THE TRANSITION BETWEEN THE MAFIC AND THE ACID PHASE OF THE BUSHVELD COMPLEX IN THE RUSTENBURG-BRITS AREA

by

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ABSTRACT

In the western Transvaal the Veekraal granite (the Lebowa Granite Suite) and the basic rocks (the Rustenburg Layered Suite) of the Bushveld Complex are separated by a thickness of acid rocks here called the transition zone. The transition zone consists predominantly of two rock rypes:

the Beestkraal granophyre, and
the Zwartbank pseudogranophyre.

In addition to these rocks, microgranite, Veekraal granite in the form of downward offshoots from the overlying granite and xenoliths of sedimentary rocks are also found in the transition zone.

The Zwartbank pseudogranophyre is a transformed rock type, the parent rocks being the uppermost portion of the Pretoria Group. Two textural varieties of the Zwartbank rocks are recognized, the pseudogranophyre and the poikilogranite. These are regarded as transformation products of coarse- and fine-grained parent rocks respectively. The transformation took place during, and as a consequence of, the emplacement of the layered sequence.

On the other hand, available evidence indicates that the Beestkraal granophyre is a magmatic rock formed by cotectic crystallization from a melt. This melt formed and intruded after the emplacement of the layered sequence and the formation of the Zwartbank pseudogranophyre. No certainty exists concerning the derivation of the granophyre melt.

Intrusion of the Veekraal granite appears to be the final event in the igneous history of the western Bushveld Complex.

Tectonism.....

Tectonism occurred during and after the intrusion of the western Bushveld Complex and is taken to be responsible for controlling the intrusive events. Tectonism has also resulted in a structure consisting of a series of folds having northwest-southeast striking fold axes. An anticline was formed in the centre of the Veekraal granite along the crest of which rocks of the transition zone are exposed. Basic rocks of the layered sequence here underlie the transition zone at a relatively shallow depth (about 500 m or less).

SAMEVATTENDE OORSIG

In Wes-Transvaal word die Veekraalgraniet (die Granietreeks Lebowa) van die basiese gesteentes (die Gelaagde Reeks Rustenburg) van die Bosveldkompleks geskei deur 'n laag suurgesteentes wat hier die oorgangsone genoem word. Die gesteentes waaruit die oorgangsone hoofsaaklik bestaan is:

die Beestkraalgranofier en
die Zwartbankpseudogranofier.

Buiten die bogenoemde gesteentes word daar ook nog mikrograniet, afwaartse tonge van die oorliggende Veekraalgraniet en xenoliete van sedimentêre gesteentes in die oorgangsone gevind.

Die Zwartbankpseudogranofier is 'n veranderde gesteentetipe, wat oorspronklik deel van die heel boonste gedeelte van die Pretoriagroep was. Daar word twee teksturele variëteite van die Zwartbankgesteentes herken, nl. die pseudogranofier en die poikilograniet, wat beskou word as omsettingsprodukte van grof- en fynkorrelrige gesteentes respektiewelik. Die omsetting het plaasgevind gedurende en as gevolg van die indringing van die basiese gesteentes.

Alle beskikbare gegewens dui daarop dat die Beestkraalgranofier 'n magmatiese gesteente is wat kotekties uit 'n smeltsel gekristalliseer het. Die ontstaan en indringing van die smeltsel het eers na die ontstaan van die Zwartbankpseudogranofier en die indringing van die gelaagde reeks plaasgevind. Dit is nie moontlik om met sekerheid die oorsprong van die smeltsel vas te stel nie.

Dit wil voorkom asof die indringing van die Veekraalgraniet die finale episode in die stollingsgeskiedenis van die westelike Bosveldkompleks was.

Tektoniese.....

Tektoniese aktiwiteit het sowel gedurende as na die indringing van die westelike Bosveldkompleks plaasgevind en het die periodes van indringing beheer. As gevolg van die tektoniese aktiwiteit het daar ook 'n struktuur ontwikkel van plooie met noordwes-suidoos gerigte plooiasse. 'n Antiklien het in die middel van die Veekraalgraniet gevorm en gesteentes van die oorgangsone dagsoom gevolglik langs die kruin van die antiklien. Basiese gesteentes van die gelaagde reeks kan gevolglik op 'n redelike klein diepte verwag word (ongeveer 500 m of minder).

TABLE OF CONTENTS

7.1.5.....

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

This thesis deals with the acid rocks of the western Bushveld Complex in the area north of Rustenburg and Brits and in particular with those acid rocks which separate the layered sequence from the Bushveld granite. These rocks form a zone here called the transition zone, the word transition being used in a spatial sense to indicate the physical separation of the layered sequence from the granite.

The field work in this area formed part of a mapping program of the Geological Survey of South Africa and the area covers parts of the Saulspoort 2527A and Beestekraal 2527B sheets. The mapping was mainly concentrated on the acid rocks of the Bushveld Complex since most of the remaining area of the two sheets had previously been mapped by various workers (F.J. Coertze, 1964-65; W.J. Verwoerd, 1962; E.A. Retief, 1963). G.F. Andrew of the Survey also mapped a portion of the acid rocks in the area at the same time as the author. The portions mapped by various workers are shown in Fig. 1.

The rocks of the transition zone consist predominantly of granophyre and granophyric rocks. A great deal of attention was given to these rocks during the field work and they were the focal point of subsequent studies, as they provide some insight into the history and genesis of the Bushveld Complex.

In addition to the field work a considerable amount of detailed information concerning the transition zone has been obtained from a bore-hole drilled for the Geological Survey by the Department of Water Affairs. This bore-hole, BK1, is the first in

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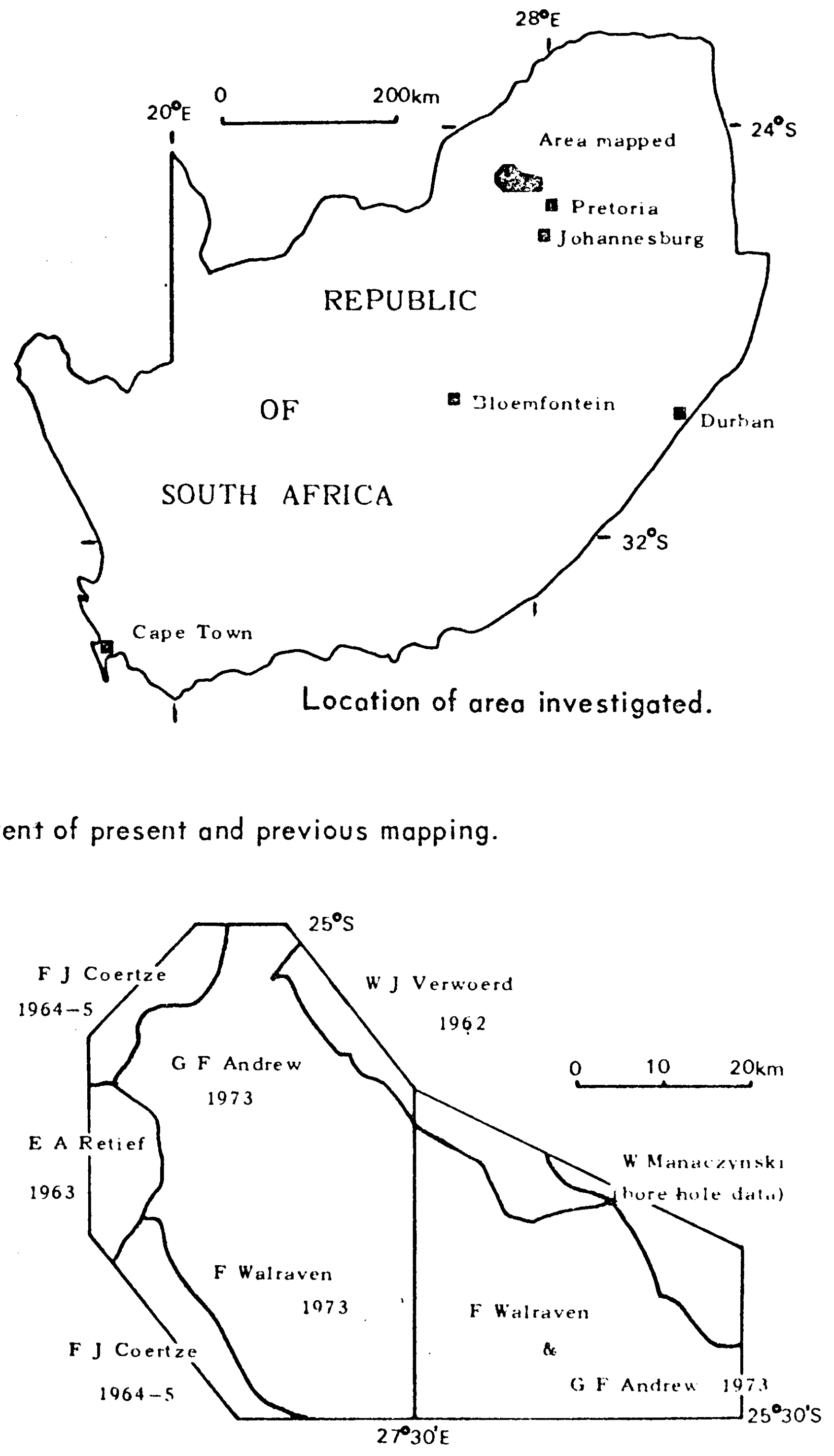

FIG. 1. Locality map and index to present and previous mapping.

a series intended to provide a complete stratigraphic record of the layered sequence in the western part of the Bushveld Complex. About 400 m of transition zone is intersected by the bore-hole.

2 PHYSIOGRAPHY

The mapped area forms part of the central Transvaal or Bushveld geomorphological province (King, 1963, p.231). The climate of the area is typical of the Bushveld and is characterized by an annual rainfall ranging between 350 and 650 mm which falls mostly during the summer months. Temperatures range between 21 and 27^{o}C in summer and between 10 and 15^{o}C in winter. The vegetation is typically savanna.

The average elevation of the area is about 1100 m above sea-level and five main physiographic regions, related to areas underlain by specific rock types, can be recognized. These are (1) the granite of the Bushveld Complex, (2) the layered sequence of the same Complex, (3) the Pilanesberg Complex, (4) the rocks of the Transvaal sequence forming the Crocodile River Fragment, and (5) the Karoo sequence.

The area underlain by the Bushveld granite has a rather flat, gently undulating topography. Over large areas the granite is covered by a thickness of between 5 and 10 m of coarse, sandy soil in which detrital quartz grains predominate. The quartz is poorly rounded, has rough surfaces and is accompanied by clay minerals formed by weathering of the feldspar. Generally the soil has formed <u>in situ</u> although slight soil movement has taken place locally, resulting in the obscuring of small features such as narrow diabase dykes which do not crop out and which can be recognized only as lines of trees or by magnetic methods.

Granite outcrops are found on river and creek

embankments.....

embankments, as low, flat rock surfaces and as granite "koppies". In a number of the latter the granite appears to have become more resistant to weathering due to the intrusion of either carbonatite or diabase and syenite dykes. Bulkop and Spitskop (Folder 1, D4) are examples of the former and Moordkop (Folder 1, C6) is an example of the latter.

On and about the farm Veekraal 221JQ (Folder 1, G6) a large circular area of granite is more resistant to weathering and stands out above the surrounding area. The granite outcrop is about 5 km in diameter and there is no visible difference between the granite here and elsewhere. No reason has been found for the difference in the topographic character of this granite and that of the remaining Bushveld granite.

The generally smooth topography of the granite is also disrupted by small prominent hills of quartzite. These quartzite bodies are present as xenoliths scattered in two elongated belts within the granite. Examples of xenoliths can be seen on the farms Beestkraal 199JQ and Leeuwfontein 35JQ (Folder 1, E5 and B3).

The second physiographic region in this area is formed by the rocks of the layered sequence of the Bushveld Complex. This region adjoins the granite region to the west and although the topography is very subdued, there is a slight but consistent fall in elevation when passing from the granite to the basic rocks. The ferrogabbro of the Upper Zone does not crop out at all in this area and only some of the magnetitite layers are seen. The soil overlying

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the ferrogabbro is fine-grained and has a distinctive red-brown colour, in contrast to the black soil overlying the gabbro of the Main Zone.

The Pilanesberg Alkaline Complex is located at the western margin of the granite and forms another topographically distinct area. It is circular in shape with a diameter of about 20 km . It consists of cone sheets and ring dykes intruded into both the granite and the rocks of the layered sequence. The alkaline intrusives form a series of discontinuous arcuate hills. These have been segmented by a centrifugal drainage system in which the rivers emerge to form "poortjies" at the outer margin of the Complex.

To the northeast of the granite region the Crocodile River Fragment consists of sediments of the Transvaal sequence of which the quartzite and banded ironstone are relatively more resistant to weathering than the other sediments and consequently form prominent, long ridges. Valleys and low-lying areas have formed on the less resistant sediments and on the carbonatite complexes which have intruded into the fragment between these ridges.

The eastern part of the area is underlain by flat-lying sediments of the Karoo sequence which outcrop poorly and which form a flat topography. The area is occupied by numerous cultivated lands.

Little physiographic expression, apart from a slight rise in elevation, is associated with the carbonatite complex located on and near the farm Tweerivier 197JQ (Folder 1, E4).

Drainage in the area consists of three main rivers. The Elands and Hex Rivers flow east and north respectively and meet at the Vaalkop Dam. The Crocodile

River.....

River flows northward from the Hartebeestpoort Dam and is an important source of irrigation water.

3 STRATIGRAPHY AND AGE RELATIONS

Although the acid igneous rocks of the western Bushveld Complex are the subject of this thesis it is also necessary to briefly consider the other rocks in this area, both those younger and older. The geology of the area north of Rustenburg and Brits involves rocks ranging from the Transvaal sequence to the Karoo sequence.

At the time of writing the South African Committee for Stratigraphy (SACS) was still engaged in determining an acceptable formal nomenclature for the major lithostratigraphic units of South Africa and South West Africa. SACS had received proposals for formal lithostratigraphic subdivisions from the working groups for the Transvaal sequence, the Rooiberg Group, the Bushveld Complex and the Karoo sequence. These proposals are adhered to as far as possible.

A synthesized stratigraphic succession of the rock units in the western Bushveld Complex is set out in Table 1. Formal names submitted to SACS are shown capitalized; informal names are shown with lower case letters.

The oldest rocks in the area are those of the Pretoria Group (Transvaal sequence) which consists predominantly of sedimentary rocks. The Rayton Formation is shown as forming the upper part of the Pretoria Group, although Stear (1976) proposes the name Leeuwpoort Formation for quartzite and shale occupying a stratigraphically similar position in the Rooiberg area. The Leeuwpoort Formation is overlain by the Smelterskop Formation which Stear redefines

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as consisting of interbedded lava flows and sediments together with the basal white quartzite which forms the lowest part of this formation.

TABLE 1

STRATIGRAPHIC SUCCESSION IN THE WESTERN BUSHVELD COMPLEX

Recent surface deposits	
Karoo sequence	
Diabase dykes	
Alkaline and carbonatite intrusions	
BUSHVELD COMPLEX	
LEBOWA GRANITE SUITE	
NEBO GRANITE (Veekraal granite) - Coarse-grained pink to grey granite	
RASHOOP GRANOPHYRE SUITE	
Beestkraal granophyre - Coarse-grained red to purplish-red granophyre	
Zwartbank pseudogranophyre - Medium to coarse-grained granophyric rocks of various colours,characterized by pseudographic and poikilitic textures	
RUSTENBURG LAYERED SUITE	
UPPER ZONE - Ferrogabbro, ferrodiorite, magnetitite layers	
MAIN ZONE - Gabbro	
CRITICAL ZONE - Pyroxenite, porphyritic pyroxenite, anorthosite	
LOWER ZONE - Norite, pyroxenite	
MARGINAL ZONE - Fine-grained marginal portions of the above rock types	
ROOIBERG GROUP	
Acid lava flows, agglomerate, ash-flow tuff	ca. 1000m
Transvaal sequence	
PRETORIA GROUP	
RAYTON FORMATION - Quartzite alternating with shale, minor andesite	1200m
MAGALIESBERG QUARTZITE FORMATION - Orthoquartzite	300m
SILVERTON SHALE FORMATION - Silty and graphitic shale with thin interbedded limestone	600m
DASPOORT QUARTZITE FORMATION - Orthoquartzite	80-95m
STRUBENKOP SHALE FORMATION - Iron-rich shale	105-120m
HEKPOORT ANDESITE FORMATION - Andesitic lava flows, agglomerate, tuff	340-550m
TIMEBALL HILL FORMATION - Shale, quartzite, minor diamictite	270-660m

The Pretoria Group is overlain by the Rooiberg Group, a succession of acid volcanic rocks which were extruded prior to the intrusion of the Bushveld Complex. The Rooiberg Group formed a part of the roof rocks of the Bushveld Complex and has been interpreted as an initial volcanic phase preceding the intrusive phase of the Complex (Willemse, 1964).

A number of radiometric age determinations are available both on rock samples collected within the

area.....

area mapped and on samples from outside the area. The most accurately determined age is that of the granite of the Bushveld Complex. A large number of granite samples from various parts of the Bushveld Complex have been dated for the Geological Survey by Dr. A.J. Burger of the National Physical Research Laboratory, C.S.I.R., using the uranium-lead method. Discordia diagrams of the results provide a reliable age of 1920 m.y. for the granite. This age agrees with other ages reported by Burger and Coertze (1973, p.12).

Uranium-lead age determinations of rocks of the Rashoop Granophyre Suite have also been carried out by Dr. Burger using samples from both the western and eastern Transvaal. These indicate an age of 2048 m.y. (Coertze et al, 1977).

A rubidium-strontium age obtained for felsite samples from the Rooiberg Group in the Loskop Dam area (analysis by the Bernard Price Institute, University of the Witwatersrand, for the Geological Survey) indicates 2030 m.y. as being a minimum age for these rocks, probably reflecting "resetting" by the intrusion of the Bushveld Complex (Burger and Coertze, 1975, p.137). This age corresponds closely to another rubidium-strontium age of 2050 m.y. obtained on biotite from the Merensky Reef from the Rustenburg Platinum Mine (Burger and Coertze, 1973, p.12).

