THE PETROGRAPHY OF ROCKS OF THE BUSHVELD COMPLEX TYPE INTERSECTED BY BOREHOLES IN THE BETHAL AREA

by

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ABSTRACT

On geophysical evidence, several Mining Companies undertook drilling programs in the country north-west and north-east of Bethal, Transvaal, in order to test for a possible extension of the Bushveld Igneous Complex.

Seven of these boreholes were examined and six intersected an igneous mass consisting of a layered sequence of mafic rocks dipping towards the north and resting on earlier diabase. The seventh borehole showed that this diabase had intruded into the sediments of the Pretoria Series. On the evidence that one of the boreholes intersected the uppermost zone of the Layered Sequence, a complete section could be constructed which shows a thickness for the Sequence of about 1900 metres, of which only 170 metres were not intersected.

The Layered Sequence is divided into five zones. These consist of a Basal Zone of peridotite and pyroxenite which pass upwards into Zone I. This zone contains abundant anorthosite and mineralized pegmatoid near the base which give way to norites and gabbros higher up. Zone II is a transition between Zone I, which is poor in magnetite and Zone III, which contains up to six magnetite layers. Zone IV is characteristically dioritic in composition and eleven magnetite seams were intersected in this zone.

Trends established from modal analyses and determinations of the composition of the plagioclase, orthopyroxene and olivine show that cyclical crystallization occurred. There is, however, an overall trend from An_{55} and Fs_{32} in the middle of Zone I to An_{38} and Fs_{62} at the top of Zone IV. The olivine and orthopyroxene of the Basal Zone are poor in iron, with values ranging from Fa_6 to Fa_{17} and Fs_{15} to Fs_{22} respectively.

Partial chemical analyses of samples of the magnetite layers reveal them as being titanomagnetites poor in vanadium.

A break in the mineralogical trend of the plagioclase in Zone I, from An_{45} to An_{56} over only 35 metres, has given rise to a very persistent mineralogical marker horizon.

The mineralized pegmatoid of Zone I gives values of up to 0,65 per cent combined copper and nickel and is considered to have been formed by filter pressing of the intercumulus volatile-rich phase of the Basal Zone. This phase may be responsible for the appearance of oscillatory zoning in the plagioclase of Zone I.

Pyrrhotite is the most abundant sulphide mineral in the Layered Sequence except just below the Marker Horizon and at the top of Zone IV, where a high proportion of pyrite is present. The proportion of pentlandite and chalcopyrite decreases upwards towards Zone IV. Pentlandite occurs predominantly as an exsolution product of pyrrhotite.

In addition to the narrow exsolution lamellae of augite parallel to the (100) plane in the orthopyroxene, additional broader lamellae, indicative of inverted pigeonite, occur near the top of Zone IV and in the diorites of Zone I just above the Marker Horizon.

Fluor-apatite enters as a prominent cumulus phase near the top of Zone IV.

On mineralogical grounds the Layered Sequence of the Bethal area can be correlated with that of the Upper Zone of the Bushveld Complex. The predominantly dioritic character of this Sequence implies that the magma migrated from the main chamber at a relatively late stage of its fractionation. The magma continued to crystallize under conditions of higher oxygen fugacity than that in the Eastern Bushveld Complex.

The diabases intersected below the Layered Sequence are considered to form part of the early intruded sill phase of the Bushveld Complex and both the Maruleng and Lydenburg types are present. The Lydenburg type diabase has assimilated sedimentary material, which resulted in enhanced differentiation trends.

Associated with the diabase are thermally metamorphosed sediments which grade from pyroxene-hornfels facies to albite-epidote-hornfels facies.

Ten new chemical analyses are presented and they have been used to confirm determinations undertaken by other methods.

SAMEVATTING

Op grond van geofisiese gegewens het 'n paar Mynboumaatskappye boorprogramme onderneem in 'n gebied noordwes en noordoos van Bethal, Transvaal, om te toets vir 'n moontlike uitbreiding van die Bosveldstollingskompleks.

Sewe van die boorgate is ondersoek. Ses het deur 'n Gelaagde Opeenvolging van mafiese gesteentes gedring, wat 'n helling na die noorde het en wat op vroeër diabase rus. Die sewende boorgat het getoon dat die diabase intrusief is in sedimente van die Serie Pretoria. Omdat een van die boorgate die boonste sone van die Gelaagde Opeenvolging deurdring het, kon 'n volledige profiel opgestel word wat 'n dikte van 1900 meter vir die opeenvolging aangedui het. Van dié profiel is net 170 meter nie deurdring nie.

Die Gelaagde Opeenvolging is in vyf sones verdeel. Aan die basis is 'n Basale Sone van peridotiet en pirokseniet wat opwaarts oorgaan in Sone I. Hierdie sone bevat baie lae van anortosiet en gemineraliseerde pegmatoïed in die onderste gedeelte wat oorgaan in noriet en gabbro hoër op. Sone II is oorganklik tussen Sone I wat arm aan magnetiet is en Sone III wat tot ses magnetietlae bevat. Die gesteentes van Sone IV het 'n kenmerkende dioritiese samestelling en bevat elf magnetietlae.

Modale analises en bepalings van die samestelling van plagioklaas, ortopirokseen en olivien wys dat sikliese kristallisasie plaasgevind het. Daar is nogtans 'n algemene neiging van An_{55} en Fs_{32} in die middel van Sone I tot An_{38} en Fs_{62} by die boonste gedeelte van Sone IV. Die olivien en die ortopirokseen van die Basale Sone is arm aan yster met waardes wat strek van Fa_6 to Fa_{17} en Fs_{15} tot Fs_{22} onderskeidelik.

Gedeeltelike chemiese analises op monsters van die magnetietlae wys dat hulle titaandraend is en arm aan vanadium.

'n Skerp onderbreking in die mineralogiese samestelling van die plagioklaas in Sone I vanaf An_{45} tot An_{56} oor 35 meter het aanleiding gegee tot 'n merkerhorison wat in die meeste boorgate waargeneem is.

Waardes tot 0,65 persent totale koper en nikkel kom voor in die gemineraliseerde pegmatoïed van Sone I. Hierdie gemineraliseerde pegmatoïed het blykbaar gevorm as gevolg van drukfiltrering van die interkumulus vloeistof, ryk aan vlugtige bestanddele, van die Basale Sone. Hierdie fase kan dalk die oorsaak wees van die ossillerende sonebou van die plagioklaas in Sone I.

Pirrotiet is die mees algemene sulfiedmineraal in die Gelaagde Opeenvolging, behalwe net onder die Merkerhorison en in die boonste gedeelte van Sone IV waar 'n groot hoeveelheid piriet aangetref word. Die hoeveelheid pentlandiet en chalkopiriet verminder opwaarts na Sone IV. Pentlandiet kom voor hoofsaaklik as ontmengings in pirrotiet.

Saam met die nou ontmengingslamelle van augiet parallel aan die (100) vlak in die ortopirokseen is daar nog breër lamelle wat daarop dui dat hierdie mineraal deur inversie van pigeoniet ontstaan het. Hierdie sogenaamde „inversie-pigeoniet" word aangetref in die boonste dele van Sone IV en in die dioriet van Sone I net bokant die Merkerhorison.

Fluoor-apatiet kom voor as 'n opmerklike fase naby die bokant van Sone IV.

Volgens mineralogiese getuienis kan die Gelaagde Opeenvolging van die Bethal gebied gekorreleer word met die Bosone van die Bosveldkompleks. Die oorheersende dioritiese aard van die opeenvolging dui daarop dat die magma op 'n betreklike laat stadium van fraksioneering van die hoofkamer geskei is. Die magma het aangehou kristalliseer onder omstandighede van hoër suurstoffugasiteit as dié in die oostelike deel van die Bosveldkompleks.

Die diabase wat in die vloer van die Kompleks ingeplaas is, word beskou as 'n deel van die hipabissale fase van die Bosveldkompleks. Die Maruleng- asook die Lydenburgtipe is teenwoordig. Die diabaas van die Lydenburgtipe het sedimentêre materiaal geassimileer wat 'n meer prominente differensiasieneiging veroorsaak het.

Geassosieer met die diabaas is termaalgemetamorfoseerde sedimente wat gradeer van die pirokseen-hornfels fasies tot die albiet-epidoot-hornfels fasies.

Tien nuwe chemiese analises word verskaf en hulle is gebruik om die resultate van die mineralogiese ondersoek te bevestig.

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I. INTRODUCTION

After the publication by the Geological Survey of a gravity map of the Republic, it became evident that an offshoot of the mafic rocks of the Bushveld Igneous Complex underlay the Karroo System north of Bethal (Fig. 1). The area was examined by various Mining Companies and several drilling projects were undertaken to determine the economic potential of the rocks.

Subsequent to the donation of core by Phelps Dodge Exploration Corporation from a borehole drilled in 1971, to the University of Pretoria, the General Mining and Finance Corporation indicated that they would supply core for a project in this area and donated core from five boreholes. When approached, Union Corporation agreed to the use of a borehole they drilled in 1960. The detailed designations and localities of the various boreholes examined in this study are given in Table I and Fig. 2.

TABLE I. BOREHOLE DESIGNATIONS AND DEPTHS DRILLED

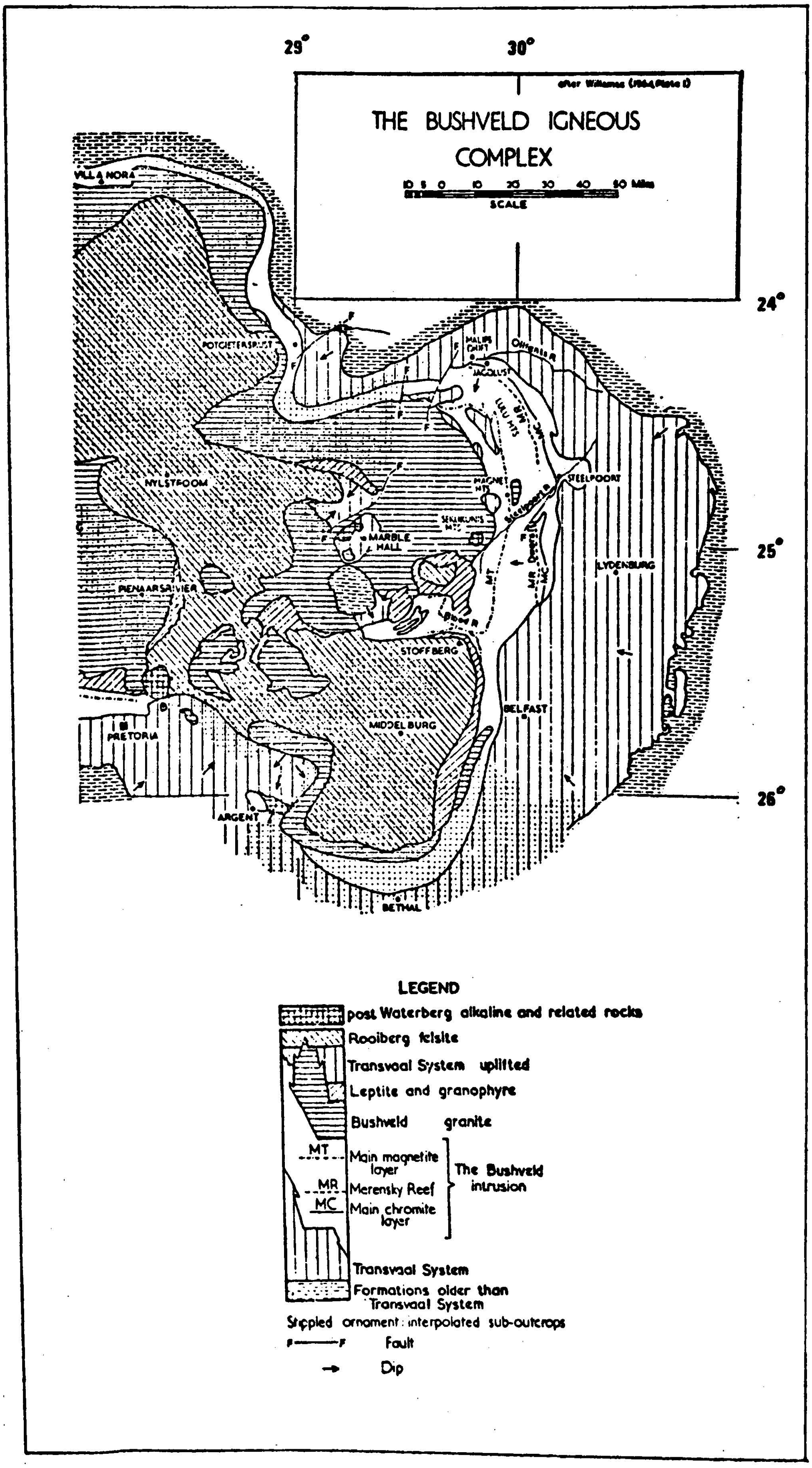
Borehole No.	Drilled by	Farm	Total Length
KLG/1	General Mining	Kaallaagte 255 IS	1367 metres
KLG/2	General Mining	Kaallaagte 255 IS	1505 metres
BKL/1	General Mining	Banklaagte 254 IS	404 metres
ONZ/1	General Mining	Ongezien 105 IS	1611 metres
ONZ/2	General Mining	Ongezien 105 IS	1539 metres
UC361	Union Corporation	Kalabasfontein 232 IS	413 metres
P.D.	Phelps Dodge	Ongezien 105 IS	542 metres
		TOTAL	7381 metres

In addition to the above-mentioned boreholes, General Mining released information on a borehole drilled on the farm Mooifontein 108 IS.

The pre-Karroo rocks intersected in this area consist of diorites, gabbros, norites, anorthosites, mineralized pegmatoids, diabases and metamorphosed sediments. As far as is known, all previous petrological work was undertaken on the rocks by the Mining Companies concerned with the drilling, and was in the form of broad classifications of the rock types intersected. The mineralogical work was concerned with identification of the ore minerals and estimates of mol. per cent anorthite in the plagioclase.

The problems encountered in these initial studies were that well defined petrological units are scarce and that correlations between boreholes were consequently

FIG. 1 LOCALITY PLAN



(From Wager and Brown, 1968, Fig. 190)

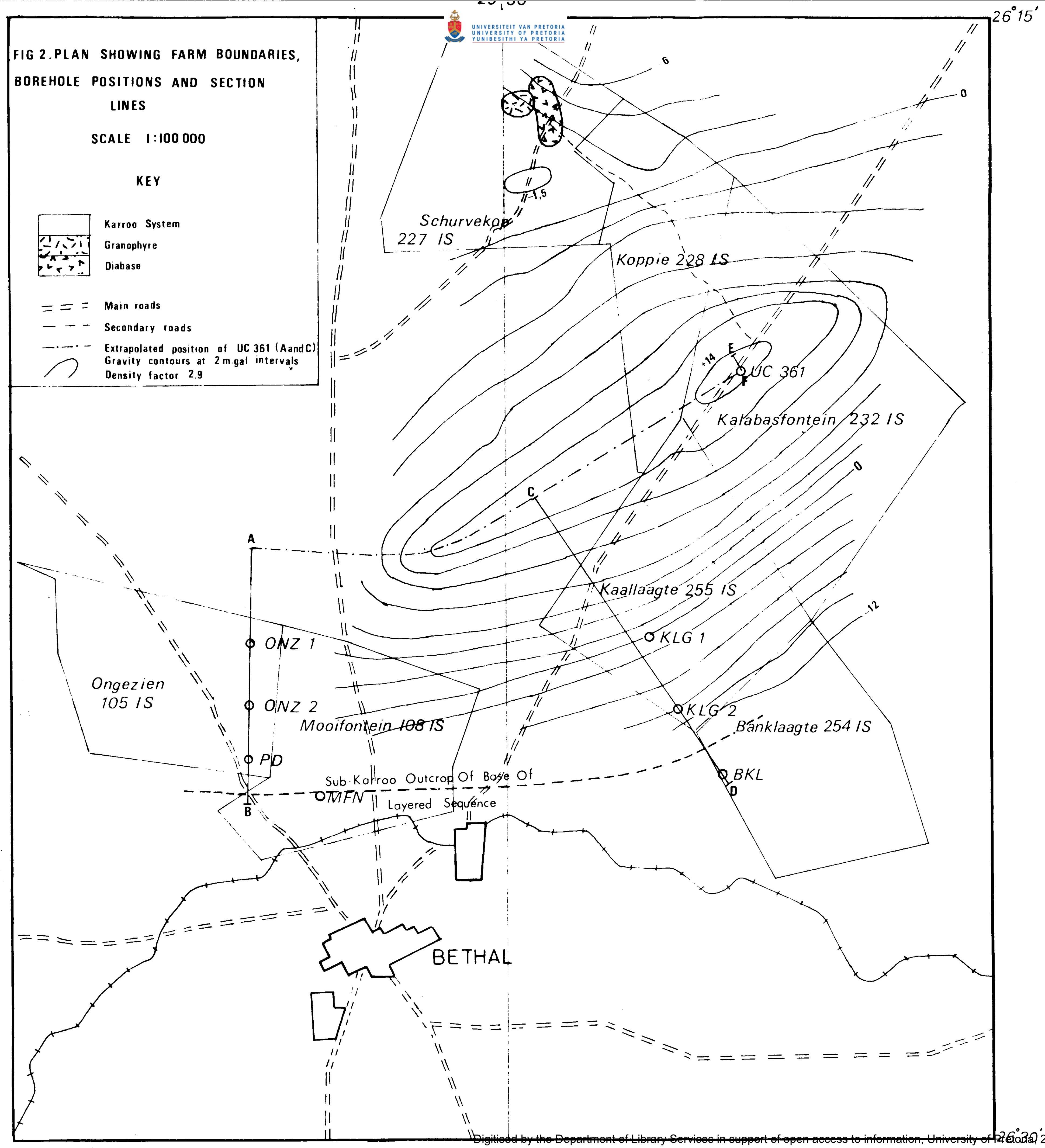


FIG 2. PLAN SHOWING FARM BOUNDARIES, BOREHOLE POSITIONS AND SECTION LINES

SCALE 1:100 000

difficult and inaccurate. In addition, the rocks did not fit readily into the known profile of the Layered Sequence of the Bushveld Complex.

This study was started in January, 1972. The main aim was to examine the rocks with a view to showing up less obvious features, in order to aid correlations between the boreholes. To achieve this aim, a detailed study of the minerals in the rocks of the Bethal area, especially orthopyroxene and plagioclase, was undertaken. It was also hoped that the Bethal rocks could be correlated with other parts of the Bushveld Complex on mineralogical grounds.

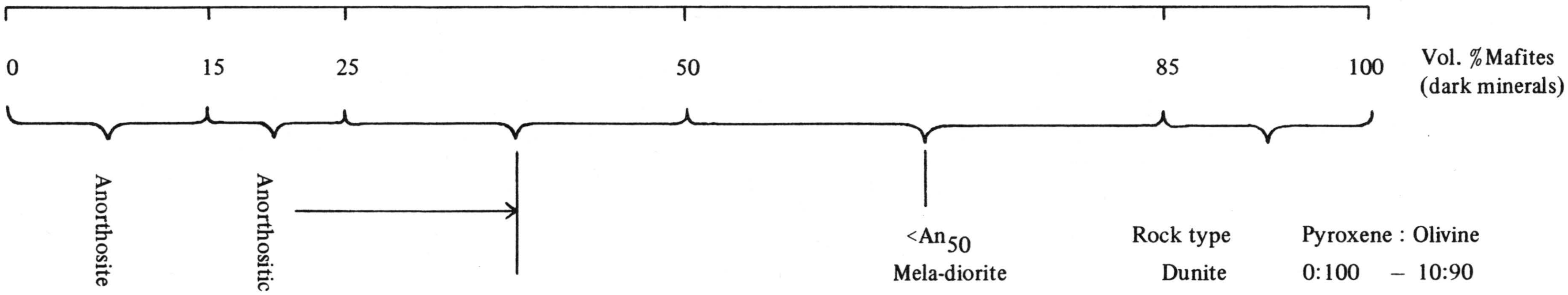
An attempt was also made to define the controlling features of the mineralized horizons and their expected position in the sequence.

In addition to the characteristically coarse-grained layered gabbros, several other, somewhat finer-grained, mafic rock types, some displaying evidence of assimilation of sediments, were also studied. As it is difficult to decide on textures alone whether these rocks are part of the gabbros of the Layered Sequence, or whether they are diabases, mineralogical criteria have again been used in their classification.

As all the boreholes were originally logged and marked in feet, it was convenient to do the sampling and undertake the laboratory work using the same system. Samples are therefore designated by their depth in feet and this depth is prefixed by the abbreviation given in Table 1 for the borehole number, for example KLG/2-2993. The actual position of the samples in the succession is given metrically and can be ascertained by reference to the tables in Appendix I.

The method of classification of the rocks of the Layered Sequence in this study is based primarily on Johannsen's Method (Johannsen, 1931, p. 141-161) and is laid out diagrammatically in Fig. 3. According to his classification, anorthosites are defined as having less than 5 per cent by volume of dark minerals. As these proportions were rarely encountered, this division was arbitrarily increased to 15 per cent in order to bring out more clearly the difference in rock types. Similarly, 85 per cent by volume of dark minerals, rather than 95 per cent, was used in classifying the rocks into ultramafic types. The system given by Raal (1965, p. 3) for the subdivision of norites and gabbros has been added to this classification. It was also found to be convenient to distinguish between magnetite-rich and magnetite-poor gabbros and norites. A value of 4 per cent modal magnetite showed up the different types best. The petrological classification of the diabases was also based on the above method.

FIG. 3 SYSTEM USED IN THE CLASSIFICATION OF THE MAFIC ROCKS



$<An_{50}$ Diorite

$>An_{50}$

Rock type	% orthopyroxene in relation to total pyroxene
Norite	75
Hyperite	75–50
Hypersthene gabbro	50–25
Gabbro	25

$>$ 4% Magnetite = Magnetite gabbro etc.

$<An_{50}$ Mela-diorite

$>An_{50}$ Mela-norite etc.

Rock type	Pyroxene : Olivine
Dunite	0:100 – 10:90
Pyroxene-dunite	10:90 – 50:50
Peridotite	50:50 – 90:10
Diallagite Bronzitite	90:10 – 100:0

II. ACKNOWLEDGEMENTS

The writer would like to thank the management of Phelps Dodge Exploration Corporation, General Mining and Finance Corporation and Union Corporation for supplying the material on which this study is based. In addition, thanks are due to Union Corporation for granting study leave and a loan.

The award of a bursary for the purposes of this study, by the Council for Scientific and Industrial Research, is also gratefully acknowledged.

The Director of the Geological Survey arranged to have a number of chemical analyses carried out on mineral and rock samples by the National Institute for Metallurgy.

Sincere thanks are due to Drs C.P. Snyman and G. von Gruenewaldt under whose guidance this work was carried out.

III. GENERAL GEOLOGY

A. GEOLOGICAL FORMATIONS

Details of the surface geology in the Bethal area have been taken from the Geological Survey Sheet 2628. This shows the area as consisting mainly of flat-lying Ecca sandstones of the Karroo System. Eighteen kilometres north of Bethal, however, where the Karroo cover has been removed, there is a small exposure of granophyre (Fig. 2). Far more extensive outcrops of felsite and granophyre occur nine kilometres further north of this exposure. Dolerites have intruded the sediments extensively in this area, although they do tend to be more concentrated to the south of Bethal.

The following succession of rocks as revealed by diamond drilling and surface outcrop, is present in the area (Fig. 4 and 5).

4. Dolerite

Dykes and sills. Very rarely intrude the Bushveld Complex type Layered Rocks.

3. Karroo System

The rocks are over 240 m thick in the south near Bethal but continuing northwards they thin to 60 m in borehole UC361, after which they are stripped away completely in places.

Ecca Series

Shales, sandstones, carbonaceous shales and occasional coal seams.

Dwyka Series

Variable thickness and irregular distribution.

2. Bushveld Complex Type Rocks

Roof Rocks

Bushveld Granite.

Felsite and granophyre.

Layered Sequence

Diorites – olivine-bearing.

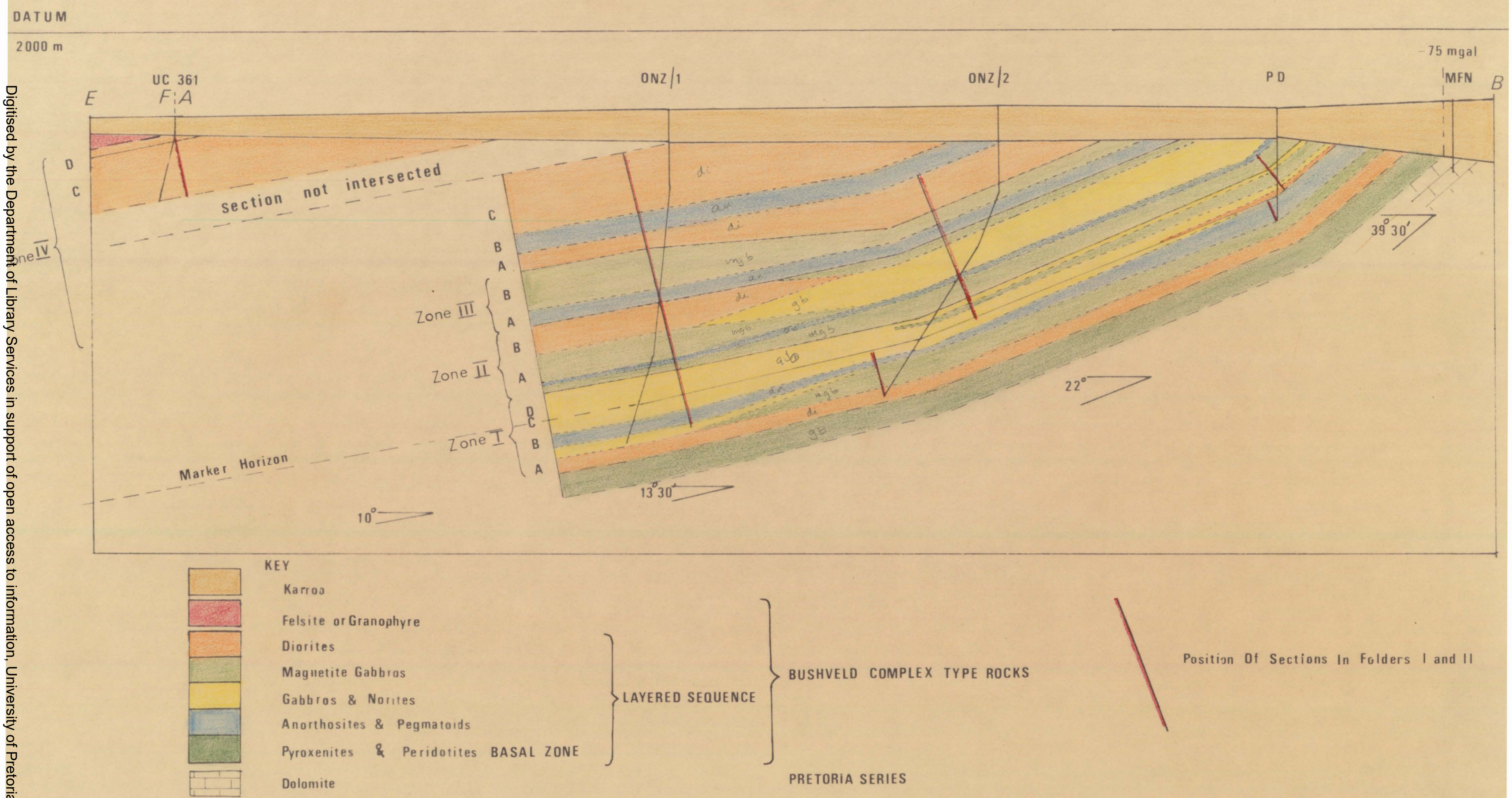
Magnetite gabbros – numerous magnetite layers are developed.

