THE UPPER ZONE OF THE BUSHVELD COMPLEX, AT TAUTESHOOGTE.

BY

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C O N T E N T S.

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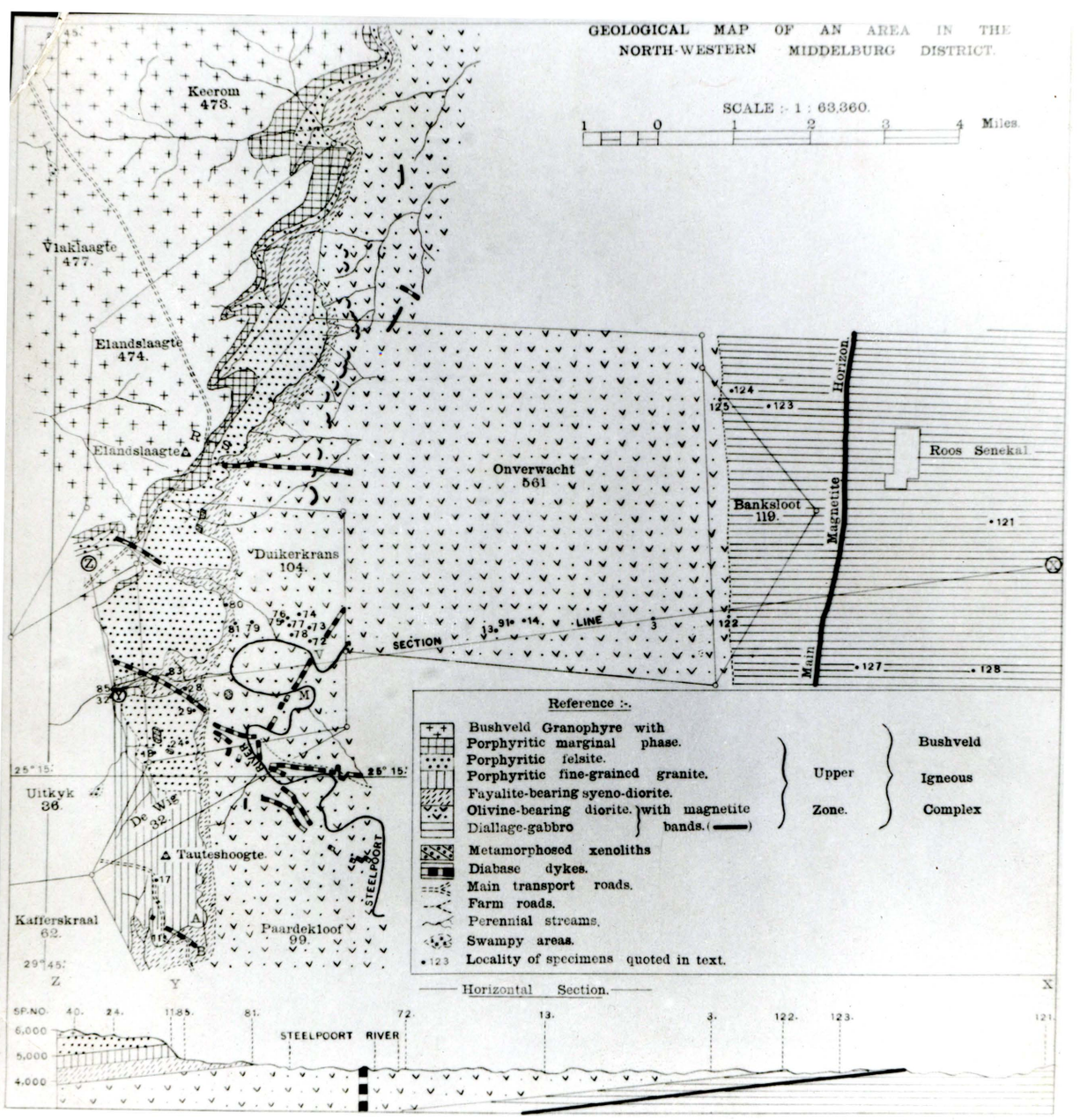

I N T R O D U C T I O N.

With the aid of a grant from the Research Grant Board the geological mapping of the area was undertaken in December 1939, and continued intermittently until July 1941. The investigation of the material was carried out in the Department of Geology, University of Pretoria, under the guidance of Prof. B.V. Lombaard.

The present study was undertaken in order to obtain more detailed petrographical data of the Upper Zone of the Bushveld Complex, and to investigate the nature of the transition from basic to acid rocks.

I wish to express my indebtedness and gratitude to: The Research Grant Board, for the above-mentioned financial assistance; Prof. B.V. Lombaard, for his guidance and unfailing interest in this work; Prof. D.L. Scholtz, for practical advice on the technique of refractive index determinations; Mr. and Mrs. A.S. du Toit of Uitkyk No.36, for their kindness and hospitality; the Director of the Geological Survey, for permission to examine rock-sections from the Survey collection; Mr. C.J. Liebenberg, Division of Chemical Services, for making three silicate analyses.

II. GENERAL DESCRIPTION OF THE INVESTIGATED AREA.

a. Physiography.

The geological map embraces a tract of rugged country, about five miles broad, extending parallel to the 29°45'th Lo., in the north-eastern corner of the Magisterial district of Middelburg, and is approximately bounded on the east by the Steelpoort river and on the west by the main transport road to Pokwani.

The area may be divided into two distinct physiographical parts, namely, an extensive high level

plateau / ...

plateauof acid rocks lying at an average elevation of 1,000 feet above the adjoining tract of depressed Bushveld country, occupied by basic rocks of the Bushveld Complex. This marked difference in topography arises mainly from the difference in the degree of susceptibility to weathering of the above-mentioned two principal geological formations, combined with the more powerful erosive action of the Steelpoort and Blood rivers.

1. The Plateau Region: Although on looking westwards from Roos Senekal this topographical feature gives the impression of a high range, the escarpment is in reality the eastern edge of an extensive high level plateau which embraces Pokwani and a considerable stretch of the more northerly portion of the Middelburg district. The term Sekukuni's Mountains is restricted to the main escarpment which presents a steep slope towards the east and runs roughly parallel to, and at an average distance of three miles, from the Steelpoort river, and ends abruptly at Tauteshoogte. Topographically, however, the escarpment continues by turning sharply towards the west and keeping along the north side of the Blood river.

On the whole the crest line maintains a fairly uniform elevation for considerable distances, but the continuity is occasionally broken by the tributaries draining the plateau and joining the main stream from the west.

The plateau region belongs in certain respects to the High Veld type of country since its average elevation is well over 5,000 feet and the growth of trees is generally scanty or even entirely wanting. It forms a wide somewhat monotonous rolling tableland occasionally diversified by gently undulating bults, and deeply incised valleys of the larger tributaries,

when / ...

when the resulting relief may become pronounced.

2. The Bushveld Country: Although the valley of the Steelpoort river belongs in part to the Bushveld type of country the characteristic Bushveld scenery is sometimes wanting and only becomes permanently established north of the southern boundary of Duikerkrans No.104

The area south of this boundary is usually devoid of marked relief and sometimes shows for several square miles nothing but the well-known deep reddish soil. Elsewhere, particularly nearer a drainage line, the familiar black turf is conspicuous. Such open country forms fairly good agricultural land.

The further one proceeds north-eastwards along the main valley the more varied does the scenery become and the more rugged the country. At the same time the vegetation increases markedly with the general fall of country. From the right bank of the river the country rises rapidly and presents highly diversified features; short somewhat irregular ridges alternate repeatedly with dark-coloured, rugged, roughly pyramidal kopjès, which lend a sombre aspect to the scenery.

b. Drainage.

The plateau is supplied with abundant permanent surface water and there are favourable indications of a good underground supply, which could be tapped at no great depth. It is drained by numerous perennial streams which flow into the Steelpoort river. The dissection of the plateau by these tributaries has not progressed beyond the youthful stage. The vigorous streams follow straight courses with steep gradients in deeply incised valleys, with steep walls which are precipitous in part and at the base of which thick accumulations of talus may occur. Several of the larger tributaries descend to the level of the Steelpoort river by means of one or more waterfalls.

Patches / ...

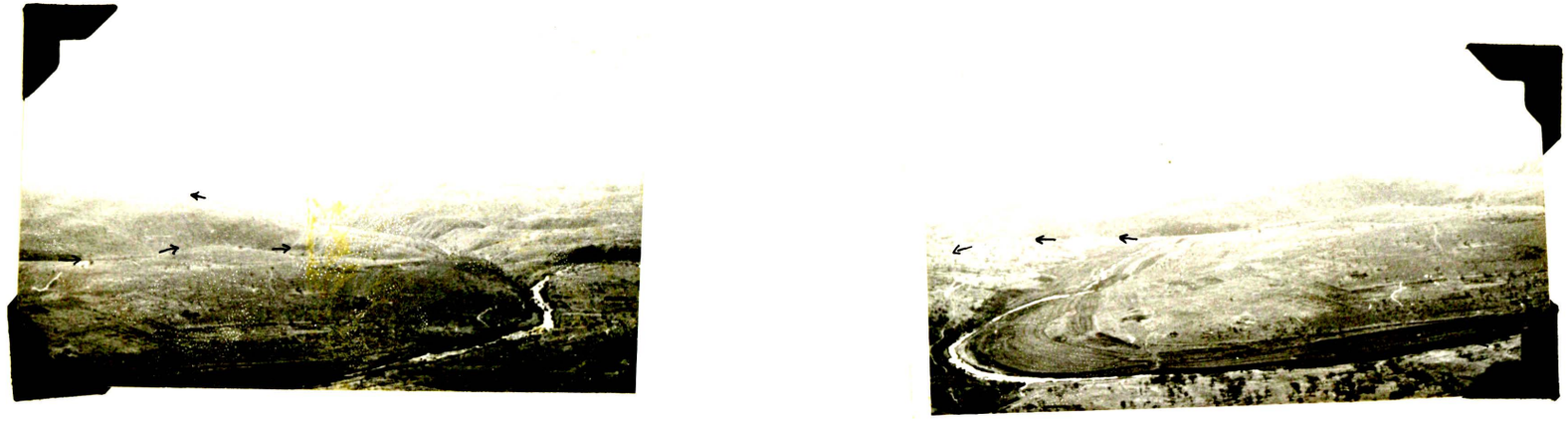

Plate.1V.- Illustrates the extensive meandering by the Steelpoort river over a linear stretch of 1 75 miles on Duikerkrans No.104. Evidence of lateral migration is furnished by the crescent-shaped meander spurs which constitute the principal arable tracts in this area. The arrows indicate direction of flow.

Patches and belts of indigenous timber are practically confined to the courses of the minor streams draining the sides of the main valleys.

The Steelpoort river meanders extensively over this particular stretch of its course. Although the following description relates to the meander designated by the letter M on the appended map, the same general features are exhibited by the other symmetrical bends in the river.

This meander is defined along its outer margin by an arc of precipitous cliffs, while the meander spur comprises a cresent-shaped strip of level country which rises only slightly above the height of the river bed over a distance of 1,000 yards, whereafter the ground rises steeply to the general elevation of the surrounding country. These relations indicate an extensive lateral migration of the river bed over an area, now devoid of outcrops and covered by soil and strewn with waterworn pebbles. Such meander spurs constitute the principal arable tracts in this area.

The main meander on Duikerkrans No.104 has a circumference of three miles while the meander neck is less than a quarter mile wide.

On Paardekloof No.99 a roughly oval-shaped depression bounded by steep walls, projects for a distance of one mile from the present course of the river. The interior of this basin is remarkably level, with a slight median ridge extending for a quarter mile from the river. These features suggest that the depression occupies the site of an abandoned meander of which the neck was cut through after a lateral migration of .75 miles, resulting in the formation of a bayou.

c. General Geology.

The geological formations of the area are shown

on the / ...

on the map and comprise the following:

Bushveld Granophyre with Porphyritic marginal phase.	3. Bushveld acid rocks overlying Upper Zone.	Rocks of the residual magma.
Porphyritic felsite.	2. Fine-grained acid rocks	Upper Zone
Porphyritic fine-grained granite.		
Fayalite-bearing syeno-diorite.	1. Basic rocks	
Olivine-bearing diorite		
Diallage-gabbro.		Main Zone.
Diabase dykes.		
Metamorphosed xenoliths.		

For the purpose of describing the general geology, these formations have been grouped into three major geological units as shown in the second column of the above table.

The gabbros and olivine-bearing diorites appearing on the eastern side of the map between the Steelpoort river and the township of Roos Senekal have not been investigated in detail other than the examination of specimens collected along a traverse across their strike.

The remaining dioritic rocks occupy the tract of depressed Bushveld country of the Steelpoort valley and ascend the escarpment to a height of 5,300 feet, from where they project in tongue-like fashion up the deeply-incised valleys of the tributaries draining the plateau.

These rocks are generally well exposed although the highest horizon is usually covered by the thick accumulations of talus skirting the precipitous escarpment, but good outcrops occur along the main transport road ascending Tauteshoogte and a complete succession is exposed in the large kloof on Duikerkrans No.104, .

The diorite is traversed by two sets of prominent joints which approximately coincide with the directions of pseudo-stratigraphical dip and strike

respectively / ...

Plate.V.- Showing the alignment parallel to the foot of the main escarpment of the several crescent-shaped ridges rising above the general elevation ofthe surrounding Bushveld country and dipping towards the west (i.e. away from the observer) at low angles.
Onverwacht No.56I.

respectively. The former set strikes 20° east of north and the latter 14° south of east. Together with the planes lying in the pseudostratification these joints are instrumental in the formation of the rectangular and subspheriodal blocks which result from the weathering of the diorite.

The rocks exhibit very little macroscopic variation. Leucocratic bands as well as short granitic and hornblende veins are occasionally encountered. These features are unchilled against the enclosing rocks. Inclusions of arenaceous, argillaceous and calcareous sediments completely enveloped by igneous rocks are frequently met with at all horizons within the diorite. The xenoliths vary from a few feet to a hundred yards in diameter and bear evidence of thermal metamorphism.

Specks of disseminated sulphidic ore are macroscopically visible on freshly fractured surfaces of some of the metamorphosed xenoliths and also on certain leucocratic varieties of igneous rocks.

At locality X, the diorite is traversed by a vein of about a foot in thickness, containing crystals of pyrite set in a matrix of calcite and igneous material.

On Paardekloof No.99 and Duikerkrans No.104 the titaniferous-magnetite is indicated at variable distances from the foot of the escarpment by isolated patches of rubble ore.

On Onverwacht No.561 and adjoining portions of Duikerkrans No.104 and Luipershoek No.541 a series of crescent-shaped ridges, all dipping towards the west at low angles, rise above the general elevation of the surrounding country. Their slightly raised rims consist of massive magnetite and the relatively depressed interiors exhibit fragments of magnetite enbedded in lateritic soil. Several of the ridges are aligned parallel to the

escarpment / ...

Plate.VI.- Showing the steep back-slopes of two adjacent crescent-shaped ridges, marked A and B, separated by streams draining the escarpment. The contact between syeno- diorite and felsite is represented by the broken curve. Onverwacht No.56I.

Plate.VII.- Pseudostratified, jointed massive titaniferous-magnetite, composing the raised rims of the crescent-shaped ridges and dipping westwards (to the right in the photograph) at 7. Dimensions of rock face shown about 3x4 feet.
Onverwacht No.56I.

escarpment but others occur slightly out of this alignment. When viewed from a distance the steep back-slopes exhibit a feeble banding conforming to the rims of the ridges. The ridges were no doubt sculptured from a continuous seam of magnetite, with a low westerly dip, by the streams now separating them.

These structures furnish the only evidence of regionally visible pseudostratification in this area, the angle of dip varying between 6° and 8°. No detailed investigation of the relationships between the magnetite seams and underlying diorite could be undertaken owing to the lack of suitable outcrops.

The fine-grained acid rocks comprising fine-grained granite and felsite, extend from the higher slopes of the Sekukuni Mountains westwards. They occupy the whole of the tableland between the southern edge of Tauteshoogte and Baviaansnek. The fine-grained granite is restricted to the southern portion of this area, but the felsite continues as a band extending northwards parallel to the escarpment, with two tongue-like projections up the deeply-incised valleys on Elandslaagte No.474.

The colour on freshly fractured surfaces varies arbitrarily within each of the two varieties enumerated above, from dark chocolate brown to reddish brown.

Both varieties frequently exhibit streaks and irregular patches of medium-grained granite which are sharply defined from, though unchilled against the enveloping rocks. The individual occurrences of medium-grained granite vary from mere streaks to outcrops of 300 square yards.

The two sets of vertical joints traversing the fine-grained acid rocks strike 14° east of north and 30° south of east respectively and are generally closely

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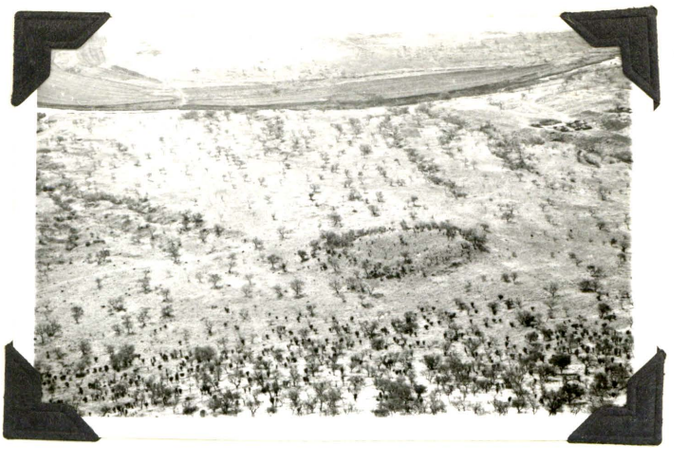


Plate.VIII.- The circular prominence marked by the more abundant vegetation, resulted from the differential weathering of an arenaceous xenolith, enveloped by relatively less resistant diorite. The diameter of the inclusion is approximately 50 yards. The Steelpoort river is seen in the background. Duikerkrans No.104.

