. Quartz is also present in subordinate quantities as irregular grains in the intergranular material.

The coarse-grained dolerite has an ophitic texture, whereas in the fine-grained variety the pyroxene is moulded on the plagioclase grains like the texture described by McDougill (1961, p.58) from Tasmania.

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PHOTO 1

Epidote (Ep) and biotite (Bi) replaces the matrix in the Steenkampsberg quartzite. Hematite (black) and quartz (light grey). Thin section CF 107, Sterkfontein 52 JT. Ordinary light, x 125.

PHOTO 2

Relicts of sericite (s) in muscovite (M) in the Steenkampsberg quartzite. The quartz grains (Q) are recrystallized. Thin section CF 107, Sterkfontein 52 JT. Crossed nicols, x 125.

PHOTO 3

Fibrous sillimanite in the Steenkampsberg quartzite. The quartz grains are recrystallized. Thin section CF 105, Kliprivier 73 - JT. Crossed nicols, x 125.

PHOTO 4

Epidote (Ep) replaces sericite (s) which has ^Sa rounded shape, similar to the quartz grains, and presumably represent original plagioclase. CF 101, Knapdaar 92 - JT. Ordinary light, x 125.

PHOTO 5

Layers of magnetite and hematite (dark), alternating with layers of quartzite, (white) in the Steenkampsberg quartzite, CF 127, Wanhoop 78 - JT. Half natural size.

PHOTO 6

Biotite (light) replaces the intergranular matrix of the black sand. The subangular black grains are hematite. CF 126, Wanhoop 78 - JT. Crossed nicols, x 450.

PHOTO 7

A relict of magnetite (dark-grey) in a grain of hematite (white) from the black sand at the base of the Steenkampsberg quartzite. CF 125B, Verloren Valei. Ordinary light, oil immersion, x 125.

PHOTO 8

A relict of magnetite (dark-grey) partially altered to hematite (white) along (111). The black sand at the base of the Steenkampsberg quartzite. CF 125C, Verloren Valei. Ordinary light, oil immersion, x 165.

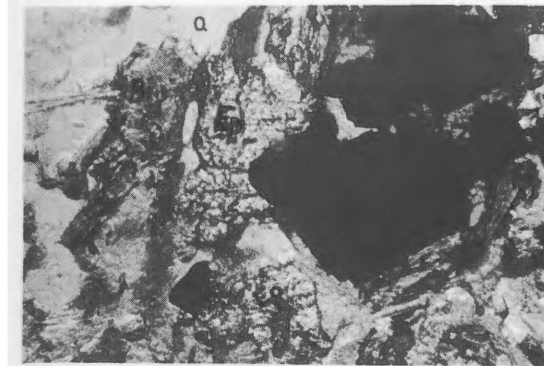
PHOTO 9

A large rounded grain, consisting of differently orientated hematite grains CF 125B, Verloren Valei. Crossed nicols, oil immersion x 250.

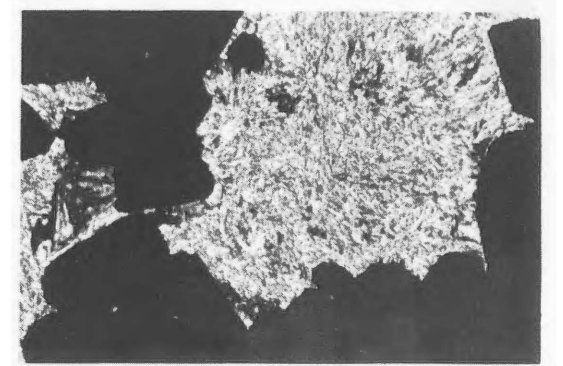
PHOTO 10

Lamellae of altered ilmenite (grey) parallel to three directions in hematite (white). CF 128A, Verloren Valei. Ordinary light, oil immersion, x 165.

