THE GEOLOGY OF THE
BUSHVELD IGNEOUS COMPLEX
EAST OF THE
KRUIS RIVER COBALT OCCURRENCE,
NORTH OF MIDDELBURG, TRANSVAAL.

by

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ABSTRACT

The area investigated covers the south-eastern flank of a dome-like structure in the Bushveld gabbro. This gabbro is intersected by two sets of faults which are older than the Bushveld granite. The investigation bears out the contention that the sedimentary rocks in the Moos River area do not represent an inclusion in the gabbro but that they represent part of an anticlinal fold caused by doming during the emplacement of the Bushveld granite.

Xenoliths in the gabbro belong to the Smelterskop Stage. A large xenolith of quartzite occupies an extensive area in the north-west, and numerous smaller xenoliths are composed of highly altered Dullstroom lava.

The Rooiberg felsite has a considerable development (probably a maximum) in this area. It attains a thickness of 10,180 ft and is subdivided into three zones:

(i) a Lower felsite which consists of micrographic felsite and leptite,

(ii) a Variable felsite, mainly black, amygdaloidal and pseudospherulitic, and

(iii) an Upper felsite which is red, glassy and porphyritic.

The total thickness of the roof-rocks of the Main Plutonic Phase is 14,680 ft. They consist of felsite and granophyre.

Three different types of granophyre seem to be present in the Bushveld Complex. One type, the so-called "Rooiberg granophyre" is found as large sheet-like masses at the base of the Rooiberg felsite in the area investigated, and is considered to have originated by melting of the felsite during emplacement of the gabbroic rocks. Another type represents a chill-phase of the Bushveld granite and a third type, termed "paragranophyre" is not present in the area investigated, but has been described by other workers

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as having originated by metasomatism of quartzo - feldspathic sediments.

Four new chemical analyses of felsite and related rocks are given. These, together with chemical data on Rooiberg felsite and Bushveld granite published previously are plotted on various variation diagrams. According to these diagrams the Rooiberg granophyre and the leptite are related to the Rooiberg felsite. The composition of the granophyre, related to the Bushveld granite, varies considerably and could not be separated from the Rooiberg granophyre on the grounds of chemical composition.

Although neither the Merensky Reef nor the Main Magnetitite Seam is present, rocks of the Main and Upper Zones of the Main Plutonic Phase of the Bushveld Complex are developed. A valuable marker in the Main Zone in this area is a gabbro which contains spherical inclusions of pyroxenite. This marker is designated the "Tennis-ball marker" and is situated about 2200 ft above the Needle-norite which in turn was found to be 1000 ft above the Merensky Reef in other localities. The gabbroic rocks are described and much attention is given to a so-called nesophitic texture of the orthopyroxene, a common texture in these rocks. The nesophitic orthopyroxene is orientated so that its crystallographic c-axis is parallel to the plane of igneous lamination. This, as well as the presence of augite lamellae orientated at random in this orthopyroxene is explained as being due to directed pressure of the superincumbent crystal mass during the inversion of the pigeonite.

The Upper Zone is developed only in the eastern part of the area and thins out gradually towards the west. This is explained as the result of a discordant relationship of the gabbroic rocks towards the roof. Outcrops are generally poor and rock types present are ferrodiorite, diorite, granodiorite and magnetitite. The granodiorite is not

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considered to be a product of magmatic differentiation, but rather to have formed by assimilation of felsitic rocks.

Magnetitite is present as seams and as a plug on Diepkloof 186-J.S. For comparative purposes magnetitite from plugs on Haakdoorndraai 169-J.S. and Maleeuwskop (both to the north of the area in question) was investigated. According to the low V_2O_5 content the magnetitite present is considered to be high up in the succession of the Upper Zone.

The magnetitite reveals several interesting exsolution phenomena, most of which may be explained as the result of the oxidation of ulvite to ilmenite. In this process of oxidation and subsequent migration of the constituents of the ilmenite, diffuse proto-ilmenite, lamellar and worm-like concentrations of ilmenite and intragranular graphic ilmenite in magnetite originated. Leucoxene is a common alteration product of the ilmenite.

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I. INTRODUCTION

During 1965 and 1966 an area east of the cobalt occurrence on Kruisrivier 74-J.S. was surveyed geologically with the object of obtaining more information on the relation between the gabbroic rocks of the Main Plutonic Phase of the Bushveld Igneous Complex and the overlying Rooiberg felsite. It was also hoped that the mapping of this area would throw some light on the relation of the sedimentary inclusion found in this area to the Moos River Fragment, and on the reason for the "gap" in the epicrustal rocks which causes the gabbroic rocks to outcrop between the Kruis and the Blood Rivers.

Leptite and granophyre were encountered during the investigation and on account of their mode of occurrence an attempt was made to explain their origin. In addition, metamorphosed rocks of the Pretoria Series, Rooiberg felsite, rocks belonging to the Upper and Main Zones of the Bushveld Complex and the Bushveld granite were encountered and are described.

The area was mapped with the aid of aerial photographs and covers about 140 square miles which extend east of longitude 29°30' and south of latitude 25°15'. The information obtained was compiled on a map on a scale of 1:50,000 (folder at back).

Previous work in this area was carried out by E.T. Mellor (1906) who mapped large portions taken up by felsite in the south, and the rest by A.L. Hall (1913). In 1945 J.M. van der Westhuizen mapped a broad belt all along the northern slopes of the Bothasberg plateau and the adjoining gabbroic rocks, while A.F. Lombaard (1949) investigated certain areas farther north.

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II. TOPOGRAPHY AND DRAINAGE

Topographically the area can be subdivided into three regions.

The southern part of the area is occupied by hard resistant felsite which builds ridges up to 4200 ft above sea-level in the west. These ridges increase gradually in altitude towards the east, up to 5600 ft in places and form a plateau in the vicinity of Bothasberg. The Selons River and the upper course of the Kruis River, as well as their tributaries, have cut deep valleys into this plateau. For the sake of convenience this whole plateau-like region can be called the Bothasberg plateau, although only the higher-lying areas above 5000 ft in the east **form** part of the Bothasberg.

A second highland, more incised and mountainous, occupies a large area in the north-west. The south-western flank of this highland is built up by gabbroic rocks of the Main Zone of the Bushveld Complex. They reach a height of 5118 ft at the trigonometrical beacon on Mineral Range 190-J.S. Towards the north-west quartzite forms several parallel ridges that strike east-west

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in the west, swing gradually towards the north and obtain a N.N.E.-S.S.W. strike. The average height of these quartzite ridges is 4700 ft, and they are parted by valleys which contain diabase sheets of varying thickness. The drainage is to a large extent superimposed.

The two highlands are separated by a triangular lowland, broad in the east and narrow in the west. Outcrops in this valley are scarce because of a thick covering of alluvium derived from the Bothasberg plateau. Two rivers, the Kruis River and the Blood River, drain this lowland and most of the area mapped. The watershed between the two rivers is approximately 4000 ft above sea-level. The Kruis River rises on the Bothasberg plateau and flows westwards in a straight valley which gradually becomes narrower. The Blood River flows from the east in a wide valley, turns northwards and meets the Olifants River in the vicinity of Groblersdal, outside the area mapped.

III. THE PRETORIA SERIES

The rocks of the Pretoria Series are found in the northwestern part of the area. They dip 55° south in the west, curve gradually northwards and then acquire smaller dips viz. 35° east. A list of the rocks of the Pretoria Series in this area, and their thicknesses is given in table 1.

TABLE 1. Thickness and succession of the Pretoria Series

Dullstroom volcanics (Main Zone)	600 ft.
Pyroxene granulite	70 ft.
Thin quartzite	150 ft.
Thin hornfels (Diabase)	
Upper quartzite	3050 ft.
Thin hornfels (Diabase)	
Lower quartzite	1010 ft.

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Thin hornfels (Diabase)	
Magaliesberg quartzite	900 ft.
Total thickness	5820 ft.

The absence of prominent argillaceous sedimentary rocks between the thick quartzite beds makes it difficult to correlate the quartzite horizons with others from known localities.

A. THE MAGALIESBERG STAGE

Quartzite on Elandsplaats 48-J.S., assumed to belong to this stage, forms the most north-westerly outcrop of sediments in this area. The chrysotile deposits on Kameeldoorn 71-J.S., a few miles to the west of the area mapped, are found in limestone of the Magaliesberg Stage, according to "The Mineral Resources of the Union of South Africa", (1959, p. 366). This limestone is situated just below this quartzite.

B. THE SMELTERSKOP STAGE

To the west of the area mapped, prominent outcrops of calcareous hornfels, which probably form the lowest horizon of the Smetlerskop Stage are found above the Magaliesberg quartzite. A considerable volume of diabase has intruded along this horizon and cuts off this calcareous hornfels, so that it does not outcrop in the investigated area, except for a thin layer on Goedgedacht 72-J.S.

The quartzite above the calcareous hornfels is designated the Lower quartzite. At its base it has a banded quartzite zone which is fine-grained and consists of alternating reddish layers rich in K-feldspar, and grey layers rich in quartz. Some layers seem to have been calcareous, judging from the amount of prehnite they now contain (W.14). Above the zone of banded rock, the quartzite, including thin discontinuous diabase sheets, is approximately 1000 ft thick.

A thick succession of diabase separates this Lower quartzite from the Upper quartzite. The latter attains a thickness of approximately 3000 ft. It outcrops generally as two prominent ridges. The northern ridge is slightly wider than the southern one and is accordingly higher. C. Frick (personal communication) found the topmost quartzite of the Smelterskop Stage north of Dullstroom to be several thousand feet thick. There seems to be little doubt that the Upper quartzite in the Kruis River area belongs to the Smelterskop Stage.

A strike-fault duplicates the quartzite horizons of the Smelterskop Stage. North of this fault, on Elandsplaats 48-J.S., Goedgedacht 72-J.S. and Wintershoek 186-J.S., the Lower quartzite has been intruded irregularly by gabbroic rocks and therefore does not form as prominent an outcrop as that to the south. The Upper quartzite, which now strikes nort south and dips somewhat gently viz. 10°-30° towards the east, forms a thick sheet rising 1000 ft above the low-lying areas to the west. The Maleeuwskop trigonometrical beacon No. 87 is situated on the highest point.

Overlying the Upper quartzite are thin sheets of diabase and layers of hornfels. They separate a thin quartzite layer, 150 to 200 ft thick, from the Upper quartzite. This thin layer also contains a banded fine-grained quartzite at its base, similar to the one at the base of the Lower quartzite. The cobalt occurrence on Kruisrivier 74-J.S. and several prospecting-pits on Roodewal 193-J.S. are on this horizon.

The quartzite usually contains a fair amount of K-feldspar which imparts a pink colour to the rock. The base of the Upper quartzite is a conspicuously finely-mottled white quartzite. The specks are caused by concentrations of biotite. This mineral is metamorphic in origin, but has now been altered mostly to chlorite (R.17,

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L.3).

Cross-bedding and ripple-markings have been observed but are generally scarce.

Thin layers of hornfels are present between the various quartzite horizons. They contain the minerals quartz, cordierite, plagioclase (An_{39}), hypersthene (39 mol. per cent $FeSiO_3$), and biotite (R.23). This assemblage corresponds to the Groothoek type of metamorphism. (Willemse, J., 1964, Table IV).

A thin band of folded and banded rocks overlies the quartzite succession (Photo 1). These rocks have been designated "pyroxene granulites" by A.F. Lombaard (1949, p. 347). The composition of the bands varies considerably; one thin section (R.14) contains chiefly clinopyroxene and feldspar, another (Bl.11) quartz and feldspar. They probably represent highly altered marls.

Xenoliths which belong to the Smelterskop Stage are present in the Bushveld gabbro, approximately 7000 ft above the quartzite succession. These xenoliths, which are up to 600 ft thick, are characterised by a considerable diversity of rock types. At the base, the rocks show a striking resemblance to the leptite and microgranophyre of the Rooiberg felsite. Microgranophyre (K.5) is present in the western xenoliths on Kruisrivier 74-J.S. and Roodewal 193-J.S., whereas microgranite (L.42) and leptitic rocks are found in the eastern xenoliths on Mineral Range 190-J.S. The leptite is fine-grained and consists of granular quartz and K-feldspar. It contains numerous inclusions which are finer-grained than the host (L.25). The inclusions are often rich in pyroxene (L.19) and possibly represent altered carbonate inclusions of sedimentary origin. The inclusions in this leptite suggest that this rock may be an agglomerate. Similar fine-grained rocks rich in quartz are present below

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the Dullstroom lava east of Laersdrif (D. Groeneveld, personal communication).

On Mineral Range 190-J.S. a feldspathic quartzite follows above the felsitic rocks and is succeeded by a thin layer of hornfels which is present in most of the xenoliths. The hornfels varies greatly in composition - from a nearly pure cordierite hornfels, which contains small amounts of plagioclase and pyrite (L.20), to an ordinary hornfels which contains minerals like quartz, cordierite, plagioclase, biotite and orthopyroxene (L.22).

The major rock type in these xenoliths is a highly altered lava, presumably the correlate of the Dullstroom lava. The amygdales, evidently originally filled with calcite, quartz and feldspar, now consist of either coarse grains of quartz and clinopyroxene and a little feldspar, or clinopyroxene alone. Where the amygdales also contain magnetite and an alteration product of ilmenite, presumably leucoxene, these minerals often possess a reaction-rim of sphene, obviously owing to reaction between Ca of the original calcite and Ti of the ilmenite (L.30).According to Buddington <u>et</u> <u>al</u>.(1955, p. 529) the formation of sphene at the expense of ilmenite in some reconstituted granite gneisses in the lower range of the amphibolite facies, leaves a magnetite usually low in titanium.

The ground-mass of the lava which consists of plagioclase and clinopyroxene, becomes coarser nearer to the gabbro contact, where orthopyroxene is also developed (Volumetric analysis Table 11, p. 59). This orthopyroxene contains thick exsolution lamellae of augite, which indicate that temperatures during metamorphism in these rocks were high enough for the formation of pigeonite. The orthopyrox-

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ene has a nesophitic texture (Walker, F. 1952, p. 2) and contains augite lamellae which have random orientations (L.32A). Where this fine-grained orthopyroxene is in direct contact with the gabbroic rocks, it has the same optic orientation as the coarse-grained orthopyroxene of the gabbro. This indicates that orientation after inversion of the one, influenced the orientation of the adjoining inverting pigeonite (Photo 2). Nesophytic orthopyroxene which contains augite lamellae orientated at random is common in the gabbroic rocks of the Bushveld Complex and this phenomenon will therefore be discussed in more detail on p. 84.

IV. DIABASE SHEETS IN THE PRETORIA SERIES

Under this heading have been grouped together gabbroic rocks which are intrusive into the quartzite as sheets and irregular masses. It is not certain whether they all belong to the Sill Phase of Diabase or whether some of these gabbroic rocks belong to the Main Plutonic Phase of the Bushveld Complex. To distinguish these two rock types in these irregular masses is difficult because the diabase is not always fine-grained.

The diabase is either a fine-grained rock which contains thin needles of amphibole in a dark ground-mass, or it is fairly coarse-grained containing plagioclase and amphibole as well as fair amounts of quartz and K-feldspar which are intergrown granophyrically. In thin section (G.5, G.12, G.11) the amphibole and the plagioclase are always altered to chloritic material and saussurite respectively, possibly owing to the metamorphism during emplacement of the Main Plutonic Phase. According to the mineral composition they are of the Lydenburg type (Willemse, J., 1959, p. xlviii).

On Goedgedacht 72-J.S., between the Magaliesberg and

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Photograph 1.

Banded and folded pyroxene granulite. Roodewal 193-J.S.

Photograph 2. Crossed nicols. X 25.

Nesophitic orthopyroxene (grey) contains exsolution lamellae of augite orientated at random. The orthopyroxene of the inclusion (right) is optically continuous with the coarse-grained orthopyroxene (CO) of the gabbro (left). Section L.32A, Mineral Range 190-J.S.

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the Smelterskop quartzite, pyroxenitic rocks were found which correspond in composition with the Maruleng type of mafic sills (Willemse, J., 1959, p. xlviii). The rock consists mostly of bronzite (17 mol. per cent $FeSiO_3$), a little interstitial plagioclase (An_{67}) and quartz (G.15). This Maruleng type of mafic rock in the area mapped does not show the high degree of alteration of the Lydenburg type. It is therefore possible that these pyroxenitic rocks are of the same age as those of the Main Plutonic Phase.

V. THE ROOIBERG FELSITE

1. General field-relationships

The felsite occupies the whole of the Bothasberg plateau in the south of the area, and the rocks investigated include nearly the complete succession. According to the Geological map, Sheet No. 11, Lydenburg, felsite on Avontuur 195-J.S. is developed to just south of the Selons River. The area mapped stops just north of the Selons River. Farther to the east, the south-eastern boundary of the investigated area cuts diagonally across the strike of the felsite as far as the southernmost beacon of Waterval 184-J.S.

In the west the felsite dips at 55° to 60° south. The dip decreases gradually eastwards. The maximum thickness of felsite mapped, which is approximately 14,600 ft, is ~~therefore~~ found in the west on Roodewal 193-J.S. and Avontuur 195-J.S. Tributaries of the Selons River cut deeply into the felsite with the result that very good exposures are available.

2. Definitions and grouping

In his treatise on the Bushveld felsite B.V. Lombaard (1932, pp. 157-159) gives a classification based on structural and textural varieties. His summary of the classification is given in table 2.

TABLE 2. Classification of felsites (Lombaard, B.V. 1932, p. 159)

1. Non-porphyritic felsite.	2. Porphyritic felsite, insets are:		3. Felsite with directed texture.	4. Pyroclastic felsite.
	a. Albite	b. Microperthite		
a. Pseudospherulitic types			Trachytic varieties.	Volcanic breccias.
b. Granophyric types.			Flow-banded	Tuffs.
c. Felsitic (glassy) types			Amygdaloidal	

The designations proposed by him are generally applicable to the felsites of the area investigated.

At this stage it seems also necessary to review the definitions of the terms "granophyric", "micrographic" and "micropegmatitic", because they are sometimes used very loosely in the literature and they play an important role in distinguishing the various felsite types. Two definitions are quoted from the "Glossary of Geology and Related Sciences" (1960, pp. 128 and 129).

(i) Granophyric: "A texture in igneous rocks characterised by the irregular intergrowth of blobs, patches and threads of quartz in a base of feldspar. It is similar to graphic and micrographic but differs from these textures in that the intergrowth of quartz and feldspar is more irregular."

(ii) Graphic: "A rock texture resulting from the regular intergrowth of quartz and feldspar. The quartz is commonly cuneiform, resembling runic inscriptions on the background of feldspar. When this kind of inter-

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growth is reduced to microscopic dimensions the texture becomes micrographic, and the material is called micropegmatite."

Micrographic textures in the felsites are common and the designation "micrographic felsite" will be used for felsite in which the intergrowth is regular, i.e. the quartz is uniformly distributed in the feldspar. The term "granophyric felsite" will be used where the intergrowth is irregular, i.e. the distribution and size of the quartz grains in the feldspar varies e.g. intergrowth-rosettes.

In the field the felsite can be subdivided into the following zones:

1. Lower felsite: porphyritic and non-porphyritic, fine-grained, micrographic and almost glassy.
2. Variable felsite: most of the types given in table 2. Predominately amygdaloidal and pseudospherulitic.
3. Upper felsite: mainly dense porphyritic red-coloured and glassy.
4. Microgranophyre and granophyre, intrusive into 1 and 2.

Thicknesses are given in table 6.

3. <u>The Lower felsite: porphyritic and non-porphyritic, fine-grained, micrographic and almost glassy</u>

These rocks which form the base of the Rooiberg felsite in the area are found only on Diepkloof 186-J.S. and Waterval 184-J.S. They outcrop in two belts; the one which consists of fine-grained felsite generally known as leptite forms the scarp of the Bothasberg plateau on Waterval 184-J.S. and is separated by a relatively coarse-grained granophyre from the other belt, a micrographic and almost glassy felsite, which outcrops on the top of the plateau on Diepkloof 186-J.S. and on Waterval 184-J.S.

The more important textural features are summarized in in table 3.

Although it is appreciated that rocks are usually described from the base of a sequence upwards, it is proposed to depart from this rule in the present instance. Accordingly in dealing with the Lower felsite the top portion will be considered first because it is farthest away from the metamorphic effects of the gabbroic rocks and it would therefore represent the proto-type of this felsite more than any other rock type in this subgroup.

(a) Micrographic and microcrystalline felsite

The top of the Lower felsite is a dark, nearly black and very fine-grained microcrystalline rock (WV.10 and WV.12). It is characterized by numerous hornblende and ore granules 0.02 mm in diameter which are often arranged in sub-parallel rows (WV.12, Photo 3). This possible flow-banding gives the rock a trachytic texture. The direction of these sub-parallel rows varies considerably and it is therefore difficult to assume that they represent any direction of flow.

Lower down in this zone the fine-grained felsite changes to a fine-grained micrographic felsite. The micrographic intergrowth in these felsites gets gradually coarser as can be seen in table 3 and photo 5. The porphyritic texture of some of the various felsites is produced by plagioclase phenocrysts, the composition of which is mostly albite as recorded in table 3.

Some of the micrographic felsite contains long bent plagioclase needles (WV.28 and WV.26). C.A. Strauss, (1947, p. 79) describes similarly bent pyroxene laths in a dolerite from the New Belgium Block, Potgietersrust District. He is of the opinion that the bending was either caused by the growth of other constituents, or that they represent intratelluric crystals which were distorted at depth. It seems that these bent plagioclase needles started to crys-

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tallize whilst the lava was still in motion.

Phenocrysts of plagioclase in the coarse-grained micrographic felsite (D.28) show reversed zoning and resorption. The Ca-rich outer zone follows the hollows left by resorption. The considerable change from An_2 to An_{18} suggests that Ca-metasomatism came into effect after solidification of the felsite and was probably caused during the emplacement of the nearby gabbroic rocks. In the same felsite olivine (20 mol.per cent Fe_2SiO_4) is found as small irregular grains.

A chemical analysis of a micrographic felsite (WV.28) is provided in table 9, p.43, and a modal analysis of the coarse-grained, micrographic felsite (D.28) in table 4.

The gradual increase in coarseness of the micrographic intergrowth downward in the succession (Table 3) may be attributed to one of the following factors.

(i) As proposed by B.V.Lombaard (1932,p.152) the portions of the felsite which are more coarsely crystalline represent the lower portions of a lava-flow that cooled more slowly than the fine-grained glassy top.

(ii) Metamorphism resulting from the emplacement of the gabbroic rocks of the Complex may have produced a progressive coarsening of a fine-grained felsite.

The relationship of the granophyre in the sequence is discussed later.

(b) Fine-grained felsite (Leptite)

As pointed out already the fine-grained felsite, also grouped under the Lower felsite, forms a separate belt of outcrops all along the scarp of the Bothasberg plateau on Waterval 184-J.S. It differs from the micrographic felsite in that it shows no intergrowth of quartz and K-feldspar.