An argon 39/40 age determination carried out on gabbro of the Bushveld Complex from north of Pretoria resulted in an age of 1907 m.y. (analysis by F.M. Consultants of Herne Bay, England). This is almost certainly a minimum age only and the emplacement of the gabbro must have taken place before this date, especially

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when seen in the light of another argon 39/40 determination on ferrogabbro of the Upper Zone which gave an age of 2096 m.y. (F.M. Consultants).

A rubidium-strontium isochron age obtained on bore-hole samples of the Hekpoort Andesite Formation by the Bernard Price Institute indicates an age of 2224 m.y. for the consolidation of the lava which took place during the deposition of the rocks of the Transvaal sequence (Burger and Coertze, 1975, p.137).

Intrusion of diabase dykes, carbonatite complexes and the Pilanesberg Complex took place after the emplacement of the Bushveld Complex. Subsequent to this the deposition of the sediments of the Karoo sequence and the intrusion of dolerite dykes took place, representing the final episode of the observable geological history of the area. An argon 39/40 age of 174 m.y. was obtained by F.M. Consultants on a dolerite dyke crossing the area from east to west (Burger and Coertze, 1977).

A summary of the available age determinations is presented in the following table.

TABLE 2

SUMMARY OF AGE DETERMINATIONS

ROCK DATED	LOCALITY	METHOD USED	AGE
Karoo dolerite dyke	Leeuwfontein 35JQ	Ar 39/40	174±3 m.y.
Nebo Granite	Various localities in the eastern and western Bushveld Complex	U/Pb discordiagram	1920±30 m.y.
Granophyre from the Rashoop Granophyre Suite	Various localities in the eastern and western Bushveld Complex	U/Pb discordiagram	2048±30 m.y.
Ferrogabbro from the Upper Zone	Bore-hole BK1	Ar 39/40	2096±12 m.y.
Gabbro from the Main Zone	Bushveld Complex	Ar 39/40	1907±24 m.y.
Biotite from the Merensky Reef, Critical Zone	Rustenburg Platinum Mine	Rb/Sr	2050±50 m.y.
Hekpoort Andesite Formation	Bore-hole on Kalbasfontein 365 IQ	Rb/Sr. 5-point isochron	2224±21 m.y.

4 GENERAL GEOLOGY

4.1 PRE-BUSHVELD ROCKS

4.1.1 THE TRANSVAAL SEQUENCE

Within and surrounding the mapped area rocks of the Transvaal sequence are found in three geological settings. They are:

(1) the floor of the Bushveld Complex underlying the layered sequence;

(2) the Crocodile River Fragment adjoining the area to the northeast;

(3) sedimentary xenoliths within the Bushveld granite and at the contact between the granite and the layered sequence.

The floor of the Bushveld Complex in this area consists of rocks of the Silverton Shale and the Magaliesberg Quartzite Formations. These formations correspond to what was formerly known as the Magaliesberg Stage. Prior to the intrusion of the Complex these sediments were undoubtedly overlain by the Rayton Formation. The lithology and thicknesses of these formations according to Visser (1969, p.10) are shown in Tables 1 and 3. The thicknesses are estimated and are complicated by small-scale folding and the presence of diabase sills in the shale. These sills appear to have contributed to the metamorphism of the shale which has in addition been altered to hornfels near the top (in the upper 300 to 500 m) suggesting further metamorphism resulting from the intrusion of the Bushveld Complex.

The Magaliesberg Quartzite is predominantly orthoquartzite, contains abundant cross-bedding and ripple marks and is purple-pink to white in colour.

Extensive.....

Extensive recrystallization has taken place due to the intrusion of the layered sequence of the Bushveld Complex and the quartzite is now characterized by coarse, glassy, interlocking grains measuring up to 5 mm in diameter.

TABLE 3

STRATIGRAPHY OF THE UPPER PART OF THE PRETORIA GROUP

(after Visser, 1969 and Stear, 1976)

ROOIBERG AREA:

PRETORIA GROUP		
SMELTERSKOP FORMATION	Amygdaloidal lava flows with interbedded thin layers of feldspathic quartzite and tuffaceous shale; white quartzite at base with conglomerate, pebble beds, grit and agglomerate	ca. 200m
LEEUWPOORT FORMATION		
Blaauwbank Shale Member		
A	Thinly bedded siltstone and shale, locally micaceous	90-250m
B	Alternating arkose, quartz sandstone, siltstone and shale	100-200m
Boshoffsberg Quartzite Member	Feldspathic quartzite, arkosite, minor conglomerate, pebble-beds and grit	1400m

PRETORIA AREA:

PRETORIA GROUP		
RAYTON FORMATION		
Beynespoort Quartzite Member	Feldspathic quartzite with silty shale, andesitic lava and minor interbedded limestone and chert	350m
	Dark-coloured shale	170m
Doornpoort Quartzite Member	Coarse-grained orthoquartzite	160m
	Subgreywacke and shale	187m
Baviaanspoort Quartzite Member	Feldspathic quartzite and arkosite	223m
	Dark-coloured shale, cross-bedded quartzite, minor dolomite	141 m

Details of the strata overlying the Magaliesberg Quartzite are available from the area to the northeast of the Crocodile River Fragment, the Rooiberg area as well as from the area northeast of Pretoria. A synthesis of this information is shown in Table 3. In each of these areas the Magaliesberg Quartzite is succeeded by a sequence of quartzite, crossbedded feldspathic quartzite, subgreywacke and subarkose together with hornfels, shale and gritty quartzite with pebble intercalations. Several thin layers of andesitic lava are found near the top of

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the sequence as well as intercalated chert, dolomite and limestone layers.

The sedimentary xenoliths are found in two belts, one located along the contact between the layered sequence and the granite extending from Potgietershoogte 134JQ (Folder 1, D6) in the south to Varkfontein 13JQ (Folder 1, B1) in the north and the other, which is located more or less centrally in the granite, extending from Klipkop 411JQ (Folder 1, G6) in the southeast to Koedoesspruit 33JQ (Folder 1, B2) in the northeast. These are named the contact and central belts respectively.

Although sedimentary xenoliths are quite abundant, they include only a limited variety of rock types. Most xenoliths consist of quartzite and a smaller number consist of feldspathic quartzite. There is a noticeable lack of xenoliths of other rock types. The quartzite is commonly massive, thick-bedded, recrystallized to various degrees and contains crossbedding and ripple marks. The xenoliths of feldspathic quartzite are also recrystallized and display traces of the original sedimentary bedding in the form of alternating layers of varying feldspar content.

A wide range of deformation can be seen in the sedimentary xenoliths. In some cases, e.g. the large xenoliths on Beestkraal 199JQ (Folder 1, E5), only slight tilting and warping has taken place. In other cases, like the xenolith on Bierkraal 120JQ (Folder 1, B6 and C6) however, folding, brecciation and evidence of plastic deformation are seen. Figure 2 shows rheomorphic structures similar to those described by Strauss (1943, p.41) from the Potgietersrus area.

Rheomorphic.....

FIG. 2. Rheomorphic structure in a metasedimentary xenolith. Leeuwfontein 35JQ.

FIG. 3. Typical low, blocky outcrop of Beestkraal granophyre. Klipkop 411JQ.

Rheomorphic structures can also be seen in outcrops of sedimentary xenoliths in the bed of the Hex River on Kafferskraal 133JQ (Folder 1, C6).

An example of a xenolith not consisting of quartzite is found immediately south of the area mapped, on the farm Potgietershoogte 134JQ. This xenolith, which forms part of the contact belt, measures 1,5 km in length and contains thins beds of chert alternating with thicker beds of impure metamorphosed limestone (now mostly wollastonite). The xenolith has been tilted and the dip of the bedding is northward at 30 degrees.

4.2 THE BUSHVELD COMPLEX

In the past the Bushveld Complex as a whole was regarded as consisting of three phases: the sill phase; the phase of basic igneous intrusion of the layered sequence; and the acid intrusive phase of the Bushveld granite (Hall, 1932). The granophyric rocks of the transition zone do not obviously belong to any of these three phases but rather appear to fit between the second and third phases. In the proposed subdivision of the Bushveld Complex (Bushveld Working Group, SACS) the granophyric rocks are grouped apart from the layered sequence and the granite, and form part of the Rashoop Granophyre Suite.

4.2.1 THE RUSTENBURG LAYERED SUITE

The Rustenburg Layered Suite consists of the basic rocks forming the layered sequence. They are found to the northwest and southwest of the area mapped, adjoining the Bushveld granite and the transition zone. In Table 4 the subdivision proposed by

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the Bushveld Working Group is shown in comparison with the classifications of Willemse (1964) and Coertze (1974). This classification is similar to that of Willemse (1964, p.101) and is a subdivision into zones which is based in part on the appearance of certain mineral phases.

TABLE 4

COMPARISON OF SUBDIVISIONS OF THE LAYERED SEQUENCE OF THE BUSHVELD COMPLEX

Coertze, 1974	Willemse, 1964	SACS, 1976
Ferrogabbro Unit	Upper Zone *Main Magnetitite Layer*	Upper Zone
Gabbro Unit	Main Zone	Main Zone
Porphyritic Pyroxenite Unit	*Merensky Reef*	
Norite Unit	Critical Zone	Critical Zone
Anorthosite Unit		
Pyroxenite Unit (incl. Harzburgite Unit)	*Main Chromitite Layer*	
Basal Norite Unit	Basal Zone	Lower Zone
(incl. Marginal Norite Subunit Quartz Norite Subunit)	Chill Zone	Marginal Zone

The alternative classification proposed by Coertze is closely related to his model of the formation of the layered sequence (Coertze, 1974, p.18). Eight units are distinguished on the basis of the intrusive relationships observed between the units, and each unit represents an individual intrusion or closely related set of intrusions of basic magma. In order of emplacement the units recognized by Coertze are (1) the basal norite unit, (2) the harzburgite unit, (3) the pyroxenite unit, (4) the anorthosite unit, (5) the norite unit, (6) the porphyritic pyroxenite unit, (7) the gabbro unit and (8)

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the ferrogabbro unit.

In the area mapped the rocks of the layered sequence are generally poorly exposed. The ferrogabbro of the Upper Zone is normally covered by between 30 and 40 m of soil and outcrops are usually found only in creek beds or road cuttings.

The individual intrusions of the layered sequence are sheetlike and generally conformable to each other and the underlying strata of the floor. Minor discordancies are found locally (Feringa, 1959) and a major discordancy exists north of the Pilanesberg where two transgressive lobes of ferrogabbro of the Upper Zone have cut across the previously emplaced parts of the sequence as far down as the floor of the Complex. The southernmost of these is shown in Fig. 29 and attention is drawn to the parallelism between the contact of the ferrogabbro with the older rocks and the strike of the magnetitite layers in the ferrogabbro.

LANDSAT images of the area show the transgressive lobes of ferrogabbro quite clearly. They can be recognized because the soil on the ferrogabbro shows up drab green, compared with the bright blue colour of the gabbro. The imagery in addition shows the existence of a third, smaller transgressive lobe located to the northeast of the large lobes, alongside the Crocodile River.

4.2.2 THE TRANSITION ZONE

The transition zone is defined here as the assemblage of acid rocks separating the layered sequence and the granite of the western Bushveld

Complex.....

Complex. The rock types of this association are granophyre, pseudogranophyre and poikilogranite together with sedimentary xenoliths and minor microgranite.

On the geological map the individual outcrops of granophyre, pseudogranophyre and poikilogranite are not indicated separately, but are shown collectively as granophyric rocks. The reason for this is that the differences between these rock types are not always visible in hand specimen, and that these rocks are often intimately mixed and single bodies are too small to be shown at the scale used for the map. The same applies to certain areas where granite and granophyre are also intimately associated; these cases are shown on the map as mixed granite and granophyre.

Rocks of the transition zone are confined to the two belts where sedimentary xenoliths are found, i.e. the central and contact belts. The contact between the granite and the rocks of the transition zone is not a sharp one, but very irregular and many offshoots of the granite have intruded into the rocks of the transition zone.

There is very little regularity in the distribution of rock types within the transition zone. The sedimentary xenoliths are randomly distributed and may be found near the base, middle or top of the zone. Similarly the vertical distribution of the granophyre, pseudogranophyre and poikilogranite is random. A lateral trend can, however, be observed in the distribution of granophyre, pseudogranophyre and poikilogranite. In the southeastern part of the transition zone granophyre is more abundant than the other rock types. Towards the west and north

pseudogranophyre.....

pseudogranophyre and poikilogranite increase in abundance until they become predominant in the vicinity of the Pilanesberg (Folder 1, B5, A4 and A2).

Names proposed for the predominant rock types of the transition zone are Beestkraal for the granophyre and Zwartbank for the pseudogranophyre and the poikilogranite together.

4.2.2.1 THE BEESTKRAAL GRANOPHYRE

The name Beestkraal is used for the granophyre sensu stricto of the transition zone. It is named after the farm Beestkraal 199JQ (Folder 1, E5) on which good outcrops of the rock can be seen. In the field the granophyre is characterized by relatively smooth, flat outcrops (Fig. 3) that contrast strongly with the rough surfaces and large boulders which characterize the outcrops of granite. On weathered surfaces the granophyre has a pale yellow-brown colour, but fresh surfaces are red to purplish-red. More rarely the fresh rock is dark grey to almost black in colour.

Characteristic features of the granophyre are also the micrographic texture, consisting of intergrowths of quartz and alkali feldspar which are normally sufficiently coarse to allow recognition by means of a hand lens, as well as its irregular distribution of mafic minerals, which tend to aggregate to form clusters.

Jointing in the granophyre is usually prominent and sharply defined, a feature which may be related to its outcrop pattern. Where the granophyre is

observed.....

observed in contact with granite the joints in the granophyre are both more strongly developed and greater in number than in the granite. It is believed that this difference is the result of a greater degree of intergranular bonding in the granophyre than in the granite, which results in the former breaking across grains rather than along grain boundaries. This difference is also noted when the granophyre is broken with a hammer.

Contacts of the Beestkraal granophyre with the other rock types of the transition zone, observed in the field as well as in core from bore-hole BK1, are usually sharp and well-defined. At contacts with the granite the change from the one rock type to the other is complete within a distance of 10 mm. Grain size variations at the contacts are not significant in the granophyre and very slight in the granite. A greater degree of grain size variation is in fact seen in the granite on a regional scale when central and marginal portions of the granite sheet are compared.

Individual bodies of granophyre vary in size from small blocks surrounded by granite to large masses of granophyre which in places are penetrated by veins and apophyses of granite (Fig. 4). The field relationships quite conclusively indicate that the granophyre predates and has been intruded by the granite.

4.2.2.2 THE ZWARTBANK PSEUDOGRANOPHYRE

The rock types making up this formation are pseudogranophyre and poikilogranite. These rocks

are.....

FIG. 4. Intrusive vein of Veekraal granite (under lenscap) in Beestkraal granophyre. Klipkop 411JQ.

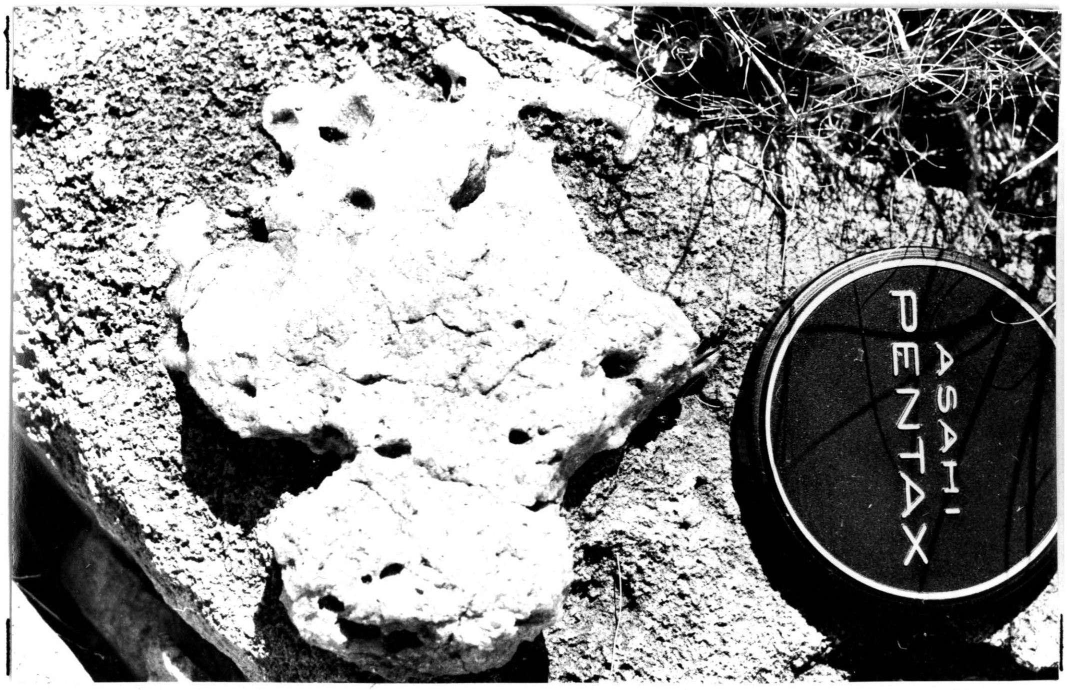

FIG. 5. Sharp contact of quartzite inclusion in Zwartbank pseudogranophyre. Zwartbank 121JQ.

are similar in most respects but differ significantly in terms of their texture. The two names are indicative of their essential texture, but in order to point out their basic similarity as well as to reduce the number of names used, they are collectively referred to as the Zwartbank pseudogranophyre. Good exposures of both rock types are to be found on Zwartbank 121JQ (Folder 1, B5) where they form outcrops similar to those of the granophyre. They are smooth, flat and also consist of small jointed blocks.