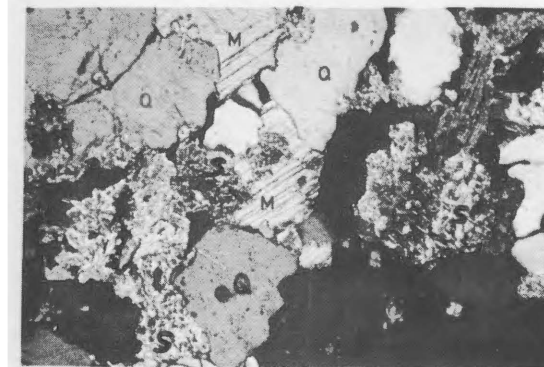
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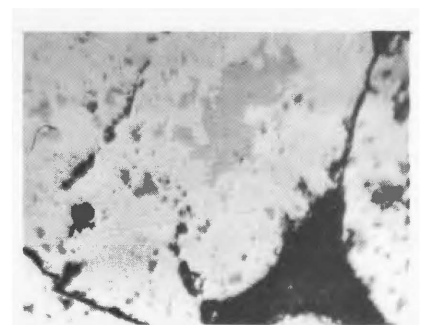
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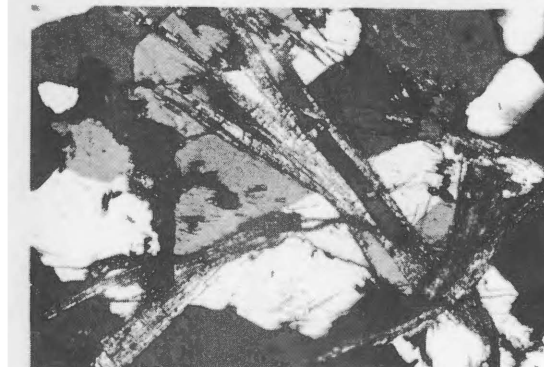
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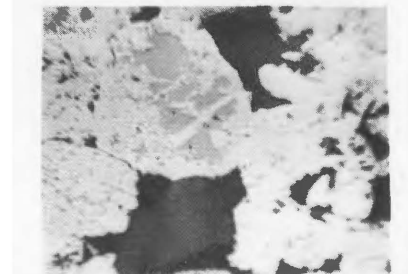
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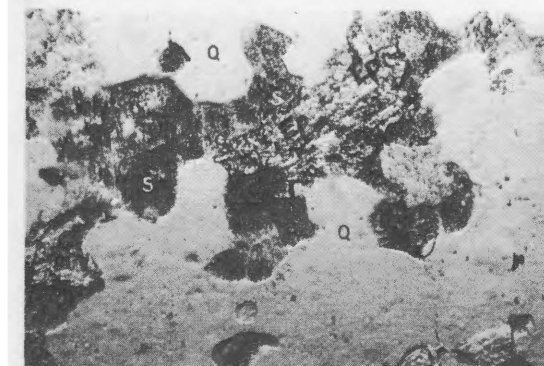
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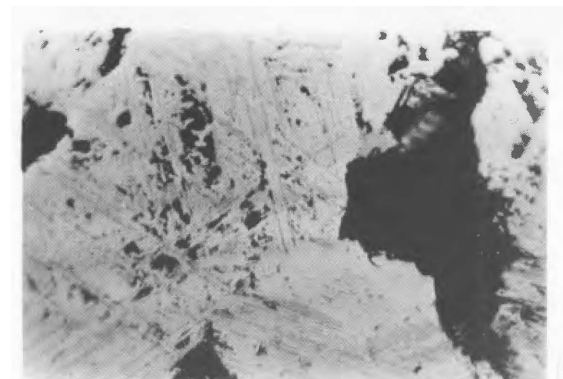


PHOTO 11

Small ribbons of hematite (white) in grains of ilmenite (grey), CF 128B, base of the Steenkampsberg quartzite, Verloren Valei. Ordinary light, oil immersion, x 165.

PHOTO 12

A zoned zircon and rounded grains of ilmenite (grey) and hematite (white). CF 128B, Verloren Valei. Ordinary light, oil immersion, x 165.

PHOTO 13

A zonal amygdale, which consists of an outer zone of hypersthene (grey) succeeded by a zone of plagioclase (twinned and light grey) and a core of quartz (black), in a fine-grained andesite. CF 80, Houtenbek 97 - JT. Crossed nicols x 75.

PHOTO 14

A quartzite inclusion in fine-grained Dullstroom lava. The quartz grains are rounded. CF 80, Houtenbek 97 - JT. Crossed nicols, x 25.

PHOTO 15

Inclusions of sericite and quartz in a large grain of cordierite in the hornfels succeeding the Lakenvlei quartzite. CF 140, Lunsklip. Ordinary light, x 125.

PHOTO 16

A zonal arrangement of quartz (white) and sericite (light grey) inclusions in cordierite porphyroblasts in the hornfels above the Magaliesberg quartzite. CF 137, Knapdaar 92 - JT. Ordinary light, x 140.

PHOTO 17

An aggregate of hematite (white) which is partly replaced, pseudomorphously by magnetite (grey) in hornfels above the Magaliesberg quartzite. CF 4A, Kwaggashoek 66 - JT. Ordinary light, oil immersion, x 125.