The reason why the micrographic felsite and the leptite were grouped together are:

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TABLE 8: Textures of the Lower felsite, i.e. fine-grained and micrographic felsite

Height in strati-graphical column.	No. of Section	Relationship of quartz and K-feldspar	Diameter of inter-growth units in mm.	Approx. diameter of quartz in units in mm.	Dimensions of plagioclase in mm and An content
2850'	WV.10 and WV.12	Very small grains of quartz and K-feldspar, irregular in size and shape. Almost glassy (microcrystalline)	-	-	Acicular 0.135 x 0.017
2500'	WV.28	Partially micrographic, granular in places.	0.31	± 0.015	Acicular, often bent. Average dimensions 0.46 x 0.05 Maximum 1.5 x 0.085 (Photo 4)
2350'	WV.27	Only micrographic (Photo 5)	0.27	0.028	Lath-like 0.275 x 0.05 (An_4 - An_2)
2100'	WV.26	Only micrographic (Photo 5)	0.38	0.047	Lath-like and acicular, sometimes bent, 0.45 x 0.075
Uncertain	D.21	Micrographic (Photo 5)	0.34	0.047	0.52 x 0.27
720'	D.28	Coarse-grained micrographic (Photo 5)	1.28	0.066	1.10 x 0.61 (core An_2, rim An_{18}) resorption common
GRANOPHYRE					
				Size of quartz grains	
120'	WV.31	Fine-grained, granular	none	± 0.047	0.68 x 0.40
20'	WV.8	Slightly coarser grained than WV.31, granular.	none	0.085	0.60 x 0.80 inclusions of hornblende and ore (An_{18})
GABBROIC ROCKS OF THE MAIN PLUTONIC PHASE					

Photograph 3. Transmitted light. X 30.

Very fine-grained microcrystalline black non-porphyritic felsite displaying a sub-parallel arrangement of ore microlites. Section WV.12, Waterval 184-J.S.

Photograph 4. Crossed nicols. X 55.

Long bent plagioclase needle in a very fine-grained micrographic felsite. Section WV.28, Waterval 184-J.S.

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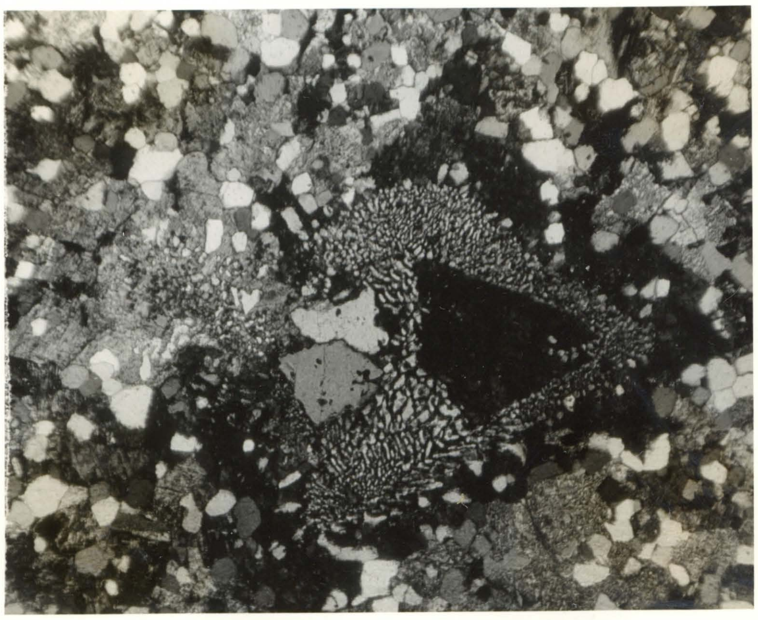
(WV.27) (WV.26) (D.21) (D.28)

Photograph 5. Crossed nicols. X 30.

A gradual coarsening of the micrographic intergrowth in the Lower felsite from left to right and downward in the succession.



Photograph 6. Crossed nicols. X 30.

Micrographic intergrowth in leptite. Hebron, north-west of Pretoria. (Section M99, M.v.R. Steyn, 1955)

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(i) The leptite evidently represents a coarser-grained variation of the fine-grained black felsite which constitutes the top portion of the micrographic felsite. In the outcrop itself a deacrease in grain-size away from the gabbroic rocks was detected (Table 3).

(ii)In similar fine-grained rocks (Photo 9) from Hebron, north-west of Pretoria (Section M99,M.v.R.Steyn,1955) micrographic intergrowth is present in places. C.A.Strauss (1954,p.13) describes pseudomicropegmatite in varying quantities in the leptite north-west of Potgietersrust.

It seems as though these rocks developed their granular texture through metamorphism of fine-grained glassy felsite. Apparently it depends on the cryptotexture of the glassy felsite whether the metamorphic product will be a micrographic or a granular rock. A submicroscopic spherulitic texture could result in a micrographic intergrowth, whereas an altogether hyaline texture could yield a granular rock.

The designation "leptite" for similar rocks associated with the Rooiberg felsite has been used by several authors (Kuschke, O.H., 1950, p. 16; Strauss, C.A., 1954, p. 12; Steyn, J.G.D., 1950, p. 55; Steyn, M.v.R., 1955, p. 20). By definition a leptite is " a metamorphic rock of rather fine grain, composed of granular quartz and feldspar" (Glossary of Geology and Related Sciences, 1960, p. 167). Geijer and Magnusson (Henriquess, A., 1966, p. 9) defined leptites as being "a metamorphic (recrystallized) supracrustal rock, of approximately granitic composition, which has a secondary grain size between 0.03 and 0.05 mm as a lower limit and 0.5(-1) mm, excluding phenocrysts which may be present". They divide leptites into those of the rhyolitic type (leptite sensu stricto) and meta-dacites plus meta-andesites. The rhyolitic type is subdivided according to the quantity and type of alkali feldspar into K-extremes, K-dominants, alkali-intermediates, Na-dominants and Na-

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extremes.

The term leptite has however no genetic significance. A. Henriques (1966, p. 57) who investigated leptite from the Ammeberg District, Sweden, describes two types: (i) red leptite which represents recrystallized lavas of kalirhyolitic composition and (ii) grey leptite which has originated from a number of petrographically dissimilar pyroclastic sediments, lava rocks, epiclastic sediments and chemical sediments.

Similarly the leptites of the Bushveld Complex have been interpreted in several different ways. J.M. van der Westhuizen (1945, p. 20) is of the opinion that the leptite of the area investigated as well as the micrographic felsite belongs to the Upper Zone of the Main Plutonic Phase of the Complex. These he called Upper Zone felsite as they correspond to the Tauteshoogte felsite described by J.C Boshoff (1942, p. 5 and p. 33). O.H. Kuschke (1950, p. 28) describes similar rocks from the vicinity of Brits and believes that they represent fine-grained quartzite. J.G.D. Steyn (1950, p. 55) who found leptite in the neighbourhood of Magnet Heights, is of the opinion that they are feldspathised quartzites. M.v.R. Steyn (1955, p. 20), in his description of an area north-west of Pretoria, maintains that leptite represents argillaceous sedimentary rocks. C.A. Strauss (1954, p. 19), F.C. Truter (1955, p. 81) and J. Willemse (1964, p. 115) also believe that the Bushveld leptite originates from quartzite, feldspathic quartzite and shaly quartzite, the Bushveld granite or the mafic rocks or both having yielded the metasomatizing fluids.

There are no indications in the investigated area that the leptite represents metamorphosed sedimentary rocks. According to the chemical analysis (Table 9) the leptite of this area is of the rhyolitic alkali-intermediate type. A

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modal analysis of a leptite is provided in table 4.

A feature of the leptite in this area, as well as in the area mapped by D. Groeneveld (research in progress) farther east along Bothasberg, on Tauteshoogte, and in the area farther north, mapped by T.G. Molyneux (research in progress), is that they are traversed by numerous veins of a micro-granite. All these areas have been visited by the author. On Droogehoek 882-K.S., Lydenburg District, investigated by Molyneux, it can be clearly seen in a riverbed that the micro-granite is derived from the leptite through gradational contacts.

TABLE 4. Modal analyses (weight per cent) of felsite types.

	Micrographic felsite D.28					Leptite
	Micrographically intergrown		Not intergrown			
Quartz	31.59	+	2.36	=	33.95	29.80
K-feldspar ..	45.54	+	2.66	=	48.20	47.60
Subtotal	77.13	+	5.02	=	82,15	
Plagioclase .					7.23	6.98
Olivine					1.70	
Clinopyroxene					4.98	0.40
Hornblende ..					0.65	9.30
Opaque					3.24	5.86
					100.04	99.94

Certain intergrowths of quartz and K-feldspar in some of the felsite on Diepkloof 186-J.S. (D.33) are similar to the "exploded bomb" textures in pseudogranophyres which are described by Strauss and Truter (1944, p. 70) and by D.P. van Rooyen (1947, p. 67) and which are considered by them to have originated by the replacement of quartz by feldspar. In certain parts of the thin section of the felsite (D.33) the

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size of the quartz grains is similar to that of the leptite. In other parts the quartz is coarse-grained, very irregular in shape and often intergrown with K-feldspar. The irregularity in the shape of the intergrowth units, which often contain small grains of quartz of different orientation casts doubt on the interpretation that these intergrowths originated by replacement of quartz by feldspar.

4. The Variable felsite

(a) General

This zone is characterized by alternating layers of different types of felsite (Table 5). The most prominent one is dark in colour and mostly amygdaloidal. Interbedded in these are lighter pseudospherulitic types, mostly porphyritic and occasionally flow-banded. Thin intercalations of agglomerate and tuff are found, but are very subordinate. Lenticular bodies of quartzite are common. One layer of quartzite and a conspicuous agglomerate below it can be followed at intervals for many miles along the strike.

Intrusive into the black amygdaloidal felsite is a microgranophyre. This rock often has gradational contacts with the pseudospherulitic felsite and it is therefore difficult to distinguish between them.

(b) Black amygdaloidal felsite

According to J.M. van der Westhuizen (1945, p. 24) the base of the Rooiberg felsite is indicated by a black amygdaloidal felsite. This black felsite does not differ much from the uppermost dark felsite of the previous zone. The appearance of amygdales in the felsite has served as a basis for the subdivision.

Amygdaloidal felsite constitutes the greatest portion of the Variable felsite. The more important textural features are described in table 5. They are black and glassy in the

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TABLE 5. Succession and thickness of the Variable and the Upper felsite on Roodewal 193-J.S. and Avontuur 195-J.S.

Unit	Thickness	Description		
UPPER FELSITE 4480 FT. (MINIMUM)		At least 2500 ft of felsite above shale on Klipnek 199-J.S.	Plane of unconformity between the Rooiberg felsite and the Loskop System.	
		(Southernmost boundary mapped)		
	1300'	Red porphyritic felsite. Flow-banded and slightly brecciated in places.	1000 ft of felsite above shale on Zeekoegat 115-J.S. (Mellor 1906, Plate 23).	1000'
	380'	Shale, well-bedded		
	1200'	Purple agglomerate. Angular fragments of felsite, in places quartzite, in felsitic matrix. Reddish-brown felsite which contains few phenocrysts.		
	1000'	Intrusive granite porphyry, approximately 1000 ft thick		
	1600'	Thin layer of tuff, fine-grained containing small fragments of brown felsite. Brown porphyritic felsite, flow-banded. Massive reddish brown porphyritic felsite. Brown porphyritic felsite. Flow-banded. Often contains numerous plagioclase phenocrysts.		
VARIABLE FELSITE 5700 FT.	2300'	Agglomerate on top. Quartzite or chert just below. Green, in places black amygdaloidal felsite. Amygdales are concentrated in groups which give rise in places to a directed texture (Photo 7). Amygdales never as large as in previous felsite. Perlitic cracks in places developed.		
	3400'	Mainly black fine-grained and glassy porphyritic amygdaloidal felsite. Amygdales up to 1 ft in diameter (Photo 7) consist of quartz and K-feldspar. Black glassy felsite exhibits perlitic textures. Black felsite characterized by numerous small red amygdales 1.5 to 3 mm in diameter, filled with K-feldspar. Red porphyritic amygdaloidal felsite. Amygdales of quartz 4-7 mm in diameter.	Pseudospherulitic felsite near top. Dual Marker, i.e. thin quartzite and agglomerate below. Fragments of felsite cemented together by chert. Interbedded pseudospherulitic felsite, in places granophyric, especially in the lower half.	

Microgranophyre and granophyre

lower half, and dark green sometimes black in the upper half. The black glassy types exhibit perlitic textures similar to those in the felsitic perlite described by C.W. Glatthaar (1956, p. 8). Except for the black perlitic markings, concentric lighter-coloured lines in the thin sections possibly also represent joints of similar origin (N.5). A third set of curved cracks filled with fine-grained vein-quartz cuts across the perlitic cracks and is possibly also due to shrinkage during cooling (Photo 8). Microlites are present throughout the ground-mass and consist of ore dust as well as pyroxene. They are often arranged in sub-parallel lines, similar to those in the very fine-grained black felsite of the Lower felsite (WV.12). Where devitrified, the groundmass of the amygdaloidal felsite consists mainly of fine-grained quartz and K-feldspar.

(c) Pseudospherulitic felsite

The pseudospherulitic felsite is an interbedded dark-brown non-amygdaloidal felsite in the black amygdaloidal varieties and is more abundant in the lower half of the Variable felsite.

Typical spherulities are never encountered in these rocks and are therefore called pseudospherulites by B.V. Lombaard (1932, p. 157). They are composed of radially intergrown quartz and K-feldspar, often imperfectly spherical (Photo 11). In this pseudospherulitic felsite the groundmass may consist completely of these pseudospherulites, or they may occur in a devitrified glassy matrix. This glassy groundmass is, as in the pseudospherulites, a very fine-grained quartz and K-feldspar intergrowth which is not radially arranged ~~(Photo 11)~~. Occasionally, the intergrowth of quartz and K-feldspar is coarser on the sides of the pseudospherulites and between them. This gives rise to a fine granophyric texture which is characterized by small quartz needles (Photo 12). B.V. Lombaard (1932, p. 157) termed similar rocks pseudospherulitic grano-

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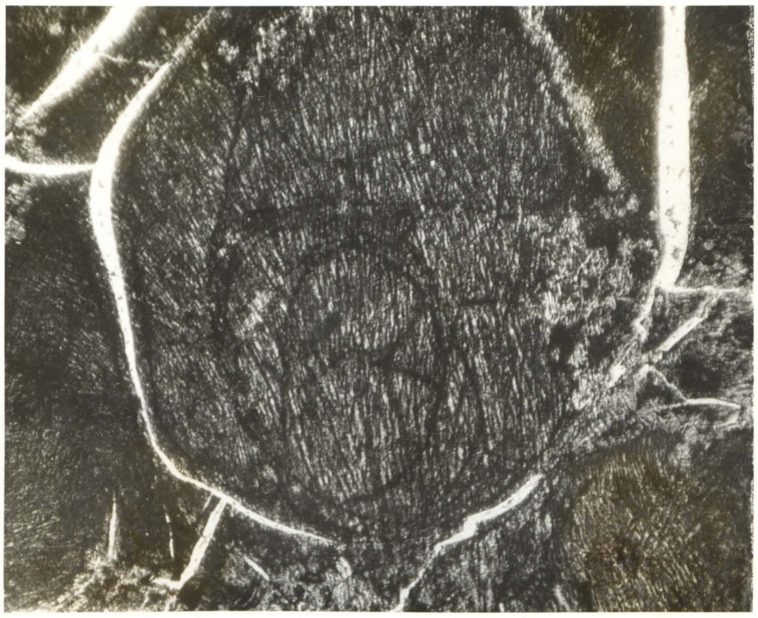
Photograph 7.

Large amygdales, up to 1 foot in diameter in black felsite. Diepkloof 186-J.S.



Photograph 8. Transmitted light. X 30.

Perlitic cracks (dark) in a glassy black felsite. White lines are cracks which are filled with vein-quartz. Microlites indicate possible flow-lines. Section N.5, Niccolton 192-J.S.

Photograph 9.

Clusters of small amygdales concentrated in an elongate mass in dark felsite. The clusters and the masses are elongated parallel to the strike of the felsite, and give rise to a directed structure. Roodepoort 75-J.S.

Photograph 10.

A layer of quartzite(Q) directly above a characteristic agglomerate (below hammer). Roodepoort 75-J.S.

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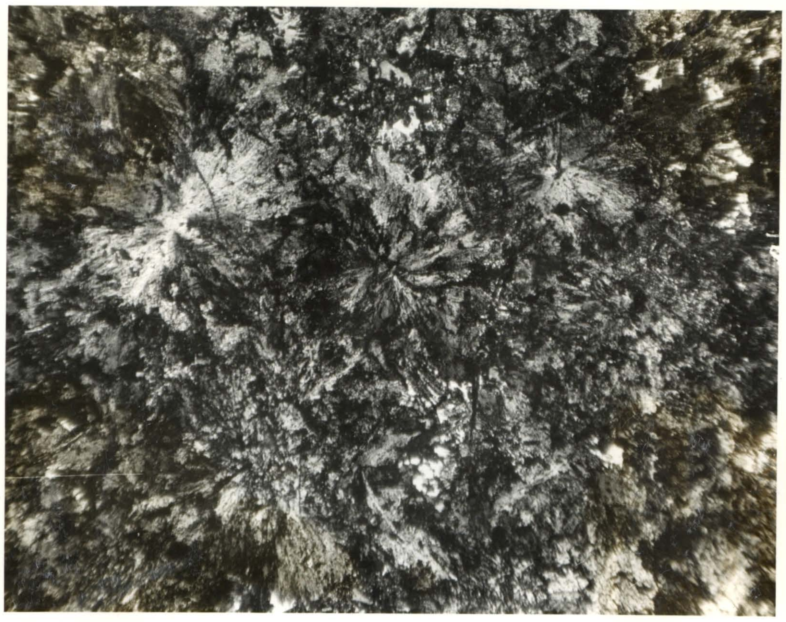

Photograph 11. Crossed nicols. X 30.

Radially intergrown quartz and K-feldspar, imperfectly spherical in pseudospherulitic porphyritic felsite.

Section D.6, Diepkloof 186-J.S.

Photograph 12. Crossed nicols. X 30.

Very fine granophyric intergrowth and small quartz needles (q) in pseudospherulitic porphyritic felsite.

Section D.5, Diepkloof 186-J.S.

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phyric felsite. This designation is considered to be superfluous, and any rock type showing signs of an extinction-cross in these pseudospherulites under crossed nicols, has been grouped with the pseudospherulitic felsite.

The microscopical and macroscopical properties of the pseudospherulitic felsite, the microgranophyre and the granophyre are summarized in table 7.

(d) Irregularities in the succession

The succession of the Variable felsite given in table 5 varies slightly from one place to another. On Roodepoort 75-J.S. a grey non-porphyritic felsite is found at the base of the black amygdaloidal felsite. This non-porphyritic felsite contains numerous rounded grains of quartz and K-feldspar. The quartz grains are all enlarged by rims of secondary quartz. The roundness of the grains indicates that the felsite was probably extruded on an unconsolidated sandy surface and quartz and feldspar grains were incorporated as inclusions. On the same farm, as well as in the vicinity of the common beacon of the farms Diepkloof 186-J.S., Waterval 184-J.S. and Kleinfontein 203-J.S. an agglomerate is present in the black amygdaloidal felsite. The fragments consist of a red felsite cemented together with felsitic material. A lithic tuff, a few hundred feet above the agglomerate on Roodepoort 75-J.S., contains angular shards of quartz and K-feldspar, as well as large felsite fragments in a glassy matrix (T.11).

On Diepkloof 186-J.S. the agglomerate of the "dual marker" (Table 5) adopts a more sedimentary character because the felsite fragments are mixed with an unsorted sandy sediment. The result is a rock which contains angular fragments of felsite and rounded unsorted quartz grains in a cryptocrystalline matrix (D.3).

The layers and lenses of quartzite, which outcrop

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irregularly throughout the succession of the Variable felsite, most probably represent erosion channels between successive lava-flows. The quartzite is mainly brown, sometimes grey or red. It is fairly fine-grained, generally poorly sorted and the quartz grains are angular. Grains of K-feldspar are quite common. Plagioclase is less common and grains of felsitic material are extremely scarce (N.6, T.19).

5. The Upper felsite

The various rock types composing the Upper felsite are mentioned in table 5.

An agglomerate separates the Variable felsite from the Upper felsite. This agglomerate probably corresponds to the one described by Worst (1944, p. 13) as being the division between the black porphyritic and the red felsite.

Although only 1300 ft of felsite has been mapped above the shale horizon, a sample of red porphyritic felsite, 2500 ft above the shale has been collected on Klipnek 199-J.S. next to the road to Middelburg. The total thickness of the felsite given in table 6 is therefore a minimum.

6. Microgranophyre and granophyre

The microgranophyre forms irregular sheet-like masses in the Variable felsite. As has already been mentioned the microgranophyre has in places gradational contacts with the pseudo-spherulitic felsite and it could be designated "granophyric felsite". The term "microgranophyre" seems more appropriate seeing that this granophyric felsite is closely related to the granophyre, which having evidently been derived from the felsite, was mobile after solidification of the felsite.

A comparison of the macroscopical and microscopical properties of the pseudospherulitic felsite and the microgranophyre is given in table 7. Modal analyses of grano-

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TABLE 6. Comparisons of thicknesses and successions of the Rooiberg felsite and Pyroclastics

North of Middelburg				North of Nylstroom	
Waterval 184-J.S.		Roodewal 193-J.S. and Avontuur 195-J.S.		Malakynsoog 199-K.R. Coetzee, G.L. (personal communication)	
Not investigated	Upper felsite	Not mapped. At least another 1200 ft. of felsite on Klipnek 199-J.S.		Quartz porphyry	1500 ft.
				Upper sedimentary zone (shale, conglomerate, thin chert)	500 ft.
		Porphyritic felsite	1300 ft.	Non-porphyritic and porphyritic felsite	3600 ft. (min.)
		Shale	380 ft.	Shale	360 ft.
		Agglomerate Porphyritic felsite	2800 ft.	Non-porphyritic felsite	15-20 ft.
				Agglomerate	200 ft.
		Variable felsite (Amygdaloidal and pseudo-spherulitic felsite and micro-granophyre)	5700 ft.	Variable felsite (Amygdaloidal and flow-banded)	800 - 1100 ft.
Lower felsite (non-porphyritic, porphyritic and micrographic)		Micrographophyre, granophyre and microgranite	4500 ft.	Porphyritic and non-porphyritic felsite	3800 ft.
		Total thickness	14680 ft.	Total thickness	10780 ft.
		Intrusive gabbroic rocks		Intrusive Bushveld granite	

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phyric rocks, including a micrograophyre (T.1) is given in table 8, and a chemical analysis of a microgranophyre (R.28) in table 9.

