

THE GENESIS AND GEOLOGICAL ENVIRONMENT
OF THE BUSHVELD MAGNETITE IN THE AREA
SOUTHWEST OF THE LULU MOUNTAINS

by

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INTRODUCTION

Location

An area of about 200 square miles of the mafic portion of the Bushveld Igneous Complex in the Eastern Transvaal was geologically surveyed during 1954. It is bordered by the Olifants River in the north, the crest of the Lulu Mountains in the east, and latitude $24^{\circ} 30'$ in the south, and it is part of the area covered by Sheet Map 2429B (Chuniespoort) of the Geological Survey of South Africa (plate I).

Physiography

The Lulu Mountains form an important landmark along the eastern boundary of the area where they rise to an average height of about 2000 feet above the turf-covered flats in the west. Only in the far west the monotonous flats are broken by a few isolated granite hills and in the southeast, near the foot of the Lulu Mountains, by a quartzite hill. The area is drained by a network of small intermittent streams which coalesce on the flats and flow into the Olifants River which breaks in a northern direction through the Lulu Mountains near their northeastern end.

Previous Work

The area was previously investigated by Hall (19¹⁴~~08~~). He gives a short description of some of the rock types in the explanation of Geological Sheet Map 13 (Olifants River). Schwellnus (1956) has made a detailed

study of the area immediately to the east of the area studied by the present writer. Many other investigators have worked on other parts of the Bushveld Igneous Complex.

Scope of Present Investigation

The present investigation was originally undertaken as part of a revision of Geological Sheet Map 13 by the Geological Survey of South Africa. As it soon became clear that the investigation of this part of the complex might throw some light on the genesis of the Bushveld magnetite, special attention was paid to the relationships of the constituent rock types of the Bushveld Igneous Complex and those of the various occurrences of magnetite which form the main subject of the present investigation.

Methods Used

Mapping was carried out on air photographs with plane-table ground control. The scale of the air photographs was approximately 1:36,000 and the data were transferred by means of a pantograph onto a base map (scale 1:50,000) supplied by the Trigonometrical Survey of South Africa. The igneous and metasedimentary rocks occurring on successive stratigraphic horizons were sampled from bottom to top and these samples were studied microscopically.

The compositions of the plagioclase feldspars were determined by means of the universal stage and the stereograms of Reinhard (1936). For the sake of accuracy the optic axial angles of the clinopyroxenes were

measured only when two optic axes entered the field of view. For the compositions of the orthopyroxenes and the olivines the diagrams of Poldervaart (1950, pp. 1076 & and 1073) were used. For the clinopyroxenes the diagram of Hess (1949, p. 634) was used.

GENERAL GEOLOGY AND STRATIGRAPHY

The distribution of the different rock types is shown on the geological map (plate I).

Except for a few dolerite sheets of Post-Karoo age, intrusive into the granite, all the igneous rocks in the area belong to the Bushveld Igneous Complex. The eastern part of the area is occupied by gabbro which forms the Lulu Mountains. The ferrogabbro to the west overlies this gabbro and is split into two parallel zones by a strip of feldspathized sedimentary rock which trends northwest. Granite occurs in the southwestern part of the area but is separated from the ferrogabbro by another strip of feldspathized sediment.

A few thin diabase sheets and one thin sheet of harzburgite occur in hornfels on Driekop 540 KS.

The sheets of magnetite in the ferrogabbro can be subdivided into a lower zone and an upper zone. Elliptical pipe-like bodies of magnetite and of magnetite surrounded by rings of dunite and pyroxenite or olivine gabbro occur in the ferrogabbro and in places also in the gabbro. Although their distribution is rather irregular a few zones of concentration can nevertheless be recognized. A lower zone stretches northwest from Driekop 540 KS across Goedverwacht 511 KS and Hoeraroep 515 KS, an upper zone trends in the same direction from Moskow 772 KS across Vlakplaats 770 KS, and a transverse zone runs west from Zwitserland 473 KS to Eersteregt 502 KS (plate I).

The rocks of the Bushveld Igneous Complex may be divided into two main groups: the mafic rocks and the felsic rocks. The mafic rocks^{investigated} are subdivided into units. Arranged chronologically these are:

- | | | |
|--------------------|---|----------------------------------|
| |) | (iii) Magnetitite sheets |
| |) | |
| |) | (ii) Magnetitite pipes with |
| |) | associated hortonolite |
| Younger intrusions |) | |
| |) | dunite, pyroxenite, and |
| |) | olivine ferrogabbro |
| |) | (i) Magnetite anorthosite sheets |
| |) | |
| |) | (iv) Ferrogabbro (more than one |
| |) | intrusion) |
| Older intrusions |) | |
| |) | (iii) Gabbro |
| |) | (ii) Harzburgite |
| |) | (i) Diabase |

The gabbro and ferrogabbro with magnetitite was previously called the "Main Zone" (Hall, 1932, p. 291).

The metamorphosed sedimentary rocks are represented by both the Magaliesberg Stage and the succeeding Smelterskop Stage^x of the Pretoria Series. These rocks form conspicuous hills near the foot of the Lulu Mountains on Driekop 540 KS and Paradys 773 KS, and the range continues further to the south across the boundary of the area mapped. Northwards the feldspathized sediments of

^x It was recently decided by the Geological Survey that the upper stage of the Pretoria Series, the Smelterskop Stage, which had not been properly defined previously, embraces all the sediments above the Main Magaliesberg quartzite (Coertze, 1961).

the Smelterskop Stage form only small outcrops in and along stream beds, and on the flats.

The only place where a more or less complete succession of the metamorphosed sedimentary rocks could be established was on Driekop 540 KS where, with the younger intrusive hypabyssal rocks, the sequence is as follows:

Feldspathized quartzite	)	
Hornfels	)	
Quartzite	)	
Hornfels	)	Smelterskop
Harzburgite (intrusive)	)	Stage
Hornfels with diabase (intrusive)	)	
Quartzite	)	
Hornfels	)	
Main Magaliesberg Quartzite	)	
Hornfels and amphibolite	)	
(intrusive)	)	
Quartzite	)	Magaliesberg
Hornfels and gneiss with diabase	)	Stage
(intrusive)	)	
? ? ? ?	)	
Hornfels with diabase (intrusive)	)	

STRUCTURE

Generally, the igneous layering of both the gabbro in the Lulu Mountains and the ferrogabbro on the flats to the west strikes northwest and dips southwest. Usually, the magnetitite sheets in the ferrogabbro are concordant with this igneous layering.

The metasediments floating in the ferrogabbro on Driekop 540 KS and Paradys 773 KS actually represent the sedimentary beds forming the floor of the Bushveld Igneous Complex. Apart from showing intense small-scale folding, the dips of these sediments are centrocinal so that they seem to have the form of a syncline. Correlation with the same horizons elsewhere, however, shows that here younger beds actually pass beneath older beds, therefore, the structure is interpreted as an ~~inverted~~ anticline^{with oversteepened limbs} (plate II).

Northwest of these sediments, in the area mapped by Schwellnus (1956), an anticline of similar sediments occurs. The two anticlines may originally have been connected in depth, and may thus represent two pitching anticlines which once formed a saddle fold. The ~~inverted~~ anticline is, however, now shifted out of position eastwards by a tongue of ferrogabbro which cuts through the structure from the north along its western limb (plate I). According to Schwellnus (1956) the sediments mapped by him represent a portion of the floor of the Bushveld Igneous Complex, lifted up into its present position by the intrusion of the gabbro. This deduction is based on the fact that the anticline is an exact

replica of a fold in the beds at the base of the mafic rocks farther to the north.

In the southeastern corner of the area the igneous layering reflects the original structure of the enclosed metasediments, as is illustrated by the main magnetitite sheet which forms a syncline on Malekskraal 509 KS and Magnetsvlakte 541 KS, followed by an anticline, as shown by the igneous layering in the gabbro along the eastern boundary of Govt. Ground 503 KS. Although the main magnetitite sheet is eroded at this place, the anticlinal structure can be seen in the lower magnetitite bands. To the west the igneous layering corresponds to the bedding of the inverted metasediments, and the main magnetitite sheet strikes from Driekop 540 KS in a northwesterly direction to Hoeraroep 515 KS. According to Truter (1955, p. 86): "The pseudostratification of the individual sill-like intrusives is due to the combined effect of chilling concordant to a constant roof, laminar flow in the magma of individual surges under more or less constant conditions of confinement and slight intergranular movement caused in one sheet by the incoming of the succeeding one."

It thus seems likely that the igneous layering in the mafic rocks is, apart from its petrological significance, also a reflection of pre-existing structures in the country rocks. If the folded sediments had acted as a roof for the surges of gabbroic magma, its flow along these existing structures and chilling concordant with the roof would have caused the minerals to become arranged in conformity with these structural surfaces.

PETROLOGY OF THE COUNTRY ROCKS

Metasedimentary Rocks

Under this heading are treated metamorphosed sedimentary rocks from both the Magaliesberg and the Smelterskop Stages of the Pretoria Series.

Quartzite

Except for the Main Magaliesberg quartzite, all the quartzite bands attain only a few feet in thickness. Apart from the dominating folded structure, the quartzites also show strong subsidiary folding on a smaller scale so that true dips could only be measured at a few places and true thicknesses could, therefore, not be established. These quartzites are recrystallized to a fair degree, but original bedding, cross bedding and ripple marks are still preserved in many places. The texture ranges from fine to medium grained but occasionally the rocks are quite coarse grained. On fresh surfaces a whitish colour predominates but the weathered surfaces are usually brownish.

Hornfels and Gneiss

The hornfeldes of the Smelterskop and Magaliesberg Stages and the contact-metamorphic gneiss of the Magaliesberg Stage are metamorphic rocks which represent original shale alternating with the quartzite bands.

The hornfeldes are usually fine grained, bluish and slightly bedded, but in places they are coarser grained and compact. The lower bands are basic in places

and consist of about 50 per cent green pleochroic hornblende and 50 per cent plagioclase with only a few grains of biotite and magnetite.

The coarse-grained contact-metamorphic gneiss consists of fairly large cordierite crystals with numerous inclusions of small biotite flakes. The cordierite crystals are fringed with small biotite and feldspar crystals.

Hall (19⁶⁸~~66~~, pp. 386 - 407) gives an extensive description of the metamorphism of the floor of the Bushveld Igneous Complex. Schwellnus (1956, pp. 37 - 67), who made a detailed study of the metamorphosed floor rocks in the adjacent area to the northeast, classifies the cordierite hornfels under thermal metamorphism. The excellent descriptions of the various contact-metamorphic rocks by these two authors cover the types which occur subordinately in the area southwest of the Lulu Mountains.

Feldspathized Quartzite

In the Smelterskop Stage rocks occur which have generally been feldspathized to such an extent that original sedimentary structures like bedding are still visible at only a few places. These rocks represent original quartzites and are locally still recognizable as such because relics of quartzitic nature occur in them.

In table I the most important features of specimens taken from the base up to the top across the two strips of feldspathized quartzite are given in descending stratigraphic order.

Throughout the succession the amphibole crys-

T A B L E I

Occurrence	Mega- scopic	Composition, Texture and Other Features	Alter- ation
Upper strip, just below granite.	Light grey rock. Medium to coarse grained.	Equal amounts of quartz and feldspar and a small amount of amphibole. Potassic feldspar as well as plagioclase. Granoblastic. Large feldspar crystals include small quartz grains and exhibit no definite crystal faces. Poikiloblastic green and strongly pleochroic amphibole crystals.	Metasomatic replacement of quartz by feldspar.
Middle of upper strip.	Light grey rock; weathers yellow. Medium to coarse grained.	45% Quartz, 45% feldspar, 10% amphibole and a few small grains of magnetite. More potassic feldspar than plagioclase. Granoblastic. Large poikiloblastic, green and strongly pleochroic amphibole crystals. Quartz relics in feldspar optically continuous.	Metasomatic replacement of quartz by feldspar. Feldspar slightly kaolinised.
Base of upper strip.	Whitish rock. Medium to coarse grained.	55% Feldspar, 40% quartz, 5% amphibole and a few grains of magnetite. Mainly potassic feldspar and some plagioclase crystals. Granoblastic. A few poikiloblastic, green and strongly pleochroic amphibole crystals. Quartz in feldspar optically continuous.	Metasomatic replacement of quartz by feldspar.
Top of lower strip.	Light grey rock. Medium to coarse grained.	50% Feldspar, 45% quartz, 5% of small crystals of pyroxene and amphibole and a few magnetite grains. Granoblastic. Mainly potassic feldspar but also a few plagioclase crystals.	Metasomatic replacement of quartz by feldspar in places.
Middle of lower strip.	Light bluish-green rock. Medium to coarse grained.	60% Feldspar, 35% quartz and 5% green pleochroic amphibole crystals. Mainly potassic feldspar. Granoblastic. Poikiloblastic amphibole crystals. Feldspar includes small relics of optically continuous quartz.	Advanced metasomatic replacement of quartz by feldspar.
Base of lower strip.	Coarse grained light coloured rock. Mottled appearance.	75% Feldspar, 20% quartz, 5% amphibole and magnetite. Potassic feldspar with a very small amount of plagioclase. Granoblastic. Only a few optically continuous quartz grains in feldspar.	Nearly complete metasomatic replacement of quartz by feldspar.

tals, probably hornblende, exhibit a poikiloblastic texture whereas the quartz is granoblastic. The feldspar is represented mainly by xenoblastic perthite. Apparently the ratio of K-feldspar to plagioclase decreases from base to top of the two strips of feldspathized quartzite and the ratio of quartz to feldspar increases from base to top.

Schwellnus (1956, p. 69) used the term "leptite" for rocks similar to the feldspathized rocks described here. The rocks described by Schwellnus, however, contain no amphibole and become fine grained with advanced feldspathization, whereas the rocks in the area investigated are fairly coarse grained. The term "leptite" as used by Swiss and Finnish geologists, applies to fine-grained, granular, metamorphic rocks composed mainly of quartz and feldspar with subordinate mafic minerals. According to Turner and Verhoogen (1960, p. 454) granulites (= leptites, leptynites of some European petrologists) are even-grained metamorphic rocks, poor in micas and rich in minerals which lack a tabular or prismatic habit, such as quartz, feldspars, pyroxene, and garnet. As none of these definitions fit the rock types investigated adequately, the term "leptite" is not used but preference is given to the more descriptive term, feldspathized quartzite.

A rock resembling granite occurs as replacement "bands", "dykes", and "stringers" in the feldspathized quartzites. These structures range in thickness from a fraction of an inch up to a foot and more and apparently occupy cracks and fissures in these meta-

sediments. The granitic rock is granoblastic, coarse grained and ranges in colour from grey to pink. It consists of quartz, K-feldspar and plagioclase with some green pleochroic amphibole and clinopyroxene. As in the feldspathized quartzite, the feldspar replaces the quartz metasomatically. This "granite" becomes more abundant near the top of the upper strip of feldspathized quartzite. In a stream bed on Haakdoorndraai 536 KS, the contact between the upper strip of feldspathized quartzite and the Bushveld granite seems to be gradational and poikilitic crystals of the same amphibole, probably hornblende, occur in the granite.

In the upper part of the ferrogabbro, near its contact with the feldspathized quartzite, the ferrogabbro contains "clusters" of quartz which indicate that the gabbro incorporated some of the sediments. Also in this ferrogabbro there are large hornblende crystals and some of the pyroxene crystals are partly altered to hornblende.

Metasomatism

The process of feldspathization of the quartzite starts with the formation of irregular patches of feldspar along the margins of, or along cracks in, the quartz grains (plate III A). With progressive feldspathization the small remnants of quartz can still be recognized as originally belonging to one large individual by the fact that they are optically continuous (plate III B).