PHOTO 18

Idioblasts of hematite (white) which are partly replaced by magnetite (grey), in hornfels above the Magaliesberg quartzite. CF 4A, Kwaggashoek 66 - JT. Ordinary light, oil immersion, x 200.

PHOTO 19

Inclusions of diopside (D) in Wollastonite (W). Diopside fels above the Magaliesberg quartzite. CF 111, Kleinzuikerboschkop 93 - JT. Crossed nicols, x 140.

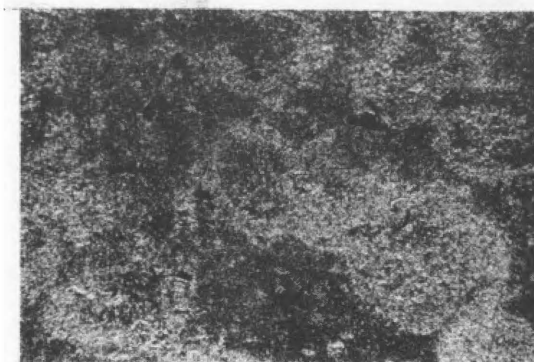
PHOTO 20

Vesuvianite (V) replacing diopside (D). Diopside fels. CF 111, Kleinzuikerboschkop 93 - JT. Crossed nicols, x 125.

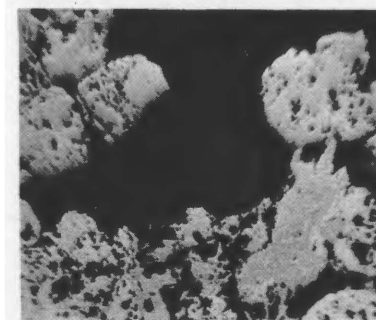
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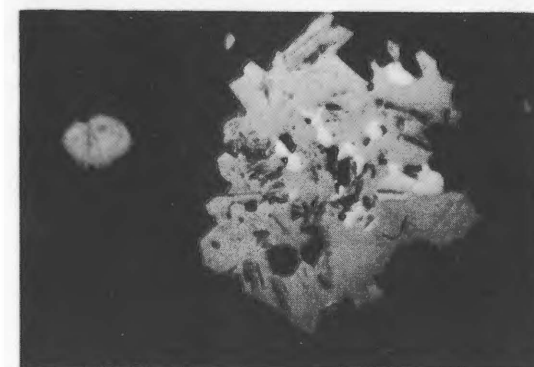
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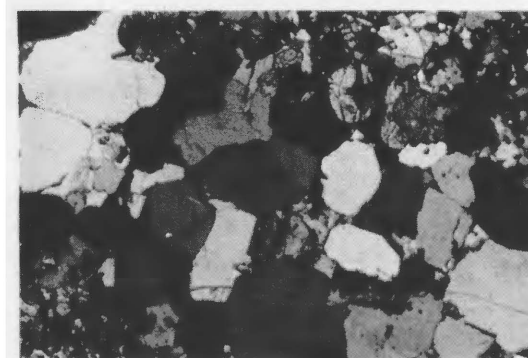
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PHOTO 21

Garnet (G) replaces diopside (D). Diopside fels. CF 111, Kleinzuikerboschkop 93 - JT. Crossed nicols, x 120.

PHOTO 22

Alternating layers of diopside (grey) and garnet (black). Diopside fels CF 112, Kleinzuikerboschkop 93 - JT. Crossed nicols, x 25.

PHOTO 23

Garnet (G) replaces Vesuvianite (V). Diopside (D). Diopside fels. CF 111, Kleinzuikerboschkop 93 - JT. Ordinary light, x 180.

PHOTO 24

Idioblasts of wollastonite (W) included in garnet (G) and in diopside (D). Diopside fels. CF 111, Kleinzuikerboschkop 93 - JT. Ordinary light, 125.

PHOTO 25

Rounded grains of olivine (O) in calcite (Ca), and grains of diopside (D) and Wollastonite (W). CF 111, Kleinzuikerboschkop 93 - JT. Crossed nicols, x 125.

PHOTO 26

An idioblast of Wollastonite altered to a fine - grained mineral which has the same $d(A^{\circ})$ values as Wollastonite, included in garnet CF 111, Kleinzuikerboschkop. Crossed nicols, x 300.

PHOTO 27

An inclusion of diorite in a differentiated sill, next to the handle. Uitspanning 106 - JT.

PHOTO 28

A dyke of Karroo dolerite (Do) cutting across an intrusive sill (Di) above the Magaliesberg quartzite. Kleinzuikerboschkop 93 - JT.