Except for quartz and K-feldspar, plagioclase is the most common constituent of the pseudospherulitic felsite as well as of the microgranophyre. Two types of plagioclase crystals are present in all the sections investigated. Firstly there are large phenocrysts averaging 0.62 mm x 0.27 mm in size but reaching dimensions of up to 1 mm x 0.5 mm. They usually impart to the felsite a glomeroporphyritic texture. Secondly, small idiomorphic crystals 0.22 x 0.09 mm in size, are spread evenly throughout the groundmass. The composition of both types is the same, varying between An_4 and An_1. It is often found that the plagioclase crystals served as crystallization nuclei for the granophyric intergrowth. The intergrowth is very fine in the immediate vicinity of the crystal and becomes coarser farther away from i

The dark mineral is a green pleochroic hornblende which is often altered to chlorite and epidote. It forms irregular patchy grains, mostly concentrated in certain areas. Biotite is very scarce; if present it is an alteration product of hornblende or it is found as a narrow rim around the opaque minerals.

Quartz needles in these rocks are very common, more so in the microgranophyre than in the pseudospherulitic types (Photo 12 and 13). It is doubtful whether they represent original tridymite as proposed by Glatthaar (1956, p. 9) and they show no resemblance to the quartz needles of the Premier Mine felsite (Lombaard, B.V., 1932, p. 135, Plate XIII, Fig. 1 and 2) which more likely represent paramorphs after tridymite. The quartz needles of the Premier Mine felsite have sharp, well-defined outlines and are composed of granular quartz. This indicates that SiO_2 crystallized

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TABLE 7. Microscopical and macroscopical properties of pseudospherulitic felsite, micrograpophyre and granophyre

	Pseudospherulitic felsite	Microgranophyre	Granophyre
Macroscopical	Appearance on weathering. Small angular fragments forming rubble.	Round, small boulders. Tends to be spheroidal.	Large round boulders, typically spheroidal.
	Dark-brown, sometimes dark-grey to black irregularly crystalline to glassy.	Red-brown, very fine grained, fully crystalline. No granophyric intergrowth visible with the lens.	Red medium to coarse-grained granophyre, intergrowth visible with the aid of a lens (in the coarse-grained ~~ed~~ varities without a lens).
Microscopical	Pseudospherulites i.e. very fine-grained intergrowths of quartz and K-feldspar exhibit an irregular extinction-cross under crossed nicols (D.6)	Pseudospherulites can still be distinguished as fine microgranophyric intergrowth units in which quartz extinguishes simultaneously, and also by the presence of long radiating quartz needles.	Large typical granophyric intergrowth units.
	Ground-mass either glassy usually devitrified i.e. fine-grained quartz and K-feldspar or very fine-grained microgranophyre containing small quartz needles.	Ground-mass usually irregular granophyric quartz and K-feldspar intergrowth, slightly coarser than in pseudospherulitic felsite.	Largely granophyric intergrowth units and large discrete quartz and K-feldspar grains.
	Small quartz-needles present (D.5) 0.2 x 0.005 mm.	Quartz needles vary in length up to 0.7 mm long and 0.015 mm wide (H.1). Where granophyric intergrowth increases the quartz-needles become more irregular in shape (T$_1$1).	No quartz needles present.
	Plagioclase as: i) Large phenocrysts often glameroporphyritic 0.62 x 0.27 mm. ii) Small crystals evenly spread throughout 0.22 x 0.09 mm. Small crystals tend to be acicular.		Usually ~~not~~ large phenocrysts up to 1.2 mm long and 0.7 mm wide.

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as a high temperature polymorph of quartz, possibly tridymite, which on cooling inverted to the more stable low temperature polymorph. In this way the different orientations originate in one needle. The quartz needles in the Rooiberg felsite extinguish in sets and are intergrown with the K-feldspar. The needles of one orientation branch have irregular outlines and are optically continuous with the adjoining quartz grains.

Lower down in the thick sheet of granophyric rocks below the Variable felsite, the granophyric intergrowth becomes gradually coarser (Photo 14) and the micrographophyre changes to a granophyre (Photo 15). The quartz needles become more irregular in shape and disappear altogether as the granophyric intergrowth gets better defined and coarser. Microgranophyre is, however, still present among these granophyres, for example on Diepkloof 186-J.S. at the trigonometrical beacon M.D.80/248 where the rock is finer grained and the colour darker.

Near the base of this granophyre, a fine-grained granophyric granite (R.45) is found in isolated localities, It could not be mapped separately on account of the varying amounts of granophyric intergrowth. A chemical analysis of a granophyric granite is given in table 9.

Coarse-grained granophyres form a separate sheet-like intrusion along the slopes of Bothasberg from Roodewal 193-J.S. eastwards to beyond Waterval 184-J.S. In the west this sheet is approximately 500 ft thick but it increases in thickness on Waterval 184-J.S. where the rock is more like a fine-grained granite in some places. Near the eastern boundary of Waterval 184-J.S. this sheet splits in two and a thick succession of micrographic felsite is present in between. The southern mass of granophyre is slightly finer-grained than the northern one. The rocks are easily recognized in the field by the large round boulders they produce on weathering

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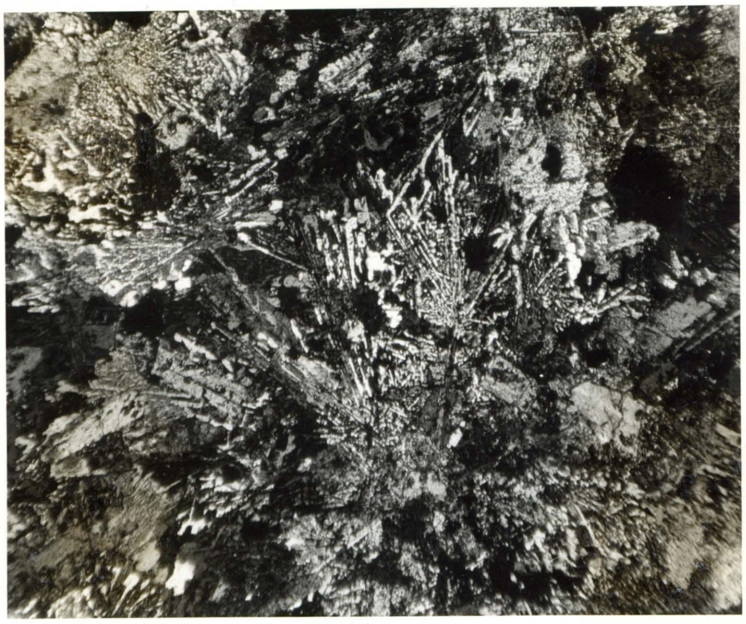

Photograph 13. Crossed nicols. X 32.

Radiating needles of quartz which extinguish in groups in microgranophyre. Section H.1, Hooggenoeg 205-J.S.

Photograph 14. Crossed nicols. X 32.

Intergrowth of quartz and K-feldspar in microgranophyre. Section T_1 1, Roodepoort 75-J.S.

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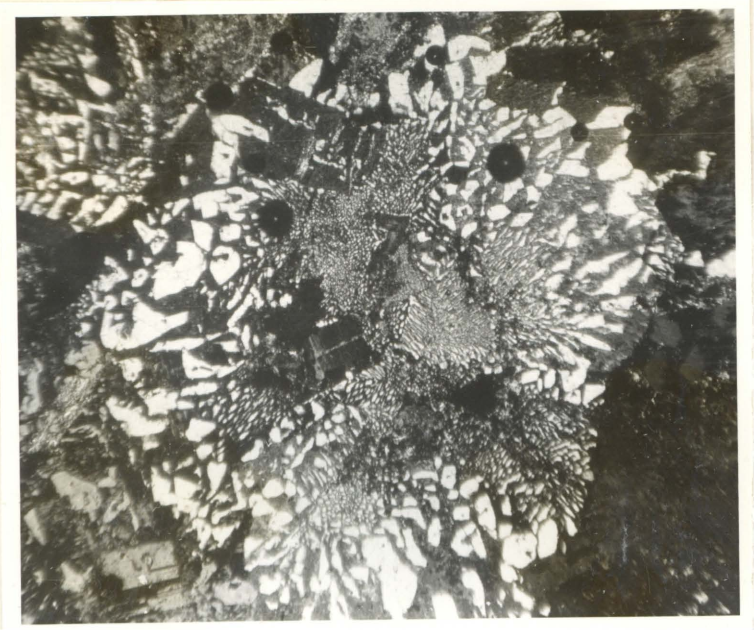
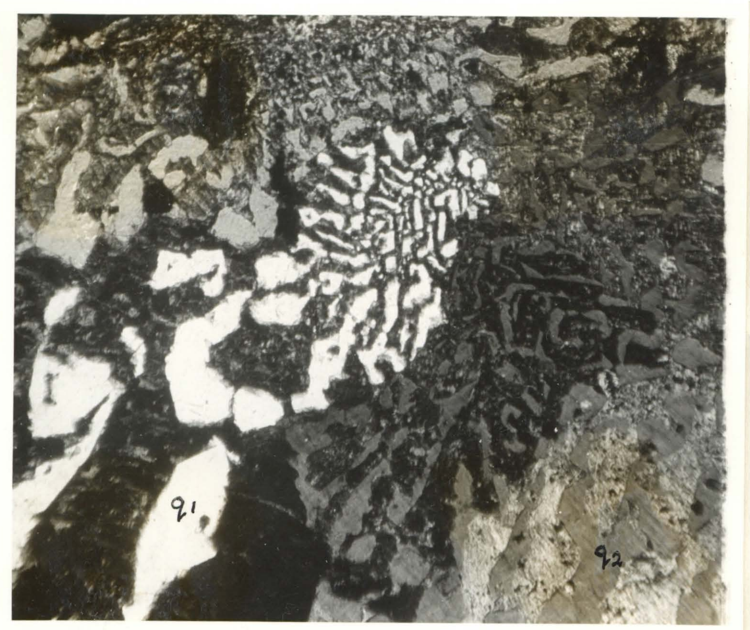


Photograph 15. Crossed nicols. X 32.

Medium-grained granophyre at the base of the microgranophyre. Section R.56, Roodewal 193-J.S.



Photograph 16. Crossed nicols. X 32.

Coarse-grained granophyre. Two orientations of quartz (q_1 and q_2) in three K-feldspar grains. Section D.17, Diepkloof 186-J.S.

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and the coarseness of their granophyric intergrowth which can be recognized with the unaided eye. In comparison with the other granophyric rocks the granophyric intergrowth of this granophyre is very coarse (Photo 16). The granophyre consists mainly of quartz and K-feldspar which are for the greater part granophyrically intergrown (Table 8, D.17). The amount of granophyric intergrowth varies considerably, especially where the rock becomes more like a granite (Table 8, WV.21 and WV.5).

TABLE 8. Modal analyses (weight per cent) of granophyric rocks

No. of section	T.1	D.17			WV.21			WV.5
Constituents	A	B	C	A	B	C	A	A
Quartz	32.02	28.84	+ 3.36	= 32.2	16.47	+ 18.03	= 34.5	29.77
K-feldspar ..	45.10	37.22	+ 13.28	= 50.5	22.65	+ 29.75	= 52.4	54.00
Subtotal		66.06	+ 16.64	= 82.7	39.12	+ 47.78	= 86.9	83.77
Plagioclase ..	7.92			6.12			3.8	2.20
Hornblende ...	-			9.94			3.68	13.65
Chlorite	5.30			-			1.80	-
Biotite	-			-			0.31	-
Epidote	2.62			-			-	-
Opaque	7.05			1.36			3.15	0.46
Apatite	-			-			0.36	-
	100.01			100.12			100.00	100.08

±15% of which are intergrown

Columns A: Ordinary modal analyses.

Columns B in example D.17 and WV.21 granophyrically intergrown quartz and K-feldspar.

Columns C in example D.17 and WV.21 quartz and K-feldspar not intergrown.

T.1 Microgranophyre, Roodepoort 75-J.S.

D.17 Coarse-grained granophyre, Diepkloof 186-J.S.

WV.21 Granophyric granite, Waterval 184-J.S.

WV.5 Granophyric granite, Waterval 184-J.S.

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Plagioclase (An_5 - An_2) forms phenocrysts 1.2 mm long and 0.7 mm wide. Resorption is common among the phenocrysts and granophyric intergrowth usually fills the resorbed cavities. Even in these coarse-grained rocks plagioclase commonly served as a crystallization nucleus for the granophyric intergrowth. Often in these rocks the plagioclase phenocrysts have been replaced by microcline microperthite (WV.21). The idiomorphic shape of the plagioclase can still be recognized and in places the core still consists of plagioclase. The original shape of the phenocrysts can also be gauged from the granophyric intergrowth, where the phenocrysts served as nuclei. The K-feldspar that replaced the plagioclase often has the same orientation as that of the adjoining intergrowth.

7. The relationship between the granophyre, the felsite and the leptite.

It is well known that an intimate genetic relationship exists between the granophyre and the felsite. B.V. Lombaard (1932, p. 157) and A.L. Hall (1932, p. 243) are of the opinion that the granophyre represents the lower portion of a felsite flow which has solidified under its own roof. Where granophyre is intrusive into the felsite, it represents, according to A.L. Hall (1932, p. 257), either an intrusion of granophyre into its own solidified felsite phase or the lower granophyric phase of a younger felsite. In this way the granophyre can even have an intrusive relationship towards the underlying, older felsite. At the same time it shows a gradual transition upwards into felsite.

Intrusive relationships between microgranophyre and felsite are common in the area investigated, for instance along the boundary of Roodewal 193-J.S. and Avontuur 195-J.S. a thin sheet of microgranophyre cuts across the strike of the felsite, and farther north on Roodewal 193-J.S. and Diepkloof 186-J.S. the thick sheet of granophyric rocks has an intrusive

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contact with the Variable felsite above. It is doubtful whether granophyre and the micrographophyre represent the lower portion of a felsite flow because similar rock types are missing away from the base of the felsite in the thick homogeneous porphyritic Upper felsite.

Other authors have proposed a metasomatic origin for the granophyres. On account of "exploded bomb" textures which are considered to originate by the replacement of quartz by K-feldspar, Strauss and Truter (1944, p. 70) ascribe Rooiberg pseudogranophyre to metasomatism of sediments. In the granophyre related to the Bushveld granite, according to them (p. 53), there are no signs of any replacement of quartz by feldspar and the intergrowth can be ascribed to simultaneous crystallization of these two minerals, but they also mention the possibility that the granophyre may owe its texture to a replacement process. Strauss (1954, p. 31) is of the opinion that, although a transition between granophyre and felsite is absent in the Zaaiplaats Tin Mining Area and only intrusive relationships exist, it does not preclude a metamorphic origin of the granophyre and that "long-continued interaction between granite magma and quartzo-feldspathic xenoliths may give rise to a transitional contact and rheomorphism may make the metamorphosed rock intrusive into overlying felsite."

Other authors who favour the theory that the granophyre of the Bushveld Complex is derived from sedimentary rocks, especially quartzite and feldspathic quartzite, are O.H. Kuschke (1950, p. 29) and F.C. Truter (1955, p. 81). This mode of origin is also mentioned by J. Willemse (1964, p. 115). Doubt exists, however, as to whether the Bushveld granite or the mafic rocks or both yielded the metasomatising fluids

Much has been said in the past about the origin of granophyric textures. Certain authors who favour simultaneous crystallization of the two constituents have found that

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quartz prefers certain orientations within the K-feldspar. According to Drescher-Kaden (1948) who investigated intergrowths of quartz and feldspar in graphic granite and granophyres, the orientation of quartz in K-feldspar is random, although certain positions of quartz in feldspar are favoured (p. 130). He also points out (p. 119-125) that it is difficult to assume how two components with different crystal structures like quartz and K-feldspar can produce granophyric and graphic intergrowth through simultaneous crystallization. He is of the opinion (p. 164) that in most of the graphic and granophyric intergrowths quartz is the younger constituent because it is continuous with the quartz which fills cleavage-fractures in the K-feldspar. Granophyric intergrowth can, according to him, also be the result of replacement of quartz by K-feldspar (p. 164) and where the quartz grain is completely broken up by K-feldspar into a rosette it cannot be distinguished from an intergrowth that resulted from replacement of K-feldspar by quartz (p. 206).

There does seem to be some evidence that certain sediments can be reconstituted to form pseudogranophyres (Strauss and Truter, 1944, p. 70, and Van Rooyen, 1947, p. 67) and granophyres (Strauss, 1947, p. 166).

Leptites have also been explained by several authors to represent metasomatised sediments as mentioned on p. 19. However, it is doubtful whether the granophyre and the leptite in the area investigated represent reconstituted sediments. The following points militate against a metasomatic origin for these rocks.

(i) The origin of the metasomatising fluids presents a problem. It seems unlikely that the mafic rocks produced these fluids, because large amounts of K-rich differentiates are lacking in the Main Plutonic Phase. Where large quantities of granite are present, as in

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the Zaaiplaats area, the magma of these rocks could have produced the metasomatizing fluids, but granite is absent from the area investigated. Moreover, Ramberg (1952, p. 184) points out that "strong alkali-silicate solutions are but rare visitors to granitized areas". It therefore seems doubtful whether the granite magma had a large enough surplus of alkaline fluids to produce from sediments the enormous amount of leptite and granophyre present in the roof. The amount of silicon in these rocks is often actually lower than in the Bushveld granite.

(ii) There is an <u>absence of quartzite grading into granophyre or leptite</u> in the area under consideration. A transition between quartzite and granophyre has been described from two localities: Firstly from the vicinity of the Leeuwpoort Tin Mine by Strauss (1947, p. 166) and secondly from the vicinity of Brits by Kuschke (1950, p. 29). In the account of the latter locality there is a clear break between the modal composition of the quartzite (Z.4) and the fine-grained feldspathic quartzite (Z.3a) which, with 58.3 per cent feldspar, can hardly be regarded as a transitional stage and is already a granophyre in composition. It is known that interbedded lenses of sedimentary rocks are commonly found in the felsite. If the granophyre represents a reconstituted felsite, then these inclusions could well be resisters. Although quartzite is not common in the granophyre investigated, it retains its identity where present even as small lenses, never showing any gradation into a granophyre.

(iii) <u>Modal analyses of granophyric intergrowths indicate an eutectic ratio of quartz and K-feldspar</u>. In the coarse grained granophyre (D.17) point-countings have been made

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with a Swift Automatic Point Counter on twelve different intergrowth units. None of the units showed a predominance of quartz over K-feldspar and the average value obtained is: quartz 43.7%, K-feldspar 56.3% and the range 47.6 : 52.4 to 36.6 : 63.4. It is remarkable how closely this value corresponds to the theoretical eutectic ratio 42.2 SiO_2 and 57.8 $KAlSi_3O_8$ of the binary system silica - leucite as described by Schairer and Bowen (Barth, 1959, p. 98). This correspondence, as well as the presence of plagioclase phenocrysts which are often found in the centre of the intergrowth-rosettes, clearly suggests that the granophyric texture resulted from the crystallization of a magma and is therefore not a replacement texture.

Although the ratio of quartz and K-feldspar in the micrographic felsite (41.32:58.68) is similar to that in the granophyric intergrowths it is doubtful whether this intergrowth is a product of simultaneous crystallization of the two components. The increasing coarseness of this micrographic intergrowth and the absence of any indication that this felsite was mobile after solidification point towards a rearrangement of constituents within the felsite owing to a rise in temperature during the emplacement of the gabbroic rocks of the Complex.

(iv) All stages of transition can be observed between pseudo-spherulitic felsite, microgranophyre, fine-grained granophyre and coarse-grained granophyre. The granophyre is found only near the base of the felsite, that is, close to or in direct contact with the gabbroic rocks where the temperatures during metamorphism must have been highest.

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From the above it seems reasonable to conclude that the granophyre, the fine-grained granite and the microgranophyre are palingenetic products of the felsite and that each one represents only a different manifestation of the same original rock.

Where fusion was complete and the material sufficiently mobile, it moved away from its place of origin, consolidating as a coarse granophyre. These rocks are invariably found close to the gabbroic rocks where temperatures were highest. The finer-grained granophyre and the microgranophyre also crystallized from their own magma, but they were not very mobile, and moved only for short distances but enough to be intrusive into the felsite. Where there was no movement and only fusion, the microgranophyre displays a gradual transition into the pseudospherulitic felsite.

The present investigation has revealed that there are two, if not three varieties of granophyre: firstly a palingenetic product of the Rooiberg felsite, secondly a chill-phase of the Bushveld granite and thirdly metasomatically altered sedimentary rock. To avoid confusion they could be referred to as the Rooiberg granophyre, the granophyric phase of the Bushveld granite and paragranophyre respectively.

8. Chemical composition of the felsite

If the conclusion is correct that one type of granophyre is related to the Rooiberg felsite and another represents a granophyric phase of the Bushveld granite, then they could be expected to show a difference in chemical composition. Accordingly four new analyses of leptite and granophyric rocks (Table 9), together with other published analyses of Rooiberg felsite and Bushveld granite have been plotted on various variation-diagrams.

All the analyses have been recalculated to atom percentages and these values have been plotted on the diagrams.

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The source of each analysis is listed at the end of this chapter (Table 10).

In the first instance Q - R diagrams were constructed (Fig. 1a and b). Q is an indication of the percentage of free quartz present (Burri 1959, p. 68) and R represents all the cations other than the Si^{4+}, expressed as a percentage of the cations. From these two diagrams it is clear that the granite in general is richer in quartz than the felsite.

It was found that a positive way in which to separate the two rock groups was to determine the variation of their femic constituents. A K - FM variation-diagram (Fig. 2) reveals that most of the felsite falls to the right of the hypothetical division line A - B whilst most of the granite falls to the left. The K-value of the felsite is generally lower than that of the granite.

Similar results are obtained when Si^{4+} is also taken into account (Fig. 3). The granite has a higher Si^{4+} and a lower FM content than the felsite. The total amount of alkalis (K^{+} + Na^{+}) is approximately the same.

From these diagrams it will be seen that the range in the composition of the granite is limited in comparison with that of the felsite. The sediments interbedded in the felsite indicate that the successive lava-flows followed each other at long intervals. During these intervals the composition of the magma from which the felsites were derived could have changed slightly.