The pseudogranophyre and poikilogranite are both characterized by fine intergrowths of quartz and feldspar. In the former the characteristic texture resembles micrographic intergrowth (Fig. 10c), while in the latter it is poikilitic (Fig. 11). In hand specimen these rocks are often indistinguishable from the Beestkraal granophyre, although the former display a greater range of colour on fresh surfaces (white, grey, pale brown and pink to red) and their intergrowths are normally less regular than those of the granophyre.

Contact relations between the pseudogranophyre and the poikilogranite are gradational and a complete range of rocks containing varying proportions of both characteristic textures can be found. Contacts of these rocks with the granophyre are usually sharp although in the core from bore-hole BK1 an example of a gradational contact between the Zwartbank pseudogranophyre and granophyre is present.

Good examples of contact relationships between the pseudogranophyre and inclusions of sedimentary rocks are found on Zwartbank 121JQ (Fig. 5). Both rounded and angular fragments of quartzite are

enveloped.....

enveloped in pseudogranophyre. Their contacts are extremely sharp and well-defined. The majority of fragments consist of orthoquartzite; some are found to contain over 95% quartz, the other constituents being a colourless to pale green amphibole, potassium feldspar and sphene.

Embayments in the quartzite fragments suggest that resorption by the surrounding pseudogranophyre has taken place to some extent. This can also be seen in the texture of some of the fragments themselves in which coarse quartz grains are embayed by feldspar (very weathered but probably potassium feldspar) which is in optical continuity over distances including two to three of the quartz grains.

Quartzite xenoliths rarely have gradational contacts with the surrounding pseudogranophyre, the only exceptions being those in which the quartzite is impure.

In this study granitic rocks with a grain size of less than about one millimetre are grouped under the term microgranite. The majority of rocks in the area that fall into this category are clearly of sedimentary origin, since they display current lamination and cross-bedding on their weathered surfaces. An example can be seen 2 km south of Wevedene, just west of the Hex River on Kafferskraal 133JQ (Folder 1, C6).

A small outcrop of fine-grained rock intruded by granite was temporarily exposed during railway excavations on the farm Hartebeestpoort 419JQ. This rock is reddish brown in colour, has the macroscopic appearance of a rather fine-grained granite and contains blebs and dendrites of a mafic mineral. It is

an.....

an albite-bearing quartzite containing poikiloblasts of hornblende. Its contact with the granite is sharp and well-defined (Fig. 6). Albite-bearing quartzite, similar to the above but lacking the hornblende poikiloblasts, is found as fragments in the pseudogranophyre on Zwartbank 121JQ.

By volume the microgranite constitutes a relatively small portion of the rocks of the transition zone. It is not believed that any significant amount of the microgranite formed as a fine-grained marginal phase of the Bushveld granite because the chilled margin of the latter, as seen in the vicinity of Bierkraal 120JQ (Folder 1, B6), is actually coarser grained than the microgranite.

4.2.3 THE BUSHVELD GRANITE

The granite of the Bushveld Complex, formally known as the Nebo Granite, is referred to as the Veekraal granite in the western Bushveld. This name has previously been used by de Waal (1973) to indicate the Bushveld granite in the western Transvaal. The name in its present usage has been taken from the farm Veekraal 221JQ (Folder 1, G6) where excellent, fresh exposures of the granite are found in a quarry. A specimen for age determination was obtained from this locality and it yielded a reliable radiometric age of 1940 m.y. (Burger and Coertze, 1975).

By far the largest part of the area mapped is occupied by the Veekraal granite. It adjoins the Crocodile River Fragment and from there extends west and south up to the rocks of the transition zone. It is accepted that the shape of the Veekraal granite

is.....

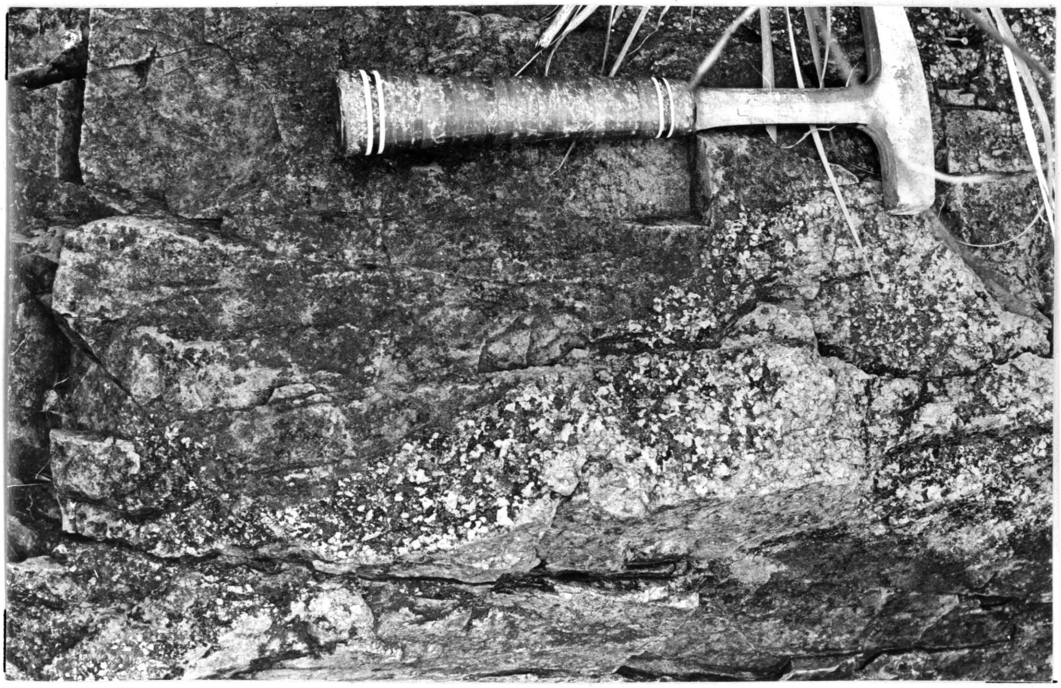

FIG. 6. Sharp contact of Veekraal granite (centre and right) intruded into fine-grained, albite-bearing quartzite in railway excavation. Hartebeestpoort 419JQ.

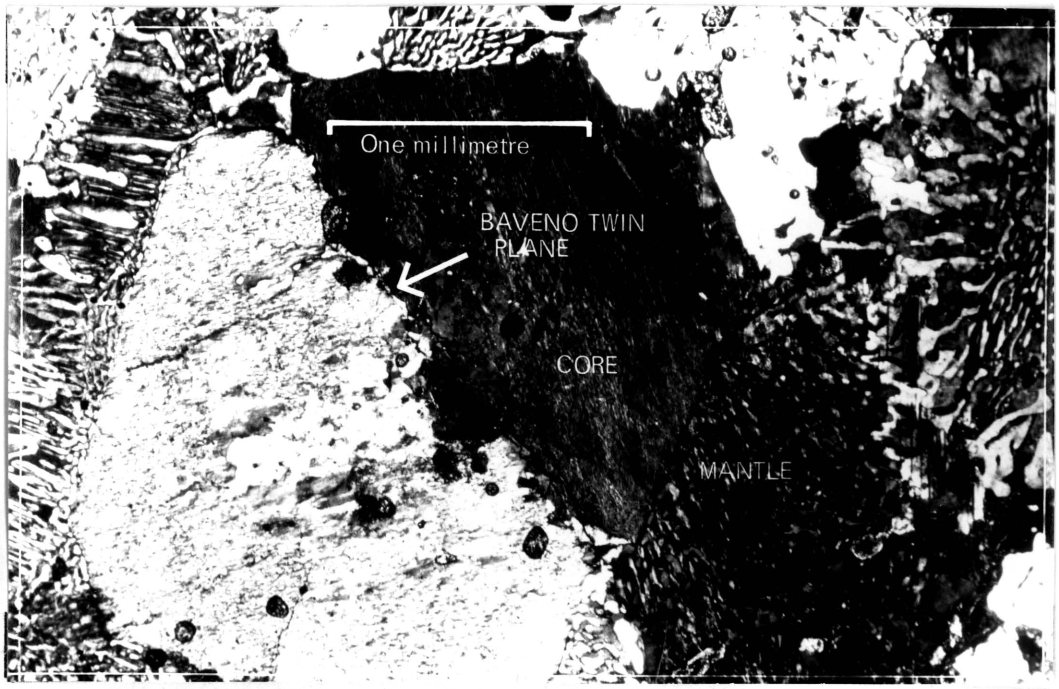

FIG. 7. Continuation of a Baveno twin plane from the core of a micrographic grain into the mantle in Beestkraal granophyre. Sample no. FW22, Welgevonden 202JQ, transmitted light, crossed polars, x34.

is sheet-like and that it more or less conformably overlies the rocks of the transition zone which separate it from the layered sequence (e.g. Hall, 1932; Willemse, 1964). The sheet has a general dip to the east and has the shape of a large basin which is open to the east. The granite intruded between a floor consisting of rocks of the transition zone and roof rocks formed by the Rayton Formation and the Rooiberg Group. A chilled margin consisting of slightly finer grained granite is found at the base of the granite sheet and the upper margin consists of a porphyritic phase of the granite. The latter has been observed to the northeast of the Crocodile River Fragment, outside the area covered in this thesis (Walraven, 1974a).

As mentioned in the foregoing sections, the contacts of the Veekraal granite with the other rock types are sharp. Near the base of the granite sheet irregular tongues and offshoots of the granite in the underlying rocks of the transition zone can be seen. Further evidence of tongue-like granite intrusions extending downward from the base of the granite sheet can be seen in bore-hole BK1 (see Appendix 1). Here the tongues are seen to occur as low as the base of the transition zone. In the bore-hole the granite is not in direct contact with the ferrogabbro of the layered sequence but is separated from it by eight metres of quartzite which seems to be a down-dip extension of the sedimentary xenolith forming the hills on Bierkraal 120JQ. Irregular intrusions of granite are found in the ferrogabbro on the farm Hartebeestspruit 88JQ (outside the area included in Folder 1).

4.3.....

4.3 POST-BUSHVELD ROCKS

A number of rocks younger than the Bushveld Complex are found in the area mapped. These include diabase dykes, dolerite dykes and carbonatite intrusions as well as the Pilanesberg Alkaline Complex. The latter is located at the western margin of the area, more a less at the contact between the Veekraal granite and the layered sequence, and from it syenite dykes extend for large distances to the southeast and northwest. Dolerite dykes of late-Karoo age traverse the area in an east-west direction.

4.3.1 DIABASE DYKES

Numerous diabase dykes traverse the Veekraal granite in the western part of the area mapped. The dykes are usually narrow, ranging between 10 and 30 m in width, and display a strong preferred orientation. Their strike direction averages 120 degrees. The majority of the dykes are restricted to a zone, approximately 30 km wide, trending 135 degrees. An en echelon pattern results from the discrepancy between the orientations of the dykes and that of the zone. The zone of dykes traverses the area from the southern margin (Folder 1, F6), past the northeastern edge of the Pilanesberg Complex, to the western margin of the area (Folder 1, A2). There is a reasonably good correspondence between the location of the zone of dykes and that of the central belt of transition zone rocks.

Within the Veekraal granite the dykes outcrop in creek beds and occasionally also on higher ground.

Good.....

Good examples of outcropping diabase dykes can be found near Heysteckrand and on the farm Olivenboom 62JQ (Folder 1, A4 and B4). However, the majority of the diabase dykes do not crop out and their presence is mainly inferred from lines of denser growth of trees.

The diabase is a medium-grained rock of gabbroic composition. It consists of labradorite, augite and magnetite together with accessory minerals. The plagioclase forms lath-like crystals which are zoned from labradorite (An_{62}) to andesine (An_{42}) and are twinned according to the albite and Carlsbad laws. The clinopyroxene is interstitial with respect to the plagioclase and the paragenetic sequence is plagioclase-pyroxene-magnetite.

4.3.2 CARBONATITE INTRUSIONS

A considerable number of carbonatite intrusions are found in the area mapped, especially in the vicinity of the Vaalkop Dam. They vary in size and the majority of the intrusions are quite small. Verwoerd (1967, p.14) notes that there appears to be a tendency for dolomitic carbonatites (beforsite) to occur as dykes and for calcitic carbonatites (sövite) to form large masses. These observations are borne out quite well in the area mapped. Many small veins and dykelets of beforsite with stringers of magnetite are found in the area, e.g. Bulkop and Spitskop on Bulhoek 75JQ (Folder 1, D4). Despite the small size of the veins and dykelets, they are surrounded by a considerable aureole of fenitized granite. The latter is more resistant to weathering than

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the surrounding granite and consequently forms prominent hills around the carbonatite. Sövite, on the other hand, is found only in the larger carbonatite intrusions of which the Tweerivier Carbonatite Complex is the only one in the area mapped (Folder 1, E4). According to Verwoerd (1967, p.75) it consists of two parts of which the northern one appears to be older and to consist of carbonatite in which arcuate tremolite-bearing zones and inward dipping arcuate beforsite dykes are developed. The southern part cuts across the northern one and consists entirely of fragments of gabbro and anorthositic gabbro (possibly of Bushveld origin) surrounded by and enclosed in veins of sövite.

5 PETROGRAPHY OF THE ACID ROCKS

Because of the varied terminology found in the literature relating to granophyre, a statement concerning the rock names used in this thesis is considered advisable. In the American Geological Institute Glossary of Geology (Howell, 1957, p.128) the rock granophyre is defined as a quartz porphyry or a fine-grained porphyritic granite characterized by a groundmass with micrographic texture.

The 1974 edition of the Glossary (Gary et al, 1974, p.308) defines granophyric as a term applied to the texture of a porphyritic igneous rock in which the phenocrysts and groundmass mutually penetrate each other, having crystallized simultaneously. The term micrographic (Howell, 1957, pp.129 and 184; Gary et al, 1974, p.450) is applied to a microscopic texture resulting from the regular intergrowth of quartz and feldspar (or, less commonly, other pairs of minerals).

Conforming to the above definitions, the predominant texture found in the Beestkraal granophyre is always micrographic and sufficient phenocrysts of perthite are present to justify the use of the term granophyre.

The names pseudogranophyre (pseudographic texture) and poikilogranite (poikilitic texture), as previously referred to on p.21 and illustrated in Figs. 10a, b, c and 11, are not commonly encountered but are considered useful descriptive names for the rock types involved. Pseudogranophyre has previously been used by Strauss (1955, p.16) for rocks encountered in the Potgietersrust area. The term granophyric is also used in a rather loose sense in this thesis to

indicate.....

indicate collectively the Beestkraal granophyre and the Zwartbank rocks.

5.1 BEESTKRAAL GRANOPHYRE

The Beestkraal granophyre is a granophyre in the strict sense of the word in that it consists almost exclusively of micrographically intergrown quartz and feldspar. It is very probably equivalent to the rock described as Bushveld granophyre in other areas (e.g. Strauss and Truter, 1944, p.52). In addition to the textural implication, the name granophyre is used here also to indicate that these rocks are magmatic in origin and have formed by crystallization from a liquid. As will be demonstrated in the following section, it is believed that the micrographic textures found in magmatic granophyre are recognizable and distinct from similar textures formed in other granophyric rocks.

The modal composition of the Beestkraal granophyre is shown in Table 5. Only a small proportion of the quartz occurs as free, single grains; the majority is found forming micrographic intergrowths with the potassium feldspar. Such free quartz grains as are found in the granophyre are interstitial to the other grains. Perthite is the predominant feldspar in the Beestkraal granophyre. It forms the euhedral cores of intergrown grains, as well as the feldspar phase intergrown with the quartz in the micrographic portions of the crystals. The perthite is either of the string or braided type and is usually rather fine in texture. A small proportion of the cores of intergrown grains consist of orthoclase. The cores are

then.....

then zoned with an inner portion that is heavily sericitized. The origin of the orthoclase is uncertain although they could possibly have been incorporated as xenocrysts.

TABLE 5

MODAL ANALYSES OF VEEKRAAL GRANITE, BEESTKRAAL GRANOPHYRE AND ZWARTBANK PSEUDOGRANOPHYRE

	I		II		III	
	Mean	s	Mean	s	Mean	s
Quartz	33,2	4,2	37,2	2,0	37,8	3,1
Alk. feldspar: Perthite	52,5	4,6	55,5	2,1	43,6	6,6
Orthoclase					10,1	4,5
Plagioclase	7,6	4,2	2,1	2,0	3,3	1,8
Hornblende and biotite	6,0	2,1	4,7	1,9	2,0	1,7
Pyroxene and olivine					1,1	1,0
Others (incl. magnetite, apatite, zircon, sphene)	0,7	0,3	0,5	0,3	2,1	1,9

I *Veekraal granite (12 samples)*
II *Beestkraal granophyre (7 samples)*
III *Zwartbank pseudogranophyre and poikilogranite (9 samples)*
s *Standard deviation*

2000 points were counted per specimen. In the case of coarse-grained rocks more than one section was used for counting. The areas covered and the IC numbers for the specimens involved result in a maximum major mineral analytical error of less than 2,45 (Chayes, 1956, p.83).

Sodic plagioclase is a relative minor component of the granophyre. It never forms micrographic intergrowths with the quartz, but instead is found as small, interstitial crystals between the larger feldspar grains.

Mafic minerals include amphibole (blue-green to brown pleochroic hornblende) and red-brown biotite. Small amounts of opaque mineral (magnetite) and accessory zircon together with apatite and occasional fluorite account for the remainder of the rock. Alteration is very pronounced in some of the surface samples and has resulted in the chloritization of the biotite and the sericitization of the potassium feldspar.

Micrographic intergrowths in the Beestkraal

granophyre.....

granophyre are confined to individual feldspar grains which range up to 5 mm in diameter. The micrographically intergrown grains commonly have a euhedral core of potassium feldspar which is surrounded by a mantle of intergrown quartz and feldspar. In the normal case the feldspar of the core and the mantle are in optical continuity throughout the whole grain. Where twinning is seen in the alkali feldspar core, the twinning continues with no change in its attitude into the feldspar of the mantle (Fig. 7).

Optical continuity is also a characteristic of the intergrown quartz in the micrographic mantle, but the continuity is confined to domains of limited size. The number of these domains varies in different feldspar grains (ranging between 2 and 6 normally) and appears to be related to the size of the feldspar grains.