The feldspathized quartzites occur as xenoliths

in the mafic rocks and were probably lifted upwards into their present positions by the intrusive ferrogabbro. The lower strip of feldspathized quartzite is included in the ferrogabbro and the upper strip occurs on top of the ferrogabbro at its contact with the granite of the Bushveld Complex. As the potassic feldspar as well as the plagioclase decrease from base to top, it seems likely that new material was added to the quartzite from below and that the gabbro was actually responsible for the metasomatism.

It is known that the Smelterskop quartzite contains feldspar in places. This feldspar is mainly plagioclase, but as the bulk of the newly formed feldspar is K-feldspar, it is clear that potassium must have been introduced metasomatically.

The plagioclase was, apparently, just recrystallized. It is also known that dolomitic limestones occur in the Smelterskop Stage (Coertze, 1961, p. 60). Although there is no evidence for the assimilation of limestone by the ferrogabbro in the area investigated, it was found that the ferrogabbro has incorporated some of the quartzites and it is, therefore, considered possible that limestone could also have been incorporated. Such limestones could then have been the source of the magnesium and calcium responsible for the formation of the amphibole and pyroxene in the feldspathized quartzite.

The fluids which caused the feldspathization of the quartzite were probably introduced along cracks in the sediment. These cracks are now filled by the granitic replacement "bands", "dykes", and "stringers" which

thus represent a more advanced stage of metasomatism.

According to Read (1951, p. 3) granitization is the process by which solid rocks are converted to rocks of granitic character without passing through a magmatic or liquid stage. He also states (p. 8) that feldspathization of sediments may produce granitic rocks. The feldspathized sediments described here, may, therefore, also be regarded as examples of granitization. Unfortunately there is only one place where outcrops can be followed from the top of the ferrogabbro across the quartzite onto the granite.

Both the contacts between ferrogabbro and the feldspathized quartzite, and between feldspathized quartzite and granite, seem to be gradational. It thus seems probable that some of the Bushveld granite may have originated by a process of granitization. The gradational contact between the ferrogabbro and the feldspathized quartzite may, partly, be due to the incorporation of quartzite in the ferrogabbro. The amphibole which subsequently formed in the upper part of the ferrogabbro, already containing quartz due to the incorporation of the quartzite, as well as in the feldspathized quartzite, homogenized both rock types further.

Igneous Rocks

Older Gabbroic Intrusive Rocks

The following are descriptions of the older intrusive rocks in which the Bushveld magnetitite and associated younger igneous rocks have been emplaced.

Diabase - A few thin diabase sheets occur in the

hornfels on Driekop 540 KS but these could not be shown on the map (plate I). The diabase is a fine-grained rock consisting of kaolinized and sericitized feldspar and amphibole needles which are apparently the alteration products of pyroxene. Megascopically the amphibole can easily be recognized on the weathered surfaces.

The diabase corresponds in place and composition to that which occurs as sheets in the Pretoria Series below the main mass of mafic rocks of the Bushveld Complex and which are generally believed to have been emplaced before the latter.

Harzburgite - Only one thin sheet of harzburgite occurs in the hornfels on Driekop 540 KS. The rock is dark coloured and the weathered surfaces are rough. It consists mainly of olivine crystals, showing characteristic cracks, and some orthorombic pyroxene. Along the cracks the olivine is altered to serpentine and magnetite. The harzburgite corresponds to that at the base of the mafic rocks of the Bushveld Complex and must be one of the first members of the main intrusive mass.

Gabbro - The whole of the highland in the eastern part of the area, known as the Lulu Mountains, consists of gabbro. The average dip of the igneous layering in the northeastern part is 10° SW. Near the southern boundary the igneous layering has a synclinal structure.

The gabbro is a grey, medium-grained rock consisting of plagioclase and pyroxene in the ratio of 3 to 1. It can be classified as a gabbro because clinopyroxene exceeds orthopyroxene. Small crystals of pleochroic biotite were observed in places.

The plagioclase crystals form polysynthetic twins and are fresh. The anorthite content ranges between An 60 and An 70 which corresponds to labradorite (plate IV).

The clinopyroxene and orthopyroxene are interstitial to the plagioclase and enclose small plagioclase crystals. The clinopyroxene is augite (approximately $Wo_{42} En_{34} Fs_{24}$) and the orthopyroxene ranges from bronzite (Of 27) to hypersthene (Of 39).

Ferrogabbro - The ferrogabbro occurs on top of the gabbro on the flats to the west of the Lulu Mountains. The following megascopic and surface features served to distinguish between the ferrogabbro and the gabbro in the field:

- (1) The gabbro builds the Lulu Mountains, whereas the ferrogabbro is almost completely weathered and eroded to a lowland so that outcrops are only found in or near stream beds.
- (2) The weathered surfaces of the gabbro are usually brown but those of the ferrogabbro are generally whitish, probably due to the more advanced decomposition of the plagioclase.
- (3) The gabbro contains no visible magnetite, whereas this mineral can always be recognized in the ferrogabbro.
- (4) Magnetite pipes are more abundant in the ferrogabbro and all magnetite sheets found in the area are confined to the ferrogabbro. The ferrogabbro contains inclusions of the lower mafic rocks like the gabbro and therefore represents a younger intrusion.

The ferrogabbro consists of plagioclase, pyroxene, magnetite, and in places, usually higher up, also olivine. Clinopyroxene usually exceeds orthopyroxene. The magnetite content ranges from about 5 per cent up to about 40 per cent in places. Throughout the ferrogabbro the magnetite was the last mineral to crystallize and it often shows reaction rims of biotite and amphibole. The anorthite content of the plagioclase ranges from An 60 at the base to An 30 in places at the top (plate IV). The orthopyroxene is hypersthene (Of 39 - 44) and the clinopyroxene ranges from augite (Wo42 En34 Fs24) to a composition approaching ferroaugite (Wo40 En30 Fs30). The olivine is hortonolite (Fa 50+).

The term ferrogabbro was introduced by Wager and Deer (1939, pp. 98 - 99). They investigated the Skaergaard intrusion and state that ferrogabbro is a group of rocks rich in iron which is largely present as ferrous iron in the olivine and pyroxene. The olivine ranges from Fa 56 to almost pure fayalite and the clinopyroxene ranges from Fs 45 to Fs 70. The plagioclase ranges from An 40 to An 30 and the rock contains up to about 5 per cent magnetite. They also state that the olivine should have more than 50 per cent Fa and, if rocks containing iron-rich pyroxene but no olivine are some day found, it would probably be desirable to extend the definition to include them.

According to the percentages given, the following differences exist between the ferrogabbro of the Skaergaard intrusion and the ferrogabbro of the Bushveld Igneous Complex:

- (1) The iron content of the clinopyroxene of the Bushveld rocks is lower than that of the Skaergaard rocks.
- (2) The magnetite content of the Bushveld rocks is higher.
- (3) The Bushveld rocks contain iron-rich orthopyroxene, whereas the Skaergaard rocks have no orthopyroxene.
- (4) The olivine of the Bushveld rocks is not so rich in iron as that of the Skaergaard rocks, but it is still high (Fa 50+).

The following similarities are obvious:

- (1) The anorthite percentages in both cases are low.
- (2) In both cases the rocks contain plagioclase, clinopyroxene, magnetite and olivine.
- (3) Although the olivine and pyroxene in the Skaergaard ferrogabbro is richer in iron than the olivine and pyroxene in the Bushveld ferrogabbro, the iron content of the pyroxene and olivine is in both cases higher than that of the other basic rocks of these intrusions.

It, therefore, seems justified to call the rocks investigated ferrogabbro. It may, however, be suggested that those which contain iron-rich pyroxene only should be called ferrogabbro and that those which contain both iron-rich pyroxene and iron-rich olivine, should be called olivine ferrogabbro.

As iron-rich olivine was found in some places high up in the main body, it may also be suggested to refer to these occurrences as the main olivine ferrogabbro.

On Middelin 538 KS pegmatite veins occur in the

ferrogabbro below as well as above a magnetitite band but not one of these pegmatites cuts the magnetitite (plate V). Inclusions of norite occur in the ferrogabbro above the magnetitite. The ferrogabbro above the magnetitite contains about 30 per cent of magnetite crystals and that below the magnetitite about 20 per cent magnetite crystals. The pegmatite veins are coarse-grained and consist of perthite and quartz. The perthite is altered to sericite and kaolin. In places the quartz is intergrown irregularly with the perthite. The sequence of events was probably as follows. When the lower ferrogabbro was emplaced, the norite inclusions were lifted upwards. After the intrusion, pegmatites were formed. Another heave of ferrogabbroic magma followed, the inclusions were lifted still higher up, and the formation of a second generation of pegmatite took place. The magnetitite was then later emplaced on the contact between the two intrusions of ferrogabbro.

Granite

As this study is mainly concerned with the mafic rocks, and especially with the magnetitite intrusive into them, the acid rocks are only briefly mentioned.

They are represented by two types of granite and only a small part of the area, the western part, is occupied by them.

The dominant type is the typical coarse-grained Bushveld granite, probably the equivalent of the "main granite" described by Truter and Strauss (1944, p. 48). On Wonderboom 532 KS some small sheet-like occurrences of a fine-grained variety, apparently intrusive into the

coarse-grained type, occurs. These occurrences are so small that they could not be mapped separately.

Both types of granite range in colour from light pink to red and consist of orthoclase, biotite, and hornblende. These minerals can usually be recognized megascopically.

THE MAGNETITITE AND ASSOCIATED
YOUNGER INTRUSIVE ROCKS

According to definition, the term "magnetite" refers to the mineral and the rock name is "magnetitite" (Johannsen, 1939, p. 265). In literature dealing with the Bushveld Complex it has, however, become general practice to refer to the rock as "magnetite". In order to avoid confusion the present author uses the defined terms in this text.

The younger intrusive rocks are represented by sheets of magnetite anorthosite, sheets of magnetitite, and pipes of magnetitite and associated dunite, pyroxenite, and olivine ferrogabbro. The distribution of the magnetitite intrusions is shown on the map (plate I).

Compared with the other mafic rocks the magnetitite is more resistant to weathering and outcrops are fairly prominent. The pipe-like bodies usually form small conical hills on the flats and the thicker sheets actually form the slopes of ridges. Outliers of magnetitite also form the cappings of hills in places. Enormous quantities of magnetitite rubble usually occupy the immediate vicinities of the outcrops. Owing to their black colour the magnetitite outcrops can always be recognized at a distance in the field and on air photographs.

Pipes of Magnetitite

Elliptical magnetitite pipes are quite abundant in the ferrogabbro. Some of these are composite, consisting of cores of magnetitite surrounded by rings of

hortonolite dunite (Fa 50-Fa 54) and pyroxenite or olivine ferrogabbro.

The olivine ferrogabbro which forms part of the pipes differs from the main olivine ferrogabbro country rock only in the amount of olivine it contains. About 30 per cent of this mineral is present in the olivine ferrogabbro of the pipes, whereas only a few crystals were observed in the main olivine ferrogabbro. The pyroxene in the olivine ferrogabbro of the pipes is monoclinic (approximately Wo₄₀ En₃₀ Fs₃₀) and practically the same as that of the ferrogabbro.

Although the distribution of the pipes is on the whole irregular, a few zones of concentration can nevertheless be recognized. A lower zone stretches from Driekop 540 KS in a northwesterly direction across Goedverwacht 511 KS and Hoeraroep 515 KS, an upper zone trends in the same direction from Moskow 772 KS across Vlakplaats 770 KS, and a transverse zone runs west from Zwitserland 473 KS to Eersteregt 502 KS.

Pipes of the Lower Zone

The pipes of the lower zone generally consist of one or more magnetitite cores, each surrounded by an older ring of dunite, which in turn is sometimes followed by pyroxenite or olivine ferrogabbro. In many of them the dunite is represented by only a few inclusions in the magnetitite, and the olivine ferrogabbro may also be absent. The pyroxenite occurs less frequently at a few places.

The most complete composite pipe (plate VI A)

occurs on Goedverwacht 511 KS. It consists of an elliptical magnetitite core surrounded by a ring of hortonolite dunite, a few yards wide, with an outer ring of pyroxenite. Veins of magnetitite cut irregularly through the dunite and the pyroxenite. The dunite is a heavy coarse-grained rock, the colour of which ranges from yellowish to black. It consists of about 80 per cent hortonolite (Fa 52) and 20 per cent magnetite which is interstitial to the hortonolite. The outer ring consists of a medium-grained, yellowish pyroxenitic rock, containing about 70 per cent bronzite (Of 24), a small amount of augite (Fs $\pm$ 30) and 30 per cent plagioclase (An 75 - 80). Some small grains of magnetite are present.

There is an interesting occurrence on Driekop 540 KS where a few composite elliptical magnetitite bodies occur in magnetite-bearing anorthosite (plate VI B). They are connected to one another by magnetitite veins cutting through the anorthosite. In places these magnetitite veins resemble the well-known regular magnetitite bands with the exception that they are smaller and are emplaced vertically. In other places these veins cut through the anorthosite in a lit-par-lit fashion.

The magnetite-bearing anorthosite differs from the magnetite anorthosite as follows:

- (1) It contains only up to 10 per cent interstitial magnetite grains, whereas the magnetite anorthosite contains up to 50 per cent magnetite grains.
- (2) The anorthite content of the plagioclase (An 80) is much higher than that of the plagioclase of the magnetite anorthosite (An45-55).

The magnetite-bearing anorthosite must, therefore, be genetically related to the pipe.

Along its northern side the most northerly magnetitite body of this composite pipe is in contact with olivine ferrogabbro. Locally the olivine ferrogabbro becomes a troctolite by decrease in the pyroxene content to a very low value.

Small tongues of magnetite extend into the olivine ferrogabbro which generally consists of about 40 per cent plagioclase (An 75-80), 30 per cent big poikilitic crystals of hortonolitic olivine (Fa 50-52), and 25 per cent clinopyroxene (Fs 30). The olivine encloses plagioclase crystals and the pyroxene is altered to brown pleochroic amphibole and, in places, to biotite.

A dunite inclusion in the magnetitite is a coarse-grained, dark-coloured rock, consisting of about 75 per cent hortonolitic olivine (Fa 50), 20 per cent magnetite, and some alteration products. A few small crystals of a green isotropic mineral, probably hercynite, are also present.

Two pegmatite veins, consisting mainly of large crystals of feldspar, quartz, and amphibole, occur in the rubble which probably covers ferrogabbro. The composition of the feldspar which is almost completely altered to sericite and kaolin could not be determined. One of these veins is apparently cut off by the magnetitite. To the east of the magnetitite there is an outcrop of hornfels, separated from the pipe by a strip of coarse-grained ferrogabbro. This hornfels dips to the southwest.

Pipes of the Upper Zone

The pipes of the upper zone are usually covered with rubble. Large magnetitite bodies occur along this zone and some of these are composed of swarms of magnetitite cores in dunite and olivine ferrogabbro. One of these composite pipes on Vlakplaats 535 KS (plate VI C) is composed of at least eight such magnetitite cores, all apparently interconnected by magnetitite stringers and veins.

The olivine ferrogabbro is a heavy, dark, medium- to coarse-grained rock. In places white plagioclase crystals can be observed on the fresh surface and veins of magnetitite cut through the rock. It consists of 45 to 60 per cent pyroxene, more or less completely altered to a brown pleochroic amphibole, 10 to 20 per cent plagioclase (An 80), 20 per cent olivine (Fa 50) and 10 to 15 per cent magnetite. The plagioclase is slightly kaolinized and chloritized.

The dunite resembles the dunite already described but in this case it consists of about 45 per cent hortonolitic olivine (Fa 50), 45 per cent magnetite and 10 per cent plagioclase (An $\pm$ 80). Amphibole reaction rims were observed in places along the margins of the magnetite, especially where it adjoins the feldspar.