Gabbros and norites.

Anorthosites and pegmatoids – contain sulphide mineralization.

Basal Zone – ultramafic rocks.

FIG 4 ONGEZIEN SECTION SHOWING DEFLECTION OF BOREHOLES, POSITION OF VERTICAL SECTIONS AND ZONING. SCALE 1:25 000



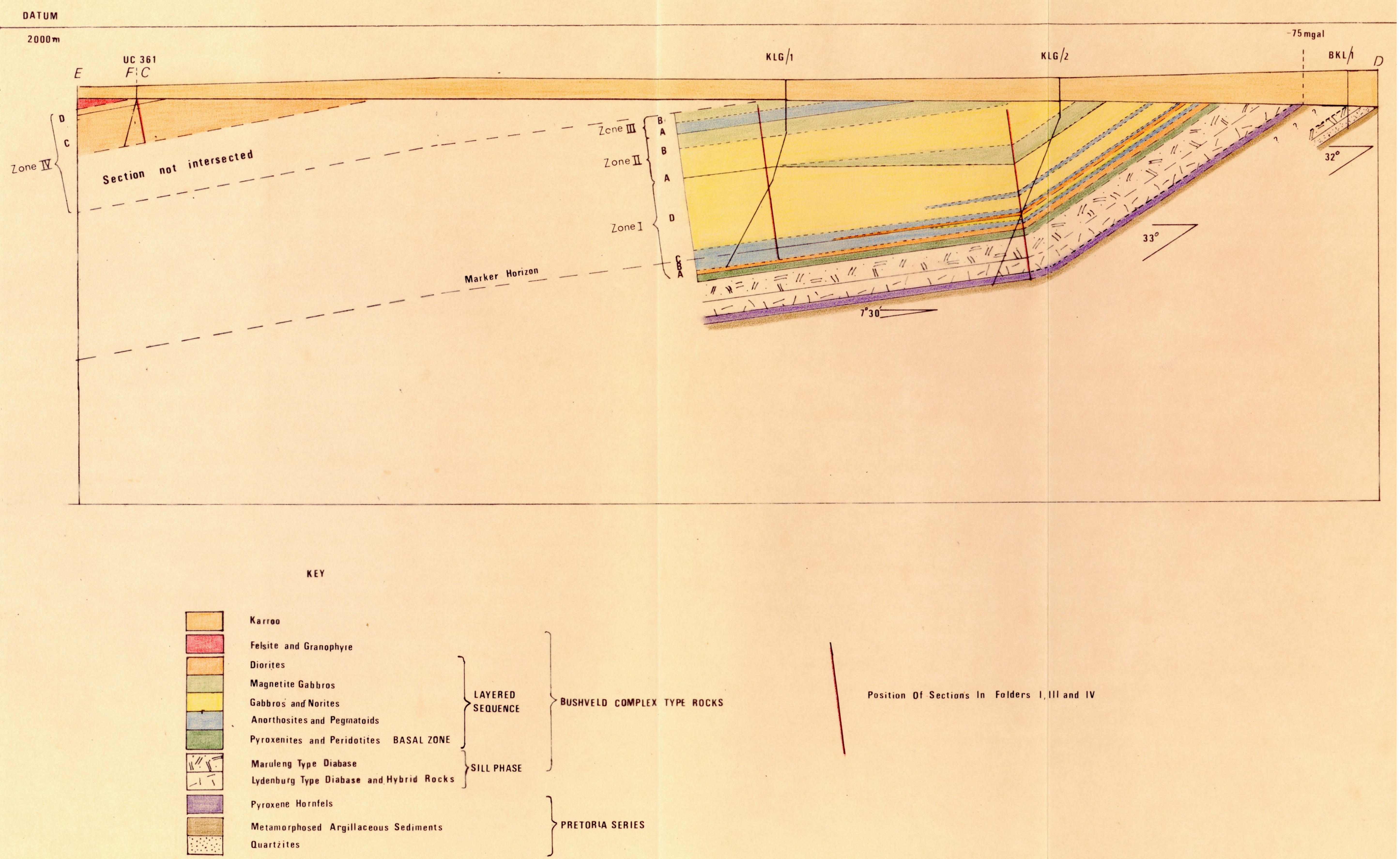


FIG 5 KAALLAAGTE SECTION SHOWING DEFLECTION OF BOREHOLES, POSITION OF VERTICAL SECTIONS AND ZONING. SCALE 1:25 000

Diabases

Maruleng type.

Lydenburg type.

1. **Transvaal System**

Pretoria Series

Interbedded shales, quartzites and limestones.

B. PRE-KARROO TOPOGRAPHY

The mafic rocks of the Layered Sequence appear to have been essentially eroded to a plane sloping to the south. This tilt increases over the diabases and Floor Rocks. At the top of the Layered Sequence there is usually a deeply weathered zone of up to 50 m which is probably due to ground water in the Karroo sediments.

IV. CONSTRUCTION OF SECTIONS

A. GEOPHYSICAL GRAVITY INTERPRETATION

A rigorous interpretation of the Bethal gravity anomaly has not been attempted in this study and the conclusions derived are therefore purely qualitative. The gravity contours given in Fig. 2 have been taken from the Company records of Union Corporation, who carried out a detailed survey of the gravity high north of Bethal. Use was also made of the 1:1000 000 gravity map of the Republic.

In the interpretation of the suboutcrop geology, the strike of the gravity contours was taken as reflecting the strike of the underlying rocks. Consequently the line of the dip sections was taken at right angles to the gravity high (Fig. 2). In addition, the gravity high has been considered as representing the contact of high density mafic rocks with the low density acid rocks of the Roof. A gravity high on this contact forms a common feature in other parts of the Bushveld Complex and mineralogical evidence in UC361 drilled on this high gives strong support for such an interpretation.

B. BOREHOLE SURVEYS

Where possible, borehole surveys were used in the construction of the sections. Collar elevations were determined from the 1:50 000 topocadastral sheets. No information was available on borehole surveys carried out on the Phelps Dodge borehole, but owing to its shallow depth any deflection is probably very small.

General Mining carried out surveys on their Kaallaagte and Ongezien boreholes, which all deflected down dip. No survey was available for the Banklaagte borehole, but again its shallowness would only allow for a limited deflection.

A survey of the Union Corporation borehole showed that it deflected to the south-east by 14^{o} whereas the two Kaallaagte boreholes deflected to the north-west. When plotted using this deflection, the dip of the layering is 37^{o} which is much greater than expected. As the gabbro contains up to 20 per cent magnetite at the depth of survey and the surveys were undertaken magnetically, there are reasonable grounds to suspect an error. If the information is replotted with the borehole deflecting to the north-west, a dip of 10^{o} is obtained which corresponds to the information obtained from other boreholes.

C. PETROLOGICAL CORRELATIONS

Before the less obvious petrographic and mineralogical features could be correlated, a prominent horizon was required in order to draw up the sections. As only

KLG/2 intersected the rocks of the well defined Basal Zone (Fig. 5) a prominent petrological horizon was not readily available. A mineralogical marker horizon in the layered mafic rocks above the Basal Zone was, however, observed in most of the boreholes. This marker, which will be dealt with more fully later in the text, consists of a break in the normal trend of differentiation of the anorthite content of the plagioclase.

The Ongezien section (Fig. 4) was drawn first. The most southerly extension of the Layered Sequence was limited by a borehole drilled on Mooifontein 108 IS, which is reported to have intersected dolomite, probably belonging to the Magaliesberg or Smelterskop Stages, below the Karroo. The resultant section shows the rocks as dipping steeply in the south and then flattening out towards the north. The relative distance of the marker from the Basal Zone is known from KLG/2 but this distance appears to have increased in the Ongezien section. The position where the contact of the Layered Sequence and the dolomite suboutcrops against the Karroo occurs in this section was determined relative to the gravity contours given on the 1:1 000 000 gravity map of the Republic. A value of -75mgals was obtained and the same equivalent position was located in the Kaallaagte section.

As KLG/2 intersected a considerable thickness of diabase and rocks of the pyroxene-hornfels facies below the Basal Zone before passing into lower density sediments, the value of -75mgals was taken as representing the base of the pyroxene-hornfels. The Kaallaagte section was then drawn with reference to the Marker Horizon and the extrapolated position of the pyroxene-hornfels contact with the sediments. The borehole BKL/1 drilled south of this position intersected quartzites, shales and interbedded diabase of the Pretoria Series. If the assumption is made that the dip of these sediments is parallel to the base of the diabases intersected in KLG/2, the dips in BKL/1 should be similar to the dips of the Layered Sequence as constructed by the above method. When measured, the two independently derived constructions for measuring the dip of the rocks near the Karroo cover agreed to within one degree.

This gives strong support for the original assumption that the strike of the gravity contours reflects the strike of the layering. The interpretation must be dealt with cautiously, however, as the presence of diabase below the Layered Sequence has given the impression of thickening of these rocks.

The detailed gravity work carried out by Union Corporation facilitated extrapolation of the rock types intersected in borehole UC361 along the strike of the contours to intersect the Kaallaagte and Ongezien section lines. This borehole is very high in the succession and thus the Marker Horizon was not intersected. As the dip in the Layered Sequence was already known from other boreholes, however, the position of UC361 in the sequence could easily be established.

D. CALCULATION OF VERTICAL SECTIONS

As some of the boreholes intersected the layering of the rocks at angles of up to 54^{o} it was essential, in order to enable accurate correlations to be carried out, that sections at right angles to the layering be constructed. These sections were constructed in such a way that they were as close as possible to the original points of intersection of the boreholes. Borehole sample points were then corrected trigonometrically with respect to these section lines. The Marker Horizon was taken as the base line and the corrected depth was adjusted to give its relative distance above (positive) or below (negative) this line. The detailed mineralogical data was then plotted (Folders I, II and III).

V. THE LAYERED SEQUENCE OF THE ROCKS OF THE BUSHVELD COMPLEX TYPE

A. GENERAL

As stated in the introduction, the main aim of this study is to classify the rocks of this area into discrete zones in order that correlations might be made between the various boreholes. The Basal Zone consists of peridotite and pyroxenite and should remain well defined and easily recognizable in future intersections. Very little information is available on the Roof Rocks, but again their characteristic properties are easy to recognize, which should make correlations straight forward.

The dioritic, gabbroic and noritic rocks, however, are difficult to distinguish from one another in hand specimens. These rocks also grade into one another, making the determination of contacts almost impossible. Reliable correlations based on macroscopic observation are therefore impossible, except for the most distinctive zones.

It was felt that the first step in carrying out any correlation was to define accurately the basic rock types. This was undertaken by using as a foundation both the determination of the mode and of the mol. per cent anorthite in the plagioclase. Contacts were determined between the rock types by plotting the mineralogical data alongside the borehole sections (Folders I, II and III). The contact between two dissimilar rocks was obtained by referring to the compositional or modal trend. In the borehole sections gabbros and norites were not subdivided with respect to the pyroxene, as this would have led to an excessive break-down of the rock types and would have obscured the main features of the less prominent horizons.

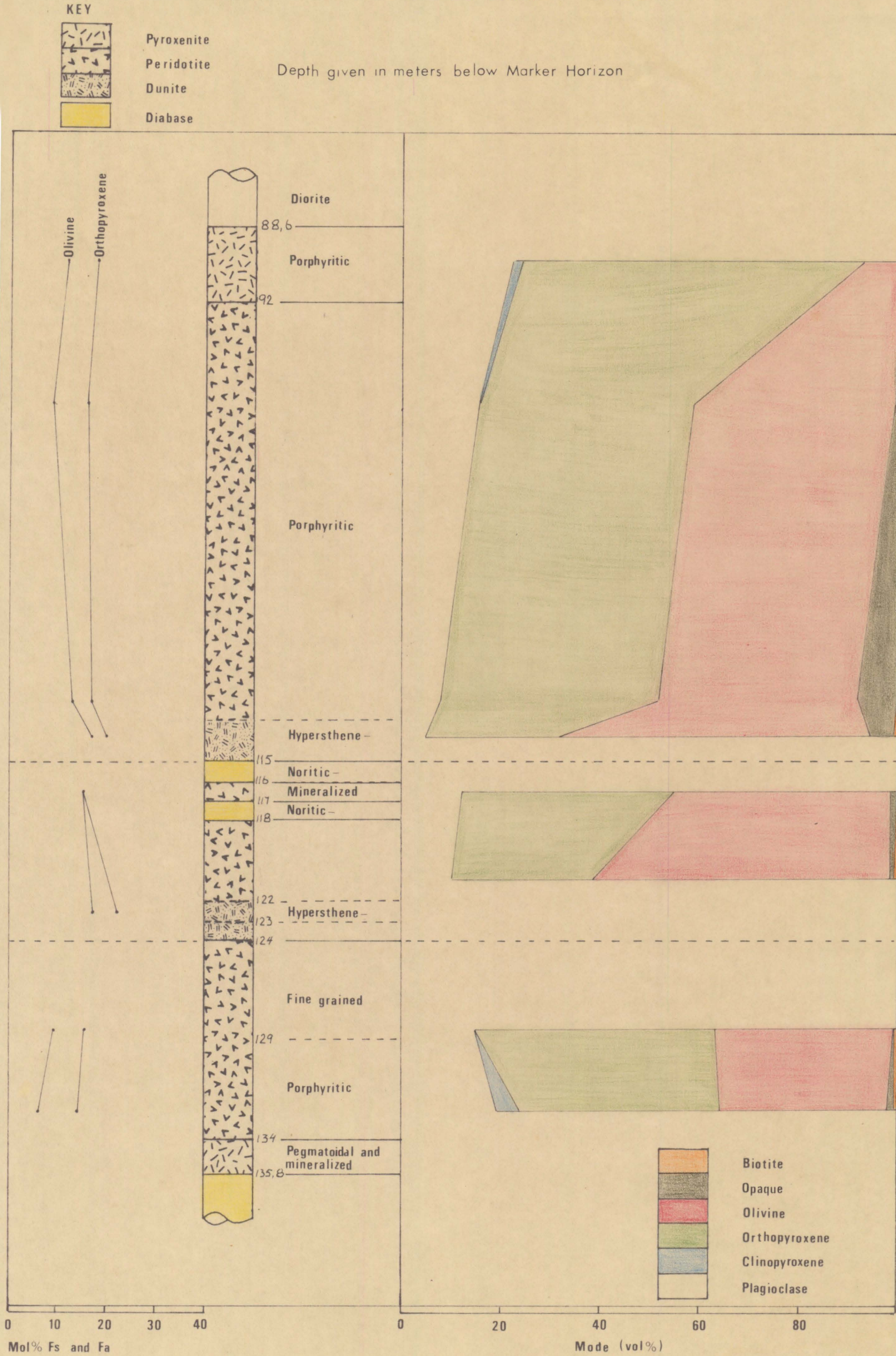
After the above precedures were carried out, the information obtained was transferred to the Ongezien and Kaallaagte sections (Fig. 4 and 5) where the rock types were correlated and subdivided into zones.

B. BASAL ZONE

The thickness of Subzones IA and IB in KLG/2 is five times as great as that of the Basal Zone. Using this ratio, the thickness of the Basal Zone in the Ongezien section could be estimated.

The section through the Basal Zone in KLG/2 is given in Fig. 6. It rests on an earlier diabase and is evidently the result of gravity settling of the mafic minerals in the magma chamber. The Zone is made up predominantly of orthopyroxene

FIG.6 KAALLAAGTE 2. SECTION THROUGH THE BASAL ZONE. SCALE 1:250



peridotites. This is a distinctive rock in the hand specimen, having a mottled appearance and consisting of large light-reflecting orthopyroxene crystals. These are associated with a dark granular mass of olivine. Thin layers of hypersthene-dunite are also present in the sequence and tend to have a mottled appearance but are much darker in colour than the peridotites and display fairly pronounced layering.

The pyroxenite at the top of the Zone is medium-grained and dark brown in colour, whereas that at the base is coarse-grained and pegmatoidal in appearance and contains abundant sulphide mineralization.

Minor amounts of diabase are also present, the origin of which is not very clear, as it is identical in appearance to that which occurs below the Basal Zone. This may, however, represent part of the floor diabase which has been disrupted.

The peridotites and dunites are considered to be the final results of gravity differentiation. They occur at -115m and at -124m, which suggests that this Zone did not result from one single cycle of crystallization, but from at least three, that is

3. -115m to -88m

----- disruption of floor diabase

2. -124m to -118m

1. -135,8m to -124m

These cyclic units may have had their origin in convection currents which caused periodic re-homogenization of the crystallizing magma (Jackson, 1961, p. 98). If the diabase had been partially shattered by the extreme thermal and pressure effects present, it is conceivable that pieces could have been swept into the margins of the magma chamber.

C. THE MAFIC ROCKS

The subdivision of these rocks and their average thickness are given in Table II.

Zone I

This zone occurs directly above the Basal Zone and is characterized by a large variety of rock types. The division of the zone is based largely on mineralogical criteria and rigorous description cannot be undertaken without reference to them. For this reason the description in this section is only a broad outline.

The most important feature of this zone is the extensive development of pegmatoid and anorthosite and the significant sulphide mineralization which is associated with the pegmatoid.

TABLE II. SUBDIVISION AND THICKNESS OF THE MAFIC ROCKS

Zone	Subzone	Rock Type	Thickness in metres			
			Ongezien	Section	Kaallaagte	Section
IV	D	Olivine bearing diorite	min 24		min 24	
	C	Diorite and magnetite layers	726		650	
	B	Anorthosite	89			
	A	Diorite	137			
		Base of diorites		976		674
III	B	Magnetite gabbro and magnetite layers	130		50	
	A	Anorthosite	67		73	
				197		123
II	B	Gabbro and norite overlain by a magnetite gabbro	180		360	
	A	Magnetite gabbro	142		58	
		Base of magnetite gabbros		322		418
I	D	Gabbro and norite	119		441	
	C	Diorite	22		11	
		Marker Horizon		141		452
	B	Gabbro, norite, anorthosite and pegmatoids	158		67	
	A	Diorite	min 54		43	
				212		110
			TOTAL	1848	TOTAL	1777

min = the minimum possible thickness

Subzone A

The diorite is medium-grained and dark grey in colour. It contains abundant magnetite and is closely associated with pegmatoid containing sulphide mineralization. There appears to be a greater thickness developed in the Ongezien than the Kaallaagte section.

Subzone B

This subzone is similar to Subzone A except that the finer-grained rocks are gabbros, magnetite gabbros and norites instead of diorites. Pegmatoid and anorthosite are still very abundant and the sulphide mineralization is significant.

Marker Horizon

The presence of this horizon cannot be recognized macroscopically because it consists of a compositional break in the cryptic layering.

Subzone C

The Marker Horizon forms the base of this subzone which is developed only in KLG/2 and P.D. The diorite is medium- to coarse-grained, dark coloured and contains fairly large amounts of mineralized pegmatoid..

Subzone D

This subzone is very much thicker in the Kaallaagte section than in the Ongezien section. The norites and gabbros form a fairly monotonous succession of brownish, medium-grained rocks with the occasional development of anorthosite and pegmatoidal layers. Disseminated sulphides occur in the coarse-grained pegmatoidal layers.

Zone II

This zone is characterized by rocks with a moderate to low amount of modal magnetite. The whole zone can be considered as transitional between the magnetite-poor Zone I and the magnetite-rich Zone III.

Subzone A

The magnetite gabbro of this subzone is brown and medium-grained and shows fairly well developed layering. A single 150 mm layer of magnetite was intersected in ONZ/1 and as it is the lowest layer intersected in the succession, it has been called layer No. 1.

Subzone B

The rocks of this subzone are virtually indistinguishable in the hand specimen from those of Subzone A. The diorite of ONZ/1 (Folder II) has been classified from only one sample and more detailed sampling would probably limit its extent considerably. It is not considered to be typical of this zone. The magnetite gabbro intersected in ONZ/2 and KLG/1 at the top of the subzone really belongs in Zone III but it was felt that the base of the overlying anorthosite of Subzone IIIA would make a more prominent horizon to act as a division between the two zones. A 0,12 m thick magnetite layer (no. 2) was intersected in ONZ/1.

Zone III

The main rock types in this zone are magnetite gabbros.

Subzone A

This subzone consists of a prominent, dark grey, medium- to coarse-grained anorthosite. It is about 70 m thick and was intersected in all the boreholes which penetrated this part of the succession.

Subzone B

Overlying the anorthosite of Subzone IIIA is a dark brownish grey, medium-grained magnetite gabbro in which several magnetite layers (no. 3–7) were intersected in ONZ/1 and ONZ/2. No magnetite layers were found in the Kaallaagte section because only the bottom 50 m of this subzone were intersected by borehole KLG/1.

Zone IV

This zone has not been fully intersected by boreholes in the Ongezien section and a gap of 170 m occurs. Three hundred and eighty metres are missing in the Kaallaagte section where Zone IV has not been intersected at all. It is important to note that additional magnetite layers may be present which have not been intersected due to this gap.

Subzone A

The diorite here is dark brown and medium-grained. Magnetite layers do not occur in this subzone, although there is a fair amount of magnetite present in the rock.

Subzone B

The anorthosite is light grey in colour and medium- to coarse-grained. Although this subzone is not intersected in ONZ/2, the trend of the modal analyses of the rock strongly suggests a similar horizon a little higher in the succession. It is possible that this anorthosite would make a very good marker horizon. Magnetite layers (no. 8, 9 and 10) are developed in ONZ/1.

Subzone C

This subzone is not fully represented in the intersection of the area. It does, however, have numerous well developed magnetite layers (no. 11–18). The diorite is light brownish grey, medium-grained and contains abundant magnetite. Layering in UC361 is well developed.

Subzone D

The diorite is dark brown in colour and medium-grained. It is characterized by occasional, well developed veins of granitic material. This zone has been classified on mineralogical grounds by the appearance of olivine. On the appearance of the hand specimens it is not possible to differentiate with any confidence this zone from Subzone C.

D. THE ROOF ROCKS

Although these rocks were not intersected by any of the boreholes, their position in the Layered Sequence (Fig. 4 and 5) has been postulated from the mineralogical composition of the rocks in UC361.

VI. METHODS OF INVESTIGATION

A. MODAL ANALYSIS

Modal analyses of the thin sections were carried out using the Swift Automatic Point Counter. Approximately 1 700 counts were registered per slide over an area of about 360 mm^2 in the case of the rocks of the Layered Sequence and 160 mm^2 in the case of the finer-grained diabase. The concept of I.C. No. of the specimen as introduced by Chayes (1956, p. 72) was also applied.

Gangue minerals were not included in the modal analyses of the sulphides. The analysis of those polished specimens which contained large amounts of sulphides was undertaken using the Swift Automatic Point Counter. As some of the intergrowths were exceptionally fine-grained, the movement of the slide was set to the minimum spacing of $^1/20$ mm. Not less than 1 000 points were counted on each specimen, although the usual number was in the order of 4 000. Where the sulphides occurred in minor amounts only, use was made of an integrating eyepiece and a mechanical stage. This enabled a statistically large enough number of points to be counted.

B. UNIVERSAL STAGE

1. Plagioclase

In most cases a Carlsbad-albite or a Carlsbad twin was selected and determinations of the vibration directions of each twin lamella were undertaken. The position of the (010) composition plane with regard to the optical orientation was also observed and the information plotted on the stereonet. The migration curves given by Burri *et al.* (1967) were then used to determine the composition of the plagioclase. This was followed by determinations of Eulerian angles (Burri *et al.*, 1967, p. 130). Finally the extinction angles of the Carlsbad-albite twins were determined and the anorthite content read off from the graph given in Tröger (1959, p. 102). This gave a total of fifteen values. Determinations of optic axial angles were undertaken using conoscopic illumination and interference figures. The values obtained were corrected for the difference in refractive index between the mineral and the hemisphere using the tables in Tröger (1959, p. 124).

Occasionally, when none were available in thin sections, twins other than Carlsbad-albite or Carlsbad were plotted and the values were read off in the usual manner from the migration curves. The values thus obtained were then checked by determining the maximum extinction angles of the Albite twins (Tröger, 1959, p. 101).

2. Orthopyroxene and Olivine

Conoscopic illumination and interference figures were used to measure the optic axial angles of the orthopyroxene and olivine. The values obtained were again corrected for refraction, using the table in Tröger (1959, p. 124). By reference to the diagram in Tröger (1959, p. 59) the mol. per cent orthoferrosilite in the orthopyroxene could be determined. Only crystals which displayed both isogyres were used and the average of about four determinations was taken. It was found that if the rock sections were cut at right angles to the plane of the layering there was a greater chance that the crystals would be suitably orientated for 2V measurements. The average of at least three direct readings of olivine was taken and the corrected value was used to obtain the composition from the curve supplied by Tröger (1959, p. 37).

3. Clinopyroxene

Conoscopic illumination was employed and the optical orientation plotted on a stereogram with the help of interference figures. Values for the optic axial angle (2V) were determined on the same crystal in the same orientation, again using the interference figures. Only crystals which gave direct readings were used. The values obtained were corrected for refraction using the tables in Tröger (1959, p. 124). Finally the pole of either the (110) cleavage or the (100) parting was plotted and from this the angle between the c crystallographic axis and the Z vibration direction could be measured directly on the stereogram.

C. X-RAY DIFFRACTION TECHNIQUES

1. Plagioclase

X-ray determinations were carried out on reasonably pure plagioclase separated from samples of crushed rock using the Franz Isodynamic Separator. The Guinier-Jagodzinski Double-Cylinder camera was used. It was mounted to give forward reflections and the samples were exposed to $CuK\alpha_1$ radiation. The $4\theta(131)$, $(\bar{1}31)$, (241) and $(\bar{2}41)$ lines were measured and the per cent anorthite was read off directly from the curves given in Tröger (1967, p. 748–749). It was found that the reflections relating to $2\theta(131)-2\theta(1\bar{3}1)$ were sensitive to small changes in composition but those relating to $2\theta(\bar{2}41)-2\theta(\bar{2}\bar{4}1)$ were not. In addition, this latter curve persistently gave values of about 3 per cent higher than those obtained by other methods. In many cases these values were not used.

Because of a flattening of the curves in the compositional range An_{32} to An_{50}, those supplied by Tröger (1967, p. 748–749) can only be used for plagioclase richer in calcium than An_{50}. A fairly large number of samples fell within this range but no suitable alternative curves appear to exist.

The plagioclase of the diabase differs from that of the Layered Sequence in that the anorthite content exceeds 60 per cent in many cases. Reference could thus be made to a curve drawn up by Desborough and Cameron (1968, p. 118) from information obtained for plagioclases from the Eastern Bushveld. This curve relates the value of $2\theta_{131}+2\theta_{220}-4\theta_{1\bar{3}1}$ to weight per cent anorthite. All other X-ray and optical determinations were expressed in mol. per cent, but according to Deer *et al.* (1966, p. 322) the divergence from weight per cent is approximately one per cent and thus within the range of experimental error.

2. Apatite and Cordierite

Determinations on samples of these minerals were undertaken in a similar manner to those used on the plagioclase as far as experimental procedure was concerned.

D. DETERMINATION OF REFRACTIVE INDEX

As the pyroxene had been separated from the plagioclase in the crushed rock, refractive indices of the orthopyroxene could conveniently be determined. No attempt was made to separate the clinopyroxene from the orthopyroxene as they could be distinguished easily under the microscope. As many of the crushed fragments of orthopyroxene lie on the (110) cleavage plane, accurate results can be obtained by matching the refractive index γ with immersion liquids.

The refractive index β of the olivine was also determined by the immersion method. Mixtures of methylene iodide and sulphur/phosphorus were used for those of Zone IV. As a universal stage was not used to orientate the fragments exactly, more reliance was placed on the values obtained by 2V measurements.