At the innermost part of the grains the quartz-feldspar intergrowth is rather fine; towards the outside of the grain it becomes distinctly coarser. Despite the coarsening of the intergrowth the proportion of quartz and feldspar is remarkably constant. Measurements made from enlargements of photomicrographs of a number of micrographic grains from several samples result in an average quartz:feldspar ratio of 45:55. In a number of cases a narrow margin can be seen separating the core and the mantle of the micrographic grains (Fig. 8). In this margin the quartz: feldspar ratio is noticeably higher than in the mantle of the same grain. Measurements have indicated ratios in the order of 72:28 for a number of such margins. This high ratio suggests supersaturation of the liquid in SiO_2 just prior to the onset of cotectic

crystallization.....

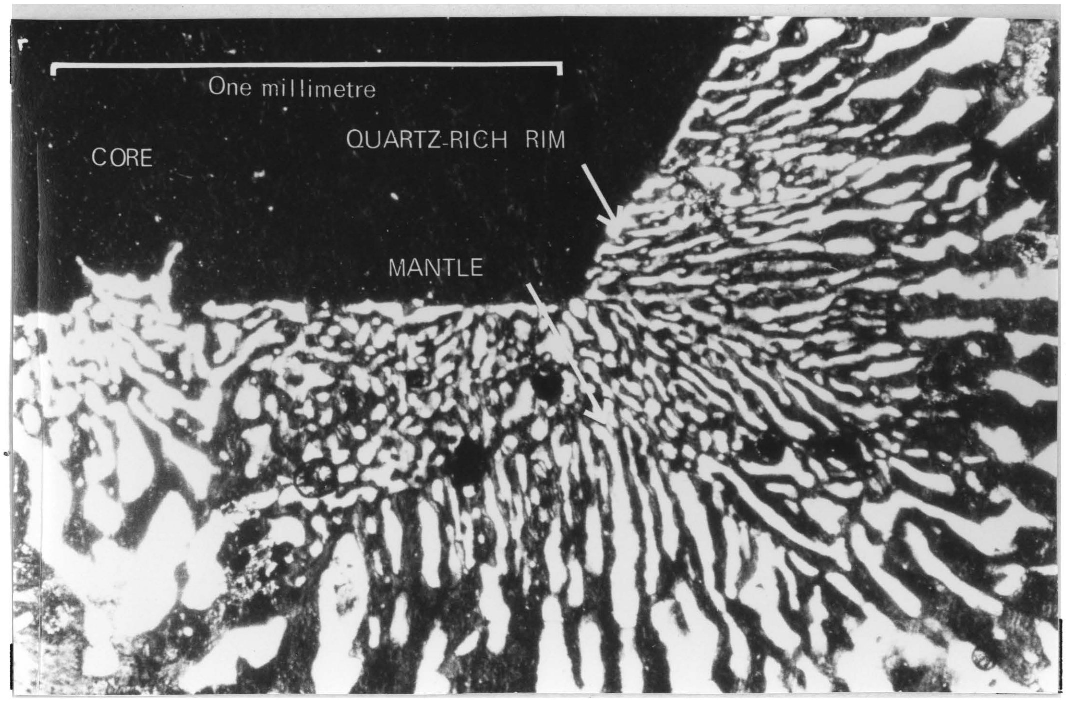


FIG. 8. Quartz-rich rim separating the core and the mantle of a micrographic grain in Beestkraal granophyre. Sample no. FW22, Welgevonden 202JQ, transmitted light, crossed polars, x67.

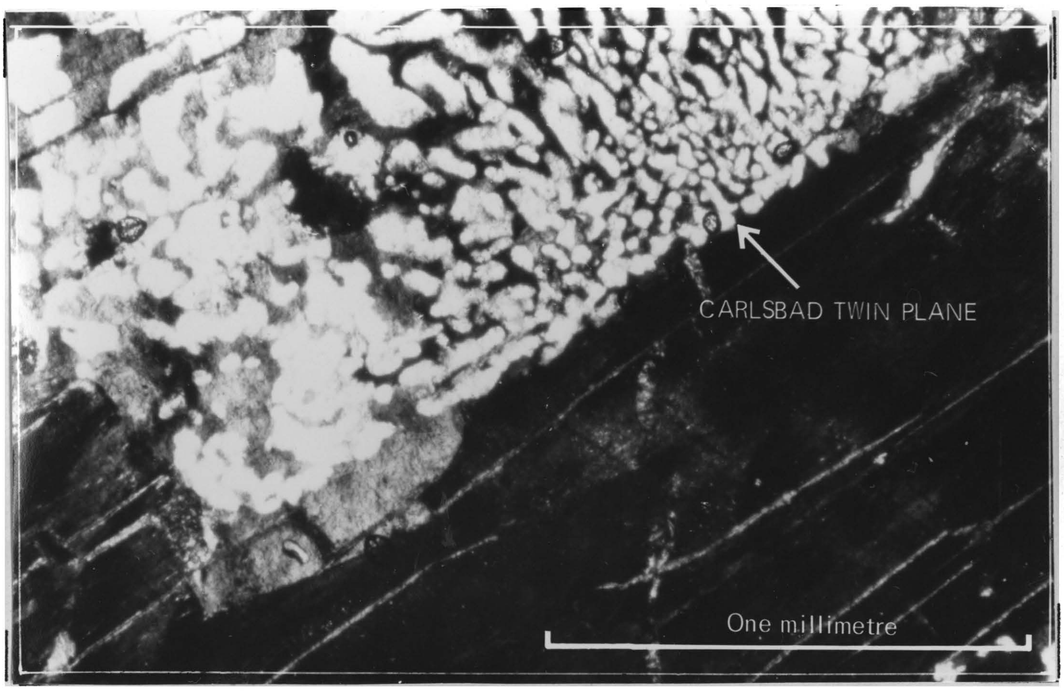


FIG. 9. Micrographic intergrowth of quartz and feldspar in one half of a Carlsbad twin [illegible] only. Sample no. FWT87, bore-hole BK1, transmitted light, crossed polars, x64.

crystallization of quartz and potassium feldspar.

Unusual forms of micrographic intergrowth can be seen in some micrographic grains, for example in Figure 9, where the micrographic intergrowth of quartz and feldspar is confined to one half of a twinned potassium feldspar grain (Carlsbad law).

5.2 ZWARTBANK PSEUDOGRANOPHYRE

As mentioned in section 4.2.2.2 the name Zwartbank pseudogranophyre is used collectively for pseudogranophyre and poikilogranite, two rock types which are texturally different but which are mineralogically similar. Although the chemical composition of both rock types is granitic, they show rather large variations (see Appendix 2).

The same minerals are to be found in both rock types but, as can be seen from Table 5, relatively large variations in the mineral percentages, especially perthite and orthoclase, are characteristic.

Perthitic feldspar is usually the most important mineral in the Zwartbank rocks. It is usually of the braided type and has a medium to fine texture. Orthoclase is usually less abundant than both quartz and perthite, and is followed by plagioclase and other minerals (Table 5). Hornblende and red-brown biotite are the most important mafic mineral, accompanied by accessory zircon, apatite and magnetite.

In a number of samples, particularly in those collected from bore-hole BK1, the mafic minerals include clinopyroxene and olivine (see Table 5). These minerals are almost invariably surrounded by a halo of bright green amphibole which appears to have

resulted.....

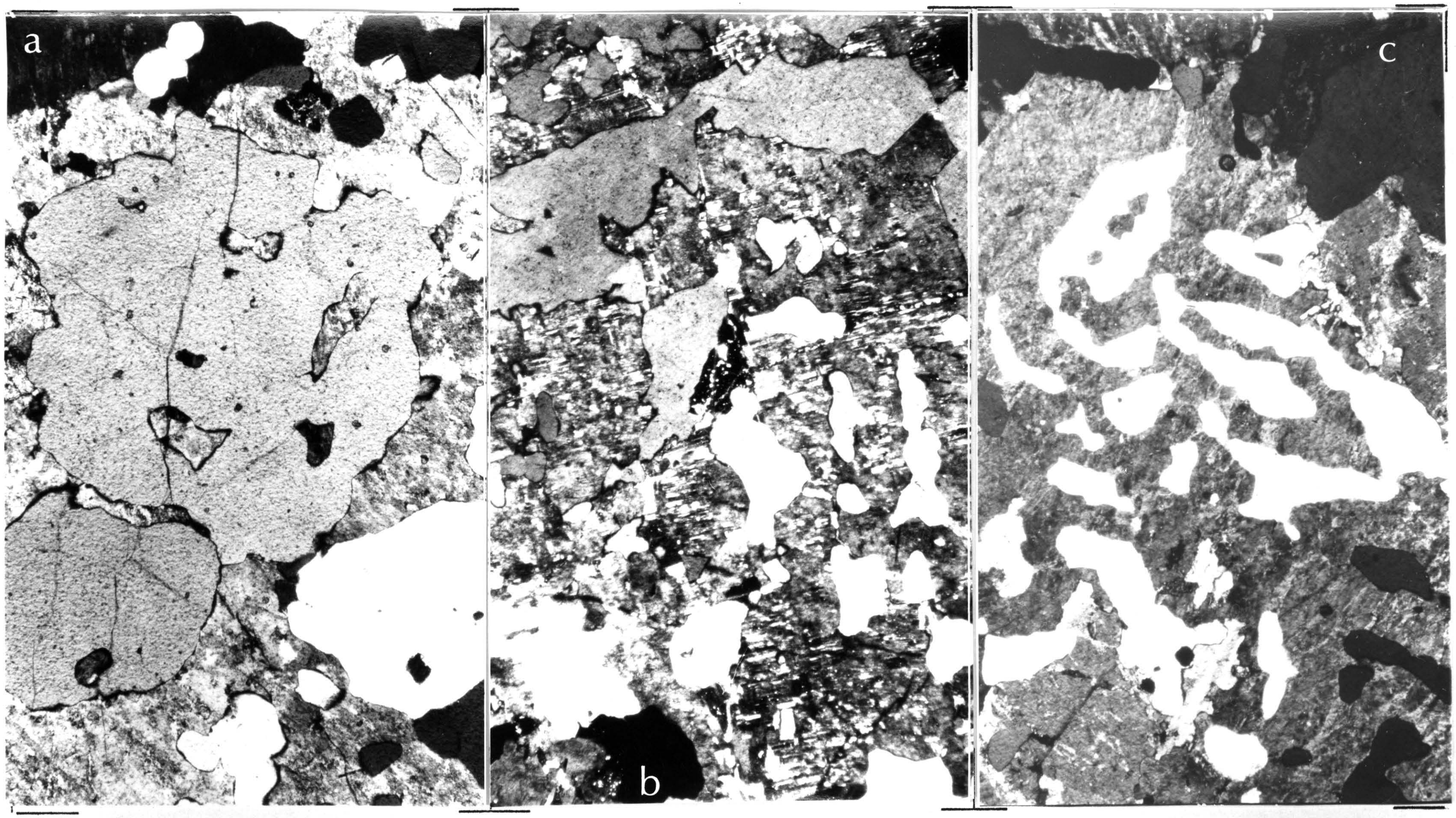


FIG. 10. Replacement of quartz by feldspar in Zwartbank pseudogranophyre, (a) initial embayment of the quartz grains, (b) intermediate stage, (c) advanced stage. Samples no. FWT30, FWT38 and FWT40 resp., bore-hole BK1, transmitted light, crossed polars, x43.

resulted from the alteration of the olivine and pyroxene.

The texture of the Zwartbank pseudogranophyre is significantly different from that of the Beestkraal granophyre. As in the granophyre, the texture consists of intergrowths of quartz and feldspar, but it is normally coarser and less regular than the micrographic intergrowth of the granophyre. Often the same quartz grain may be intergrown with more than one feldspar grain and the intergrowths may also involve any one of the feldspars present in the rock, i.e. perthite, orthoclase or plagioclase. The quartz-feldspar intergrowths vary widely in the degree of their development and range from embayments in the quartz to textures very similar to the micrographic intergrowths in granophyre sensu stricto. Various degrees of development of pseudographic texture are illustrated in Figures 10a,b and c. Criteria which can be used to distinguish between the texture of pseudogranophyre and granophyre are listed in Table 6.

In addition to the intergrown quartz and feldspar the rock also contains equant grains of quartz and feldspar. Junction points with 120° angles are observed between adjoining quartz grains.

As noted in section 4.2.2.2 poikilogranite is sometimes characterised by a texture which consists of small, equant, rounded grains of quartz poikilitically enclosed in large feldspar grains (Fig. 11). Although in hand specimen the poikilogranite resembles the pseudogranophyre and the granophyre, it can be immediately recognized in thin section. The small quartz grains are not optically continuous and the

quartz.....

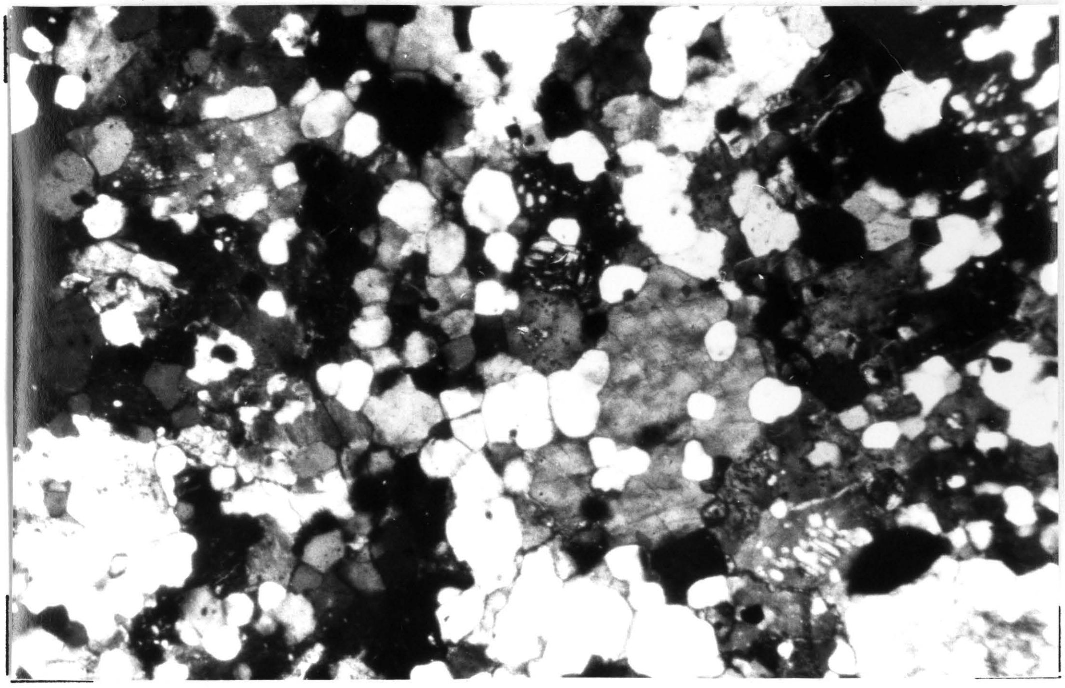


FIG. 11. Characteristic texture of Zwartbank poikilogranite. Sample no. FW349, transmitted light, crossed polars, x42.

quartz grains are about an order of magnitude smaller than the feldspar grains. The enclosing feldspar is usually perthite, but may also be orthoclase. Plagioclase, mafic minerals and also some quartz occur interstitially to the large feldspar grains.

TABLE 6

DISTINCTION BETWEEN THE CHARACTERISTIC TEXTURES OF GRANOPHYRE AND PSEUDOGRANOPHYRE

Micrographic texture	Replacement texture
1. Quartz units are confined to single feldspar crystals and do not penetrate adjacent feldspar crystals to any significant extent. More than one unit of quartz may occur in a single feldspar crystal.	*1. Quartz units commonly extend from one feldspar crystal into another. Such extension may also occur from one kind of feldspar into another (e.g. perthite - plagioclase).*
2. Micrographic intergrowths often form the mantle surrounding a euhedral non-intergrown core.	*2. No examples of cores and mantles are observed.*
3. Micrographic intergrowths tend to coarsen from centre to margin of the feldspar crystal.	*3. Intergrown quartz often coarsens outward and can coallesce into a solid mass with slightly embayed margins.*
4. Quartz-feldspar contacts show persistent preference for a limited number of orientations (usually three) which are apparently related to crystallographic directions in the quartz.	*4. Quartz-feldspar contacts display some degree of orientation, especially at the margins.*
5. The quartz:feldspar ratio in the intergrowths is more or less constant (about 45:55).	*5. There is a wide range in the quartz: feldspar ratio in the intergrowths.*

5.3 VEEKRAAL GRANITE

The Veekraal granite is a coarse-grained, equigranular rock which has a grey to pink colour on fresh surfaces and which becomes more reddish when weathered. Perthite is the predominant mineral and forms grains measuring over 5 mm in diameter and which tend to be euhedral. Its perthitic texture is usually coarse and is either of the braided or of the patch type. Braided perthite is slightly more common than

patch.....

patch perthite. Quartz is less abundant than perthite and forms smaller grains, averaging between 3 and 4 mm in diameter. Occasionally a small number of quartz grains are found clustering together, but normally they are separated. Plagioclase is a fairly minor constituent of the granite and has an average composition of An_{12}. It is interstitial to the perthite and quartz grains.

Pleochroic brown to olive-green hornblende is the most important mafic mineral in the Veekraal granite in this area. Green-brown biotite is found in small quantities in most samples but is important in only some of the samples. A tendency is noticed for the biotite content to increase towards the top of the granite sheet. Other minerals include opaque minerals (magnetite), zircon and, in some samples, fluorite. The modal composition of the Veekraal granite is shown in Table 5.

The Veekraal granite intersected in bore-hole BK1 is generally indistinguishable from the Veekraal granite on the surface. However, in the section between 358 and 400m from the surface, (see Appendix 1) the composition of the granite changes rapidly as the rocks of the layered sequence are approached. Besides chemical differences (see next section) this change involves a gradual increase in the anorthite content of the plagioclase (Fig. 19), and the appearance of olivine and clinopyroxene which increase in abundance towards the base of the granite.