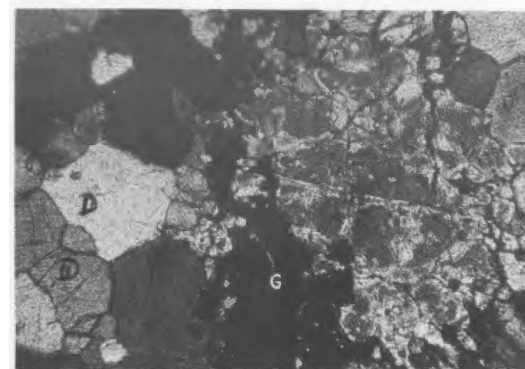
PHOTO 29

A large phenocryst of orthopyroxene (Op) bordered by a light-coloured glass (LG) in a dark, magnetite - bearing glass (DG) the glassy dolerite of the chilled margin of a differentiated sill. CF 6, Schaapkraal 68 - JT. Ordinary light, x 150.

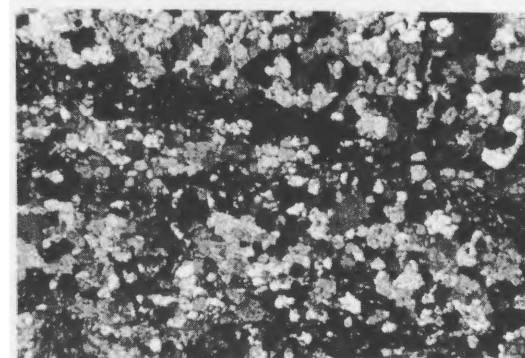
PHOTO 30

A phenocryst of orthopyroxene (Op) replaced along its margin by clinopyroxene (CP) in a devitrified mesostasis which shows a trachytoidal texture. CF 17, Schaapkraal 68 - JT. Crossed nicols, x 150.

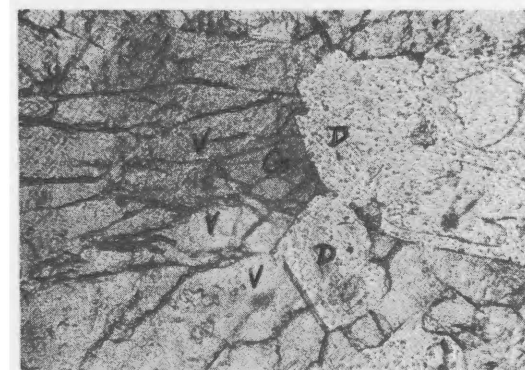
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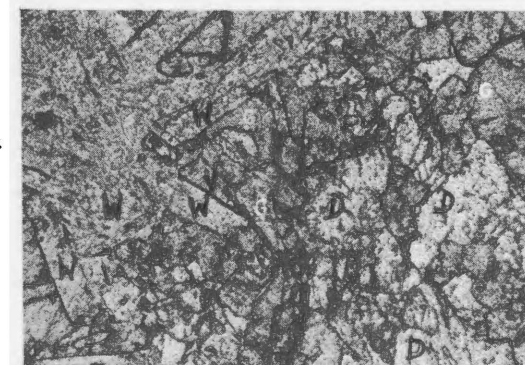
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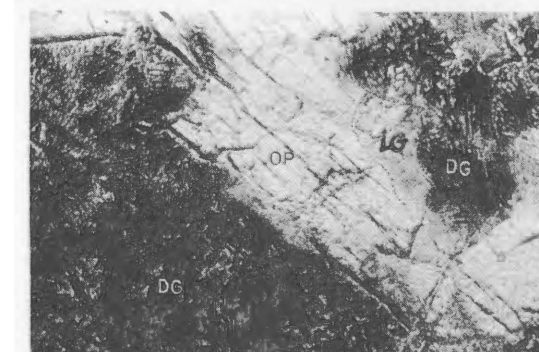
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PHOTO 31

A bent phenocryst of orthopyroxene in a devitrified mesostasis, in devitrified glassy dolerite. CF 27, Weimershoek 81 - JT. Ordinary light, x 75.

PHOTO 32

A resorbed phenocryst of orthopyroxene in a devitrified mesostasis of laths of plagioclase and intergranular grains of augite. CF 18, Kleinzuikerboschkop 93 - JT. Ordinary light, x 75.

PHOTO 33

Phenocrysts of orthopyroxene arranged in a radiating pattern ⁱⁿ a devitrified mesostasis. CF 27, Weimershoek 81 - JT. Ordinary light, x 75

PHOTO 34

An orthopyroxene grain (white) partially altered to uralite (black). CF 2, Kleinzuikerboschkop 93 - JT. Ordinary, x 160.