VII. THE MINERALOGY OF THE LAYERED SEQUENCE

A. MODAL ANALYSES

1. General

In order that the rocks of the Layered Sequence could be classified accurately, a modal analysis was essential. In addition, it was hoped that a study of the mode would reveal information on the differentiation trends and variations between the relative proportions of minerals in the sequence. Modal analyses were also undertaken to obtain an idea of which specimens could be considered average in the various zones for representative chemical analyses. Most of the rocks have an I.C. No. in the region of 50 and no determinations were undertaken on rocks with an I.C. No. of less than 20.

2. The Basal Zone

The suggestion, based on macroscopic observations, that this zone consists of three cyclic units, is supported by evidence obtained from modal analyses (Fig. 6), especially in rocks which occur between -115 m and -88 m. The content of olivine increases downwards to form a very prominent dunitic horizon at the base. There is a well defined break just below this dunite. The same increase in modal olivine occurs towards the base of the next cyclic unit at -124 m. Although modal orthopyroxene tends to decrease downwards, the increase in the olivine is large enough to result in an overall increase in the content of the mafic minerals of the rocks.

The rocks between -134 m and -124 m do not show the above relationship, although a similar trend may be observed with further sampling. The base of this unit consists of a mineralized pegmatoidal pyroxenite.

3. The Mafic Rocks

One of the strongest trends revealed by modal analyses (Folders I–III) is the inverse relationship between magnetite and orthopyroxene. This relationship was readily observed when the examination of the orthopyroxene was undertaken. The Kaallaagte section, which has very little modal magnetite, has large amounts of orthopyroxene, adequate for optical determinations. In the rocks of the Ongezien section, however, there is abundant magnetite and consequently the orthopyroxene is comparatively scarce, often intercumulus and difficult to work on. In addition, because of the few crystals present in the slide, they do not always have convenient orientations.

No clear relationship between the orthopyroxene and the clinopyroxene could be established, although they do tend to be inversely related. This may be due to the very pronounced inverse relationship between magnetite and orthopyroxene. An interesting feature of the Ongezien section is the virtual absence of modal orthopyroxene from the Marker Horizon downwards.

The behaviour of plagioclase is best illustrated by reference to ONZ/1 where the content drops to as low as 45 per cent in Subzone IVC and then rapidly increases to such an extent that anorthosite is formed in Subzone IVB. Repetition of this trend results in at least four felspathic layers separating more mafic layers. It is possible that each of these mafic layers represents the beginning of a period of gravity settling followed by homogenization of the crystallizing magma directly above the unit formed.

B. PLAGIOCLASE

1. General

The values used in plotting the curves in Folders I, II and III have been obtained from the average of universal stage and X-ray diffraction methods. The vast majority of the rocks fell in the region of An_{50} and reference was seldom made to optic axial angles, as the curve is very flat in this region.

2. Chemical Analyses

Three rock samples were crushed and the plagioclase separated and submitted for chemical analysis. The results are given in Table III. Specific gravity determinations were undertaken using a pycnometer. In Table IV the anorthite content obtained from the various optical and X-ray methods for these three samples is compared with the mol. per cent anorthite calculated from the chemical analyses. There is a reasonable agreement in anorthite content calculated from the chemical analyses and that determined by other methods for sample P.D.–910. Very poor agreement, however, was obtained for KLG/1–1769 and UC361–391. As particular care was taken in selecting samples in which the plagioclase showed little or no zoning and in obtaining pure samples, the reason for this discrepancy is not easy to explain. Von Gruenewaldt (1971, p. 92) noted a similar poor agreement in the plagioclase of the Eastern Bushveld. It is significant, however, that the chemical analysis of only P.D.–910 adds up to nearly one hundred per cent whereas UC361–391 is almost one per cent out. If the error is in the sodium determination the anomalously high proportion of calcium in the plagioclase can be explained.

Appendix to Table III (p.26)

UC361–391	from diorite of Zone IVC
KLG/1–1769	from hypersthene gabbro of Zone IIB
P.D.–910	from anorthositic norite of Zone ID

TABLE III. CHEMICAL ANALYSES AND FORMULAE OF PLAGIOCLASE FELDSPARS

		UC361–391	KLG/1–1769	P.D.–910
	SiO_2	57,40	55,48	56,35
	Al_2O_3	25,83	28,05	27,83
	Fe_2O_3	0,03	0,17	0,05
	TiO_2	0,06	0,07	0,10
	MgO	0,00	0,28	0,25
	FeO	0,43	0,31	0,52
	CaO	8,95	11,05	10,25
	Na_2O	4,63	3,41	3,74
	K_2O	0,79	0,40	0,35
	P_2O_5	0,68	0,03	0,01
	H_2O^+	0,25	0,11	0,30
	H_2O^-	0,03	0,02	0,04
		99,08	99,38	99,79
	Numbers of ions on the basis of 32(0)			
Z	Si	10,378	10,031	10,143
Z	Al	5,504	5,978	5,905
Z	Fe^{+3}	0,004	0,024	0,006
Z	Ti	0,009	0,010	0,014
X	Mg	–	0,075	0,067
X	Fe^{+2}	0,065	0,047	0,078
X	Ca	1,734	2,140	1,977
X	Na	1,623	1,195	1,304
X	K	0,182	0,091	0,080
X	P	0,104	0,004	0,002
	Z	15,90	16,04	16,07
	X	3,71	3,55	3,51
Mol.	Ab	45,9	34,9	38,8
Mol.	An	49,0	62,5	58,8
Mol.	Or	5,1	2,6	2,4
	D	2,67 (± 0,01)	2,68 (± 0,01)	2,70 (± 0,01)

Analyst: National Institute for Metallurgy, Johannesburg.

TABLE IV. VALUES OBTAINED FOR MOL. PER CENT ANORTHITE IN PLAGIOCLASE USING DIFFERENT DETERMINATIVE METHODS

Method	UC361–391	KLG/1–1769	P.D.–910
Chemical analyses	49	63	59
Extinction angles	38	52	56
Migration curves	39	52	58
Carlsbad-albite twin	37	52	56
Eulerian angle	37	52	56
n glass*	37	54	54
$2\theta_{131}$-$2\theta_{1\bar{3}1}$(Cu$K\alpha_1$)	–	53	56
$2\theta_{\bar{2}41}$-$2\theta_{\bar{2}\bar{4}\bar{1}}$(Cu$K\alpha_1$)	–	53	57

*Determined by A.A.C. Klop, I.S. Venter, C.J.B. Smit and P. Vermaak, from the curve supplied by Tröger (1959, p. 99).

3. Compositional Variations in the Mineralized Pegmatoid and the Anorthosite of Zone I

a. General

This zone occurs just above the Basal Zone and reference to Folders II and III indicates the following factors which serve to distinguish it from the rock types higher in the succession.

1. In contrast to the general tendency of a magma to become enriched in albite with progressive differentiation, Subzone IC, observed in KLG/2 and P.D. is dioritic in composition. From this zone a trend towards a lower albite content is observed in an upward direction. This trend, which is present to a greater or lesser degree in all the boreholes shown in Folders II and III, reaches a maximum value of anorthite at about the middle of Subzone ID. The orthopyroxene shows a sympathetic trend towards a lower ferrosilite content in an upward direction.

2. The distinct break in the trend at the Marker Horizon has not been observed elsewhere in the Layered Sequence. Directly below the marker the plagioclase is up to 11 per cent richer in the anorthite end member than 35 m higher in the succession.

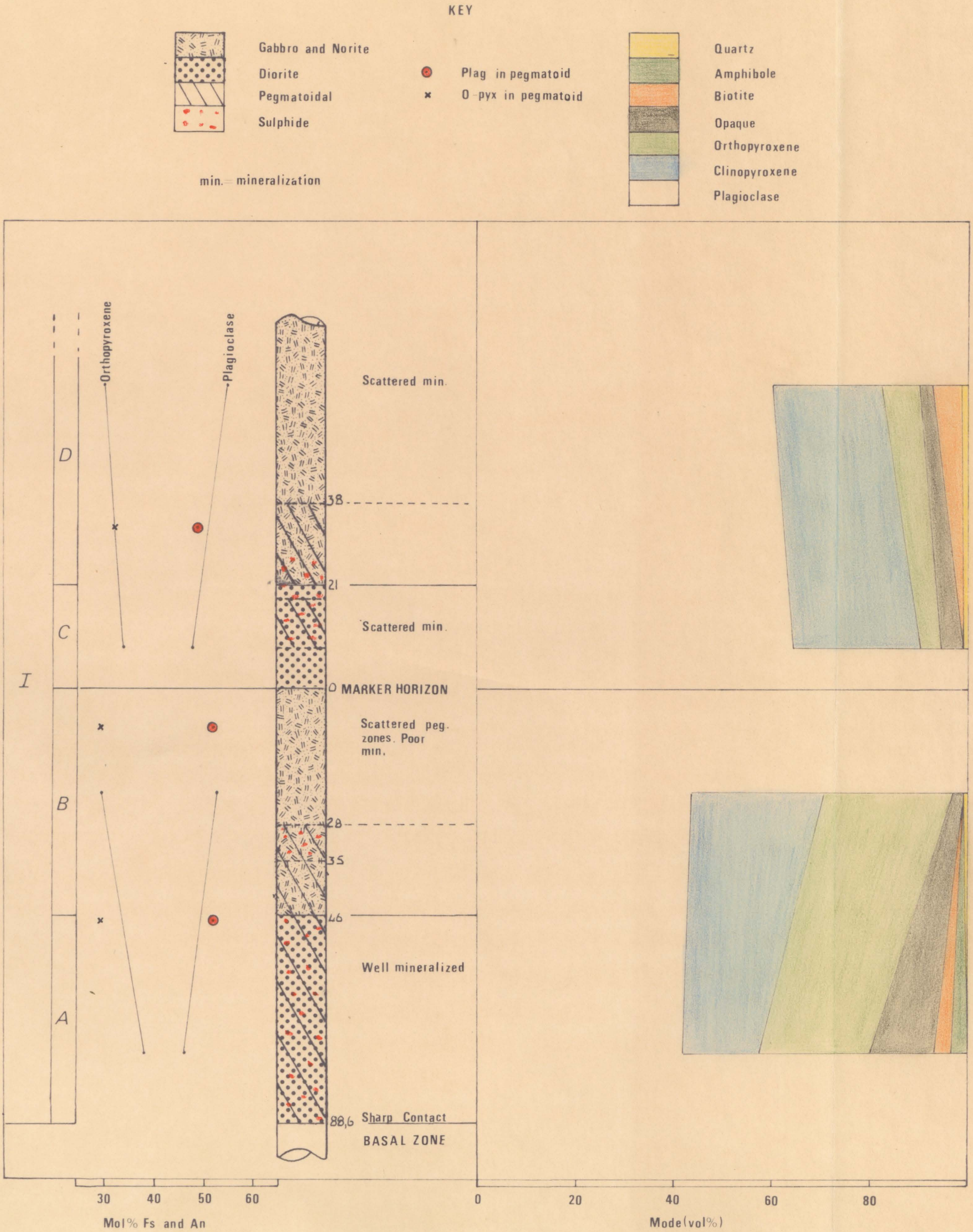
3. This zone is characterized by a much greater abundance of anorthosite and pegmatoid than other zones in the Layered Sequence.

b. Petrographic Description

The only complete intersection of this zone was obtained in KLG/2 and for this reason it is used as the type section (Fig. 7) in this description. It differs, how-

FIG 7. KAALLAAGTE 2. SECTION THROUGH ZONE 1 SHOWING THE DISTRIBUTION OF THE PEGMATOIDS

SCALE 1:1000



ever, from most of the other boreholes which intersected Zone I in that pegmatoid predominates over anorthosite.

Subzone A. – Although not as clearly shown in KLG/2 as in ONZ/2, there appears to be a steady decrease in the albite content of the plagioclase from this subzone upwards towards the Marker Horizon. The upper limit of this subzone is taken from where the value becomes greater than An_{50}. The depth of penetration of some of the boreholes has been insufficient to reveal the subzone. The orthopyroxene crystallized as primary pigeonite and is associated with up to 13,3 per cent magnetite. The pegmatoid which occurs in this subzone is characterized by a coarse grain size (up to 5 mm) and is made up of orthopyroxene, clinopyroxene and plagioclase which shows strong zoning.

Subzone B. – The upper limit of this subzone is the Marker Horizon. The gabbros and norites that are developed are nearly always very coarse-grained and the transition between them and the pegmatoid is very vague. Likewise it is difficult to detect the transition between the anorthosite and the pegmatoid. The plagioclase in the coarse-grained varieties of rocks is usually strongly zoned and often saussuritized, whereas orthopyroxene occurs in minor amounts and is usually intercumulus.

The sulphide mineralization is very abundant and is usually associated with pegmatoid and magnetite-rich rocks. The anorthosite grades from medium- to coarse-grained and is dark grey in colour. It contains only minor amounts of disseminated sulphide.

Subzone C. – As with Subzone A, the diorite of Subzone C in boreholes KLG/2 and P.D. has been delineated on mineralogical grounds. This subzone does not seem to be developed in boreholes ONZ/1, ONZ/2 and KLG/1. It is, however, of interest that the anorthite content of the plagioclase in the lower half of Subzone D in these boreholes tends to decrease downwards. Closer investigation of the rocks may reveal the existence of a dioritic zone in these boreholes. The plagioclase of this subzone does not appear to be as strongly zoned as that in the lower horizons.

Subzone D. – This subzone is characterized by a very marked decrease in sulphide mineralization and contains only poorly developed pegmatoid and anorthosite. The upper limit is taken as the first appearance of the magnetite gabbro of Subzone IIA.

4. Compositional Variations in the Mafic Rocks

The compositional trend of the plagioclase starts at a maximum value of about An_{55} just above Subzone IC and decreases to a minimum value of about An_{38}

at the top of Subzone IVD. Generally speaking there is a gradational trend between these two extreme values, but fluctuations occur of up to 10 mol. per cent anorthite in the norites, gabbros and magnetite gabbros of Zones II and III. The tendency is for the more calcic plagioclase to occur in rocks with a high content of mafic minerals; this would seem to suggest the presence of cyclic units.

Subzones IVA, B and C are marginally dioritic with a composition of An_{48} in the plagioclase. From the top of Subzone IVC there is a rapid decrease to An_{38} in the plagioclase to near the top of Subzone IVD.

5. Zoning

Zoning of the plagioclase feldspars in the medium-grained rocks of the Layered Sequence is usually present only to a minor extent. Zoning does, however, become better developed in the coarse-grained pegmatoid and anorthosite of Zone I. Two types of zoning have been observed, that is normal and oscillatory zoning.

a. Normal Zoning

Determinations of mol. per cent anorthite on zoned plagioclase in P.D.–1770 gave a value of An_{53} at the core and An_{49} at the rim, while UC361–346 gave values of An_{39} and An_{34} respectively. In order to obtain an idea of how the anorthite content varies in the successive shells of zoning, use was made of a mechanical stage fitted to the universal stage. Values determined on a crystal could then be reproduced accurately by reference to co-ordinates. The results for normal zoning using this method are given in Fig. 8a..

According to Wager and Brown (1968, p. 65) low temperature rims will result in plagioclase orthocummulates when the residual trapped liquid fails to react with the cumulus crystals over a range of falling temperatures.

b. Oscillatory Zoning

An example of this type of zoning is given in Fig. 8b. Oscillatory zoning appears to be confined to the pegmatoid and the anorthosite of Zone I.

Phemister (1934, p. 553) gives four possible causes which could give rise to oscillatory zoning. These are:

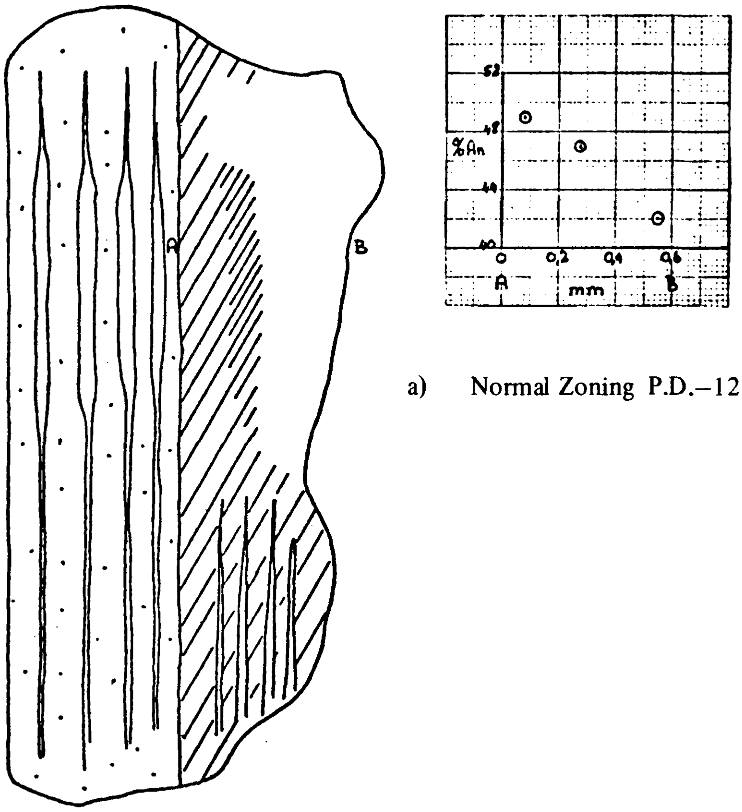
(a) Movement of crystals in the magma, whether by gravitational settling or by convection currents.

(b) Movement of the magma as a whole into a region where different conditions of temperature and pressure prevail.

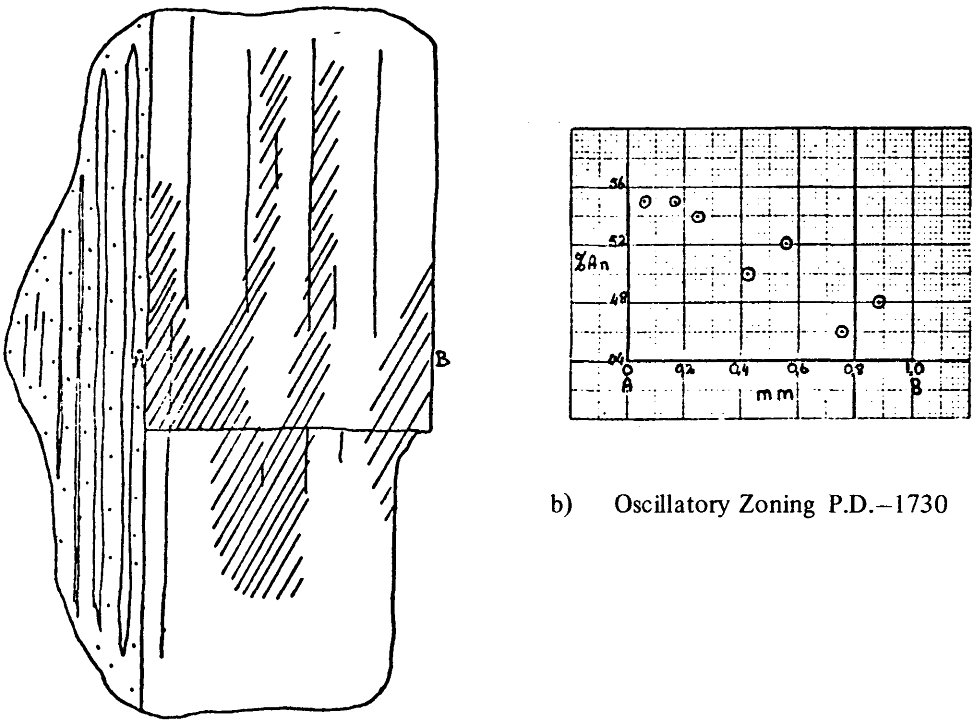
(c) Eruption of additional magma into the crystallizing liquid.

(d) Loss of volatile constituents.

FIG. 8 DIAGRAM ILLUSTRATING THE VARIATION IN ANORTHITE CONTENT IN ZONED PLAGIOCLASE CRYSTALS



a) Normal Zoning P.D.–1210



b) Oscillatory Zoning P.D.–1730

As oscillatory zoning is rare in the rocks studied, it is felt that had the first two alternatives been responsible, it would have been far more widespread. The third alternative may have had some influence as injection of sodic pegmatoidal fluids into the rocks of Zone I is suggested in a later chapter as having taken place. In view of the coarse grain size of the rocks, a factor which is associated with a high volatile content of magma, it is considered that the last alternative had an important effect.

Eales (1959, p. 93) cites volatiles as playing an important part in the development of oscillatory zoning in the Kale Dolerite Sheet, where evidence of volatiles is partially furnished by the presence of thick lenses of dolerite pegmatite. Turner and Verhoogen (1960, p. 101) explain oscillatory zoning as being due to fluctuating water pressures. An increase in the water pressure would result in the production of crystals of a more calcic composition.

6. Textural Features

Bending of the plagioclase crystals is a common feature in most of the thin sections and is illustrated in Fig. 9. Interpenetration of one plagioclase crystal by another is also widespread. According to Von Gruenewaldt (1971, p. 98) both features are due to compaction.

Myrmekitic intergrowths are very rare but the development of symplektite at the expense of plagioclase is common. The symplektite always surrounds a magnetite crystal and is separated from the magnetite by biotite (Fig. 10).

Intercumulus plagioclase occurs to a significant degree only in the Basal Zone (Fig. 11).

C. ORTHOPYROXENE

1. Compositional Variations

In plotting the results of determinations made on orthopyroxene, consideration had to be given as to whether the mineral represents cumulus or intercumulus phases. In most cases this could be determined visually without any difficulty. The composition of the intercumulus orthopyroxene is found to be up to 10 mol. per cent richer in Fs than values obtained in associated rocks on cumulus orthopyroxene. In ONZ/2 the composition of the orthopyroxene just above the Marker Horizon has a higher iron content than that of rocks slightly higher in the sequence. For this reason, the former is taken as being intercumulus, although this is not obvious in the thin sections.

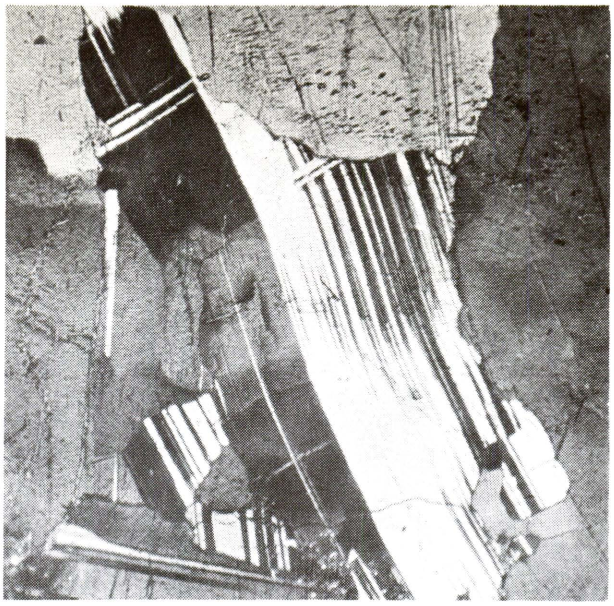


Fig. 9 Bent plagioclase crystal. Magnetite gabbro of Subzone IIB. ONZ/2–2000. Crossed nicols, x33.

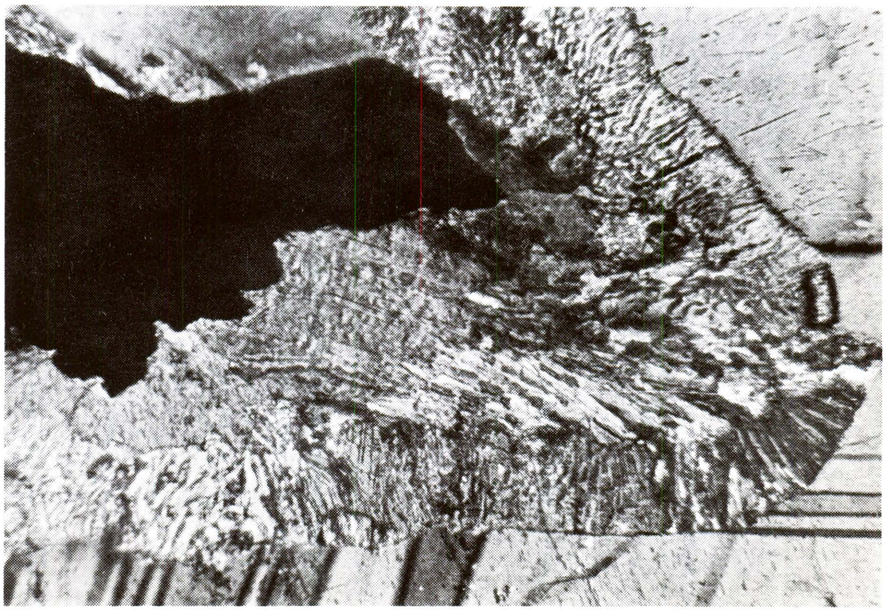


Fig. 10 Symplektite surrounding an outer zone of biotite and a core of magnetite. Magnetite gabbro of Subzone IIB. ONZ/2–2000. Crossed nicols, x120.

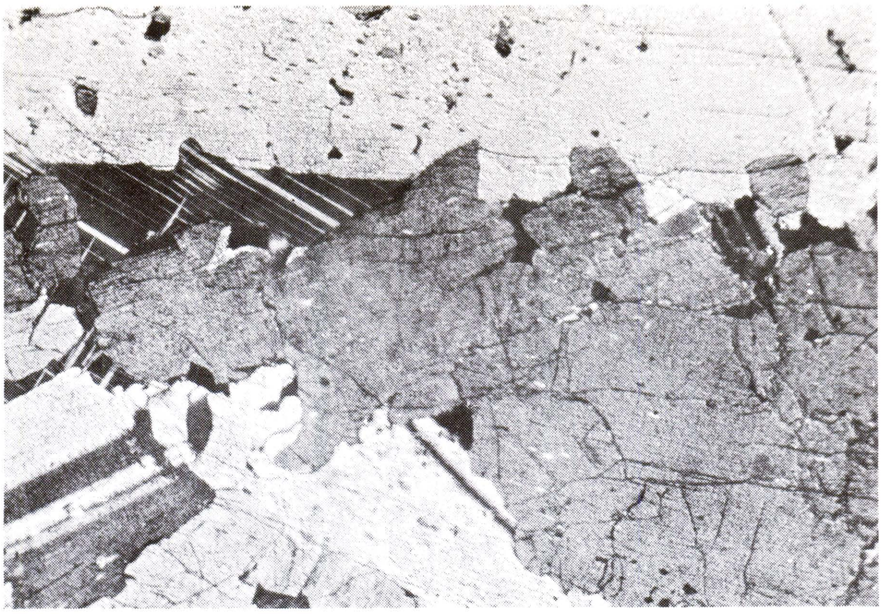


Fig. 11 Porphyritic pyroxenite of the Basal Zone showing large orthopyroxene crystals and intercumulus plagioclase. KLG/2–3559. Crossed nicols, x26.

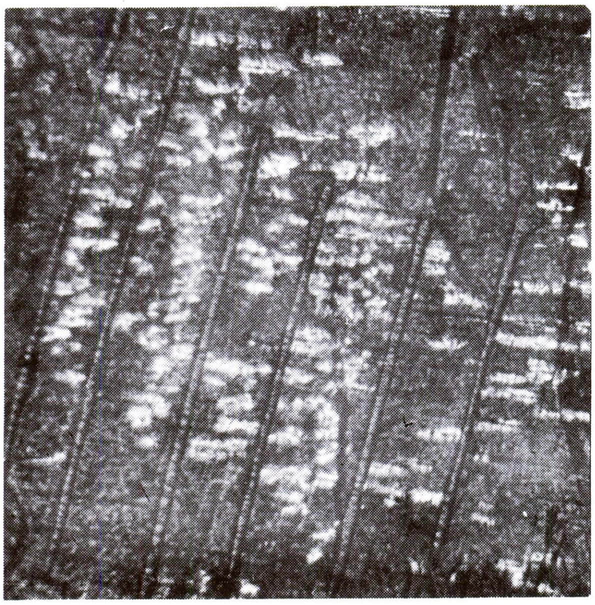


Fig. 12 Orthopyroxene showing broad pre-inversion exsolution lamellae of augite and narrow post-inversion exsolution lamellae of augite parallel to the (100) plane. Olivine diorite of Subzone IVD. UC361–331. Crossed nicols, x120.