Both the clinopyroxene ($Wo_{42}En_5Fs_{53}$) and the olivine (Fa_{98}) are very iron-rich and in this respect resemble the clinopyroxene and olivine of the ferrogabbro of the underlying layered sequence. Halos of

bright.....

bright green amphibole surround both minerals. The texture of the granite is equigranular and is slightly finer grained than the Veekraal granite elsewhere.

Inclusions of sedimentary rock as well as ferrodiorite are found in the Veekraal granite, especially in the lowermost intersection in the bore-hole. The sedimentary inclusions show a considerable degree of metamorphism. The inclusions of ferrodiorite have the appearance of mottles in the granite. They have a slightly diffuse contact with the granite which is marked by a concentration of hornblende surrounding the inclusion. The mineralogy of a typical inclusion of ferrodiorite is as follows: clinopyroxene, olivine and plagioclase (about An_{38}) together with magnetite, apatite and interstitial brown-green hornblende. Patches of alteration products are seen within and surrounding the clinopyroxene and olivine and small amounts of interstitial quartz are also seen.

The mineralogy of the inclusions closely resembles that of the ferrodiorite from the uppermost portion of the Upper Zone.

6 CHEMISTRY OF THE ACID ROCKS

Chemical analyses have been carried out on a number of different rock types collected in the field as well as from bore-hole BK1. The analyses were performed by the National Institute for Metallurgy on behalf of the Geological Survey. Elements determined include the major elements in the case of all the samples and, in addition, the trace elements Ba, Rb, Sr, Zr, Sn, Zn, Co and F in the case of the surface samples.

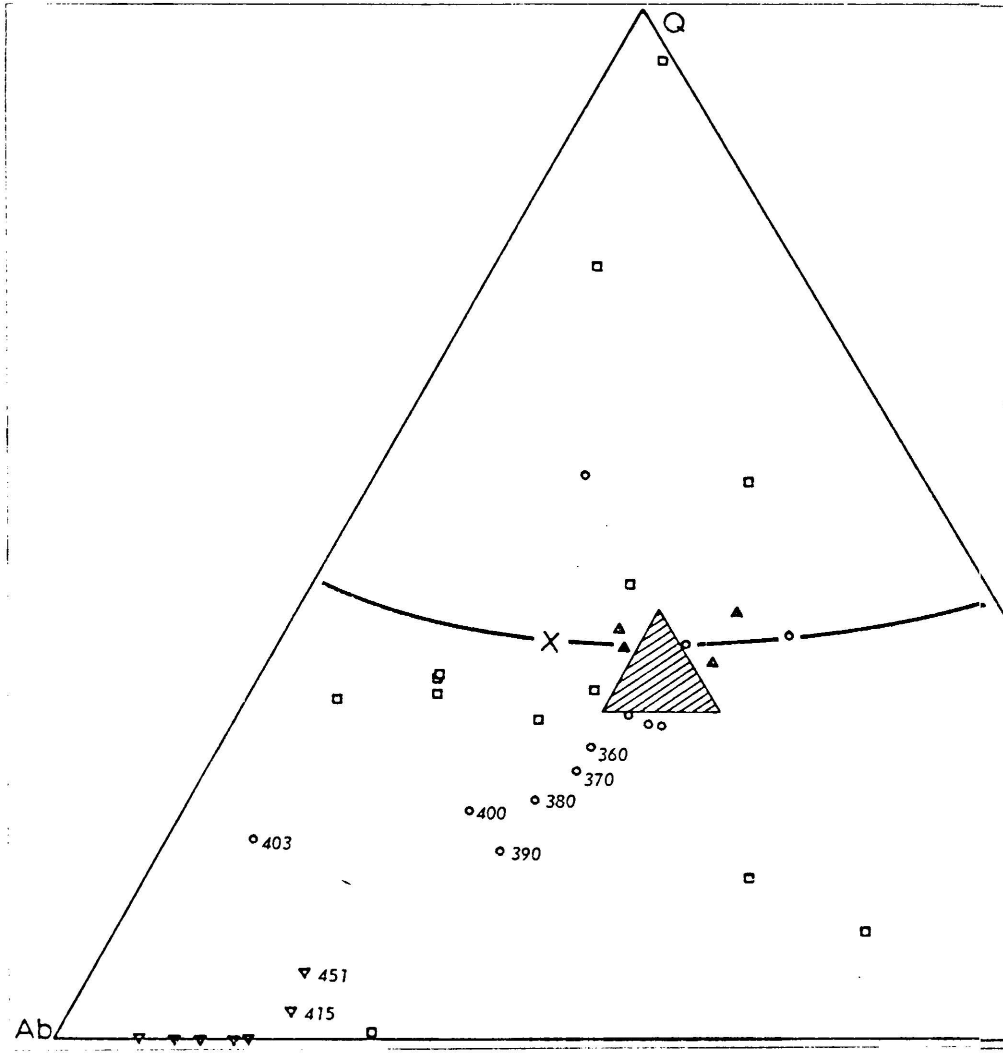
CIPW norms and mesonorms have been calculated from the chemical data according to the methods described by Kelsey (1965) and Barth (1959) respectively. Chemical analyses and norms are listed in Appendix 2.

The chemical data have been plotted on a number of phase diagrams and variation diagrams (Figs. 12 to 21) and statistical examinations of the data, using cluster, factor and discriminant analyses, have been carried out.

6.1 VARIATIONS IN CHEMICAL AND NORMATIVE COMPOSITION

Figures 12 to 15 are quartz-albite-orthoclase phase diagrams (Winkler, 1967, p.204) on which the normative compositions of the analysed samples are plotted. Figures 12 and 13 show the position of all the samples using the CIPW norm. Since a large number of the samples plot within the shaded triangle of Figure 12, this area is reproduced in an enlarged version as Figure 13. Although the position of the boundary is

subject.....

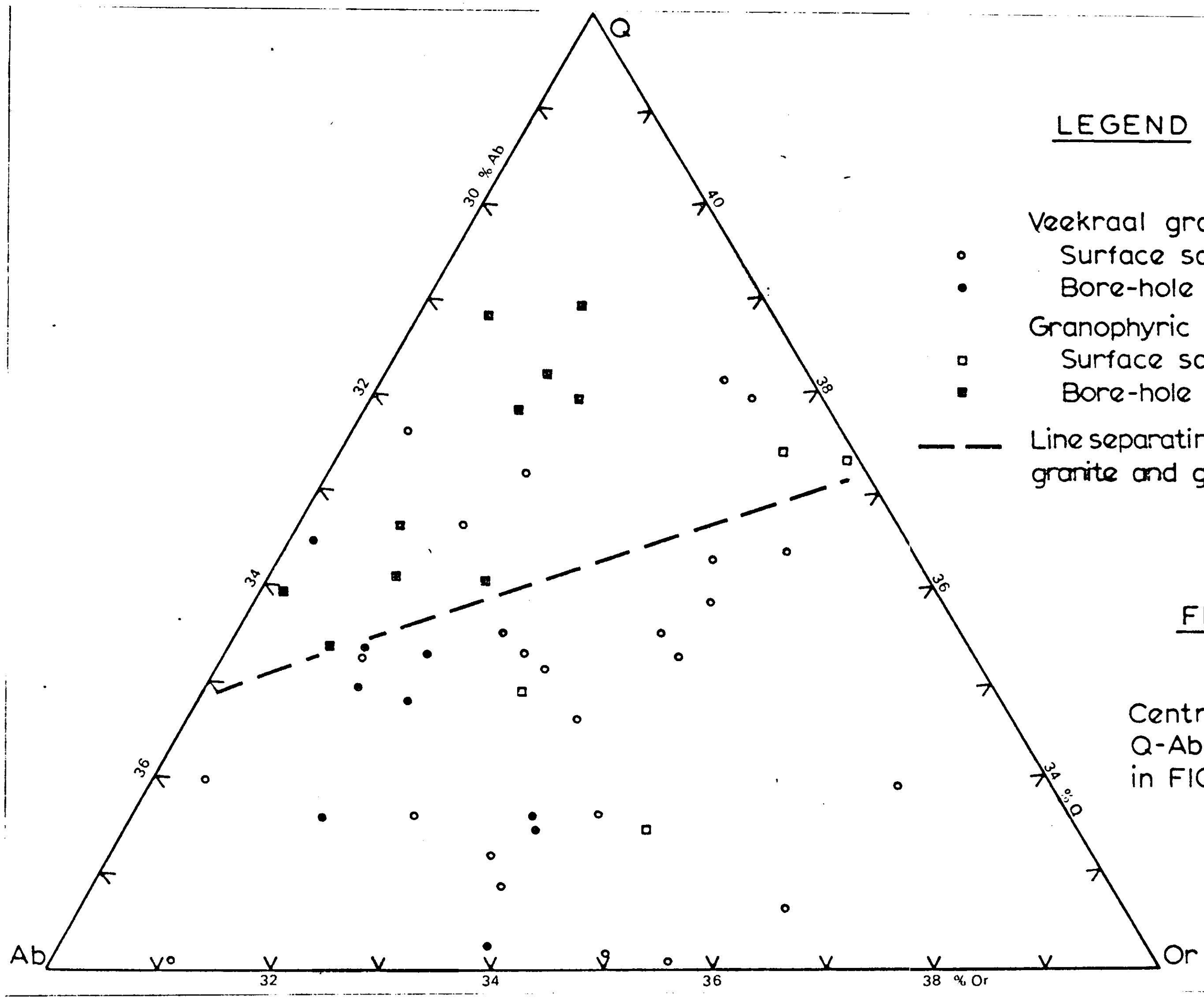


LEGEND

- Veekraal granite
- Granophyric rocks
- Ferrogabbro
- Metasediment
- Cotectic for P_{H_2O}=2000 bar and Ab/An=7,8 ; X = minimum melting point (Winkler, 1967)
- Field shown in FIG. 13.
- 360 Depth of selected bore-hole samples in metres

FIG. 12.

Q-Ab-Or phase diagram of all analyzed samples using the CIPW norm.



LEGEND

Veekraal granite
- ∘ Surface samples
- • Bore-hole samples

Granophyric rocks
- ▫ Surface samples
- ▪ Bore-hole samples

— — Line separating fields of predominantly granite and granophyre

FIG. 13.

Central portion of the Q-Ab-Or phase diagram in FIG.12.

subject to criticism in an enlarged diagram of this nature, possibly as a result of the effects of analytical error, this diagram does serve to illustrate that the bulk of the granite samples do occupy an area separate from the granophyre samples.

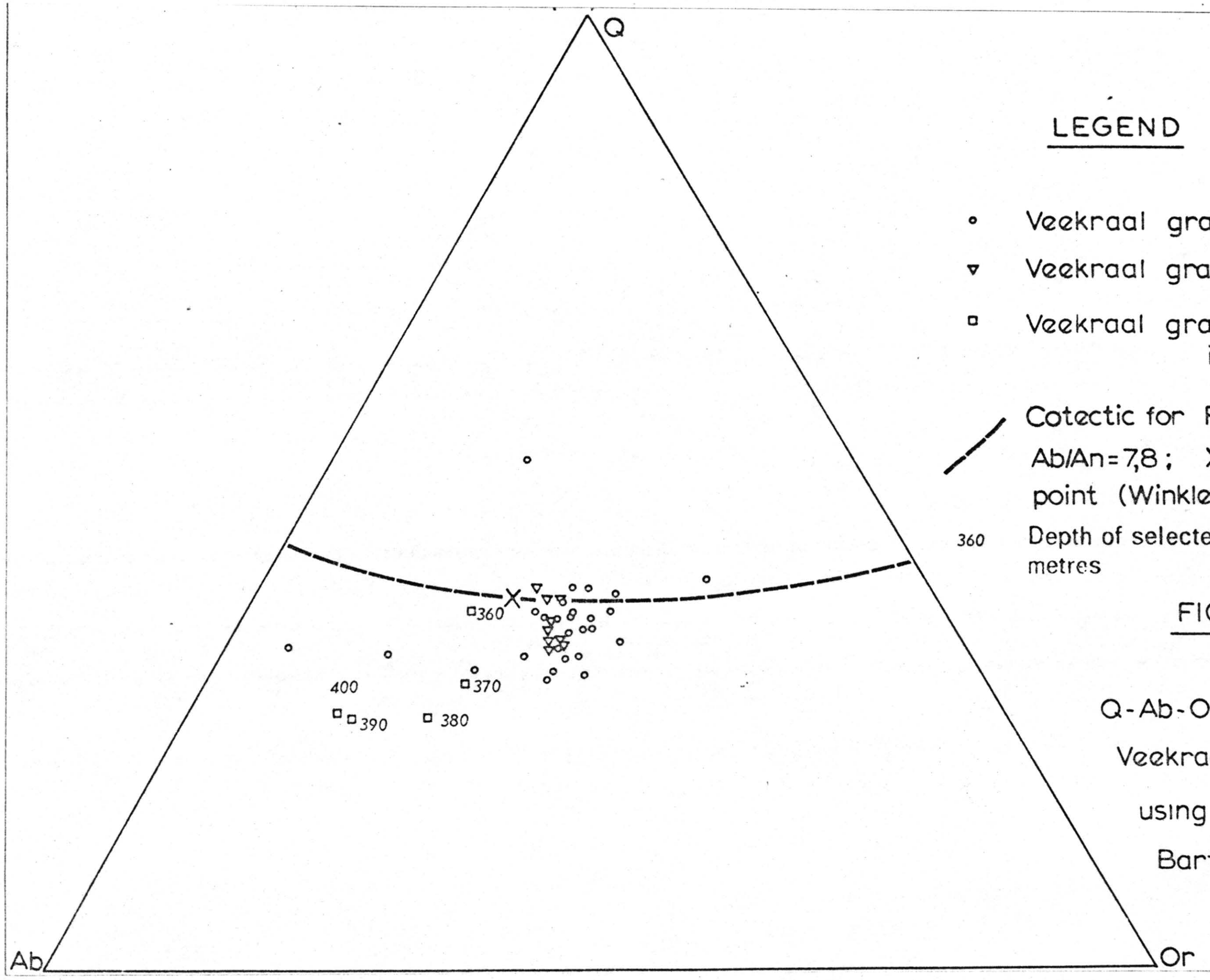
The mesonormative compositions of the Veekraal granite and the other rock types are shown in Figures 14 and 15 respectively. The granite samples have been plotted separately for clarity (Fig. 14) and the field occupied by the granite in Figure 14 has also been outlined in Figure 15.

It can be seen from both Figures 12 and 14 that the samples of Veekraal granite occupy a relatively small field only. This field lies to the right of the ternary minimum melting point at a water pressure of 2 kb and an Ab/An ratio of 7,8 (Winkler, 1967, p.204). A small number of the granite samples fall outside the field; in each case these are samples collected from positions near to younger intrusions such as carbonatite plugs.

Samples of the Beestkraal granophyre and the Zwartbank pseudogranophyre plot within the field of the Veekraal granite (Fig. 15). The Beestkraal granophyre and the Veekraal granite both predominantly plot towards the orthoclase apex of the minimum melting point. Von Gruenewaldt (1972, p.125) noted a similar relationship between the ternary minimum melting point and the composition of the granophyre from the eastern Transvaal, which he attributed to a significant partial pressure of fluorine in the vapour phase.

The samples of metasedimentary rocks plot in widely scattered positions and extend towards all three

corners.....



LEGEND

- ∘ Veekraal granite (surface samples)
- ▿ Veekraal granite (bore-hole BK1)
- ▫ Veekraal granite (lowermost intersection in BK1)
- Cotectic for P_{H_2O} = 2000 bar and Ab/An = 7,8 ; X = minimum melting point (Winkler, 1967).
- 360 Depth of selected bore-hole samples in metres

FIG. 14.

Q-Ab-Or phase diagram of Veekraal granite samples using the mesonorm of Barth (1959).

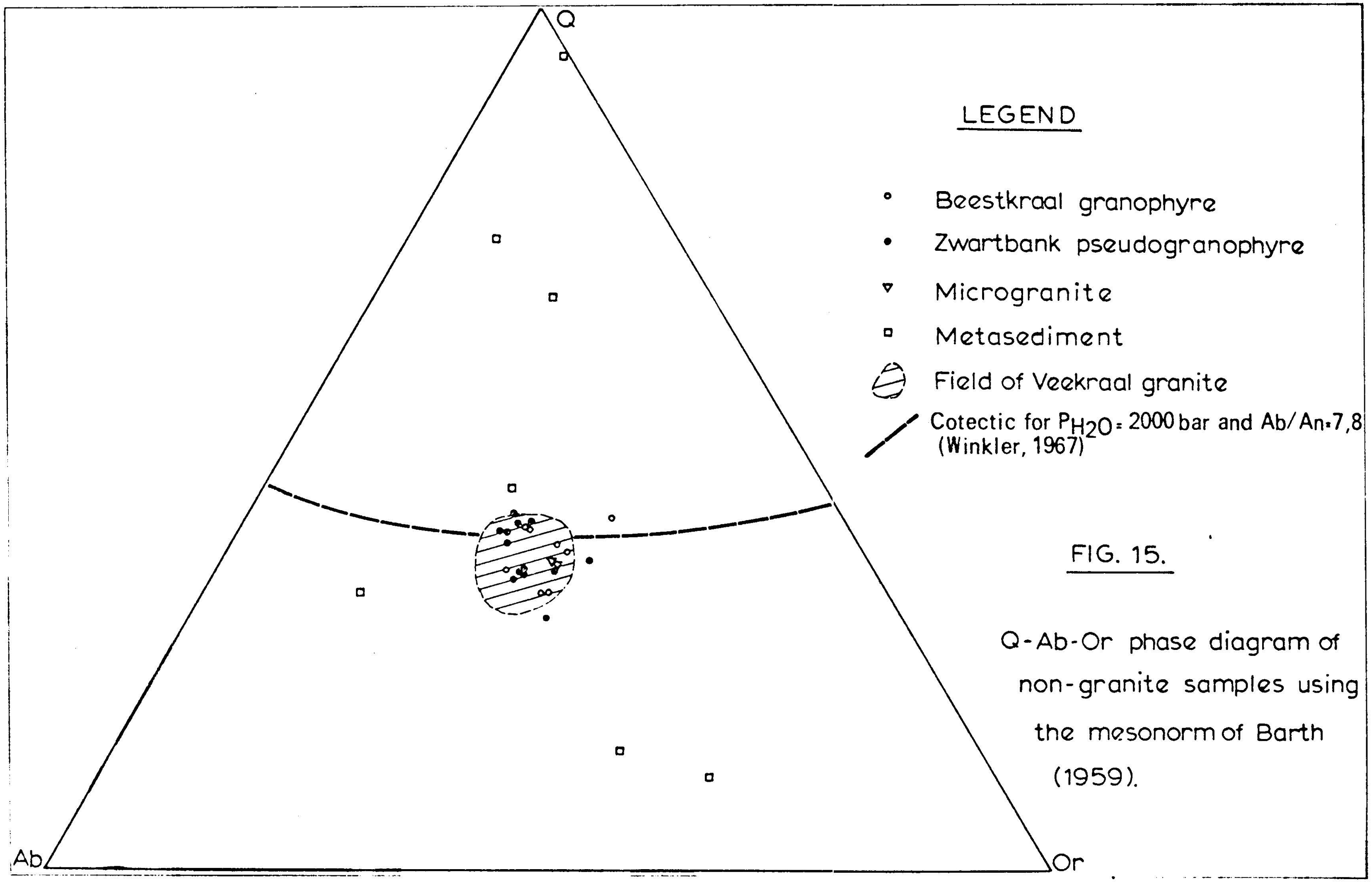


FIG. 15.