The composition of the leptite (felsite analyses 4, 21, and possibly also 14, 15 and 16) falls in the felsite field and this precludes a metasomatic origin of these rocks. The same applies to the so-called Rooiberg granophyre and the associated fine-grained granite (felsite analyses 1, 2, 17 and 18). From the diagrams it may be seen that the granophyric phase of the Bushveld granite cannot be separated from

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TABLE 9. New Chemical Analyses of Rooiberg Felsite and related rocks

	1	2	3	4
SiO_2	68.34	70.46	68.21	69.58
TiO_2	0.45	0.37	0.53	0.48
Al_2O_3	12.52	12.51	12.63	12.41
Fe_2O_3	3.74	1.85	3.14	2.22
FeO	3.49	3.92	3.97	4.31
MnO	0.14	0.10	0.13	0.11
MgO	0.42	0.10	0.40	0.34
CaO	2.24	1.88	2.92	2.58
Na_2O	3.51	3.42	3.03	3.23
K_2O	3.92	4.18	4.33	3.78
H_2O^+	0.66	0.72	0.17	0.34
H_2O^-	0.09	0.04	0.13	0.13
CO_2	0.15	-	-	-
P_2O_5	-	-	0.18	-
	99.67	99.55	99.77	99.51
Niggli values				
si	310	349	300.5	324
al	33.5	36.5	33	34
fm	29.5	24	28	27.5
c	11	10	14	13.5
alk	26.0	29.5	25	26
k	0.42	0.45	0.49	0.43
mg	0.10	0.03	0.09	0.08
c/fm	0.37	0.42	0.49	0.47
Norms				
Q	29.00	27.67	25.57	27.99
or	24.08	25.75	26.63	22.91
ab	29.95	31.64	27.90	30.11
an	6.16	6.66	8.48	8.65

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TABLE 9 (continued)

Norms				
hy	1.41	3.13	1.89	3.68
di	2.58	0.46	2.10	1.84
hed	1.88	2.07	3.15	1.84
ilm	0.64	0.55	0.69	0.70
mt	4.14	2.25	3.37	2.42
	99.84	100.18	99.78	100.14

1. Micrographophyre, R.28, Roodewal No. 193-J.S., Groblersdal District.
2. Fine-grained granite, R.45, Roodewal No. 193-J.S., Groblersdal District.
3. Micrographic felsite, WV.28, Waterval No. 184-J.S., Groblersdal District.
4. Fine-grained felsite (leptite), WV.4, Waterval No. 184-J.S., Groblersdal District.

Analyses by the National Institute for Metallurgy, Johannesburg.

the Rooiberg granophyre on account of their chemical composition. The composition of certain rocks of the granophyric phase of the Bushveld granite falls in the granite field (granite analyses 12, 17 and 21), others fall in the felsite field (granite analyses 3 and 22). It is possible that the range in composition of the granophyre related to the Bushveld granite is due to selective assimilation of country-rocks, which is indicated by the large number of resisters, especially quartzite present in these rocks (Wagner 1921, p. 29 and Steyn, J.G.D., 1962, p. 7).

The composition of the felsite of Paardekop (No. 13) falls in the middle of the granite field. B.V. Lombaard (1932, p. 163) is of the opinion that the felsite of Paardekop is a chill-phase of the Bushveld granite. The chemical com-

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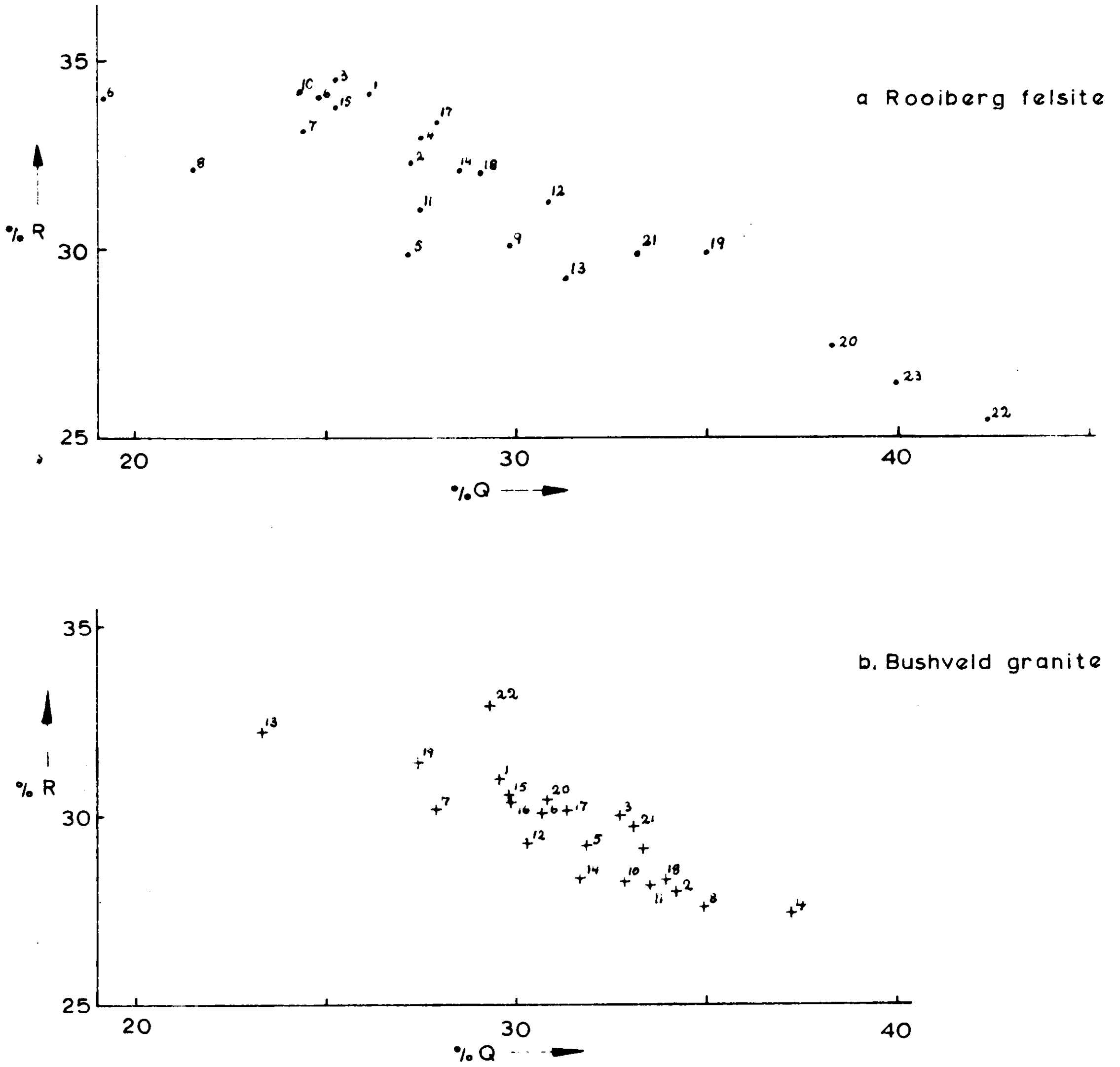

FIG.1. Q–R diagrams for Rooiberg felsite and Bushveld granite.
Q = free quartz of the equivalent norm (Burri,C.,1959 p.69).
R = all the cations other than Si^{4+}.

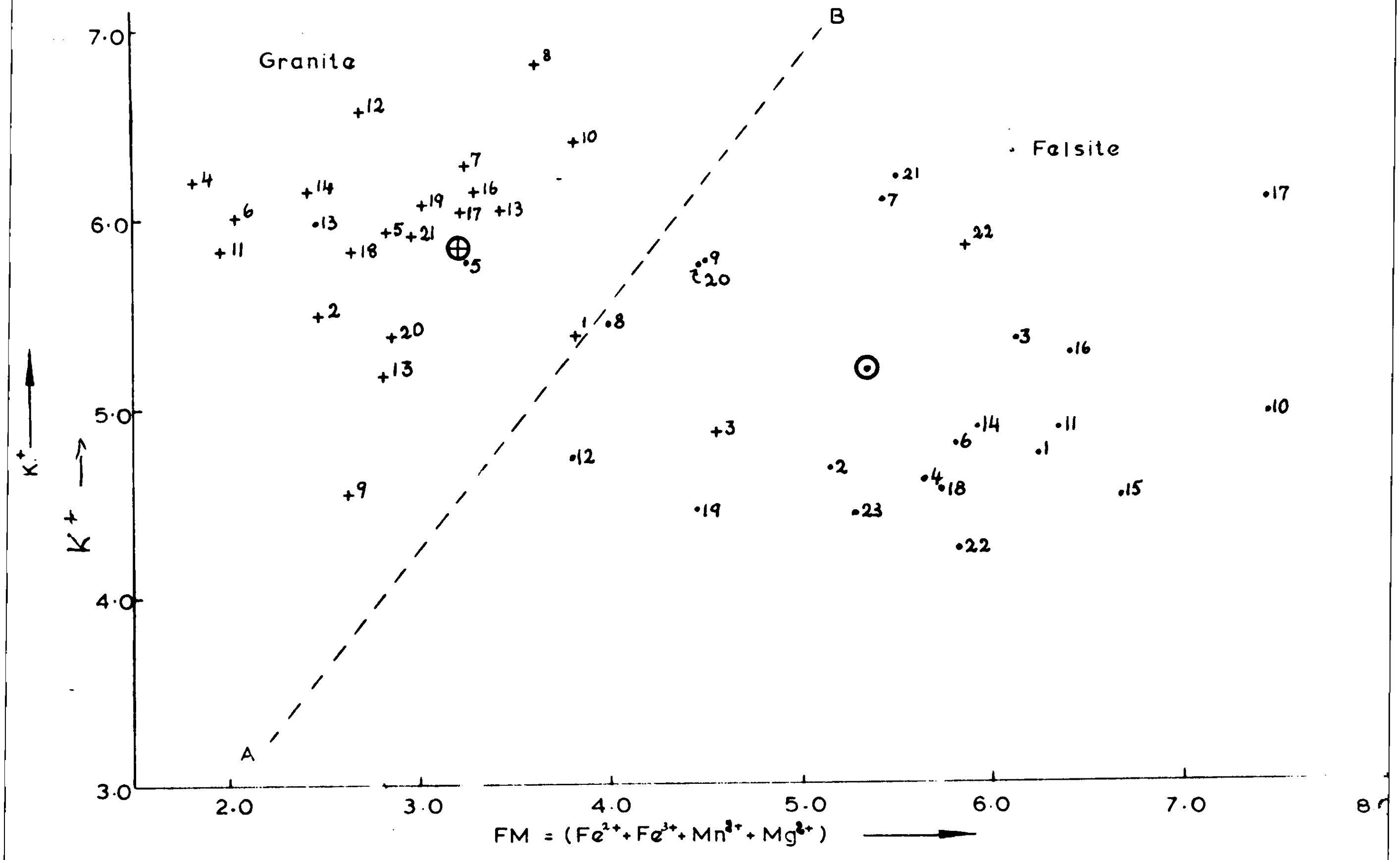

FIG. 2. K–FM diagram for Rooiberg felsite and Bushveld granite.
• Felsite. ⊙ Average of felsite.
+ Granite. ⊕ Average of granite.

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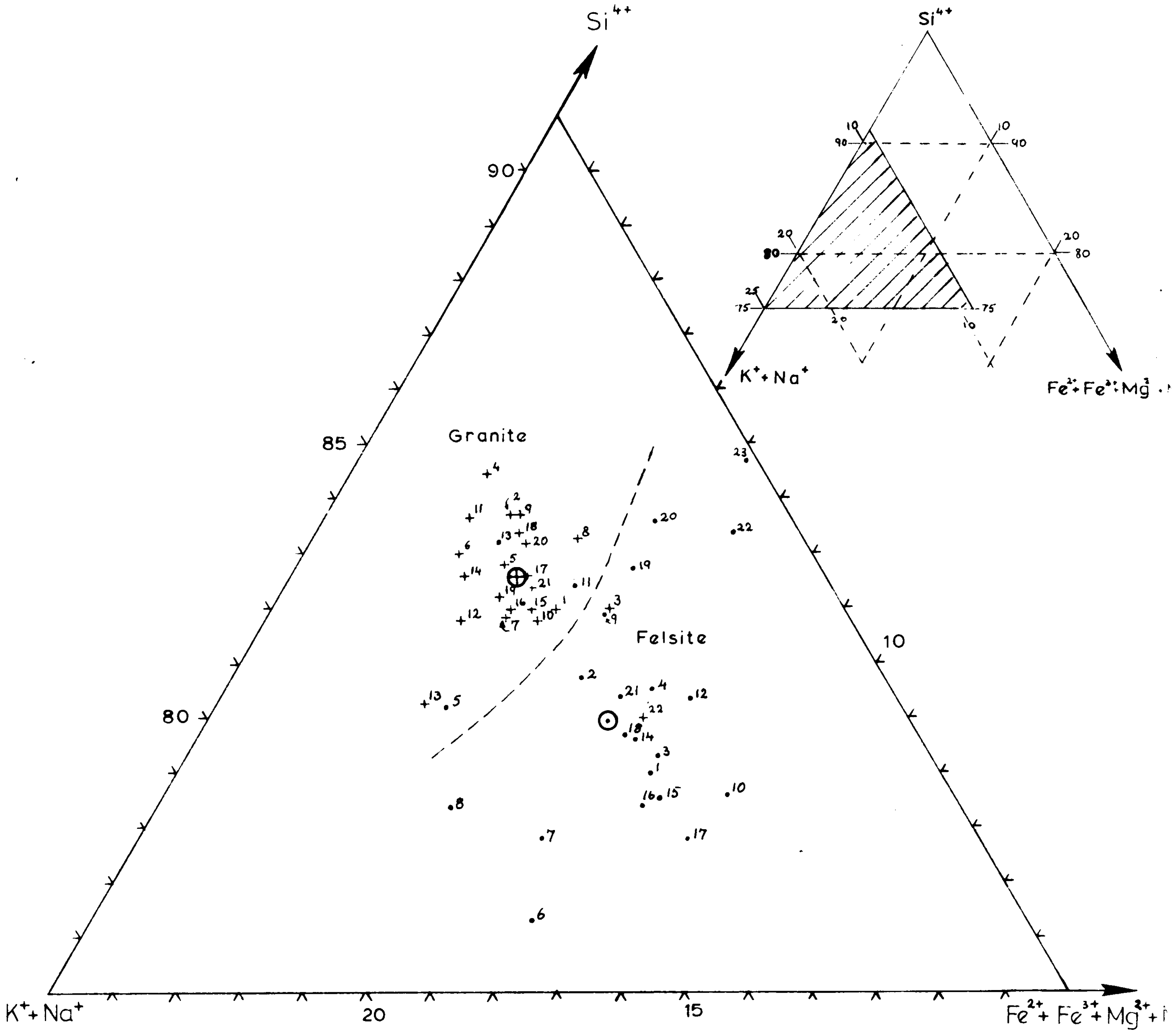

FIG. 3. Variation in composition of Bushveld granite and Rooiberg felsite with regard to alkalis, femics and silicon (atom %)

• Felsite. ⊙ Average of felsite

+ Granite. ⊕ Average of granite.

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position certainly supports this view.

For comparative purposes the composition of two examples of the Premier Mine felsite (felsite analyses 22 and 23, fig. 3) have been plotted. They have a higher Si^{4+} and a lower K^+ + Na^+ content than the Rooiberg felsite.

TABLE 10. Sources of information on chemical analyses of Rooiberg felsite and Bushveld granite.

A. Felsite and related rocks

1 to 4 table 9 above.

5. Nodular, partly spherulitic felsite, Hartebeestfontein No. 240-K.R., Bronkhorstspruit District. Analyst: B.V. Lombaard. (Lombaard, B.V., 1932, p. 150, a).
6. Dark felsite, Spitsrand No. 430-J.R., Bronkhorstspruit District. Analyst: S. Parker. (Lombaard, B.V., 1932, p. 150, b).
7. Dark slightly porphyritic felsite, left bank of the Elands River, Springfontein No. 213-J.R., Bronkhorstspruit District. Analyst: B.V. Lombaard. (Lombaard, B.V., 1932, p. 151, c).
8. Dark, slightly porphyritic felsite, S.W. beacon of Rietfontein 90-J.S., Bronkhorstspruit District. Analyst: S. Parker. (Lombaard, B.V., 1932, p. 152, d).
9. Red felsite, Derwent Siding, east of Middelburg. Analyst: H.G. Weall. (Hall, A.L., 1932, p. 252, No. I).
10. Dark greyish felsite, Tauteshoogte, north of Middelburg. Analyst: H.G. Weall. (Hall, A.L., 1932, p. 252, No. II).
11. Purplish-grey felsite, Baviaansnek, north of Tauteshoogte. Analyst: H.G. Weall. (Hall, A.L., 1932, p. 252, No. III).
12. Dark grey felsite, Wonderhoek No. 376-J.S., north-east of Belfast. Analyst: E.G. Radley. (Hall, A.L., 1932, p. 252, No. IV).
13. Dark reddish-grey felsite, summit of Paardekop. Analyst: E.G. Radley. (Hall, A.L., 1932, p. 252, No. V).

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14. Silica-rich rock, Tauteshoogte. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, Lieb-10).
15. Silica-rich rock, Tauteshoogte. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, Lieb-12).
16. Silica-rich rock, Tauteshoogte. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, Lieb-13).
17. Fine-grained granite, Tauteshoogte. Analyst: B.V. Lombaard. (Lombaard, B.V., 1934, p. 12, a).
18. Granophyre, Uitkyk No. 172-J.S., Middelburg District. Analyst: B.V. Lombaard. (Lombaard, B.V., 1934, p. 12, c).
19. Felsite, Uitkyk No. 172-J.S., 200 yards from 18. Analyst: H.G. Weall. (Lombaard, B.V., 1934, p. 12, d).
20. Brick-red felsite, Zaagkuil No. 102-J.S., Witbank District. Analyst: A. Kruger. (Wolhuter, L.E., 1954, p. 13, No. I).
21. Leptite, Lisbon No. 288-K.R., Potgietersrust District. Analyst: C.J. Liebenberg. (Strauss, C.A., 1954, p. 30, No. 6).
22. Premier Mine Type felsite, Doornkloof No. 171-J.R., Bronkhorstspruit District. Analyst: B.V. Lombaard. (Lombaard, B.V., 1932, p. 132, c).
23. Premier Mine Type Felsite, 125 m depth, Premier Mine, Bronkhorstspruit District. Analyst: B.V. Lombaard. (Lombaard, B.V., 1932, p. 132, d).

B. Bushveld granite and related granophyre

1. Coarse red-grey granite, Welgevonden No. 45-J.S., Groblersdal District. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, Lieb-6).
2. Coarse granite, 3 miles from Jane Furze next to main road. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, Lieb-24).
3. Granophyre, Kalkfontein No. 49-J.S., Groblersdal District. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961,

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p. 73, Lieb-5).

4. Coarse red granite, 11 miles from drift in felsite on the main road from Tauteshoogte to Pokwani. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, Lieb-15).
5. Granite, 700 yards from the cross roads to Ottensville, on the Groblersdal - Adriaans road. Analyst: C.J. Liebenberg. (Liebenberg, C.J., 1961, p. 73, B.23).
6. Coarse red granite, Salt Pan. Analyst: J. Moir. (Hall, A.L., 1932, p. 375, No. III).
7. Coarse red granite, Petronella Siding, north of Pretoria. Analyst: H.G. Weall. (Hall, A.L., 1932, p. 375, No. IV).
8. Coarse pale-red granite, on main road about 2 miles north of Pokwani on Sekhukhuni's Plateau. Analyst: H.G. Weall. (Hall, A.L., 1932, p. 375, No. V).
9. Coarse red granite, Zoutpansleegte No. 177-J.Q., Pienaars River. Analyst: E.G. Radley. (Hall, A.L., 1932, p. 375, No. VI).
10. Coarse pink granite, Morgenzon No. 849-K.S., near Sekwati River, north of Pokwani on Sekhukhuni's Plateau. Analyst: E.G. Radley. (Hall, A.L., 1932, p. 375, No. VIII).
11. Granite, Fairfield No. 238-J.R., Bronkhorstspruit District. Analyst: S. Parker. (Lombaard, B.V., 1932, p. 148, No. 1)
12. Granophyric granite, Fairfield No. 238-K.R., Bronkhorstspruit District. Analyst: S. Parker. (Lombaard, B.V., 1932, p. 148, No. 2).
13. Porphyritic granite, next to the old Albert Silver Mine, Roodepoortjie No. 250-J.R., Bronkhorstspruit District. Analyst: S. Parker. (Lombaard, B.V., 1932, p. 154, e).
14. Granite, Zaaiplaats Tin Mines, Potgietersrust District. Analyst: S. Parker. (Lombaard, B.V., 1932, p. 154, f).
15. Coarse-grained, grey mesotype facies of the Main granite, Groenfontein No. 227-K.R., Potgietersrust District. Analyst: C.J. Liebenberg. (Strauss, C.A., 1954, p. 56, No. 1).

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16. Medium-grained facies of the Main granite, Lone Tree Hill, Appingendam No. 805-L.R., Potgietersrust District. Analyst C.J. Liebenberg. (Strauss, C.A., 1954, p. 56, No. 2).
17. Fine-grained red granophyric facies of the Main granite, Roodepoort No. 222-K.R., Potgietersrust District. Analyst C.J. Liebenberg. (Strauss, C.A., 1954, p. 56, No. 3).
18. Foot-hills granite, Groenfontein No. 227-K.R., Potgietersrust District. Analyst: C.J. Liebenberg. (Strauss, C.A., 1954, p. 56, No. 4).
19. Bobbejaankop granite, Zaaiplaats Mine, Potgietersrust District. Analyst: C.J. Liebenberg. (Strauss, C.A., 1954, p. 56, No. 5).
20. Lease granite, Giant Quarry, Groenfontein Mine, Potgietersrust District. Analyst: C.J. Liebenberg (Strauss, C.A., 1954, p. 56, No. 6).
21. Red Bushveld granophyre, Salomons Temple No. 230-K.R., Potgietersrust District. Analyst: C.J. Liebenberg. (Strauss, C.A., 1954, p. 30, No. 1).
22. Granophyre, Gaasterland No. 677-K.S., Stavoren Area. Analyst: J. Moir. (Hall, A.L., 1932, p. 255).

VI. THE MAIN PLUTONIC PHASE OF THE BUSHVELD COMPLEX

Although gabbroic rocks of the Upper and the Main Zones are developed, neither the Main Magnetitite Seam, nor the Merensky Reef outcrops in the Kruis River area. A gabbro horizon characterized by spherical inclusions of pyroxenite proved to be a good marker in the Main Zone and was also found useful by J.M. van der Westhuizen (1945, p. 11) and A.F. Lombaard (1949, p. 355). Unfortunately this prominent marker is not known to be developed anywhere else in the Main Zone of the Bushveld Complex. Except for a few layers of mottled anorthosite no other prominent marker exists in the Main Zone of this area. It was therefore necessary to investigate

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certain gabbroic rocks that were described by A.F. Lombaard (1949, p. 375) as possibly belonging to the Critical Zone. It has been found that the lowest horizon in these gabbroic rocks on Blaauwbank 163-J.S. corresponds to the Needle norite (Willemse, J., 1967a) which is approximately 1000 ft above the Merensky Reef. This Needle norite seems to be a very constant marker and is present in the western and the eastern parts of the Bushveld Complex. The elevations of all the gabbroic rocks have been calculated in feet relative to this Needle norite (Fig. 4).

A. The Main Zone

1. The Needle norite

The Needle norite forms the lowest horizon of the Main Zone on Blaauwbank 186-J.S. The rock consists mainly of idiomorphic needles of orthopyroxene up to 10 mm in length lying with their crystallographic c-axis in the plane of igneous lamination. These needles are enclosed partially by plagioclase which is slightly zonally built. The intercumulus material is clinopyroxene, enclosing plagioclase ophitically, and orthopyroxene. Quartz is the last product to have crystallized (Bl.13).

The Needle norite represents an orthocumulate, (Wager, L.R., et al., 1960, p. 79) the orthopyroxene having crystallized simultaneously with plagioclase, whereas clinopyroxene and quartz crystallized from the intercumulus liquid.