Plate.IX.- Showing the fine scale banding generally prominently displayed on weathered surfaces of the argillaceous xenoliths. Dimensions of rock face shown approximately 2 x I feet. Uitkyk No.36.

Plate.X.- Showing the superimposed rectangular and subspheriodal blocks characteristically resulting from the weathering of the Bushveld Granophyre. Uitkyk No.36.

spaced.

Xenoliths of argillaceous and arenaceous sediments are occasionally met with, but are less abundant and of smaller dimensions than those occurring in the diorite. They bear evidence of thermal metamorphic alteration. Bands of the order of a fraction of an inch in thickness are usually prominent on weathered surfaces, and in some instances specks of sulphidic ore are macroscopically visible on freshly fractured surfaces.

The typical Bushveld Granophyre forms a belt of high country extending from the edge of the plateau towards the north-western corner of the map. The area is characterised by hummocky outcrops of super-imposed sub-spheriodal blocks, with intervening boulder-strewn strips. But for variations in colour, ranging from brick-red to grey the rocks are remarkably uniform in appearance.

Diabase dykes, varying in width from one to fifteen feet, traverse in various directions the three major geological units enumerated above. The width for any one dyke remains fairly constant over the whole of its length. They are generally fine-grained, with prominent chilled margins, and weather to reddish grey hexagonal blocks of which the major axes are arranged perpendicular to the walls of the intrusion. The dykes are traversed by anostomizing veins of prehnite usually $\frac{1}{4}$ inch thick, and of which the density of distribution varies from place to place and may even be entirely absent.

The intrusions occasionally exhibit minor deviations in strike, usually making short, right angle bends before continuing in their respective directions of general strike. They sometimes converge and may even coalesce. Subsidiary dykes emanating from the larger

ones / ...

Plate.XI.- The several prominences indicated by arrows mark the outcrop of a basic dyke traversing the diorite. Note the symmetrical bend in the Steelpoort river.
Duikerkrans No.104.

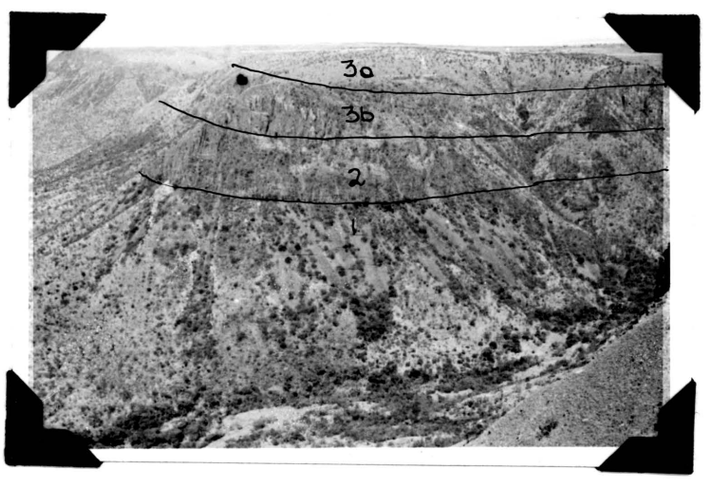
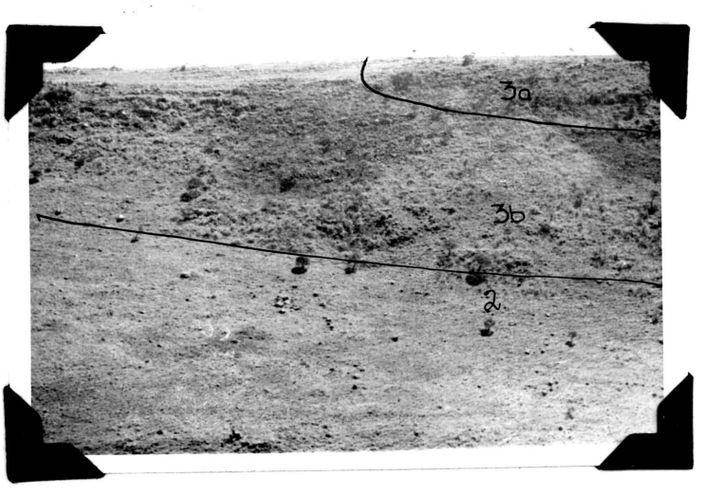


Plate.XII.- Shows the sheet-like arrangement of the major geological units in the succession exposed along the precipitous walls of the deep valleys incised by the streams draining the plateau. Elandslaagte No.471.
3a.Bushveld Granophyre with
3b.Porphyritic marginal phase.
2.Tauteshoogte Felsite.
1.Fayalite-bearing-syeno-diorite.



ones are frequently encountered. They either taper out rapidly or return to the parent dykes.

Judging from the geological map the dykes are more numerous in the Bushveld country than on the plateau. This difference may not be real since the dykes are difficult to detect on the plateau because they closely resemble the fine-grained acid country rocks in respect of colouring on weathered surfaces, susceptibility to weathering and grain size.

In the Bushveld country on the other hand, the dykes build prominent topographical features and are further accentuated by marked differences in colour on weathered surfaces and grain size as compared with the diorite in which they occur here.

Several of the larger dykes have, however, been followed continuously from one formation to another without notable variations in course or dimensions.

d. Relationships in space of the three major geological units.

All the types of igneous rocks, other than the transgressive intrusions, are distributed in sheets following the same strike, analogous to that of a conformable succession of sedimentary rocks.

The contacts separating the fine-grained acid rocks from the overlying typical Bushveld acid rocks and the underlying diorites sometimes traverse highly dissected country, thus affording good opportunities for their study. Up the steep valleys incised perpendicular to the general strike of the rocks, the two contacts are seen to recede westwards from the general strike and to be inclined to the horizon at low angles to the west. In other words the two contacts are regular planes dipping westwards.

In keeping with this analogy to a sedimentary

formation, several of the larger kloofs are floored by diorite which is succeeded along the precipitous walls by acid rocks. Similarly, the tongue-like projections of felsite up the valleys on Elandslaagte No.474 show granophyre resting on felsite with the junction having a low westerly dip.

Further evidence is provided by the low-lying valley between Tauteshoogte and Bothasberg to the south. The down-cutting of this country exposed the basic rocks along the valley of the Blood river and left circumdenuded outliers of acid rocks resting on diorite. The latter feature is well illustrated by the prominent landmark named Spitzkop on which stands the common beacon of the farms Paardekloof K No.99, Blaauwbank No.35 and Kaffirskraal No.62.

The distribution of these rocks near the roof of the complex therefore conforms to the general pseudo-stratification as indicated in the rocks lower in the succession by bands of magnetite, pyroxenite, chromitite, etc. As stated by Hall (9, p.271)[x] the pseudo-stratification in the sense of being regionally visible, is very feeble. As defined by Wager and Deer (5) the cryptic layering is, however, excellently developed.

III. PETROGRAPHY.

a. General features.

The average rocks[*] may be divided into five distinct petrographical types or units on the basis of the orderly variation in the composition and relative abundance of the essential minerals with height in the succession, combined with the sudden appearance or

disappearance / ...

x. Bracketed numbers refer to the bibliography listed at the end of the paper.

*. This qualification excludes those varieties which contain an abnormal concentration of either the light or heavy constituents.

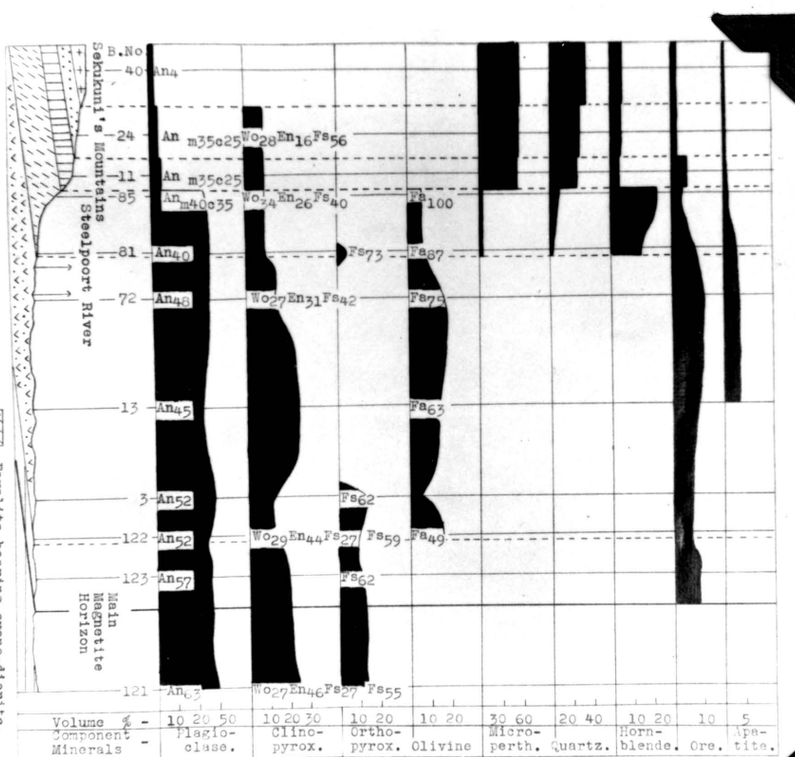


Fig.1B.- Diagrammatic summary of the modal composition by volume of average rocks characterising significant horizons and the composition of certain of their essential minerals.

Fig.1A.- Graphical representation of the subdivision into petrographical types or units, in a generalised diagrammatic section across the strike of the pseudostratified succession.

disappearance of certain significant mineral phases at definite horizons in the pseudo-stratified series.

The arrangement in space of the several petrographical units conforms to the general pseudo-stratification; the lateral variation within each unit is relatively insignificant. The sub-division into petrographical types is illustrated graphically in figure 1A, which represents a generalised diagrammatic section across the strike of the pseudostratified succession from below the Main Magnetite Horizon at Roos Senekal to the granophyre on the Sekukuni Plateau. The modal composition of average rocks characterising significant horizons and the composition of certain of their essential minerals are summarised diagrammatically in figure 1B which illustrates i.a. the dominantly continuous character of the variation resulting in the production of rock types which are transitional into one another.

The rocks characterising the lowest band are diallage-gabbros of a type extensively encountered in the Main Zone of the Bushveld Complex. They are succeeded by olivine-bearing diorites of a type hitherto unreported from the Complex. The major variation in the latter unit comprises the enrichment of the essential minerals in the less refractory component of their particular solid solution series with rise in the succession. Orthopyroxene is restricted to the lower third of this layer and apatite occurs exclusively in its upper horizons.

Alkali felspar, quartz and hornblende make an abrupt appearance in the diorites close to the base of the escarpment and serve to demarcate the fayalite-bearing syeno-diorites from the underlying olivine-bearing diorites. These late-stage minerals continue to be present in small quantities in the former rocks up to their junction with the overlying fine-grained acid rocks.

At this / ...

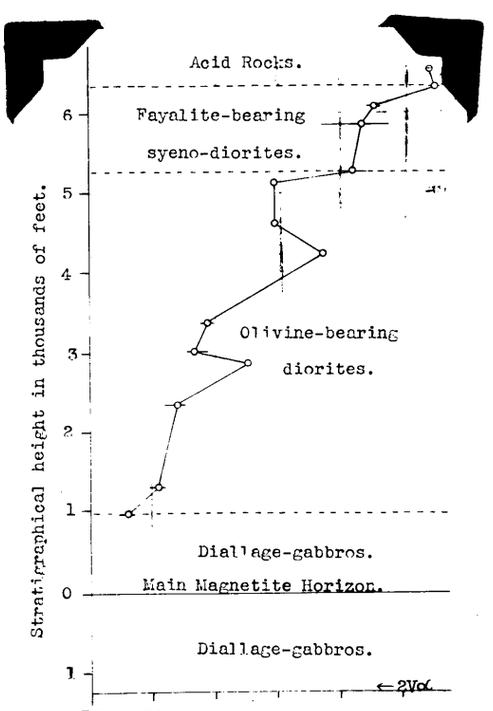


Fig. 2. Variation of 2Vα of the Olivines along a profile across the olivine-bearing varieties.

At this stage an abrupt change occurs in the trend of the curves depicting variations in modal composition of the rocks. Quartz and alkali felspar become the dominant constituents to the virtual exclusion of basic plagioclase and a notable decrease in femic constituents. The fine-grained acid rocks are fairly homogenuous throughout and are succeeded by the typical Bushveld Granophyre without notable changes in modal composition. In the latter rocks a further increase of alkali felspar and quartz takes place, mainly at the expense of femic minerals and no plagioclase more basic than albite is present

b. The component minerals.

1. Olivine.

This mineral does not occur in the diallage-gabbro but appears abruptly on an horizon lying about 1,000 feet vertically above the Main Magnetite Horizon due west of Roos Senekal. There is a slight increase in quantity with rise in the succession followed by a steady decrease in the fayalite-bearing syeno-diorite unit. Olivine also occurs sporadically in the overlying fine-grained acid rocks in quantities not exceeding 3% by volume.

Figure 2 is a graphical representation of the variation of the axial angle of the olivine with height in the succession. In each case the encircled points represent the most prevalent values of $2V_{\alpha}$, while the extremities of the lines drawn through these points indicate the maximum variation in each section. It will be noticed that the variation of $2V_{\alpha}$ in any one section does not exceed 2^{o} in the olivine-bearing diorites but becomes more pronounced after the appearance of the late stage minerals, quartz, alkali felspar and hornblende, when variations of up to 5^{o} are obtained. Even in such

extreme / ...

extreme case the most prevalent value can be selected without much difficulty.

The most notable feature of the variation is the general enrichment of the olivine in the less refractory component, Fe_2SiO_4, with rise in the succession. The rate of enrichment is, however, not constant and increases in the iron-content are generally followed by smaller decreases resulting in the zig-zag course of the curve. The general tendency towards the formation of fayalite is however well marked.

The olivine is characterised throughout by well developed cleavages and cracks parallel to the principal sections of the indicatrix as follows:

	(010)	(001)	(100)
Cleavages	Distinct, regularly and closely spaced	Poor, irregularly spaced	Not developed
Cracks	Irregularly spaced but generally straight and mutually parallel	Short and straight or long and curved	Rarely developed and at best comparable only to those parallel to (001).

2. Orthopyroxene.

This mineral is constantly present in small though variable quantities in the dillage-gabbro and lower third of the olivine-bearing diorite unit. Above the latter horizon hypersthene is rarely encountered and was detected in only two sections, Sp. B. Nos. 79 and 81, in which the orthopyroxene is intimately associated with olivine, which it is seen to replace. The respective compositions of the two members of the reaction pair are listed in table 1.

TABLE 1. / ...

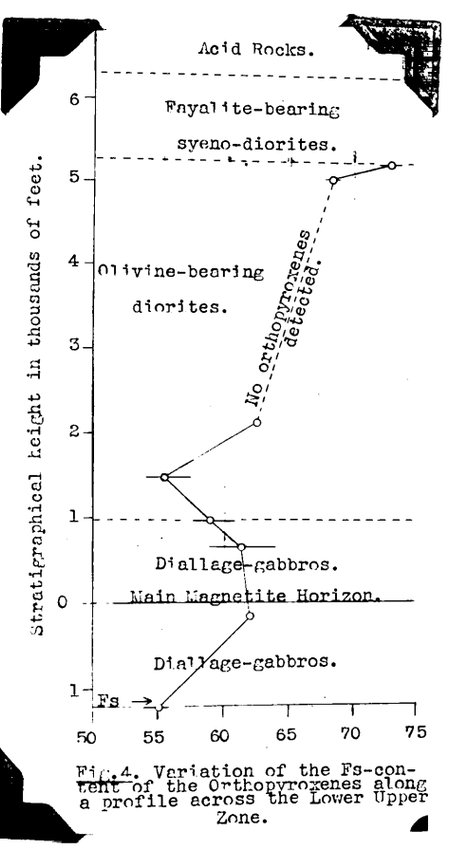


Fig.4. Variation of the Fs-content of the Orthopyroxenes along a profile across the Lower Upper Zone.

TABLE 1.

Sp.B.No.	Composition of olivine	Composition of replacing orthopyroxene
81	87% Fa.	73% Fs.
79	75% Fa.	68.5% Fs.

The disappearance of orthopyroxene in the lower horizons of the olivine-bearing diorite unit is not preceded by a gradual decrease in quantity. This value displays rapid oscillations, which may be attributed in part to the fact that the mineral occurs i.a. as rare interstitial patches of considerable dimensions, which may be partly or completely missed in sectioning.

Figure 3 is a graphical representation of the variation of the axial angle of the orthopyroxene with height in the succession; the corresponding variation in composition is presented in figure 4. Differences in the value of $2V_{\alpha}$ for pyroxenes occurring in a single section are frequently encountered and may amount to as much as 3^{o}.

Owing to the lack of appropriate curves some difficulty was experienced in deducing the chemical composition from the optical properties. The curves furnished by Henry (1, p.—) indicate a minimum value for $2V_{\alpha}$ of 51^{o}, which is higher than the value realised by the majority of the pyroxenes under consideration. The curves supplied by Hess and Phillips (2, p.280) and Winchell (3, p.218) do not include the iron rich varieties.

In one instance the composition of an orthopyroxene as deduced from its determined values of $2V_{\alpha}$ and n_{γ} respectively with the aid of Winchell's curves did not nearly lead to the same result as is evidenced by the following data:

(15. / ...

Determined values	Deduced Composition
$2V_{\alpha}$ = 47°	62% Fs.
n_{γ} = 1.721	34% Fs.

A relevant curve compiled by Hess and Phillips (2, p.282) indicates that the axial angle of an orthopyroxene having n_{γ} = 1.721 should equal 46° which is in close agreement with the determined values listed above.