Q-Ab-Or phase diagram of non-granite samples using the mesonorm of Barth (1959).

corners of the diagrams (Figs. 12 and 15). None of the metasediment samples plot within the field containing the granite or the granophyre.

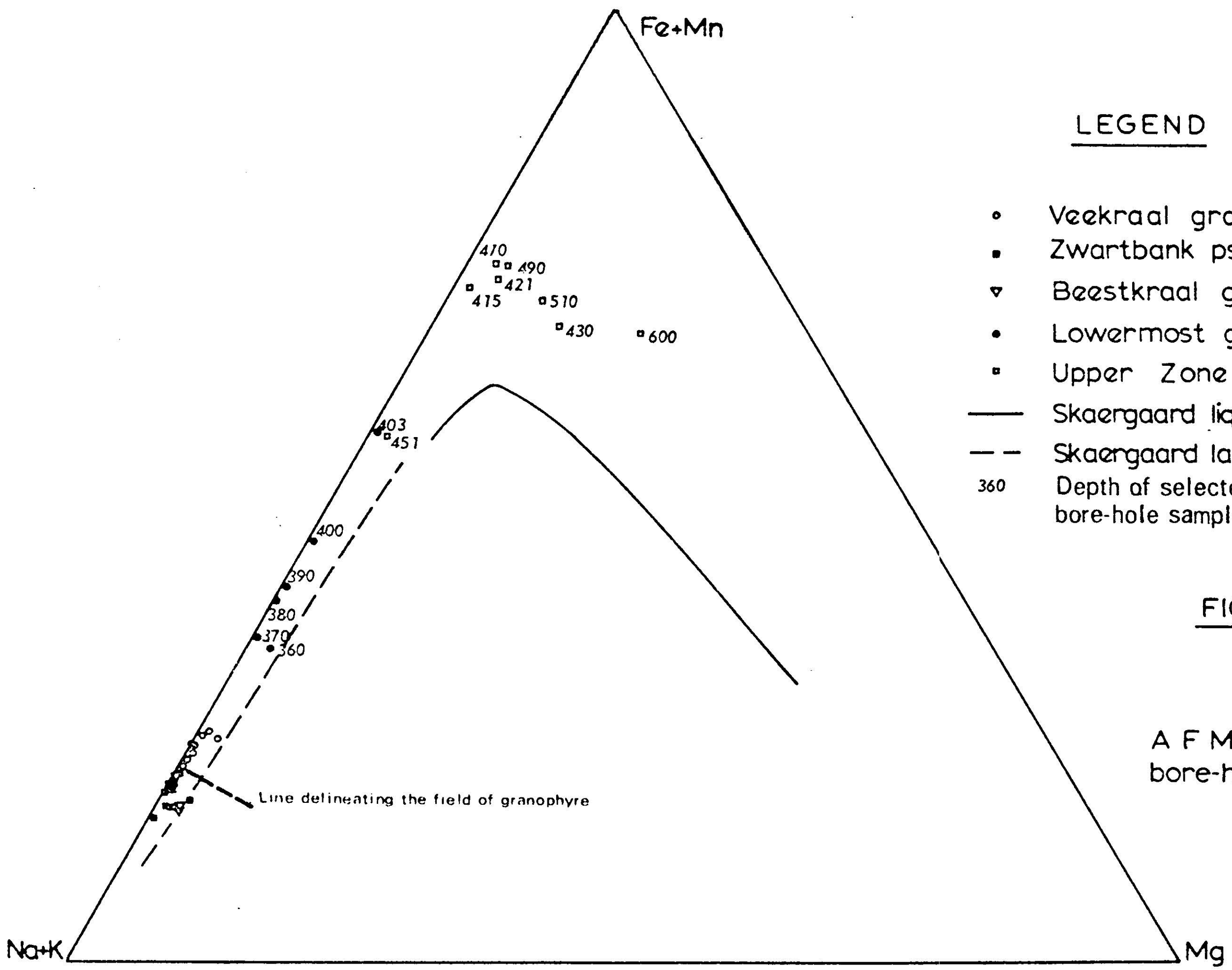
Plots of the sample positions on AFM diagrams are shown in Figures 16 and 17. As is to be expected the granite, granophyre and pseudogranophyre plot in the alkali corner of the diagrams and ferrogabbro samples from bore-hole BK1 plot closer to the iron corner. Figure 16 clearly illustrates that the lowermost samples of granite in the bore-hole have compositions intermediate between the granite higher up and the ferrogabbro.

In the alkali corner of the diagram (Fig. 16), a separate field can be delineated for the granophyric rocks. In Figure 17, which represents an enlargement of the alkali corner of the AFM diagram, this line is seen to separate granite samples obtained from near the base of the granite sheet, from samples located higher in the sheet.

Figure 18 shows the variation in the K-Na-Ca contents of the bore-hole samples. The granite and granophyre samples form a relatively small field and the samples from the lowermost intersection of granite can again be seen to have compositions intermediate between the granite higher up and the ferrogabbro. Within the field occupied by the acid rocks a separation of the granite and granophyre samples can again be seen, the granite samples being slightly richer in calcium than the granophyre samples.

A fairly consistent difference in the major element chemistry is found between the Veekraal granite and the other acid rocks in bore-hole BK1. Higher contents of TiO_2, Al_2O_3, CaO and Fe-total distinguish

the.....

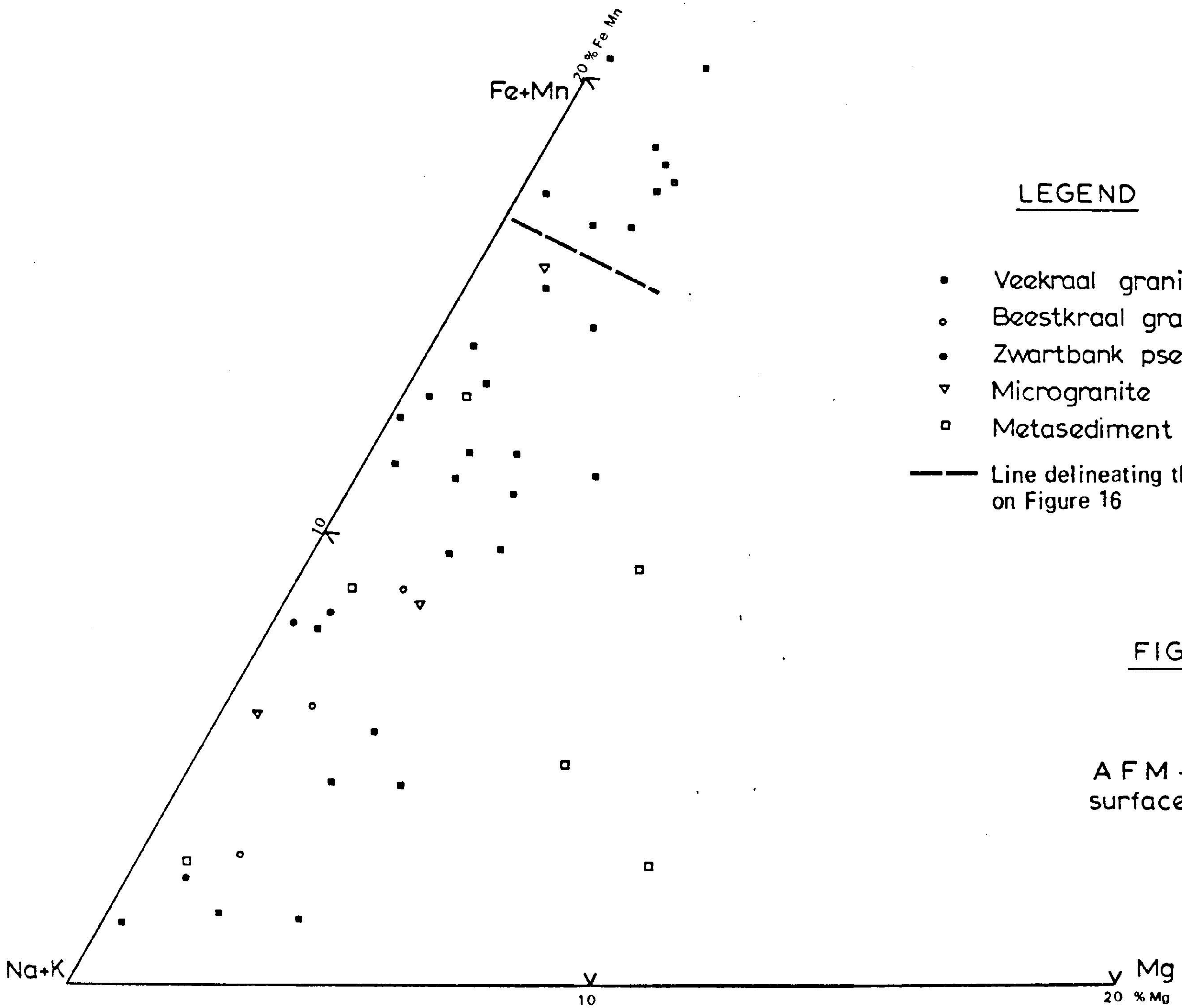


LEGEND

- ∘ Veekraal granite
- • Zwartbank pseudogranophyre
- ▿ Beestkraal granophyre
- • Lowermost granite
- ▫ Upper Zone ferrogabbro
- ——— Skaergaard liquid trend
- – – Skaergaard late differentiate trend
- 360 Depth of selected bore-hole samples in metres

FIG. 16.

A F M - diagram of samples from bore-hole BK1.



LEGEND

- ▪ Veekraal granite
- ∘ Beestkraal granophyre
- • Zwartbank pseudogranophyre
- ▿ Microgranite
- ▫ Metasediment
- —— Line delineating the field of granophyre on Figure 16

FIG. 17.

AFM - diagram of surface samples

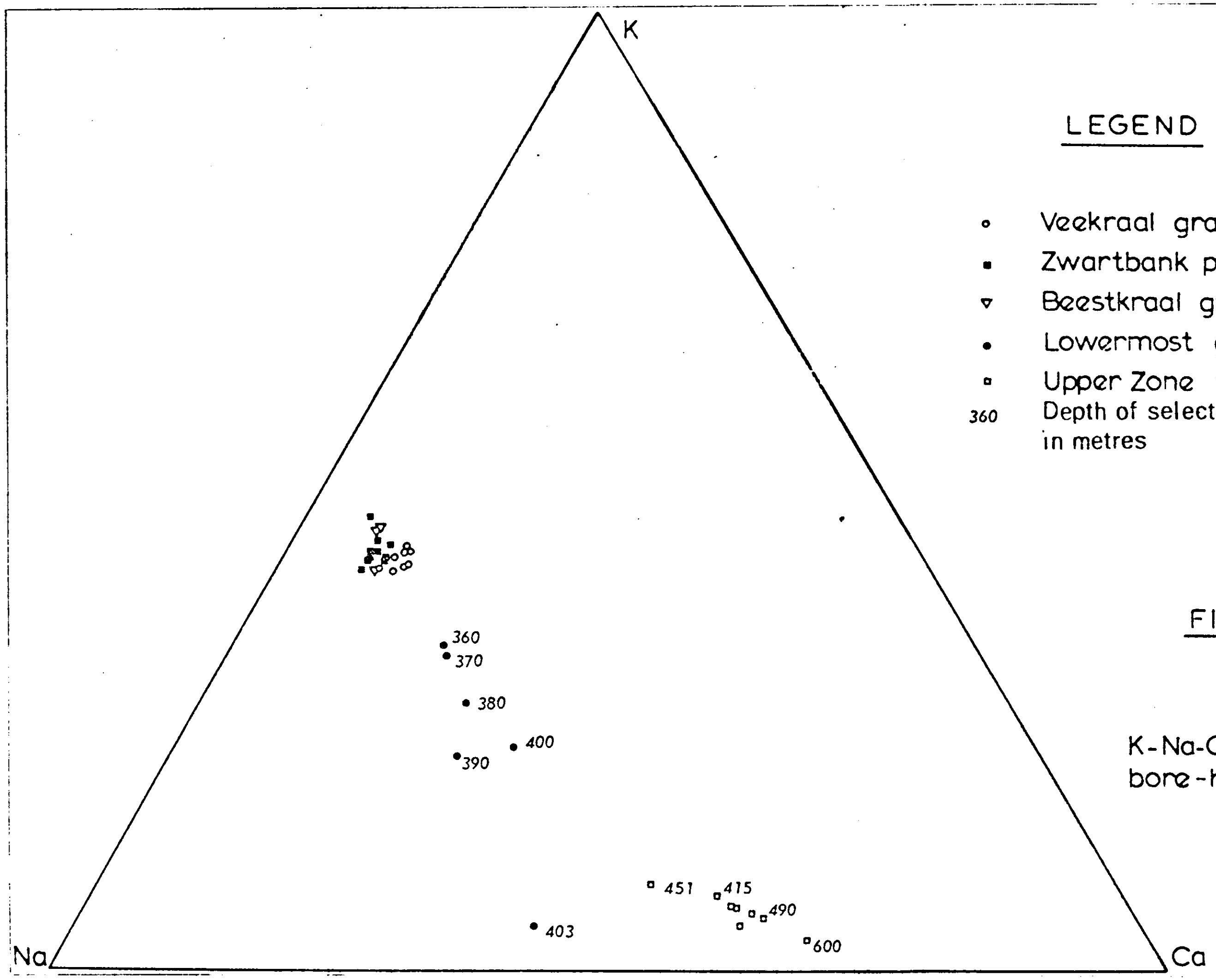


FIG. 18.

K-Na-Ca-diagram of samples from bore-hole BK1.

the granite, while the granophyric rocks have a slightly higher SiO_2 content. Variations of the Al_2O_3, CaO and K_2O contents in the bore-hole are shown in Figure 19 to illustrate these relationships. Figure 19 also serves to illustrate the changes in the chemical composition across the contact between the acid rocks and the ferrogabbro of the Upper Zone. The actual contact at 400 m is marked by 8 m of quartzite. The most rapid variations are shown by the contents of K_2O and CaO. Both of these have extremely steep gradients across the contact and thereby clearly and accurately define the contact. The shape of the curves across the contact zone furthermore indicates that the lowermost granite intersected is genetically related to the Veekraal granite. In each case the curves show a gradual steepening downward but kink sharply at the contact with the ferrogabbro. More gradual variations are found in the contents of Fe-total and SiO_2.

A number of the elements in the Veekraal granite and Beestkraal granophyre show a high degree of correlation with the Larsen Index (calculated as $1/3SiO_2 + K_2O - CaO - MgO - FeO(total)$). Some of these are shown in Figure 20. The Beestkraal granophyre appears to have a smaller spread than the Veekraal granite and in addition the mean of the granophyre does not coincide with that of the granite. A test of the significance of this difference has been made using an F-approximation of Hotelling's T^2 statistic (Davis, 1973, p. 450). The results are shown in Table 7 where values significant for the number of samples are shown and indicate dissimilarity between the groups of samples being compared at a confidence level of 95 percent.

Lenthall.....