Pipes of the Transverse Zone

About five magnetitite pipes are situated in gabbro along the transverse zone. Apparently there is no dunite, olivine ferrogabbro, or pyroxenite associated with this magnetitite. However, the immediate vicinities

of the pipes are covered by rubble so that no exact relationships could be determined.

Other Pipes

A few pipes do not occur along any of the zones mentioned above. There is, for instance, one near the southern boundary of Govt. Ground 503 KS. Another occurs on Driekop 540 KS at the southern end of the main magnetitite band. In the last-mentioned occurrence there is actually a swarm of closely spaced elliptical magnetitite bodies (plate VII). They are separated by ferrogabbro and magnetite-bearing anorthosite through which magnetitite veins, connecting them, cut irregularly. The magnetitite also includes fragments of anorthosite and thin reaction rims of amphibole occur between the magnetite and plagioclase. This composite pipe-like body is connected with the main magnetitite sheet (plate VII).

Sheets of Magnetitite and

Magnetite Anorthosite

Both magnetitite sheets and sheets of magnetite anorthosite are found in the area. As both types occur in association with one another, they will be treated under one heading.

A thick sheet of magnetitite forms a syncline, about 5500 yards long and 1500 yards wide, on Malekskraal 509 KS and Magnets Vlakte 541 KS. At the foot of the Lulu Mountains, on the flats, a prominent magnetitite sheet trends from Driekop 540 KS in the south, across Goedverwacht 511 KS to Hoeraroep 515 KS. This sheet dips to the southwest and seems to be part of the one forming

the syncline. The crest of the succeeding anticline is ~~weathered away~~^{eroded}. [Below this main magnetitite band in the ferrogabbro, a thick sheet of magnetite anorthosite occurs concordant with the magnetitite band (plate I). Both the upper and lower contacts with the ferrogabbro are sharp. In the magnetite anorthosite the magnetite crystals show a tendency for fine-scale rhythmic layering.

Thinner magnetitite bands occur both below and on top of the main magnetitite sheet and may be called the lower and higher bands respectively. In a stream bed near the southern boundary of Govt. Ground 503 KS, the lower bands occur in magnetite anorthosite but transgress the igneous layering in places. The contacts between the magnetitite bands and the magnetite anorthosite are sharp.

Near the top of the ferrogabbro a suite of at least six thin bands of magnetitite^{which may be called the upper magnetite bands} (shown as one on the map) strikes parallel to the main sheet from Vlakplaats 770 KS in the south to Haakdoorndraai 536 KS.

In contrast with the main sheet which outcrops very prominently, the lower and upper bands can, apart from rubble, only be seen in the stream beds. These sheet-like bodies will be dealt with in ascending order.

The Lower Magnetitite Bands

The lower magnetitite bands are exposed in the stream bed below the main band as well as in the stream beds on Paradys 773 KS where there are two parallel magnetitite bands close to each other (plate I). The lowermost band is about 5 feet thick and the uppermost one about 1 foot. To the east, near the syncline on Govt.

Ground 503 KS, one of the lower bands, apparently the uppermost, is exposed in the stream bed.

The last-mentioned occurrence is in the magnetite anorthosite and contains inclusions of magnetite anorthosite, norite, and anorthosite. The magnetite anorthosite which is transgressed by the magnetitite, contains inclusions of norite and anorthosite. In one place the magnetitite band partly swings around a large inclusion of norite, similar to the norite below the gabbro, and there are apophyses of the magnetitite into the inclusion.

The Main Magnetitite Band

The main magnetitite band trends from Driekop 540 KS in a northwesterly direction for about 7000 yards on to Hoeraroep 515 KS where it ends. The thickness ranges from a few feet up to 10 feet and more. It is connected with the pipe-like bodies on Driekop 540 KS (plate VII) but does not extend southwards. The same band also caps koppies on Goedverwacht 511 KS and Driekop 540 KS. The syncline of magnetitite on Malekskraal 509 KS is also part of this main magnetitite sheet. Below the main magnetitite there is a thin band, about 4 feet thick, of coarse-grained anorthosite.

The Higher Magnetitite Band

The higher magnetitite band, about one foot thick, occurs on Middelin 538 KS on the contact of the two intrusions of ferrogabbro (plate V). The general dip is to the southwest and to the north this band pinches out but continues a few feet farther on. Near its south-

ern end it engulfs a large noritic inclusion so that the dip is no more constant. An apophysis of magnetitite occurs in the inclusion. There are also numerous smaller norite inclusions in the magnetitite. Further south the band thins suddenly to a few inches but almost immediately becomes thicker again and from there a tongue, a few feet long, cuts into the lower ferrogabbro (plate VIII).

The Upper Magnetitite Bands

There are at least six closely spaced bands in the upper part of the ferrogabbro. They dip about 15° SW. Although actual outcrops of these seams occur at only one or two places, the distribution of the magnetitite rubble made it possible to map this zone. The few outcrops are very much weathered. Inclusions of weathered gabbroic rock occur in the magnetitite.

Irregular Magnetitite Bodies

Two elongated irregular magnetitite bodies, which could neither be classified with the pipes nor with the sheets, occur in the lower zone of magnetitite pipes, just above the main magnetitite sheet. The one on Driekop 540 KS strikes more or less parallel to the main magnetitite sheet but transgresses the ferrogabbro in the south. In places dips could be measured but in other places this body creates the impression of consisting of composite connected pipes. It is probably connected with the main sheet in depth and thus probably represents an apophysis from this sheet. Tongues of magnetitite from this body also cut through the ferrogabbro and the magnetitite also contains inclusions of the country rock.

The other irregular body occurs to the north on Goedverwacht 511 KS. It is also elongated and seems to be a sheet-like body, cutting at right angles across the igneous layering of the ferrogabbro with an apparent dip to the south. The probable reason for this transverse emplacement may be an inclusion of older gabbroic rock in the ferrogabbro. The magnetitite apparently follows the contact between this inclusion and the ferrogabbro.

In the stream bed on Govt. Ground 503 KS, near its southern boundary, another magnetitite body is also emplaced quite irregularly in anorthosite (plate IX).

MINERALOGY OF THE MAGNETITITE

The magnetitite is a heavy, lustrous and coarsely crystalline rock. The colour on weathered surfaces is usually black and on fresh surfaces it ranges from blackish to brownish red.

In places the magnetitite is extremely magnetic but the magnetism varies considerably over short distances. As shown by the magnetometer, the magnetism changes from positive to negative over short distances both across and along strike.

In fresh samples ilmenite can usually be recognized megascopically. It figures as irregular patches in the rock, showing a metallic lustre.

Representative Samples

Ten samples were chosen for microscopic investigation and chemical analysis (sampling points are shown on the map, plate I). In addition one sample of magnetitite from the old Mooihoek Platinum Mine was also studied and compared with the other samples. The following is a short description of the various minerals observed in each sample, the samples are treated in ascending order:

- (1) Sample 1 was taken from a pipe-like body below the main magnetitite band on Goedverwacht 511 KS. The section contains coarse, granular ilmenite which is interstitial to magnetite. There are no exsolution lamellae of ilmenite in the magnetite. No alteration products of the magnetite or the ilmenite such as maghemite or goethite were observed. The ore minerals are intersti-

tial to plagioclase and olivine crystals. The magnetite is grey pink with a slight brownish tint and it is isotropic. The ilmenite, which shows a light-brown colour with a pink tint, is strongly pleochroic and anisotropic.

(2) This sample was taken from one of the lower bands on Govt. Ground 503 KS. The rock consists of magnetite and a small amount of grey-white maghemite and ilmenite. A few plagioclase crystals are interstitial to the ore minerals.

(3) Sample 3 represents the magnetitite of one of the pipes connected with the main magnetitite band on Driekop 540 KS. It is a coarse-grained rock containing a few plagioclase crystals. Apart from magnetite and granular ilmenite it also contains maghemite, one grain of pyrite which exhibits high reflectivity, and a thin vein of limonite which cuts the magnetite and maghemite (plate X A). The maghemite occurs along a few cracks in the magnetite and is clearly an alteration product thereof.

(4) Sample 4 comes from the main magnetitite band on Driekop 540 KS. Many cracks predominate in this granular rock which consists mainly of maghemite and ilmenite. In or near some of the cracks an unidentified alteration product, which may be leucoxene, was seen. Thin veins of goethite cut the maghemite. A few exsolution lamellae of spinel of microscopic dimensions occur in the maghemite and are arranged according to the crystallographic directions. No magnetite was observed.

(5) Taken from the same band as sample 4, but higher up and farther northwards on Goedverwacht 511 KS, this sample contains a fair amount of magnetite together with

maghemite and ilmenite. Spinel lamellae occur in both the magnetite and the maghemite. The ilmenite is interstitial to the magnetite which is partly altered to maghemite. The grey-white maghemite begins to form all along the contacts between the magnetite grains, along cracks, and around spinel lamellae in the grains, and from there it spreads into the crystals so that the magnetite, grey pink with a brownish tint, figures as irregular patterns within the grains of the rock. This is an example of the so-called "moth-eaten structure" to which Schwellnus and Willemse (1943, p. 29) refer. The alteration proceeds from the magnetite through a ring of a less brownish mineral to maghemite. Actually more stages exist between magnetite and maghemite, but as identification is based on colour intensity, which seems to change gradually in places, whereas in other places there seems to be more than one shade, it seems best to describe this alteration product as "a ring of less brownish mineral". The "moth-eaten structure" is clearly illustrated in plate XI A, and the alteration in the enlargement, plate XI B.

(6) This sample is from a pipe in the upper zone on

Middelîn 538 KS. The rock consists mainly of maghemite, limonite and ilmenite. The limonite, actually a mixture of goethite and hematite, is dull grey with a bluish tint. Alteration of maghemite to limonite takes place along zones which are composed of alternating bands of grey-white maghemite and bluish limonite. The alteration probably also takes place in stages, because with the highest magnification in oil at least two ^{shades} ~~grades~~ of blue were recognized. Microscopic inclusions and cracks

probably determine the direction of this alteration.

(7) This sample was taken from a magnetitite band, near sample 6 on Middelin 538 KS. It is a granular rock showing some large cracks and consisting of magnetite, maghemite, ilmenite, spinel lamellae, and some plagioclase. Magnetite is the main constituent. Its alteration to maghemite begins along the contacts between grains and also along cracks and around small inclusions, or even around spinel lamellae, and thus represents the beginning of the formation of the "moth-eaten structure". The spinel lamellae occurring in the magnetite and maghemite are crystallographically oriented, apparently parallel to ^{///}(~~HH~~).

(8) This sample is from a pipe higher up in the upper zone on Vlakplaats 770 KS but is, unfortunately, not as fresh as the others. The rock is granular and contains a fair amount of weathered crystals, probably olivine and plagioclase, which are corroded by the ore minerals. The ore minerals also cut irregularly along cracks into these crystals. Only maghemite and ilmenite could be identified.

(9) This sample represents a pipe still higher up on Vlakplaats 770 KS. Maghemite and ilmenite were identified. The ilmenite occurs as large crystals but also as exsolution lamellae, crystallographically oriented.

(10) This sample is from the upper magnetitite bands on Strydkraal 537 KS. The rock consists of maghemite, ilmenite, and a few pyrite grains. The maghemite is full of cracks, especially parallel to the contacts between

grains. Numerous small inclusions of microscopic dimensions are present and they are also concentrated in zones parallel to the contacts of the grains. No exsolution lamellae were observed.

(11) This sample is a loose piece from ^{the old} Mocihoek Platinum Mine, probably from a considerable depth in the pipe ^{and} consists of magnetite with exsolution lamellae of ilmenite (plate X B) and a few crystals of ilmenite.

Discussion

Schwellnus and Willemse (1943, pp. 29 - 31) describe the mineragraphy of some magnetite samples from the western Bushveld. They identified the following minerals: magnetite, ilmenite, spinel, sulphide, maghemite, hematite (martite), and occasional silicates and secondary minerals like goethite. All these minerals were also identified in the samples investigated by the present author. Schwellnus and Willemse state that the unreplaced parts of the rock consist of what is presumably the magnetite, conspicuously brown in colour. This brown magnetite is surrounded by altogether isotropic magnetite, less brown in colour, and this in turn by maghemite. These findings are in accordance with observations made on sample 5, where the alteration from the magnetite through a zone of a less brownish mineral to maghemite was recognized.

Strauss (1946, pp. 35 - 47) investigated samples from Magnet Heights in the Eastern Transvaal. He also identified these three minerals and states as follows: "In the Magnet Heights material an isotropic,

pale pinkish-brown mineral is the most abundant constituent. In it lie rugged areas, up to 2 mm. in diameter, of an isotropic, grayish-white mineral, while between these two types of material there is a narrow border of a pale grayish-pink, feebly anisotropic mineral."

Schwellnus and Willemse (1943, p. 29) state the opposite, in that they consider the greyish-pink mineral to be isotropic and the other two anisotropic.

In all the sections examined during the present investigation it was found that both the magnetite and the maghemite are isotropic minerals. On the other hand, Strauss (1946, p. 37) made some illustrations to show that the sequence of the minerals is as follows: "first the gray-white mineral, then the pinkish-brown mineral, and lastly the grayish-pink mineral". He also states that where the process of alteration was carried to extremes the relationships may appear uncertain if observation is confined to too small an area.

In all specimens examined during the present investigation, the exact opposite was found. The sequence is: a grey-pink mineral with a brown tint (magnetite); a less brown mineral, and a grey-white mineral (maghemite). This sequence is in accordance with that found by Schwellnus and Willemse (1943, pp. 29 - 31). It seems as if Strauss confined his observation to too small an area. In plate XI A the field of observation is so large that the crystal outlines can be seen, and it leaves no doubt about the true sequence of formation. It will later be shown that this sequence is also supported by the chemistry of the magnetitite.

Strauss (1946, p. 46) concludes as follows:

"The minerals differed sufficiently to justify new varietal names for them, but their properties are at present too imperfectly known for the coining of such names. The terms 'light grayish-pink mineral', 'grayish-white mineral' and so forth, are very tiresome to the reader, but they are at present perhaps preferable to an indiscriminate use of mineral names." He also states that it is possible that the Bushveld magnetite was originally a complex, variable, and unstable compound which under certain conditions broke down to the inhomogeneous material now known, and he suggests that the first stage of this disintegration may be the exsolution of ilmenite and spinel, and further stages may be the formation of a fine network and the progressive development of the "moth-eaten" pattern.

It should be noted that in sample 1 no maghemite has been observed; in samples 4, 6, 8, 9 and 10 no magnetite has been recognized, and in the other samples both these minerals occur in varying amounts. In the only subsurface sample (probably from considerable depth), from the old Mooihoek Mine, no maghemite but only magnetite and ilmenite were identified. Samples 1 - 10 were all collected at or near the surface. With this in mind, it is suggested that just after crystallization the original rock was composed of magnetite and ilmenite. Alteration took place, at or near the surface, and the magnetite was altered to maghemite, goethite, and hematite. The alteration, which is probably still proceeding, takes place through a series of intermittent stages, and the

rock at the surface may exist in any one of these stages. It will later be shown that both microscopical observation and chemical analysis support these views.

CHEMISTRY OF THE MAGNETITITE

In table 2 are given the chemical analyses of the 10 samples of magnetitite described above.