The curves depicting the variation of the axial angle and deduced chemical composition display much oscillation whereby the tendency towards the enrichment of the pyroxene in the less refractory component, $FeSiO_3$, with rise in the succession, is largely obscured although it is well manifested in the two highest pyroxenes. The following results were obtained for refractive index determinations by the immersion method in Na-light:

Sp.B. No.	Stratigraphical height in feet[x]	Refractive index	Average value for $2V_{\alpha}$
81	+ 5,184	$n_{\beta} > 1.745$	64°
79	+ 5,028	$n_{\beta} = 1.745$	59°
3	+ 1,664	$n_{\gamma} = 1.721$	47°
122	+ 973	$n_{\gamma} < 1.721$	49°

The orthopyroxenes occurring in the lowest horizons of the olivine-bearing diorite unit frequently exhibit inclusions of clinopyroxene, which assumed the form of fairly accurately parallel-sided sheets, with minor undulations and rarely breaking up into rows of flattened blebs. The sheets are arranged in sets of which the individual members are mutually parallel and optically continuous. More than one set is but rarely developed / ...

[x] Being the most conspicuous marker in this area the Main Magnetite Horizon has been employed as reference line for all stratigraphical heights quoted in the text. Positive and negative values refer to specimens collected above and below this horizon.

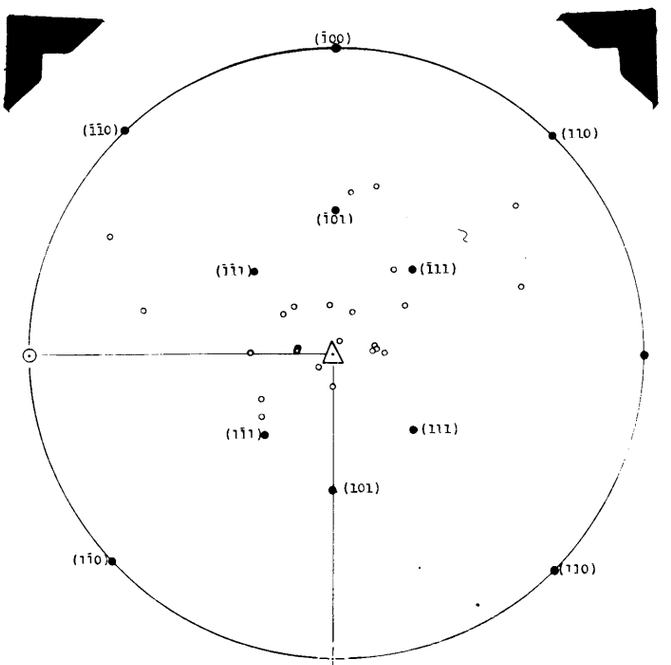


Fig.5. Illustrates the positions of the contact planes between inclusions of clinopyroxene and hosts of orthopyroxene, relative to the ether axes and principal crystallographic faces of the orthopyroxene.

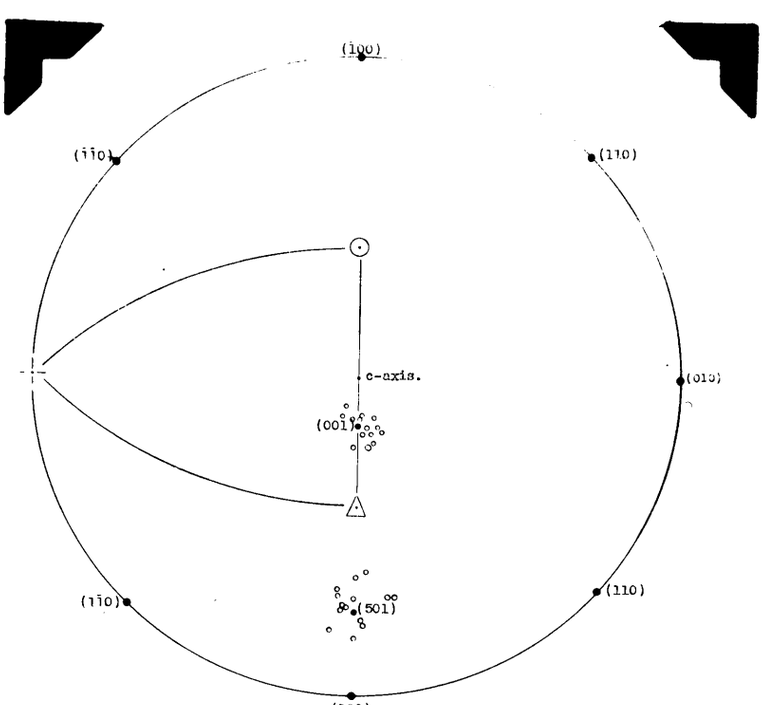


Fig.6. Illustrates the positions of the contact planes between inclusions of clinopyroxene and hosts of orthopyroxene relative to the ether axes and principal crystallographic faces of the clinopyroxene inclusions.

developed in a single host. The sheets comprising a set occasionally extinguish simultaneously with a large adjacent crystal of clinopyroxene, which may be present.

At attempt has been made to determine the position of the sheets within the host, as well as the relative orientation of their respective indicatrices. The method adopted is briefly as follows: The co-ordinates relating to the contact plane as well as those pertaining to the indicatrices of both hosts and inclusions were determined with the aid of the universal stage, and plotted on the same plate. The crystallographic c-axis of each component was then transferred in turn to the centre of the stereogram and the contact plane and ether axes transferred accordingly. Two c-axes were provisionally constructed for each clinopyroxene on the assumption that the extinction angle $Z \wedge c$ equalled 44°: one possible c-axis would then lie 44° from Z in the one direction to X, and the other at the same angle in the opposite direction from Z to X.

In order to obtain a clearer representation of the results obtained collective diagrams were constructed illustrating:

1. The positions of the planes of contact between the inclusions of clinopyroxene and the hosts of orthopyroxene, relative to the principal crystallographical faces and ether axes of the orthopyroxene (figure 5).

2. The same for the clinopyroxenes for each of the two constructed c-axes (figure 6.)

3. The positions of the axial planes of the inclusions relative to the ether axes of the host (figure 7).

The principal crystallographical faces were inserted in the respective diagrams as deduced from the known optic orientation of the minerals concerned and with the aid of Goldschmidt's "Winkeltabellen".

The tendencies / ...

The tendencies shown in each diagram may be summarised as follows: In figure 5 the contact planes do not indicate any tendency either to cluster or to coincide with the pole to any crystallographic face of the host. In figure 6 the contact planes exhibit a marked tendency to be assembled around the pole of either the basal pinacoid or the (501) dome.

It stands to reason that with the method adopted of constructing a pair of positions representing the c-axis in each case, only one position could be the correct one. It is believed that each incorrect position falls near the dome (501) and each correct position coincides with the base (001). The reasons for this belief are as follows:

a. In those instances where the sets of inclusions were in optical continuity with adjacent crystals of clinopyroxene exhibiting traces of the prismatic cleavage, the c-axis was constructed according to the method described by Burri (4). In such case the contact plane after transference invariably approached the pole of the basal pinacoid.

b. The clinopyroxenes are characterised throughout the succession by the presence of minute rods of an opaque substance arranged in closely spaced sheets which were invariably found to be aligned parallel to (001). In each of the investigated examples these structures, exhibited by the inclusions, were found to coincide with the contact plane.

Figure 7 illustrates that while a large percentage of the inclusions have their axial planes orientated approximately perpendicular to that of the host, a number bear no rational relationship towards the latter.

From the enumerated relationships it may be concluded that the inclusions of clinopyroxene are in

the nature of sheets elongated parallel to their basal faces and that their orientation within the host is arbitrary.

These deductions are corroborated by the rare association of the two pyroxenes shown in figure 8. The orthopyroxene host exhibits the characteristic striations parallel to the axial plane (100), which are seen to coincide with the composition plane (100) of the adjacent herring-bone twin of which the two components respectively occur in optical continuity with an adjacent set of sheet inclusions contained in the host. Hence the c-crystallographic axis of the host and the inclusions are parallel to each other, and their respective axial planes are perpendicular to one another. The mutually parallel contact planes of the inclusions are seen to be coincident with the ribs of their respective counterpart in the herring-bone twin, and hence coincide with the basal plane of the clinopyroxene. At the same time they are inclined at an angle of 17° to the basal plane of the host, and consequently do not coincide with any known crystallographic face of the latter.

A single instance was encountered of a different association of the two pyroxenes, i.e. in which the clinopyroxene acted as host to sheet inclusions of orthopyroxene. The relative orientation of the respective indicatrices after transference of their respective crystallographic c-axes to the centre of the stereogram and their remaining optical constants through the same angle, is presented in figure 9

The diagram illustrates that the α_1 of the orthopyroxene (α_1) and the β of the clinopyroxene (β_2) coincide, while the other vibration directions occur in a plane to which the directions of α_1 and β_2 are normal. It further indicates that the plane occupied by the inclusions is coincident with the basal pinacoid of the clinopyroxene host but does not correspond to any crystallographic face in the orthopyroxene. The relative orientation of the indicatrices of the two pyroxenes is identical to that quoted by Nel (10, p.49) for instances where hypersthene was surrounded by clinopyroxene.

The pleochroism of the hypersthene is variable though generally distinct in sections parallel to (100) as

follows / ...

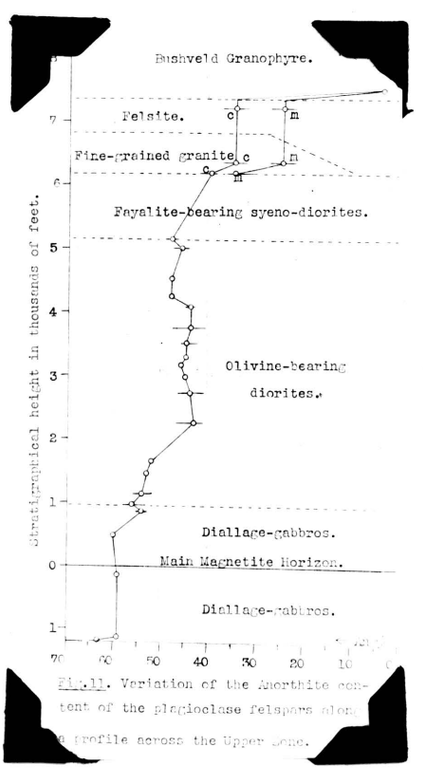


Fig.11. Variation of the Anorthite content of the plagioclase felspars along a profile across the Upper Zone.

follows: α = pale pink, γ = greenish. The striations parallel to the axial plane, which characterise the orthopyroxenes of the Bushveld type are less prominently displayed by the pyroxenes under consideration than by those occurring in the lower zones of the Complex.

3. Clinopyroxene.

This mineral occurs in all the rock types excluding the granophyre. The variation in the axial angle of the unzoned clinopyroxenes with height in the succession is presented graphically in figure 10. The curve is characterised by alternate gradual increases followed by decreases with minor oscillations. Variations in the value of the axial angle in a single section are frequently encountered and usually range from 1° to 3°, although a variation of 7° was obtained in Sp.B. No.83 which yielded the following values for $2V_\gamma$: 55°, 55°, 52°, 51°, 51°, 50.5°, 47°.

The refractive index n_β for Na-light was determined for the pyroxenes of five specimens which were regarded as reasonably representative of the whole range in the succession. The results obtained are arranged in pseudo-stratigraphical order in table 2, to which the corresponding compositions of the pyroxenes as deduced from their optical properties with the aid of the curves compiled by Wager and Deer (5, pp.79-80) have been appended.

TABLE 2.

Sp.B. No.	Rock type	n_β	Composition	Average value for $2V_\gamma$
17	Fine-grained granite	1.738	$Wo_{28}En_{16}Fs_{56}$	54°
85	Fayalite-bearing syene-diorite	1.717	$Wo_{34}En_{26}Fs_{40}$	58°
72	Olivine-bearing diorite	1.717	$Wo_{27}En_{31}Fs_{42}$	48°
125	-do-	1.696	$Wo_{29}En_{44}Fs_{27}$	45°
127	Diallage-gabbro	1.694	$Wo_{27}En_{46}Fs_{27}$	47°

A perusal / ...

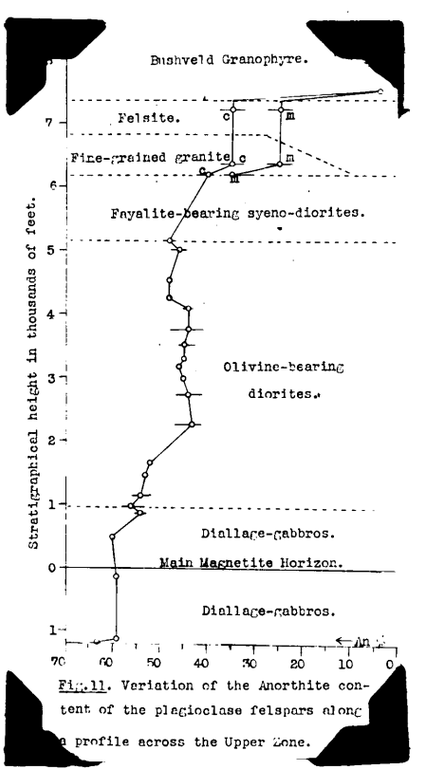


Fig.11. Variation of the Anorthite content of the plagioclase felspars along a profile across the Upper Zone.

TABLE 3.

AVERAGE, MAXIMUM AND MINIMUM DIMENSIONS IN MM. OF CERTAIN OF THE ESSENTIAL MINERALS ARRANGED IN PSEUDO-STRATIGRAPHICAL ORDER.

Stratigraphical height in feet	Plagioclase Elongation		
	4 : 1	2 : 1	1 : 1
6,213	1.6 x 0.4	0.9 x 0.5	0.6 x 0.5
4,659	1.9 x 0.4	1.4 x 0.7	0.5 x 0.4
2,789	2.1 x 0.5	0.8 x 0.4	0.4 x 0.5
973	2.3 x 0.6	1.5 x 0.8	1.0 x 1.2
614	3.3 x 0.8	2.5 x 1.4	1.0 x 1.3
1,126	3.9 x 0.9	2.1 x 1.0	1.0 x 1.1

OLIVINE			Clinopyroxene		
Average	Maximum	Minimum	Average	Maximum	Minimum
0.8 x 0.5	1.2 x 0.6	0.4 x 0.2	1.0 x 0.6	2.0 x 1.0	0.7 x 0.5
1.1 x 0.7	1.8 x 1.0	0.7 x 0.4	1.2 x 0.6	2.7 x 0.8	0.4 x 0.4
1.2 x 0.7	2.7 x 1.2	0.8 x 0.6	1.1 x 0.5	1.9 x 0.4	0.4 x 0.2
2.2 x 1.4	2.8 x 1.8	1.2 x 1.0	0.8 x 0.5	1.2 x 0.7	0.2 x 0.5
Olivine-free			1.1 x 0.7	1.8 x 2.0	0.3 x 0.2
Diallage-gabbros			1.1 x 0.7	2.0 x 1.3	0.3 x 0.2

The salient feature exhibited by the curve relates to the general enrichment of the plagioclase in the less refractory component, $NaAlSi_3O_8$, with rise in the succession. The change in composition is alternately progressive and retrogressive and less pronounced than in the enumerated ferro-magnesian solid solutions.

Zoning is an exceptional feature in the lower horizons but as the top of the fayalite-bearing syeno-diorite is approached it becomes a general feature and is universal in the case of the phenocrysts of the fine-grained acid rocks.

c. Average dimensions of certain of the essential minerals.

The maximum, minimum and average dimensions of certain of the essential minerals at various heights in the succession are listed in table 3. Since the plagio-clase laths exhibit an extensive range in dimensions and elongation in each section it was deemed desirable for the purpose of the comparative table to classify them according to their most prevalent ratios of elongation.

A perusal of the data contained in table 3 will serve to indicate i.a. that whereas the olivine and plagioclase exhibit a gradual and considerable decrease in grain-size from the base to the top of the succession, the dimensions of the diallage crystals remain fairly constant throughout with the lowest values realised at the base of the olivine-bearing diorite unit.

The latter feature can be ascribed to the tendency of the diallage at this particular horizon to occur as a large number of small crystals, frequently assembled in clusters, whereas the clinopyroxenes characterising the higher horizons occur as less numerous but larger individuals.

d. Petrography of the average rocks:

1. Diallage-gabbros.

The / ...

The bed-rock overlying the Main Magnetite Horizon at Roos Senekal is obscured by a thick mantle of red turf, for a surface distance of 1.5 miles. A specimen collected from a solitary outcrop (Sp.B. No.123) shows a much closer agreement with the diallage-gabbros underlying the magnetite than with the overlying olivine-bearing diorites and has therefore been referred to the former group although it is customary to regard the Main Magnetite Horizon as the natural boundary between the Main and Upper Zones of the Bushveld Complex.

Table 4 contains the data relating to this specimen and three others collected below the magnetite.

TABLE 4.

DATA PERTAINING TO THE DIALLAGE-GABBROS.

Sp.B. No.	Stratigraphical height in feet	Modal composition by volume and most prevalent composition of certain of the essential minerals							
		Plagioclase		Pyroxenes			Quartz	Hbl.	Ore
				Ortho-		Clino-			
		Vol.%	An.%	Vol.%	Fs.%				
123	+ 614	57	60	12	62	21	-	X	10
127	- 154	68	60	3	62	29	.5	X	X
128	- 1,126	70	59	5	-	24	.5	X	X
121	- 1,207	59	63	14	55	26	1	X	X

Note: A cross (X) indicates the presence in quantities not exceeding .5% by volume of the mineral concerned.

Under the microscope the diallage-gabbros are seen to be composed of:

Plagioclase laths which exhibit an extensive range in dimensions and elongation. The mineral is usually unaltered and with faint zonal structure. In some of the larger crystals the zoning is more marked with differences in composition between core and mantle amounting to 4% An. The zoning is of the normal type with the core and mantle not sharply defined. Regular cracks lined with green material of which the identity is uncertain, occasionally traverse the crystals.

Clinopyroxene / ...