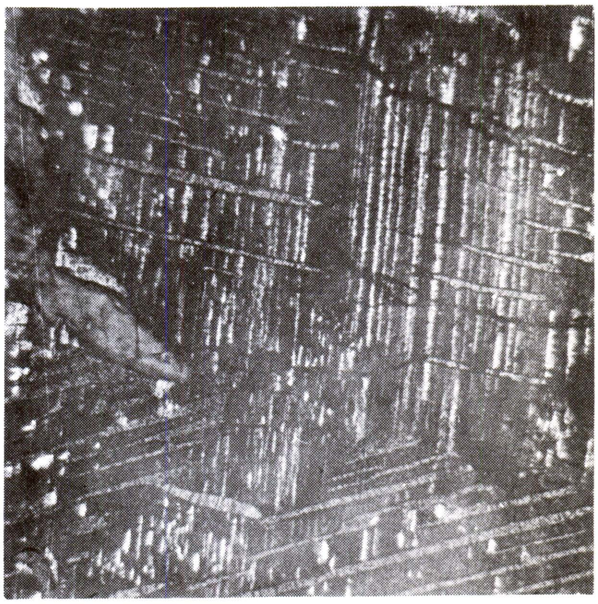


Fig. 13 Orthopyroxene showing broad pre-inversion exsolution lamellae of augite in two different orientations and narrow post-inversion exsolution lamellae of augite parallel to the (100) plane. Olivine diorite of Subzone IVD. UC361–331. Crossed nicols, x120.

a. Basal Zone

As the iron content of the orthopyroxene and the olivine varies sympathetically (Fig. 6) in this zone they can conveniently be described together. The most important feature of this zone is the iron-poor nature of these minerals. As the peridotite represents an accumulation of the early formed iron-poor crystals of orthopyroxene and olivine, this feature can be considered the normal result of the differentiation of a mafic magma.

Variations in composition within the Basal Zone duplicate the findings of the modal analyses which have shown that there are at least three periods of gravity settling. The decrease in iron in both the olivine and orthopyroxene in an upward direction between -124 m and -115 m and in the lower part of the following unit is anomalous. Jackson (1970, p. 420) quotes a similar case from the lower part of the Western Bushveld Complex and is of the opinion that the reversal is due to supercooling at the lower margin.

b. The Mafic Rocks

The increase in the iron content of the orthopyroxene is always reflected by a decrease in the anorthite content of the plagioclase. The trends observed in the plagioclase thus also apply to the orthopyroxene. The generalized trend is towards an increase in iron from Fs_{32} just above the Marker Horizon to a value of Fs_{35} in the upper part of Zone IV whence a rapid increase to Fs_{62} is observed.

2. Exsolution Textures

In addition to the narrow exsolution lamellae of augite parallel to the (100) plane of most of the orthopyroxene crystals in the Layered Sequence there are, amongst the dioritic rocks, several cases where sets of broad exsolution lamellae have developed (Fig. 12 and 13). These are indicative of inversion of primary pigeonite to orthopyroxene, as described by Poldervaart and Hess (1951, p. 482–483). This takes place when the magma crystallizes at a higher temperature than the pigeonite-orthopyroxene inversion. The orientation of the pre-inversion exsolution lamellae of augite in the orthopyroxene has been dealt with by Von Gruenewaldt (1970, p. 70), who concludes that they have a random orientation.

When the magma crystallizes at a lower temperature than that at which inversion from primary pigeonite to orthopyroxene takes place, discrete crystals of augite and orthopyroxene form. Approximately $3^1/_2$ per cent Ca^{+2} ions are contained in the structure of the primary orthopyroxene and in slow-cooling plutonic bodies this calcium exsolves as augite in the form of exceedingly narrow exsolution lamellae parallel to the (100) plane in orthopyroxene (Poldervaart and Hess, 1951, p. 481–482).

The composition of the orthopyroxene where the crystallization curve of the magma intersects the pyroxene inversion curve in basaltic magmas is given by Poldervaart and Hess (1951, p. 478) as usually Fs_{30}. In the Layered Sequence inverted pigeonite occurs in abundance in Zone IV from +1381 m upwards. This represents the point of intersection of the crystallization curve of the magma and the pyroxene inversion curve and occurs at a value of Fs_{35}. Primary orthopyroxene was observed at +1513, 6 m when the iron content dropped to Fs_{33}. Exsolution textures were not observed in UC361–475, where a value of Fs_{50} was recorded. This may be due to the pigeonite being calcium-poor. The low anorthite content of the plagioclase in this sample, together with the large amounts of modal apatite, suggests that the calcium in the magma may have been taken up preferentially by the apatite.

In the dioritic rocks of Subzone IC where values of Fs_{38} are reached, well developed pre-inversion exsolution lamellae of augite occur in the orthopyroxene. In the mafic rocks higher in the sequence the composition of the primary orthopyroxene increases to as much as Fs_{39}.

D. OTHER SILICATES

1. Clinopyroxene

The optical properties of a number of clinopyroxenes are given in Table V.

TABLE V. OPTICAL DETERMINATIONS CARRIED OUT ON THE CLINOPYROXENES OF KAALLAAGTE/2

Sample number	Height from marker	$c \wedge \gamma$	2V	β	Zone	Sub-zone
610	+711,9	40°	52°	–	II	B
1043	+593,8	39,5°	53°	–		
1583	+446,5	42,5°	49°	–	II	A
1775	+394,1	41°	49°	–		
2206	+276,6	32,5°	46,5°	–	I	D
3300	– 21,2	40°	46°	1,686	I	B
3586	– 97,1	42°	50,5°	1,706	Basal Zone	

Clinopyroxene is almost always present in the rocks of the Layered Sequence and an attempt was made to determine its compositional trends. Owing, however, to the very small changes in the optical and crystallographic properties of the clinopyroxene with composition, together with the large number of variables involved, it is difficult to obtain accurate results. The best means of determination are those of chemical analyses and without them no reliable conclusions can be drawn.

2. Olivine

Owing to the fact that olivine occurs in significant amounts only in the Basal Zone, very few determinations have been undertaken on them.

The variations in the Basal Zone have already been discussed and the only other occurrence of olivine is in Zone IVD which is made up of the first 23 m of UC361. As only the last 10 m was unweathered rock no trends could be distinguished. The composition of the olivine was found to be Fa_{75}.

The termination of the crystallization of olivine and its subsequent reappearance higher in the sequence very much enriched in iron is well known in other parts of the Bushveld Complex (Von Gruenewaldt, 1971, Folder III; Molyneux, 1970a, Fig. 12) and in the Skaergaard Intrusion (Wager and Brown, 1968, p. 38). This feature is caused by the strong gravity differentiation of the crystals which prevents complete reaction with the liquid and gives rise to the temporary cessation of olivine crystallization (Wager and Brown, 1968, p. 38; Barth, 1962, p. 103).

E. APATITE

The modal analyses of the rocks of the Layered Sequence indicate that apatite occurs in significant quantities (up to 11 per cent) only at the top of Zone IVC and in Zone IVD.

1. Determinative Methods

a. X-Ray Diffraction

The cell parameters a_o, c_o and c/a were obtained by indexing the lines with the aid of the Powder Data File and calculating a_o and c_o using the reflections 41.0 and 00.4 respectively. The $\sin^2\theta$ values for the other lines are then calculated so that the measured 2θ values for the 41.0 and 00.4 can be checked. The ratio c/a was also measured, using the method of Brasseur as modified by Förtsch (1970, p. 224) from the relationship:

$$c/a = \sqrt{\frac{4+2m}{4m+7}}$$

$$\text{where } m = \frac{\text{distance between 41.0 and 00.4}}{\text{distance between 21.3 and 32.1}}$$

The results are given in Table VI. The specific gravity of the mineral was determined by using the pycnometer and the refractive indices were determined using immersion liquids.

b. Chemical Analyses

Chemical analyses on two samples of apatite were undertaken by the National Institute for Metallurgy in order to check the findings obtained by X-ray diffraction. The calculation of the chemical formula was carried out using the procedure given by Deer *et al.* (1966, p. 515) and the results are given in Table VI.

The presence of about 2 per cent silica in the analyses is anomolous and is ascribed to the abundant inclusions observed in the apatite (Fig. 15). These inclusions consist of lath-shaped pleochroic and colourless minerals oriented parallel to the c axis, as well as irregular, randomly orientated, opaque and colourless grains.

As can be seen, both analyses add up to only about 98,5 per cent. In view of the above considerations, this is probably due to alumina. No distinction was made between combined and hygroscopic water, thus the value for hydroxile is probably a little too high.

2. Compositional Variations and Economic Potential

Deer *et al.* (1962, p. 324) gave the following cell dimensions for end members of apatite:

	a(Å)	c(Å)	c/a
Fluor-apatite	9,35	6,87	0,735
Chlor-apatite	9,61	6,76	0,704
Hydroxy-apatite	9,41	6,87	0,731

The apatites thus show a variation of fluor-apatite in Subzone IVC to hydroxy-apatite at the very top of Subzone IVD (Fig. 14). The chemical analyses confirm this trend and both samples are fluor-apatites.

On the results of the phosphorus pentoxide values given in the chemical analyses of the samples a feasibility study on the economic potential of the apatite in UC361 may be considered justified. The results represent 3,4 and 4,1 weight per cent phosphorus pentoxide in the whole rock in samples UC361–311 and UC361–537 respectively.

TABLE VI. **CHEMICAL ANALYSES, FORMULAE AND PHYSICAL PROPERTIES OF APATITE FROM BOREHOLE UC361.**

UC361–311					UC361–537					UC361–391	
	Weight of oxides	Number of ions in formula				Weight % of oxides	Number of ions in formula				
P_2O_5	42,66	P	6,047	6,047	P_2O_5	41,47	P	5,895	5,895		
SiO_2	1,40	Si	0,234		SiO_2	2,10	Si	0,352			
Fe_2O_3	0,48	Fe^{+3}	0,060		Fe_2O_3	0,08	Fe^{+3}	0,010			
MgO	0,52	Mg	0,130		MgO	1,24	Mg	0,311			
FeO	0,29	Fe^{+2}	0,040		FeO	0,43	Fe^{+2}	0,061			
MnO	0,02	Mn	0,003	9,751	MnO	0,02	Mn	0,003	9,973		
Na_2O	0,28	Na	0,091		Na_2O	0,26	Na	0,085			
K_2O	0,04	K	0,008		K_2O	0,04	K	0,008			
CaO	51,18	Ca	9,182		CaO	50,80	Ca	9,140			
SrO	0,03	Sr	0,003		SrO	0,03	Sr	0,003			
F	2,92	F	1,546		F	3,37	F	1,790			
H_2O^+	0,23	OH	0,258	1,835	H_2O^+	0,12	OH	0,135	1,962		
Cl	0,11	Cl	0,031		Cl	0,13	Cl	0,037			
	100,16					100,09					
O≡F,Cl	1,25				O≡F,Cl	1,45					
	98,91					98,64					
ε	1,630	(±0,002)			1,630	(±0,002)					
ω	1,634	(±0,002)			1,634	(±0,002)					
D	3,15	(±0,01)			3,11	(±0,01)					
aÅ	9,394	(±0,003)			9,376	±0,003				9,382	±0,003
cÅ	6,889	(±0,003)			6,877	±0,003				6,881	±0,003
c/a calc.	0,733				0,733					0,733	
c/a meas.	0,734				0,734					0,734	

UC361–311 from olivine diorite of Zone IVD

UC361–537 from diorite of Zone IVC

UC361–391 from diorite of Zone IVC

Analyst: National Institute for Metallurgy, Johannesburg.

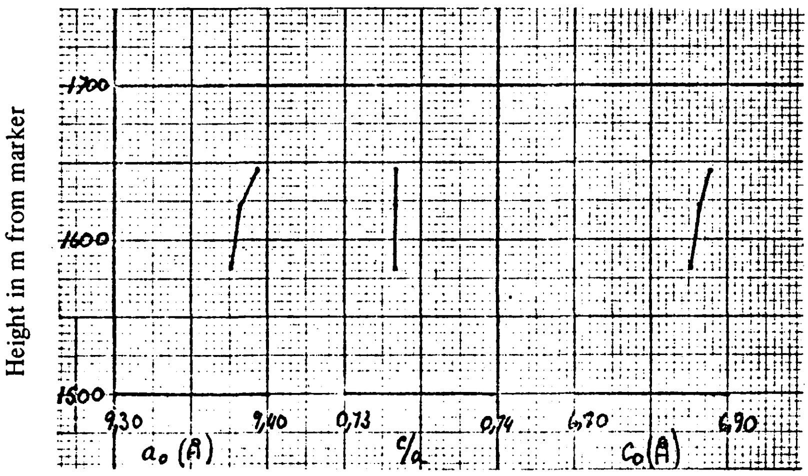


Fig. 14 Variation of cell parameters of apatite with height in the diorites of Zone IVC and D.

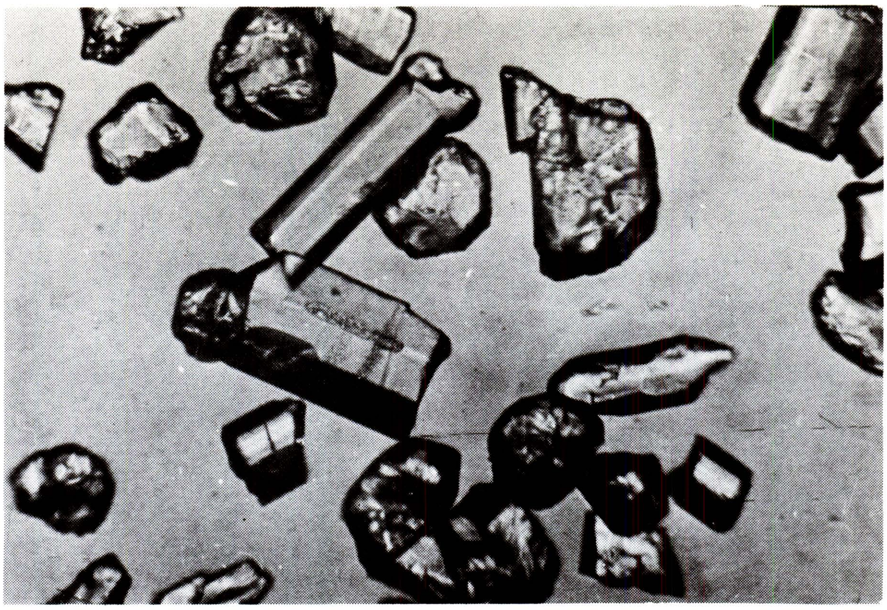


Fig. 15 Apatite grains showing prismatic habit and inclusions. Concentrate from UC361–391. Uncrossed nicols, x120.

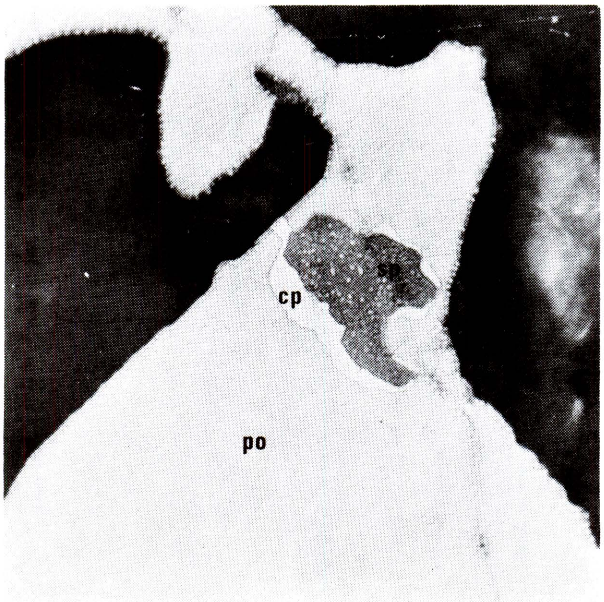


Fig. 16 Bleb of sphalerite (sp) with a rim of chalcopyrite (cp) set in pyrrhotite (po). Minute exsolution bodies of chalcopyrite occur in the sphalerite. Diorite of Subzone IVC. UC361–504. Reflected light, x260.

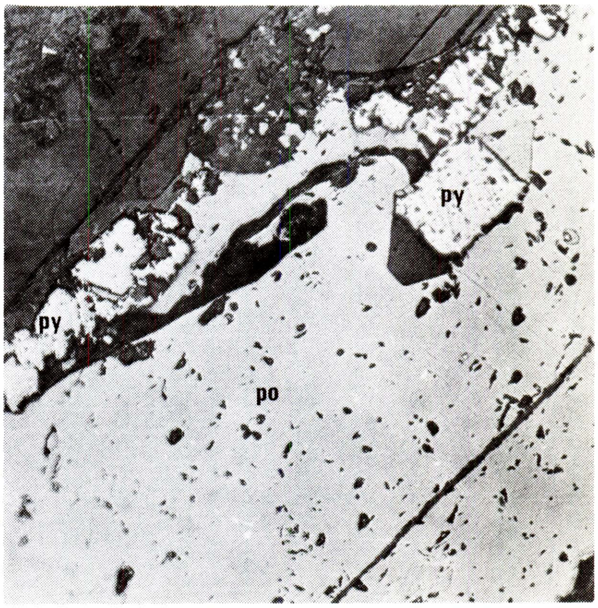


Fig. 17 Grain boundary of pyrrhotite (po) showing the characteristic occurrence of pyrite (py) at the outer margin. Diorite of Subzone IC. KLG/2–3201. Reflected light, x150.

According to Grobler and Whitfield (1970, p. 212) 5 weight per cent phosphorus pentoxide was used as the cut-off grade in the feasibility study of the apatite-bearing magnetites which are present in the Upper Zone of the Bushveld Complex in the Villa Nora area. They do say, however, that the value of 5 per cent phosphorus pentoxide is arbitrary, but it is assumed that it is not completely divorced from economic considerations. The deposits were considered to be uneconomic on the grounds that the apatite-rich zones were relatively narrow and steeply dipping (between 30^{o} and 60^{o}). This meant that mining could not be undertaken using open cast methods (Grobler and Whitfield, 1970, p. 226). An additional factor was the low grade of the deposit.

The dips of the rocks in UC361 are 10^{o} and this, together with an apatite-rich zone of over 70 m in width, may well make the top of Subzones IVC and D economically interesting. The average of only 4 per cent phosphorus pentoxide in the rock as a whole, however, is not encouraging, but further drilling may reveal deposits of a higher grade.

F. THE SULPHIDES

Minor amounts of disseminated sulphides occur throughout the Layered Sequence. Thirty-three representative specimens of ore were prepared for examination under the ore microscope.

1. Modal Analyses

The results obtained are given in Appendix II.

The graphical representation is given in Fig. 18 and shows a generalized trend. The trend was obtained by averaging the values from the same subzones in different boreholes. The boundary between two sets of analyses was taken as being the mid-point between the average sample heights.

The main features shown in Fig. 18 is the high proportion of pyrite at the top of the succession and just below the Marker Horizon, and the high concentration of chalcopyrite just above the Marker Horizon. There is a sharp decrease in the pentlandite content from the middle of the succession, where the highest values occur, to the top where it was not observed. A similar trend is shown by the chalcopyrite although trace amounts do occur at the top. Minor amounts of sphalerite occur near the top of the Layered Sequence (Fig. 16).

FIG 18 GENERALIZED SECTION SHOWING THE MODAL VARIATION OF THE SULPHIDE MINERALS

2. Assay Results

A large number of assay results were made available by the various Mining Companies and are summarized in Appendix II.

Not all the mineralized horizons have been sampled, but generally speaking the most significant mineralization occurs in Zone I. If KLG/2 is used as the type section, then Subzone B contains the highest values of 0,35 per cent nickel and 0,29 per cent copper.

In Table VII the copper and nickel content of the sulphides, calculated from the modal analyses, is compared with that obtained from chemical analyses. As can be seen, the chemical analyses show a higher nickel to copper ratio than the modal analyses. This is probably due to the presence of some nickel in solid solution in the pyrrhotite.

TABLE VII. COMPARISON BETWEEN Ni:Cu RATIO OBTAINED FROM MODAL AND ASSAY ANALYSES ON THE SULPHIDES OF KLG/2

Sample No.	Modal Analysis	%	Ni %	Cu %	Ni:Cu Ratio
3343	Pentlandite	3,0	0,66	–	29:71
	Chalcopyrite	4,7	–	1,62	
	Assay				
	Total in Rock	–	0,11	0,10	52:48
3472	**Modal Analysis**				
	Pentlandite	4,1	0,90	–	52:48
	Chalcopyrite	2,4	–	0,83	
	Assay				
	Total in Rock	–	0,16	0,10	61:39

3. Unmixing Relations in the System Cu-Ni-Fe-S and the Resultant Textures

Von Gruenewaldt (1971, p. 137–139) has summarized, from the existing literature, the main features of the Cu-Ni-Fe-S system which is applicable to the sulphides found in the Upper Zone of the Eastern Bushveld Complex. According to this study (1971, p. 138) pyrite is formed at 743°C from the reaction of the iron-rich portion of an Fe-Ni monosulphide solid solution (Mss) with sulphur liquid. A $Ni_{3\pm x}S_2$ phase reacts at 610°C with the Mss to form pentlandite. With decreasing temperature the field of the Mss in the Cu-Fe-Ni-S system gradually decreases as a result of the development of more pyrite in the sulphur-rich portion and the exsolution of Ni as pentlandite in the metal-rich portion.

The presence of pyrite is thus indicative of excess sulphur in the system and its characteristic texture is shown in Fig. 17. The typical textures of pentlandite exsolved from pyrrhotite are shown in Fig. 19 and 20.

The pyrrhotite of the Mss can take approximately two weight per cent Cu in solid solution at high temperatures and exsolves as chalcopyrite from the pyrrhotite at temperatures below 450^{o}C. (Von Gruenewaldt, 1971, p. 139). Much of the chalcopyrite in the sulphides observed occurs in this form. Where more than two weight per cent Cu is present in the sulphide liquid, a chalcopyrite solid solution usually crystallizes directly from the liquid at 970^{o}C. The chalcopyrite solid solution breaks up at 590^{o}C into chalcopyrite and cubanite. If pyrite is present, it reacts with the cubanite to form chalcopyrite and pyrrhotite at 334^{o}C (Von Gruenewaldt, 1971, p. 139). Fig. 21 illustrates the typical association of pyrrhotite and chalcopyrite. Cubanite was observed only in a very narrow band of sulphide mineralization in a pegmatoid intersection at -117 m in the Basal Zone (Fig. 6). This band proved to be very rich in chalcopyrite and prominent lamellae of cubanite were developed parallel to the (111) of chalcopyrite to form a triangular arrangement.

Sulphides occur in the diabase in pegmatoidal zones immediately below the Basal Zone in KLG/2 (Folder IV). These have essentially the same association of pyrrhotite with pentlandite, chalcopyrite and pyrite as the sulphides of the Layered Sequence. Little work has been done on these sulphides but visually it is apparent that there is a greater proportion of chalcopyrite and pentlandite associated with the pyrrhotite.

G. THE MAGNETITE LAYERS

The position in the sequence and the thickness of the magnetite layers are given in Folder II. Several polished sections were prepared for examination with the ore microscope.

1. Texture

In most of the polished sections examined there were abundant coarse grains of ilmenite. Molyneux (1970a, p. 105) considers similar grains to represent a cumulus phase precipitated directly from the magma. Microscopic examination of the textures of the oxide minerals gave evidence of a crystallization history

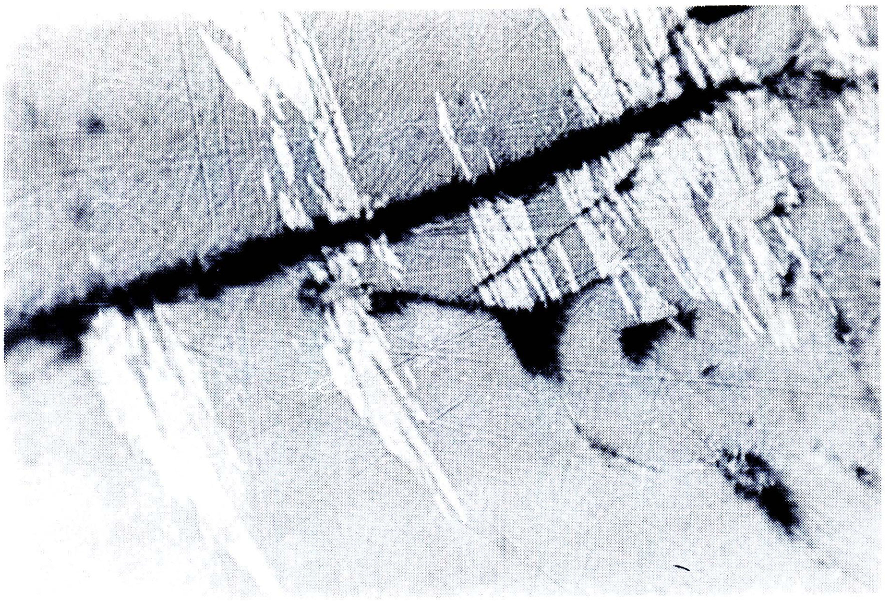


Fig. 19 Pentlandite exsolved from pyrrhotite and occurring as subparallel flames. Anorthosite of Subzone IB. ONZ/1–5158. Reflected light, x560.

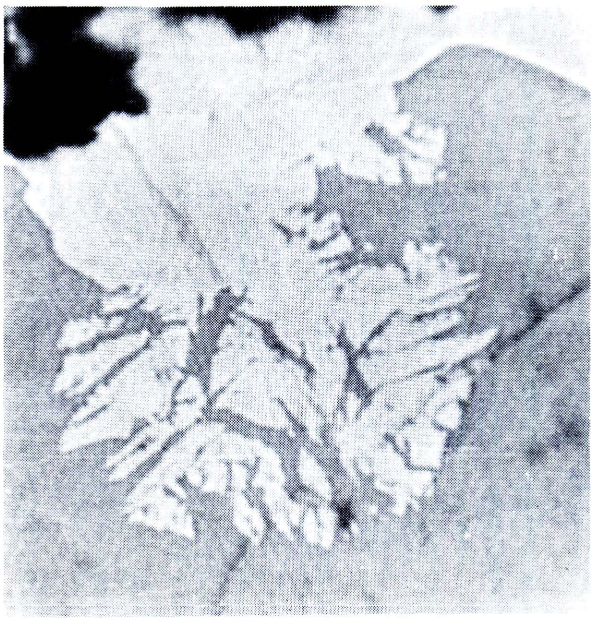


Fig. 20 Pentlandite exsolved from pyrrhotite and occurring as a feathery intergrowth. Anorthosite of Subzone IB. ONZ/1–5158. Reflected light, x560.