PHOTO 35

Small exsolved grains of clinopyroxene (white) in an orthopyroxene grain (dark). CF 1, Goedehoop 79 - JT. Crossed nicols, x 160.

PHOTO 36

Layered norite from the Critical Zone of the Bushveld Complex, $\pm$ 10 feet above Ug3, De Kafferskraal 53 JT.

PHOTO 37

Schiller exsolution of magnetite (white) in orthopyroxene (black), in hyperite of the Critical Zone. CF 63 A, De Kafferskraal 53 - JT. Ordinary light, oil immersion, x 360.

PHOTO 38

Idiomorphic grain of magnetite, containing an exsolution lamellae of ilmenite (grey) in hyperite of the Critical Zone. CF 63A, De Kafferskraal 53 - JT. Ordinary light, oil immersion, x 160.

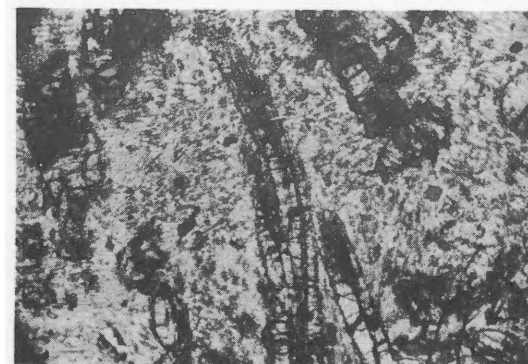
PHOTO 39

Intergranular ilmenite in hyperite of the Critical Zone. CF 63 A. De Kafferskraal 53 - JT. Ordinary light, oil immersion, x 160

PHOTO 40

An inclusion of quartzite in norite of the Critical Zone, $\pm$ 40 feet from the contact between the Pretoria Series and the Bushveld Complex. De Kafferskraal 53 - JT.

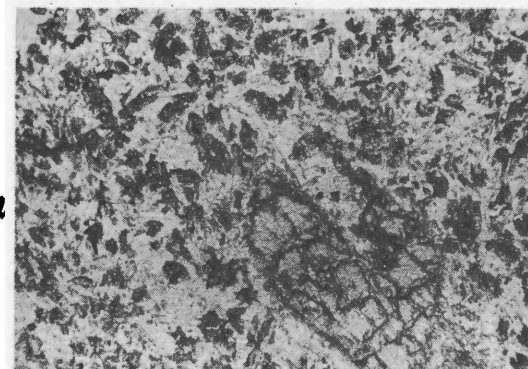
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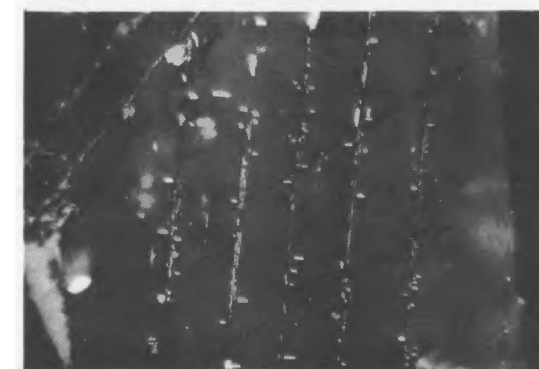
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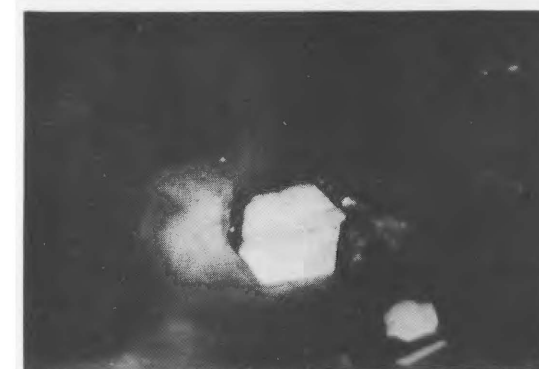
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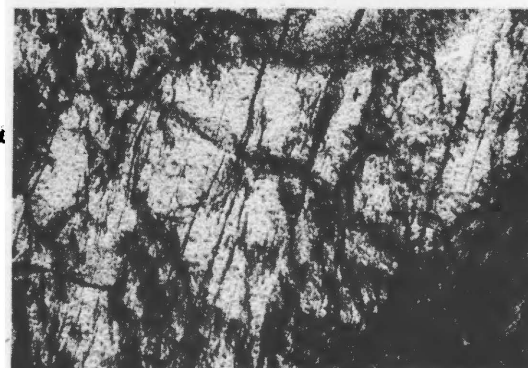
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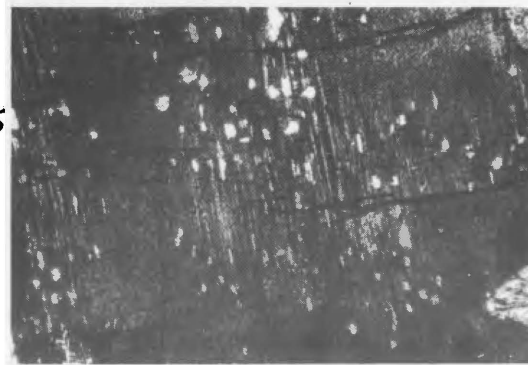
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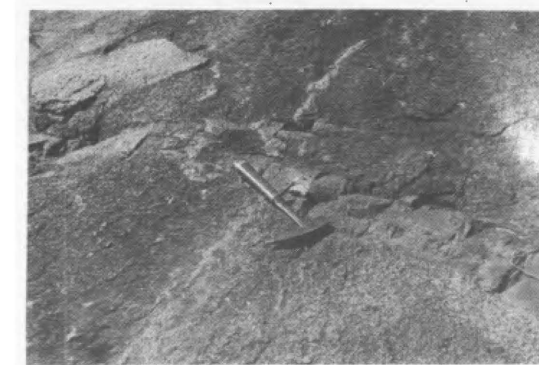