Clinopyroxene is the dominant femic mineral and occurs as large interstitial crystals with arm-like projections between felspar laths, or as small grains wedged between adjacent laths, or assembled in clusters with little or no mutual interpenetration. Broad bands of lesser birefringence are prominent in sections approximately perpendicular to the plane of the optic axes. The bands are of variable lengths, and do not traverse the whole crystal, nor do they extinguish simultaneously with the host and frequently contain hair-like inclusions of an opaque material orientated perpendicular to the walls of the individual bands. Lombaard (6,p.164) suggests "that the lamellae owe their low birefringence to the separation of the opaque material, which seems to be iron oxide."

Zoning is a conspicuous feature and is best seen on rotating crystals around the control (or east-west) axis of the universal stage after having brought their optic normals to coincide with this axis. The core gradually merges into the mantle and the axial angle of the latter exceeds that of the former by as much as 10^{o} in extreme cases, indicating a progressive enrichment in $FeSiO_3$ from core to mantle.

The clinopyroxene occasionally exhibits incipient alteration in which case it becomes slightly turbid and clouded by flakes of hornblende and specks of ore.

Orthopyroxene occurs in two distinct forms as follows: Subhedral crystals of moderate dimensions commonly extinguishing in groups: also in larger interstitial patches, reaching dimensions of 12 x 8 mm. in extreme cases, and partially or completely enveloping felspar laths resulting in a sub-ophitic texture. In this respect the texture differs markedly from that

characterising / ...

characterising the Bushveld Gabbros in general and described by Lombaard (6, p.26) as follows: "Hypersthene sometimes also exhibits a uniform orientation over large areas. Such areas of hypersthene, however, are not markedly ophitic or sub-ophitic ..... The relationship of felspars to hypersthene mostly conforms to his (Krokström's) definition of sub-doleritic texture."

A poikilitic texture results from lamellar and rounded inclusions of diallage embedded in orthopyroxene. Interpenetration of the two varieties of pyroxene is much in evidence.

Quartz occurs sporadically in small quantities as angular grains wedged between felspar laths and generally extinguish in groups. The silicate minerals frequently exhibit incipient alteration in the proximity of quartz grains.

Hornblende occurs exclusively as small flakes associated with clinopyroxene which it is seen to replace. In the gabbros underlying the Main Magnetite Horizon ore appears as occasional specks, generally embedded in diallage. Above this horizon iron ore is well represented as irregular grains, partially enclosing felspar laths and "growing round" ferromagnesian minerals.

2. Olivine-bearing Diorites.

The topographical depression extending westwards from the extensive dipslopes of the Main Magnetite Horizon at Roos Senekal is terminated on Banksloot No. 119 by a prominent north-south trending ridge aligned parallel to the general direction of strike in this area. The rocks composing the ridge are rendered macroscopically distinguishable from the underlying diallage-gabbros by their relatively closer grain, the darker colour of their femic constituents and by the presence

of / ...

of yellowish grains of olivine. They mark the base of the olivine-bearing diorites, which occupy the tract of Bushveld country extending westwards for a distance of 7 miles from the above-mentioned ridge to the foot of the main escarpment of the Sekukuni's Mountains.

Table 5 contains the data pertaining to average rocks from significant horizons within this petrographical unit.

TABLE 5.

DATA PERTAINING TO THE OLIVINE-BEARING DIORITES.

Sp.B. No.	Stratigraphical height in feet	Modal composition by volume and most prevalent composition of certain of the essential minerals								
		Plagioclase		Pyroxenes			Olivine		Ore	Apatite
		Vol.%	An.%	Ortho-		Clino-	Vol.%	Fa.%		
				Vol.%	Fs.%					
72	+ 4,659	55	48	-	-	14	18	75	11	4
13	+ 2,943	47	45	-	-	27	15	63	8	3
14	+ 2,700	48	43	-	-	29	15	61	8	-
3	+ 1,166	59	52	17	? 63	12	5	-	7	-
122	+973	50	52	11	59	16	17	49	6	-

The rocks composing the upper nine tenths of this unit contain andesine felspar and are hence diorites (7). Although the underlying one tenth contains labradorite (and hence composed of gabbro) it is linked to the rest by the presence of olivine, thus forming a unit. For convenience of reference this unit is referred to as composed of diorite in spite of the gabbro contained in its basal portion.

Microscopic investigation reveals the olivine-bearing diorites to be composed of:

Olivine which in the lower third of this unit exhibits a distinct tendency to occur as relatively few but large crystals, with occasional marginal indentations due mainly to interference with plagioclase laths. Less

frequently / ...

frequently small laths of plagioclase are completely enclosed within the marginal portions of the larger crystals. These relationships suggest that the orthosilicate is of relatively early crystallization but that at least small plagioclase laths were available for incorporation towards the cessation of olivine crystallization.

In the upper two-thirds of this unit the olivine occurs in a different way, i.e. as a larger number of smaller crystals, which occasionally form clusters of interlocking crystals, of which the total area is approximately equal to that of the individual crystals occurring in the lower horizons. In addition, the ferro-hortonolite bears a distinct interstitial relationship towards the andesine, and penetration of olivine by diallage is much in evidence. These relationships indicate a relatively late period of crystallization for the ferro-hortonolite.

Diorites with a low olivine-content furnish evidence of resorption and repair of olivine by orthopyroxene. In such cases the latter either occupies embayments in the olivines or completely envelops them. A decrease in the olivine-content is however not accompanied by a corresponding increase in the amount of orthopyroxene.

The orthosilicate is generally unaltered and free from inclusions, and the cracks are dusted with iron ore. The intensity of the pleochroism increases with the tenor of iron, and becomes distinct in the ferro-hortonolite in the following tints: β - orange yellow, α - γ - pale yellow.

There is close agreement in respect of the nature and range of zonal structure, the presence of bands of lesser refraction and the development of salite structure between the clinopyroxenes occurring in the

lower / ...

lower 1/8th of the olivine-bearing diorite unit and those of the underlying diallage-gabbros. Whereas the last feature is common to the clinopyroxenes throughout the succession, the first two are peculiar to the diallage occurring in the lower horizons. In addition, the clinopyroxene of the lower 1/8th of this unit shows a marked tendency to be assembled in clusters of interlocking grains of varying shapes and sizes.

From Specimen B. No.3 (+1,166 ft.) upwards the diallage assumes a different habit: clustering diminishes as the mineral tends to form fewer but larger crystals, with marked interstitial relationships towards the plagioclase and penetration of olivine. The change in habit is accompanied by a change in colour, which, though feeble at first, rapidly increases in intensity, with the pyroxenes in the upper half of this unit exhibiting a distinct pleochroism as follows: α = brownish green, $\beta = \gamma$ - dull brown.

Plagioclase occurs as regular lath-shaped crystals, exhibiting minor indentations resulting from interference with other crystals during the closing stages of felspar crystallization. The mineral is generally unaltered with weak zonal build. Occasionally the zoning is more marked with differences in the composition of core and mantle amounting to 6% An. The zoning is of the normal type and the core and mantle merge gradually.

The hypersthene occurring in the lower third of this unit contains abundant shoot inclusions of clinopyroxene, and generally forms physical units with projections partially enveloping clinopyroxene or penetrating between adjacent felspar laths. Less frequently the mineral occurs as interstitial patches enclosing plagioclase laths, clinopyroxenes and ore grains.

In the / ...

In the upper 2/3rds of this unit the hypersthene occurs sporadically in small quantities, and is usually intimately associated with olivine.

Oxidic ore is present in small but fairly constant quantities throughout this unit. It occurs as irregular grains, partially enclosing felspar laths, and "growing round" ferro-magnesian minerals, indicating a relatively late period of crystallization. Specks of sulphidic ore occur sparingly and are usually enclosed by oxidic ore.

Kelyphitic borders about ore grains are a prominent feature in the lower half of the olivine-bearing diorite. In contact with felspars the corona is composed of strongly pleochroic brown mica, or feathery reaction products or both, with the latter forming the outer fringe. Lombaard (8, p.166) observed analogous structures in a magnetite-norite and states that the feathery rims, where sufficiently coarse to be determined, were composed of intergrown felspar and pyroxene. In commenting upon the very sporadic development of feathery reaction rims between iron-ore and felspar, Wager and Deer (5, p.96) state that although no conclusive evidence can be given the coronas were probably produced at moderately low temperatures at points where volatile constituents happened to be concentrated.

In contact with pyroxene, especially ortho-pyroxene, the rims are composed of small olivine crystals of variable orientation. In some instances where an ore grain abutts against both pyroxene and felspar, an olivine rim may occur against the former and a composite biotite and feathery corona against the latter. The arrangement is sometimes remarkably uniform, although the olivine rims occasionally overlap into the felspar contact.

Apatite first appears in Sp.B.13 (+2,945 ft.)

and is ...

TABLE 6.

DATA PERTAINING TO THE FAYALITE-BEARING SYENO-DIORITES

Sp.B. No.	Stratigraphical height in feet	Modal composition by volume and most prevalent composition of certain of the essential minerals.														
		Plagioclase		Pyroxenes			Olivine		Quartz	Micro-perthite	Hornblende		Biotite	Ore	Apatite
				Ortho-		Clino-									
		Vol.%	An.%	Vol.%	Fs.%	Vol.%	Vol.%	Fa.%			Green	Colour-less			
85	6,273	50	40_c35_n	-	-	8	6	100	7	3	22	X	X	3	1
83	5,772	54	44	1	-	12	7	90	2	2	7	3	1	6	3
81	5,184	53	48	5	73	7	7	87	2	3	6	3	4	7	3

According to the quantitative classification proposed by P. Niggli these rocks should be described as fayalite-quartz-alkali felspar-bearing diorites, but to avoid repetition of this rather lengthy designation, they will be referred to as fayalite-bearing syeno-diorites despite the slight discrepancy in their content of quartz and alkali felspar.

and continues to be well represented in the upward succession. The idiomorphic crystals measuring 0.1 x 0.1 mm. in cross-section and 0.3 x 0.1 mm. in longitudinal section exhibit a tendency to be restricted to the marginal portions of the andesine and ferro-hortonolite. The diallage and ore usually contain apatite from core to mantle. The apatite therefore appears to be relatively late in the crystallization sequence from the moment of its first appearance.

3. Fayalite-bearing Syeno-diorites.

Despite their being quantitatively subordinate to the rocks comprising the various other units, these diorites are of special significance in view of the remarkably ferriferous nature of their femic constituents and the appearance of the late stage minerals, quartz, alkali felspar and hornblende. They represent a significant stage in the differentiation and herald the development of granitic rocks, at a junction when the ferromagnesian minerals have been thoroughly enriched in the less refractory component of their respective solid solution series.

Table 6 contains the data relating to specimens collected respectively from the base, centre and roof of this unit.

Investigation with the microscope reveals the following:

The appearance of the late stage minerals, quartz, alkali felspar and hornblende is accompanied by a higher degree of alteration and replacement of the relatively more refractory minerals, than that characterising these silicates in the lower horizons.

Zoning of the plagioclase in two rather special ways is a prominent feature: in the more prevalent type the laths are for their greater part homogenuous (An_{c40})

with / ...

with narrow, sharply defined mantles of less basic material (An_{m20}) separating them from interstitial quartz. A number of particularly large cyrstals are composed of three layers of which the core and mantle of approximately identical compositions (An 35) are separated by a more basic median layer (An_{43}). Decomposition is irregular and not very intense .

Olivine occasionally occurs as large subhedral crystals, but more frequently as small crystals, exhibiting a tendency to form clusters. The orthosilicate was evidently affected by late stage reactions with the residual magma, resulting in partial resorption and subsequent repair by either orthopyroxene or colourless amphibole.

Platy inclusions of an opaque substance, orientated parallel to one or more crystallographic directions in a single crystal are much in evidence, particularly towards the cores of the larger crystals. The inclusions are most frequently arranged parallel to the pinacoids (001) and (100).

Although the pleochroism is to some extent masked by the presence of opaque inclusions it is nevertheless distinct with β - orange yellow and γ - α - pale yellow.

The occasional unaltered crystals of clinopyroxene exhibit a brown colour and distinct pleochroism as follows: γ - β - dull brown, α - brownish-green. The majority, however, occur in various stages of replacement by hornblende whereby the colour and pleochroism are obscured. The dominantly subhedral character suggests a relatively early period of crystallization.

Quartz and microperthite are constant constituents, present in small quantities and variable proportions. The former occurs mainly as angular grains

wedged / ...

wedged between the more refractory silicates and in optical continuity over considerable areas.

The microperthite occupies the interstitial areas and completely envelops various silicates of earlier crystallization. In addition the mineral frequently forms protective mantles about the plagioclase laths, particularly when the laths are bordered by quartz, when it may frequently be graphically intergrown with the latter. The intergrowth of alkali felspar is on a very fine scale and exhibits a turbid reddish appearance.

The green hornblende originated largely by alteration of clinopyroxene. The replacement is selective being more intense along the margins, where the uralite commonly forms a continuous rim, with disconnected projections towards the interior. The various disconnected patches of hornblende replacing a single crystal of pyroxene extinguish simultaneously and are orientated in such a way that the respective optic axial planes of the reaction pair are parallel to each other. In addition one optic axis of the hornblende invariably coincides with a similar optical direction in the clinopyroxene, but the respective remaining vectors are inclined to one another.

A small proportion of the hornblende occurs as interstitial patches enclosing felspar laths and apatite crystals, without there being direct evidence of the derivation of this type of hornblende from diallage. Although such patches are occasionally in optical continuity with uralite, it is probable that they represent material precipitated directly from the magma. All the green hornblende is strongly pleochroic as follows: α = pale brown, β = brownish green, γ = dark green. The axial angle $2V_{\alpha}$ varies between 58° and 60°.

When present in relatively large quantities the biotite occurs as large interstitial patches "growing

around" / ...

around" olivine and pyroxene, and containing inclusions of andesine, apatite and ore. In the higher horizons this mica is sparingly represented as interstitial flakes and scaly aggregates associated with rods of iron ore. The mineral is strongly pleochroic as follows: α = pale brownish yellow, β = reddish brown, γ = deep red brown.

Orthopyroxene is restricted to the lower horizons where it occurs sporadically in small quantities, largely associated with olivine in a reaction relationship. The replacement is markedly selective, thus whereas a considerable percentage of olivine crystals were probably not involved in the late stage reactions others have been extensively resorped. The remnants of orthosilicate embedded in the replacing pyroxene are frequently clouded with iron ore, probably liberated during the reactions.

A considerable percentage of the hypersthene occurring as interstitial patches bear no evidence of their derivation from olivine and have probably been directly precipitated from the magma.

Ore is uniformly distributed as small grains, with a greater tendency towards idiomorphism than in the lower units.

The apatite is concentrated mainly in the late stage minerals, is fairly abundant in the olivine and pyroxenes and is occasionally enclosed within the marginal portions of the andesine laths.

Colourless amphibole attains its strongest development in the lower horizons, where it is commonly associated with olivine in one of the following ways: As a partial or complete marginal selvedge; as a groundmass of variously orientated fibres containing remnants of olivine, and finally as isolated aggregates of partially superimposed scales embedded in olivine. Instances

of / ...

TABLE 11.

CHEMICAL ANALYSES OF GABBROS AND DIORITES.

Sp. No.	L.400	L.410		B.72[x]	B.85[x]
Text No.	1	2	3	4	5
SiO_2	51.52	50.72	52.48	45.26	49.30
TiO_2	0.44	0.44	0.56	1.70	1.80
Al_2O_3	17.10	16.40	16.95	13.42	13.87
Fe_2O_3	2.64	1.55	1.62	4.63	2.38
FeO	5.74	6.66	6.68	18.35	16.78
MnO	0.02	0.02	0.22	0.39	0.43
MgO	10.72	8.55	7.50	4.19	1.77
CaO	10.00	13.30	11.06	8.50	7.49
Na_2O	1.70	2.20	2.50	2.97	3.52
K_2O	0.20	0.20	0.30	0.25	1.17
P_2O_5	0.02	0.06	0.10	trace	0.45
H_2O	0.13	0.40	0.30	0.76	1.27
H_2O	0.01	0.00	0.07	0.03	0.06
Total	100.06	100.50	100.34	100.45	100.29

Norms.

Q	2.4	-	1.98	-	-
or	1.11	1.11	1.67	1.67	6.68
ab	14.15	18.34	20.96	25.15	29.89
an	38.64	34.47	34.47	22.52	18.64
di (Wo	4.64	13.22	8.12	8.24	6.74
di (En	3.30	8.40	4.90	2.30	1.00
di (Fs	0.92	3.96	2.77	6.34	6.33
hy (En	23.50	8.40	13.80	1.50	2.21
hy (Fs	6.86	4.22	7.66	3.83	13.72
ol (Fo	0.00	3.22	0.00	4.62	0.84
ol (Fa	0.00	1.63	0.00	13.67	5.09
il	0.76	0.76	1.06	3.19	3.49
mt	3.71	2.09	2.32	6.73	3.47
Ap	0.00	0.00	0.34	0.00	1.01
H_2O	0.18	0.46	0.37	0.79	1.33
Total	100.17	100.28	100.42	100.55	100.44

Molecular values.

Si	114.0	111.0	123.0	99.47	125.70
al	22.0	21.0	23.5	17.42	20.83
fm	50.5	42.5	42.5	55.80	48.08
c	23.5	31.5	28.0	20.04	20.52
alk	4.0	5.0	6.0	6.73	10.56
k	0.08	0.05	0.07	0.06	0.17
mg	0.71	0.66	0.62	0.25	0.14
c/fm	0.47	0.74	0.65	0.36	0.43

x Denotes new analyses.

1. Spotted norite, Schaapkraal No.442, Lydenburg District. Analyst: B. Lombaard (Quoted from 6, p.18).

2. Norite, ½ mile east of township of Roos Senekal. Analyst: B. Lombaard (same source as 1).

3. Norite, Bon Accord Quarry, North of Pretoria. Analyst: F. de Quervain. (Quoted from 8, p.165).

4. Olivine-bearing diorite, Duikerkrans No.104, Middelburg District. Analyst: C.J. Liebenberg.

5. Fayalite-bearing Syeno-diorite, Duikerkrans No.104, Middelburg District. Analyst: C.J. Liebenberg.

of grünerite (3, p.244) occurring as interstitial grains wedged between felspar laths are rarely encountered and afford the only evidence of colourless amphibole not obviously related to olivine.