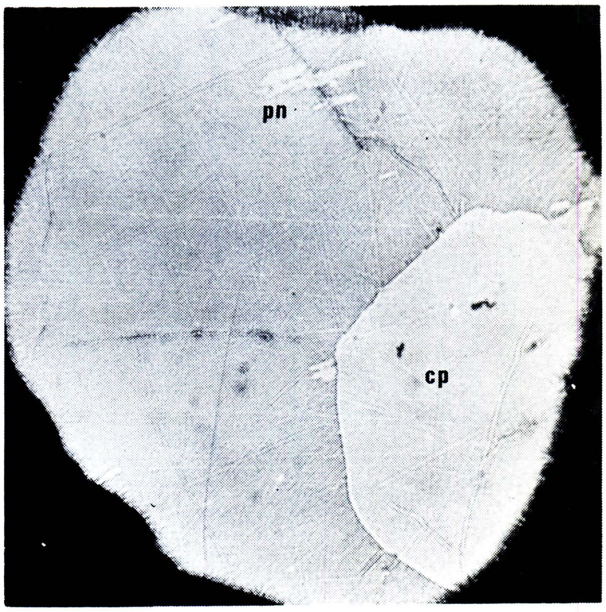


Fig. 21 Rounded pyrrhotite bleb containing chalcopyrite (cp) and flames of pentlandite (pn). Gabbro of Subzone ID. ONZ/2–3771. Reflected light, x260.

similar to that of the Eastern Bushveld Complex (Molyneux, 1970a, p. 91–92). Pleonaste was exsolved from the magnetite at high temperatures to develop along the (100) plane as poorly reflecting spindles (Fig. 22 and 23). Also exsolved at high temperatures were ilmenite lamellae which developed along the (111) plane of magnetite (Fig. 24). Under high magnification the pleonaste spindles are seen to be set in a boxwork of very fine ilmenite lamellae, also developed along the (100) plane (Fig. 22 and 23). This ilmenite is an oxidation product of ulvöspinel which was exsolved directly from the magnetite. The ilmenite was produced according to the following reaction:

$$3Fe_2{}^{2+}TiO_4 + O \rightarrow 3FeTiO_3 + Fe_3O_4$$

(ulvöspinel) (ilmenite) (magnetite)

2. Chemical Analyses

Partial chemical analyses of the magnetite layers in ONZ/1 were available and are given in Table VIII. Reference to this table shows that the magnetite layers of the Ongezien section are very impure, due to the high proportion of co-existing silicates. Raal (1965, p. 34–35) has given a number of analyses of magnetite from the Main Magnetite Seam where the iron content averages 55 per cent.

Raal (1965, Diagram 15) has also shown that an inverse relationship exists between the titanium dioxide and vanadium pentoxide content of the Main Magnetite Band. In order to illustrate the values given in Table VIII graphically, a similar plot was attempted (Fig. 25) where it was found that the only way in which the large scattering of the points could be eliminated was to divide the values into two fields, that is those values which occur above the 955 m mark and those below it.

Molyneux (1970b, p. 24) has shown that the vanadium pentoxide content of the magnetite in the Upper Zone of the Bushveld Complex in the Eastern Transvaal decreases in an upward direction. In order to ascertain whether this trend was duplicated in the Ongezien section, the values were plotted, but due to very pronounced scattering no conclusions could be drawn.

The information presented in Fig. 25 has been interpreted as illustrating a chemical break and it is interesting to note that this break coincides with the base of a gravity differentiated zone established from modal analyses. The value obtained for the magnetite pegmatoid did not fall within the field of the magnetite layers. This suggests that the pegmatoid has a completely different mode of origin.

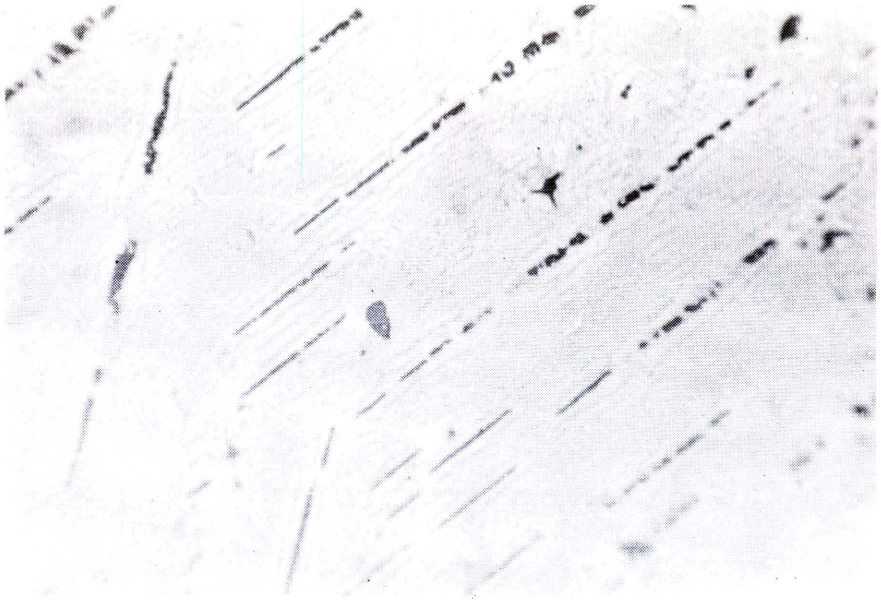


Fig. 22 Pleonaste spindles (black) exsolved from magnetite on the (100) plane with parallel development of ilmenite (dark grey) after ulvöspinel. Magnetite layer (no. 2) in diorite of Subzone IIB. ONZ/1–2993. Reflected light, x560.

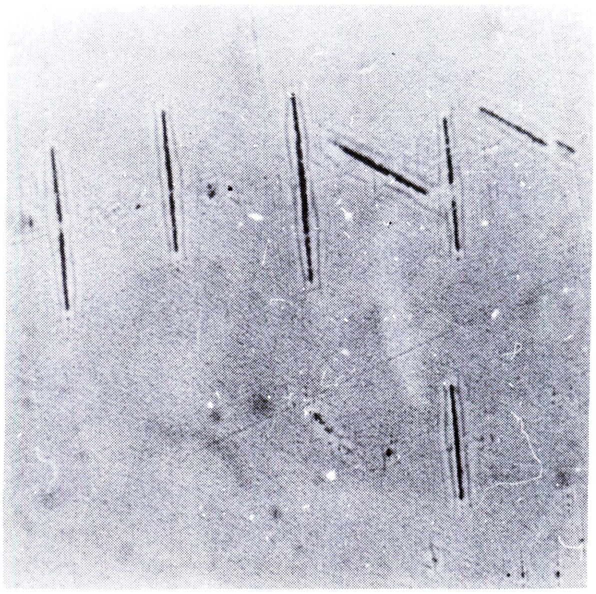


Fig. 23 Pleonaste spindles (black) exsolved from magnetite on the (100) plane and surrounded by a rim of ilmenite after ulvösspinel. Thin magnetite layer (no. 2) in diorite of Subzone IIB. ONZ/1–2993. Reflected light, x560.

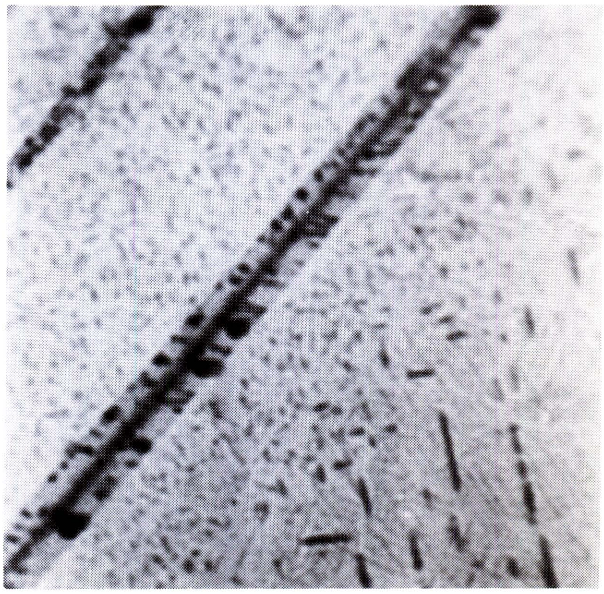


Fig. 24 Ilmenite lamellae exsolved directly from magnetite in the (111) plane. Dark blebs in the ilmenite are probably pleonaste. Magnetite in gabbro of Subzone IIA. ONZ/2–2878. Reflected light, x560.

TABLE VIII. CHEMICAL ANALYSES OF THE MAGNETITE LAYERS IN THE BOREHOLE ONZ/1

Seam No.	Height in metres from Marker	Thickness in mm	Bulk Sample Analyses %				Titano-Magnetite only Recalculated to 100%		
			Fe	Fe_3O_4 (calc)	V_2O_5	TiO_2	Fe_3O_4	V_2O_5	TiO_2
18	1123,6	910	31,83	43,93	0,21	14,75	74,60	0,36	25,04
17	1081,9	200	29,36	40,52	0,27	16,21	71,09	0,47	28,44
15	1029,4	530	46,87	64,68	0,48	16,65	79,06	0,59	20,35
14	1025,0	230	40,54	55,95	0,34	19,16	74,16	0,45	25,39
13	1017,5	610	25,22	34,80	0,21	10,58	76,33	0,46	23,21
12	960,7	150	47,38	65,38	0,32	19,33	76,89	0,39	22,72
11	950,0	720	37,26	51,42	0,30	11,85	80,89	0,47	18,64
10	865,0	610	27,05	37,33	0,21	9,24	79,80	0,45	19,75
8	813,0	1520	30,76	42,45	0,27	10,31	80,05	0,51	19,44
7	699,0	1050	10,35	14,28	0,09	3,53	79,78	0,50	19,72
6	686,8	240	30,17	41,63	0,21	9,02	81,86	0,41	17,73
5	669,7	1600	40,89	56,43	0,35	13,60	80,18	0,50	19,32
2	440,0	1200	51,15	70,59	0,52	18,80	78,51	0,58	20,91
M.P.	-28,0	230	36,46	47,55	0,60	11,93	79,14	1.00	19,86

Analyst: General Mining Group Research Laboratory.

M.P. = Magnetite Pegmatoid

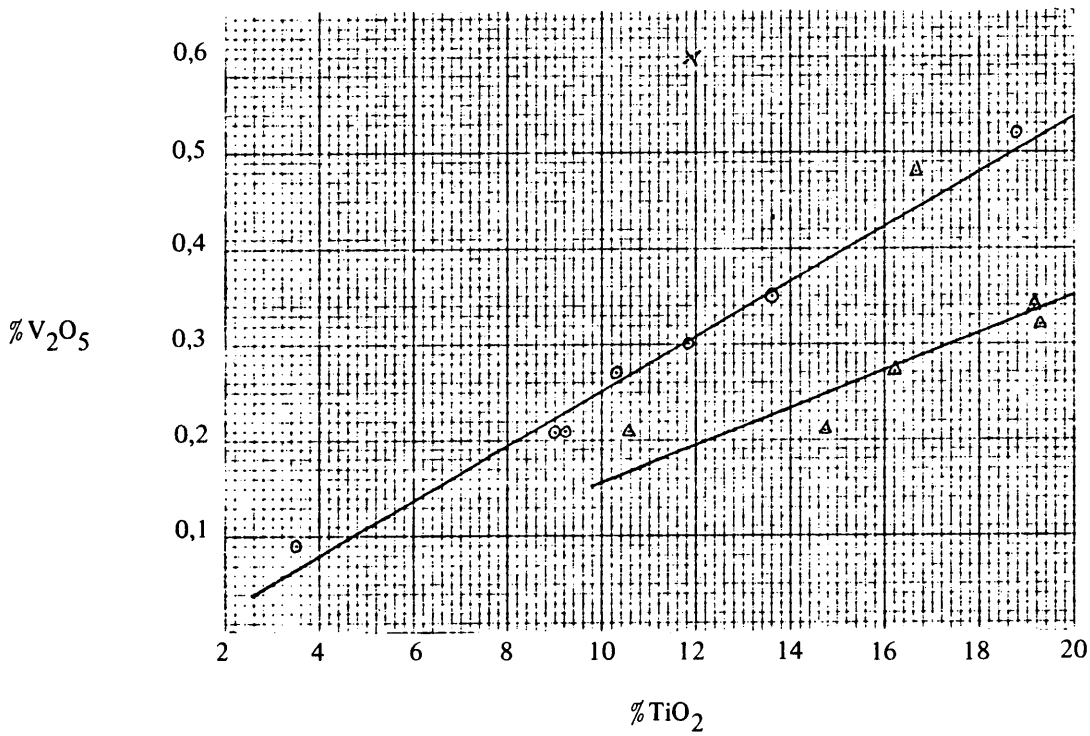


Fig. 25 Variation in the TiO_2 and V_2O_5 content of the bulk samples of the magnetite layers of borehole ONZ/1. Values above 955 metres denoted by (△) and those below by (⊙) .

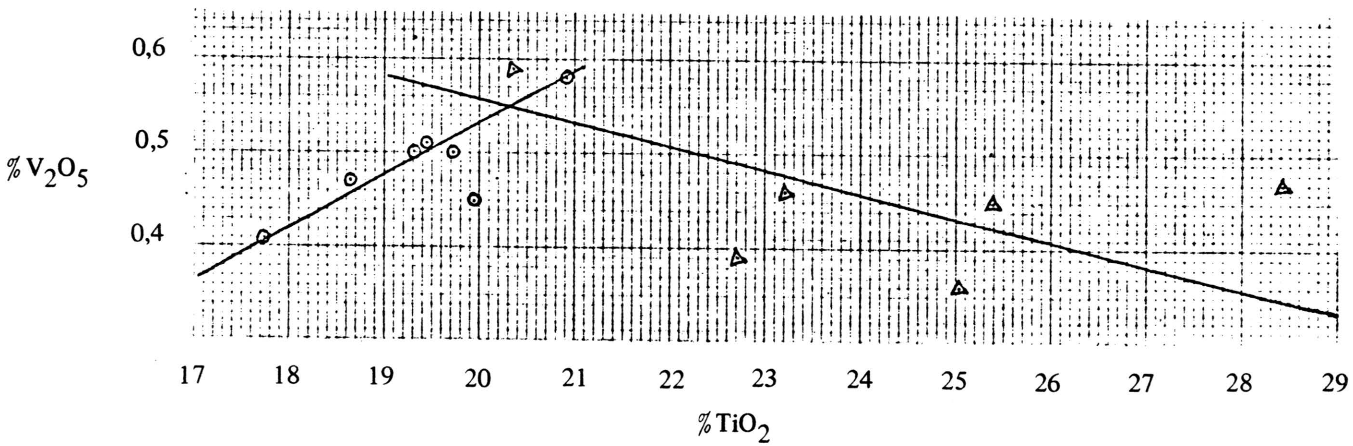


Fig. 26 Variation in TiO_2 and V_2O_5 from the recalculated values representing pure titanomagnetite in the magnetite layers of borehole ONZ/1. Values above 955 metres denoted by △ and those below by ⊙.

The results discussed above were obtained from values on the whole rock sample. On the assumption that all the iron in the bulk samples is present as titanomagnetite, the values were recalculated to 100 per cent to obtain some idea of the variation in the pure titanomagnetite. When plotted, these values still have a very large field of scatter, but the same fields above and below the 955 m mark have to be observed in order to obtain any kind of trend. A fairly well defined difference between the two methods of plotting is indicated and is illustrated in Fig. 26. It can be seen that the normal relationship between titanium dioxide and vanadium pentoxide changes to an inverse one above 955 m.

H. CHEMICAL ANALYSES OF THE LAYERED ROCKS

The following four unweathered samples of rock were submitted for chemical analyses, the results of which are given in Table IX.

UC361–717	Diorite of Subzone IVC
KLG/1–1258	Hypersthene gabbro of Subzone IIB
KLG/2–610	Hypersthene gabbro of Subzone IIB
KLG/1-3751	Hypersthene gabbro of Subzone ID

The results confirm the trends established in the previous sections on the minerals. One of the more prominent features shown by the norm is the more albitic nature of the plagioclase in UC361–717 which is a diorite of Subzone IVC and the higher ratio of anorthite to albite in the lower zones. As is expected the orthopyroxene has a high proportion of iron in UC361–717, which decreases in the lower zones. The greater proportion of modal apatite in the rocks of Zone IV than in those of the lower zones is also reflected in the norm of UC361–717. A high proportion of ilmenite is present in the upper zone (UC361–717).

TABLE IX. CHEMICAL ANALYSES OF ROCKS FROM THE LAYERED SEQUENCE

	UC361–717	KLG/1–1258	KLG/2–610	KLG/1–3751
SiO_2	46,39	51,35	53,27	52,68
Al_2O_3	15,95	17,90	20,56	20,64
Fe_2O_3	3,46	1,92	1,48	1,26
FeO	11,39	7,26	4,47	6,10
MgO	4,21	6,98	4,48	4,47
CaO	9,31	8,75	10,82	9,66
Na_2O	2,94	2,45	2,36	3,05
K_2O	0,41	0,28	0,39	0,37
TiO_2	3,84	1,02	0,75	1,03
P_2O_5	0,51	0,09	0,15	0,07
Cr_2O_3	0,18	0,18	0,20	0,15
Mn_3O_4	0,21	0,17	0,09	0,10
H_2O^-	0,09	0,32	0,06	0,07
H_2O^+	0,30	0,74	0,33	0,18
CO_2	0,24	0,23	0,24	0,21
	99,43	99,64	99,65	100,04
	C.I.P.W. NORMS			
Qz	0,84	3,66	7,56	3,66
Or	2,22	1,67	2,22	2,22
Ab	24,63	20,96	20,44	26,20
An	29,47	36,70	44,20	41,14
Di Wo	5,57	2,55	3,60	2,55
Di En	2,60	1,50	2,20	1,40
Di Fs	2,90	0,92	1,19	1,06
Hy En	7,90	16,00	9,00	9,80
Hy Fs	8,71	9,11	4,49	7,26
Mt	5,10	2,78	2,09	1,86
Il	7,30	1,98	1,52	1,98
Ch	0,22	0,22	0,22	0,22
Ap	1,34	0,34	0,34	0,34
H_2O^+, H_2O^- & CO_2	0,63	1,29	0,63	0,46
	99,43	99,68	99,70	100,15

VIII. PETROGENESIS OF THE LAYERED SEQUENCE

A. ORIGIN OF THE MARKER HORIZON, ANORTHOSITE AND PEGMATOID OF ZONE I

The most difficult features to explain in the Layered Sequence are the mineralogical trends in the plagioclase and orthopyroxene which have given rise to the Marker Horizon. Without considerably more detailed work which would help to define the nature of the mineralogical break more clearly, any explanation can only be highly speculative. For this reason no comprehensive attempt to define the origin of the Marker Horizon has been made. Any explanation should, however, bring into consideration the abundant development of anorthosite associated with the Marker Horizon and Subzone IB in boreholes KLG/1, ONZ/1 and P.D. The development of anorthosite at the base of the Layered Sequence is in itself difficult to explain. Finally, the appearance of abundant pegmatoidal development in KLG/2 and of less significant amounts in ONZ/2 and P.D., all limited to Zone I, should also be taken into account.

A factor which may have given rise to the anorthosite has been described by Elsdon (1971, p. 509) who attributes the formation of massive gabbro units at the base of the Kap Edvard Holm intrusion to the nucleation of primocrysts near the base of the magma chamber. This occurs in addition to the more usual nucleation near the roof. According to Turner and Verhoogen (1960, p. 326) sedimentary accumulation of plagioclase crystals plays a significant role in the origin of anorthosite layers. It is feasible therefore that the anorthosite observed may represent the felspathic fraction of a gravity differentiated orthocumulate which was formed by basal nucleation of the magma. The ultramafic portion of the differentiate would be represented by the Basal Zone.

Elsdon (1971, p. 502) also describes the presence of large amounts of gabbro-pegmatite (pegmatoids) within the massive gabbro units at the base of the Kap Edvard Holm intrusion. These are thought to signify large quantities of residual magma which was trapped within the cumulus pile at the base of the magma chamber. It is suggested that in rocks of the Basal Zone filter pressing of an intercumulus albite-rich pegmatoidal liquid could take place, forcing it up into the partially consolidated layers of rock above. According to Liebenberg (1970, p. 169) an albite-rich intercumulus liquid of this nature could contain abundant volatiles. In addition, because of the low melting point of the sulphides, they would be enriched in the intercumulus liquid.

The trends shown by the plagioclase immediately above the Basal Zone may thus have resulted from reaction between it and the pegmatoidal fluid. A gradient would form from a point of low anorthite content near the Basal Zone where the fluid was very albitic, to one of high anorthite content just under the Marker Horizon where most of the fluid had already reacted and reached equilibrium with the cumulus plagioclase.

A further consideration is that of the possible effect of volatiles on the crystallization of the plagioclase and evidence of this influence is given in the zoning previously described. As zoning with extreme values of up to 9 mol. per cent anorthite was observed in the plagioclase of some of the anorthosites intersected in borehole P.D., the effect of volatiles cannot be underestimated. They could well have given rise to a mineralogical break similar to that observed in the Marker Horizon.

Although the sulphides which occur in the pegmatoidal zones of the diabase immediately below the Basal Zone have the same association as that of the pegmatoid in Zone I, it cannot be stated conclusively that they originated from the intercumulus fluid of the Basal Zone.

B. CORRELATION AND COMPARISON WITH THE BUSHVELD COMPLEX

1. General

According to Wager and Brown (1968, p. 406) the Upper Zone of the Bushveld Complex is characterized by a marked iron enrichment of the magma, accompanied by an increase in the oxidation state, resulting in the formation of titaniferous magnetite layers. Precipitation of cumulus olivine occurs again in the Upper Zone and an increase in the phosphorus content of the magma results in the occurrence of cumulus apatite. The plagioclase occurs as andesine and the calcium-poor pyroxene is inverted pigeonite. Extreme dioritic differentiates are found at the very top of this zone, together with minor amounts of titaniferous magnetite.

From the information presented, it can be seen that there are strong similarities between the rocks of the Bethal area and those of the Upper Zone as described above. In addition there is a good correlation between the thickness of the Upper Zone in several different areas of the Bushveld Complex and of the Layered Sequence in the Bethal area (Table X).

TABLE X. THICKNESS OF THE UPPER ZONE IN DIFFERENT AREAS OF THE BUSHVELD COMPLEX

Area	Thickness in metres	Reference
Stoffberg, Eastern Transvaal	2140	Groeneveld (1970, p. 40)
Tauteshoogte-Roossenekal, Eastern Transvaal	2270	Von Gruenewaldt (1971, p. 32)
Sekhukhuneland, Eastern Transvaal	1790	Molyneux (1970a, p. 14)
Western Transvaal	1530	Coertze (1970, p. 6)
Bethal (Kaallaagte Section)		
From Marker Horizon	1660	
From bottom of Basal Zone	1700	

There are however, apart from the above points of similarity, several features which indicate different conditions of crystallization.

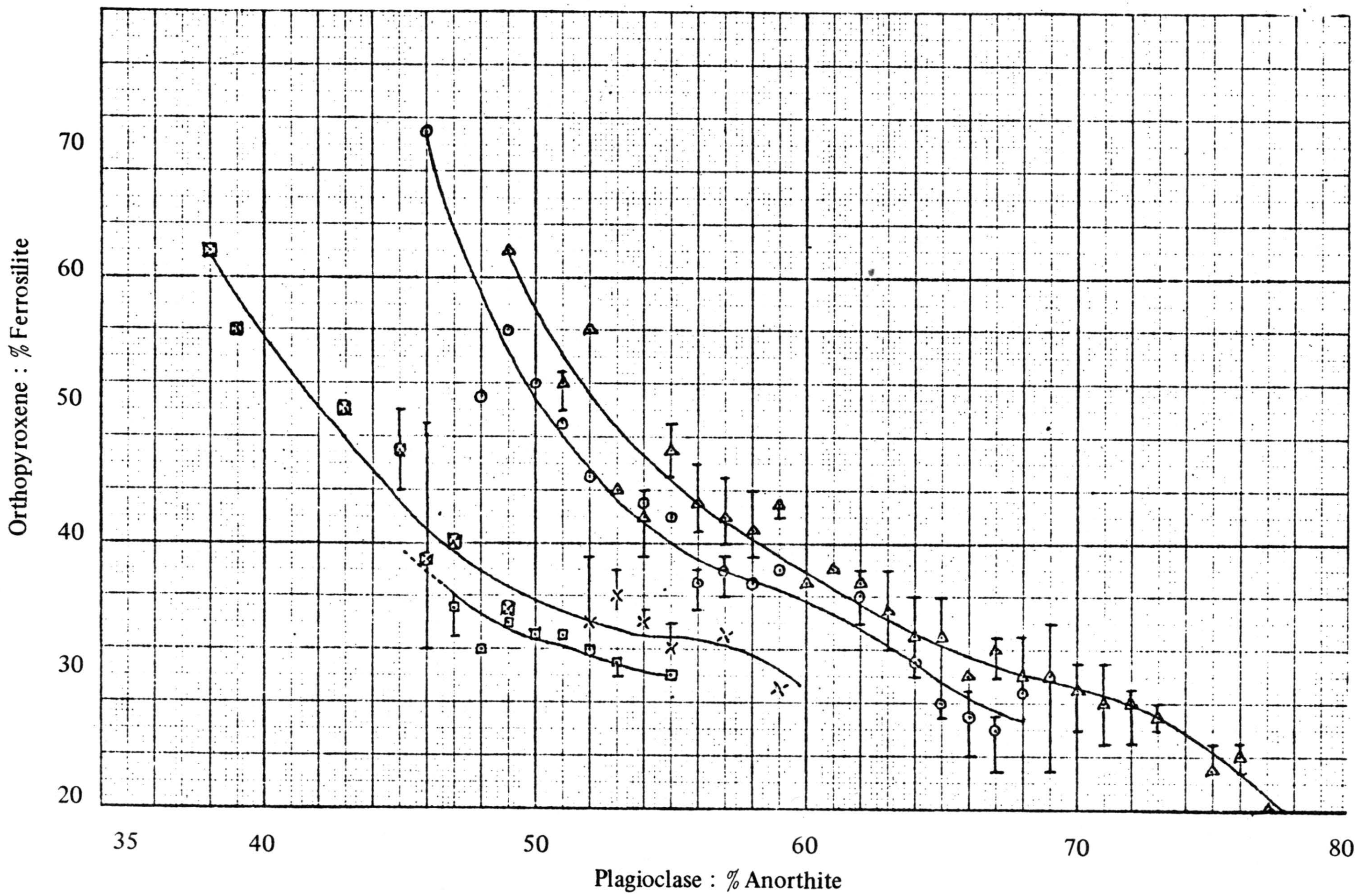
2. Effects of Oxygen Fugacity

The normal trend of differentiation of a tholeiitic magma results in a rock in which the iron content of the orthopyroxene and olivine increases progressively as the anorthite content of the plagioclase decreases towards the Roof. In order to obtain an idea of how corresponding values of orthopyroxene and plagioclase in the same rock compare, values for cumulus crystals were plotted in Fig. 27. Owing to the special conditions of crystallization which apply, values for anorthosite, pegmatoid and rocks below the Marker Horizon were not used. In addition, the values obtained by Von Gruenewaldt (1971) and Molyneux (1970a) for the Main and Upper Zones of the Bushveld Complex in the Eastern Transvaal were plotted.

As can be seen, orthopyroxene in the Bethal area contains far less iron than that of the Eastern Bushveld for a corresponding value of anorthite in the plagioclase. This discrepancy is attributed to the differing oxygen fugacity of the magma in the two areas.

Fugacity is a thermodynamic term and in a non-ideal gas is defined as the product of its activity coefficient and its partial pressure (Turner and Verhoogen, 1960, p. 21). In this case the gas is oxygen. Speidel and Osborn (1967, p. 1143) have shown that an increase in oxygen fugacity results in an enrichment in the magnesium component of the orthopyroxene and olivine. The important consideration implicit in conditions of high oxygen fugacity is that of oxidation. If ferrous iron were oxidized to ferric iron, magnetite would be precipitated, leaving the magma poorer in the ferrous

FIG. 27 DIAGRAM SHOWING THE VARIATION IN MOL. PER CENT FERROSILITE FOR FIXED VALUES OF MOL. PER CENT ANORTHITE



(△) Von Gruenewaldt, 1971 (⊙) Molyneux, 1970 (X) Kaallaagte Section (⊡) Ongezien Section (⊠) UC361 iron required for the formation of olivine and orthopyroxene. These minerals would thus be effectively enriched in magnesium, whereas the composition of the plagioclase would not be affected.