Layering is a prominent feature of this horizon. Darker layers which contain greater concentrations of orthopyroxene needles and have sharp contacts at the bottom, pass gradually into lighter layers which have less orthopyroxene and sharp contacts at the top.

A modal analysis of the rock is given in table 11.

2. The Lower mottled anorthosite

Mottled anorthosite is found in large quantities approxi-

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mately 200 ft above the Needle norite, as well as in several thin bands higher up in the succession. The mottling varies considerably from one layer to another, the coarseness and the diffuseness depending largely on the trend of the crystallization. In all the mottled anorthosites, the plagioclase represents the cumulus material whereas the orthopyroxene, as well as clinopyroxene poikilitically enclose the plagioclase. In rock types where the mottles are well defined, the pyroxene ratio is high (Walker, F., 1957, p. 2) because the enclosed crystals of plagioclase are small. This indicates that crystallization of the pyroxene started early. Crystallization nuclei were few; pyroxene therefore occupies large areas which enclose a few small plagioclase crystals. Where the mottles are large and have more diffuse outlines, the pyroxene ratio is lower, because the poikilitically enclosed plagioclase crystals are larger. Crystallization of the pyroxene commenced later. Nuclei were few and optically continuous pyroxene again spread over large areas. In anorthosites which contain evenly disseminated pyroxene this mineral represents the intercumulus material.

3. Banded "anorthosite"

Overlying the Lower mottled anorthosite on Blaauwbank 168-J.S. is a thin layer of banded "anorthosite" (Lombaard, A.F., 1949, p. 353). The rock is extremely finely banded and intensely folded (Photo 17). The banding is caused by alternating thin layers of plagioclase, plagioclase and clinopyroxene, and clinopyroxene. The grain-size of these two principal constituents varies considerably. In one layer they are very fine-grained, in another coarser (Bl.14). The larger crystals of plagioclase tend to be subhedral, but they are never as subhedral as the plagioclase in the gabbroic rocks above and below. Furthermore the presence of numerous small, round plagioclase grains indicates that

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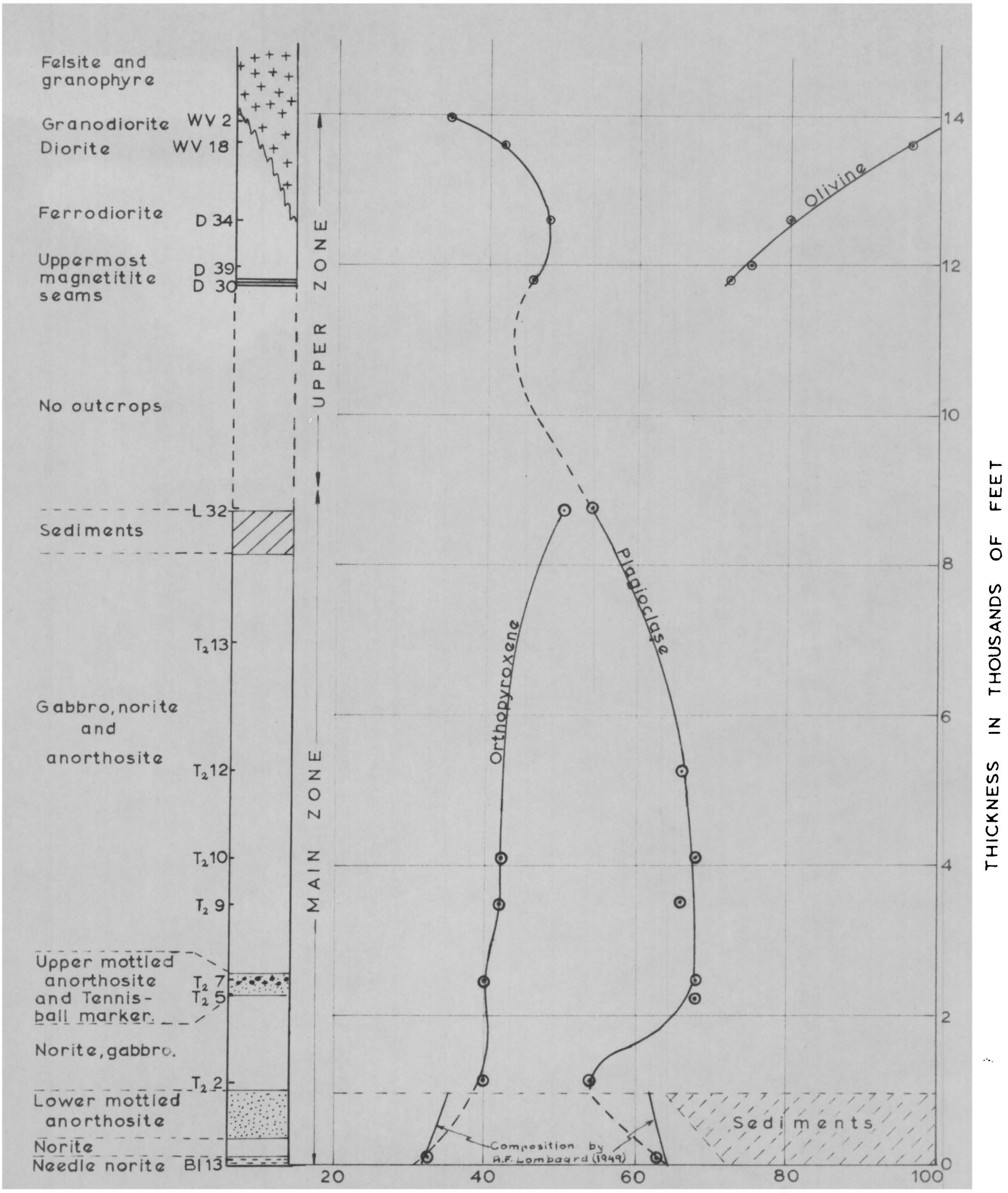

Orthopyroxene: mol.% $FeSiO_3$.

Plagioclase: An.%.

Olivine: mol.% Fe_2SiO_4.

Fig. 4. Variation in composition of three major components in the gabbroic rocks.

(After J. Willemse, 1964, p.120, Fig. 2)

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this rock is not of magmatic origin.

It is remarkable that the position of this rock in the gabbroic sequence on Blaauwbank 168-J.S., approximately 1200 ft below the Tennis-ball marker, corresponds to the position of the pyroxene granulite below this marker immediately above the quartzite on Roodewal 193-J.S. and Mineral Range 190-K.S. The pyroxene granulite is absent above the quartzite where the latter is duplicated. It seems as though the banded "anorthosite" represents a more intensely metamorphosed inclusion of the pyroxene granulite which could originally have been a marl.

4. The Upper mottled anorthosite and the Tennis-ball marker

Above the banded "anorthosite" the main rock type is norite or gabbro which is inclined to be spotted in the lower half. Several mottled anorthosites are found within this zone. The most conspicuous marker however, is an ordinary gabbro which contains round inclusions of pyroxenite (Photo 18). On account of the size of the inclusions, this marker is called the "Tennis-ball marker". The inclusions in the gabbro are usually small, but become larger where the rock changes gradually into a mottled gabbro, which in places shows layering (Photo 19). The spheres consist mainly of orthopyroxene which has been altered extensively to amphibole and biotite as well as to chlorite. Plagioclase is present in all the spheres and quartz varies considerably in quantity from one sphere to another. Where sulphides are present in the adjoining anorthosite, there is usually a fair amount present in the spheres as well. It is noteworthy that the orthopyroxene in the spheres has a composition of 10 mol. per cent $FeSiO_3$ lower than that of the host-rock (T_27). This suggests that they might represent inclusions of a pyroxenite from a lower layered horizon.

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Photograph 17.

Intensly folded, banded "anorthosite". Blaauwbank 168-J.S.

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Photograph 18.

Tennis-ball marker. Round concentrations of pyroxene in gabbro. Mineral Range 190-J.S.

Photograph 19.

Top of the Tennis-ball marker characterized by large spherical concentrations of pyroxene in a mottled anorthosite. Roodewal 193-J.S.

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An analogous layer, the so-called "Boulder anorthosite" (Cousins, C.A., 1964, p. 228) is found approximately 110 ft below the Merensky Reef at the Rustenburg Platinum Mine. Although their mode of origin might be the same, they do not occupy the same horizon in the two areas.

Mottled anorthosite is common approximately 150 ft below, as well as immediately above the Tennis-ball marker. The mottled anorthosite on Blaauwbank 168-J.S. is characterized by a relatively high content of quartz. On the same farm irregular bodies of coarse-grained gabbro pegmatoid which carries sulphides in places, is present within the mottled anorthosite just above the Tennis-ball marker. The platinum deposits of the Blaauwbank Type (Wagner, P.A., 1929, p. 202) are found mostly in the mottled anorthosites immediately above the Tennis-ball marker, although the anorthosite below, as well as that a few hundred feet above the marker, was prospected intensively. The Tennis-ball marker, with the mottled and speckled norite and anorthosite immediately above and below it, most probably corresponds to the Upper mottled marker of Molyneux (Willemse, J. 1967a).

A.F. Lombaard (1949, p. 356) and J.M. van der Westhuizen (1945, p. 11) used a mottled anorthosite as an additional marker in the gabbroic rocks to the southeast of the large xenoliths of Smelterskop quartzite on Rooikraal 188-J.S., Mineral Range 190-J.S. and Roodewal 193-J.S. Although this marker is very prominent at the trigonometrical beacon on Mineral Range 190-J.S. a large number of lenticular bodies of anorthosite on Rooikraal 188-J.S. hampers the positive identification of this marker in the field.

5. Gabbroic rocks

By adopting the classification of gabbroic rocks by J. Willemse (1965) and utilizing volumetric analyses done by A.F. Lombaard (1949, Table 6, p. 352), J.M. van der Westhuizen

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(1945, Table 3, p. 9) and the author, an attempt was made to find any notable variation of the amounts of orthopyroxene and clinopyroxene in the large succession of gabbroic rocks above the Tennis-ball marker. No variation could be found. The most common rock type in the succession seems to be gabbro and hypersthene gabbro and a small amount of hyperite and norite.

The irregular contacts between plagioclase and inverted pigeonite, characterized by plagioclase partly enclosing orthopyroxene in places and orthopyroxene enclosing small plagioclase crystals, indicate that plagioclase crystallized before pigeonite, but that in most of the gabbroic rocks the crystallization of these two constituents commenced simultaneously. Augite, which started to crystallize after plagioclase and pigeonite, does not always represent the intercumulus material It depends largely on the amount of augite present whether it forms part of the intercumulus material or one of the primary products of crystallization. The last products of crystallization are quartz and ore, if present.

Most of the rock types of the Main Zone in this area represent adcumulates and mesocumulates, because of the zonally built plagioclase which is the most abundant cumulus material.

6. Chill-phase of the Main Zone

Rocks probably representing a chill-phase of the Main Zone are found along the southern and the south-eastern contact of the quartzite xenolith, particularly on Mineral Range 190-J.S. They are generally fine-grained and have an irregular spotted and mottled appearance. The small, anhedral grains of plagioclase usually have a lower An content than the adjoining gabbros ($T_2 2$, Fig. 4). The orthopyroxene is slightly richer in Fe, and forms irregular grains which enclose small round grains of plagioclase poikilitically (L.37). Clinopyroxene is found either as small, irregular grains spread evenly

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throughout the section or it encloses plagioclase poikilitically (L.34). It is possible that assimilation of argillaceous sediments above the quartzite produced these irregular gabbroic rocks.

TABLE 11. Volumetric composition of gabbroic rocks

	Bl.13	T_29	L.32	L.32A	D.31	D.34	WV.18	WV.2
Plagioclase	46.3	57.1	53.15	62.0	58.3	65.2	40.90	32.6
Orthopyroxene	40.4	13.97	16.07	13.6	-	-	-	-
Clinopyroxene	6.1	14.18	12.17	20.05	9.88	9.51	18.64	-
Olivine	-	-	-	-	22.8	15.3	4.03	2.7
Amphibole	-	13.87	-	-	Trace	-	16.15	23.7
Biotite	-	0.29	1.7	Trace	0.24	Trace	-	0.7
Chlorite	-	-	-	-	-	-	2.96	-
Quartz	6.6	0.59	3.32	Trace	Trace	Trace	4.51	15.0
K-feldspar	-	-	-	-	-	Trace	5.22	22.3
Apatite	-	-	-	-	3.25	3.3	1.07	1.1
Opaque	0.5	-	13.60	4.27	5.54	6.68	6.53	1.9
	99.9	100.00	100.01	99.92	100.01	99.99	100.01	100.00

Bl.13	Needle norite, Blaauwbank 168-J.S.
T_29	Hypersthene gabbro, Roodewal 193-J.S.
L.32	Hyperite, Mineral Range 190-J.S.
L.32A	Highly metamorphosed inclusion of Dullstroom lava in hyperite (L.32), Mineral Range 190-J.S.
D.31	Ferrodiorite, Diepkloof 186-J.S.
D.34	Ferrodiorite, Diepkloof 186-J.S.
WV.18	Diorite, Waterval 184-J.S.
WV.2	Granodiorite, Waterval 184-J.S.

B. The Upper Zone

Rocks belonging to this zone outcrop in a narrow strip along the slopes of the Bothasberg plateau on Waterval 184-J.S. and Diepkloof 186-J.S.

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On the plains north of the Bothasberg plateau only sporadic outcrops are found on the same farms. The most common rock types are ferrodiorite, anorthosite, diorite, granodiorite and magnetitite.

1. The ferrodiorite

These rocks outcrop in three localities above the magnetitite seams on Diepkloof 186-J.S. (Geological map). Two volumetric analyses of ferrodiorite (D.31 and D.34) are provided in table 11. Apatite, the first product of crystallization in these rocks is present as small euhedral grains. The plagioclase crystals are not as euhedral as those of the Main Zone. Contacts between plagioclase crystals and between plagioclase, olivine and pyroxene are very irregular. The olivine and the pyroxene contain small inclusions of plagioclase, indicating that plagioclase started to crystallize before them, but that most of the crystallization of these three constituents was simultaneous. The intercumulus material is quartz and K-feldspar. Magnetite is present either as subhedral grains or forms part of the intercumulus material. The ferrodiorite from this area is a mesocumulate.

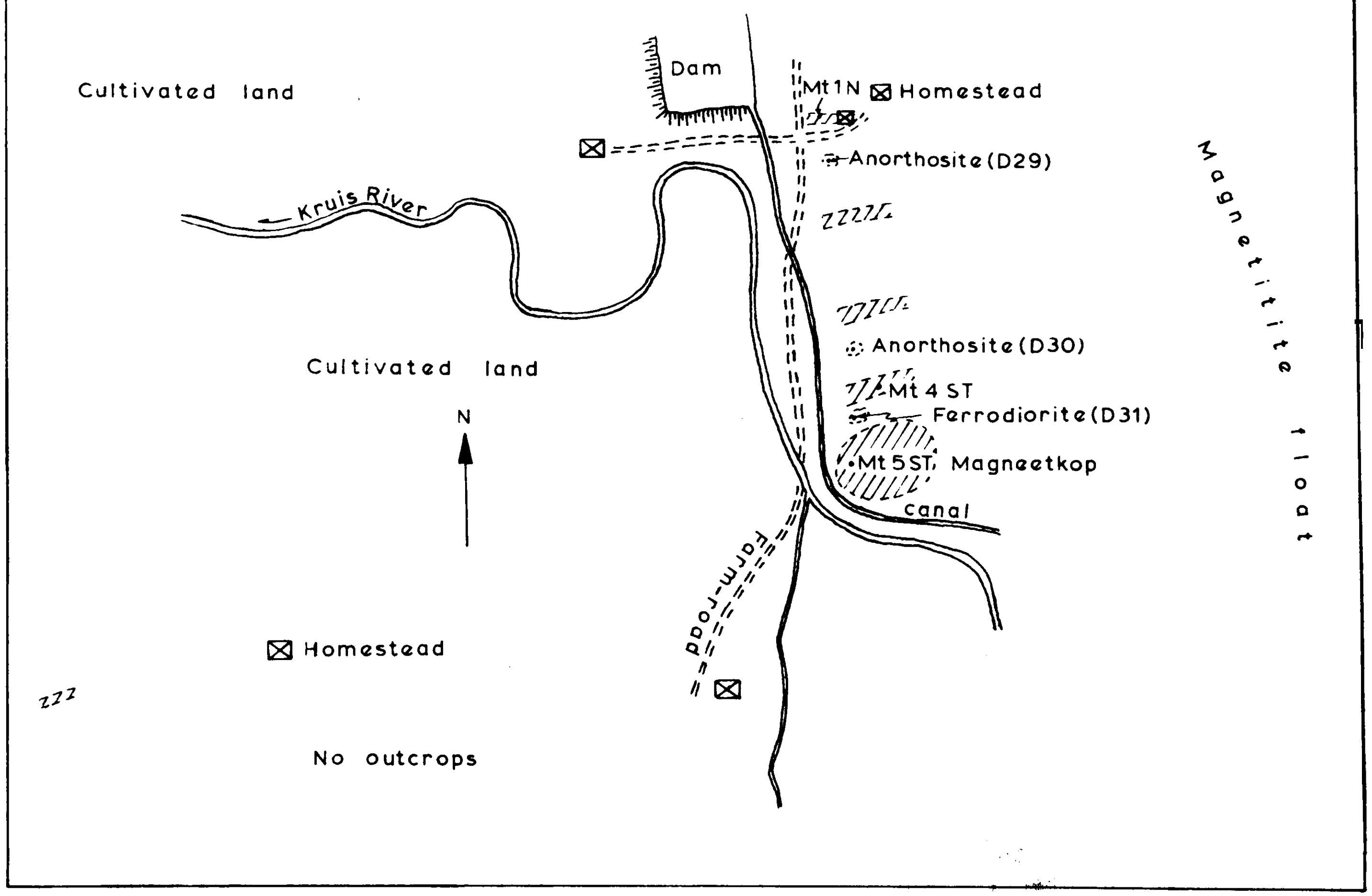
2. The diorite and the granodiorite

A narrow belt of outcrops along the lower slopes and the foot of the Bothasberg plateau consists of these rocks. The diorite is composed mainly of plagioclase (An_{42}), clinopyroxene and amphibole. A large amount of the amphibole is due to the alteration of clinopyroxene. Quartz and K-feldspar are present in small amounts. In comparison the granodiorite consists mainly of plagioclase (An_{35}), amphibole, quartz and K-feldspar (Table 11). This sudden increase in the amount of quartz and K-feldspar in the top 200 ft of the intrusion can possibly indicate that the granodiorite is not a product

FIG. 5. THE MAGNETITITE OCCURRENCE ON DIEPKLOOF 186-J.S.

(based on an aerial photograph)

Scale: approx. 1 inch = 500 ft



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Even where rocks of the Main Zone are in direct contact with the microgranite of the roof-rocks, as in the valley of the Kruis River on Roodewal 193-J.S., the gabbro obtains an increasingly red colouration within a few feet of the contact owing to increasing amounts of K-feldspar. This cannot be explained by differentiation. The contact can only be traced with difficulty in this outcrop due to the similarity in colour of the gabbroic rock and the microgranite. In some places a distinct separation could not even be found.

Where the Upper Zone of the gabbroic rocks are developed and magmatic differentiation has progressed towards a diorite, assimilation of roof-rocks would result in the development of relatively more granodiorite than farther down in the succession.

Although the diorite (WV.18) might still be a mesocumulate, the increasing amount of quartz and K-feldspar in the granodiorite, interstitial to the euhedral plagioclase crystals, indicates that the latter is an orthocumulate.

3. Magnetic iron ore

The Geological map, Sheet No. 11, Lydenburg, indicates that magnetitite seams are present on Diepkloof 186-J.S. J.M. van der Westhuizen (1945) found an additional outcrop on the eastern boundary of Waterval 184-J.S. He considers this occurrence to be one of the uppermost seams and he regarded the largest outcrop on Diepkloof 186-J.S. as the Main Magnetitite Seam.

Close investigation revealed that the occurrence on Diepkloof 186-J.S. is an elongated pipe-like body, measuring approximately 400 x 250 ft and situated above four seams (Fig. 5). This pipe generally known as Magneetkop, protrudes approximately 150 ft above the surrounding alluvial plain. A little farther west, between this pipe and the road to Loskop Dam, an additional magnetitite outcrop has been found.

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The chemical composition of three magnetitite samples (Table 12) indicates that all the magnetitite occurrences probably belong to the uppermost seams. If the V_2O_5 content is plotted on the diagram given by Molyneux (1964, Fig. 64) it is evident that they correspond to the magnetitite seams of his Subzone D, which is approximately 4000 ft above the Main Seam.

Two magnetometer traverses were made perpendicular to the strike of the gabbroic rocks east and west of the Diepkloof plug. The largest anomalies were registered in the east and west, on the same horizon as the magnetitite occurrence on Diepkloof, whereas anomalies farther to the north could possibly indicate lower magnetitite seams.

The reason why the Main Magnetitite Seam does not outcrop, is not definitely known. In other parts of the Bushveld Complex where this seam is developed it usually forms prominent outcrops. Several factors could have played a role in eliminating its outcrop.

(i) Discordant relationships of and proximity to the roof as well as the occurrence of sedimentary inclusions just below the position where the Main Seam should outcrop could have prevented differentiation.

(ii) Faulting in the area might have cut off the Main Seam (p.94 and Fig. 7).

(iii) Alluvium close to 100 ft thick in places and washed down from the Bothasberg plateau could cover up the seam.

C. A granite pegmatite

On Mineral Range 190-J.S. small irregular pockets of a coarse-grained pegmatite in the gabbroic rocks (Photo 20) consist of small phenocrysts of albite, a little chalcopyrite and mainly of quartz and flesh-coloured K-feldspar which are granophyrically intergrown. This pegmatite has previously

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Photograph 20.

Pocket-like bodies of pegmatite (light) in gabbro (dark).

Mineral Range 190-J.S.

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been described by A.L. Hall (1913, p. 31) and probably represents a quartz-rich residue of assimilated sedimentary rocks in the gabbroic rocks.

VII. MINERAGRAPHY OF THE MAGNETITITE

The magnetitite investigated is from Waterval 184-J.S. (WV.36) and from Diepkloof 186-J.S. (Mt.1N, Mt.4ST and Mt. 5ST; localities given in fig. 5). Polished sections were also made of a magnetite gabbro (D.40) from a quarry on Diepkloof 186-J.S. and of a similar rock from Mineral Range 190-J.S. (L.30). During the investigation of the geological structure of the area samples of magnetitite were also collected from a pipe and a thin seam on Haakdoorndraai 169-J.S. (Mt.6 and Mt.7 respectively) as well as from a pipe of Maleeuwskop (Mt.8) on Rietkloof 166-J.S. The localities where all these samples were collected are indicated on fig. 7.

The minerals present in the samples of magnetitite are magnetite, ilmenite, maghemite, hematite (martite), goethite, ulvite and spinel as well as an oxidation product of ilmenite, possibly leucoxene.