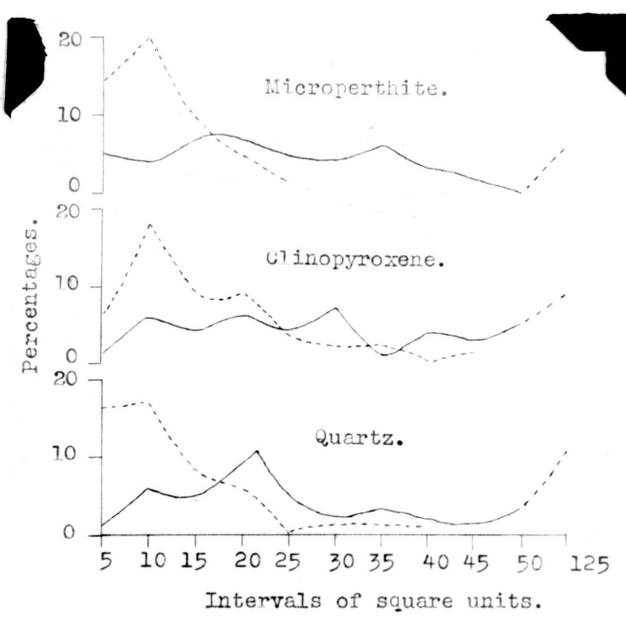
The colourless non-pleochroic grünerite encloses patches of amphibole exhibiting the following pleochroism: β = colourless, γ = green. Similarly the above-mentioned marginal selvedges are occasionally of a composite character, with the colourless selvedge enclosed by an outer ring of green amphibole.

The prismatic cleavages are well developed and pass uninterruptedly from one variety to the other, and lamellar twinning on (100) is a common feature. Owing to its fibrous nature, small dimensions and repeated twinning it is difficult to obtain more than an approximate idea of the optical properties of the colourless amphibole. The value of $2V_{\alpha}$ ranges from 83° to 87°, the extinction angle $Z \wedge c$ from 16° to 18° and the refractive indices are n_{γ} = 1.6938 and n_{β} = 1.6810

4. <u>The fine-grained acid rocks</u>.

This group comprises fine-grained porphyritic granophyric granite and porphyritic granophyric felsite. The former variety is restricted to the southern portions of the Sekukuni's Mountains where it is seen to separate the diorite from the overlying felsite by which it is succeeded rather abruptly after becoming slightly more fine-grained. Traced northwards along the escarpment the fine-grained granite is seen to taper out on De Wig No.32 after which the diorite is seen in direct contact with the felsite which continues as a band parallel to the escarpment. A tongue-like projection of granite extends down the valley of the main stream on Uitkyk No.36 showing felsite resting on granite. The enumerated features indicate that the granite occurs in the form of a sheet-

like / ...



Diag.1. Comparative representation of the variation in grain-size of the essential minerals, excluding phenocrysts, composing the acid rocks.
---- Trend in the felsite.
—— Trend in the granite.

like body separating diorite from felsite and tapering out towards the north.

The crystalline character of the granite is readily seen in handspecimen; the average dimensions of its essential constituents being .09 x 1.1 mm. It is therefore too coarse to be termed a felsite, and is best described as a fine-grained granite.

The felsite closely resembles the Bushveld Felsite in respect of general appearance in handspecimen, and grain-size which averages .05 x .07 mm. Under the microscope the felsite occasionally exhibits sub-ordinate streaks and irregular patches of relatively coarse grained material having a grain-size comparable to that of the fine-grained granite.

Diagram 1 is a comparative representation of the variations in grain-size of the essential minerals, excluding phenocrysts, composing the felsite and fine-grained granite respectively. The major and minor diameters of 50 consecutive grains of each constituent encountered on traverses 1 mm. apart were determined in units equalling .02 mm. and the percentage frequency calculated for intervals of 5 square units. The results obtained are embodied in the diagram which illustrates the following features: The felsite is not only more fine-grained but also more even-grained than the granite; the dominant grain-size of the latter exhibits a greater range, and the total range is similarly more extensive than in the felsite.

Other minor differences relating mainly to the relative abundance of various phenocrysts will be noted in the following microscopic description, which will be given collectively for both varieties in order to avoid unnecessary repetition.

Plagioclase occurs exclusively as phenocrysts

which / ...

which are generally thoroughly decomposed. The occasional unaltered crystals exhibit normal zoning with the core and mantle not sharply defined, ($An_{c35}An_{m25}$), and are enclosed by extensive selvedges of microperthite which frequently occupies deep embayments. The phenocrysts are relatively more abundant in the granite where they exhibit a tendency to cluster, whereas in the felsite they occur as uniformly distributed individuals.

Clinopyroxene occurs in the matrix as small subhedral crystals. Close scrutiny of their contacts with quartz and microperthite reveals minor irregularities indicating an overlap in their respective periods of crystallization.

Large crystals of clinopyroxene associated with the clusters of plagioclase phenocrysts, to which they bear an interstitial relationship, are encountered in the granite. Long blade-like individuals with ragged margins and physical discontinuities are exceptionally seen to traverse the groundmass. The pyroxenes enclose small ore particles and occasionally exhibit a moderate replacement by hornblende. The clinopyroxenes are characterised throughout by a green colour and the following pleochroism: α - yellowish green, β - green, γ - green.

The small and variable quantities of hornblende occur in various stages of replacement of pyroxene. The several disconnected patches of uralite replacing a single crystal of pyroxene generally extinguish simultaneously, more rarely, the replacement yields an aggregate of variously orientated, partially superimposed scales.

Microperthite occurring as anhedral grains, with sinuous margins, is the dominant constituent and in conjunction with quartz and subordinate clinopyroxene

acts / ...

acts as matrix to plagioclase phenocrysts. Individual grains of microperthite rarely attain such dimensions as would justify their designation as phenocrysts and would moreover be macroscopically indiscernible in the general ground-mass. The alkali felspar is characterised by a turbid red colour.

The quartz occurs as clear, sub-angular grains. In specimen B. No.32, however, a large proportion of the quartz crystals contain a nucleus of opaque inclusions. A variable proportion of the quartz and microperthite are graphically intergrown.

The micropegmatite-content of the fine-grained acid rocks varies from zero to 80% and appears to vary indiscriminately, although the highest values are generally attained in the lower horizons. Since the most prevalent values lie between 10 and 50% the names of these rocks should be qualified by the prefix "granophyric".

Apatite is sparingly present as small idiomorphic grains. More rarely it assumes the form of relatively large blade-like crystals.

Magnetite occurs in two distinct forms: The relatively anhedral grains are mainly associated with the clusters of plagioclase phenocrysts, whereas the smaller idiomorphic crystals are uniformly distributed throughout the matrix.

Fluorite is sparingly represented as interrupted irregular shreds and larger anhedral grains.

Calcite is occasionally present as irregular stringers and anhedral grains.

The modal composition by volume of average fine-grained granite and felsite is presented under columns I and II respectively of table 7.

TABLE 7 / ...

TABLE 7.

	I	II
Sp. B. No.	17	24
Plagioclase	3	1
Microperthite	58	59
Quartz	24	28
Clinopyroxene	9	8
Hornblende	2	3
Ore	4	1
Apatite	.5	.5
Fluorite	X	X
Calcite	X	X

Whilst being indistinguishable in other respects from the typical Tauteshoogte felsite one specimen B. No.28, from Duikerkrans No.104 is marked by containing 3% by volume of fayalite which exhibits no evidence of a derived origin, or of having been affected by late stage reactions. The olivine occurs as subhedral grains measuring .07 x .08 mm., uniformly distributed through the general matrix, or as larger crystals measuring 0.5 x 0.4 mm., frequently assembled in groups and generally associated with the above-mentioned patches of relatively coarse-grained material.

Although the pleochroism is to some extent masked by the presence of platy inclusions of an opaque substance, orientated parallel to one or more crystallographic directions within a single crystal, and which are particularly abundant towards the cores of the larger crystals, it is nevertheless distinct as follows: α - γ - pale yellow, β = orange yellow. The average value of $2V_{\alpha}$ for seven determinations which ranged from 47^{o} to 49^{o} amounted to 48^{o}, indicating an average composition of Fa_{100} which is in accordance with the remarkably ferriferous character of the ferro-magnesian minerals

characterising / ...

characterising the highest horizons of the Upper Zone in general.

Refractive index tests by the immersion method in Na-light indicated that n_β exceeded 1.843.

Mineralogically the fine-grained acid rocks of Tauteshoogte can be distinguished from the Bushveld Felsites mainly by their relatively more basic phenocrysts ($An_{c35}An_{m25}$) and slightly lower quartz content. The composition of the insets characterising the Bushveld Felsites are stated by Lombaard (8, p.138) "to range from An_0 to An_{10} and that the figure An_5 must be very near the average." In addition, clinopyroxene is the dominant ferro-magnesian constituent of the Tauteshoogte rocks which are on the whole slightly more melanocratic than the typical Bushveld acid rocks, of which hornblende and subordinate biotite are the exclusive femic minerals.

The chemical analyses listed in Table 12 reveal that the fine-grained granite also differs from the typical Bushveld acid rocks by a relatively lower silica content and higher content of total iron; the Tauteshoogte felsite differs similarly though to a lesser extent.

These distinguishing features characterise the fine-grained granite, and to a lesser extent the Tauteshoogte Felsite, as being more basic than the typical acid rocks which are considered to represent the residual magma.

It further seems advisable to include these slightly less acid rocks in the Upper Zone where they conform by their sheet-like distribution to the general pseudo-stratified structure.

A rock-section cut perpendicularly across the plane of contact between the fayalite-bearing syeno-diorite and felsite exhibits the following features: The

felsite / ...

x (Note to Table 12.)

Microscopic investigation of a section cut from the analysed rock which is described by Hall (8, p.253) as "a dark grayish, slightly less compact felsitic rock, that is fairly extensive over the highest parts of Tauteshoogte.", revealed that it corresponded in every respect to a fine-grained granite, as previously defined in the text. This conclusion is corroborated by its chemical characteristics, which bear a close resemblance to the analysis quoted under 1.

TABLE 12.

CHEMICAL ANALYSES OF ACID ROCKS.

Text No.	1	2	3	4	5	6
SiO_2	67.83	68.25	72.60	71.35	70.12	72.50
TiO_2	0.45	0.50	0.30	0.30	0.45	0.20
Al_2O_3	11.10	11.15	11.90	10.15	10.50	12.40
Fe_2O_3	5.24	1.95	3.05	3.10	3.90	3.35
Fe O	4.20	6.50	2.30	4.70	3.64	2.15
MnO	0.08	0.00	0.00	0.00	0.07	0.00
MgO	0.30	0.50	0.40	0.30	0.20	0.25
CaO	1.83	3.40	1.60	2.90	1.60	0.50
Na_2O	2.80	3.00	3.05	3.20	3.70	2.80
K_2O_5	4.90	4.05	3.65	3.60	3.74	4.70
P_2O_5	0.10	0.35	0.10	0.00	0.10	0.10
H_2O	0.75	0.05	0.70	0.30	0.80	0.75
H_2O	0.10	0.05	0.10	0.30	0.10	0.20
Total	99.68	99.75	99.75	100.20	99.92	99.90

Norms.

Q	28.68	25.98	36.66	32.34	31.68	36.84
or	28.91	24.46	21.68	28.91	21.68	27.80
ab	23.58	25.18	25.68	19.91	30.39	23.58
an	3.34	5.00	7.23	2.78	4.45	1.67
c	0.00	0.00	0.00	0.00	0.00	2.14
di (Wo	2.09	3.94	0.00	4.87	1.16	0.00
di (En	0.50	0.50	0.00	0.60	0.20	0.00
di (Fs	1.72	3.83	0.00	4.75	1.06	0.00
hy (En	0.20	0.70	1.00	0.10	0.30	0.60
hy (Fs	1.06	5.54	1.19	0.79	1.72	0.79
il	0.76	0.91	0.61	0.61	0.76	0.46
mt	7.66	3.02	4.41	4.14	5.57	4.87
ap	0.34	1.01	0.34	0.00	0.34	0.34
H_2O	0.85	0.04	0.80	0.60	0.97	0.95
Total	99.69	100.47	99.60	100.40	100.28	100.04

Molecular Values.

si	305	294	385	339	340	399
al	29.50	28	37.5	28.0	33.0	40.0
fm	35.5	32.5	25.5	31.5	30.5	25.5
c	9.0	16.0	9.0	15.0	8.5	3.0
alk	26.0	23.5	28.0	25.5	28.00	31.5
k	0.54	0.57	0.44	0.42	0.40	0.52
mg	0.06	0.09	0.13	0.06	0.05	0.08
c/fm	0.25	0.51	0.35	0.48	0.28	0.12

1. Fine-grained granite, Tauteshoogte, Middelburg District. Analyst: B.V. Lombaard. (Quoted from 6, p.13)

2. Fine-grained granite, Tauteshoogte, Middelburg District, Analyst: H.G. Weall (Same source as 1.)

3. Felsite, Uitkyk No.36, Middelburg District. Analyst: H.G. Weall. (Same source as 1.)

4. Purplish grey felsite, Baviaansnek, North of Tauteshoogte. Analyst: H.G. Weall. (Quoted from 9, p.252).

5. Granophyre, Uitkyk No.36, Middelburg District. Analyst: B.V. Lombaard. (Same source as 1.)

6. Typical Bushveld Felsite, Derwent Siding, east of Middelburg. Analyst: H.G. Weall. (Quoted from 8, p.155).

note / ...

felsite retains its normal characteristics up to approximately 2 mm. from the line of junction. Over the adjacent relatively narrow band, extending parallel to the contact, the felsite is markedly enriched in green clinopyroxene and microperthite to the virtual exclusion of quartz.

The fayalite-bearing syeno-diorite on the other hand exhibits no such marginal modification, but retains its normal features up to the line of junction, which is of a slightly undulatory character with the embayments occupied by the modified felsite.

These features suggest that the felsite crystallized subsequent to the fayalite-bearing syeno-diorite.

5. The Bushveld Granophyre.

The typical granophyre which is widely distributed in the Bushveld Complex, has been investigated on several occasions, and since that portion of it appearing on the map does not present notable new features, only a brief description will be presented.

Micrographic intergrowths of quartz and turbid red microperthite are the dominant constituents and vary from rather coarse to feathery, pinnate types. A small percentage of the quartz and alkali felspar is not intergrown and appears as phenocrysts in the fine-grained matrix of micropegmatite. Phenocrysts of albite (An_{4-6}) evidently free from potash felspar are occasionally encountered.

Green hornblende is the dominant melane and occurs as interstitial anhedral flakes, long needles and aggregates of partially superimposed scales. Subordinate biotite is either associated with the hornblende aggregates or occurs as individual flakes. Ore, titanite and fluorite are relatively abundant accessories, whereas

zircon / ...

zircon and apatite are rare.

The volumetric mode of a selected specimen of which the micropegmatite was of a sufficiently coarse nature to permit the separate measurement of its component minerals is listed in table 8.

TABLE 8.

VOLUMETRIC MODE OF A GRANOPHYRE.

Microperthite	60	Titanite	X
Quartz	35	Fluorite	X
Melanes	4	Apatite	X
Ore	1	Zircon	X

The Bushveld Granophyre is generally separated from the Tauteshoogte felsite by an intervening strip of porphyritic granophyre of variable thickness, though 100 feet would represent a fair average.

The porphyritic rocks are sharply defined from the underlying felsite, with both varieties retaining their respective characteristics up to their plane of junction, but merge gradually into the overlying Bushveld Granophyre.

The transition can be studied in the field and takes place as follows: The typical porphyritic-granophyre succeeding the felsite and characterising the base of this unit is composed predominantly of white and flesh-coloured felspar phenocrysts, contained in a dense matrix of micropegmatite. On approaching the granophyre the phenocrysts gradually decrease in quantity and are accompanied by a corresponding increase in the micropegmatite-content, until the predominance of the latter eventually becomes so marked that the rocks are indistinguishable from Bushveld Granophyre.

The relative proportions of phenocrysts and matrix in seven specimens collected at regular intervals along the traverse marked RS on the appended map and

extending / ...

extending from the base of the porphyritic varieties to the granophyre proper, is presented in table 9. It serves to illustrate the antipathetic relationship of the phenocrysts and matrix, whereby the transitional character of the two extreme varieties is fully confirmed.

TABLE 9.

AVERAGE DIMENSIONS AND RELATIVE PROPORTIONS OF PHENOCRYSTS AND MATRIX.

Designation	Porphyritic Granophyres		Transitional Types				Bushveld Granophyre
Sp.B No.	1	2	3	4	5	6	7
Phenocrysts	48	48	45	34	28	17	10
Matrix	52	52	55	66	72	83	90
	Average dimensions of phenocrysts in mm.						
	1.7 x 1.5	1.9 x 1.1	1.6x 1.5	1.5x 1.3	1.3x 1.0	1.2x 1.0	1.1 x 0.9

The average dimensions of the phenocrysts are seen to remain fairly constant throughout; such slight variation as there is leads to successively lower values as the granophyre is approached.

Investigation with the microscope reveals that the phenocrysts are generally thoroughly decomposed, rendering identification uncertain. They are typically composed of a core, comprising 3/4 of the individual crystals and exhibit the clouded appearance of saussuritized plagioclase, with occasional irregular patches and rods of turbid red appearance, enveloped by a mantle in which the latter colour predominates.

In a number of instances portions of the cores of the phenocrysts were preserved in such a condition as to render possible their investigation with the universal stage. The determinations reveal that the anorthite-content remains constant throughout the succession and lies between 5 and 7%, and that the turbid red inclusions

are / ...