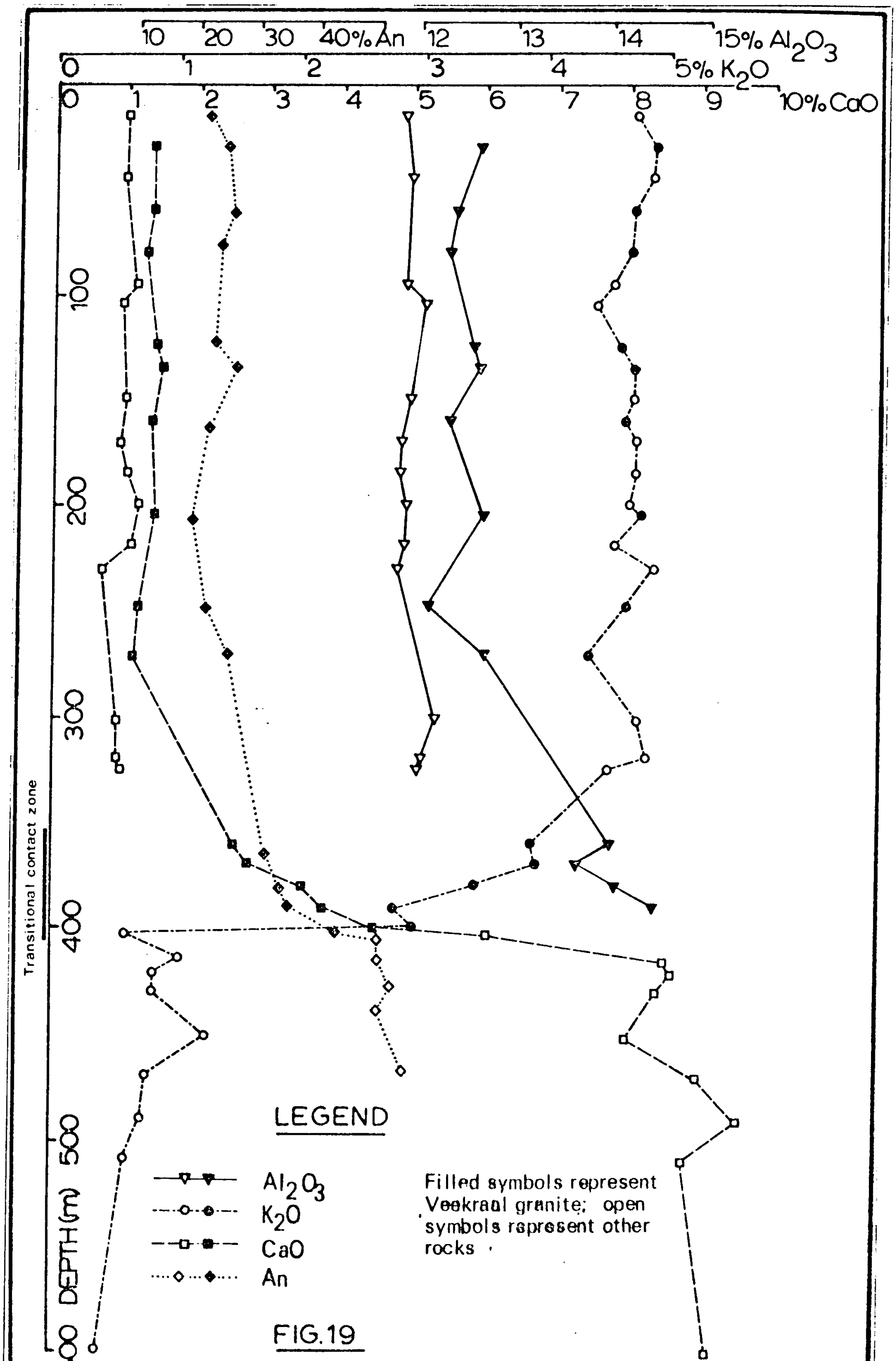


FIG.19

VARIATION IN CONTENT OF SELECTED OXIDES AND PLAGIOCLASE AN-CONTENT WITH DEPTH IN BORE-HOLE BK1

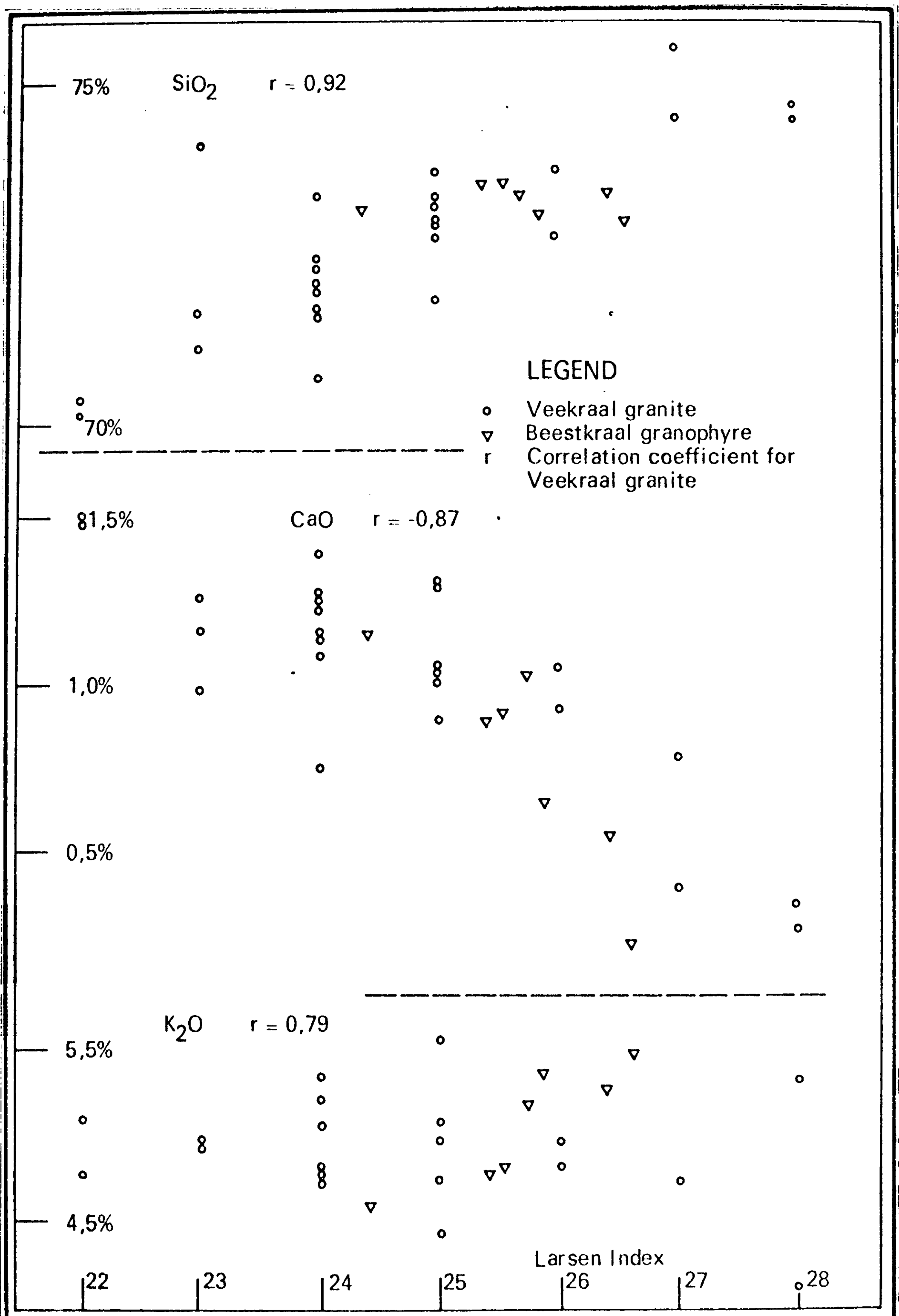


FIG. 20. VARIATION OF SELECTED ELEMENTS VS. LARSEN INDEX IN VEEKRAAL GRANITE AND BEESTKRAAL GRANOPHYRE

TABLE 7

F-VALUES FROM MULTIVARIATE T^2

	I Granite	II Granophyre	III Pseudo-granophyre	IV Metasediment
I	0,0	8,254	4,338	18,173
II		0,0	N.S.	N.S.
III			0,0	N.S.
IV				0,0

N.S. Not significant; sample size too small

Lenthall (1975) and Hunter (1973) have studied the relations between the major and trace element contents of the Sekhukhune granite and the granites of the Kaapvaal craton respectively. The mean K/Rb, Ba/Sr and K/Sr ratios (200, 15 and 25 respectively) of the Veekraal granite are similar to those of Lenthall's Groups I and II Sekhukhune granite, which are located within or near the mesocratic border (base) of the granite sheet in the eastern Transvaal. One possible interpretation of this similarity could be that the Veekraal granite in the area mapped represents the lower portion of the granite sheet.

Figure 21 shows the variation in the K/Rb ratio with K content of the analysed granite samples. For comparison the fields of a number of other granite types are included (Hunter, 1973, Fig.12). The majority of Veekraal granite samples plot in a field which only partly overlaps that of the Sekhukhune granite, thereby suggesting slight chemical differences between the Veekraal and Sekhukhune granite.

Many samples of Veekraal granite have a higher K/Rb ratio than the Sekhukhune granite, (Fig. 21) as has already been noted by Hunter (1973, p.2). The higher K/Rb ratio for the Veekraal granite implies that magma from which this granite crystallized was less fractionated than the Sekhukhune granite, and

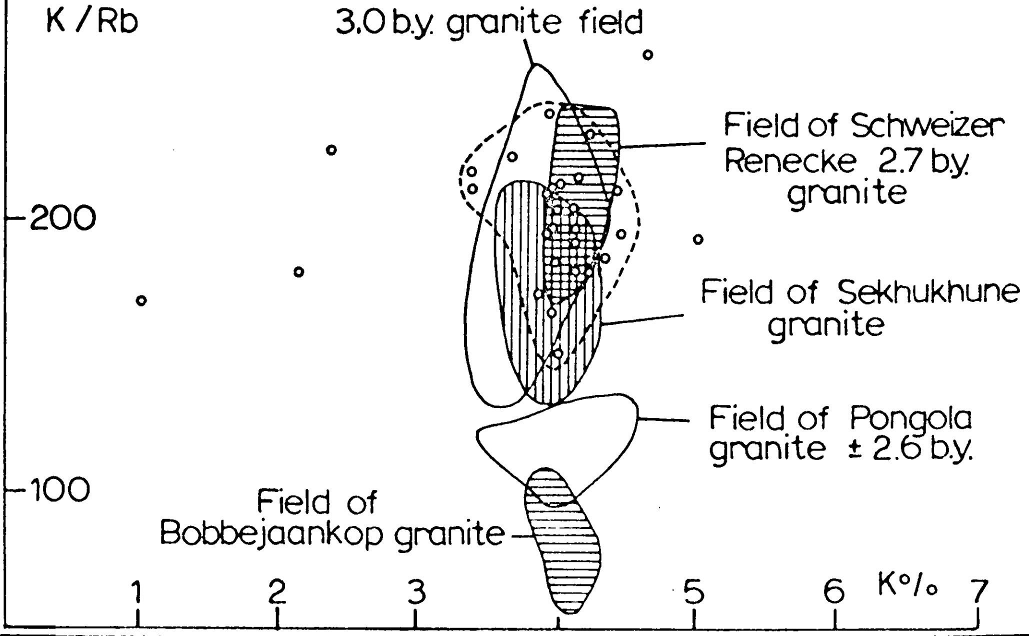
therefore.....

FIG. 21

Variation of K/Rb ratio with K-content for Veekraal granite.
Data plotted on graph modified from Hunter (1973) showing fields of other granites.

LEGEND

° Veekraal granite
---- Field of Veekraal granite



therefore seems to corroborate the above findings that the granite exposed in this area represents a lower part of the intrusion.

Alternatively the difference in the K/Rb ratios between these two granites could also indicate a slightly higher melting temperature during generation of the Veekraal granite magma.

Variations in other trace element parameters, e.g. Ca vs. Ca/Rb ; log K vs. log Ba; log K vs. log Rb; log Ba vs. log Sr (not shown as graphs), tend to show a similar offset between the positions of the granite and the granophyre samples. The granophyre samples tend to have slightly higher contents of K but similar contents of Rb. Ca, Ba, Mg and Fe-total are slightly lower in the granophyre than in the Veekraal granite.

6.2 STATISTICAL ANALYSIS OF CHEMICAL DATA

Statistical methods are available whereby it is possible to examine relatively large amounts of data and to obtain indications of the relationships and/or variations that exist in these data (Harbaugh and Merriam, 1968; Krumbein and Graybill, 1965; Davis, 1973). Different statistical techniques have been applied to the chemical data of the acid rocks. They are cluster analysis, factor analysis and discriminant analysis. It is beyond the scope of this thesis to go into details concerning the mathematical theory of the statistical background to these procedures and only brief outlines are given before the results are presented.

Cluster analysis is a technique whereby complex

interrelationships.....

interrelationships between objects (samples) with many variables (contents of different elements) may be effectively displayed in a two-dimensional diagram. The process involves the calculation of some measure of the similarity or difference between the objects, after which the objects are grouped together to form a hierarchical branching structure, the dendrogram, in which objects that are most similar to each other are joined to form clusters at high levels of similarity and less similar objects are joined at lower levels of similarity.

Most commonly the measure of similarity used in cluster analysis is either the correlation coefficient or the distance function (Parks, 1966; Davis, 1973). In this case use is made of the distance function. The distance function is the multidimensional equivalent of the geometric distance between two points in space. Low values of the distance function mean greater similarity between the objects being compared and high values mean lower similarity.

The dendrogram shown in Figure 22 shows the results of a cluster analysis carried out on the analysed surface samples. Correlation between the orignal matrix of distance functions and the matrix of cophenetic values is r=0,896 which means that the clusters found by this analysis are significant.

As might be expected the samples of metasedimentary rocks differ rather widely from the other rock types. They cluster with the other rocks at rather low levels of similarity (i.e. at large values of the distance function). High levels of similarity are seen in a fairly coherent cluster, marked A in

Figure.....

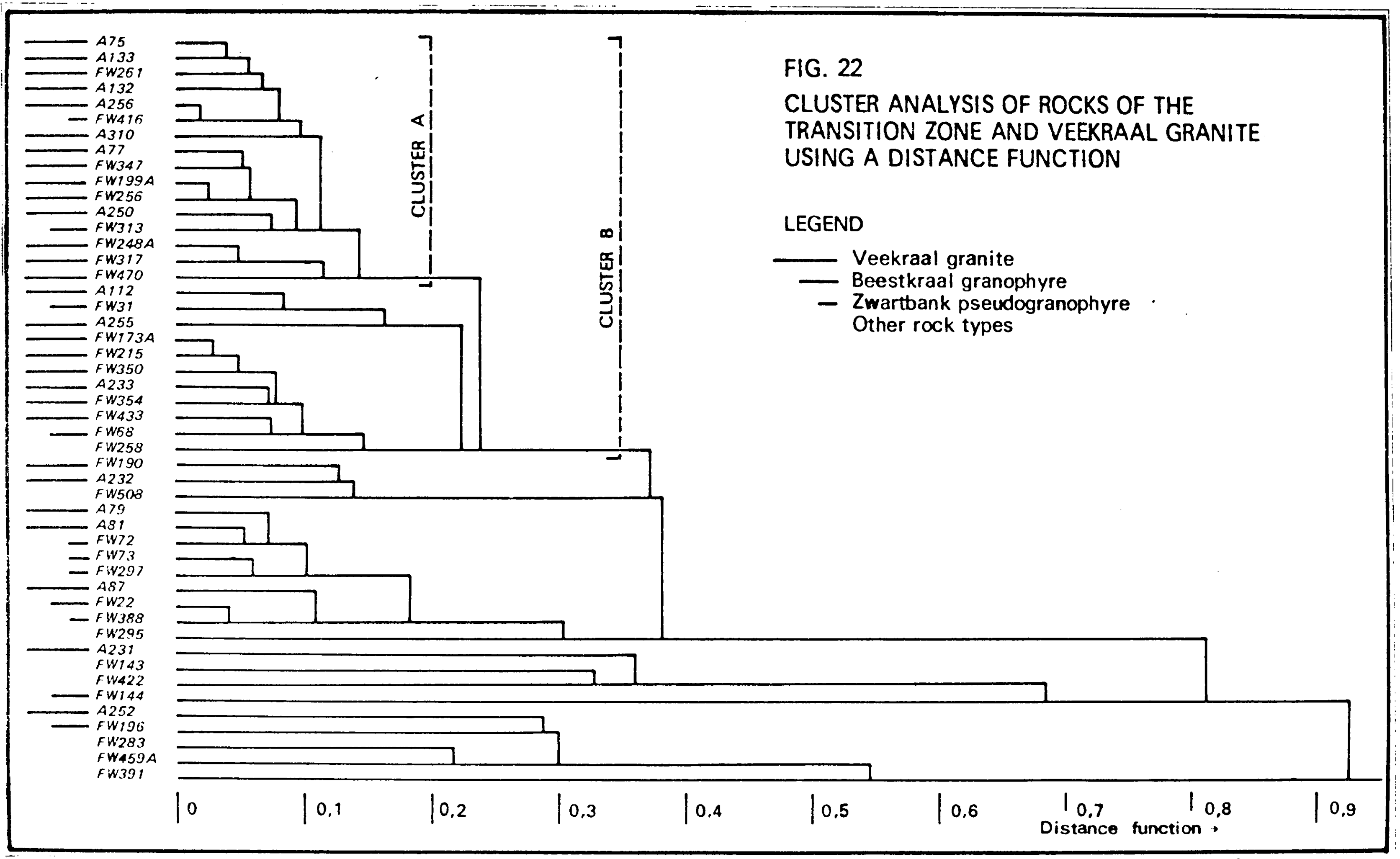


FIG. 22

CLUSTER ANALYSIS OF ROCKS OF THE TRANSITION ZONE AND VEEKRAAL GRANITE USING A DISTANCE FUNCTION

Figure 22, which consists almost exclusively of Veekraal granite. The majority of the samples that make up this cluster have been collected from near the base of the granite sheet, near to the lower contact of the granite with the rocks of the transition zone.

Cluster A joins with a number of other granite samples to form a larger cluster (marked B on Figure 22) which contains 22 out of 29 of the analysed granite samples and 5 samples of other rock types.

Factor analysis has data reduction as its general objective. It attempts to discern simplifying relationships in large collections of raw data and in addition to provide indications of the nature of these relationships. The technique may be used to examine relationships between samples as well as between variables.

In the present case factor analysis was carried out on all the analysed samples. However, the results proved to be inferior to those obtained from the discriminant analysis as far as relationships between groups of samples is concerned, and the results of the factor analysis are consequently not further discussed.

In the case of discriminant analysis the object is to find a linear combination of the variables which produces the maximum difference between previously defined groups, (Davis,1973, p.443). If a function is found which produces a significant difference, it can be used to allocate new samples of unknown origin to one or other of the original groups using Bayes' decision rule (Pearce, 1976). In this case the defined groups consist of Veekraal granite (29 samples), Beestkraal granophyre (5 samples), Zwartbank

pseudogranophyre.....

pseudogranophyre (6 samples) and metasediment (8 samples). The results of the discriminant analysis are shown in Figure 23 which is a territorial map of discriminant function 1 versus discriminant function 2 (% of variance: F1=76%, F2=22%). The high percentages of variance indicates that two functions are in this case a reliable means of classification. Table 8 lists the predicted group membership and the percentage of "grouped" cases correctly classified by the discriminant functions is 96 percent. A slight degree of overlap exists between the granite and pseudogranophyre (3,4%) and between granophyre and pseudogranophyre (17%). These results support the conclusion that there exist significant differences between the Veekraal granite and metasediments and the other rock types (Hotelling's T^2 statistic, see p.53) and furthermore also suggests significant chemical differences between the granophyre and pseudogranophyre.