Interesting exsolution phenomena have been observed and are discussed under several headings.

A. Exsolution of ilmenite above the magnetite-ulvite solvus

1. Large ilmenite grains

Large ilmenite grains are present in most of the sections investigated. The magnetitite from the seam on Haakdoorndraai 169-J.S. contains ilmenite grains with thin exsolution lamellae of hematite parallel to the (0001) plane of ilmenite (Mt.7).

These ilmenite grains which are present in magnetitite are, according to Buddington et al. (1955, p. 778) and Heier (1956, p. 509), probably products of primary crystallization. Wright (1961, p. 778) reckons that only ilmenite grains pre-

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sent as aggregates in silicates are products of primary crystallization. He is of the opinion that any aggregates of titaniferous magnetite and ilmenite are due to exsolution at high temperature because of the identical Fe : Ti ratios in different aggregates of this nature.

This does not conform with the contention of Basta (1960, p. 1024) who found that ilmenite is hardly soluble in magnetite at high temperatures.

2. Intergranular ilmenite and exsolution lamellae of ilmenite parallel to the (111) plane of magnetite

When a homogeneous solid solution of Fe_3O_4, $FeTiO_3$ and Fe_2TiO_4 cools, the solubility of ilmenite in magnetite decreases and the ilmenite therefore exsolves as long, thick (0001) lamellae parallel to the (111) plane of magnetite.

These long lamellae often merge into intergranular ilmenite which has the same orientation and which therefore creates the impression that all the exsolved ilmenite could not be accommodated along the (111) planes of magnetite. The constituents of ilmenite therefore seem to have migrated and collected between the magnetite grains. A typical example of this nature is provided by the magnetitite from Maleeuwskop (Mt.8, Photo 21).

As mentioned before, Basta found that ilmenite is hardly soluble in magnetite at high temperatures. This however is not in accordance with the large number of ilmenite lamellae present in certain magnetitites (Ramdohr, 1956, p. 10) (Photo 22). Basta (1960, p. 1046) is therefore of the opinion that at high temperatures an isometric γ-$FeTiO_3$ polymorph is present in solid solution in magnetite. On cooling, this γ-$FeTiO_3$ inverts to α-$FeTiO_3$ which exsolves as lamellae in magnetite.

Vincent (1960, p. 1009) distinguished between two generations of exsolution lamellae in magnetite from the Skaer-

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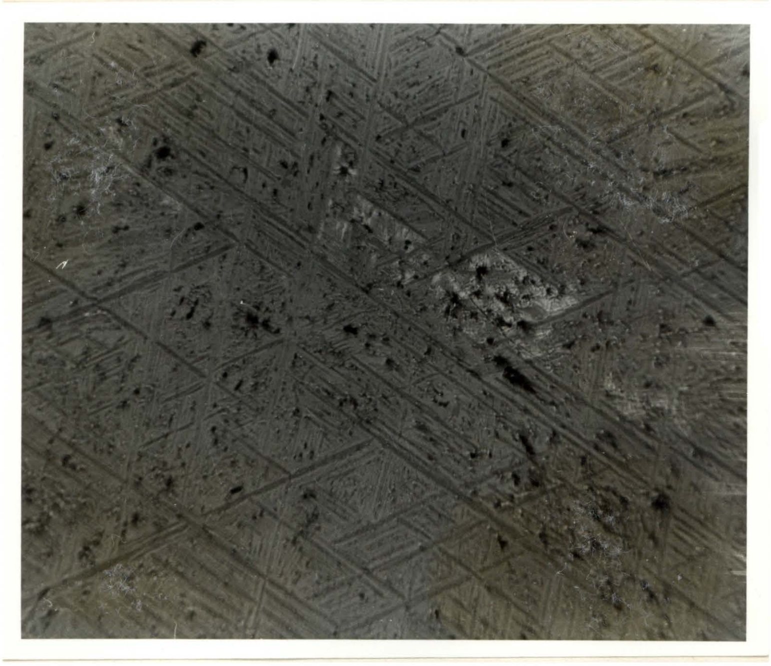
Photograph 21 Reflected light, oil immersion. X 265.
Ilmenite lamellae terminating against intergranular ilmenite. Section Mt.8, Maleeuwskop.



Photograph 22. Reflected light, oil immersion. X 100.
Ilmenite lamellae (first generation) exsolved parallel to the (111) plane in magnetite. Section Mt.7, Haakdoorndraai 169-J.S.

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gaard intrusion. The first set is a primary or high temperature exsolution of ilmenite and the second is a second generation of ilmenite lamellae which are found mostly near cracks in the titaniferous magnetite and are more irregular. The absence of ulvite in the vicinity of these lamellae indicates that the ulvite has contributed to the formation of the lamellae. This exsolution is therefore below the magnetite-ulvite solvus.

B. Exsolution phenomena below the magnetite-ulvite solvus

The above two forms of ilmenite can be explained by exsolution of ilmenite above the magnetite-ulvite solvus. On account of the insolubility of ilmenite at high temperatures in magnetite, certain authors, (Ramdohr, 1956, p. 15; Vincent, 1960, p. 1011; Basta, 1960, p. 1044) are inclined to believe that the majority of ilmenite present in magnetite is possibly due to the oxidation of ulvite to ilmenite below the magnetite-ulvite solvus. The constituents of this ilmenite then seem to have migrated to give rise to certain exsolution phenomena in magnetite.

1. Ulvite-ilmenite as a network parallel to the (100) planes of magnetite.

Ulvite exsolves as a delicate network parallel to the (100) plane in magnetite. Vincent and Phillips (1954, p. 4) call this exsolution pattern "cloth-texture" and Vincent (1960, p. 1006) distinguishes an additional plane parallel to (110) in magnetite, parallel to which ulvite also exsolves. Magnetite is commonly anisotropic where this cloth-texture is developed. This anisotropism is not evenly distributed over a grain, but is patchy (Willemse, J., 1967b) (Photo 23). The size of the patches varies greatly from one part of the section to another. They may occupy the whole or mostly only parts of the magnetite grain so that isotropic areas of the

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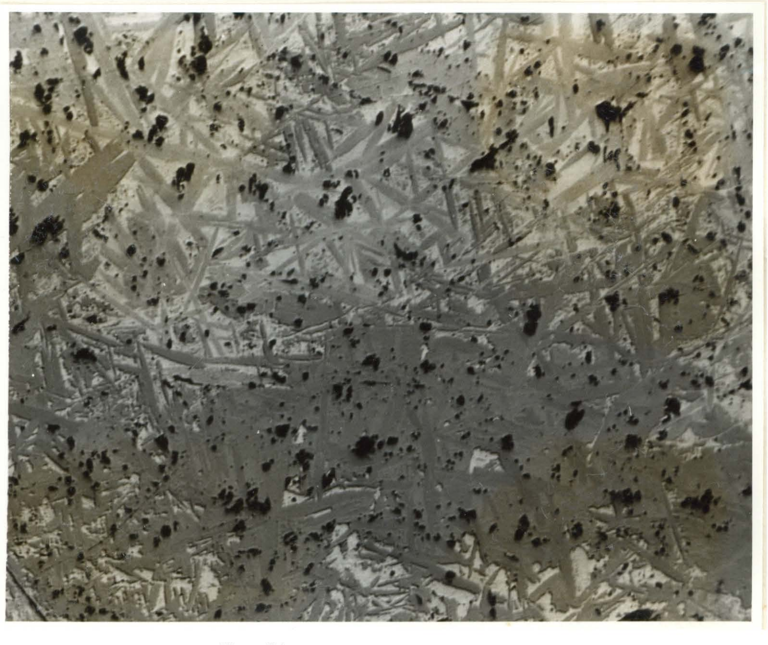
Photograph 23. Reflected light, oil immersion, crossed nicols. X 265. Patchy anisotropism in magnetite, caused by proto-ilmenite. Section Mt.4ST., Diepkloof 186-J.S.



Photograph 24. Reflected light, oil immersion. X 105. Intergrowth of lamellar ilmenite and magnetite (grey) in

section remain in between. Vincent (1960, p. 1010) observed an analogous but more lamellar phenomenon in the magnetites of the Skaergaard intrusion and ascribed it to a second generation of exsolution of ilmenite by the oxidation of ulvite to ilmenite. Three sets of patches have the same optic orientation. Sometimes thin lamellae can be observed in these patches under crossed nicols. Each patch contains its own set of fine, similarly orientated lamellae of ilmenite. It is doubtful whether the patchiness is caused by a later exsolution of ilmenite from magnetite, seeing that ilmenite is not soluble in magnetite in large quantities. J. Willemse (1967b) is of the opinion that the anisotropism is caused by a dispersed form of ilmenite. He assumes that the ilmenite is pseudomorphous after the ulvite and suggests the name "proto-ilmenite" for this dispersed form of ilmenite.

2. Proto-ilmenite, a lamellar and worm-like intergrowth of ilmenite and magnetite.

Lenticular bodies of ilmenite in magnetite were first observed in magnetitite from Rhenosterfontein 86-J.Q. by F. Raal (1965, p. 36). Similar lamellar to leaf-like bodies of ilmenite have been observed in magnetite from the plug on Haakdoorndraai 169-J.S. (Photos 24 and 25). Close investigation revealed that this ilmenite is not pure but is a delicate intergrowth of ilmenite and magnetite in magnetite. The lamellar ilmenite is anisotropic, whereas the pure magnetite between the lamellae is isotropic. Under crossed nicols it may be seen that the lamellae have a tendency to be orientated parallel to the (111) plane of magnetite. Some of the lamellae, however, are orientated at random (Photo 25). The pure magnetite is usually altered directly to martite with the result that brown intergrowth lamellae of ilmenite and magnetite are present in white hematite. The magnetite of the lamellae is altered firstly to maghemite and later to

Photograph 25. Reflected light, oil immersion, crossed nicols. X 105.

Four sets of lamellar bodies of intergrown ilmenite and magnetite showing the tendency to be arranged parallel to the (111) plane of magnetite. Small light lamellae are martite. Section Mt.6., Haakdoorndraai 169-J.S.

Photograph 26. Reflected light, oil immersion,

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hematite so that the lamellae now appear lighter in colour. Under high magnifications brown spots of ilmenite can still be observed, although on further oxidation this ilmenite alters to a grey substance, probably leucoxene.

In the magnetite from the first seam north of Magneetkop (Mt.4ST) the intergrowth of ilmenite and magnetite is worm-like. In one part of the polished section the "worms" form three well defined sets (Photo 26), probably orientated parallel to the (111) plane of magnetite, whereas in other parts of the section more irregular worm-like intergrowths can be observed (Photo 27). Three sets of "worms" exist in one magnetite grain. It is significant that these three sets of "worms" extinguish simultaneously with the three sets of anisotropic patches in the adjoining magnetite.

It is possible that this type of intergrowth is caused by a migration of the constituents of proto-ilmenite to form these lamellar or worm-like concentrations of ilmenite. Vice versa, the proto-ilmenite may be caused by a delicate worm-like intergrowth of ilmenite and magnetite in the magnetite.

In the same section (Mt.4ST) it may be observed that migration took place to a considerable extent (Photo 28). There is no doubt that this pure ilmenite grain has formed from the intergrowth, of ilmenite and magnetite, firstly because the optic orientation is similar to the adjoining ilmenite of the intergrowth of ilmenite and magnetite, and secondly because a rim of pure magnetite surrounds the ilmenite grain.

Intragranular bodies of ilmenite in the same section probably also originated by the migration of the constituents of proto-ilmenite. These irregular grains of pure ilmenite form groups in magnetite which often have the same optic orientation and are mostly optically continuous with lamellae of ilmenite in the vicinity and with a very fine worm-like

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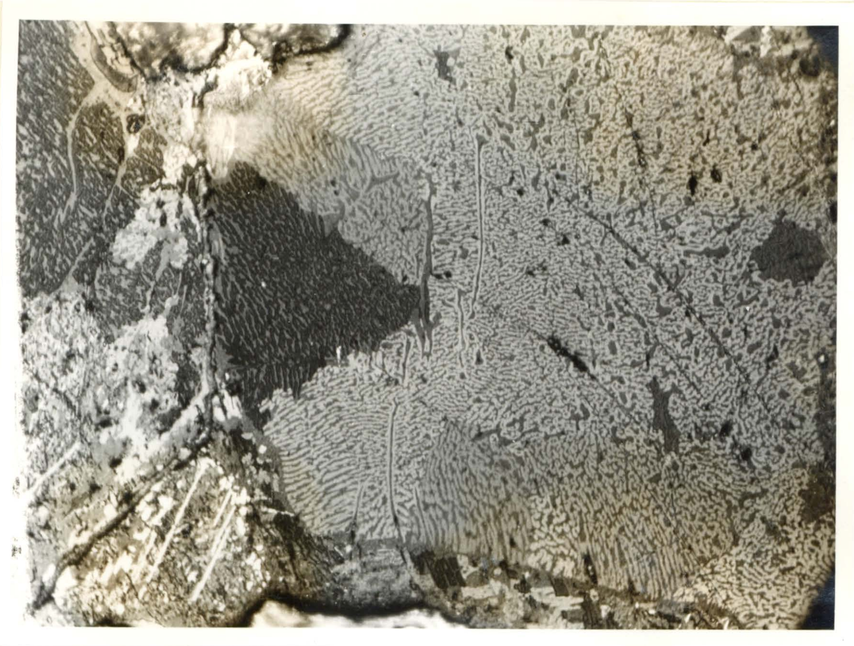

Photograph 27. Reflected light, oil immersion, crossed nicols. X 105.

Three sets of irregular intergrown ilmenite and magnetite "worms" in magnetite. Section.Mt.4ST., Diepkloof 186-J.S.

Photograph 28. Reflected light, oil immersion, crossed nicols. X 105.

Ilmenite of the integrowth of ilmenite and magnetite in magnetite exsolving to form pure ilmenite (Il). Section Mt.4ST., Diepkloof 186-J.S.

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intergrowth of ilmenite and magnetite in the adjoining magnetite (Photo 29). It is evident that these ilmenite grains are connected in three dimensions and therefore give rise to a type of graphic intergrowth. Ramdohr (1956, p. 10) mentions the possibility that this type of intragranular ilmenite represents lamellae which merged together during metamorphism.

On cooling of a titaniferrous magnetite, the ulvite exsolves parallel to the (100) plane of magnetite. Owing to late stage oxidation this intergrowth of magnetite and ulvite could be transformed to an intergrowth of magnetite and ilmenite. This ilmenite seems to be unstable in the (100) planes of magnetite, and the constituents seem to migrate to form a diffuse proto-ilmenite which causes the anisotropic patches. Further migration of these constituents may give rise to several textures, e.g.:

(a) Lamellae of secondary ilmenite parallel to the (111) plane of magnetite (Vincent, 1960, p. 1009).

(b) Lenticular (Raal, 1965, p. 36) to lamellar intergrowths of ilmenite and magnetite in magnetite.

(c) Worm-like intergrowths of ilmenite and magnetite. This ilmenite may exsolve still further to form intragranular ilmenite optically continuous with the proto-ilmenite.

Where the patchy anisotropism is present in the magnetite, the cloth-texture can still be observed in most cases. Where the constituents of the proto-ilmenite migrated as in the three examples described above it leaves a pure magnetite in which cloth-texture no longer prevails, although the fine intergrowth of ilmenite and magnetite is probably still based on the (100) directions of magnetite.

In the magnetitite from Maleeuwskop (Mt.8) the magnetite has largely been oxidized to hematite. In this section most of the oxidized ulvite remained in the (100) planes of the original magnetite. Therefore it seems as though the ilmenite is un-

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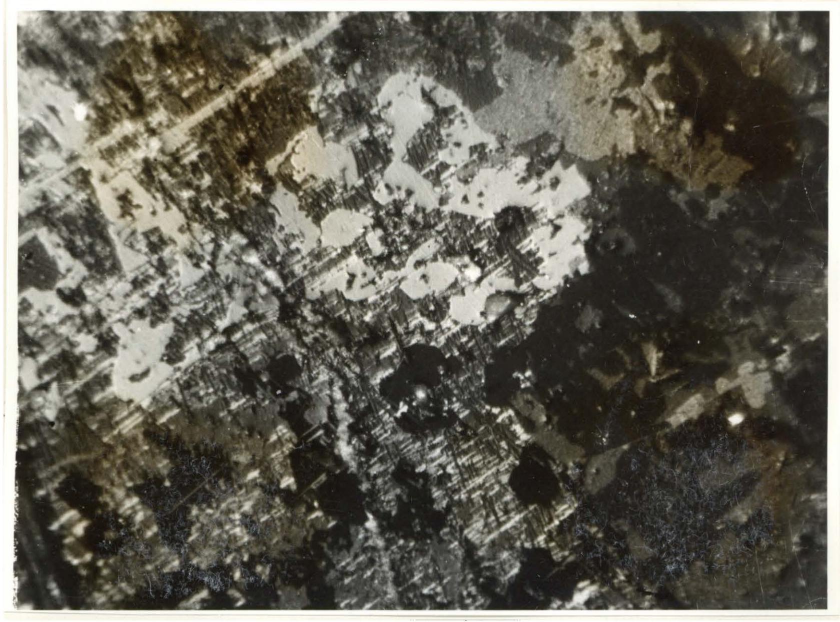

Photograph 29. Reflected light, oil immersion, crossed nicols. X 265. Intragranular ilmenite (white and black) optically continuous with ilmenite lamellae (upper left hand corner) and fine worm-like intergrowth of ilmenite and magnetite (light grey and very dark grey) in magnetite (grey), which is partially oxidized to martite (small white lamellae). Section Mt.4ST., Diepkloof 186-J.S.

stable only in the (100) planes of magnetite. As soon as the magnetite is oxidized to hematite the constituents of ilmenite stop migrating, and are probably stable in the hematite. Most of the ilmenite in this occurrence has been altered to a grey mineral, probably leucoxene.

In the magnetitite from the pipe on Haakdoorndraai 169-J.S (Mt.6), veins of late magnetite cut through the magnetitite. Along these fractures the magnetite was oxidized to hematite before the emplacement of the veins of late magnetite and before the constituents of proto-ilmenite could migrate to form lamellar concentrations of ilmenite. A combination of the anisotropism of the hematite and that of the diffuse proto-ilmenite causes a flamboyant anisotropism in the vicinity of these veins (Photo 30). This proto-ilmenite, which causes the flamboyant anisotropism gradually passes over, away from the vein of late magnetite, into the lamellar intergrowths of ilmenite and magnetite. Fan-like intergrowths of ilmenite and magnetite (Photo 31) are fairly common in this polished section and represent an intermediate stage between proto-ilmenite and lamellar intergrowths of ilmenite and magnetite. This may be seen from the number of these fan-like textures close to the vein of late magnetite where they contribute towards the flamboyant anisotropism.

C. Additional oxidation phenomena

It is generally known that magnetite oxidises to Fe_2O_3. This can happen in two ways.

(a) Magnetite oxidises to γ-Fe_2O_3, i.e. maghemite which then inverts to α-Fe_2O_3, i.e. hematite.

(b) Magnetite is martitized i.e. oxidises directly to α-Fe_2O_3

In this respect H. Lepp (1957, p. 679) and K. Egger (1963 p. 493) have studied synthetic, as well as natural magnetites. They obtained the same results, namely that finely ground

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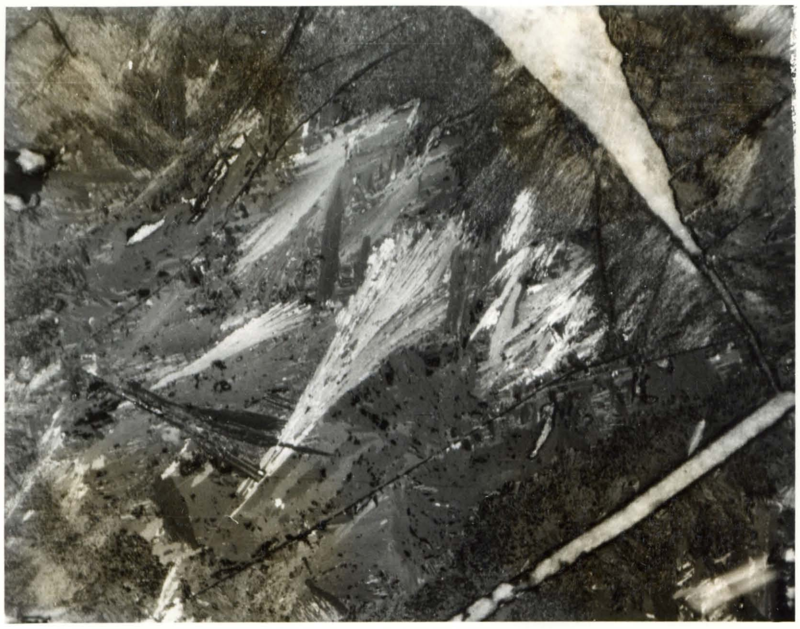
Photograph 30. Reflected light, oil immersion, crossed nicols. X 265.

Flamboyant anisotropism in hematite, caused by proto-ilmenite which is now largely altered to leucoxene. Section Mt.6, Haakdoorndraai 169-J.S.



Photograph 31. Reflected light, oil immersion, crossed nicols. X 105.

Fan-like intergrowth of ilmenite and magnetite (white and light grey) in hematite (grey). Section Mt.6, Haakdoorndraai 169-J.S.

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magnetite (<3000Å) oxidizes at ± 200°C to γ-Fe_2O_3 and later at ± 525°C this γ-Fe_2O_3 inverts to α-Fe_2O_3. In large grains of magnetite (~6000Å) no γ-Fe_2O_3 developes on heating, but oxidizes at ± 550°C directly to α-Fe_2O_3. Any magnetite powder of grain size between the two extremes given above, oxidizes partially to γ-Fe_2O_3 at ± 200°C. At ± 550°C the γ-Fe_2O_3 portion inverts to the α-Fe_2O_3 phase, whilst the other magnetite oxidises directly to α-Fe_2O_3.

Lepp (p. 680) concluded that the formation of γ-Fe_2O_3 is a surface phenomenon and therefore proportionately more of this material will form in the finer-grained magnetite powders than in the coarser ones. Egger (p. 494) however is of the opinion that the grain size of natural magnetites plays an important role in the formation of γ-Fe_2O_3.

The present microscopic investigations substantiate in part the conclusions reached by Egger. It seems as though the the exsolution network of ulvite plays an important role in the oxidation of magnetite. Pure magnetite, without any exsolution of ulvite, can oxidize to maghemite which later inverts to hematite, or it can oxidize directly to hematite. If however, ulvite, whether oxidized to ilmenite or not, is present, magnetite never oxidizes directly to martite, but there is always a transitional stage of maghemite present. It seems as though the cloth-texture subdivides the magnetite grain into numerous small compartments which oxidized first to maghemite and then inverted to hematite.