Plate.XIII.- Shows the fine-grained melanocratic nodules in the porphyritic granophyre. Dimensions of rock surfaces shown about 2 x 1 feet. Elandslaagte No.474.

are due to the presence of potash-felspar. The mantle is occasionally seen to be composed of the same constituents as the core but in more equal proportions.

Fringes of micropegmatite, of which the felspar-component occurs in optical continuity with the microperthite composing the above-mentioned mantles, are much in evidence, especially about the smaller phenocrysts.

The phenocrysts either occur as single individuals, or are assembled in clusters, giving rise to the large, apparently homogenuous phenocrysts which are so conspicuous on weathered surfaces.

Quartz grains occasionally act as phenocrysts, but in relatively small though constant quantities. The components of the matrix, comprise micrographic intergrowths of quartz and microperthite, subordinate melanes and several accessories which are identical to those entering into the composition of the Bushveld Granophyre and presented, for example, in table 8.

The close mineralogical similarity and transitional character of the granophyre and porphyritic-granophyre suggest that they represent textural modifications of the same magma, and that the latter is to be regarded as a marginal phase of the former.

In addition to the above-mentioned characteristics the porphyritic-granophyre exhibits one more feature worthy of comment, although it must be emphasised that it is of extremely local development.

Lenticular bodies of normal porphyritic-granophyre measuring approximately 30 x 10 yards, of which the major axes are aligned roughly parallel to the line of junction with the felsite and containing relatively fine-grained melanocratic granitic nodules are rarely encountered and restricted to the lower horizons, immediately overlying the felsite. The

dimensions / ...

dimensions of the nodules are variable although 2 inches would represent a fair average. They weather out and are hence conspicuous on weathered surfaces. In consequence of their roughly spherical shape and fairly uniform distribution there is no evidence of any alignment of the nodules.

Close scrutiny under the microscope reveals that the line of junction between the nodules and enveloping porphyritic-granophyre is of a slightly undulatory nature though sharply defined and with both varieties retaining their respective characteristics up to the contact.

The modal compositions by volume of a nodule and enveloping porphyritic granophyre are listed respectively under columns I and II of table 10, and serve to indicate that both varieties are composed of the same mineral assemblages, including accessories, but that the nodules contain more hornblende and less microperthite than the porphyritic-granophyre.

TABLE 10.

	I	II
Microperthite	59	72
Quartz	17	15
Hornblende	22	11
Ore	1	1
Apatite	X	X
Titanite	X	X
Fluorite	X	X
Zircon	X	X

(A perusal of the relevant data assembled in tables 8 and 10 will serve to indicate that the Bushveld Granophyre contains more quartz and less microperthite and hornblende than its porphyritic counterpart.)

The nodules are uniformly medium-grained, with

the / ...

the dominant constituent, microperthite, occurring as turbid red anhedral grains measuring .44 x .22 mm. The quartz occurs as interstitial grains, occasionally extinguishing in groups, while micrographic intergrowths are almost entirely wanting. Green hornblende with strong absorption occurs as anhedral grains and long needles. Ore, titanite and fluorite are relatively abundant accessories whereas zircon and apatite are rare.

The enumerated features suggest that the nodules are in the nature of schlieren developed locally in the lowest horizons of the porphyritic marginal phase of the granophyre.

IV. TIME SEQUENCE OF THE AVERAGE ROCKS.

Most writers on the Bushveld are agreed that the sequence of consolidation was from the sedimentary floor upwards. The observation that the component minerals vary gradually from relatively high to progressively lower temperature assemblages as the pseudo-stratified succession is ascended, furnishes the most compelling evidence in favour of this contention.

In the following section an attempt has been made to illustrate, that the average rocks characterising progressively higher horizons in the Complex, fall close to an even curve when plotted on a triangular diagram of which the three corners represent normative amounts of the more, medium and less refractory compounds. The distribution of the points suggests that the pseudo-stratified series resulted from an orderly process of differentiation and the trend of the curve indicates that the temperature of consolidation decreases progressively as the successive supplies of crystals gradually accumulated upwards into a pseudo-stratified series.

The available evidence relating to the marginal modifications exhibited by the granophyre and felsite

relative / ...

relative to their respective underlying types is in harmony with this view.

The convergence of these lines of evidence indicates that for at least the area under consideration the sequence of consolidation of the average rocks conforms to their superposition in space.

V. THE DIFFERENTIATION.

a. General features.

The salient feature of the variation in the composition of the average rocks in passing upwards relates to the enrichment of the various silicate minerals which are solid solutions, in their less refractory components. The change in composition, however, does not proceed at a uniform rate, nor is it constantly in the same direction, but takes place in step-like manner with notable interruptions, giving rise to partial repetitions of the variation.

These features are not peculiar to the rocks under consideration but appears to be characteristic of the variation in the Bushveld Complex in general.

Most writers on the Bushveld are agreed that the observations pertaining to the variation in composition conform best to the idea of two separate phases of differentiation. These are, firstly, the differentiation in a deep-seated magma reservoir, the magma so produced being emplaced in the form of surges and, secondly, the differentiation in situ of the separate supplies of magma.

b. The differentiation in depth.

This phase of the differentiation has been formulated by Lombaard (8, p.171) as follows: "The differentiation in depth determined the generation of magmas which differed in composition from time to time. As they were generated these magmas were emplaced by successive heaves whereby, normally, each heave of magma

came / ...

came to rest upon the previous one. Each heave of magma may follow closely on the preceding one, when the latter is still liquid, or be separated from it by a longer interval and may only be emplaced after the preceding supply had already consolidated."

In view of the additional information furnished by recent investigation the trend of the differentiation in depth will be considered in some detail with the aid of chemical analyses of average rocks characterising progressively higher horizons in the Bushveld Complex.

The triangular diagram, figure 12, of which the three corners represent normative amounts of the more, medium and less refractory components is constructed after the method suggested by Wager and Deer (5, p.231). The group of more refractory compounds is taken as consisting of anorthite, enstatite, forsterite and half the wollastonite; the group of compounds intermediate in their refractory nature comprises fayalite, ferrosilite, iron ores and the remaining half of the wollastonite and the third group of least refractory compounds is taken as consisting of albite, orthoclase and quartz.

A perusal of the diagram will serve to indicate that the trend in composition of the average rocks is at first away from the refractory compounds, mainly towards the medium refractory, but also slightly towards the least refractory, and the rocks formed vary from norites, through hypersthene-gabbros to diallage-gabbros.

After passing through an iron-rich stage represented by the olivine-bearing diorites, the trend changes abruptly and is directed towards the least refractory components, resulting in a succession of rocks passing from fayalite-bearing syeno-diorites, through various "syenites" and moderately acid granites to acid rocks composed almost entirely of quartz and alkali felspar.

The / ...

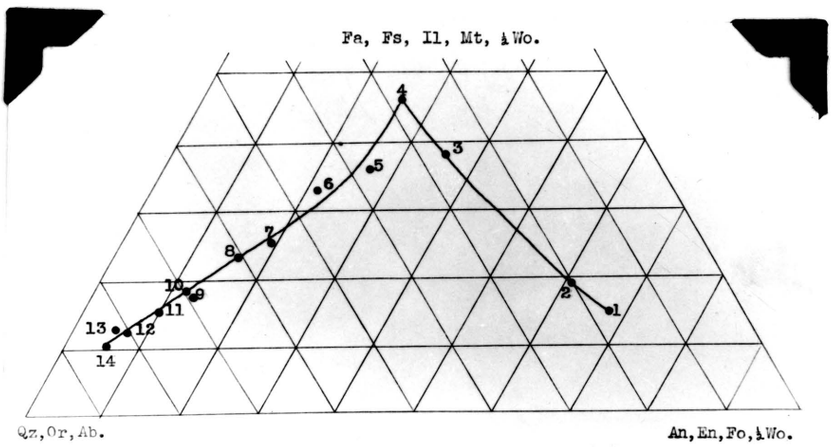


Fig.12. Analyses of average Bushveld Rocks plotted on a triangular diagram showing the more, medium and less refractory normative compounds.

1. Spotted norite, Schaapkraal No.442, Lydenburg District. Analyst: B. Lombaard. (Quoted from 6, p.18). Basal Zone.

2. Norite, ½ mile east of township of Roos Senekal. Analyst: B. Lombaard. (Same source as 1.) Main Zone.

3. Olivine-bearing diorite, Duikerkrans No.104, Middelburg District. Analyst: C.J. Liebenberg. (Sp. B. No.72) Upper Zone.

4. Fayalite-bearing syeno-diorite, Kaffirskraal No.352, Rustenburg District. Analyst: C.J. Liebenberg. (Quoted from 11, p.21).

5. Fayalite-bearing syeno-diorite, Duikerkrans No.104, Middelburg District. Analyst: C.J. Liebenberg. (Sp. B. No.85) Upper Zone.

6. "Upper Norite", Tauteshoogte, Middelburg District. Analyst: J. Jakop. (Quoted from 8, p.169). Upper Zone.

7. Hornblende-rich syenite, Doornpoort No.506, Pretoria District. Analyst: H.G. Weall. (Quoted from 9, p.307). Upper Zone.

8. Hornblende-quartz syenite, Stoffberg, Middelburg District. Analyst: H.G. Weall. (Same source as 7.) Upper Zone.

9. Albite Syenite, Hebron Mission Station, Pretoria District. Analyst: C.J. Liebenberg. (Unpublished data furnished by Prof. Lombaard.) Upper Zone.

10. Hornblende-granite, Lisbon No.2366, Potgietersrust District. Analyst: H.G. Weall. (Same source as 7).

11. Hornblende-quartz syenite, Keerom No.473, Middelburg District. Analyst: E.G. Radley. (Same source as 7.) Upper Zone.

12. Granite, moderately acid, Kaffirskraal No.352, Rustenburg District. (Unpublished data furnished by Prof. Lombaard) Upper Zone.

13. Fine-grained granite, Tauteshoogte, Middelburg District. Analyst: B.V. Lombaard. (Quoted from 6, p.13) Upper Zone.

14. Granophyre, Uitkyk No.36, Middelburg District. Analyst: B.V. Lombaard. (Same source as 11). Favoured residual magma.

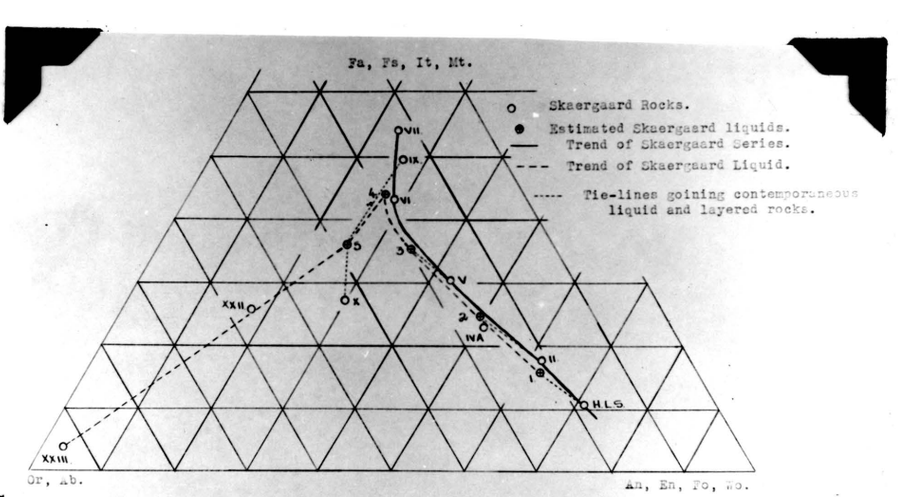


Fig.13. Analyses of Skaergaard layered rocks and estimated compositions of residual liquids plotted on a triangular diagram as in figure 12.

The observed trend of the differentiation bears a remarkably close resemblance to that exhibited by the average Skaergaard rocks which the authors have been led to regard as being typical of the fractional crystallization of average basalt and on which they (5, p.307) offer comment as follows: "The trend of the differentiation may be explained roughly in terms of the solubilities or melting point ranges of the different mineral phases. The available experimental evidence suggests that iron-olivines and hedenbergite pyroxenes separate from silicate melts approaching basic magma in composition at a higher temperature than albite, orthoclase and quartz and at a lower temperature than the magnesian-rich pyroxenes and olivines."

The trend in the Bushveld rocks, as depicted in figure 12 is in harmony with this, since the sequence is, firstly, rocks consisting mainly of basic plagioclase, and magnesian-rich ferro-magnesian minerals, then rocks composed of medium plagioclase and iron-rich melanes and, finally, acid rocks made up of acid plagioclase, quartz and orthoclase, with but little melanocratic constituents.

The data contained in diagram 13 (5, p.233) indicates that the successive residual liquids generated during the fractional crystallization of the Skaergaard magma and the trend of the composition of the average rocks follow closely similar courses. Hence, should the differentiation in depth in the Bushveld Complex be controlled by the fractional crystallization of an originally basaltic magma, it follows that the successive assemblages of crystals need not be remelted in order to furnish magmas of composition suitable for the evolution of an igneous series characterised by a major variation like that actually found in the Bushveld Com-

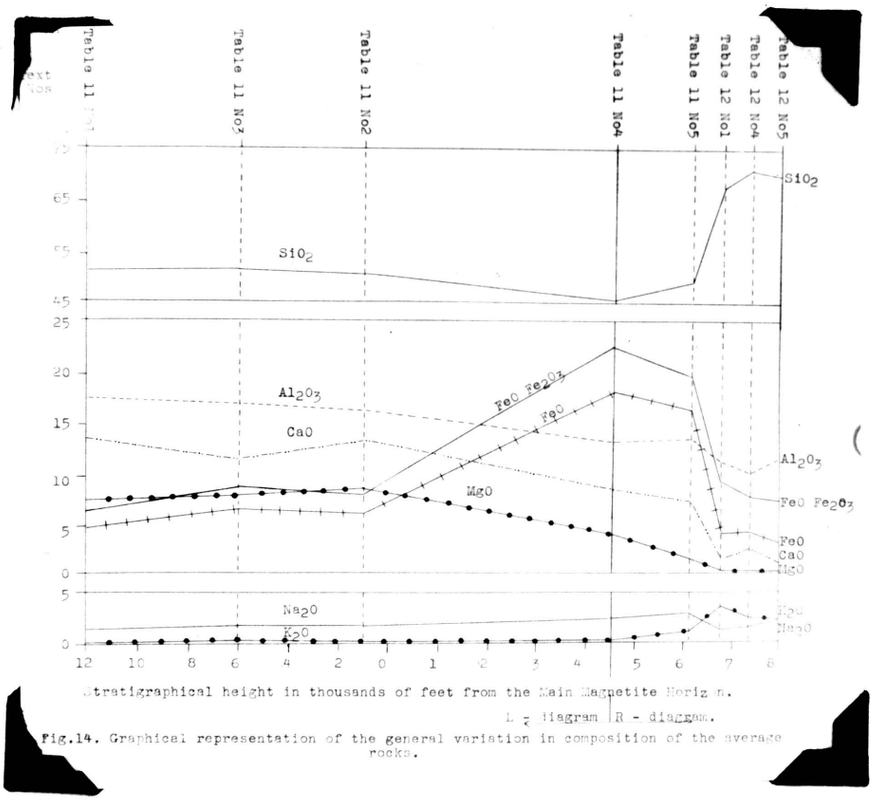


Fig.14. Graphical representation of the general variation in composition of the average rocks.

plex, since the fractional crystallization of the originally basaltic magma would suffice to generate successive residual liquids of the required composition.

The general variation in composition of the average rocks is presented graphically in figure 14, by plotting the percentages of the various oxides against height in the intrusion. In the present instance it is not practicable to plot the variation diagram against silica-percentages, since there is scarcely any variation in this value during the greater part of the differentiation.

In order to facilitate the description of the variations the diagram has been divided, by an ordinate passing through the point representing the stratigraphical height of Sp. B. No.72 into two parts, which will be referred to as the R (right) and L (left) diagrams. In the L-diagram the variation shown by most of the oxides is small, except that ferrous iron increases rapidly, whereas magnesia falls. In the R-diagram the curves for iron, lime and magnesia fall steadily and those for silica, soda and potash rise rapidly.

The most significant feature shown by the curve for silica is the small amount of variation during the greater part of the differentiation, what slight variation there is leads to successively lower values. The silica content only begins to rise towards the closing stages of the differentiation.

In the L-diagram the curve for total iron rises and bears an antipathetic relationship towards the magnesia. On entering the field of the R-diagram the iron-content declines rapidly, while the magnesia decreases to almost vanishing point.

On the strength of the available experimental data relating to the thermal behaviour of the pyroxene and

olivine / ...

olivine solid solutions in silicate melts approaching basic magma in composition the cause of the observed variations can be assessed in a general way as the result of the amount of iron and magnesia precipitated in the solid phases during the early stages being respectively less and greater than was present in the magma. Hence the residual magma is impoverished in magnesia and enriched in iron. At a later stage, represented by the R-diagram the iron-compounds also become relatively insoluble and are precipitated in excess of the amount contained in the magma, whereby the late residual liquids are similarly impoverished in iron.

The curve for Na_2O shows only a very gradual upward tendency in the L-diagram due to the enrichment of the plagioclase in the albite molecule, whereas the K_2O-content remains fairly constant over this range. During the closing stages the curves for both oxides rise rapidly owing to the concentration of the alkali felspars in the late residual magma in consequence of the low temperatures at which these minerals solidify.

The curve for lime shows a slight increase, followed by a steady decrease. Since the wollastonite-content of the clinopyroxenes in the Upper Zone has been shown to remain fairly constant throughout, the depression of the curve for lime, may be ascribed mainly to the progressive acidification of the plagioclase, combined with the virtual absence of plagioclase more basic than albite, clinopyroxene and hornblende, owing to their relatively refractory nature, in the last fractions to solidify.

The curve for Al_2O_3 remains remarkably constant throughout, being mainly controlled by the composition and relative abundance of the felspars.

b. / ...

b. The differentiation in situ.