It would thus appear that the rocks of the Bethal area crystallized under conditions of higher oxygen fugacity than those of the Eastern Bushveld. An interesting feature shown by Fig. 27 is the differing trends of the Kaallaagte and Ongezien sections. The Ongezien section appears to have been precipitated under conditions of higher oxygen fugacity; this would explain the greater proportion of modal magnetite present and the relatively low values for modal orthopyroxene.

According to Ulmer (1969, p. 129) a sudden increase in oxygen fugacity would cause dominant crystallization of spinel over that of silicates. Von Gruenewaldt (1971, p. 163) has extended this argument to explain the formation of the magnetite layers of the Eastern Transvaal, where periodic increases in the oxygen fugacity would enhance the crystallizing of the titanomagnetite to form magnetite layers. The magnetite layers in the Ongezien section may have had a similar mode of origin.

3. Compositional Trends in Zone IV

The overall compositional variations of the orthopyroxene and plagioclase at the top of Zone IV are similar to those given by Von Gruenewaldt (1971, Folder III) and Molyneux (1970a, Fig. 12) for rocks near the Roof. The main difference seems to be the very restricted development of inverted pigeonite and of olivine to the topmost zone of the Bethal rocks. As the rocks of the Bethal area are much reduced in thickness compared with what is normal in the Bushveld Complex, faster cooling took place, which may account for the trends shown by the above minerals.

Additional evidence for the close proximity of the Roof Rocks is furnished by the presence of numerous lenses of granite pegmatite at the top of Zone IV. These lenses are rich in quartz, albite and amphibole and may be related to the Bushveld Granite. It would be expected that a borehole drilled a few hundred metres north of UC361 would intersect felsite or granophyre of the roof of the Complex. A minor outcrop of granophyre does in fact appear on the farm Schurwekop 227 IS (Fig. 3) 8 km north-west of UC361.

Von Gruenewaldt (1971, p. 118) has shown that there is a strong trend from hydroxy-apatite towards fluor-apatite at the top of the Upper Zone, just under the Roof Rocks. The apatite examined from the top of Zone IV is also a fluor-apatite; this further confirms the idea that UC361 intersected the olivine diorite just below the contact of the Roof Rocks. Finally, the high proportion of pyrite in the sulphide observed at the top of Zone IV also occurs characteristically at the top of the Upper Zone of the Bushveld Complex (Liebenberg, 1969, p. 142; Von Gruenewaldt, 1971, p. 126).

ERRATUM

Page 59, heading C.-For "Implacement" read "Emplacement".

C. IMPLACEMENT AND CRYSTALLIZATION

The rocks of the Bethal area seem to be similar to those of the Villa Nora occurrence (Fig. 1) (Grobler and Whitfield, 1970, p. 225) and are, as in the Belfast area (Fig. 1), almost certainly an extension of the rocks of the Upper Zone. According to Wager and Brown (1968, p. 348) the absence of the lower zones in these areas implies that the magma migrated into these subsidiary basins at a relatively late stage of its fractionation within the main chamber.

The isolated magma then continued to crystallize, but under different conditions of temperature and pressure. This appears to have occurred in a cyclic manner as a series of separate units with the development of heavy mafic minerals at the base. The rocks grade upwards into an anorthosite whence another mafic layer begins. On the basis of this evidence, it would appear that the magma crystallized from the base upwards with periodic re-homogenization above each differentiated unit.

An additional consideration which should be borne in mind is that the Bethal rocks may represent a mode of implacement similar to that described by Coertze (1958, p. 391) for the mafic portion of the Bushveld Complex north of the Pilanesberg. In this area the ferrogabbros of the Upper Zone cut across the earlier Bushveld rocks to give sections which show ferrogabbro resting on pyroxenite of the Basal Zone. If a similar situation occurred in the Bethal area it would imply that the Basal Zone described in this study is in fact the true Basal Zone of the Bushveld Complex. The whole succession may thus have been present in the Bethal area, prior to the transgression of the magma of the Upper Zone across the earlier formed cumulates.

IX. THE DIABASES AND CONTACT METAMORPHIC ROCKS

A. GENERAL

In the description of the mafic rocks which occur below the Layered Sequence, the term diabase rather than dolerite has been used in spite of the fact that they are virtually free from alteration. This has been done in order to be consistent with the general usage of the term diabase when describing the mafic sills associated with the Bushveld Complex. The examination of the diabase in this study has been undertaken mainly on the intersections obtained in KLG/2 and to a very much lesser extent on those obtained in BKL. The petrographic information for the KLG/2 intersection is given in Folder IV. The system of calculating the depth is consistent with that used for the rest of the borehole, that is the depths given are in metres below the Marker Horizon.

As can be seen in Fig. 5, the diabases of BKL have been postulated as occurring in sill-form in the sediments of the Pretoria Series. It may be argued that the diabases intersected in KLG/2 were intruded after the implacement and solidification of the main magma mass, owing to the presence of diabase in the Basal Zone (Fig. 6). According to Willemse (1959, p. xxxii) however, the mafic sills in the Pretoria Series were injected just prior to or during the injection of the main magma mass.

The boreholes drilled in the Ongezien section (Fig. 4) did not intersect the Basal Zone and thus no information is available as to whether or not diabase occurs below it. The evidence obtained from the borehole drilled on Mooifontein 108 IS however, allows for only limited thickness of diabase.

Provisional examination of the diabase resulted in two distinct types being recognized, namely a noritic diabase (Fig. 28 and 29) and a gabbroic diabase (Fig. 30). Interbedded with the diabase are several zones of rocks which show typical metamorphic textures and are apparently the original shales of the Pretoria Series which have been extensively altered by the intrusion of the diabase and by the overlying Layered Sequence.

B. THE MINERALOGY OF THE DIABASES

Before an attempt was made to compare and classify the diabases with respect to those described in association with other parts of the Bushveld Complex, a detailed mineralogical examination of the rocks was undertaken. These results are tabulated in Appendix I.

1. Plagioclase

The plagioclase of the noritic diabase is very rich in anorthite. Its discontinuous trend between -294 m and -206 m is possibly due to its being intercumulus. Only normal

Fig. 28 Maruleng type diabase (= mela-norite). KLG/2–4000. Crossed nicols, x33.

Fig. 29 Maruleng type diabase (= mela-norite). BKL–975. Crossed nicols, x33.

Fig. 30 Lydenburg type diabase (= olivine gabbro). KLG/2–4370. Crossed nicols, x33.

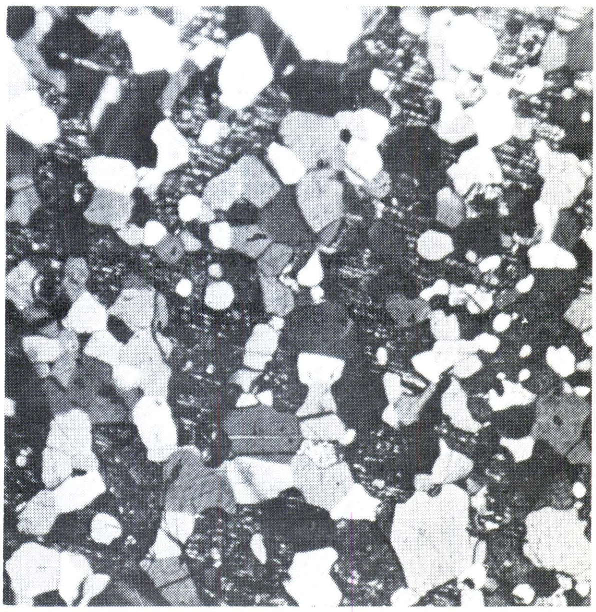


Fig. 31 Typical metamorphic texture of the pyroxene-hornfels showing a large orthopyroxene crystal poikiloblastically enclosing plagioclase crystals. KLG/2–4462. Crossed nicols, x33.

zoning was observed in the noritic diabase and in specimen KLG/2–3851 a value of An_{78} was obtained at the core whereas only An_{61} was recorded at the rim. KLG/2–3881 gave values of An_{79} and An_{66} at the core and rim respectively. The plagioclase of the gabbroic diabase shows an enhanced differentiation trend, especially between -391 m and -340 m.

2. Orthopyroxene

Owing to the very fine-grained nature of much of the diabase and the small amounts of orthopyroxene present, the optic axial angle could not always be measured with ease. Values obtained for the noritic diabase are considered to be reliable, but those for the more gabbroic zones are probably not very accurate.

The most strongly developed trend was obtained for the noritic diabase occurring between -293 m and the Basal Zone and was used to define the limits of this zone. The orthopyroxene shows the normal trend of a gravity differentiated sequence together with a sharp increase in the iron content in the chill zone.

3. Olivine

The same difficulty of very fine grain size encountered in the determination of the orthopyroxene was experienced for olivine. The olivine of the gabbroic diabase shows a decrease in iron with a decrease of anorthite content of the plagioclase. This is opposite to what one would expect in a normally differentiated rock.

4. Effect of Assimilation on Differentiation Trends

According to Bowen (1928, p. 206) the addition of kaolin (represented by shale) to a basaltic magma tends to increase the amount of enstatite in the pyroxene and of anorthite in the plagioclase. The production of minerals caused by this process is equivalent to adding material to the magma which is high in the reaction series, thus it will react by converting some of the liquid to crystals and thereby evolving latent heat. The increase in the proportion of crystals in the melt would mean an enhancement in differentiation. According to Vermaak (1970, p. 251) this will also occur if an excess of water is brought into the magma by the shale inclusions, which will lower the viscosity of the magma.

The very pronounced differentiation trends observed in the gabbroic diabase can thus be explained by assuming that assimilation of argillaceous sediments of the Pretoria Series took place, although there are no textural indications for this.

5. Modal Analyses

Although the sharp break in the anorthite content of the plagioclase from An_{50} above the Basal Zone to An_{75} below was a very strong indication that a different rock type had been intersected, it was hoped that a modal analysis would show up such a break even more clearly.

In addition, a modal analysis on both the gabbroic and noritic diabases would demonstrate more clearly the mineralogical differences between them. As strong cryptic layering was observed in the plagioclase, orthopyroxene and olivine it was hoped that differentiation trends would also show up. Finally, a mode was necessary to determine which samples represented the average noritic diabase in order that a representative chemical analysis could be carried out.

The I.C. No. of the diabases is usually about 150. According to Chayes (1956, p. 77) the standard deviation is therefore less than 1,7.

The results of the modal analyses (Folder IV and Appendix I) confirmed the trends obtained from the other mineralogical determinations which have been described above.

C. CLASSIFICATION OF THE DIABASES

Once the basic mineralogical data had been collected, an attempt could be made to compare and correlate the diabases of the Bethal area with those of other parts of the Bushveld Complex. The basic criteria employed to carry out the comparisons were those laid down by Willemse (1959, p. 1xiv) and from these it would appear that the noritic diabase is equivalent to the Maruleng type and the gabbroic diabase to the Lydenburg. The diabase intersected in BKL has been classified as a Maruleng type. According to Willemse (1969, p. 7) the Chill Zone of the Bushveld Complex comprises the early sills injected into the Pretoria Series and is included in the Maruleng type diabase.

In order to check the classification based on mineralogical criteria, a Maruleng type diabase (KLG/2–4000) was submitted for chemical analysis. The results are given in Table XI. The Niggli values were calculated and the position of the rock was plotted on the diagram given by Willemse (1959, p. xiv) (Fig. 32). As can be seen the sample falls within the field of the Maruleng type diabase.

D. THE METAMORPHIC ROCKS

1. Pyroxene-Hornfels Facies

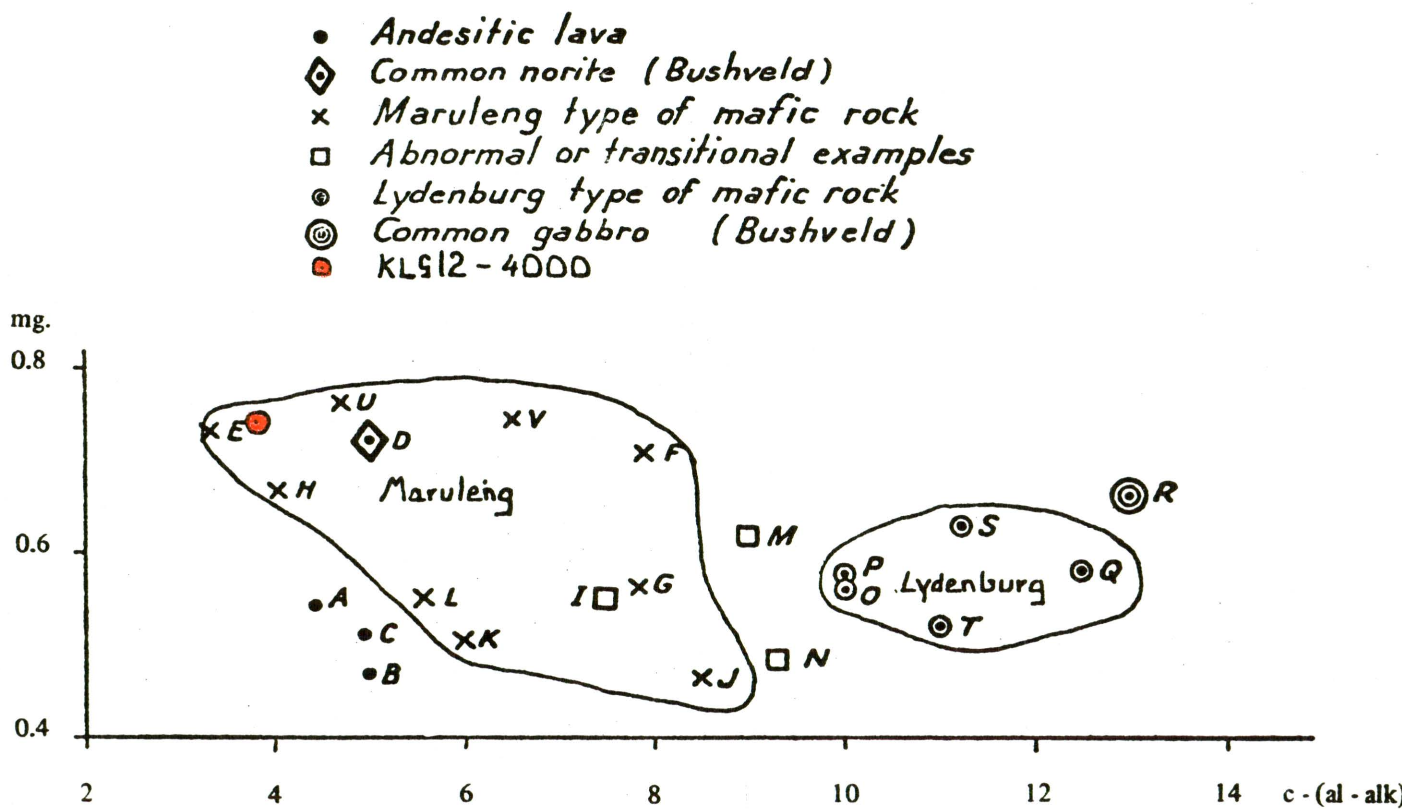
Rocks of the pyroxene-hornfels facies are found in the innermost zones of contact metamorphic aureoles (Turner and Verhoogen, 1960, p. 520). Most of the meta-

TABLE XI. CHEMICAL ANALYSIS AND NIGGLI VALUES OF KLG/2–4000 (MARULENG TYPE DIABASE)

SiO_2	51,96	si	104,4	
Al_2O_3	8,98	al	10,9	
Fe_2O_3	0,26	fm	74,4	
FeO	11,29	c	13,3	
MgO	18,35	alk	1,4	c-(al-alk) = 3,8
CaO	6,24	k	0,08	
Na_2O	0,72	mg	0,74	
K_2O	0,09	c/fm	0,18	
TiO_2	0,38			
P_2O_5	0,16			
Cr_2O_3	0,49			
Mn_3O_4	0,21			
H_2O^-	0,07			
H_2O^+	0,05			
CO_2	0,09			
	99,34			

Analyst: National Institute for Metallurgy, Johannesburg.

FIG. 32 DIAGRAM SHOWING THE POSITION OF NIGGLI VALUES FOR MAFIC ROCKS OF SILLS AND CONTEMPORANEOUS LAVA



(After Willemse, 1959, p. xiv)

morphic rocks intersected in KLG/2 belong to this facies (e.g. pyroxene hornfels, cordierite hornfels and calc-silicate fels) and a wide range of textures has been observed in them, the most characteristic being the poikiloblastic texture of the plagioclase and orthopyroxene (Fig. 31). The inequigranular texture of the plagioclase illustrated in Fig. 33 has given rise to the very well developed macroscopic banding observed in many of the rocks.

The cordierite hornfels is a distinctive bluish colour in the hand specimen and in thin section is often shown to be monomineralic and the grains are uncontaminated with inclusions (Fig. 34). Cordierite was initially incorrectly identified as plagioclase. It is interesting to note that if the vibration directions of the twin lamellae in cordierite are plotted on a stereogram, the position of the composition plane on the $0\bar{2}1$ migration curve gives a value of An_{29}. The optic axial angle of $2V_{\alpha} = 81^{\circ}$ gives a value of An_{25}. Willemse (1937, p. 63) obtained similar results for cordierite. The identification was checked by means of X-ray diffraction using $CuK\alpha_1$ radiation and by measuring the d values. These results agreed closely with the Powder Data File, Card No. 9–472 for cordierite. Generally speaking the rocks of the pyroxene-hornfels facies examined consist of well developed mineral assemblages and the only example of incomplete reaction is illustrated in Fig. 35.

A wide range of values was obtained for mol. per cent anorthite in the plagioclase but without additional work being undertaken no conclusions can be drawn.

2. Hornblende-Hornfels Facies

Near the bottom of KLG/2 poorly crystalline, schistose type rocks were intersected. Thin sections showed a mineral assemblage of biotite, cordierite, plagioclase and magnetite. These rocks have been assigned provisionally to the hornblende-hornfels facies.

3. Albite-Epidote-Hornfels Facies

In the rocks occurring in the last 4 m of KLG/2 the mineral assemblage quartz, clinozoisite, biotite, magnetite and tremolite was identified. These rocks were therefore assigned to the albite-epidote-hornfels facies. According to Turner and Verhoogen (1960, p. 510) this facies typically occurs on the outer margins of zoned aureoles and passes inwards into rocks of the hornblende-hornfels facies.

The metamorphic rocks examined thus represent the full range of conditions of contact metamorphism under low pressure and decreasing temperature away from the diabase contact.

Fig. 33 Pyroxene-hornfels made up of clinopyroxene and plagioclase showing seriate distribution of grain size typical of rocks which have macroscopic pseudobedding. KLG/2–4495. Crossed nicols, x33.

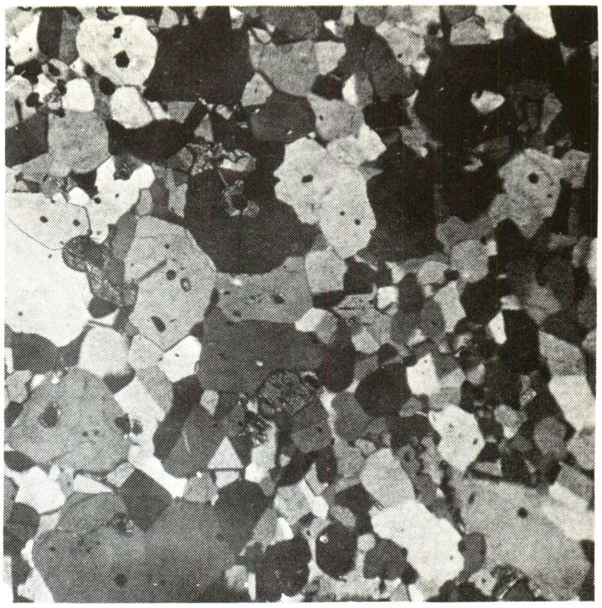


Fig. 34 Cordierite hornfels which is virtually monomineralic. KLG/2–4315. Crossed nicols, x33.

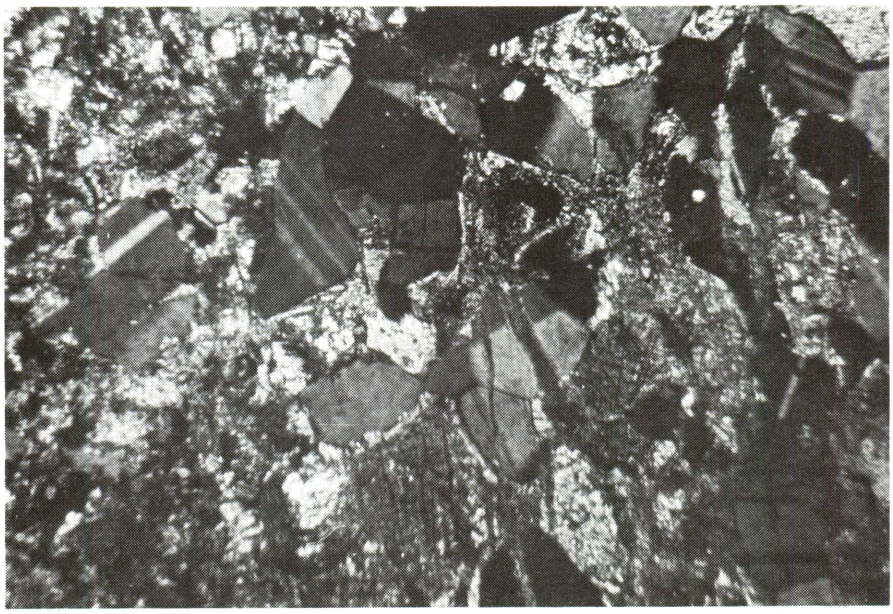


Fig. 35 Highly altered calc-silicate fels minerals. KLG/2–4760. Crossed nicols, x120.

X. SUMMARY AND CONCLUSIONS

The system of zoning that has been proposed represents an attempt to fulfil the main purpose of this study, that is to enable the correlation of similar rock types in the different boreholes. The zoning was based primarily on the identification of a mineralogical marker horizon, which facilitated the construction of sections showing the base of the Layered Sequence. These sections were used in the construction of vertical sections. The mineralogical data determined on the borehole was then transposed onto these. The rock types were accurately classified on mineralogical grounds and enough characteristic features were revealed to enable fairly confident correlations to be carried out between the boreholes.

After the various rock zones had been defined, it became evident that the mineralized pegmatoids had been fully intersected in KLG/2 only and that very little further deepening of the existing holes would be required to obtain complete intersections through the Basal Zone. It is suggested that the mineralized pegmatoid was formed from the intercumulus material of the Basal Zone, expelled by filter pressing. It is possible that the anorthosite found below the Marker Horizon is the felspathic fraction of a gravity differentiated orthocumulate which was formed by basal nucleation of the magma. The Basal Zone would thus represent the ultra-mafic fraction. No satisfactory explanation can at present be found for the Marker Horizon, but it is suggested that volatiles may have played an important part in its formation.

On mineralogical grounds it was decided that the rocks of this area can be considered as an offshoot of the Upper Zone of the Bushveld Complex. UC361 intersected olivine diorite just below the Roof Rocks, while KLG/2 went through the Basal Zone into diabase. Thus, apart from a narrow section not intersected, the full succession of Bushveld Complex type rocks in the Bethal area has been revealed.

The significance of the exsolution textures in the orthopyroxene and various trends in the solid solution series of the plagioclase, orthopyroxene and olivine was discussed. The distribution of the main sulphide phases in the various zones was determined. A deposit of apatite-bearing rocks with up to 4,1 weight per cent phosphorus pentoxide was examined in the upper parts of Zone IV.

It was concluded that the rocks of the Bethal area crystallized under conditions of higher oxygen fugacity than those of the typical Bushveld Complex. Crystallization took place from the floor upwards in a number of separate phases of gravity differentiation, followed by re-homogenization of the magma chamber above.

The Layered Sequence of rocks in this study has been examined with the view to producing a generalized section giving the various petrological zones and the main mineralogical trends. Any further work carried out on these rocks should most certainly include a detailed chemical examination of the clinopyroxene. In addition, the olivine should be re-examined using X-ray diffraction techniques.

Very few chemical analyses were undertaken and nothing is known about the distribution of the trace elements. The proposed origin of the pegmatoids also requires closer scrutiny as it could be useful in predicting the position of mineralized horizons of economic importance in the Bethal area.

Included in this study is a description of diabases, which are also considered to be associated with the injection of the Bushveld Complex. The noritic Maruleng type diabase occurs just below the Basal Zone in KLG/2. The more gabbroic Lydenburg type was intersected below the Maruleng type diabase and due to its having assimilated sediments, enhanced differentiation has resulted.

The thermally metamorphosed rocks associated with the diabases were also examined.

There is abundant scope for additional work on the assimilation of the sedimentary rocks by the diabase and the metamorphic effects of the latter.

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APPENDIX I

MODAL DETERMINATIONS AND VALUES OF COMPOSITION FOR MINERALS OF THE LAYERED ROCKS AND DIABASES

Plagioclase

Values of per cent anorthite used in Folders I–IV represent the average of the values obtained from the various determinative methods. Those denoted with an asterisk have been excluded from this average.

Where determinations using the universal stage were undertaken on optical properties other than those of Carlsbad and Carlsbad-albite twins, the values obtained have been given the following subscripts to denote the methods used:

52_A = An_{52} from maximum extinction angle on Albite twin

52_B = An_{52} from migration curves on Albite twin

52_C = An_{52} from migration curves on Ala twin

52_V = An_{52} from optic axial angle

52_D = An_{52} from refractive index of β

Orthopyroxene and Olivine

Where determinations of both refractive index and 2V were undertaken on the orthopyroxenes and the values did not agree, the refractive index was taken as more accurate. The converse is true of the olivine.