In most of these highly oxidized sections ilmenite is the last mineral to be affected by oxidation. X-ray diffraction patterns of this alteration product show no ilmenite lines, but hematite, as well as weak lines indicative of pseudobrookite and anatase. These results coincide with those of Karkhanavala and Momin (1959, p. 1059) who found that leucoxene, as an alteration product of ilmenite consists mainly of rutile, pseudo-

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brookite, anatase and hematite. Optically this mineral corresponds with the leucoxene described by B.H. Flinter (1959, p. 723). It is grey in colour when compared with the brown of ilmenite and the white of hematite. It is less anisotropic than ilmenite, is not pleochroic and has yellowish to red internal reflections.

The thin lamellae of ilmenite and the fine-grained ilmenite of the intergrowth of ilmenite and magnetite oxidize more readily to leucoxene than the coarser-grained ilmenite. In the latter, the alteration to leucoxene has been observed only along the margin of the grains (Photo 32). The amorphous iron - titanium oxide, which is considered to be an intermediate stage in the formation of leucoxene by Bailey et al. (1956, p. 265), is absent in the sections where leucoxene is present. In the magnetite from Maleeuwskop (Mt.8) a further alteration product of leucoxene is present (Photo 33), This mineral is not present in quantities large enough to be identified positively. It is also possible that this is not a product of alteration but a mineral which replaces the leucoxene.

D. Chemical composition

The magnetitite samples investigated are oxidized to a large extent as can be seen from the low FeO values in the chemical composition (Table 12). It is futile therefore to try to draw any conclusions on the oxygen pressure during crystallization of the magnetitites, of which the amount of FeO in fresh samples seems to be an indication (Vincent and Phillips, 1954, p. 23).

TABLE 12. Chemical analyses of magnetitites

	1	2	3
SiO_2	0.66	0.05	0.55
TiO_2	18.75	19.81	19.92
Al_2O_3	2.61	2.18	2.63

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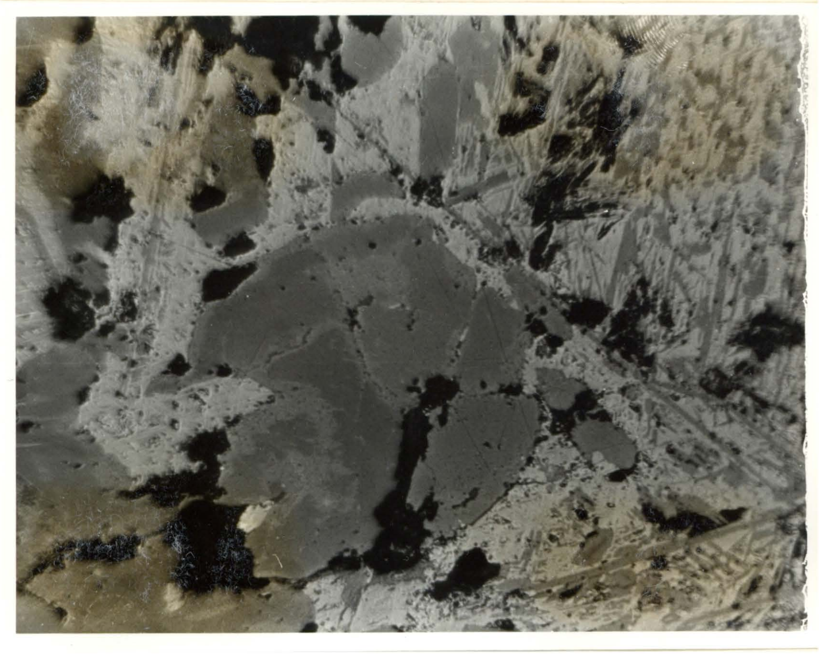

Photograph 32. Reflected light, oil immersion. X 285 Ilmenite (grey) oxidized to leucoxene (light grey). The magnetite has been completely oxidized to hematite (white). Section Mt.5ST., Magneetkop, Diepkloof 186-J.S.

Photograph 33. Reflected light, oil immersion. X 1500 Leucoxene in the cloth-texture altered to a black mineral. Section Mt.8, Maleeuwskop.

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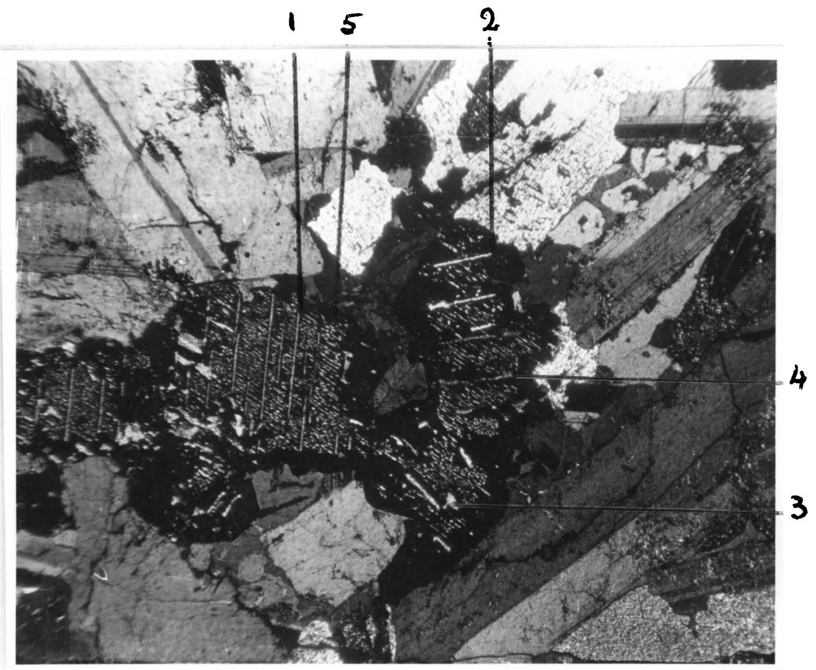

Photograph 34 Crossed nicols. X 32.

Nesophitic orthopyroxene which contains four sets of pre-inversion exsolution lamellae of augite orientated at random (1 - 4), and one set of post-inversion exsolution lamellae of augite which exsolved parallel to the (010) plane of orthopyroxene (5). Section L.13., Mineral Range 190-J.S.

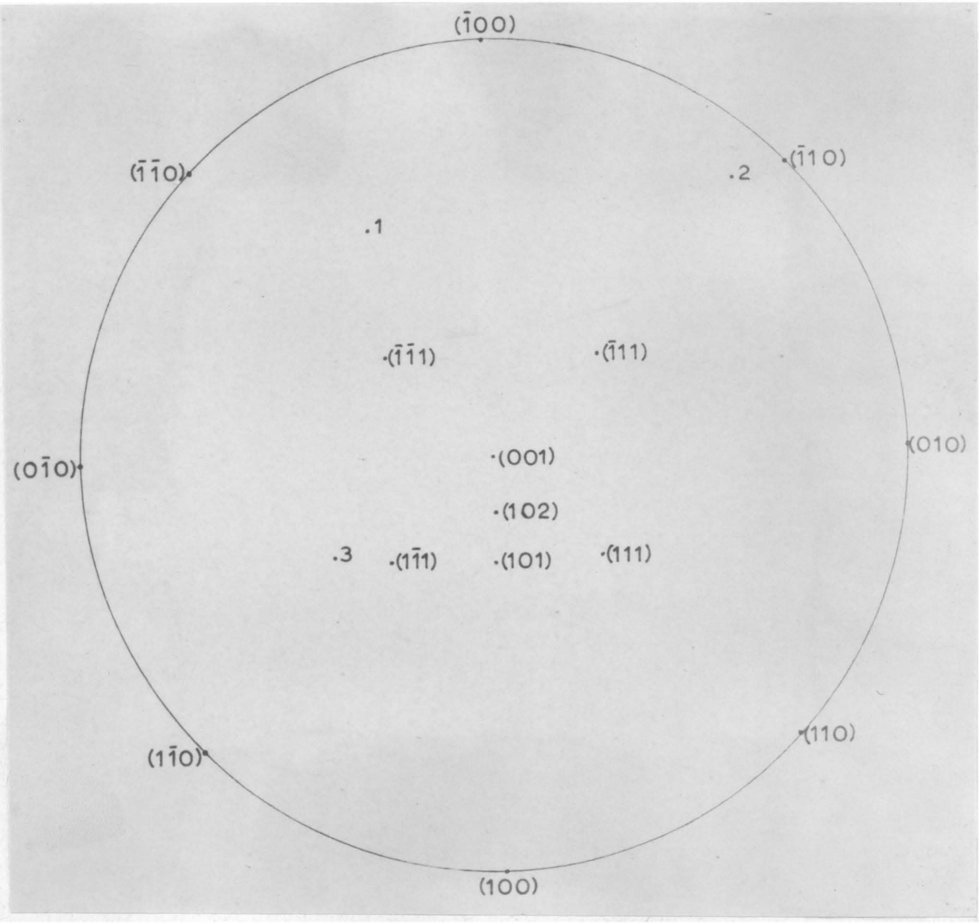

Fig. 6.

Orientation of pre-inversion exsolution lamellae 1, 2 and 3 (Photo 37) of augite in orthopyroxene. The orientation of the section prohibited plotting of the fourth set of augite lamellae on the stereogram.

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	1	2	3
Fe_2O_3	68.97	73.07	55.06
Cr_2O_3	0.006	0.018	0.22
FeO	6.32	3.25	19.45
H_2O^+	1.60	1.33	0.78
H_2O^-	0.24	0.22	0.21
V_2O_5	0.11	0.17	0.30
	99.266	100.368	99.12

1. Magnetitite Mt.1N a few hundred feet north of the plug on Diepkloof 186-J.S.
2. Magnetitite Mt.5ST., the plug on Diepkloof 186-J.S.
3. Magnetitite WV.36, a seam on Waterval 184-J.S.

Analyses by the National Institute for Metallurgy, Johannesburg.

The amount of TiO_2 is high and compares favourably with the TiO_2 content of the Upper Seams (Schwellnus, C.M. and Willemse, J., 1943, Table 1).

VIII. MINERALOGY OF THE GABBROIC ROCKS

1. Plagioclase

Plagioclase constitutes the most abundant mineral in these rocks, usually more than 50 per cent of the rock types encountered. It is usually present as subhedral laths which are tabular, parallel to (010). Although the plagioclase seldom exhibits an orientation, a parallelism in the orientation is observed in some sections, which coincides with the layering of the intrusion.

The anorthite content is fairly constant throughout the Main Zone, ranging from 60 to 70 per cent An. The gabbro close to the quartzite xenolith on Roodewal 193-J.S. and Mineral Range 190-J.S. probably represents a chill-phase of the Main Zone, which explains the low An content of its plagioclase (Fig. 4).

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Although the Upper Zone is very poorly exposed in this area, the elevation in the layered sequence of the few outcrops can be determined fairly accurately from the composition of the plagioclase and the olivine. The anorthite content ranges from 50 to 30 per cent and the feldspar is therefore andesine.

Nearly all plagioclase crystals are zonally built. Contacts between the zones are never sharp, which indicates a gradual change in the composition of the intercumulus liquid. In the most extreme cases, the rim is approximately 15 per cent poorer in An than the core. Generally the difference in the anorthite content is not more than 10 per cent. Nearly all plagioclase crystals show twinning, the most common laws are Albite, Carlsbad and Roc Tournè.

The plagioclase is fairly fresh in most samples, except in specimens from the upper parts of the Main Zone where it is altered nearly completely to saussurite.

In the Upper Zone, at the Diepkloof plug, the plagioclase of the anorthosite is also highly altered (D.30), whereas from the same outcrop, plagioclase from the ferrodiorite is fresh (D.31, Fig. 5). A similar tendency has been observed by F. Raal (1965, p. 19) in anorthosite derived from boreholes. He ascribes the alteration to deuteric conditions which prevailed mostly in the vicinity of the anorthosite. Plagioclase in the diorite and the granodiorite show a similar degree of alteration to saussurite.

In an inclusion of anorthosite in ferrodiorite (D.39) the plagioclase has been altered to prehnite. The aggregates of prehnite which are mostly white and arranged radially where they penetrate the plagioclase, have brown cores that are isotropic to weakly anisotropic under crossed nicols. X-ray diffraction patterns show that this mineral is also prehnite.

2. Orthopyroxene

(a) General

Orthopyroxene was only found in sections of the Main Zone

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and it never constitutes more than 20 per cent of the volume of the gabbroic rocks, except in the Needle norite (Bl.13) where it forms 40.4 per cent of the rock (Table 11). The composition ranges from hypersthene in the lower portions of the Main Zone to ferrohypersthene in the upper portions (Fig. 4).

Two types of orthopyroxene have been encountered:

(i) Orthopyroxene, which represents a product of primary crystallization, without any exsolution lamellae of clinopyroxene, e.g. in the Needle norite. The composition of the orthopyroxene in the Needle norite is 33 mol. per cent $FeSiO_3$. From the diagram given by H.H. Hess (Poldervaart, A. and Hess, H.H., 1951, p. 478) the temperature of the magma during the crystallization of the lower portion of the Main Zone must therefore have been approximately 1090°C, i.e. below the clinopyroxene-orthopyroxene inversion curve.

(ii) Inverted pigeonite, because the orthopyroxene contains exsolution lamellae of clinopyroxene. This orthopyroxene is found in the upper portion of the Main Zone and contains more than 40 mol. per cent $FeSiO_3$, which indicates that the temperature of the magma was below 1090°C but above the clinopyroxene-orthopyroxene inversion curve.

In the inverted pigeonite ,exsolution lamellae of augite are orientated parallel to the (001) plane of the pigeonite. According to A. Poldervaart and H.H. Hess (1951, p. 482) they are retained in the orthopyroxene along a relict (001) plane, a plane near to (101). However, D. Bruynzeel (1957, p. 509) found that the lamellae lie closer to the (102) plane of the orthopyroxene. In the thir sections investigated all the pre-inversion exsolution lamellae of augite are orientated at random in the orthopyroxene (Photo 34 and Fig. 6).

Fine striae, developed parallel to the (100) plane, have been observed in all the orthopyroxenes. Maske (1964, pp. 77-

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82) made a detailed investigation of them. He discards the possibility that they represent thin exsolution lamellae of clinopyroxene, as postulated by Hess (1960, p. 23), because each set has identical optical properties. Bruynzeel (1957, p. 505) found that the lamellae possess a monoclinic symmetry and postulated that the structure was initiated by the introduction of unit cells of high temperature clinopyroxene in to the enstatite structure. N.F.M. Henry (1942, p. 187) maintains that the striations are a result of deformation, possibly caused during the crystallization of the orthopyroxene, and they must therefore be regarded as due to twin-gliding. On the grounds that the lamellae possess a monoclinic symmetry, Maske (1964, p. 80) suggests that they represent a low-temperature monoclinic polymorph of the $MgSiO_3$-$FeSiO_3$ series, and therefore represents a type of transformation-twinning.

(b) Orientated orthopyroxene

In most thin sections in which orthopyroxene is present, groups of grains possess the same optical orientation. This has previously been observed in gabbroic rocks of the Bushveld Complex by A.F. Lombaard (1949, p. 353) and F. Raal (1965, p. 16) as well as by S. Maske (1964, p. 91) in similar rocks from the Ingeli Mountain Range. This texture corresponds to the nesophitic texture, defined by F. Walker (1957, p. 2) as "pyroxene interstitial to plagioclase and in isolated but optically continuous areas (like islands in a sea), though connected in three dimensions". This however has nothing to do with the pyroxene ratio, because clinopyroxene can be present in variable amounts.

Careful measurement of the optic orientation of these nesophitic grains on an orientated section (T_29), shows that the optical orientation from grain to grain is not exactly the same but varies slightly. The same was found by F. Raal (1965, p. 17 and Diagram 9) in the orthopyroxene of the Bon Accord

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hyperite. He ascribes this to relatively few pigeonite nuclei that were formed in the interprecipitate liquid. Somewhat imperfect propagation (p. 48) of the single crystal-structure in a three dimensional way might result in different optical orientations at certain points. He also suggests the possibility that instability in the feldspar framework might cause a slight shifting of the feldspar grains during crystallization of the pigeonite, thus causing a slight disorientation of the orthopyroxene grains. The presence of lamellae of clinopyroxene, of different optical orientation and orientated at random in this optically continuous orthopyroxene (Photo 2 and 34) indicates that in this case Raal's explanation does not hold true, because the augite lamellae should then still show a constant orientation in the slightly disturbed nesophitic pigeonite. It is therefore obvious that the crystallographic b- and c-axes of the pigeonite are not always retained in the secondary orthopyroxene, as contended by Poldervaart and Hess (1951, p. 482). They do however, describe exceptions to this rule. It seems as though rotation of the crystallographic b- and c-axes is quite common in secondary orthopyroxene. G.M. Brown (1957, p. 532) has recorded it from the Skaergaard intrusion, D. Bruynzeel (1957, p. 513) from Insizwa and S. Maske (1964, p. 91) from Ingeli.

Bowen and Schairer (1935, p. 151) who investigated the inversion relationship of orthopyroxene on heating, found that members approaching the two ends of the $MgSiO_3$-$FeSiO_3$ series are transformed readily into the monoclinic modification, whereas the intermediate members were only transformed with the aid of a catalyst and (p. 169) that "in general, a single crystal or crystal fragment of orthorombic pyroxene is transformed into an aggregate of several grains of monoclinic pyroxene of random orientation with respect to each other and to the original orthorombic substance". They ascribe the

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sluggishness of inversion of the intermediate members to structural complexities and the steady decline in the inversion temperature with enrichment in iron. G.M. Brown (1957, p. 534) also found that "grains of inverted pigeonite that show rotation rather than retention of axes on inversion, increased with iron content". Whether this is also valid for the Bushveld Complex remains to be proved, seeing that only intermediate members of the $MgSiO_3$-$FeSiO_3$ series have been investigated up to the present.

Wagner (1924, p. 40), Schwellnus, C.M. (1932, p. 11), Van den Berg (1946, p. 183) and Schmidt, E.R. (1952, p. 254) found that the orthopyroxenes of the Bushveld Complex are orientated so that nearly all the grains lie with their crystallographic c-axes in the plane of igneous lamination. Crystal settling cannot altogether account for this orientation because much of the inverted pigeonite crystallized from the liquid intercumulus to a plagioclase mesh. The orientation therefore seems to be superimposed. This can only be explained by pressure from the accumulating superincumbent mass; on inversion the orthopyroxene would favour an orientation most stable under prevailing pressure conditions, obviously with the crystallographic c-axes perpendicular to the direction of pressure. The orthopyroxene thus formed would contain clinopyroxene lamellae that exsolved parallel to the (001) plane of pigeonite, but the orientation in the orthopyroxene would be random.

However, this does not explain the random orientation of the augite lamellae in the nesophitic orthopyroxene. In groups this mineral has a common orientation with its crystallographic c-axis parallel to the plane of igneous lamination. Maske (1964, p. 93) suggests that owing to the sluggishness of the structural rearrangement, inversion did not take place at the appropriate temperature. He is of the opinion that primary hypersthene was one of the first minerals to be precipitated

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from the interstitial liquid around the pigeonite grain below the inversion temperature, thus forming lamellae-free rims. This stable orthorombic phase would then trigger off the inversion of the pigeonite in such a manner that the orientation of the secondary orthopyroxene would be continuous with the late hypersthene mantles. This explanation is not applicable to the nesophitic orthopyroxene of the Bushveld Complex because of the absence of lamellae-free mantles of orthopyroxene.

It is obvious that, before inversion, the nesophitic orthopyroxene consisted of several pigeonite grains orientated at random, which occupied the interstitial spaces in the plagioclase mesh. On cooling, lamellae of augite were exsolved parallel to the (001) plane of each pigeonite grain. When the inversion temperature was reached, directed pressure of the accumulating crystals developed and the first pigeonites to invert must have been those which, after inversion produced an orientation most stable under the prevailing conditions of directed pressure. It is obvious that the pigeonite grains with different orientations would take longer to invert owing to the sluggishness of inversion. As the pigeonite grains were in contact with one another, the first formed orthopyroxene which ~~were~~ was fav~~k~~ourably orientated could set off the inversion in the adjoining grain, which would adopt an orientation continuous with that which triggered off the reaction. This process would then carry on until all the pigeonite grains were inverted, and this would result in the nesophitic orthopyroxene containing augite lamellae of random orientation.

A.F. Lombaard (1949, p. 353 and Fig. 2) describes several adjacent hypersthene grains of different orientation. These contain parallel exsolution lamellae of clinopyroxene with the same optic orientation, which pass from one grain into another. In this case a single grain evidently produced on inversion several hypersthene grains of different orientation.

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Nesophitic texture can also be the result of metamorphism, already described (p. 8). How the nesophitic texture which transgresses the contact of an inclusion was derived is not quite clear (L.32A, Photo 2). Either directed pressure was exerted on the inclusion of Dullstroom lava or the orientation of the orthopyroxene in the inclusion was influenced by the orientation of the orthopyroxene in the adjoining gabbro.

Thin post-inversion exsolution lamellae of augite parallel to the (010) plane of the nesophitic orthopyroxene were only encountered in one section (Photo 34, L.13). The (010) lamellae of clinopyroxene have the same orientation in adjoining grains which contain thick, pre-inversion exsolution lamellae of clinopyroxene orientated at random.

3. Clinopyroxene

Clinopyroxene is present in varying amounts in all the thin sections investigated, usually about 14 per cent in the hypersthene gabbro, more in the ordinary gabbro and less if orthopyroxene increases. The composition remains fairly constant throughout the Main Zone. $2V_{\gamma}$ and $\gamma \wedge c$ vary slightly averaging 46° and 43^{c} respectively. N_{β} is 1.700. The clinopyroxene is therefore an augite containing Wo38, Fs26 and En36 mol. per cent (after Tröger, 1959, p. 62).

The clinopyroxene from the Upper Zone has a slightly smaller optic axial angle ($2V_{\gamma}$ 44°), $\gamma \wedge c$ is 43° and n_{β} is 1.719. The composition therefore is Wo32, Fs41, En27 and the clinopyroxene is a ferroaugite.

Twinning on (001) and (010), partings, and exsolution lamellae of orthopyroxene, are common in the clinopyroxene of the Main Zone and give rise to herring-bone patterns. The clinopyroxene, often replaces orthopyroxene, and when the latter contains lamellae of augite, the former is nearly always optically continuous with these exsolution lamellae.

The clinopyroxene of the ferrodiorite does not show any

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parting and twinning is very rare.

The clinopyroxene is altered to hornblende and chlorite. The presence of tiny biotite flakes all around the grains of clinopyroxene and orthopyroxene in a mottled anorthosite (M.3) is interesting. These flakes all have a similar orientation: they protrude half-way into plagioclase and half-way into the pyroxene (Photo 35). This biotite formed evidently at the expense of the plagioclase and the pyroxene in the deuteric stage of the consolidation process.

4. Olivine

Olivine is present only in rocks of the Upper Zone in the area under consideration. It forms anhedral grains which may contain small apatite crystals, but it very seldom encloses plagioclase completely. This indicates that it crystallized soon after the plagioclase started.