This phase of the differentiation involves the non-selective fraction crystallization in situ of the magma emplaced with each heave, whereby the successive generations of crystalline phases, which are richer than the contemporaneous liquids in the more refractory components, accumulate on the inclined floor of the intrusion under the action of gravity due to their density being greater than that of the liquid.

Crystals accumulating as a precipitate in this way would gradually build upwards into an igneous series having a major variation like that actually found in the pseudo-stratified succession, i.e. vary from high to low temperature varieties as the series is ascended.

The successive surges of magma from which the various diorites crystallized apparently followed closely upon one another, each evidently being relatively less basic than the preceding one, as is suggested by the fact that the first crystals to separate from each heave (these occupy turning points from high to low temperature varieties on the curves depicting the trend in composition of the various silicate minerals) correspond in composition to those formed during an intermediate stage of the crystallization of the preceding heave.

The existence of a discontinuous transition from fayalite-bearing syeno-diorite to fine-grained acid rocks implies that there has been a considerable interval between the successive intrusions and that the composition of the magma generated in depth had changed appreciably during that interval as a result of the progress made towards the final residual liquid.

The previously enumerated mineralogical, chemical and stratigraphical relationships relating to the three principal varieties of acid rocks, which are

individually / ...

individually homogenuous and characterised by discontinuous transitions are believed to be interpreted as indicating that the three units resulted from three successive intrusions of progressively less basic magma generated during the closing stages of the differentiation in depth and emplaced after each preceding supply had probably already consolidated. The first heave crystallized to the relatively basic fine-grained granite; the second gave rise to the felsite, while the third which is represented by the Bushveld Granophyre was emplaced after the differentiation in depth had finally attained the composition of the favoured residual magma.

The homogeneity of the individual types is to be attributed to the fact that the magma from which they crystallized had actually or nearly attained the composition of the favoured residual magma, whereby the possibility of extensive differentiation through fractional crystallization in situ is excluded.

VI. PSUEDO-STRATIFIED ROCKS DIFFERING FROM THE ASSOCIATED AVERAGE ROCKS.

(a) Extreme leucocratic varieties.

Extreme rock types containing an abnormal concentration of either the light or the dark constituents are common occurrences in the Bushveld Complex in general, being particularly characteristic of the Critical Zone, and becoming progressively less prominent in the Main and Upper Zones. No instances of rocks markedly enriched in ferromagnesian constituents were observed in the investigated area but leucocratic varieties, generally occurring as lenses of limited lateral extent and disposed in conformity with the pseudo-stratification were encountered at various horizons. (Sp. B. Nos. 124, 91, 55).

In harmony with the salient features characterising the Bushveld anorthosites in general (6, p.36) the plagioclase composing the individual leucocratic bands encountered at successively higher horizons in the area under consideration exhibits a progressive enrichment in the albite-molecule and correspond in composition to the felspars entering into the constitution of the respective associated average rocks. These features indicate a common source for the felspars occurring in the anorthosites and in their associated diorites.

Microscopic investigation reveals that the leucocratic varieties are composed predominantly of a tightly compacted collection of prismatic crystals of andesine with average dimensions varying between 2.6 m.m. x 1.1 m.m. and 0.7 m.m. x 0.5 m.m. The laths occasionally exhibit minor identations resulting

from mutual / .....

from mutual interference during crystallization, and evidence of selective though not intense decomposition. The zonal structure is of the same nature and degree as that characterising the felspars occurring in the average rocks. The interstices are occupied by ophitic clinopyroxene, ore and late stage minerals.

The pyroxene occurs as extensive ophitic crystals, as distinct from the granular habit assumed in the average rocks, and exhibits a turbid greenish colour and moderate replacement by uralite. The oxidic ore individuals bear an interstitial relationship towards the felspar laths and are frequently partially enveloped by variously constituted kelyphitic rims. Biotite occurs as rare interstitial flakes and quartz is sporadically developed and maintains a uniform orientation over considerable areas.

The enumerated minerals are occasionally traversed by rudely parallel branching veins, occupied by decomposition products, probably saussurite and sericite. These structures exhibit minor deviations and local swells particularly when traversing felspars and occasionally envelop fragments dislodged from adjacent crystals .

Leucocratic varieties of a distinctly different character are occasionally encountered in the tract of depressed Bushveld country between the Steelpoort river and the Sekukuni mountains (Sp. B. Nos. 75, 80, 66). They are rendered macroscopically conspicuous by their sparkling white colour and large dimensions of their component felspars, which approach 5 m.m. in length. Investigation of their regional

extent, / .....

extent, disposition and contact with the country rock is, however, rendered impossible by extensive coverings of surface soil.

The existing outcrops consist of clusters of detached rectangular and subspheroidal blocks occupying areas of about 10 to 20 square yards. The rocks under consideration resemble the previously described anorthosites in being composed predominantly of a tightly compacted collection of prismatic felspar crystals, but differ from them in respect of the decidedly more basic character and large dimensions characterising their felspars.

The plagioclase occurs in two dominant sizes averaging 5.1 x 2.1 m.m. and 1.4 x 0.8 m.m. respectively. The latter individuals are relatively homogeneous and vary in composition between 50% An. and 60% An. The larger laths are composed of a core constituting approximately 90% of the individual crystals and varying in composition from 70 to 80% An. whereas the anorthite content of the mantle varies between 5% and 60%. (The composition of the plagioclase occurring in the average rocks and associated anorthosites characterising this particular horizon of the olivine-bearing diorite unit averages approximately 44% An.). The laths are moderately decomposed and exhibit subordinate indentations arising from mutual interference during crystallization or minor embayments occupied by late stage ferromagnesian minerals.

The interstitial areas are occupied by extensive subophitic individuals of hornblende exhibiting tapering projections extending between

adjacent laths / ....

adjacent laths. The amphibole occasionally contains interpositions of calcite, generally associated with muscovite and chlorite, the latter occasionally showing radial extinction. Interstitial flakes of intensely pleochroic brown mica, are rarely encountered and are generally extensively replaced by chlorite.

(b) Olivine-free Average Rocks.

The designation of the average rocks occupying the tract of depressed Bushveld country between the Steelpoort river and the Sekukuni mountains as universally olivine-bearing is not strictly accurate, since olivine-free varieties are occasionally encountered.

Thus a series of specimens collected from the fayalite-bearing syeno-diorite unit at the southern extremity of Tauteshoogte along the traverse designated A-B on the appended map, revealed no traces of olivine; specimens B. Nos 73, 74, 76, 77, 78 collected from the olivine-bearing diorite unit on Duikerkrans No. 104 are similarly devoid of olivine.

Although the regional extent of the olivine-free varieties could not be accurately ascertained on account of inadequate outcrops, they appear to be in the nature of lenticular bodies of limited lateral persistance, enveloped by olivine-bearing varieties to which they are quantitatively greatly subordinate. The transition is abrupt and the immediately underlying rocks exhibit no evidence of having been enriched in olivine.

Data pertaining / .....

Data pertaining to olivine-bearing and associated olivine-free varieties respectively have been assembled and contrasted in table 13. They illustrate the close agreement in respect of their bulk chemical composition as well as in the composition of the silicate minerals common to both varieties, and finally that the absence of olivine is quantitatively compensated in both instances by a corresponding increase in clinopyroxene.

TABLE 13.- CHEMICAL COMPOSITION, VOLUMETRIC MODE AND COMPOSITION OF CERTAIN OF THE ESSENTIAL MINERALS OF OLIVINE-BEARING AND ASSOCIATED OLIVINE-FREE VARIETIES.

Sp. B. No.	72	74	85	10
Designation	Olivine-bearing diorite	Diorite	Fayalite-bearing syeno-diorite	Syeno diorite
Locality	Duiker-krans No. 104	Duiker-krans No. 104	Duiker-krans No. 104	Paarde-kloof No. 99
Plagioclase	53(An_{48})	56(An_{46})	50($40_c 35_m$)	47($42_c 37_m$)
Clinopyroxene	14(n_β 1.717)	32(n_β 1.717)	8(n_β 1.717)	12(n_β 1.717)
Olivine	18(F_{a75})	-	6(F_{a100})	-
Hornblende	-	2	22	25
Quartz	-	-	7	4
Microperthite	-	-	3	4
Apatite	4	-	1	1
Ore	11	10	3	7
SiO_2	45.26	46.83	49.30	53.20
TiO_2	1.70	2.50	1.80	1.91
Al_2O_3	13.42	15.55	13.87	12.53
Fe_2O_3	4.63	5.26	2.38	3.29
FeO	18.35	11.90	16.78	14.17
MnO	0.39	0.30	0.43	0.12
MgO	4.19	3.29	1.77	1.08
CaO	8.50	10.01	7.49	6.58
Na_2O	2.97	3.41	3.52	2.73
K_2O	0.25	0.40	1.17	2.37
P_2O_5	trace	trace	0.45	0.16
H_2O^+	0.76	0.71	1.27	1.68
H_2O^-	0.03	0.02	0.06	0.00
	100.45	100.18	100.29	99.82

Consideration of the data assembled in the triangular diagram (fig. 12, p.46) reveals that the points representing the above-mentioned olivine-free varieties fall close to the curve depicting the trend in the variation of the average rocks, by reason of which they are considered to be normal products of the differentiation.

The development of the subordinate olivine-free lenses could conceivably have resulted in one of the following ways: the destruction of olivine by reaction with the residual liquid, its segregation under the action of gravity or the failure of the magma to precipitate olivine.

The first possibility is considered unlikely because in the sheet-like body of olivine-bearing diorite, (where the olivine-free lenses occur) the orthosilicate shows no sign of resorption. In the overlying fayalite-bearing syeno-diorites on the other hand resorpiton of olivine is indicated by characteristic reaction products associated with remnants of unaltered olivine.

Fayalite is constantly present in small quantities in the fayalite-bearing syeno-diorite on Duikerkrans No. 104 but no bands relatively enriched in olivine were found to support the second suggestion.

By elimination the third alternative remains, suggesting the failure of the magma to precipitate olivine.

VII. TRANSGRESSIVE INTRUSIVES.

(a) Varieties Genetically Related to the Bushveld Complex.

1. Granitic veins traversing the diorites.

Leucocratic veins varying in thickness from 6 to 12 inches and composed predominantly of alkali felspar and quartz, are frequently encountered occupying the prominent joints traversing the olivine-bearing diorites. These are sharply defined from, though unchilled against the enveloping rocks. Lack of adequate outcrops unfortunately preclude precise statements relating to their lateral persistance.

Whilst being composed of essentially similar mineral assemblages throughout, the veins exhibit rapid variations in the relative abundance of their component minerals, which, in order of abundance comprise, microperthite, quartz, subordinate plagioclase, hornblende, biotite and ore.

The dominant constituent, microperthite, occurs as large individuals exhibiting irregular boundaries, occasional marginal interpositions of quartz and rare poikilitic inclusions of small plagioclas e laths which appear to have suffered extensive resorption. The intergrowth is composed of delicate anostomizing stringers of plagioclase, varying in composition from An_{10} to An_{16}, contained in a matrix of orthoclase with $2V_{\alpha} = 76^{o}$ and the extinction angle on (010) against (001) = $\pm 5^{o}$.

Plagioclase is generally well represented as uniformly distributed stout individuals. Less frequently abundant small laths in association with

quartz grains / .....

quartz grains exhibit a pronounced tendency to be concentrated in veinlets of marked persistance. The mineral appears to be zonally built, and the composition varies between An_{15} and An_{25}. Owing to the advanced decomposition of the plagioclase, whereby the determination of its optical constants is rendered difficult and generally impossible, the composition quoted above should be regarded as being approximate only.

Quartz is present as large individuals exhibiting pronounced undulose extinction and evidence of cataclastic disruption, or enters into the constitution of the subordinate coarse micropegmatite.

The melanes, comprising hornblende and biotite, are generally associated in aggregates of variously orientated partially superimposed scales and flakes, and characterised respectively by the following intense pleochroism: α = pale brownish, β = green, γ = dark green and α = pale yellow, β = reddish brown, γ = reddish brown. Both ferromagnesian constituents occasionally occur as interstitial anhedral grains, the mica exhibiting strained lamellae and the amphibole containing rare remnants of a colourless, non-pleochroic, relatively strongly birefringent mineral, probably clinopyroxene.

Oxidic ore generally occurs as sagenitic webs associated with the melanes, and less frequently as uniformly distributed subhedral individuals. Apatite and zircon are relatively abundant accessories, and veinlets composed predominantly of calcite are occasionally encountered.

The granitic / .....

The granitic veins, no doubt, represent residual magma developed by differentiation in situ, and available when all the dioritic rocks were solid and well jointed.

2. Sub-acid varieties occurring in the Fine-grained acid rocks.

The previously described varieties of fine-grained acid rocks, comprising fine-grained granite and Tauteshoogte felsite, separating the fayalite-bearing syeno-diorite from Bushveld granophyre, exhibit widely scattered streaks and patches of quantitatively subordinate medium-grained material ranging in composition from sub-acid grano-diorites to sub-acid granites.

Although being of extremely irregular shape, these bodies are of fairly uniform distribution but are not characteristic of any particular horizon nor do they conform to the general pseudo-stratification.

Owing to the lack of adequate outcrops the following description relating to shape and dimensions, must be regarded as being approximate only. The existing outcrops vary from mere streaks to patches covering 300 square yards in rather extreme instances. Their contact with the country rock is sharply defined since both varieties retain their respective characteristics up to the line of junction. This contact is, however, of an extremely sinuous character in consequence of the frequent swelling and pinching and the development of subsidiary branches projecting in various directions and eventually tapering out in highly felspathic veinlets. The mineralogical composition and average grain-size

remains fairly / .....

remains fairly constant in the individual outcrops.

Their appearance in handspecimen is controlled mainly by the relative abundance of plagioclase and microperthite and their contents of melanes. The grano-dioritic varieties in which plagioclase is the dominant felspar are relatively melanocratic, even-grained rocks, composed of grey plagioclase laths, exhibiting a pearly lustre, subordinate pink microperthite, vitreous quartz grains and greenish-black hornblende. The granitic varieties are composed of essentially similar mineral assemblages but in different relative proportions giving rise to leucocratic rocks, characterised by a dominantly red colour arising from the presence of abundant alkali-felspars.

The data presented in table 14 relates to three speciments collected from widely separated outcrops, and are regarded as being fairly representative of the whole range in composition.

TABLE 14.- DATA PERTAINING TO THE SUB-ACID GRANODIORITES AND GRANITES.

Sp. B. No.	Designation.	Modal composition by volume and the most prevalent composition of certain of the essential minerals.							
		Plagioclase		Clinopyrox		Microperthite	Hornblende	Quartz	Ore
		Vol. %	An. %	Vol. %	n_β				
31	Sub-acid granite	16	35_c20_m	1	1.738	49	20	12	2
29		29	35_c20_m	1	1.738	34	19	16	1
18	sub-acid granodiorite	46	35_c20_m	7	1.738	17	15	11	4

In view of the close agreement in their microscopic characteristics these may be considered collectively for both varieties.

The felspars, plagioclase and microperthite, vary antipathetically. The former occurs as stout laths measuring 1.5 x 1.0 m.m., exhibiting advanced selective decomposition, and pronounced zonal structure. The composition of the cores and mantles varies from An_{38} to An_{27} and from An_{35} to An_{25} respectively; that of the relatively homogenuous individuals varies between An_{35} and An_{25}. (It will be noticed that the total range in composition is very similar to that of the felspars occurring as phenocrysts in the country rocks). The laths are generally enveloped by marginal selvedges of microperthite of variable dimensions, which are frequently partially intergrown with adjacent quartz crystals. Apart from constituting protective mantles, the alkali felspar occurs as individual anhedral grains with average dimensions of 0.8 x 0.6 m.m., of which the arm-like projections traversing adjacent quartz grains, break up into angular blebs which extinguish in group and hence resemble coarse micropegmatite. The microperthite is occasionally interspersed with shreds of hornblende.

Microperthite is the dominant felspar in the sub-acid granites, in which several of the larger individuals generally exhibit cores composed of coarsely intergrown soda and potash felspars, with the latter occupying rods and irregular patches in the former, and enveloped by a delicately intergrown marginal selvedge.

A considerable / .....

A considerable proportion of the quartz occurs as optically continuous irregular patches measuring 2.4 x 1.6 m.m. enveloping angular shreds of microperthite and occupying interstices between plagioclase laths. Less frequently the mineral occurs as anhedral individuals with average dimensions of 0.9 x 0.6 m.m.

The clinopyroxene generally occurs in an advanced stage of replacement by uralite, to which it bears an antipathetic relationship. The occasional unaltered subhedral crystals are characterised by a green colour and the following pleochroism: α = yellowish green, $\beta = \gamma$ = green. The axial angle $2V_{\gamma}$ varies between 54° and 58° and the refractive index $n\beta = 1.738$, indicating an approximate composition of $Wo_{38}\ En_{8}\ Fs_{54}$. The remarkably ferriferous nature of the clinopyroxene is in agreement with those characterising the higher horizons of the Upper Zone in general.

The extensive replacement of clinopyroxene generally results in the production of optically continuous individuals of uralite, and less frequently yields aggregates of variously orientated partially superimposed scales of hornblende associated with biotite and ore. The markedly interstitial patches of amphibole which bear no evidence of their derivation from clinopyroxene, evidently represent primary hornblende. The biotite is greatly subordinate to the uralite and exhibits the following pleochroism: α = pale yellow, $\beta = \gamma$ = grass-green.

Although no olivine was actually detected the rare aggregates composed of feebly pleochroic

vibrous amphibole and sagenitic webs of ore bear so close a resemblance to the assemblages of reaction products observed in the fayalite-bearing syeno-diorites and which clearly resulted from the resorption of early formed olivine crystals as is evidenced by the remnants of orthosilicate preserved in them, as to suggest an analogous origin for the structures under consideration.