PHOTO 41

Ribbon-like exsolution of hematite (white) in ilmenite (grey) from norite of the Main Zone. CF 69A Houtenbek 97 - JT. Ordinary light, oil immersion, x 500.

PHOTO 42

A coronophitic texture consisting of rounded orthopyroxene in clinopyroxene (CP). Idiomorphic plagioclase (pl) optically included in clinopyroxene. CF 66, Klipbankspruit 76 - JT. Crossed nicols, x 125.

PHOTO 43

A large grain of orthopyroxene and inclusions of plagioclase, surrounded by large grains of plagioclase, from the porphyritic norite of the Critical Zone. CF 62, De Kafferskraal 53 - JT. Crossed nicols, x 125.

PHOTO 44

An inclusion of silicate (black) in an idiomorphic grain of chromite (white). CF 50 A De Kafferskraal 53 - JT. Ordinary light, oil immersion, x 120.

PHOTO 45

Two layers of chromitite in norite of the Critical Zone. Many lenslike inclusions of norite in the chromitite layer. De Kafferskraal 53 - JT (U¹ on Map 1).

PHOTO 46

An inclusion of norite in a chromitite seam on De Kafferskraal (U² on map 1).

PHOTO 47

A chain of chromite grains in plagioclase, from Ug2. CF 51, De Kafferskraal 53 JT. Ordinary light, x 125.

PHOTO 48

Chromite grains, surrounded by a film of plagioclase in bronzite of Ug2. CF 51, De Kafferskraal 53 - JT. Ordinary light, x 125.

PHOTO 49

Idiomorphic grains of chromite (cr) enclosed in plagioclase (pl) CF 50 De Kafferskraal 53 - JT. Ordinary light, x 125.

PHOTO 50

Chromite grains surrounding a bronzite grain, which also contains inclusions of chromite. CF 52, De Kafferkraal 53 - JT. Ordinary light, x 125.