TABLE 2Chemical Analyses of Magnetitite

No.	1	2	3	4	5	6	7	8	9	10
SiO ₂	3.71	2.91	0.70	0.09	0.80	1.73	0.50	7.08	10.72	9.94
TiO ₂	13.20	13.60	15.80	13.00	14.30	13.80	14.60	14.50	12.92	12.06
Al ₂ O ₃	8.14	6.34	5.31	5.39	4.03	2.97	5.01	3.27	2.66	4.72
Cr ₂ O ₃	0.36	0.12	0.35	0.01	0.06	0.15	0.03	0.01	0.03	0.07
Fe ₂ O ₃	38.64	46.20	42.99	74.89	60.84	75.89	53.55	64.36	63.55	64.35
FeO	33.19	25.57	29.38	1.72	15.45	1.72	22.63	7.76	7.04	5.60
MnO	0.17	0.30	0.15	0.08	0.27	0.15	0.29	0.26	0.32	0.27
NiO	---	---	---	---	traces	---	---	---	---	---
MgO	1.26	0.74	1.05	0.13	0.69	0.12	0.12	0.87	1.34	0.80
CaO	0.60	2.23	1.74	0.50	1.37	0.37	1.12	0.30	0.30	0.30
K ₂ O	0.20	0.20	0.20	0.30	0.15	0.20	0.20	0.40	0.20	0.15
Na ₂ O	0.40	0.35	0.18	0.18	0.24	0.24	0.18	0.22	0.24	0.35
P ₂ O ₅	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
V ₂ O ₅	0.36	1.56	1.74	1.74	1.75	0.62	0.76	0.43	0.48	0.56
S	0.10	0.41	0.16	0.22	0.22	0.22	0.22	0.05	0.05	0.05
H ₂ O ⁺	0.14	0.03	0.41	1.58	0.17	2.09	1.26	1.17	0.68	0.22
H ₂ O ⁻	0.10	0.09	0.11	0.26	0.05	0.23	0.14	0.15	0.20	0.38
Total	100.62	100.70	100.32	100.14	100.44	100.55	100.66	100.88	100.78	99.87

Analyst: C. Lessing.

Modified Partial C.I.P.W. Norms

From the chemical analyses (table 2) modified partial C.I.P.W. norms were calculated by allotting molecular amounts in the order and ratios stated below:

1. S: FeO = 2:1 for pyrite
2. MgO: FeO = 1:1 for hypersthene and
olivine
3. TiO_2 : FeO = 1:1 for ilmenite
4. Residual TiO_2 for rutile
5. FeO: Fe_2O_3 = 1:1 for magnetite
6. Residual Fe_2O_3 for hematite.

Thus, first some iron is used to form pyrite. According to the optical properties of the pyroxene and the olivine, more or less equal amounts of FeO and MgO must be used to form them. Next some iron is used to form ~~some~~ ilmenite and the rest is used for magnetite, hematite, and related minerals. It is obvious that some of the MgO, used to form pyroxene and olivine, form together with Al_2O_3 the spinel $\text{MgO}.\text{Al}_2\text{O}_3$. This was not included in the partial norm as the exact relative amounts of pyroxene and olivine, on the one hand, and spinel on the other, are unknown. This, however, does not affect the composition of that part of the rock which consists of ore minerals.

The V_2O_5 and Cr_2O_3 are added to Fe_2O_3 for these calculations. The form in which the V_2O_5 is present and its possible mineral forms, as well as the state of the "residual" TiO_2 , will be discussed later on. No chromite was observed in the polished sections, and the mineral

chromite $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ was therefore, not calculated separately.

As the silicate content may vary considerably from place to place in the same band or pipe of magnetitite, and actually may represent older crystals and inclusions, it is not regarded as an inherent part of the rock and was, therefore, not calculated in the modified partial norm, except for the allowance of FeO for the pyroxene and olivine.

The modified partial C.I.P.W. norms of the ore minerals are tabulated in table 3.

T A B L E 3

Modified Partial Norms of Magnetitite

Calculated with Respect to Ore Minerals Only

No.	Magnetite Fe_3O_4	Magnetite, Goethite, Hematite Fe_2O_3	Ilmenite FeTiO_3	Rutile TiO_2	Pyrite FeS_2	Total
1	56.84	-	25.08	-	0.24	82.16
2	36.89	22.24	25.84	-	2.40	87.37
3	42.46	11.36	30.10	-	0.36	84.28
4	-	76.32	2.74	11.60	0.48	91.14
5	4.41	59.36	27.21	-	0.48	91.46
6	-	76.32	2.89	12.32	0.48	92.01
7	29.70	33.76	27.82	-	0.48	91.76
8	-	64.64	14.59	6.80	0.36	86.39
9	-	63.84	10.18	7.60	0.12	81.74
10	-	64.80	10.18	6.72	0.12	81.82

According to these modified partial C.I.P.W.

norms, the ore minerals constitute between 81.82 and 92.01 per cent of the analysed rocks. It is also clear that three different assemblages of ore minerals may occur in different samples of magnetitite:

1. magnetite and ilmenite;
2. magnetite, maghemite (+ goethite and hematite), and ilmenite;
3. maghemite (+ goethite and hematite), ilmenite, and "rutile".

Assemblage 1, (sample 1) is found in a pipe-like body which occurs near the base of the ferrogabbro on Goedverwacht 511 KS. Assemblage 2 occurs in a lower sheet very near to the base of the ferrogabbro on Govt. Ground 503 KS (sample 2); in the main sheet on Goedverwacht 511 KS (sample 5); in a pipe connected with the main sheet on Driekop 540 KS (sample 3); and in the higher band on Middelin 538 KS (sample 7). Assemblage 3 occurs in the main sheet on Driekop 540 KS (sample 4); in pipes higher up on Middelin 538 KS (sample 6), and Vlakplaats 770 KS (samples 8 and 9); and in the upper magnetitite band on Strydkraal 537 KS (sample 10).

It is quite clear that the mineral composition of the magnetitite does not depend on its relative position in the succession of the ferrogabbro. There may be more than one type in the same band, as is the case in the main magnetitite sheet. Neither does it depend on the structure of the magnetitite bodies, for assemblages 2 and 3 occur in both sheets and pipes.

Assemblage 2 consists of magnetite, maghemite, and ilmenite, but no "rutile". In assemblage 3, in which

there is no magnetite, between 6.72 and 12.32 per cent of "rutile" has been calculated.

According to the ore-microscopic observations, assemblage 1 consists only of magnetite and ilmenite. The modified partial norms confirm this observation. Also in assemblage 2 the microscopic observations are confirmed by the modified partial norms which show that the ore consists of varying amounts of magnetite, maghemite, and ilmenite.

In assemblage 3 no magnetite was observed under the microscope and no magnetite is shown by the modified partial norms, but both microscopic observation and the modified partial norms show that maghemite and ilmenite are present. The excess of TiO_2 was calculated as "rutile", but no rutile was observed under the microscope. There are, however, alteration products which may be leucoxene, an alteration product of ilmenite.

Basta (1959, p. 713) suggests that the excess TiO_2 in titanium-rich magnetite is only normative. He could not detect any rutile, anatase, brookite, or other titanium mineral. He concludes that the TiO_2 must be present in the maghemite structure, and that the homogeneous maghemite in this case should be called titanomaghemite. In this connection it may be of interest to mention that a yellowish-green encrustation found on some weathered magnetite samples near Brits, was identified as anatase in the laboratory of the Geological Survey.

It is clear from both microscopic investigations and the modified partial norms that the different

assemblages of minerals in the 10 magnetitite samples represent different stages in the alteration of magnetite to maghemite, goethite, and hematite by oxidation. The ilmenite probably alters to a certain extent to leucoxene at the same time.

It is also obvious that in depth the magnetitite consists of magnetite and ilmenite but that at the surface the magnetite may occur in any stage of alteration or oxidation.

Vanadium and Iron Content

Owing to its economic value, the vanadium in the magnetitite has become of great importance during the past few years. Today, the Bushveld magnetite can be considered one of the largest sources of vanadium in the world.

A beginning with the recovery of vanadium from Bushveld magnetite was made recently (Coertze^{and Schumann,} 1962, p. 43). The method of recovery consists of grinding the ore and roasting it with sodium chloride. By the addition of ammonium chloride to the sodium metavanadate formed by reaction with the sodium chloride, ammonium metavanadate is formed which is precipitated and then heated to drive off ammonium, and the remaining vanadium pentoxide is then recovered.

The V^{3+} , Fe^{2+} , Fe^{3+} , and total Fe in the 10 analysed samples were calculated and are given in table 4. In addition, the Fe:V ratios are also shown.

In plate XII a correlation between the percentage vanadium and the percentage iron is made. According

T A B L E 4
Vanadium and Iron Content and Fe:V Ratios
of Analysed Magnetitite

P e r c e n t a g e					
No.	V ⁺⁺⁺	Fe ⁺⁺	Fe ⁺⁺⁺	Total Fe	Fe:V ratio
1	0.20	25.80	27.02	52.82	264
2	0.87	19.87	32.29	52.16	60
3	0.97	22.84	30.05	52.89	55
4	0.97	1.34	52.35	53.69	55
5	0.98	12.00	42.53	54.53	56
6	0.35	1.34	53.06	54.40	155
7	0.43	17.59	37.44	55.03	128
8	0.24	6.03	44.99	51.02	213
9	0.27	5.47	44.42	49.89	185
10	0.31	4.35	44.98	49.33	159

to the vanadium content, the magnetite ore can be subdivided into two types. The type with the high vanadium content occurs low down in the succession of the ferro-gabbro and the type with the low vanadium content occurs in the upper part. Sample 1, from a pipe-like body near the base, is an exception. The significance of this exception will be discussed later.

Frankel and Grainger (1941, p. 105) state that vanadium-bearing titaniferous iron ores occurring in India have been the subject of a comprehensive study by Dunn and Dey. In these ores vanadium, reported as V_2O_3 , ranges from just over 0.5 per cent to as much as 7 per

cent, and Dunn and Dey found that the vanadium is present in a mineral, coulsonite, isostructural with magnetite. Frankel and Grainger suggest that the term "coulsonite" might be applied to maghemite which is rich in vanadium. They suggest that "coulsonite" may well be a vanado-maghemite instead of a vanado-magnetite; i.e. $(\text{Fe},\text{V})_2\text{O}_3$ rather than $\text{FeO} \cdot (\text{Fe},\text{V})_2\text{O}_3$.

De Wet (1956, pp. 457 - 462) determined the vanadium content of a number of representative samples of purified chromite from the eastern and western chromite belts of the Bushveld Igneous Complex which had previously been analysed for chromic, ferrous, and ferric oxides. He shows that there exists a definite correlation between vanadium on the one hand and total iron on the other. He points out the remarkably constant Fe:V ratio which only occasionally falls outside the limits of 80 and 120. De Wet (p. 462) also states that, on calculating the total Fe:V ratios for the Bushveld magnetic iron ores from existing analyses, close constancy is observed over only a limited vertical range. Nevertheless, the ratios for all but two of his samples fall within the range 50 to 200 and are thus not much different from those found by him for chromite.

The Fe:V ratios of the ten samples analysed show that, on the one hand there exists very close constancy in the range 55-60 over the magnetitite bands and pipes in the lower part of the ferrogabbro, whereas, on the other hand, a close constancy in the range 128-213 exists in the magnetitite bands and pipes in the upper part of the ferrogabbro. The only exception is sample 1 with a Fe:V ratio of 264, according to which it should

be included with the higher group, although it occurs in the lower part of the lower group.

De Wet (1956, p. 461) plots about sixty iron-vanadium ratios and from these it was possible to conclude that there exists, on the average, a sympathetic relationship between the iron and vanadium in the chromite. It seems as if a similar relationship may exist in the magnetitite group with the higher vanadium content (plate XII), but on the other hand, the group with the lower vanadium content does not show such a relationship equally well. Many more analyses will have to be made before any definite conclusions in this connection can be drawn. However, with the data available, it seems as if there are more than one type of magnetitite and that within each type there may exist a sympathetic relationship between the iron and vanadium.

Radtke (1962, pp. 1284 - 1290) states that coulsonite has been identified in polished sections of magnetite-bearing rocks from the Buena Vista Hills east of Lovelock, Nevada.

J. Kent Perry (1963, pp. 948 - 951) discusses Radtke's paper and states that Radtke failed to distinguish between hematite and coulsonite : the thin lamellae along octahedral planes in the magnetite which Radtke took to be exsolved coulsonite, are actually hematite.

No coulsonite, as $\text{FeO.V}_2\text{O}_3$, could be identified in fresh Bushveld magnetitite. Neither could it, as $(\text{Fe,V})_2\text{O}_3$ be identified in the weathered magnetitite. There is, however, not much difference between the ionic radii of V^{+++} (0.65Å) and Fe^{+++} (0.67Å). It is, there-

fore, very likely that vanadium may substitute for ferric iron in magnetite, and then it would be present as $(\text{Fe,V})_2\text{O}_3$.

As the fresh magnetite is constituted mainly of magnetite and the weathered magnetite mainly of magnetite, it can be expected that the vanadium replacing Fe^{+++} in the fresh magnetite will also be in a less oxidized state than in the weathered ore mineral.

As the plants erected for the extraction of vanadium have, up to the present, treated only the oxidized ore, it should be stressed that the fresh ore from depth should be tested to ascertain whether this type of ore is also amenable to the same treatment. The low vanadium content of the fresh ore (sample 1), which consists mainly of magnetite, may probably serve as a warning in this connection.

Ulvöspinel or Ulvite

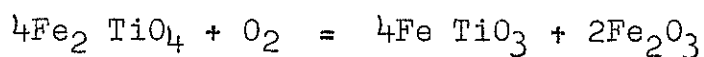
According to Ramdohr (1953, pp. 846 - 848) ulvöspinel or ulvite is an iron-titanium spinel (Fe_2TiO_4), and it forms an exsolution "cloth texture" parallel to (100) in magnetite.

Nickel (1958, pp. 191 - 199) used the electron microscope to determine the microtexture of an ulvöspinel magnetite intergrowth in titaniferous iron ore from Rouville County, Quebec. The electron micrographs show an exsolution texture of magnetite cubes in an ulvöspinel matrix.

According to heating experiments made recently by various workers, it seems as if the exsolution "cloth

texture" of ulvöspinel gradually disappears with progressive oxidation. Verhoogen (1962, p. 175) states that at all temperatures ulvöspinel is more easily oxidised than magnetite.

This means that part of the TiO_2 in the fresh magnetite must be present as ulvöspinel. On the other hand, it may be assumed that in the weathered magnetite (nine of the samples investigated) most of the ulvöspinel is probably oxidised to ilmenite according to the following reaction:



Microscopic investigation confirms these inferences. Only in the relatively "fresh" samples very faint intergrowths of probable ulvöspinel-magnetite were seen. Owing to the fact that the samples did not polish very well, this could, however, not be confirmed.

PETROGENESIS OF THE MAGNETITITE

Differentiation in the Mafic Rocks

According to the intrusive relationships observed in the field, the mafic rocks in the area investigated, can be chronologically subdivided into the following successive units: Gabbro, ferrogabbro (more than one intrusion), magnetite-anorthosite sheets, composite magnetitite pipes and magnetitite sheets.

The following points are of importance in connection with the sequence of emplacement of these successive units:

1. The ferrogabbro contains inclusions of the lower mafic rocks like gabbro and norite.
2. There is proof of at least two separate intrusions of ferrogabbro.
3. Pipe-like bodies of magnetite dunite pierce the ferrogabbro.
4. There are sheets of magnetitite and older sheets of magnetite anorthosite, cut by the magnetitite.
5. Magnetitite veins were injected from the pipes into the country rock in a lit-par-lit fashion or quite irregularly.
6. Magnetitite sheets are connected with magnetitite pipes.
7. Magnetitite sheets and pipes contain inclusions of the ferrogabbro.
8. In the pipes, veins of magnetitite cut through the

associated rings of dunite and pyroxenite.