Apart from the rods and sagenitic webs of oxidic ore associated with the above-mentioned scaley aggregates, subhedral crystals of fairly uniform distribution are well represented. Peculiarly decomposed, weakly birefringent zircon and apatite are relatively abundant accessories; fluorite and titanite are rare, all of which exhibit a distinct tendency to be concentrated in the ferromagnesian constituents.

These sub-acid varieties have no sheet-like equivalents disposed in conformity with the general pseudo-stratification in the area under consideration, but bear a close similarity in respect of quantitative and qualitative mineralogical composition to average rocks, stated to occur as sheets in the pseudo-stratified succession and to characterise the highest horizons of the Upper Zone, immediately underlying the composite granophyre-granite roof, at widely separated localities in the Bushveld Complex of which some examples are presented in table 15. In other words, the sub-acid trangressive intrusions of this area have their petrographic equivalents in other localities in the form of pseudo-stratified bodies.

Table 15 / .....

TABLE 15.- DATA PERTAINING TO SUB-ACID ROCKS CHARACTERISING THE HIGHER HORIZONS OF THE UPPER ZONE AT VARIOUS LOCALITIES.

LOCALITY.	POTGIETERSRUST DIST.		MIDDELBURG DISTRICT.		PRETORIA DISTRICT.			RUSTENBURG DISTRICT.
	LISBON NO. 2366.		STOFFBERG.	KEEROM NO. 473.	DOORNPOORT NO. 506.	HAAKDOORN-LAAGTE 504	HEBRON MISSION STA.	KAFFIRS-KRAAL 352.
Source	(13, p.22)	(9, p.305)	(9, p.305)	(15, p.739)	(9, p.305)	(9, p.305)	(11, p.16)	(11, p.22)
Designation	Hornblende granite	Hornblende quartz-syenite	Hornblende quartz-syenite.	Hornblende quartz-syenite	Hornblende rich syenite	Hornblende augite syenite	Albite-syenite	Moderately acid granite.
Disposition	?	"Conformable"	"Conformable"	Transgressive	"Conformable"	"Conformable"	"Conformable"	?
			VOLUMETRIC MODES.					
Plagioclase	9(An_{14})		35(An_{32})				45(An_{3-7})	16(An_{5-7})
Microperthite	48		20				7	56
Clinopyroxene			3				7	traces
Hornblende	(15		(18				(35	8
Biotite	(		(				(8	2
Quartz	25		15					18
Ore	1		8					X

The data contained in tables 14 and 15 indicate that the rocks concerned vary considerably but that the range in composition shown in table 15 overlaps that contained in table 14.

Information yielded by the investigation of microscopic slides of the Lisbon and Stoffberg rocks (kindly loaned by the Director of the Union Geological Survey) and assembled in table 15 indicates that the rocks concerned conform to Niggli's definition of a granite and grano-diorite respectively. It may be added that their microscopic characteristics correspond in detail to those previously described for the relevant Tauteshoogte rocks (p. 62)

Consideration of the information presented in the triangular diagram (fig. 13, p. 47) reveals that the normative values pertaining to the specimens listed in table 15 fall close to the smooth curve depicting the trend in composition during the closing stages of the differentiation, indicating that the rocks concerned resulted from the same orderly process of differentiation already described. Further that, in harmony with their pseudo-stratigraphical position, they represent a stage intermediate between that characterised by the olivine-bearing syeno-diorites and the Bushveld granophyre.

While the available evidence largely satisfies the requirements of a transitional relationship between the various average rock-types in the pseudo-stratified succession as far up as the syeno-diorite, a distinct hiatus exists in this area between the latter rocks and the acid varieties representing the residual magma. Similarly, in other localities of the Complex

the composite / ....

the composite granite-granophyre roof has been noted to be sharply separated from any underlying rocks.

Recent investigations (13) and (11), however, reveal that this hiatus is partially bridged at any specific locality by the development of sub-acid rocks varying in composition from place to place within the limits stated above. It must be emphasized, however, that the complete succession of sub-acid rocks presented in figure 12 is not known to be developed at any one locality in the Complex, where discontinuous transitions are the rule.

Although the stratigraphical and petrological relationships relating to this group of sub-acid rocks are imperfectly known, owing largely to inadequate investigation they appear to be characterised by discontinuous transitions and "conformable" dispositions. Less frequently they bear an intrusive relationship to pseudo-stratified rocks, representing a relatively later stage in the normal crystallization sequence, as is exemplified by the occurrence at Tauteshoogte.

It is considered that an adequate explanation of the origin of all the "conformable" varieties of the Complex is furnished by the same process of differentiation as that suggested for the fine-grained granite and felsite at Tauteshoogte.

In the case of the transgressive varieties encountered at Tauteshoogte, their origin is considered to be slightly different, though analogous. It has been postulated (p.46) that the normal process of differentiation in depth produced a.o. a succession of sub-acid types, emplaced in sheet-like bodies and

composed of / .....

composed of rocks, which, as a class, closely resemble those constituting the transgressive varieties (p. 64). It is conceivable that relatively acid residuums could have developed by a similar process of differentiation operating in situ in the syeno-dioritic magma after its emplacement and during its consolidation. Subsequently the residuums were injected into the composite roof provided by the fine-grained granite and Tauteshoogte felsite, where they gave rise to the sub-acid transgressives in much the same way as pegmatites.

The transgressive bodies further resemble pegmatites in the absence of chilled margins and a grain-size greater that that of the enveloping rocks. They differ from pegmatites, however, in being of very irregular shape. This may be due to the imperfect development of joints in the country rocks at the time of the emplacement of the transgressive bodies, or to their large volume relative to the spaces available in joints.

In discussing the characteristics of the Upper Zone in general and at Tauteshoogte in particular, Daly (15, p. 738) and Hall (9, p. 305) i.a. express the following views:

> "The rocks underlying the composite quartzite-granophyre roof and representing the highest horizons of the Upper Zone are hornblende-augite-quartz syenites, disposed in conformity with the pseudo-stratification. At intervals along the high escarpment of the Sekukuni mountains this mafic quartz-syenite sub-layer sends narrow apophyses into / .....

physes into the felspathized quartzites of the great xenoliths and into the base of the overlying granophyre."

(The "hornblende-augite-quartz-syenites" are equivalent to the sub-acid grano-diorites and granites under consideration and the "felspathized quartzites" comprise the fine-grained granite and felsite of the present paper).

No instances were encountered during the present investigation of dykes emanating from and corresponding in composition to the fayalite-bearing syeno-diorites which underly the fine-grained acid rocks.

(b) Post-Bushveld Basic Dykes.

Microscopic investigation reveals that the equi-granular fine-grained, greenish grey dykes are composed of zoned, slender laths of plagioclase measuring 0.6 x 0.1 m.m. The cores and mantles merge gradually, and vary in composition from An_{78} to An_{72} and from An_{64} to An_{60} respectively. The laths generally exhibit selective though not intense decomposition. Subhedral crystals of orthopyroxene with average dimensions of 0.7 x 0.2 m.m. are occasionally traversed by slender laths and invariably occur in an advanced stage of replacement by fibrous decomposition products. The replacement was apparently initiated from the margins of the irregular transverse cracks, in which vicinity the decomposition is markedly intense. The colourless remnants of hypersthene exhibit no pleochroism and their average value of $2V_{\alpha}$ for several determinations, which ranged from 67° to 72° /.....

to 72°, amounted to 70°, thereby indicating an average composition of 32% Fs.

The colourless subhedral to anhedral crystals of clinopyroxene measuring 0.5 m.m. x 0.2 m.m. are generally characterised by a marginal yellowish green tinge, and bear an interstitial relationship towards the felspar laths, but are not markedly ophitic or sub-ophitic although their designation as such is perhaps still justified. Subordinate fringes of diallage are occasionally marginally moulded on crystals of hypersthene. The axial angle $2V_{\gamma}$ varies between 42° and 43° and the extinction angle $Z \wedge c$ between 42° and 44°. The irregular patches of crypto-crystalline igneous material, occupying the interstitial areas, probably represent late magmatic acid residuums. The uniformly distributed subhedral grains of oxidic ore and rare flakes of hornblende, biotite and chlorite are generally present in very subordinate quantities.

The previously mentioned prehnite veins are of an equigranular nature and composed of interlocking anhedral individuals exhibiting pronounced undulose extinction, but no tendency to be arranged perpendicular to the sharply defined line of junction with the parent rock. The mineral is characterised i.a. by the following optical properties: $2V_{\gamma} = 68°$, $n_{\gamma} = 1.634$, $n_{\alpha} = 1.613$ and $B_{x_o} \perp$ the plane of the prevalent cleavage.

The volumetric mode listed in table 16 represents the average of three determinations of specimens collected from widely separated outcrops, and which yielded closely similar values.

Table 16 / .....

TABLE 16.- AVERAGE VOLUMETRIC MODE OF THE BASIC DYKES.

Plagioclase	66
Clinopyroxene	20
Orthopyroxene	5
Ore	3
Cryptocrystalline igneous material	4
Combined hornblende, biotite and chlorite	2

The dykes are best described as equigranular fine-grained allotriomorphic diabases (16, p. 312).

VIII. XENOLITHS OF SEDIMENTARY ORIGIN ENVELOPED BY IGNEOUS ROCKS.

(a) Xenoliths occurring in the diorites.

These comprise, in order of abundance, arenaceous argillaceous and calcareous varieties, collectively greatly subordinate to the country rock and becoming relatively more abundant in the higher horizons as the escarpment is approached. The isolated individual outcrops vary from a few scattered blocks to masses of several hundred square yards, the latter generally being of arenaceous character. In all the investigated instances the enveloping igneous rocks furnished no evidence of contamination in proximity to the inclusions, and the latter exhibited no signs of alteration other than those pertaining to thermal metamorphism.

The arenaceous varieties may be designated as medium-grained, moderately pure quartzites, exhibiting the following microscopic characteristics:

Although the quartz crystals exhibit an extensive range in dimensions individuals with average dimensions of approximately 1.2 x 0.9 mm. predominate. The exceptionally large crystals are fairly uniformly distributed whereas grains of smaller dimensions are generally assembled in clusters. Minor marginal interpenetration of adjacent quartz crystals is much in evidence.

Two distinct varieties of mineral assemblages were recognized, depending upon whether various acid felspars or sillimanite and muscovite acted as ground-mass to the quartz grains.

The latter association is frequently encountered. The sillimanite occurs as slender prisms and tapering needles, the latter generally arranged in sub-parallel or sheaf-like aggregates, exhibiting radial extinction. The mineral is characterised by the following optical properties: $2V_{\gamma} = 30^{o}$

$N_{\alpha} = 1.652$/.....

N_α = 1.652 and N_γ = 1.673. The values pertaining to its principal refractive indices are lower than those quoted by Larsen (14, p.120) and Winchell (3, p.200) but are in close agreement with the values obtained by Coetzee (12, p.201)

The muscovite occurs as one or more flakes intimately associated with the individual sheaves of sillimanite needles. The optic axial angle $2V_\alpha$ = ±41°

No traces of sillimanite and muscovite were detected in the felspathic varieties. Although the identity of the felspars is rendered uncertain in consequence of their advanced decomposition and turbid appearance the presence of microcline, microcline-perthite andalbite was established beyond doubt. The felspars occur as irregular stringers wedged between adjacent quartz grains, and maintain a uniform orientation over considerable areas, despite physical interruptions.

Ore, zircon and apatite are rare but constant constituents of both varieties, but biotite extensively replaced by chlorite, is encountered only in the felspathic varieties.

The evolution of the sillimanite and muscovite may be attributed to the thermal metomorphism of either the decompcsition products of allogenic alkali felspars or suitably constituted argillaceous impurities. Although the former alternative is favoured no final decision could be arrived at owing to the inadequate evidence available.

The argillaceous varieties, represented by cordierite hornfelses of marked purity have suffered complete reconstitution. Despite the close general agreement in respect of texture and mineralogical

composition two/.....

composition two varieties, which may be designated as cordierite-hornfelses and cordierite-oligoclase-hornfelses respectively, can be distinguished.

The former variety is composed predominantly of a mosaic of cordierite crystals occurring in two distinct sizes measuring respectively about .24 x .01 mm. and .12 x .06 mm. in longitudinal and .08 x .08 and .04 x .04 mm. in transverse sections. Traces of incipient decomposition are occasionally encountered, while multiple twinning is much in evidence. The optic axial angle $2V_{\alpha}$ varies between 75 - 76°, thereby indicating a high content of iron.

Idioblastic crystals of ore occur in 3 distinct sizes measuring about .3 x .3 mm., .14 x .12 mm. and .04 x .02 mm. respectively. The subordinate biotite, exhibiting the following pleochroism:

α = pure yellow, β = reddish brown, γ = reddish brown, occurs exclusively as marginal selvedges about the smaller grains of ore.

The cordierite-hornfelses are characterised by a conspicuous lamination resulting from the alternation of various combinations of the enumerated constituents, in sharply defined parallel lamellae varying in width from 0.1 mm. to 1.7 mm. The differentially constituted lamellae comprise varieties exhibiting:

(i) Uniformly distributed medium and small ore grains contained in approximately equal proportions in a granoblastic matrix of relatively large cordierite crystals.

(ii) Abundant small and occasional large ore grains invariably fringed by biotite and contained in a mosaic of small cordierite crystals.

(iii) An identical/.....

(iii) An identical mineral assemblage as (ii) but for the absence of biotite.

(iv) Relatively abundant large and occasional small ore grains uniformly distributed in a matrix of large cordierite crystals.

Chains of closely spaced ore grains occasionally occupy the contact between adjacent lamallae. A rhythmic repetition of a set of lamellae is occasionally met with.

The finely banded arranged is, no doubt, in the nature of a palimpsest structure, representing a clear transcript of the rapid alternation of variously constituted lamellae which entered into the constitution of the original sediment.

The lamination is less conspicuous in the oligoclase-cordierite-hornfelses and arises mainly from the alternation of parallel bands composed respectively of relatively coarse and fine-grained mosaics of cordierite individuals, corresponding in dimensions and microscopic characteristics to those composing the cordierite-hornfelses. Further diversity is occasionally introduced by the presence of felspathic layers. The latter are characterised by a poikiloblastic texture resulting from the presence of numerous cordierite crystals embedded in the interlocking felspar laths which exhibit advanced selective decomposition and vary in composition from An_{30} to An_{25}.

The larger cordierite crystals generally exhibit moderate replacement by interlacing micaceous decomposition products. The replacement proceeds inwards from the margins. Uniformly distributed idioblastic crystals of ore appear in 3 sizes, similar to those

previously mentioned/.....

previously mentioned. The subordinate biotite occurs as flakes, interstitial shreds and rare fringing growths about the ore grains.

The only instance of a calcareous xenolith was encountered on Onverwacht No.561. The diameter of the roughly circular outcrop amounts to about 100 yards.

Microscopic investigation reveals the rock to be a granoblastic forsterite-marble, composed predominantly of an even-grained mosaic of calcite crystals, which evidently resulted from the thermal metamorphism of an impure magnesian limestone.

The carbonate crystals effervesce vigorously when treated with cold dilute hydrochloric acid, and take a violet stain after 5 or 10 minutes on exposure to a freshly prepared Lemberg's solution, and are hence concluded to be calcite.

The larger forsterite individuals are idioblastic against calcite and largely confined to the marginal areas of the carbonate crystals. A poikiloblastic structure, however, results from the presence of orthosilicate crystals of inferior dimensions embedded in calcite grains. The olivine occurs in various stages of replacement by serpentine, the alteration being initiated from the prominent transverse cracks. The optic axial angle $2V_{\gamma}$ averages 84° and N_{β} = 1.636, thereby indicating a composition of Fo_{98}.

Pale pink isotropic garnets assuming spherical and sub-angular shapes and attaining maximum dimensions of 0.6 x 0.8 mm, are fairly uniformly distributed.

Sub-spherical unidentified fibrous aggregates typically composed of a semi-opaque dark brown core, crowded with disseminated ore particles enclosed by

concentric zones/.....

concentric zones of radially arranged, alternating colourless and light brown, weakly birefringent fibres of which N_{α} = ±1.570 accounts for a considerable proportion of the marbles. These structures are occasionally partially fringed by elongated individuals of ore.

The volumetric mode of a forsterite-marble is presented in table 17.

TABLE 17.- VOLUMETRIC MODE OF A FORSTERITE-MARBLE.

Calcite	...	...	64
Forsterite	...	...	7
Garnet	...	...	1
Ore	...	...	X
Serpentine	...	...	11
Unidentified fibrous aggregates		...	17

(b) Xenoliths occurring in the fine-grained acid rocks.

These are represented mainly by subordinate isolated outcrops of indurated shales, which have apparently suffered little reconstitution. The rocks are generally composed of alternating bands of essentially similar quantitative mineralogical composition but differing in respect of the relative proportions of their constituent minerals. The relatively leucocratic bands either alternate with subordinate lamellae richer in melanes or act as groundmass to melanacratic streaks and patches of varying shapes and sizes.

The following mineral assemblage accounts for the leucocratic portion: the dominant constituent,

quartz, occurs/.....

quartz, occurs as sub-angular individuals of fairly uniform grain-size. Unaltered, zonally-built, stout laths of plagioclase, varying in composition from An_{35} to An_{45} are well represented. Flakes and interstitial shreds of intensely pleochroic brown mica, occur in various stages of replacement by chlorite, which is generally crowded with disseminated ore particles, while uniformly distributed octahedra of oxidic ore are much in evidence. The abundant pale green aggregates composed of unidentified strongly birefringent interlacing micaceous flakes evidently represent decomposition products, derived from a mineral with pronounced idioblastic tendencies, as is suggested by their regular prismatic shape. The melanocratic bands largely result from concentrations of the above-mentioned fibrous aggregates associated with relatively abundant biotite and chlorite and subordinate quartz, plagioclase and ore.

Isolated masses of sediments are conspicuous features in the higher horizons of the Upper Zone in general, Hall (9, p.222) considers that these did not form a continuous roof, but are due to their dislodgement from the sedimentary floor, and floating upwards until arrested at a level governed by density relationships.

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