The composition varies considerably across the thickness of this Zone (Fig. 4). In the lower horizons of the Upper Zone investigated, the olivine is a ferrohortonolite (28 mol. per cent Fo., D. 30). Higher up in the succession, the Fo content decreases rapidly, and the olivine in the diorite (WV.18) is practically a pure fayalite which contains only 4 mol. per cent Fo.

Alteration of olivine to serpentine along cracks and around the rim of grains is common in the ferrodiorite (D.39). Higher up in the succession the mineral contains small grains of magnetite (WV.18). Ramdohr (1960, p. 1013) mentions that grains of magnetite can form during serpentinization of olivine and also that magnetite grains have been observed in unaltered fayalite.

5. Ilvaite

This mineral was first described by J. Willemse (1967a) from the ferrodiorite of the Bushveld Complex and seems to be

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fairly common. It is dark brown to opaque in thin section, highly pleochroic in bright blue and grey in polished sections. Under crossed nicols it has a bright reddish-brown to yellowish-brown internal reflections. It is mostly found in the vicinity of pyrrhotite.

6. Ilmenite

Ilmenite is often present as groups of blebs in quartz and hornblende in the diorite (Photo 36) as well as in the anorthosite of the Upper Zone. In reflected light, groups of blebs have the same optic orientation. In other polished sections (D.29) ilmenite is present as lamellae in hornblende and biotite. It is possible that this ilmenite represents relics of titanomagnetite. Buddington et al. (1955, p. 529) state that in some metagabbros, reconstituted in the amphibolite facies, hornblende develops at the expense of magnetite, leaving only the ilmenite.

7. Sulphides

Sulphide-bearing anorthosite is present mainly on Blaauwbank 168-J.S. and Rooikraal 188-J.S., where numerous prospecting-pits are found, which date back to the days of the intensive search for platinum. On Blaauwbank 168-J.S., payable amounts of platinum have actually been found in small quantities. The deposits are designated the Blaauwbank Type by P.A. Wagner (1929, p. 202). This type is described by him as being lenticular to pocket-like platinum-bearing bodies of anorthosite. The sulphides in this anorthosite are sperrylite (Wagner, P.A., 1929, p. 203), pyrrhotite, pentlandite, bravoite and chalcopyrite.

The copper occurrence on Roodewal 193-J.S. has nothing to do with the gabbroic rocks of the Bushveld Complex as far as its origin is concerned. It is of hydrothermal origin and consists of veins of quartz and chlorite with which some copper

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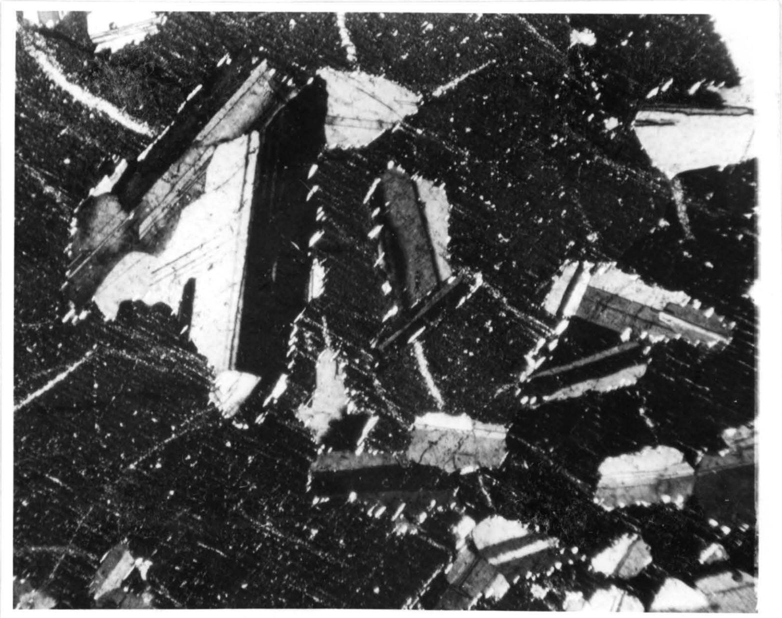

Photograph 35. Crossed nicols. X 32

Tiny biotite flakes all around the pyroxene in a mottled anorthosite. Section M.3., Rietkloof 166-J.S.

Photograph 36. Transmitted light. X 32.

Irregular blebs of ilmenite (I) in quartz and hornblende, and small bodies of magnetite (Mt) in olivine (Ol) due to exsolution. Section WV.18., Waterval 184-J.S.

mineralisation is associated. Similar small deposits are found on Mineral Range 190-J.S. and Goedgedacht 72-J.S. the copper-bearing minerals are chalcopyrite and malachite.

IX. THE BUSHVELD GRANITE AND THE RELATED ROCKS

Granophyre which belongs to the Late Plutonic Phase of the Complex outcrops in the most north-westerly corner of the area on Rietkloof 166-J.S. and Elandsplaats 48-J.S. and forms part of the southerly tongue of granophyre related to the large mass of granite north of Groblersdal. This granophyre is not as coarse-grained as the types related to the felsite and is usually of a lighter colour. Phenocrysts of microcline perthite and plagioclase are present in a ground-mass of mostly quartz and K-feldspar, which are for the greater part granophyrically intergrown. The mafic constituent is a dark pleochroic hornblende (M.2).

A sill-like intrusion of granite prophyry about 1000 ft thick is present in the Upper felsite. It is a red-coloured rock, which contains phenocrysts of K-feldspar up to 10 mm in length, as well as smaller phenocrysts of quartz up to 4 mm in diameter. A smaller, more irregular, dyke-like intrusion of the same rock intrudes the Variable felsite lower down in the succession. E.T. Mellor (1906, p. 68) mapped these porphyries as part of the Bushveld granite. The central portions of the intrusions are according to him coarse-grained in places and indistinguishable from the Bushveld granite.

X. YOUNGER INTRUSIVE ROCKS

A. A post-Waterberg dyke

A syenitic dyke intrusive into gabbroic rocks on Roodewal 193-J.S. is reddish brown in colour and contains large phenocrysts of clinopyroxene and plagioclase, the latter altered to saussurite, in a feldspathic ground-mass which contains very small amounts of quartz. This dyke is probably of Post-Waterberg age and related to the Pilanesberg and Spitskop Complexes.

B. Karroo dolerite

A fairly prominent dolerite dyke, which builds a narrow ridge that cuts across the general topography, is present on Elandsplaats 48-J.S. Other small outcrops are present on Waterval 184-J.S. in a river-bed which follows this dyke for a few hundred feet along the strike, on Mineral Range 190-J.S. and on Avontuur 195-J.S. The dolerite has not been investigated microscopically.

XI. GEOLOGICAL STRUCTURE

A structural map (Fig. 7) illustrates the possible faulting in this area as well as in the area towards the north. Two sets of faults are developed; one set strikes N.E.-S.W. and includes the Steelpoort River fault; another set strikes W.N.W.-E.S.E. and includes the Laersdrif fault discovered by D. Groeneveld (personal communication). Block-faulting has apparently taken place in a way illustrated in figures 8 and 9. The position of the faults is based on the following evidence.

Fault F_1 - F_1

The V_2O_5 content of the magnetitite from Maleeuwskop is 0.32 per cent. The plugs are therefore high up in the succession of gabbroic rocks and no prominent fault is necessary between the narrow belt of roof-rocks, which strike approximately N.N.E.-S.S.W. on Welgevonden 45-J.S., and these pipes. The composition of the plagioclase and the orthopyroxene of the gabbro immediately to the east of F_1 - F_1 is given by A.F. Lombaard (1949, p. 349, Table 1) as 62 per cent An and 50 mol. per cent $FeSiO_3$ respectively. According to the composition deduced from the general scheme of properties of the Bushveld minerals (J. Willemse, 1964, p. 120, Fig. 2) the

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Fault F_5 - F_5

This east-west striking fault on Mineral Range 190-J.S. which is revealed by a prominent quartz-vein has a horizontal displacement of 3200 ft. The downthrow side of this fault is on the south. It can be followed westwards onto Goedgedacht 72-J.S. where it stops abruptly and is probably neutralized by the fault F_3 - F_3 that duplicates the Smelterskop quartzite.

Fault F_6-F_6

This fault, to the north of Blood River, strikes W.N.W.-S.E.S. and is postulated on the grounds of the difference in strike and dip of the rocks in the outcrops to the north and the south of it, especially on Weltevreden 45-J.S. and Haakdoorndraai 169-J.S.

The faulting does not seem to have affected the Bushveld granite and the related granophyre, a fact which indicates that the doming and blockfaulting is either older than the Bushveld granite, or of the same age as the Bushveld granite. According to C.P. Snyman (1958, p. 255) this granite caused the doming and folding in the Moos River Fragment. Hammerbeck (1965, p. 58 found that the granite of Steelpoort Park lies along the strike of the Dwars River fault which is parallel to the Steelpoort River fault. He is of the opinion that this granite is of the same age as the Bushveld granite. It seems therefore that the faults are older than the Bushveld granite and that the doming in the Moos River area was caused by emplacement of the Bushveld granite. If so, the Rooiberg granophyre is older than the granophyric phase of the Bushveld granite, because the former has been displaced considerably by the Steelpoort River fault (Lombaard, A.F., 1949, Plate 19).

It is doubtful whether the Moos River Fragment represents a sedimentary inclusion as proposed by B.V. Lombaard (1931, p. 15) and Hall (1932, p. 221) on the grounds that the complete

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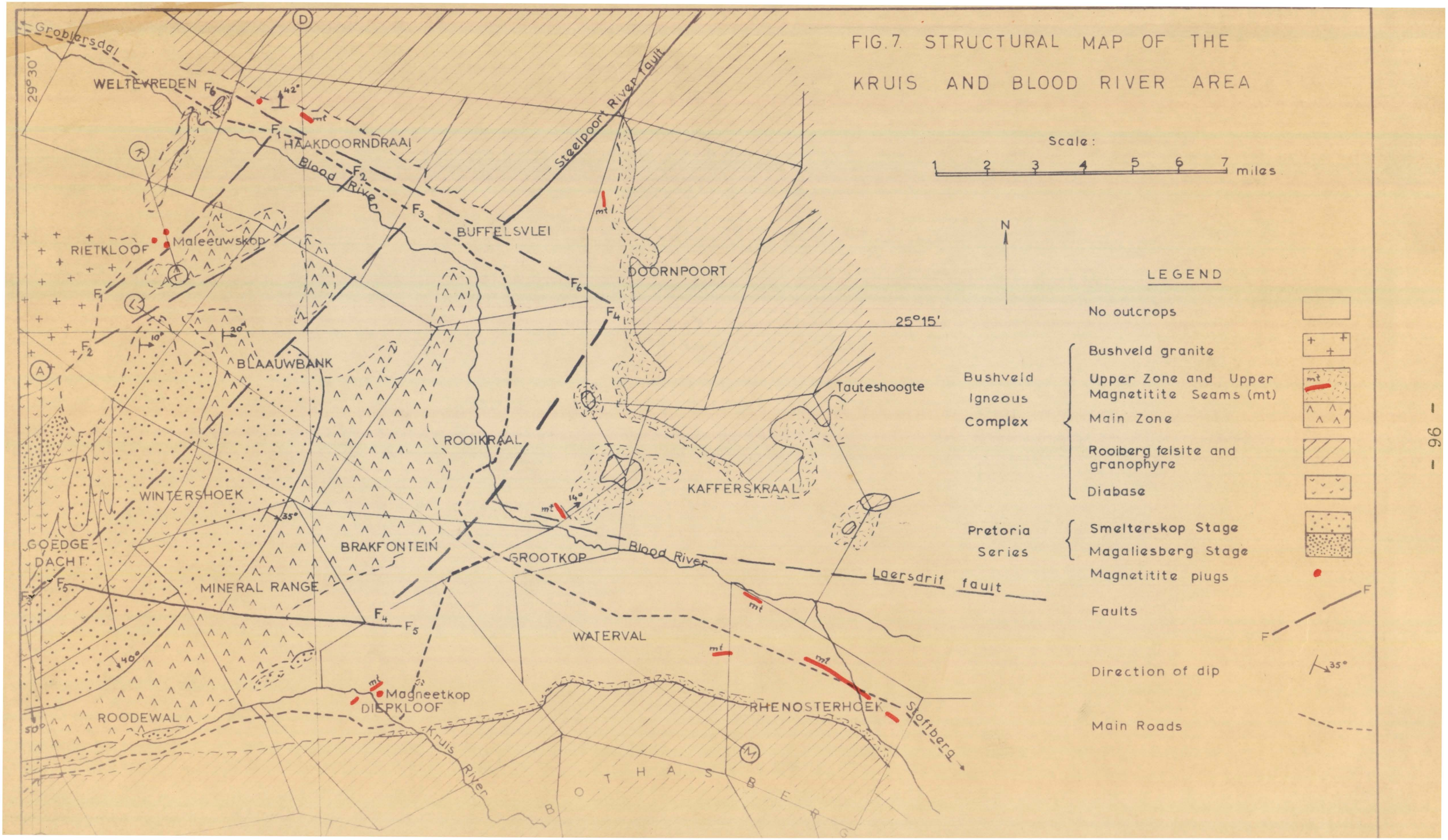

FIG. 7 STRUCTURAL MAP OF THE KRUIS AND BLOOD RIVER AREA

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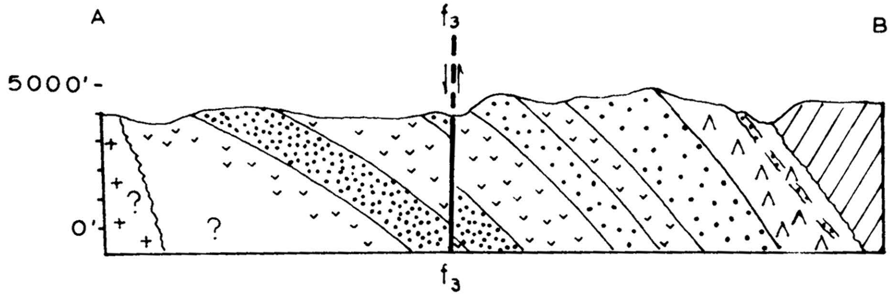
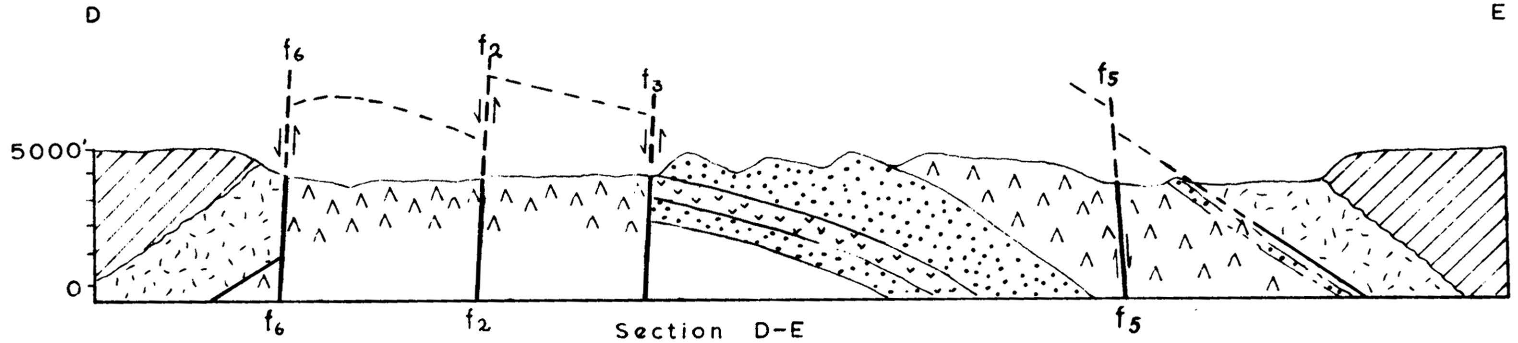
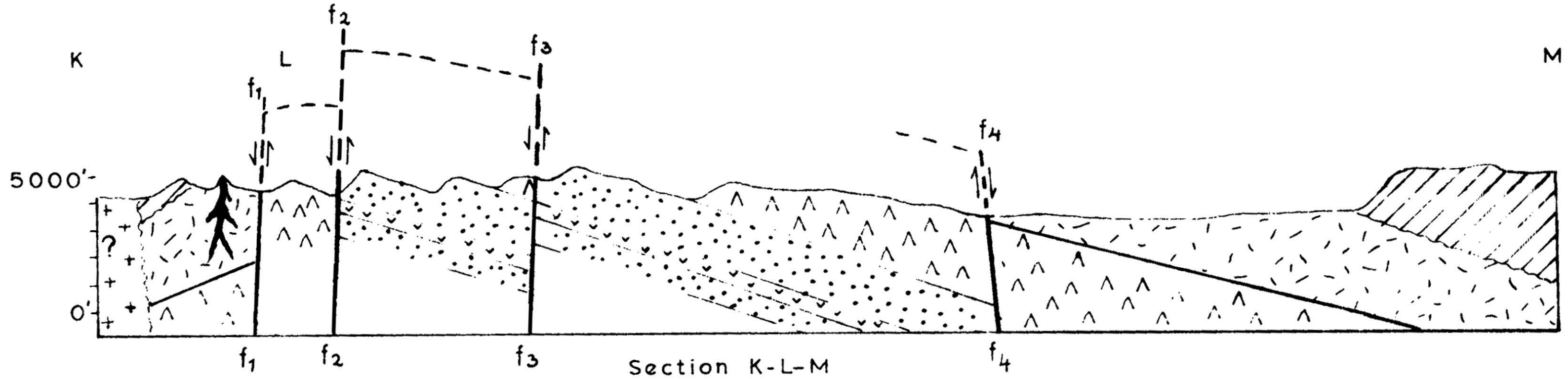


Section A–B



Section D–E



Section K-L-M

FIG. 8 Profiles through the area of fig 7

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succession of sediments of the Pretoria Series is not present in the area. The thick succession of sedimentary rocks between the Kruis and the Blood Rivers accounts for the incomplete succession in the Moos River area. The contention of P.A. Wagner (1927, p. 18) that an anticlinal fold caused part of the metamorphosed floor of the Complex to protrude from the surrounding granite seems more acceptable. The quartzites of the Magaliesberg and Smelterskop Stages were wedged away from the floor during emplacement of the gabbroic rocks. The "gap" in the roof is therefore caused by doming and block-faulting that weakened the roof which was therefore removed more readily by erosion than the formations towards the north and the south.

Because no outcrops of the Upper Zone are present west of Diepkloof 186-J.S., it is clear that a discordant relationship is present between the gabbroic rocks and roof of the Complex. West of Diepkloof 186-J.S. the Upper Zone gradually becomes thinner and is absent along the section A - B (Fig. 7 and 8). The absence of the Main Magnetitite Seam on Mineral Range 190-J.S. and Roodewal 193-J.S. can therefore be ascribed to the proximity of the roof, which prevented differentiation of the magma.

The felsite was almost certainly in place before consolidation of the Main and Upper Zones of the Main Plutonic Phase. This is evident from the clear intrusive relationship of the gabbroic rocks in several localities, e.g. on Waterval 184-J.S.; the contacts in the beds of the Kruis and the Olifants Rivers and the irregular relationship of the diorite and the leptite on Tauteshoogte.

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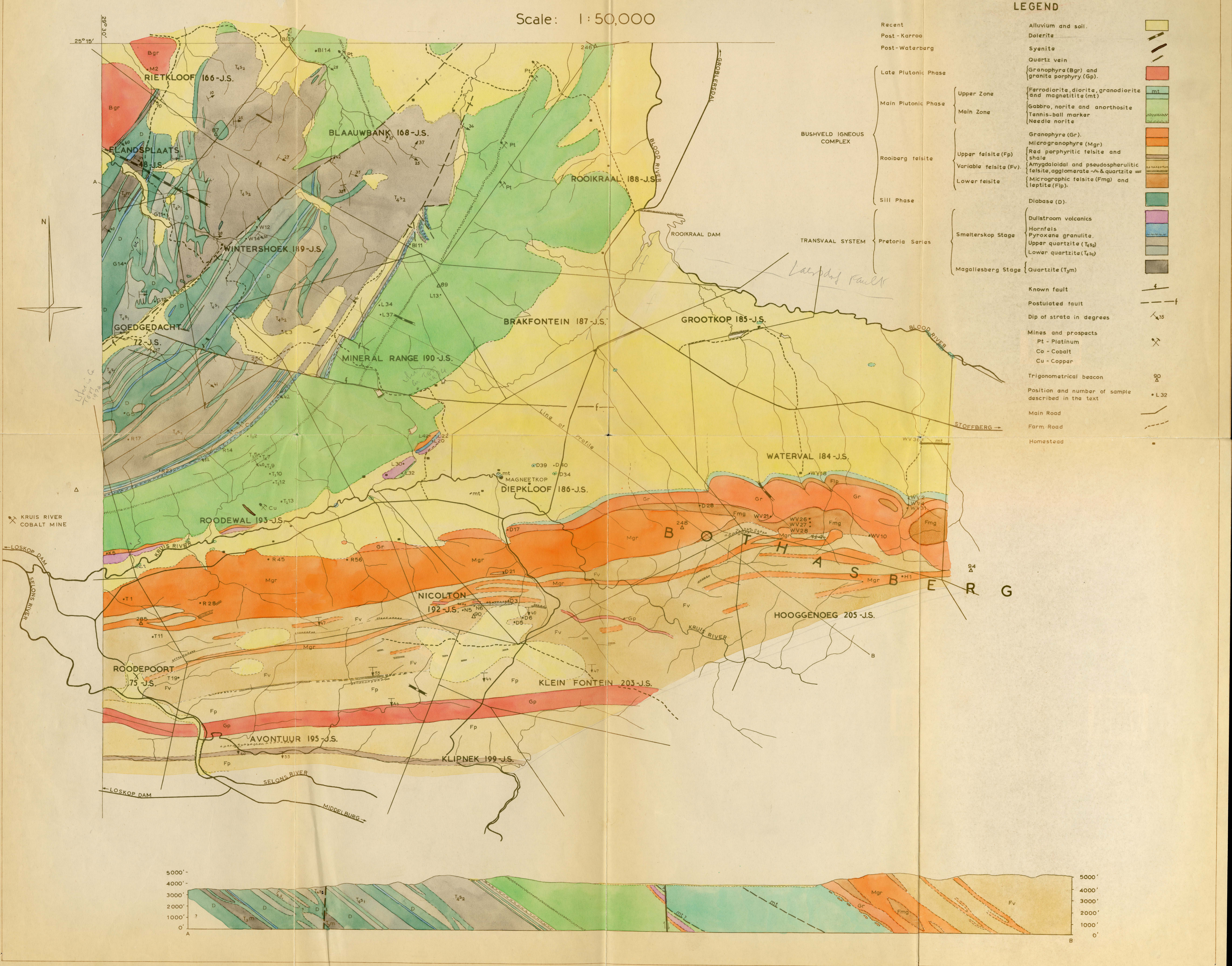
THE GEOLOGY OF THE BUSHVELD COMPLEX EAST OF THE KRUIS RIVER COBALT OCCURRENCE, NORTH OF MIDDELBURG, TRANSVAAL.

Scale: 1:50,000



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