9. In all the rocks containing magnetite crystals, these crystals were the last to crystallize.

In plate IV the anorthite values of the plagioclase at various levels in the succession of the mafic rocks are shown. The trend of differentiation is thus clearly shown graphically. One significant point brought out by this diagram is that the ferrogabbro gradually becomes more sodic from its base upwards, and also that there is a definite break in this general trend wherever the sampling route runs across sheets of magnetite anorthosite, composite magnetite bodies, or inclusions of older gabbro.

The diagram shows the compositional variation of the plagioclase in the following rocks:

1. ferrogabbro below the lower feldspathized quartzite ($An_{57} - An_{63}$);
2. ferrogabbro directly on top of lower feldspathized quartzite ($An_{50} - An_{53}$);
3. upper ferrogabbro (An_{45} , although the extremely low value of An_{30} was also encountered near the top);
4. magnetite anorthosite ($An_{45} - An_{55}$);
5. olivine ferrogabbro and pyroxenite of the magnetite-dunite pipes ($An_{75} - An_{85}$);
6. inclusions of gabbro in magnetite anorthosite and ferrogabbro ($An_{57} - An_{60}$).

In connection with the rocks lower down, Schwellnus (1956, p. 150) states that the anorthite content of the plagioclase below the Merensky Reef may be

as high as An_{80} . According to Van Zyl (1960, p. 72) the anorthite content of the plagioclase below the Merensky Reef in the Western Bushveld may be as high as An_{82} .

Comparing these data with the intrusive relationships, it is clear that it is not the ferrogabbro which gradually becomes more sodic higher up, but that in reality each successive intrusion of mafic magma, except the composite pipe-like magnetite-dunite bodies, was more sodic than the preceding one.

Apparently there were three successive intrusions of ferrogabbro. The compositions of the plagioclase of these intrusions are An_{57-63} , An_{50-53} , and An_{45} respectively. Presumably just after the emplacement of the third ferrogabbro, magnetite anorthosite (plagioclase An_{45-55}) was intruded as two sheets into the first ferrogabbro. Fragments of the lower gabbroic rock (plagioclase An_{57-60}) were included in the second ferrogabbro and in the magnetite anorthosite.

After the intrusion of the magnetite anorthosite the composite pipe-like magnetite-dunite bodies were emplaced. In contrast with the general differentiation trend of the plagioclase, the plagioclase of these bodies, that is to say mainly of the olivine ferrogabbro in the magnetite-dunite pipes, is calcic (An_{75-85}), and the jump of the plagioclase from An_{45} in one intrusion to An_{85} in the succeeding one must be explained.

Van Zyl (1960, pp. 66 - 70) describes an occurrence of wehrlite in the platinum mine on Swartklip in the western part of the Bushveld Igneous Complex. He

considers the wehrlite to be part of the ferrogabbro intrusive unit. According to Van Zyl the anorthite content of the plagioclase of the ferrogabbro ranges between An_{48} and An_{50} but that of the wehrlite is An_{75} . Some of the large crystals are rounded and many of them are bent. Van Zyl concludes that the plagioclase might have been derived from older intrusive rocks like the Merensky Reef.

Coertze (1960, pp. 75 - 85) describes intrusive magnetite-bearing mottled anorthosite in the gabbro south of Pilanesberg. The plagioclase crystals (An_{75-80}) are bent and granulated, and are included in, or surrounded by, a younger generation of plagioclase (An_{64}). He discusses the genesis and emplacement of the anorthosite, and stresses that field and microscopic data strongly suggest that the anorthosite was formed by the partial re-fusion of the lower anorthosite in place and re-injection as a crystal mush into the overlying gabbro along a shear zone. He believes that the magnetite was emplaced as a ferrous hydroxide liquid and that the rapid rise of dunite magma and the ferrous hydroxide re-heated the lower anorthosites. Coertze (1960, p. 80) describes the rest of the process as follows: "The change from compressional to tensional conditions would have been accompanied by reduction of pressure and consequently the liberation of water from the ferrous hydroxide. Under conditions of high temperature and in the presence of water the last crystallized portion of the feldspar was probably remelted and the anorthosite re-injected as a crystal mush at a higher horizon."

It is noteworthy that in both cases mentioned above, as well as in the pipes southwest of the Lulu Mountains, the rocks are intrusive, and are thus younger than the country rocks. According to the differentiation trend, the plagioclase should, therefore, be sodic in composition, but instead the anorthite content is as high as An₇₅₋₈₀. In all three cases the plagioclase is associated with olivine and magnetite. South of Pilanesberg, as well as in the area investigated, the feldspar is part of or closely associated with pipe-like bodies. The wehrlite in the mine on Swartklip occurs as a dyke, but there are magnetite-dunite bodies nearby with which it might be connected.

Southwest of the Lulu Mountains the magnetitite pipes also occur along zones which can only be explained as zones of weakness, as is the case south of Pilanesberg. In the process of intrusion of the pipes, the lower anorthosites must have been pierced by them. Truter (1955, pp. 77 - 91) maintains that after the emplacement of the lower part of the Bushveld Igneous Complex north-south tensional stresses prevailed which were superseded by compression, and that subsequently tensional conditions set in again. The effect of the change from compression-al to tensional conditions along the zones of weakness southwest of the Lulu Mountains would have been the same as that southwest of Pilanesberg. It thus seems that the most suitable explanation for the calcic plagioclase in the composite magnetitite pipes, is that the plagioclase was derived from older rocks below. Probably it was incorporated as a crystal mush in the dunite magma and ferrous hydroxide-bearing liquid by the partial re-

solution of lower-lying gabbroic rocks. The fact that the plagioclase crystals are actually rounded, supports this view.

Schwellnus (1956, pp. 146 - 153) used the orthopyroxene to show the differentiation trend in the various intrusive mafic units of the Bushveld Complex. Unfortunately, orthopyroxenes are not found in all rock types in the upper part of the mafic zone, and the only deduction that can be made from the orthopyroxene in the rocks investigated, is that it becomes richer in iron higher up, and thus also richer in iron for the successive groups of intrusions. The optic axial angle ranges between 50° and 55° . Comparing this with Schwellnus' figures, the differentiation trend is clear:

<u>Rock type</u>	<u>2Vx orthopyroxene</u>	<u>Source of information</u>
Magnetite anorthosite	$50^{\circ} - 55^{\circ}$)	determined
Ferrogabbro	$52^{\circ} - 54^{\circ}$)	
Gabbro	$54^{\circ} - 64^{\circ}$)	
Norite	$\pm 70^{\circ}$)	deduced from Schwellnus' figures
Chromiferous pyroxenite	$\pm 80^{\circ}$)	

The optic axial angles of the clinopyroxenes range between 48° and 54° , but cannot, unfortunately, be used to determine a differentiation trend. As has already been pointed out, the clinopyroxene of the ferrogabbro is, however, at least in places, more iron rich than the clinopyroxene of the gabbro.

Another mineral which also gives an indication of the trend of differentiation, is magnetite. (In the gabbro no magnetite can be recognized microscopically.

In the ferrogabbro magnetite can always be recognized megascopically, in fact, the magnetite content of the ferrogabbro ranges approximately between 5 and 40 per cent. The magnetite anorthosite contains about 50 per cent magnetite, the composite pipe-like magnetite bodies up to 70 or 80 per cent, and the sheets and pipes of magnetite nearly 100 per cent. This also points to a differentiation trend. It is clear that each successive intrusion was not only more sodic in composition but also richer in iron. The broad trend of differentiation was clearly towards enrichment in iron and sodium.

Wager and Deer (1939, pp. 262 - 289) investigated the Skaergaard intrusion and put forward the idea that significant currents existed in the Skaergaard magma. To account for the circulation they mention convection, due to increase in density of the magma on cooling. Cooling must have taken place mainly from the top and the cooled and partly crystallized magma along the top and walls would have a higher specific gravity than the rest and would ~~have to~~ sink. Thus a convective circulation would be established in which currents descended along the walls, crossed the floor to about the centre, and then rose to the top where they would spread out to the walls again.

According to Hess (1960, pp. 133 - 137) the Stillwater Complex represents a natural example of fractional crystallization on a vast scale. Crystals separated from the magma and accumulated on the floor, but motion also took place in the magma in the same way as suggested by Wager and Deer for the Skaergaard intrusion.

In both intrusions iron enrichment took place as crystallization proceeded.

In the Bushveld Igneous Complex southwest of the Lulu Mountains the facts given in connection with the intrusive relationships and the differentiation trend suggest that the differentiation took place before emplacement.

The following facts also indicate that crystal settling did not play an important role: From bottom to top the magnetite content in the ferrogabbro may be anything between 5 and 40 per cent. At Magnet Heights magnetite anorthosite occurs on top of pure magnetite. This fact was taken as sure proof of gravity accumulation (Hall, 1932, p. 348). The fact that magnetite anorthosite occurs below the pure magnetite in the area investigated, however, definitely proves this idea to be wrong. There is also no sign that the pyroxenes in the gabbro or the ferrogabbro tend to be concentrated in layers.

If gravitative accumulation of crystals did not take place, as seems to be the case, the problem is to explain the differentiation which is evident in terms of some other mechanism.

Schwellnus (1956, pp. 153 - 154) states that pre-intrusive differentiation can take place in depth, as is indicated by the separate injections of different magma fractions out of which the rocks of the Bushveld Complex were formed. He does not give any indication of how such differentiation in depth could have taken place but states that any discussion on the mode of formation

of such different fractions would be mere speculation as the physico-chemical conditions prevailing within a magma chamber ^{are} ~~is~~ not definitely known. Hess (1960, pp. 178 - 185) discusses partial fusion and crystallization differentiation. He states that commonly intrusions of basaltic magma are followed and overlain by granitic magma and that these associations are nicely accounted for by the process of generation of successive magmas by partial fusion. According to him the process of partial fusion, however, permits of much less variability in the resulting liquids than does crystallization differentiation.

Coertze (1958, p. 399) mentions the complicated physico-chemical conditions prevailing in a magma chamber. He thinks that each intrusion could have formed under entirely different conditions. According to him factors like fractional crystallization, differential fusion and assimilation, as well as subordinate factors like gravitational differentiation, the development of a gas phase, the building of a continuous mush, and a mechanism analogous to elutriation may all have played an important role but that it is too speculative to tell which was the most important mechanism. He concludes that field evidence like intrusive relationships proves differentiation to have taken place in depth.

Van Zyl (1960, pp. 90 - 95) discusses the existing ideas on differentiation. He states that it is difficult to visualize the generation of separate fractions with different composition from the same magma differentiating in depth. He thinks that if the crust and the upper mantle of the earth are built of layers like layered

intrusions, the fusion of these in depth may yield separate magmas with different compositions. He mentions that some of these ideas had previously been expressed by Buddington (1943, pp. 131 - 140) and later also by Wager (1958, pp. 9 - 13). He concludes that the re-fusion of the different layers in the mantle might have formed separate magmas which were responsible for the formation of the different main units in the mafic zone of the Bushveld Complex. According to Van Zyl differentiation in place is responsible for the differences within the main units.

In the area southwest of the Lulu Mountains differentiation in place seems to have played a minor role. The rocks investigated, however, occur high up in the succession, whereas those investigated by Van Zyl are confined to the lower part of the mafic zone. Investigation of some of the mafic rocks in the western part of the Bushveld Igneous Complex (Coertze, 1960) indicates that re-fusion of the older mafic rocks played a more important role than was previously thought. Apparent differentiation in depth may, therefore, actually be caused by re-fusion of previously formed layers in the upper mantle.

Genesis of the Magnetitite Bodies

Various authors have attempted to explain the genesis of the magnetitite bodies in the Bushveld Igneous Complex in terms of crystal settling, liquid accumulation, liquid accumulation and injection, and intrusion.

As described previously it is, however, quite

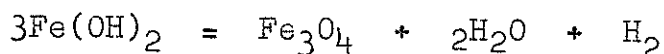
clear that the magnetitite is intrusive. The magnetitite bodies are confined to certain zones which probably represent zones of weakness in the ferrogabbro. They occur as sheets, pipes, and irregular bodies cutting the country rock and containing inclusions of the latter. The sheets transgress the igneous layering to encircle big inclusions and they pinch out and send offshoots into the country rock. The magnetitite of the sheets is continuous with that of the pipes where these occur in association with one another and they must, therefore, be contemporaneous. Reaction rims always occur between magnetite and the minerals of the country rock.

Temperature of Emplacement and Character of Ore Fluid

The melting point of magnetite is ~~about~~ 1591°C and that of ilmenite ~~about~~ 1450°C . The melting points of the silicates are much lower, and below 1300°C for plagioclase ($\text{Ab}_{50}\text{An}_{50}$). It is also known that pressure and the presence of other silicates and vapour cause a considerable depression of the melting points and temperatures of crystallization. If the magnetite could have existed in a molten state, it should have been the first to crystallize on cooling. This, however, is not the case but the magnetite was the last mineral to crystallize in all the rock types investigated.

According to Shand (1947, pp. 634 - 636) the "ore fluid" has been variously described by different authors as "highly heated solutions of iron and other compounds", "products of endphase igneous activity", "the last juice", and so on. Shand attempts to indicate the

composition of the ore fluid. He states that previous workers were right as far as they went, but beyond a few tentative suggestions about "mineralizers" and "volatile agents" they did not indicate the composition of the fluids which carried these very refractory ores in solution. He thinks the reason is that they thought about the problem in terms of the final products. He starts out from the chemistry of gabbroic magma and states that in most deep magmas ferrous oxide largely exceeds ferric oxide. Since no independent ferrous mineral is formed, there must be a relative concentration of FeO in the residual liquid - the "last juice". He argues that if the residual liquid is alkaline, as any solution must be which contains "strong" cations and "weak" silicon and aluminium anions, then the iron can only be present as a hydrosol of ferrous hydroxide, peptized by the alkali. He concludes that the residual solution from gabbroic magma does not contain magnetite but a ferrous hydroxide hydrosol. Atmospheric oxidation is excluded in deep magma, but another process is possible, namely self-oxidation. The hydrosol loses water, and the hydroxide oxidises itself to magnetite according to equation:



Shand concludes that this reaction has been demonstrated in the course of investigation of the corrosion of iron boilers.

Subsequently many other workers have carried out experiments in this connection. Holster and Schneeer (1961, pp. 369 - 385) give a short summary of the results of experiments carried out by them. They began with an

attempt to measure the solubility of magnetite in pure water at high temperature and pressure, and they also investigated the effect of HCl on ~~this~~^{its} solubility. They found that 300 ppm ferrous iron dissolved in 0.0002 N HCl at 390°C. They state that the solubility of iron compounds in acid solvents will decrease with decreasing acid concentration, but they can suggest no mechanism by which it will increase in basic solutions. They think that Shand was forced to depend on a ferrous hydroxide hydrosol for transport in an alkaline medium and point out the instability of this sol at high temperatures. On the other hand, they admit that it is difficult to reconcile acid transport of iron with the cogent arguments of many petrologists like Shand, Kennedy, Ridge, and Turner and Verhoogen that the final derivative of many magmas is probably alkaline rather than acid.

It is not out of place to mention here the recent ideas of Desborough (1963, pp. 332 - 346) in connection with the mobilization of iron by alteration of magnetite-ulvöspinel in basic rocks in Missouri. According to him the replacement of magnetite-ulvöspinel by sphene caused the iron to move elsewhere to form small magnetite and/or hematite deposits, deficient in titanium. In the Bushveld, however, all the magnetitite bodies contain a high amount of titanium and could, therefore, not have been formed by such a process.

Crystal Settling

According to Hall (1932, pp. 347 - 348) early formed crystals of magnetite sank under the influence of gravity until arrested at a lower level determined by a

critical viscosity. Alternatively, they came to rest on a solid layer of interlocking crystals of anorthosite.

This hypothesis is inapplicable because recent work has shown that the magnetite crystallized after the feldspar and all the other silicates present in the Bushveld magnetitite.