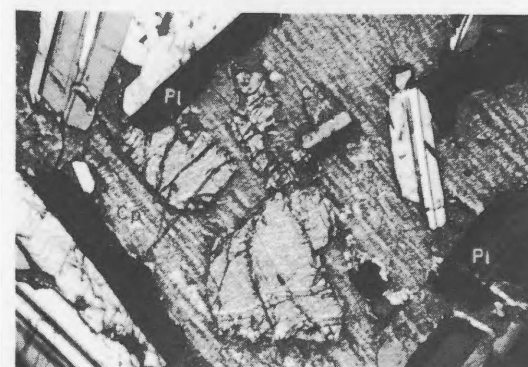
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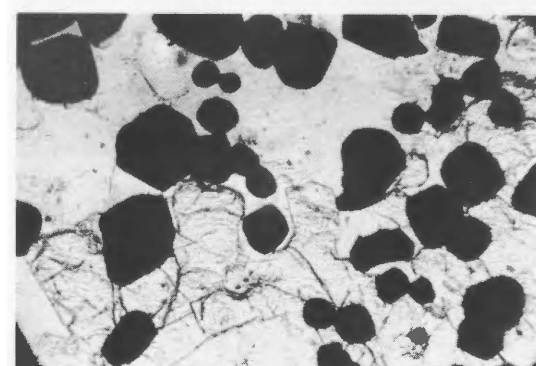
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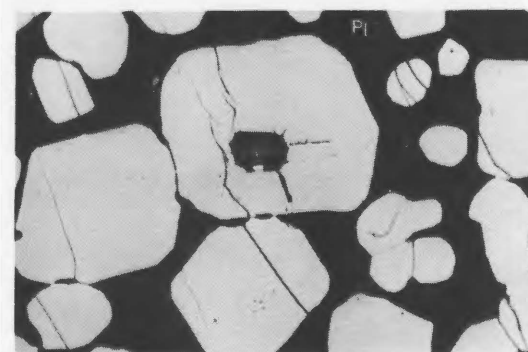
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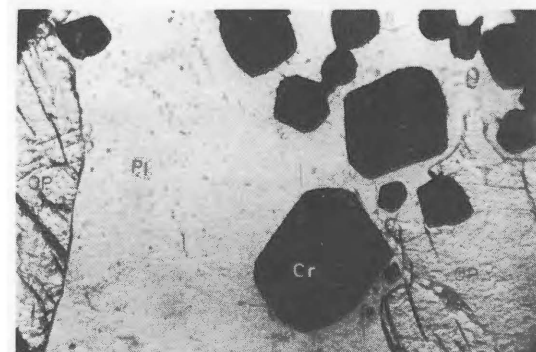
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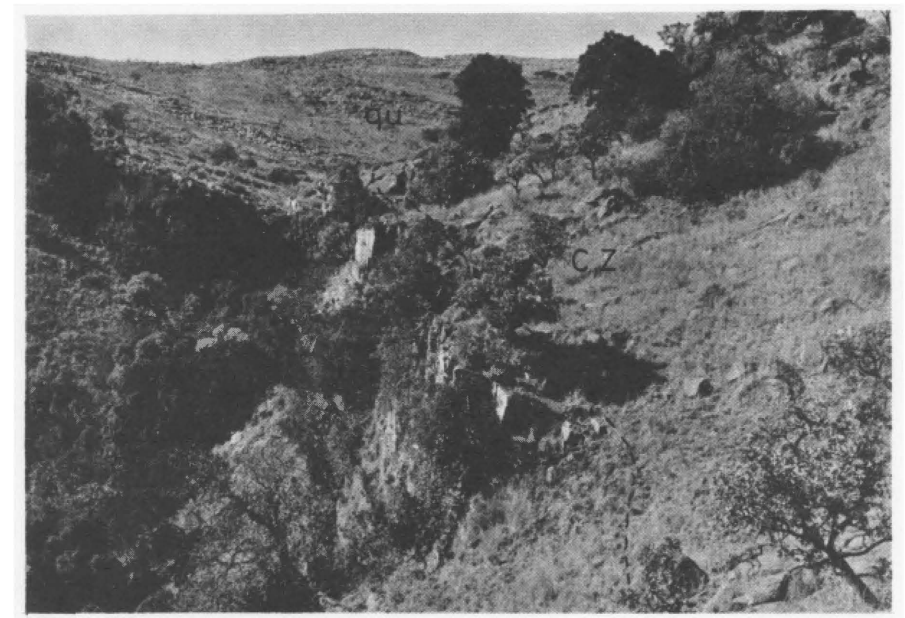
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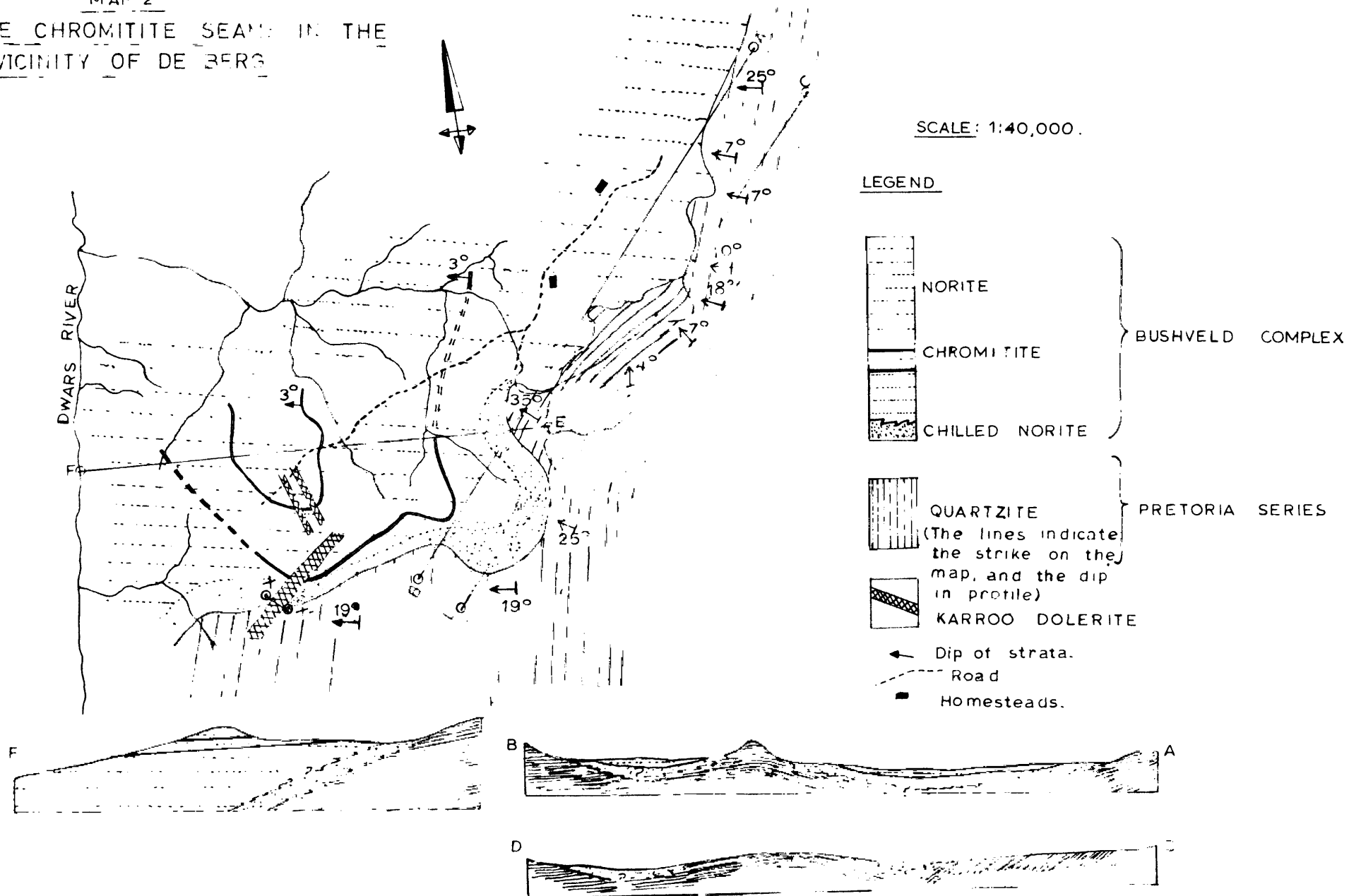
PHOTO 51