PHELPS DODGE

SAMPLE NUMBER (depth in feet)	770	830	910	1000	1060	1110	1210	1310	1430	1560	1600	1770
Distance in metres from marker	+136,4	+122,3	+103,5	+82,3	+68,2	+56,4	+32,9	+9,4	−22,7	−59,6	−70,9	−118,9
Modal Analysis (vol. %)												
Plagioclase	81,2	50,3	79,3	–	62,9	–	82,5	88,9	–	–	–	–
Orthopyroxene	–	9,2	9,6	–	–	–	12,0	–	–	–	–	–
Clinopyroxene	16,0	36,0	9,7	–	29,3	–	–	6,9	–	–	–	–
Amphibole	–	–	–	–	0,9	–	0,3	–	–	–	–	–
Biotite	–	1,3	T	–	–	–	0,2	–	–	–	–	–
Symplektite	T	0,3	0,7	–	T	–	–	1,3	–	–	–	–
Quartz	0,2	–	–	–	–	–	–	–	–	–	–	–
Apatite	1,0	–	–	–	T	–	0,3	–	–	–	–	–
Opaque	1,6	2,9	0,7	–	6,9	–	4,7	2,9	–	–	–	–
I.C. No.	33	107	23	–	42	–	31	31	–	–	–	–
Plagioclase : mol. % An from:												
Extinction angle	52	51	56	52	53	–	52	45	–	55	–	52
Migration curves	51	51	58	52	–	–	53	45	57_B	57	–	52
Twins	52	52	56	52	–	–	52	45	56_B	57	–	53
Eulerian angles	52	51	56	52	–	–	52	45	–	56	–	53
Other determinations	–	–	–	–	56_A	51_A	–	–	57_A	–	–	–
$2\theta_{131}-2\theta_{1\bar{3}1}(CuK\alpha_1)$	52	55	56	53	56	53	53	–	55	53	53	53
$2\theta_{\bar{2}41}-2\theta_{\bar{2}\bar{4}1}(CuK\alpha_1)$	56*	56*	57*	57*	59*	54	56	–	57	–	54	54
Value used	52	52	56	52	55	53	53	45	56	56	54	53
Orthopyroxene: mol. % Fs from:												
2V	–	32	32–38	–	–	–	32	–	–	–	–	–
nz	–	32	–	–	–	–	32	–	–	–	–	–
Name of rock and remarks	Anorthositic gabbro	Gabbro	Anorthositic norite Orthopyroxene intercumulus	Anorthosite	Gabbro	Pegmatoid	Anorthositic norite Orthopyroxene intercumulus	Anorthosite	Anorthosite	Anorthosite	Pegmatoid	Anorthosite

SAMPLE NUMBER (depth in feet)	311	317	331	346	391	475	537	612	674	718	784	861	900	1012	1100	1209	1308
Distance in metres from marker	+1645,2	+1643,6	+1639,7	+1635,5	+1623,0	+1599,6	+1582,3	+1561,5	+1544,5	+1531,9	+1513,6	+1492,1	+1481,3	+1450,1	+1425,6	+1395,2	+1367,7
Modal Analysis (vol. %)																	
Plagioclase	50,5	–	–	41,2	43,6	45,5	38,9	58,2	81,9	66,9	59,7	–	80,2	83,6	71,6	41,4	47,9
Olivine	7,2	–	–	1,3	–	–	–	–	–	–	–	–	–	–	–	–	–
Orthopyroxene	–	–	–	44,4	22,3	19,4	18,1	15,1	–	5,8	3,6	–	2,7	3,2	5,8	5,9	11,5
Clinopyroxene	19,6	–	–	2,4	10,5	16,8	7,1	9,9	10,1	18,2	23,0	–	9,9	5,4	10,0	29,8	21,6
Amphibole	4,9	–	–	–	–	–	T	–	3,4	–	T	–	–	–	–	–	–
Biotite	T	–	–	0,6	2,5	1,4	2,8	2,0	1,3	1,4	3,4	–	2,2	1,2	1,0	0,8	1,3
Quartz	T	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Apatite	8,1	–	–	6,1	8,5	8,9	11,1	3,0	0,8	2,1	2,4	–	1,6	2,2	3,5	0,4	T
Opaque	9,7	–	–	4,0	12,6	8,0	22,0	11,8	2,5	5,6	7,9	–	3,4	4,4	8,1	21,7	17,7
I.C. No.	59	–	–	59	91	143	115	79	39	63	59	–	63	59	50	131	99
Plagioclase: mol. % An from:																	
Extinction angle	39	–	–	39	38	43	45	46	55	47	46	–	45	46	46	49	51
Migration curves	38	–	–	40	39	44	46	46	55	47	45	–	46	46	46	48	49
Twins	37	–	–	39	37	43	45	46	55	47	46	–	45	46	46	48	49
Eulerian angles	37	–	–	39	37	43	45	46	55	47	46	–	45	46	46	48	49
2V	–	–	–	–	–	–	–	–	–	–	–	–	45	46	46	48	49
Value used	38	–	–	39	38	43	45	46	55	47	46	–	45	46	46	48	49
Orthopyroxene: mol. % Fs from:																	
2V	–	–	62	56	56	50	50	49	–	40	35	43	44	–	35	–	35
nz	–	–	62	56	56	50	50	49	–	40	32	–	44	–	35	–	35
Olivine: mol. % Fa from:																	
2V	–	75	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ny	–	75	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Name of rock and remarks	Olivine diorite	Olivine diorite	Olivine diorite Inverted pigeonite	Diorite Inverted pigeonite	Diorite Inverted pigeonite	Diorite	Diorite Inverted pigeonite	Diorite Inverted pigeonite	Anorthositic gabbro	Diorite Inverted pigeonite	Diorite	Diorite Orthopyroxene intercumulus	Felspathic diorite Inverted pigeonite – Intercumulus	Felspathic diorite	Felspathic diorite Inverted pigeonite	Diorite Inverted pigeonite	Diorite

SAMPLE NUMBER (depth in feet)	555	706	959	1258	1466	1769	1995	2250	2500	2750	3000	3250	3502	3751	4000	4240	4365	4484
Distance in metres from marker	+963,2	+919,6	+846,4	+760,0	+700,0	+612,3	+547,0	+473,3	+401,9	+340,3	+278,6	+217,0	+154,9	+93,5	+32,1	−27,1	−57,9	−87,3
Modal Analysis (vol. %)																		
Plagioclase	75,5	93,9	82,3	72,9	81,0	73,3	65,8	74,0	60,6	62,0	73,9	72,0	86,5	70,9	–	–	–	90,9
Orthopyroxene	3,4	–	1,0	8,3	4,8	6,6	6,6	6,1	11,2	7,5	7,2	10,6	T	10,1	–	–	–	3,9
Clinopyroxene	17,0	4,5	11,6	13,3	11,2	19,3	23,4	19,1	27,8	15,8	17,0	15,7	7,9	16,3	–	–	–	2,6
Biotite	–	T	–	0,2	T	T	0,4	–	–	T	T	–	–	T	–	–	–	0,6
Quartz	–	1,6	–	–	–	–	–	–	–	–	–	–	–	T	–	–	–	–
Apatite	0,1	–	1,3	1,1	0,2	–	T	–	–	–	–	0,4	1,6	–	–	–	–	0,6
Opaque	4,0	–	3,8	4,2	2,8	0,8	3,8	0,8	0,4	0,7	1,9	1,3	0,9	1,9	–	–	–	1,4
Amphibole	–	–	–	–	–	–	–	–	–	14,0	–	–	3,1	0,8	–	–	–	–
I.C. No.	52	24	44	45	53	64	62	56	64	55	58	48	45	46	< 20	<20	< 20	<40
Plagioclase: mol. % An from:																		
Extinction angle	51	53	53	52	55	52	–	54	52	60	57	55	52	53	52	55	53	53
Migration curves	50	52	51	53	55	52	51	–	51	60	57	56	52	53	53	55	52	54
Twins	51	53	53	53	55	52	50	55	52	60	57	56	52	53	52	55	53	53
Eulerian angles	51	53	52	52	54	52	51	54	52	60	57	55	52	53	52	55	53	52
2V	–	–	–	–	–	–	52	–	–	–	–	–	–	–	52	–	–	–
$2\theta_{131}-2\theta_{1\bar{3}1}$ (CuKα_1)	52	53	52	50	56	53	55	55	53	55	55	53	55	55	53	55	53	55
$2\theta_{\bar{2}41}-2\theta_{\bar{2}\bar{4}1}$ (CuKα_1)	54	56	57*	54	54	53	58*	59*	57*	58	58	56	57*	58*	52	56	54	54
Value used	52	53	52	52	55	52	52	54	52	59	57	55	53	53	52	55	53	53
Orthopyroxene: mol. % Fs from:																		
2V	32	–	–	33	33	33	33	33	34	31	33	34	37	32	–	34	–	35
nz	32	–	–	33	33	33	33	33	34	29	33	34	37	32	37	34	–	35
Name of rock and remarks	Magnetite gabbro	Anorthosite	Anorthositic gabbro Orthopyroxene intercumulus	Magnetite hypersthene gabbro	Anorthositic hypersthene gabbro	Hypersthene gabbro	Gabbro	Gabbro	Hypersthene gabbro	Hypersthene gabbro Highly altered	Hypersthene gabbro	Hypersthene gabbro	Anorthosite Orthopyroxene intercumulus	Hypersthene gabbro Orthopyroxene intercumulus	Anorthosite Orthopyroxene intercumulus	Anorthosite Highly altered Orthopyroxene intercumulus	Anorthosite Highly altered	Anorthosite Orthopyroxene intercumulus

SAMPLE NUMBER (depth in feet)	610	1043	1200	1583	1775	1986	2206	2428	2703	2798	2993	3100	3190	3250	3300	3399	3500	3559
Distance in metres from marker	+711,9	+593,8	+551,0	+446,5	+394,1	+336,6	+276,6	+216,0	+141,0	+115,1	+61,9	+32,7	+8,2	–8,0	–21,2	–47,5	–74,3	–89,9
Modal Analysis (vol. %)																		
Plagioclase	66,9	71,9	72,2	54,6	66,3	55,5	61,2	58,0	–	69,3	61,8	–	65,5	–	44,0	–	42,2	23,0
Olivine	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	7,4
Orthopyroxene	14,8	7,7	8,2	23,0	11,6	21,4	5,2	18,7	–	13,0	7,4	–	4,1	–	26,5	–	22,5	68,2
Clinopyroxene	15,0	16,6	14,7	15,7	9,6	18,0	28,0	18,0	–	15,3	22,1	–	25,9	–	27,1	–	15,5	1,4
Amphibole	1,8	–	T	–	T	T	–	–	–	T	T	–	–	–	–	–	3,1	–
Biotite	0,9	0,7	1,2	1,7	2,4	1,7	1,7	1,8	–	1,8	5,3	–	T	–	T	–	3,4	–
Symplektite	–	–	–	–	–	1,1	0,7	1,1	–	–	–	–	0,3	–	0,7	–	T	–
Quartz	–	0,7	2,4	0,2	–	–	–	–	–	–	1,1	–	T	–	–	–	–	–
Apatite	–	T	–	–	–	–	–	–	–	–	–	–	T	–	–	–	T	–
Opaque	0,6	2,4	1,3	4,8	10,1	2,3	3,2	2,4	–	0,6	2,3	–	4,2	–	1,7	–	13,3	T
I.C. No.	72	44	43	56	48	50	45	53	< 20	46	43	–	63	–	73	–	45	45
Plagioclase: mol. % An from:																		
Extinction angle	54	–	55	–	53	51	54	–	51	–	55	50	47	52	–	51	–	–
Migration curves	54	54	53	53	52	52	53	54	51	52	55	49	49	53	52	51	46_B	–
Twins	53	53	54	52	52	52	53	55	51	52	55	49	48	52	53	52	46_B	–
Eulerian angles	53	54	53	52	53	52	54	54	52	51	55	49	48	52	53	52	–	–
Other determinations	–	–	–	--	–	52_B	–	–	–	–	–	–	48_B	52_V	–	52_A	45_A	–
$2\theta_{131}-2\theta_{1\bar{3}1}$ ($CuK\alpha_1$)	55	53	58	–	53	52	53	56	52	53	53	–	–	50	53	53	–	–
$2\theta_{\bar{2}41}-2\theta_{\bar{2}\bar{4}1}$ ($CuK\alpha_1$)	–	52	62	–	56	52	53	55	52	57*	56	–	–	53	–	56	–	–
Value used	54	53	56	52	53	52	53	55	52	52	55	49	48	52	53	52	46	–
Orthopyroxene: mol. % Fs from:																		
2V	35	37	35	39	35	35	35	31	32	33	–	32	34	–	29	29	38	18
nz	35	38	35	39	35	35	35	31	32	33	30	32	34	29	28	28	38	18
Olivine: mol. % Fa from:																		
2V	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	12
ny	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	13
Name of rock and remarks	Hypersthene gabbro	Hypersthene gabbro	Hypersthene gabbro	Magnetite hyperite	Magnetite hyperite	Hyperite	Gabbro	Hyperite	Pegmatoid	Hypersthene gabbro	Hypersthene gabbro	Pegmatoid	Diorite	Pegmatoid	Mela-hypersthene gabbro	Pegmatoid	Diorite Inverted pigeonite	Mela-norite Plagioclase intercumulus

SAMPLE NUMBER (depth in feet)	3586	3642	3649	3659	3676	3682	3703	3720
Distance in metres from marker	–97,1	–112,0	–113,8	–116,5	–121,0	–122,6	–128,5	–132,6
Modal Analysis (vol. %)								
Plagioclase	14,5	8,4	4,8	12,3	10,3	–	14,9	19,1
Olivine	40,7	39,7	62,8	43,8	59,2	–	36,1	34,0
Orthopyroxene	43,9	43,9	27,3	42,8	28,9	–	48,6	40,7
Clinopyroxene	T	–	–	–	–	–	–	4,6
Amphibole	–	–	–	–	–	–	–	–
Biotite	0,3	T	0,9	T	0,9	–	0,4	0,3
Symplektite	–	–	–	–	–	–	–	–
Quartz	–	–	–	–	–	–	–	–
Apatite	–	–	–	T	–	–	–	–
Opaque	0,6	8,0	4,2	1,1	0,7	–	–	1,3
I.C. No.	113	83	73	80	79	–	58	73
Plagioclase: mol. % An from:								
Extinction angle	–	–	–	–	–	–	–	–
Migration curves	–	–	–	–	–	–	–	–
Twins	–	–	–	–	–	–	–	–
Eulerian angles	–	–	–	–	–	–	–	–
Other determinations	–	–	–	–	–	–	–	–
$2\theta_{131}-2\theta_{1\bar{3}1}$ ($CuK\alpha_1$)	–	–	–	–	–	–	–	–
$2\theta_{\bar{2}41}-2\theta_{\bar{2}\bar{4}1}$ ($CuK\alpha_1$)	–	–	–	–	–	–	–	–
Value used	–	–	–	–	–	–	–	–
Orthopyroxene: mol. % Fs from:								
2V	15	17	20	15	–	22	15	14
nz	17	17	20	15	–	22	–	15
Olivine: mol. % Fa from:								
2V	9	13	17	15	–	17	9	6
ny	10	12	17	15	–	17	–	7
Name of rock and remarks	eriodotite lagioclase intercumulus	eriodotite agioclase intercumulus	ypersthene dunite lagioclase intercumulus	ypersthene dunite agioclase intercumulus	ypersthene dunite agioclase intercumulus	ypersthene dunite agioclase intercumulus	eridotite agioclase intercumulus	ela-gabbro agioclase intercumulus

KAALLAAGTE/2 (DIABASE)

SAMPLE NUMBER (depth in feet)	3759	3851	3881	4000	4120	4152	4288	4300	4325	4350	4370	4400	4412	4439	4462	4495	4515	4570
Distance in metres from marker	–143,0	–167,4	–175,4	–206,9	–238,8	–247,3	–283,3	–286,5	–293,2	–299,8	–305,1	–313,1	–316,2	–323,4	–329,5	–338,5	–343,6	–358,1
Modal Analysis (vol. %)																		
Plagioclase	43,5	–	26,0	29,2	33,1	–	20,6	–	–	–	45,2	49,7	–	–	–	–	49,2	51,2
Olivine	–	–	–	–	–	–	1,7	–	–	–	17,4	8,9	–	–	–	–	14,2	1,8
Orthopyroxene	54,1	–	71,6	65,0	65,6	–	76,3	–	–	–	–	–	–	–	–	–	–	4,8
Clinopyroxene	0,9	–	1,8	5,0	0,3	–	0,2	–	–	–	35,5	40,2	–	–	–	–	31,4	38,5
Amphibole	–	–	–	–	–	–	–	–	–	–	T	T	–	–	–	–	2,6	1,4
Biotite	0,7	–	0,6	0,4	1,0	–	0,4	–	–	–	–	–	–	–	–	–	–	–
Opaque	0,8	–	T	0,4	T	–	0,8	–	–	–	1,9	1,2	–	–	–	–	2,6	2,3
I.C. No.	144	–	104	129	109	–	71	–	–	–	173	157	–	–	–	–	162	163
Plagioclase: mol. % An from:																		
Extinction angle	77	–	–	74	70	77	–	78	82	68	68	67	–	51	72	45	45	63
Migration curves	–	78_B	79	76	68	78	73_C	77	82	69	70	67	43	52	73	43	48	62
Twins	78	78_B	79	76	68	77	73_C	78	81	68	70	67	44	51	72	42	48	62
Eulerian angles	78	–	78	76	68	76	–	78	81	68	68	67	42	50	72	41	47	62
2V	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$2\theta_{131}-2\theta_{1\bar{3}1}$ ($CuK\alpha_1$)	74	–	81	79	–	–	–	79	85	69	67	67	–	52	76	–	–	64
$2\theta_{\bar{2}41}-2\theta_{\bar{2}\bar{4}1}$ ($CuK\alpha_1$)	74	–	84	74	–	–	–	–	82	71	74	65	–	56*	75	–	–	66
$2\theta_{131}+2\theta_{220}-4\theta_{1\bar{3}1}$ ($CuK\alpha_1$)	76	–	80	77	–	–	–	81	83	70	68	70	–	–	76	–	–	63
Value used	76	78	80	76	68	77	73	79	82	69	69	67	43	52	74	43	47	63
Orthopyroxene: mol. % Fs from:																		
2V	29	–	25	27	22	22	16	29	43	57	–	–	–	–	39	–	–	56
nz	30	–	26	27	22	22	16	29	43	53	–	–	–	–	41	–	–	–
Olivine: mol. % Fa from:																		
2V	–	–	–	–	–	–	–	–	–	–	63	58	–	–	–	–	63	65
ny	–	–	–	–	–	–	–	–	–	–	–	57	–	–	–	–	–	–
Name of rock and remarks	Mela-norite	Mela-norite	Mela-norite	Mela-norite	Mela-norite Plagioclase intercumulus	Mela-norite Plagioclase intercumulus	Mela-norite Plagioclase intercumulus	Mela-norite	Mela-norite	Hypersthene gabbro	Mela-gabbro	Mela-gabbro	Plagioclase in cordierite hornfels	Pyroxene hornfels	Hypersthene gabbro	Gabbro	Gabbro	Gabbro

KAALLAAGTE/2 (DIABASE)

SAMPLE NUMBER (depth in feet)	4600	4640	4680	4710	4736	4740	4780	4803	4850	4890
Distance in metres from marker	–366,1	–376,7	–387,3	–395,3	–402,2	–403,3	–413,9	–420,0	–432,5	–443,1
Modal Analysis (vol. %)										
Plagioclase	54,0	56,3	46,7	–	–	–	–	–	–	–
Olivine	T	0,4	12,5	–	–	–	–	–	–	–
Orthopyroxene	3,3	10,3	T	–	–	–	–	–	–	–
Clinopyroxene	39,0	26,5	36,0	–	–	–	–	–	–	–
Amphibole	1,3	5,9	1,5	–	–	–	–	–	–	–
Biotite	–	–	–	–	–	–	–	–	–	–
Opaque	2,4	0,6	3,3	–	–	–	–	–	–	–
I.C. No.	201	169	144	–	–	–	–	–	–	–
Plagioclase: mol. % An from:										
Extinction angle	65	74	63	–	76	59	–	49	–	–
Migration curves	66	77	63	79_B	75	62	67_B	48	43_B	54_B
Twins	65	76	63	80_B	76	59	66_B	48	42_B	55_B
Eulerian angles	64	75	62	–	77	59	–	49	–	58_B
2V	–	–	–	81_A	–	–	–	–	–	58
$2\theta_{131} - 2\theta_{1\bar{3}1}$ (CuKα_1)	67	79	68	82	81	72	60	–	–	58
$2\theta_{\bar{2}41} - 2\theta_{\bar{2}\bar{4}1}$ (CuKα_1)	70	77	63	–	79	68	65	–	–	60
$2\theta_{131} + 2\theta_{220} - 4\theta_{1\bar{3}1}$ (CuKα_1)	69	78	65	83	81	73	62	–	–	–
Value used	67	77	64	81	78	71	64	49	43	57
Orthopyroxene: mol. % Fs from:										
2V	–	40	–	–	29	–	–	–	–	37
nz	–	40	–	–	29	–	–	–	–	37
Olivine: mol. % Fa from:										
2V	–	–	–	43	–	51	–	65	46	–
ny	–	–	–	–	–	–	–	64	47	–
Name of rock and remarks	Gabbro	Hypersthene gabbro	Mela-gabbro	Olivine-biotite-plagioclase hornfels	Mela-norite	Olivine-hornblende-plagioclase hornfels	Pyroxene hornfels	Pyroxene hornfels	Pyroxene hornfels	Pyroxene hornfels

ONGEZIEN/1

SAMPLE NUMBER (depth in feet)	700	1005	1244	1500	1750	2000	2250	2500	2900	3200	3500	3750	3950	4250	4500	4740	4990	5282
Distance in metres from marker	+1116,1	+1027,7	+958,4	+884,2	+811,7	+739,3	+666,8	+594,3	+478,4	+396,4	+314,4	+246,0	+191,4	+109,4	+41,0	–24,6	-92,9	–172,8
Modal Analysis (vol. %)																		
Plagioclase	77,5	64,2	45,5	94,4	84,8	61,7	73,9	78,7	89,8	65,3	54,4	49,1	86,0	80,0	69,6	70,1	88,2	84,0
Orthopyroxene	3,2	3,5	26,7	–	2,3	6,2	–	6,4	0,3	1,4	3,2	7,6	2,7	12,4	11,1	–	0,5	–
Clinopyroxene	13,1	0,4	12,4	2,4	6,6	21,5	0,9	8,0	2,2	18,9	29,0	26,5	1,7	4,4	18,6	25,2	10,8	13,6
Amphibole	–	T	–	–	–	–	–	–	–	–	–	–	–	–	–	2,3	–	2,4
Biotite	0,6	2,2	0,6	T	0,5	T	0,7	–	0,3	0,3	T	0,7	0,3	–	T	–	–	–
Symplektite	–	T	0,6	–	T	T	1,0	–	0,6	–	–	–	0,2	0,8	–	–	–	–
Quartz	–	–	–	0,5	–	–	–	–	–	–	–	–	–	–	–	0,8	0,5	–
Apatite	–	T	0,4	1,6	1,5	0,3	T	–	–	–	–	T	0,4	–	–	–	–	–
Opaque	5,6	29,7	13,8	1,1	4,3	10,3	23,5	6,9	6,8	14,1	13,4	16,1	8,7	2,4	0,7	0,3	T	T
Calcite	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1,3	–	–
I.C. No.	40	62	36	36	48	69	58	46	50	48	75	96	73	51	61	37	25	27
Plagioclase: mol. % An from:																		
Extinction angle	48	48	47	–	50	50	53	50	50	47	52	50	51	53	51	55	53	51
Migration curves	48	47	47	50	49	49	53	50	52	46	50	50	51	54	51	54	50	52
Twins	48	48	47	49	50	49	54	50	50	46	50	50	51	54	52	56	52	53
Eulerian angles	49	49	47	49	50	49	53	50	51	45	50	50	51	54	52	56	52	52
$2\theta_{131} - 2\theta_{1\bar{3}1}$ (CuK α_1)	–	–	–	–	52	–	55	52	53	–	52	52	50	52	52	53	53	55
$2\theta_{241} - 2\theta_{\bar{2}\bar{4}1}$ (CuK α_1)	–	–	–	–	53	–	57	54	56*	–	56*	54	54	–	54	57	52	57*
Value used	48	48	47	49	50	49	54	51	51	46	51	51	51	53	52	55	52	53
Orthopyroxene: mol. % Fs from:																		
2V	–	–	36	–	–	–	–	–	–	–	32	33	–	31	32	–	–	–
nz	–	–	36	–	33	34	–	–	–	–	32	33	–	31	32	–	–	–
Name of rock and remarks	Felspathic diorite Ortho-pyroxene intercumulus	Diorite Ortho-pyroxene intercumulus	Diorite	Anorthosite	Anorthositic hypersthene gabbro	Diorite	Magnetite gabbro	Anorthositic magnetite gabbro	Anorthosite	Diorite Ortho-pyroxene intercumulus	Magnetite gabbro Ortho-pyroxene intercumulus	Magnetite gabbro	Anorthosite Ortho-pyroxene intercumulus	Anorthositic hyperite	Hypersthene gabbro	Gabbro	Anorthosite	Anorthositic gabbro

SAMPLE NUMBER (depth in feet)	679	750	1000	1250	1500	1750	2000	2250	2500	2750	3002	3250	3500	3750	4000	4250	4500	4750	5048
Distance in metres from marker	+715,8	+698,8	+638,7	+578,7	+518,6	+458,6	+398,5	+338,5	+278,4	+218,4	+169,8	+125,4	+80,6	+35,8	−10,7	−64,1	−117,5	−170,9	−234,6
Modal Analysis (vol. %)																			
Plagioclase	82,3	60,3	23,1	55,8	78,5	94,6	79,8	83,5	76,3	86,1	77,2	59,7	88,4	67,8	80,9	58,9	83,1	73,4	49,3
Orthopyroxene	2,4	1,8	18,2	3,0	1,1	3,7	0,5	11,9	9,3	4,7	10,8	2,0	9,7	6,9	0,3	–	–	10,0	1,8
Clinopyroxene	10,5	24,9	29,6	25,2	9,7	0,6	12,7	2,9	13,9	8,6	3,5	27,7	0,7	22,1	10,9	39,9	6,0	10,7	35,1
Biotite	0,2	0,2	0,5	0,7	0,6	–	1,2	T	T	–	0,7	0,8	T	0,3	–	0,3	0,2	1,5	T
Quartz	–	–	–	–	T	0,5	–	–	–	–	–	–	–	T	–	–	0,9	–	–
Apatite	–	T	–	–	T	0,3	–	–	–	–	–	–	–	–	0,5	–	–	–	–
Symplektite	–	T	T	1,4	T	–	0,4	T	–	–	–	T	–	T	–	–	0,6	T	–
Amphibole	–	–	–	3,5	3,0	–	0,2	–	T	0,6	0,8	1,3	1,2	0,6	7,4	0,3	–	–	1,3
Opaque	4,6	12,8	28,6	10,4	6,3	0,3	4,6	1,7	0,5	–	7,0	8,5	–	2,3	T	0,6	9,2	4,4	12,5
Calcite	–	–	–	–	0,8	–	0,6	–	–	–	–	–	–	–	T	–	–	–	–
I.C. No.	58	73	61	96	36	37	42	45	78	53	50	51	32	53	40	26	26	71	55
Plagioclase: mol. % An from:																			
Extinction angle	45	48	48	47	52	50	49	54	52	54	51	52	51	52	–	52	53	49	48
Migration curves	44	48	49	48	52	50	50	55	51	54	51	53	53	52	60	53	54	49	47
Twins	45	48	48	47	53	50	50	55	53	54	51	52	51	52	60	53	52	50	49
Eulerian angles	45	47	48	47	52	52	50	54	53	53	51	52	50	52	–	52	52	50	48
$2\theta_{131} - 2\theta_{1\bar{3}1}$ (CuKα_1)	–	–	–	–	53	52	50	56	53	53	50	52	–	52	53	53	53	–	–
$2\theta_{\bar{2}41} - 2\theta_{\bar{2}\bar{4}1}$ (CuK α_1)	–	–	–	–	56	56	53	58	56	52	54	56	–	56	54	54	56	–	–
Value used	45	48	48	47	53	52	50	55	53	53	51	53	51	52	60	53	53	50	48
Orthopyroxene: mol. % Fs from:																			
2V	–	–	32	33	–	–	–	30	–	–	37	–	34	37	–	–	–	–	–
nz	–	–	32	33	31	–	–	30	31	30	37	–	34	37	–	–	–	–	–
Name of rock and remarks	Felspathic diorite Orthopyroxene intercumulus	Diorite Orthopyroxene intercumulus	Diorite	Diorite	Anorthositic gabbro Orthopyroxene intercumulus	Anorthosite Orthopyroxene intercumulus	Magnetite gabbro	Anorthositic norite	Anorthositic hypersthene gabbro	Anorthosite	Anorthositic gabbro Orthopyroxene intercumulus	Magnetite gabbro Orthopyroxene intercumulus	Anorthosite	Gabbro	Anorthositic gabbro	Pegmatoid	Anorthositic gabbro	Hypersthene gabbro	Diorite

BANKLAAGTE/1

SAMPLE NUMBER (depth in feet)	875	975
Plagioclase: mol. % An from:		
Extinction angle	76	83
Migration curves	78	85
Twins	77	82
Eulerian angles	77	80
Orthopyroxene: mol. % Fs from:		
2V	35	35
nz		
Name of rock and remarks	Mela-norite	Mela-norite