Liquid Accumulation

Hall (1932, pp. 348 - 349) thinks that gravitational concentration could equally well have operated on the fluid from which the magnetite crystallized as on the crystals which had already been formed. It may, therefore, be conceived that this fluid could have sunk to, and become concentrated at, a lower level determined by a given anorthosite band. The upper part of such a band would first be covered by the heavy magma fraction and its feldspar crystals could be expected to rise upwards through the future magnetitite layer, just as lighter particles would float up through a layer of mercury, until there is a feldspar-rich portion at the top with stragglers of plagioclase crystals below. According to this view, the space occupied by the magnetitite seam would have originally formed the upper part of the underlying anorthosite layer. Hall suggests that there would be no difficulty in conceiving repetitions of the above cycle so as to produce several magnetitite bands, the establishment of each being preceded by the separation of feldspar. Hall (1932, p. 349) admits that such arguments are somewhat speculative, and that a complete solution of the genesis of these remarkable iron-ore deposits still remains "one of the many glorious puzzles of the Bushveld

Complex".

Liquid Accumulation and Injection

After the intrusive nature of some of the magmatic magnetite deposits in the world became known, Bateman (1951, p. 404 - 426) suggested that late gravitational liquid accumulation as described above, is responsible for the formation of the bands. If pressure is exerted on this liquid accumulation, which rests on a floor of early crystallized silicates, the mobile residual liquid accumulation is squirted out either along or across existing structures of the host rock to form late magmatic injections. In this way he also tries to explain the genesis of the platinum-bearing pipes in the Bushveld Complex.

Direct Intrusion

Coertze (1958, pp. 387 - 392) puts forward the hypothesis of separate intrusions to explain the emplacement of the different members of the mafic portion of the Bushveld Igneous Complex in the western Bushveld. He suggests that dunite and magnetite fluids were injected as pipe-like bodies and that from these feeders, the magnetite fluid spread out along planes of stratification or along the contacts between the anorthosite and the gabbro to form intrusive bands. This hypothesis implies that differentiation took place below the present level of exposure. It is also shown by Coertze (1962, pp. 253 - 262) that pipe-like and sheet-like bodies of magnetite occur along a fault zone very low down in the succession of mafic rocks, southwest of Pilanesberg.

According to Schwellnus (1956, p. 166) the reason why there are transgressing bodies of magnetitite, associated with hortonolite dunite, is that "magnetite liquor" continued to be fed to the pipes even after the peridotite was virtually crystalline. This also explains the magnetitite veins cutting the dunite and dunite inclusions in the magnetitite.

Preferred Hypothesis

Field observations prove the magnetitite bands and pipes to be intrusive. The hypotheses of liquid accumulation and liquid accumulation plus injection do not explain all the facts. Magnetitite pipes were emplaced along zones and are connected with the sheets. In the ferrogabbro, which contains a fairly high percentage of magnetite, this mineral is distributed through the whole mass of the ferrogabbro. In some places the magnetite crystals are, however, more concentrated than in others. As seen in the core of boreholes drilled through the magnetitite bands north of Pretoria, there are some plagioclase crystals in the upper parts of some of the bands which indicates that in the individual bands a certain amount of liquid accumulation did take place. In the ferrogabbro the concentrations of up to 40 per cent of magnetite crystals may thus represent the lower parts of separate intrusions.

According to the accumulation/and injection hypothesis, the exertion of pressure before final consolidation caused the magnetite fluid to be squirted out to form injections, i.e. the pipe-like bodies. This hypothesis does not explain the existence of the composite

pipe-like bodies. There are no layers of dunite or pyroxenite associated with the magnetitite sheets as one would expect from their association with the magnetitite in the pipes. Although the lower magnetitite is "folded" it was found that this "folding" was not caused by direct pressure, but that the igneous layering is a reflection of the structure of the enclosed folded sedimentary rocks in the vicinity of Driekop, and that the magnetitite was emplaced along planes already having a folded structure.

The only hypothesis which fits all the facts is that of direct intrusion from below of the liquid from which the magnetite crystallized. This liquid could have been in the form of a hydroxide which oxidised itself after intrusion. On the other hand the existence of components such as P_2O_5 , HCl, CO_2 , and HF in the magnetite-bearing fluid cannot be denied and further experimental work should be carried out before any conclusions can be made regarding the true nature of the liquid from which the magnetite crystallized.

This explanation fits the trend of differentiation as well as the fact that the magnetite was the last mineral to crystallize. The temperature of the liquid from which the magnetite crystallized was lower than the melting point of the silicates, but under favourable conditions of high pressure, probably caused by the liberation of water from the liquid, this liquid may have redissolved some of the silicates, as was previously suggested in connection with the description of the pipes.

Mode and Sequence of Emplacement

Truter (1955, pp. 77 - 91) maintains that after

the emplacement of the "Critical Zone" of the Bushveld Complex, northsouth tensional stresses prevailed which were superseded by compression, and that subsequently tensional conditions took over again. "Weak zones" could have resulted from the tensional stresses and along these dunite and magnetitite were eventually emplaced. The compression postulated by Truter would have tended to close up the magmatic orifices, and as the fluid containing iron in the form of ferrous hydroxide, was then probably subjected to considerable hydrostatic pressure, it would have spread out along planes of less resistance where such planes were pierced. The liquid from which the magnetite crystallized can thus be considered to have accumulated in the magma chamber from where it invaded the country rock in pipe-like fashion. These pipes then acted as feeders for the magnetitite sheets.

Planes of less resistance are represented by the contacts between the different gabbroic rocks. The main sheet of magnetitite was emplaced on the contact between an anorthosite unit and the ferrogabbro. Such a plane of weakness also occurs between the two successive sheets of ferrogabbro, along which the magnetitite sheet on Middelin 538 KS was emplaced, and also along the contact between the inclusions and the ferrogabbro on Middelin 538 KS and Govt. Ground 503 KS.

In places the iron-bearing fluid may not have found such planes, as described above, and was then injected lit-par-lit along the planes of igneous layering, as on Driekop 540 KS. During and after emplacement, reaction took place between the plagioclase and pyroxene

of the country rock and the volatiles derived from the iron-rich liquid, and reaction rims were thus formed.

The following is a short summary of the probable mode of emplacement of some of the magnetitite bodies described above.

On Middelin 538 KS (plate V) two sheets of ferrogabbro of different age occur with a magnetitite band emplaced on their contact. Not very far from this outcrop is a magnetitite pipe, probably the feeder of the band. By piercing the ferrogabbro from below, the iron-bearing fluid, on cutting the contact, would have spread out along it to form a sheet. On the contact, but in the younger ferrogabbro, there is a large inclusion of norite. During emplacement the iron-bearing liquid would probably also have spread around this inclusion, following the path of least resistance, and would also have invaded it along cracks and joints. Tongues into the older ferrogabbro can also be explained by the inflow of the liquid along such cracks.

The main magnetitite band is definitely connected with at least one of the feeder pipes. The anorthosite band below the main magnetitite band was probably already solidified when the feeder pipe pierced it and the iron-rich liquid spread out along this contact. Above the magnetitite band there are some magnetitite pipes and irregular magnetitite bodies. The irregular bodies may be offshoots from the band or may also represent feeders, but they are in any case probably connected with the band in depth.

The magnetitite pipes above the main magneti-

tite band must also be connected with it in depth, but they did not originate from the main band because they are composite pipes, containing dunite which does not occur along the band. It is quite possible, however, that the magnetite from these pipes contributed to the formation of the main band. In the upper part of the ferrogabbro, about six magnetitite pipes, which probably acted as feeders, occur below the upper magnetitite bands.

In conclusion, the suggestion is made that the magnetite invaded the country rock in the form of pipes and as a liquid, probably containing iron hydroxide. By a process of spreading-out and injection, the other magnetitite bodies originated and derived their material from these pipes, except for some of the silicates which were incorporated from the country rock.

Different ages for the pipes and sheets of magnetitite could not be established but, on the contrary, all the evidence indicates simultaneity of emplacement. It seems as if the pipes acted as feeders for the sheets.

There are, however, chemical differences between the magnetitite pipes and sheets in the lower ferrogabbro and those in the upper ferrogabbro. On the basis of vanadium content, two types of magnetitite can be distinguished: (1) those with a high vanadium content in the lower ferrogabbro; and (2) those with a low vanadium content in the upper ferrogabbro. It is hard to believe that these two types were emplaced simultaneously from the same magma chamber. If different ages for these two types are assumed, the chemical differences do not seem so incompatible. The one pipe in the lower zone with a

very low vanadium content was probably emplaced simultaneously with those in the upper zone.

SUMMARY

The field relationships of the Bushveld magnetite and the associated mafic igneous, sedimentary, and metasedimentary country rocks in the area southwest of the Lulu Mountains are described and discussed.

A petrographic and mineragraphic study has been made of the magnetitite, and 10 new chemical analyses are presented and discussed.

The sedimentary and metasedimentary rocks are members of the Magaliesberg and Smelterskop Stages of the Pretoria Series and represent a portion of the floor of the Bushveld Igneous Complex, lifted up into its present position by the intrusion of the gabbro of the Bushveld Igneous Complex. These rocks have undergone a fair amount of metasomatism, and some of the quartzite has been feldspathized and even granitized. It is suggested that the gabbro was responsible for this metasomatism.

The igneous rocks are represented by mafic and felsic rocks. The felsic rocks are represented by granite only, but the mafic rocks are sub-divided into older and younger intrusive rocks. Diabase, harzburgite, gabbro, and ferrogabbro are the members of the older intrusive suite, and the younger intrusive suite, emplaced in the ferrogabbro, is represented by magnetite anorthosite sheets, magnetitite pipes with associated dunite, pyroxenite, and olivine ferrogabbro, and lastly magnetitite sheets and pipes.

The observed intrusive relationships show that the different members of the mafic portion of the Bush-

veld Complex represent separate intrusions. The composite pipe-like bodies of magnetitite as well as the magnetitite sheets occur along fairly well-defined zones. There are also irregular magnetitite bodies that could neither be classified with the pipes nor with the sheets. Magnetitite veins were injected in a lit-par-lit fashion or irregularly from the pipes into the country rock and the magnetitite sheets are connected with the magnetitite pipes.

The magnetitite is composed of magnetite, maghemite, goethite, hematite, ilmenite, spinel, sulphides, and some silicates. Fresh magnetitite is composed of magnetite only with ilmenite. Alteration has taken place at or near the surface, so that the magnetite is altered to maghemite, goethite, and hematite. This alteration takes place through a series of intermediate stages, so that the rock at the surface may exist in any one of these stages.

Modified C.I.P.W. norms were calculated for those parts of the analyzed magnetitite which consist of ore minerals. According to these partial norms there are three different assemblages of ore minerals: magnetite and ilmenite; magnetite, maghemite (+ goethite and hematite) and ilmenite; and maghemite (+ goethite and hematite), ilmenite and "rutile". These mineral compositions do not depend on the relative position in the succession, and neither do they depend on the structure of the magnetitite bodies - whether pipe-like or sheet-like. It is clear from both microscopic investigations and the modified partial norms that the different

assemblages represent stages of alteration.

According to vanadium content the magnetitite can be subdivided into two types: a type with a "high" vanadium content low down in the succession of mafic rocks, and a type with a "low" vanadium content in the upper part of the succession of mafic rocks. It seems as if there are more than one type of magnetitite and within each type there may exist a sympathetic relationship between the iron and vanadium. It is suggested that vanadium substitutes for ferric iron in the magnetite.

Comparison of the anorthite content of the plagioclase, the iron content of the pyroxenes and the percentage of magnetite crystals of the different rock types with their intrusive relationships, shows that each successive intrusion of mafic magma was, not only more sodic in composition than the preceding one, but also richer in iron. It seems that the refusion of layers of mafic rock previously formed in the upper mantle might have been partially responsible for apparent magmatic differentiation in depth.

The genesis of the magnetitite bands have been explained by various authors in terms of crystal settling, liquid accumulation, liquid accumulation and injection, and direct intrusion. The intrusive character of the magnetitite is pointed out, but it is made clear that the magnetite could not have existed in a molten state. It is suggested that the liquid from which the magnetite crystallized was probably alkaline and that this liquid was injected through pipe-like feeders from which it spread out along planes of less resistance to form the magnetitite bands in the ferrogabbro.

ACKNOWLEDGMENTS

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PLATE II

Section showing the structure of the metasedimentary rocks on Driekop 540 KS - Paradys 773 KS.

PLATE II

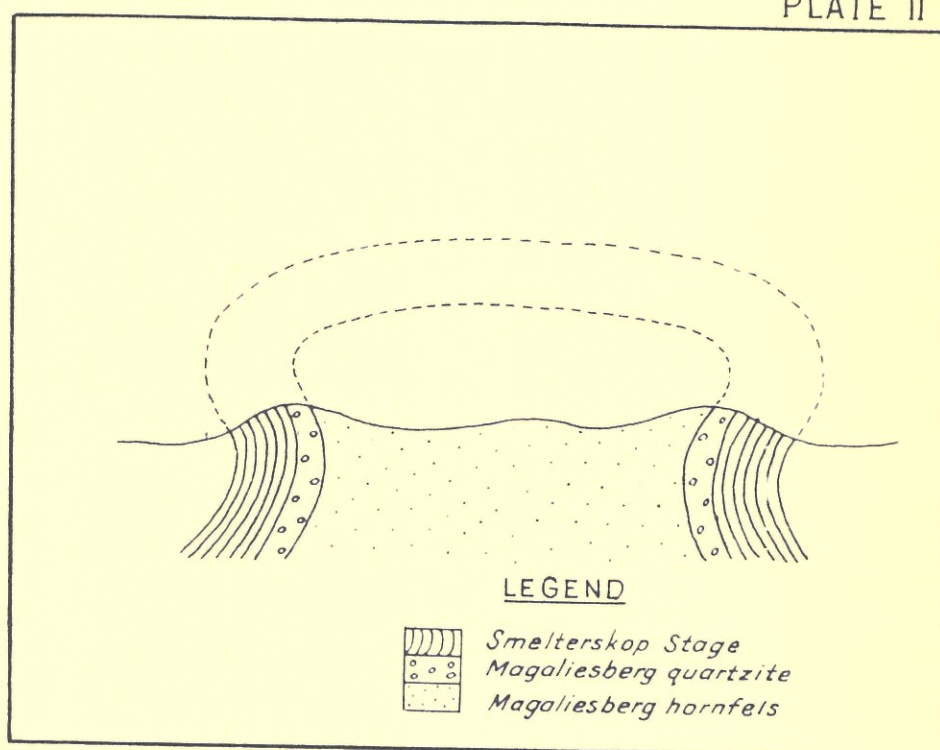


PLATE III

A - Feldspathized quartzite: quartz (white and black), feldspar (striped). Haakdoorndraai 536 KS.

B - Advanced feldspathization of quartzite:
quartz (white and black), feldspar (striped).
Goedverwacht 511 KS.

PLATE III



1mm

A



1mm

B

PLATE IV

Anorthite contents of plagioclase in rock samples taken across the succession of the mafic rocks on Govt. Ground 503 KS, Driekop 540 KS, Goedverwacht 511 KS, Hoeraroep 515 KS, Middelin 538 KS, Vlakplaats 770 KS, Strydkraal 537 KS and Haakdoorndraai 536 KS.