The "floor" contact of the Bushveld Complex on De Kafferskraal 53 - JT. The norite of the Critical Zone (CZ) cuts across the Steenkampsberg quartzite (qu).

51



MAP 2
THE CHROMITITE SEAMS IN THE
VICINITY OF DE BERG

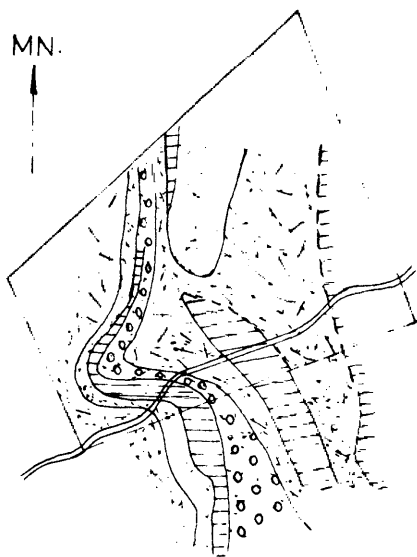


MAP. 3.

THE RELATIONSHIP BETWEEN THE DIFFERENTIATED
MAFIC SILLS AND THE DIORITE ON UITSPANNING 106 JT

Scale 1:40,000

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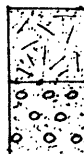


Legend



Quartzite

Hornfels



Differentiated sill

Diorite



Dullstroom - Lydenburg
road.

MAP 4

THE DISTRIBUTION OF THE METAMORPHIC FACIES IN THE VICINITY OF DE BERG, NORTH OF DULLSTROOM.