APPENDIX II

MODAL DETERMINATIONS AND ASSAY VALUES FOR THE SULPHIDES OF THE LAYERED ROCKS

LOCALITIES OF SULPHIDE SPECIMENS ON WHICH MODAL ANALYSES HAVE BEEN DETERMINED

No.	Borehole	Sample No.	Metres above Marker	Rock Type	Subzone
1	KLG/2	3472	–67	Diorite with abundant pegmatoid	IA
2	KLG/2	3343	–33	Pegmatoid	
3	P.D.	1510	–45,2	Anorthosite	
4	P.D.	1470	–33,9	Anorthosite	IB
5	ONZ/2	4363	–89	Magnetite gabbro	
6	KLG/2	3201	+5	Diorite with abundant pegmatoid	IC
7	KLG/2	3120	+27	Gabbro and norite	ID
8	ONZ/2	3771	+33	Gabbro and norite	
9	ONZ/2	2929	+183	Magnetite gabbro	
10	ONZ/2	2875	+193	Magnetite gabbro	IIA
11	KLG/2	1583	+446,5	Magnetite gabbro	
12	ONZ/2	1389	+545	Magnetite gabbro	IIIB
13	UC361	783	+1513,6	Below +1560 mineralized diorites	
14	UC361	643	+1552,5		
15	UC361	612	+1561,5		
16	UC361	537	+1582,3	Above +1560 mineralized diorites	IVC
17	UC361	504	+1591,5		
18	UC361	475	+1599,6		

RESULTS OF MODAL ANALYSES ON THE SULPHIDES OF THE LAYERED ROCKS

Zone	IA	IB					IC	ID			IIA				IIIB	IVC Below +1560			IVC Above +1560				
Number	1	2	3	4	5	Av	6	7	8	Av	9	10	11	Av	12	13	14	Av	15	16	17	18	Av
Pyrrhotite	93,5	92,3	32,5	19,5	80,4	56,1	71,4	87,5	94,4	90,9	95,9	94,7	84,3	91,6	85,4	98,2	84,2	91,2	–	–	97,8	–	24,5
Pentlandite	4,1	3,0	0,1	T	19,6	5,7	2,6	7,8	3,8	5,8	3,4	3,9	2,5	3,3	8,7	–	10,9	5,5	–	–	–	–	–
Chalcopyrite	2,4	4,7	0,5	T	–	1,3	20,1	4,5	1,8	3,2	0,7	1,4	9,1	3,7	5,9	1,8	2,8	2,3	T	T	1,7	T	0,4
Pyrite	–	–	66,9	80,5	–	36,9	5,9	0,2	–	0,1	–	–	4,1	1,4	–	–	1,4	0,7	100,0	100,0	–	100,0	75,0
Sphalerite	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–	–	0,5	–	0,1
Gersdorffite	–	–	–	–	–	–	–	–	–	–	–	–	–	–	T	–	0,7	0,3	–	–	–	–	–
No. of pts counted	3023	4831	1130	3988	4879	–	1221	4058	5054	–	4420	1490	1100	–	1052	4475	2737	–	–	–	5136	–	–
Metres from marker	–67	–33	–45	–34	–89	–50	+5	+27	+33	+30	+183	+193	+447	+274	+545	+1514	+1553	+1534	+1562	+1582	+1592	+1600	+1584

RESULTS OF ASSAYS UNDERTAKEN ON SULPHIDE ZONES

Zone	Sub-zone	UC361 Depth from	to	Assay Cu	Ni	ONZ/2 Depth from	to	Assay Ni	Pt	KLG/2 Depth from	to	Assay Ni	Cu	Cr	Co	Pt	P.D.
IV	C & B	+1643	+1361	<0,01	<0,1												Between +207,0 and –121,4 m the core was sampled and assayed for Cu, Ni and Pt. Only trace amounts were found,
I	D					+33,5	+32,5	0,20	0,05	+30,00	+28,20	0,12	0,19	0,02	T	0,3	
										+22,00	+21,70	0,19	0,19	0,03	T	0,1	
	C									+18,00	+15,55	0,10	0,11	0,03	T	< 0,1	
										+10,00	+ 8,20	0,10	0,11	0,02	T		
										+ 5,00	+ 4,10	0,15	0,15	0,02	0,01	< 0,1	
	B									–33,00	–33,23	0,35	0,29	0,02	0,06	< 0,1	
	A									–66,00	–66,65	0,19	0,11	0,04		< 0,1	
										–71,00	–71,15	0,15	0,09	0,01		< 0,1	
										–89,00	–89,30	0,15	0,13	0,02		< 0,1	

gms per tonne

dwt per ton

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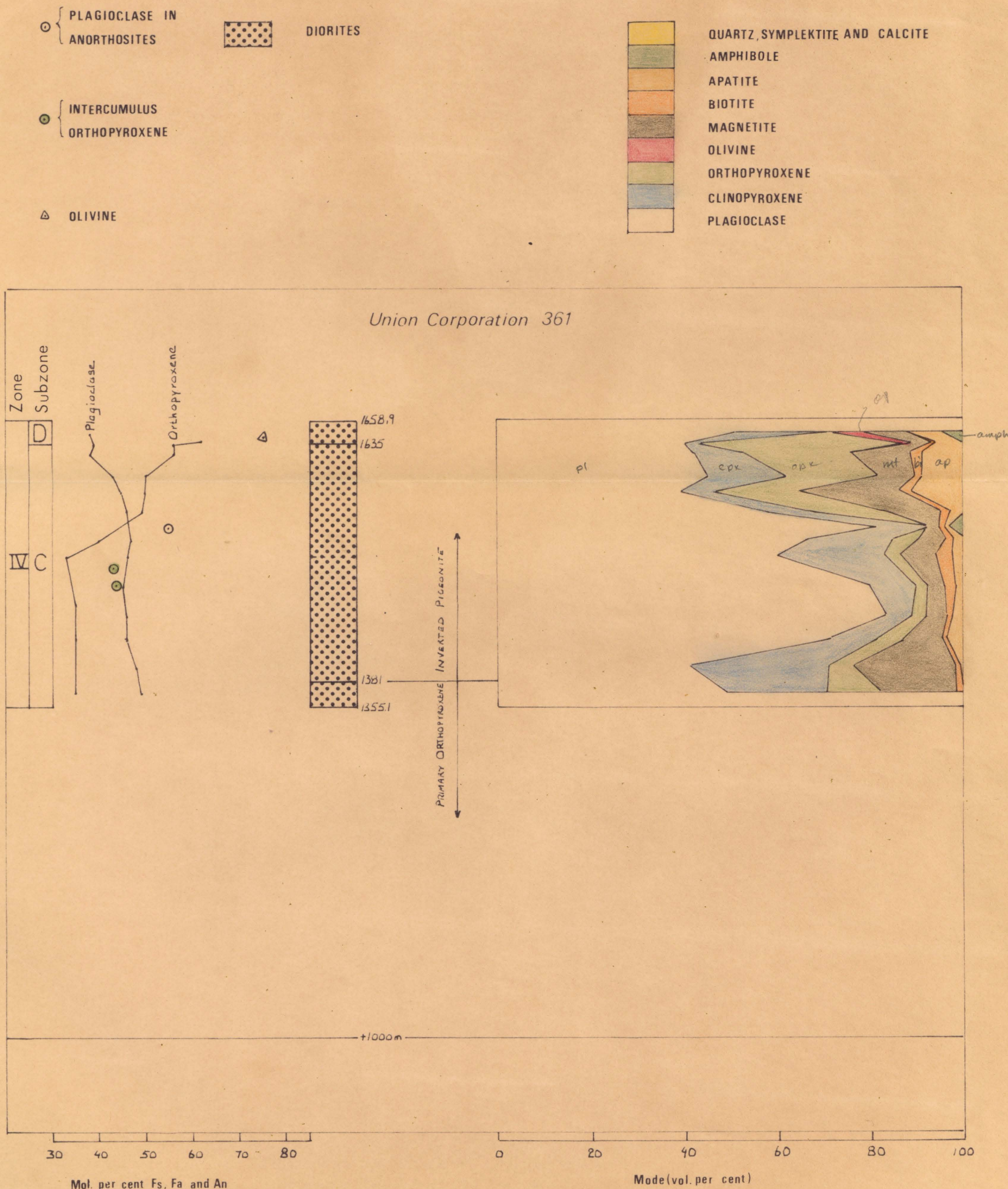
FOLDER I. COMPOSITIONAL VARIATIONS AND MODAL DISTRIBUTION OF MINERALS

Scale 1:5000



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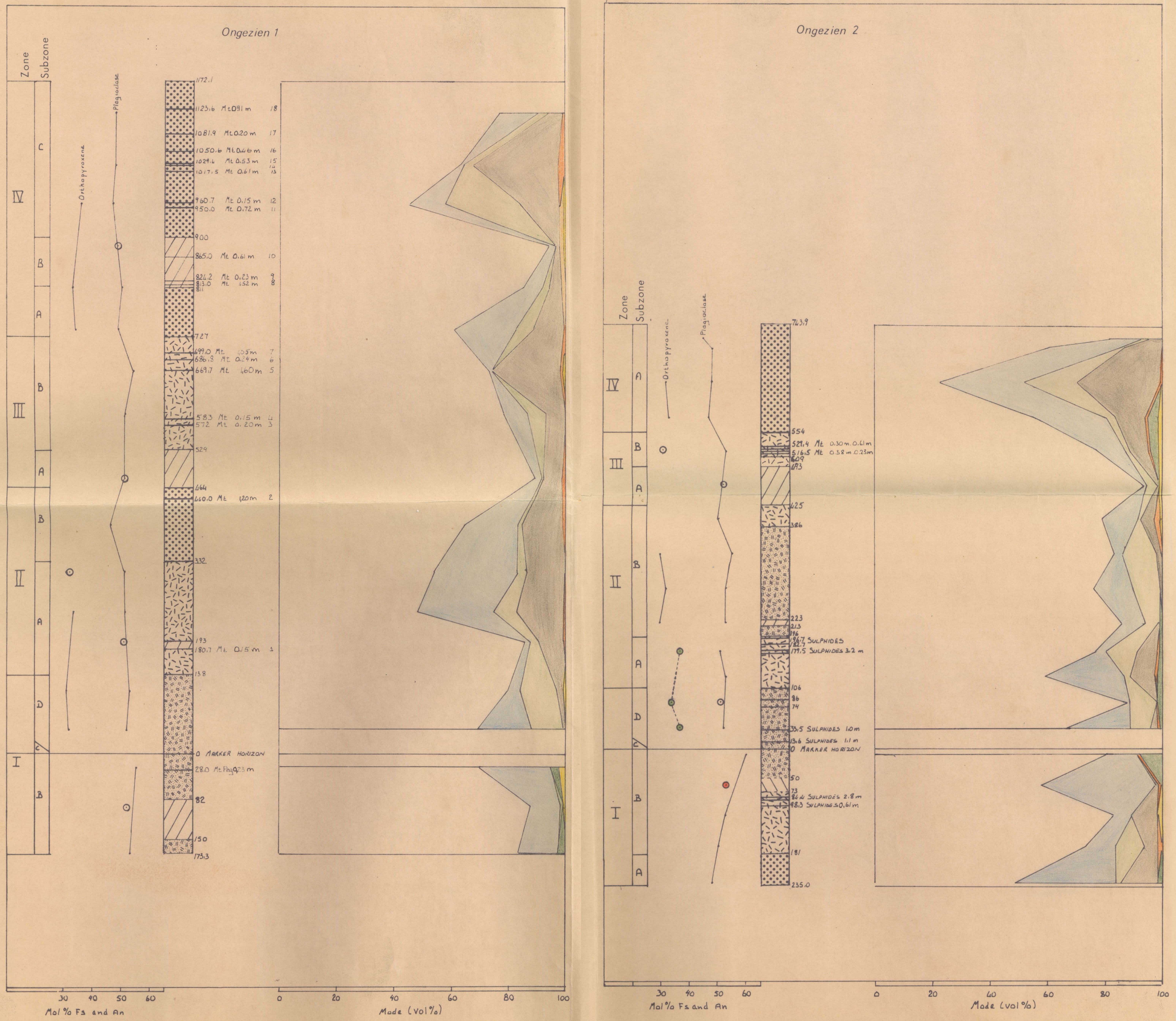
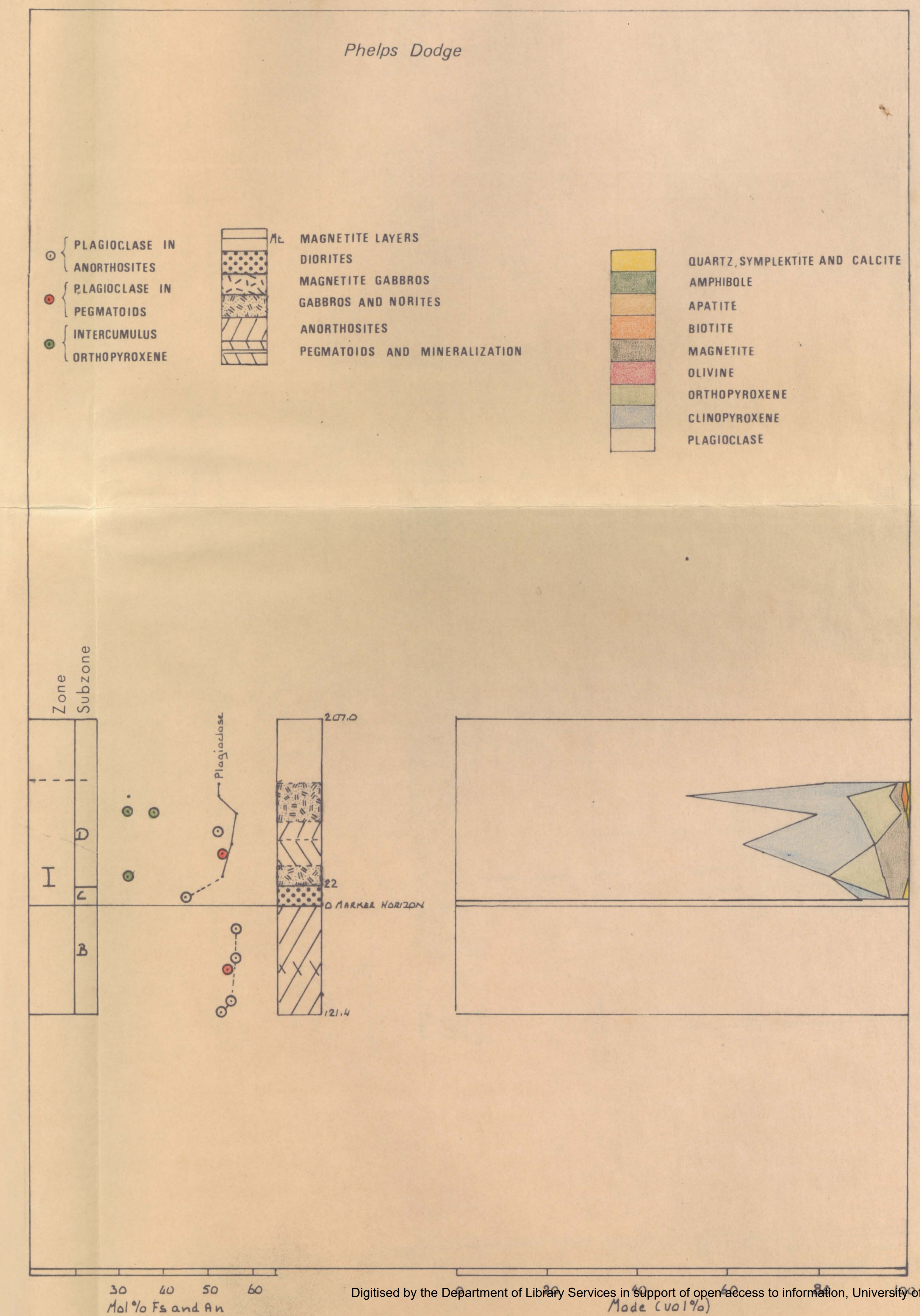
FOLDER II. COMPOSITIONAL VARIATIONS AND MODAL DISTRIBUTION OF MINERALS IN BOREHOLES ON THE FARM ONGEZIEN

Scale 1:5000





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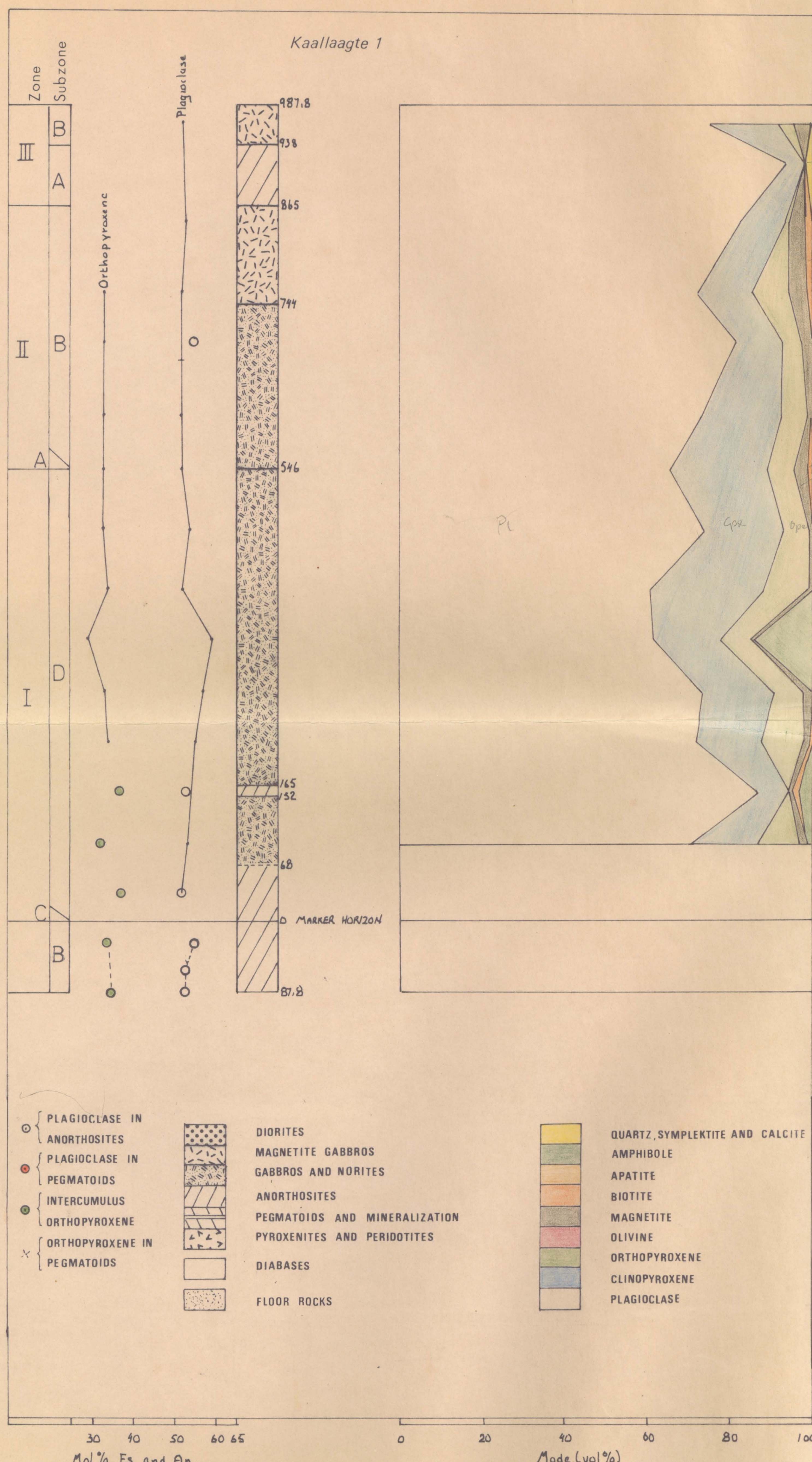
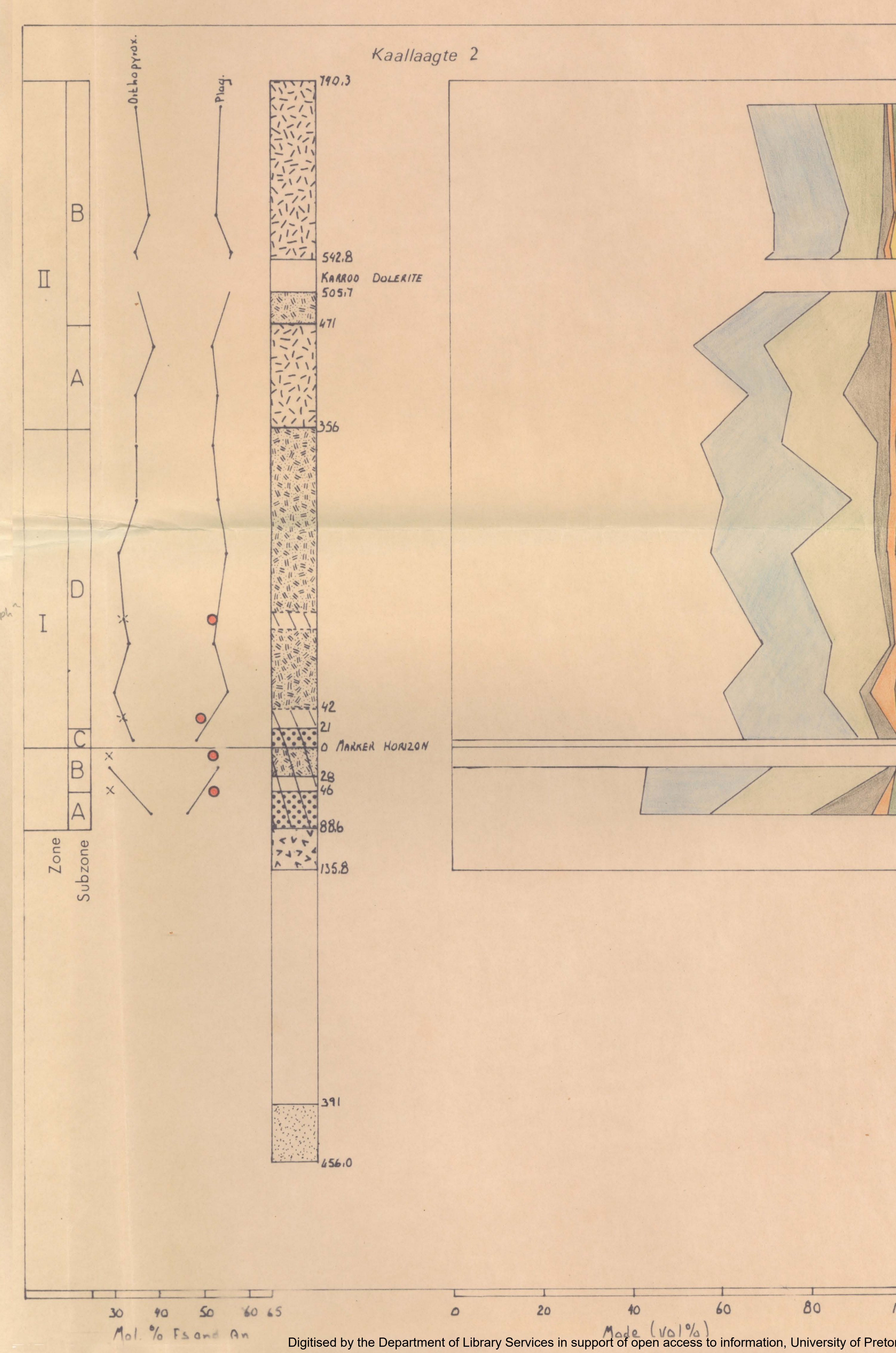
FOLDER III. COMPOSITIONAL VARIATIONS AND MODAL DISTRIBUTION OF MINERALS IN THE BOREHOLES ON THE FARM KAALLAAGTE

Scale 1:5000.





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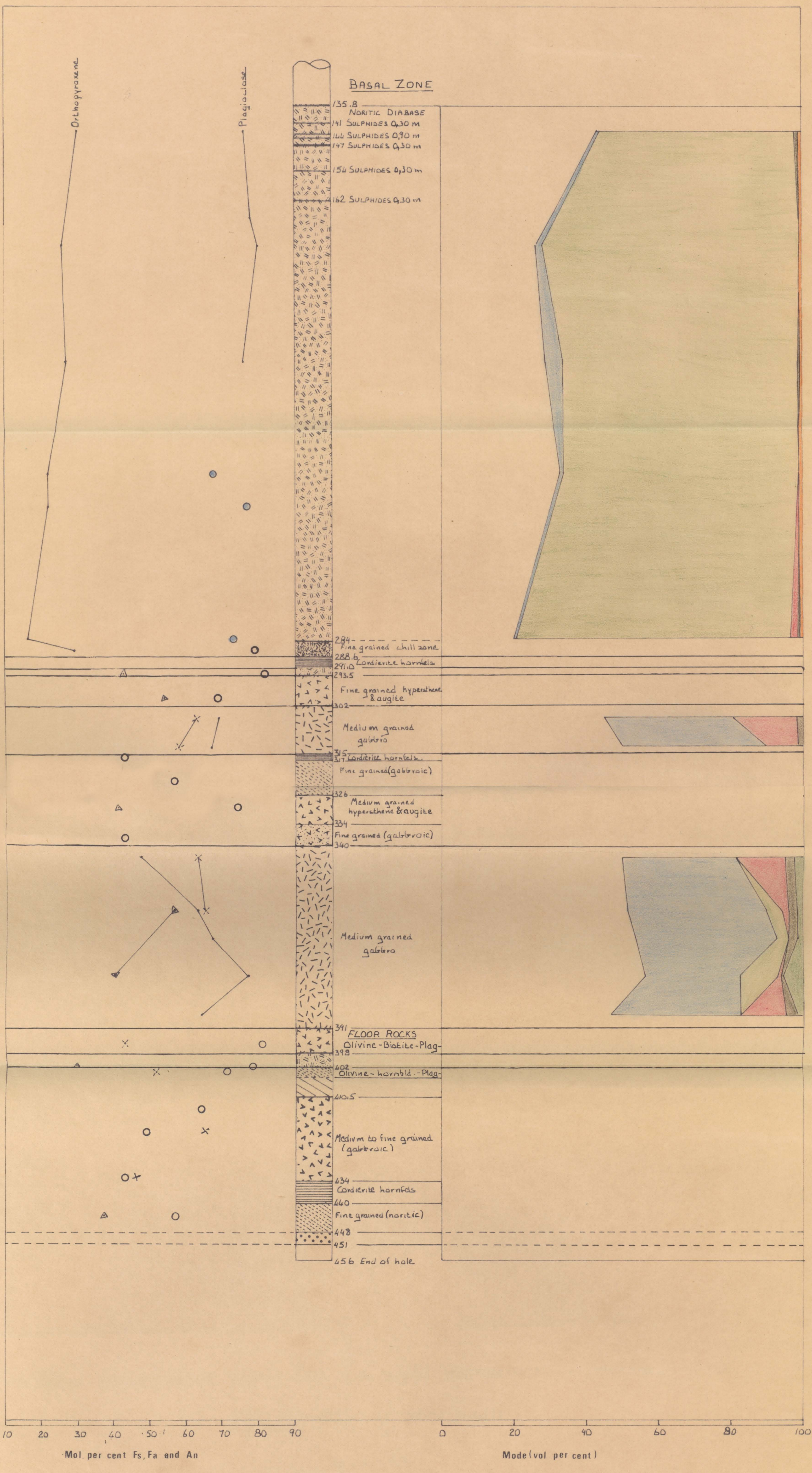
FOLDER IV. COMPOSITIONAL VARIATIONS AND MODAL DISTRIBUTION OF MINERALS IN THE DIABASES OF KAALLAAGTE 2

Scale 1:1000



Key (mode given in Folder I)

Maruleng Type	Diabase
Lydenburg Type	Diabase
Cordierite–Hornfels	Pyroxene–Hornfels Facies
Granofels	Pyroxene–Hornfels Facies
Banded Pyroxene Granofels	Pyroxene–Hornfels Facies
Calc–Silicate Fels	Pyroxene–Hornfels Facies
Hornblende–Hornfels Facies	
Albite–Epidote–Hornfels Facies	

● INTERCUMULUS } PLAGIOCLASE
○ CUMULUS } PLAGIOCLASE
✕ OLIVINE
△ ORTHOPYROXENE