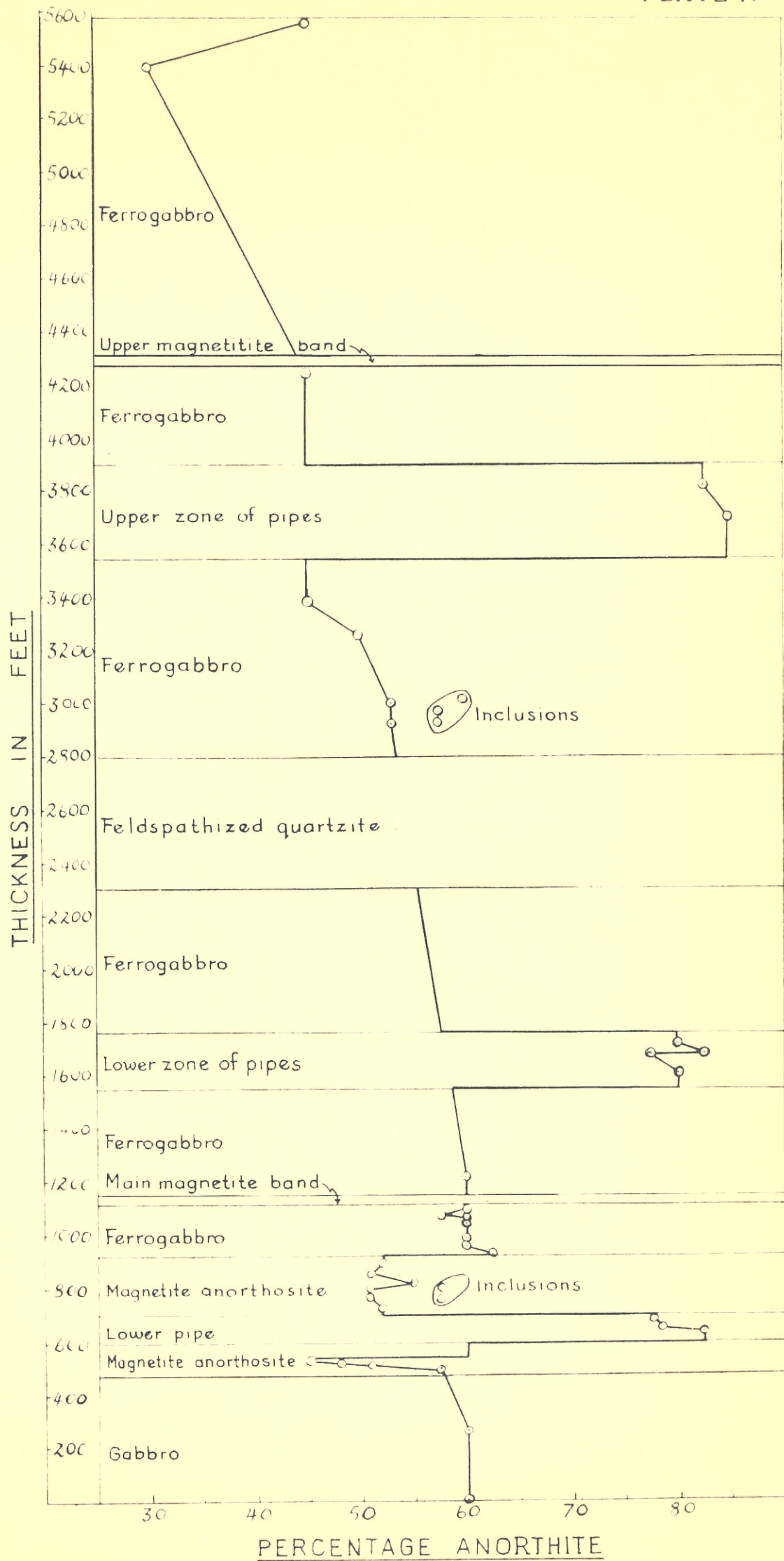


PLATE V

Magnetitite sheet intrusive along the contact
between two heaves of ferrogabbro, Middelin 538
KS.

PLATE V.

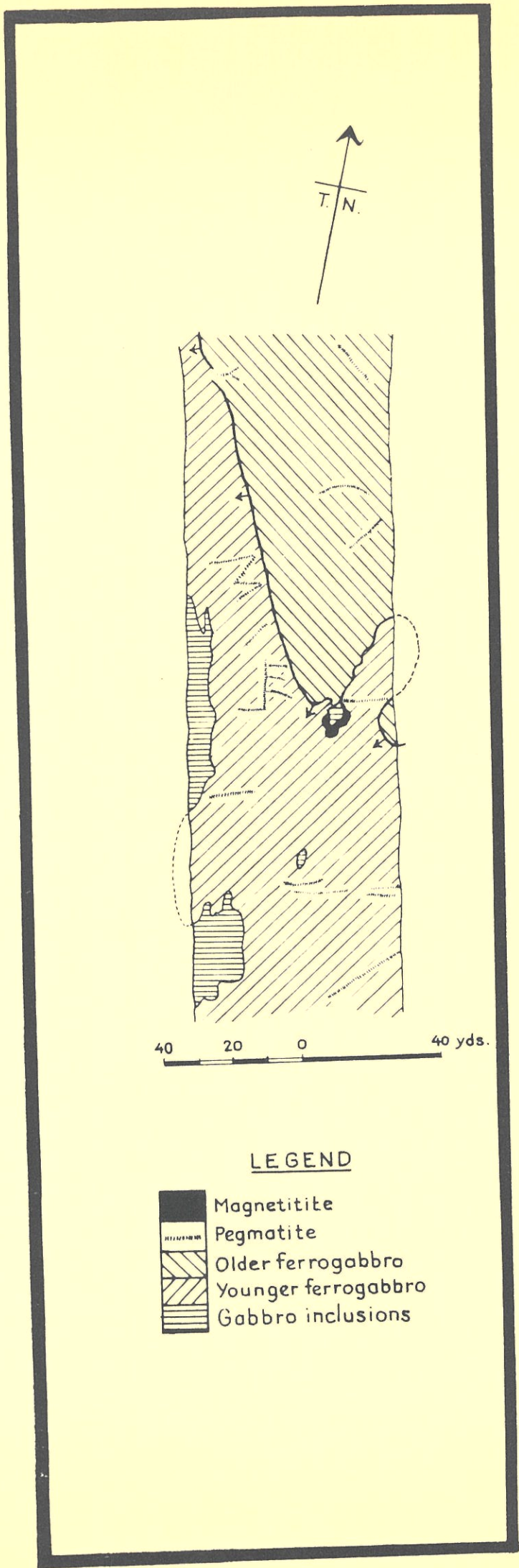


PLATE VI

A. Composite magnetitite pipe, Goedverwacht 511
KS.

B. Composite magnetitite pipes, Driekop 540 KS.

C. Composite magnetitite pipes, Vlakplaats 770
KS.

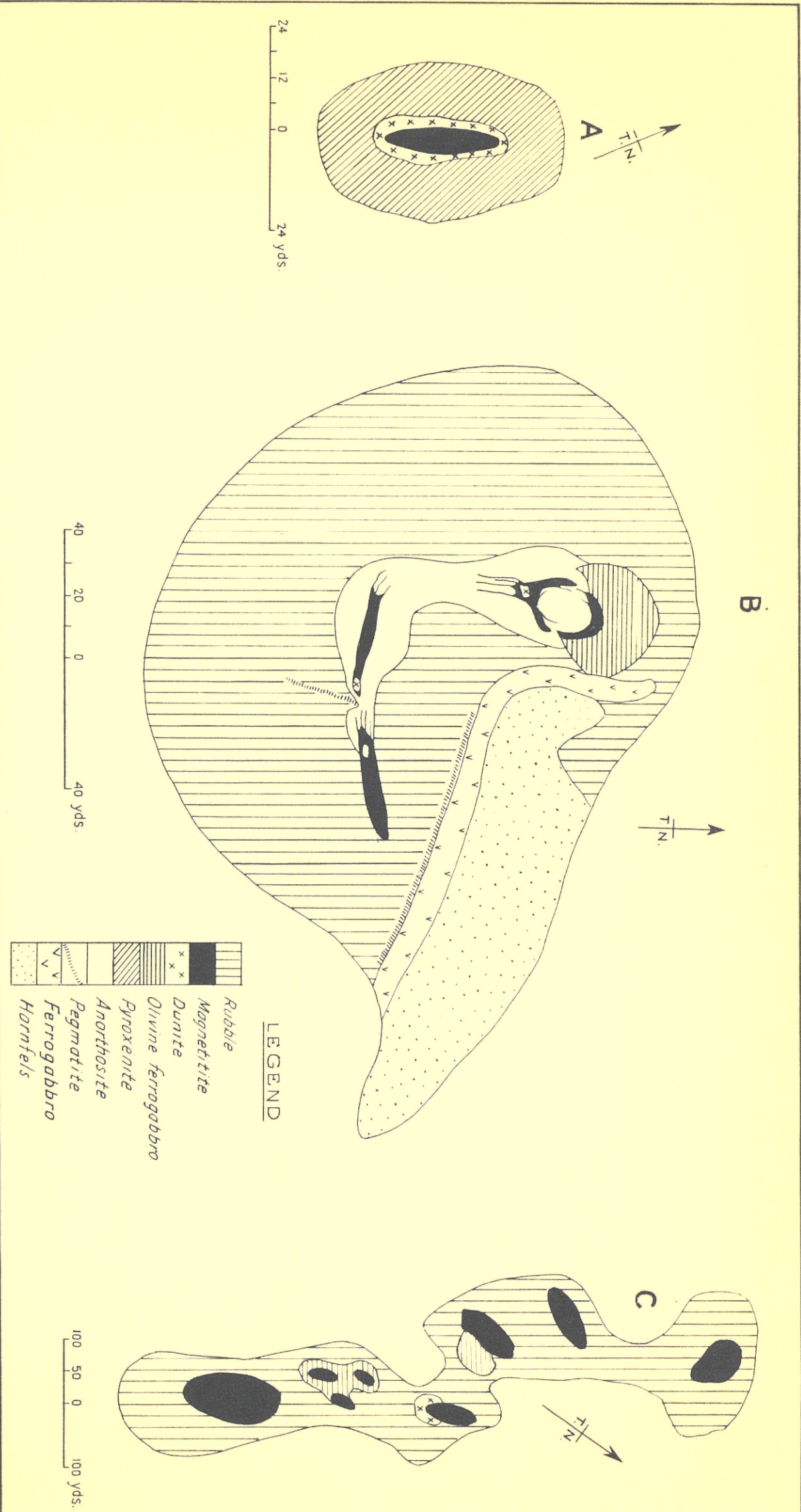


PLATE VIII

Tongue of magnetitite into older ferrogabbro,
Middelin 538 KS.

PLATE VIII

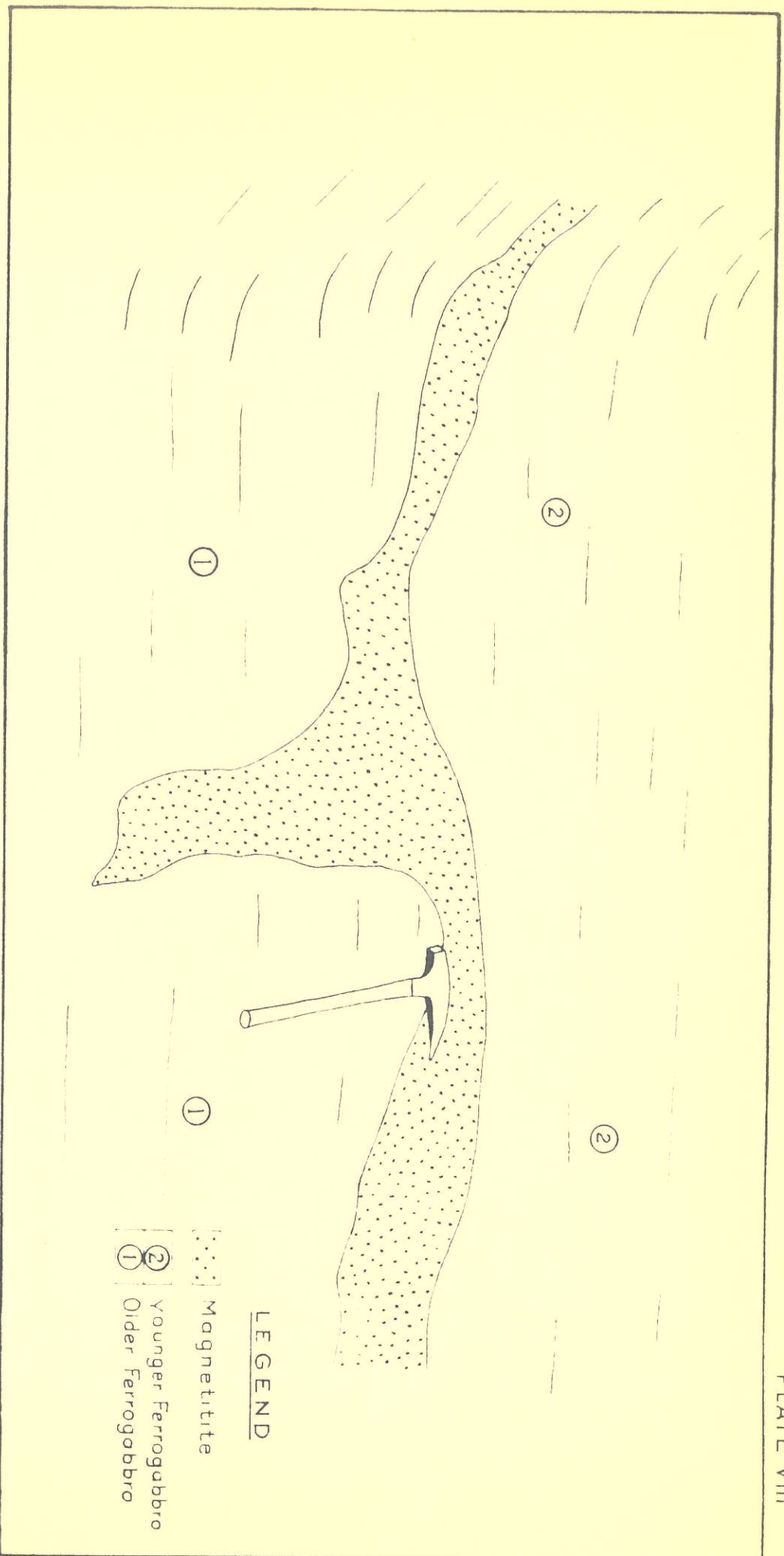


PLATE IX

Magnetitite emplaced irregularly in anorthosite,
Govt. Ground 503 KS.

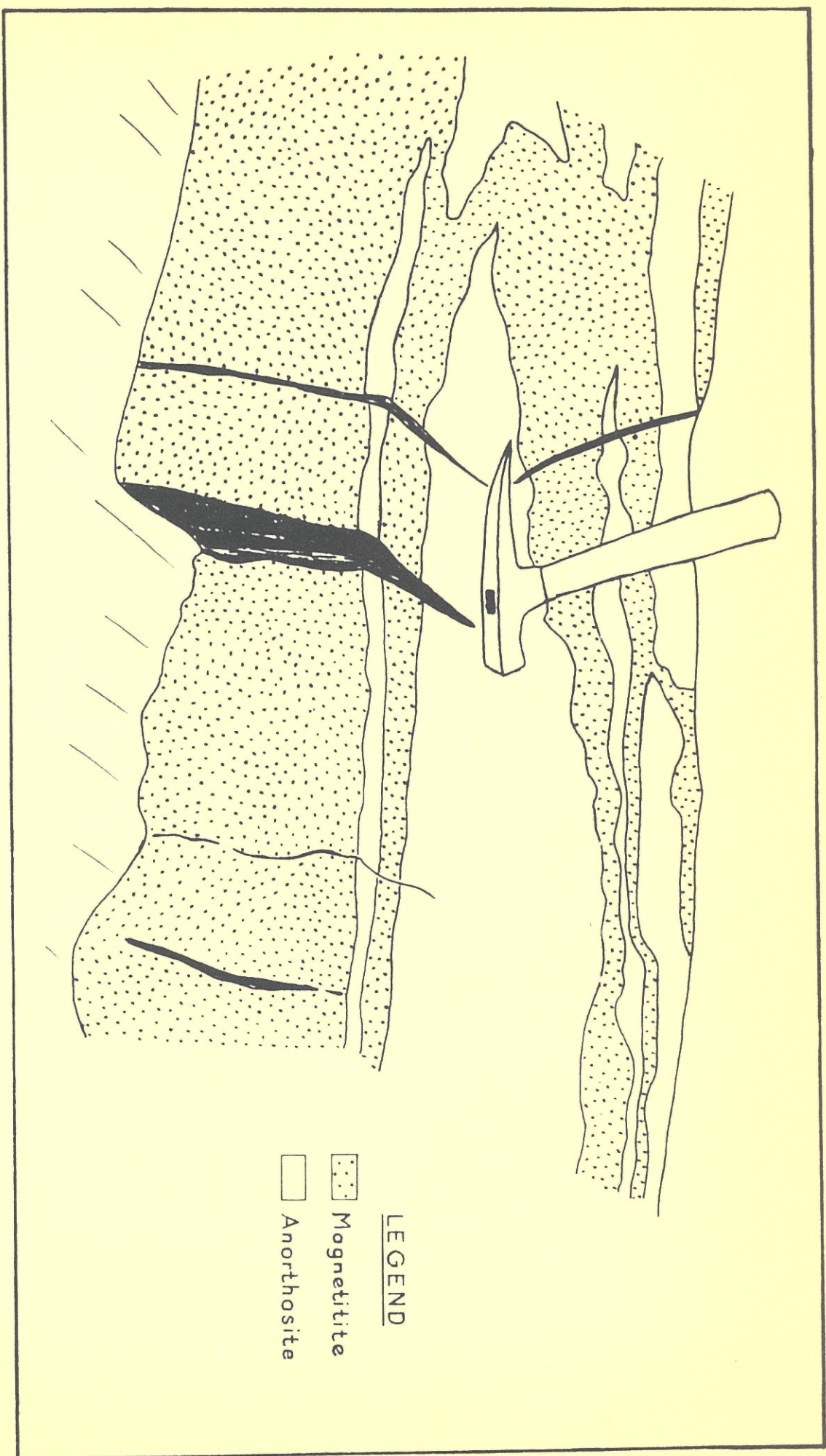
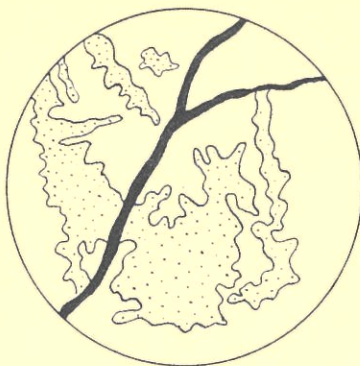


PLATE X

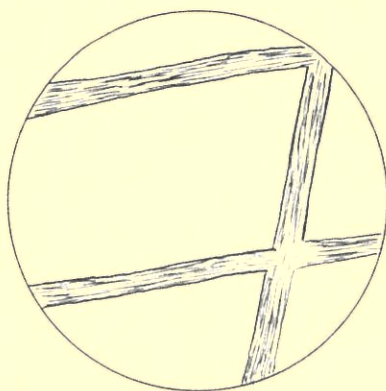
A. Limonite vein cutting magnetite (dotted) and maghemite (white). Driekop 540 KS.

B. Exsolution lamellae of ilmenite in magnetite.
Mooihoek Platinum Mine.

PLATE X



0.1 mm.
A



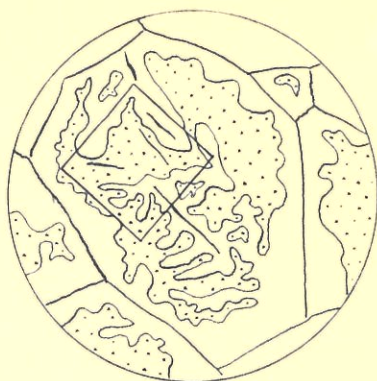
0.1 mm
B

PLATE XI

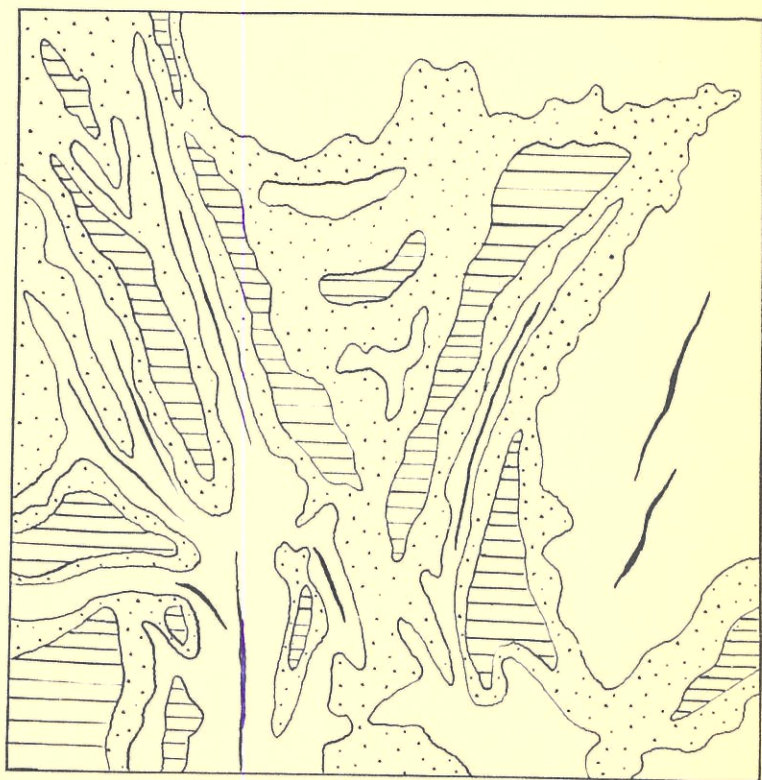
A. "Moth-eaten" structure. Alteration of magnetite (dotted) to maghemite (white). Goedverwacht 511 KS.

B. Part of Plate XIA enlarged: magnetite (striped), less brown mineral (dotted) and maghemite (white). Goedverwacht 511 KS.

PLATE XI



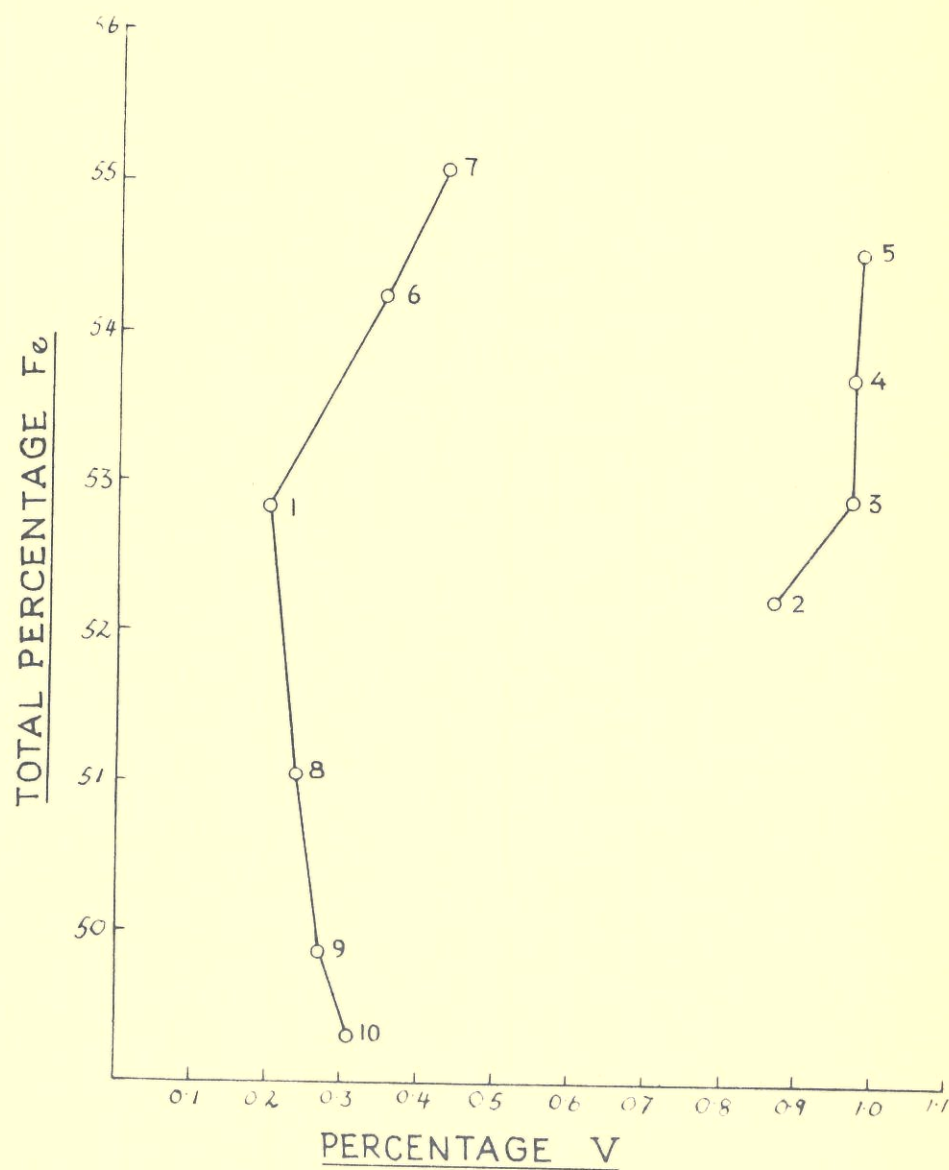
0.1 mm.
A



0.1 mm.
B

PLATE XII

Vanadium : iron ratios of the ten magnetitite samples analysed. Sampling points shown on plate I.



29° 35'

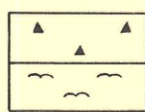
29° 40'

24° 20'

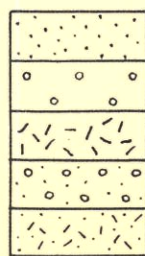
GEOLOGICAL MAP OF THE AREA SOUTH OF THE LULU MOUNTAINS

0 1 2 3 Miles
Scale 1:50,000

LEGEND



Rubble
Alluvium

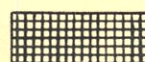


Feldspathized quartzite
Quartzite
Hornfels with sheets of diabase
Quartzite
Hornfels with sheets of diabase,
gneiss and amphibolite

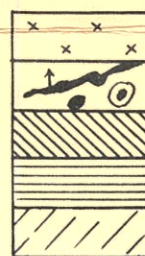
Smelterskop
Stage
Magaliesberg
Stage

Pretoria
Series

INTRUSIVE ROCKS



Dolerite



Granite
Magnetite sheets ↑, magnetite pipes ●, pipes of magnetite and (○)
Magnetite anorthosite. (associated mafic and ultramafic rocks (○))
Ferro gabbro
Gabbro

15° Dip of sedimentary stratification and igneous layering

Water course

Road

PI.V

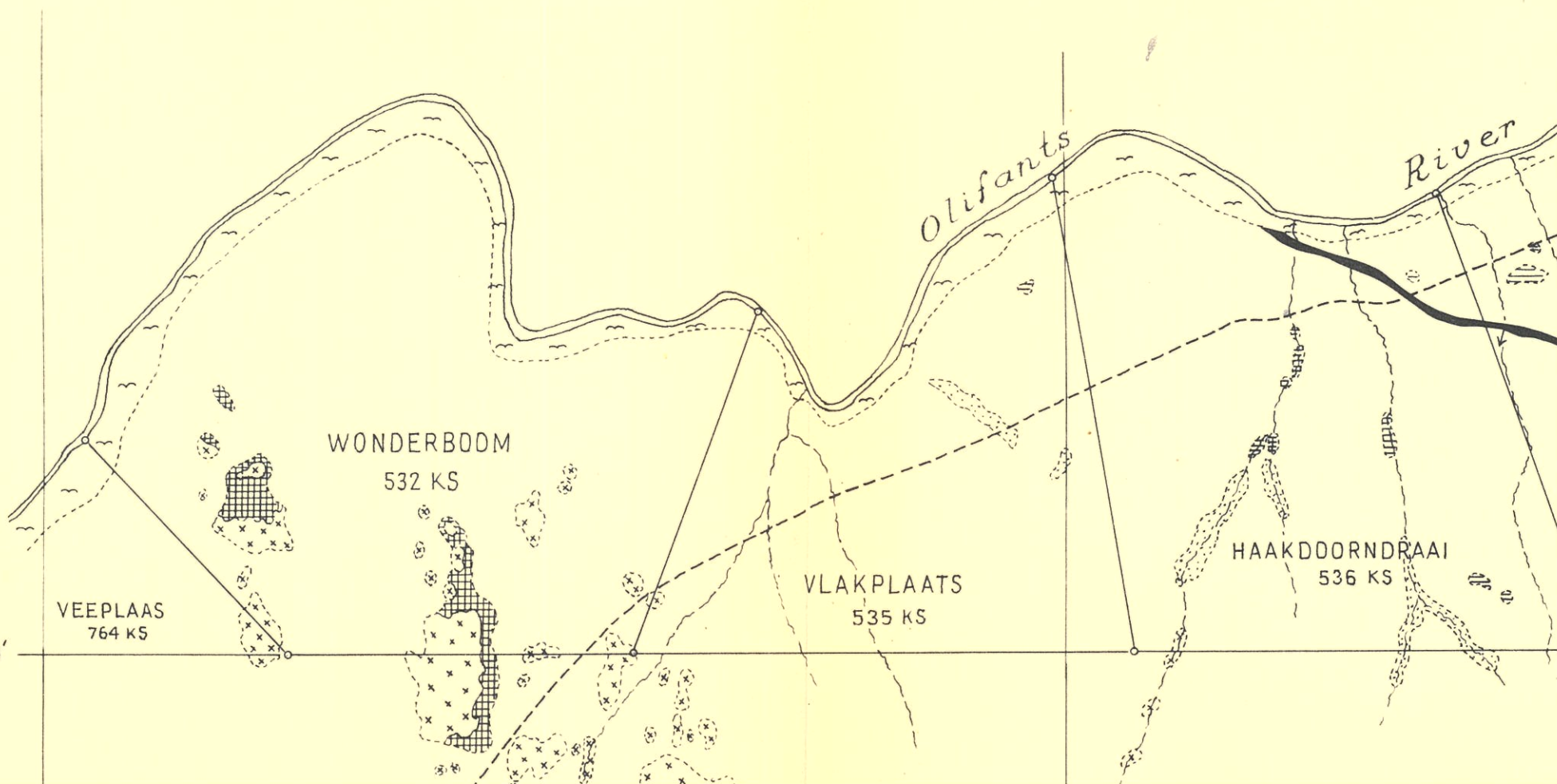
Portions mapped on a larger scale: Plates V, VI, and VII

①

Sampling points of magnetite

24° 25'

24° 30'



$29^{\circ} 50'$

EST



29° 50'

29° 55'

T. N.

ZWITZERLAND
473 KS

Swnd.
▲122

AVOCA
472 KS

DE KAMP
507 KS

FESANT LAAGTE
506 KS

GOVT. GROUND
503 KS

BALMORAL
508 KS

MALEKSKRAAL
509 KS

Fete
10

MAGNETS
VLAKTE
541 KS

DRIEKOP
540 KS

PARADYS
773 KS

DINGAANS KOP
543 KS

GOEDVERWACHT
511 KS

PI. VII
PI. VIB

N