TABLE 8

DISCRIMINANT ANALYSIS - PREDICTION RESULTS

	PREDICTED GROUP MEMBERSHIP GROUP 1	GROUP 2	GROUP 3	GROUP 4
GROUP 1 (29) VEEKRAAL GRANITE	28 96,6%	0 0,0%	1 3,4%	0 0,0%
GROUP 2 (6) GRANOPHYRE	0 0,0%	5 83,3%	1 16,7%	0 0,0%
GROUP 3 (5) PSEUDOGRANOPHYRE	0 0,0%	0 0,0%	5 100%	0 0,0%
GROUP 4 (8) METASEDIMENT	0 0,0%	0 0,0%	0 0,0%	8 100%

Percent of "grouped" cases correctly classified: 95,8%

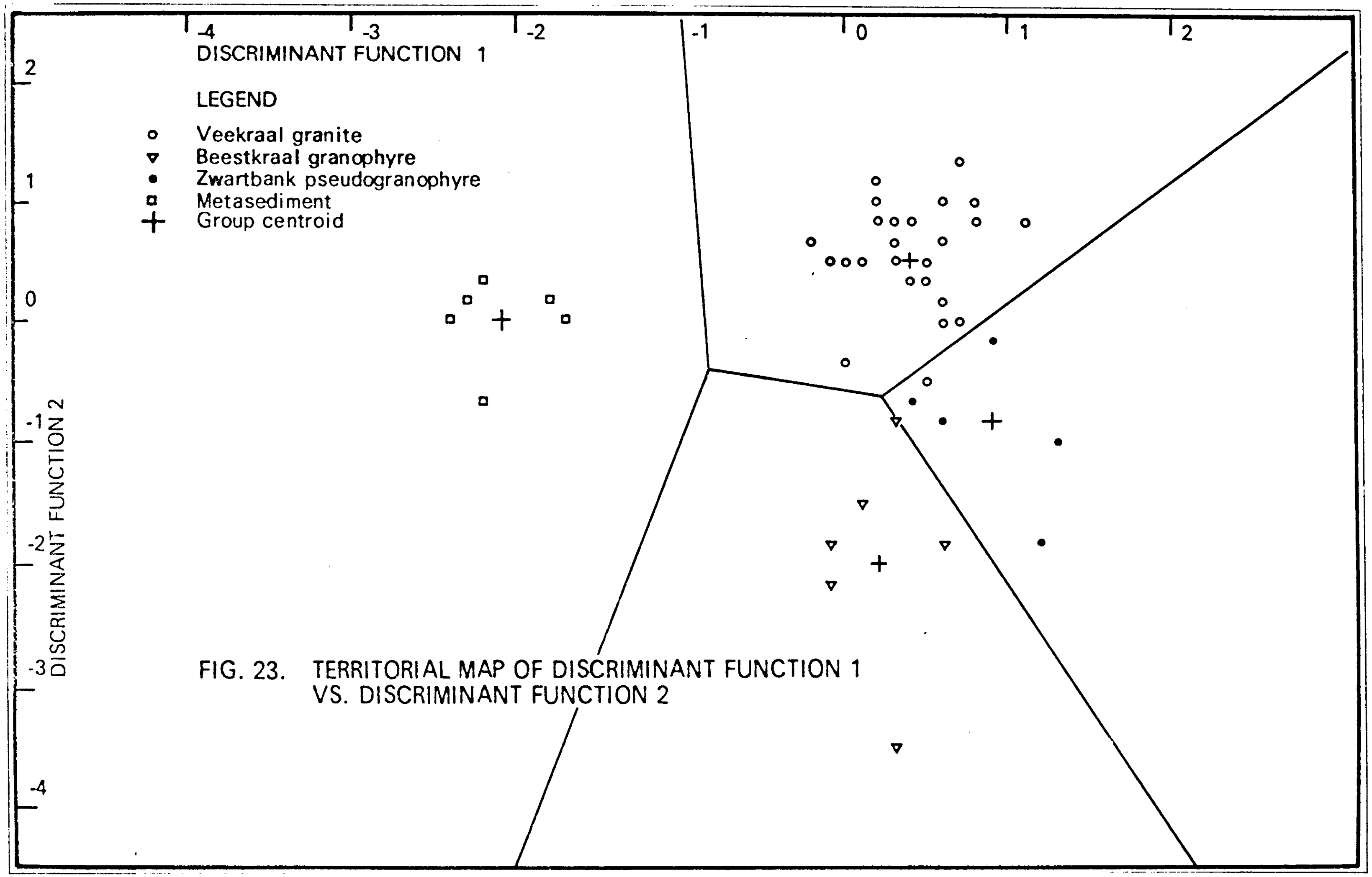


FIG. 23. TERRITORIAL MAP OF DISCRIMINANT FUNCTION 1 VS. DISCRIMINANT FUNCTION 2

7 STRUCTURE

Various hypotheses are put forward in existing literature to explain the structure of the Bushveld Complex. The Complex consists of three main lobes which were at various times thought to be part of a lopolith (Hall, 1932, p.459); a series of intrusions along an east-west axis (Truter, 1955, p.81); a set of deep, curved troughs filled with basic rocks (Cousins, 1959, p.182) and more recently a succession of funnel-shaped cone-sheet intrusions (Willemse, 1964, p.113; Wilson, 1956, p.290 and Coertze, 1974, p.51, Hunter, 1975, p.3).

In each of these hypotheses the structure of the western Bushveld Complex north of Rustenburg and Brits is considered to be relatively simple and uncomplicated. It is thought to have the shape of a gentle basin, open at the eastern end, in which the layers dip inward towards the centre. Discordancies in the layered sequence are recognized both on a small scale (as in the Union Section, Feringa, 1959) and on a large scale (as in the major discordancies of the Upper Zone, Coertze, 1974).

7.1 FOLDING

During the mapping and subsequent investigations of the western Bushveld Complex it became evident that a simple basin shape could not account for the observed distribution of rock types, especially the rocks forming the transition zone. These rocks are found not only along the contact of the layered sequence and the Veekraal granite, but also within the

Veekraal.....

Veekraal granite, where they form the central belt of granophyric rocks. It is suggested that the rocks in these two areas form part of the transition zone and that its exposure in the central belt is the result of folding along a northwest striking fold axis. The central belt is interpreted as the crest of an anticline along which rocks of the transition zone are exposed (Fig. 24).

Both geological and geophysical evidence having a bearing on the structure of the western Bushveld Complex are examined in the light of the proposed model of the structure. This evidence includes the distribution of rock types, aeromagnetic evidence, gravimetric evidence and structural data.

7.1.1 THE DISTRIBUTION OF ROCK TYPES

The complement of rock types in both the contact and central belts is exceedingly similar. All five main rock types (granophyre, pseudogranophyre, poikilogranite, microgranite and sedimentary xenoliths) are found in both belts. Similar relationships are found between these rock types and furthermore the sedimentary xenoliths include the same lithologies and exhibit the same range of deformation.

At first sight the granophyre and pseudogranophyre of the central belt present an apparently anomalous situation. Granophyre is found in many parts of the Bushveld Complex and Lenthall (1973, p.76) proposed a classification of the known types of granophyre in the Complex. It is significant that every proposed class of granophyre is associated with a contact of some sort or another and no granophyre is

described.....

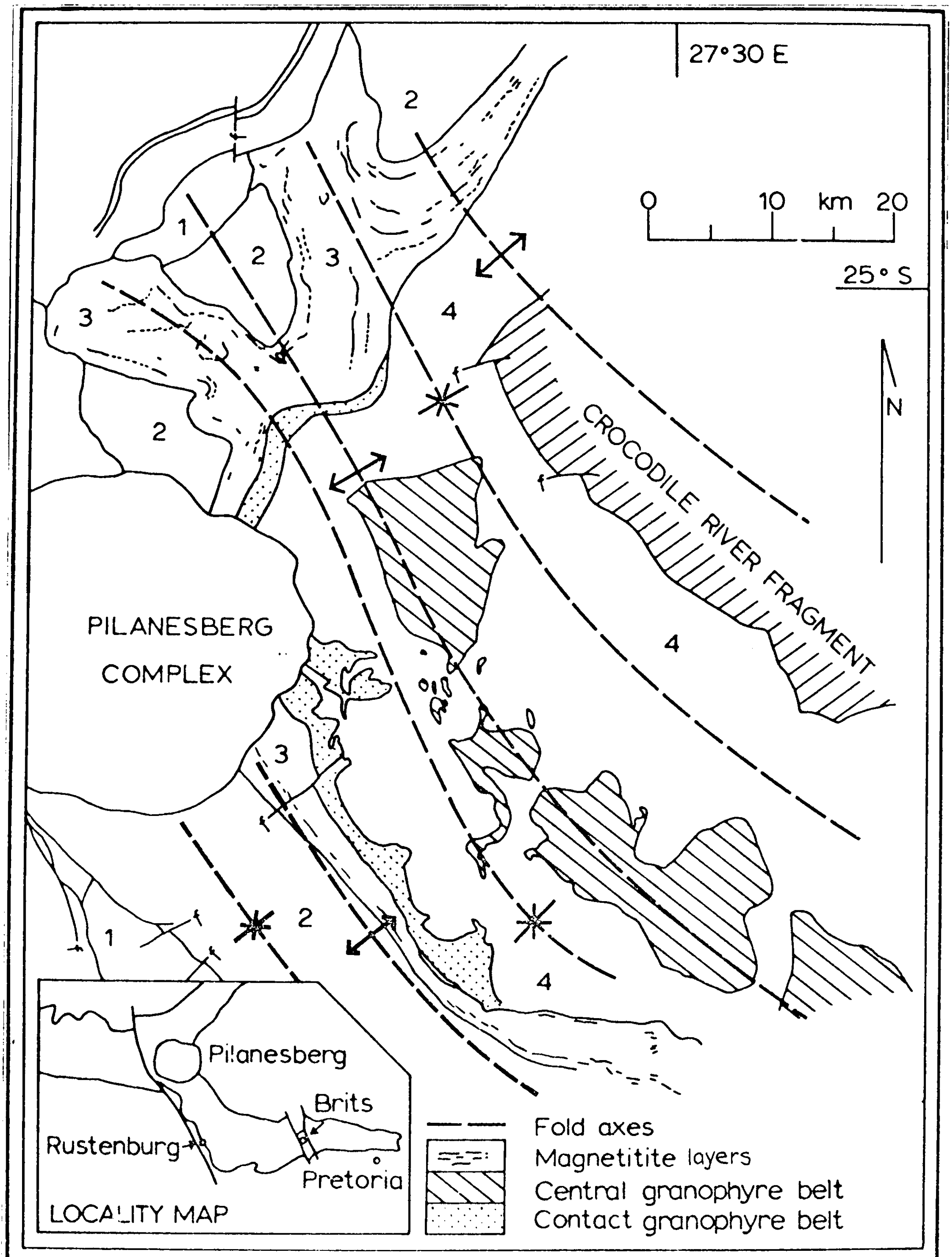


FIG. 24. LOCATION OF ANTICLINAL AND SYNCLINAL FOLD AXES

(1. Layered sequence below Main Zone; 2. Main Zone; 3. Upper Zone; 4. Veekraal granite)

described as occurring in the central part of a granite body, away from intrusive contacts with other rocks. On this basis the granophyric rocks of the central belt either constitute yet a different type of granophyre, previously unknown, or these rocks are indeed located near a contact. The second alternative suggests that the proposed structural model is correct and that the contact between the acid rocks and the layered sequence could be located at shallow depth underneath the rocks of the central belt. This configuration, together with the other possible alternatives, is illustrated in Fig. 25. In this figure three schematic cross-sections across the western Bushveld Complex are presented. The first possibility (a) is that no folding has taken place and that the central belt represents granophyric rocks at the contact of two sheets of granite. This possibility is discarded for lack of any supporting evidence.

Possibilities (b) and (c) involve a folded structure whereby either granophyric rocks located at the roof or at the floor of the granite sheet are folded into the position of the central belt. The similarity of the rocks in the central and contact belts, both in terms of the rock types and their relationships, suggests that the folded structure in configuration (c) is the most likely one and that the central belt is therefore located at the crest of an anticline.

7.1.2 AEROMAGNETIC OBSERVATIONS

Published aeromagnetic maps of the area (Aeromagnetic survey of area 7/69, Rustenburg), show good

correlation.....

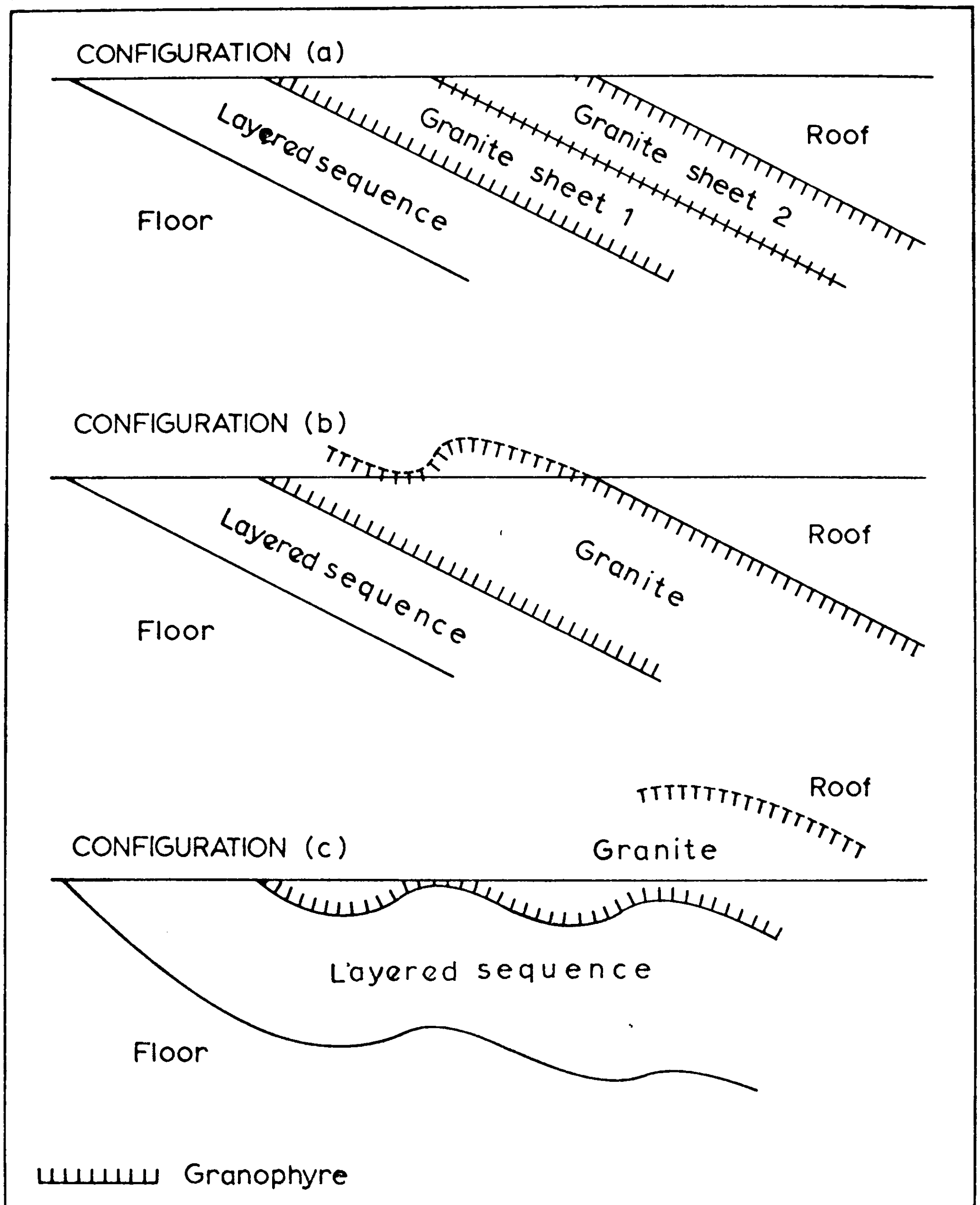


FIG. 25. ALTERNATIVE STRUCTURAL MODELS TO ACCOUNT FOR THE OBSERVED DISTRIBUTION OF GRANOPHYRIC ROCKS

correlation between the magnetic anomalies and known geological features, such as for instances the Pilanesberg Alkaline Complex and the ferrogabbro of the Upper Zone of the layered sequence.

The Upper Zone is characterized by high magnetic gradients and numerous maxima and minima. This contrasts with the gabbro of the Main Zone which shows lower gradients and has fewer maxima and minima per unit area than the ferrogabbro. The area underlain by the Veekraal granite does not appear homogeneous on the aeromagnetic maps, but instead is seen to consist of two bands of gentle magnetic gradients separated by a band of high gradients and many maxima and minima (Fig. 26). The pattern of the latter band is rather similar to that of the ferrogabbro of the Upper Zone, but the amplitude of the maxima and minima is smaller. The bands have a northwest orientation; there is moderately good agreement between the position of the band of high gradients and the central belt of granophyre as well as between the positions of the bands of low gradients and the Veekraal granite on either side of the central belt.

These observations are consistent with the proposed structural model. If the central belt is located on the crest of an anticline, the ferrogabbro of the Upper Zone would be found at relatively shallow depths below the acid rocks. This would result in an aeromagnetic pattern similar to that observed over the Upper Zone, but with reduced amplitude of the anomalies due to the masking effect of the overlying acid rocks, which do not produce any strong anomalies of their own.

Away from the central belt, in the areas

underlain.....

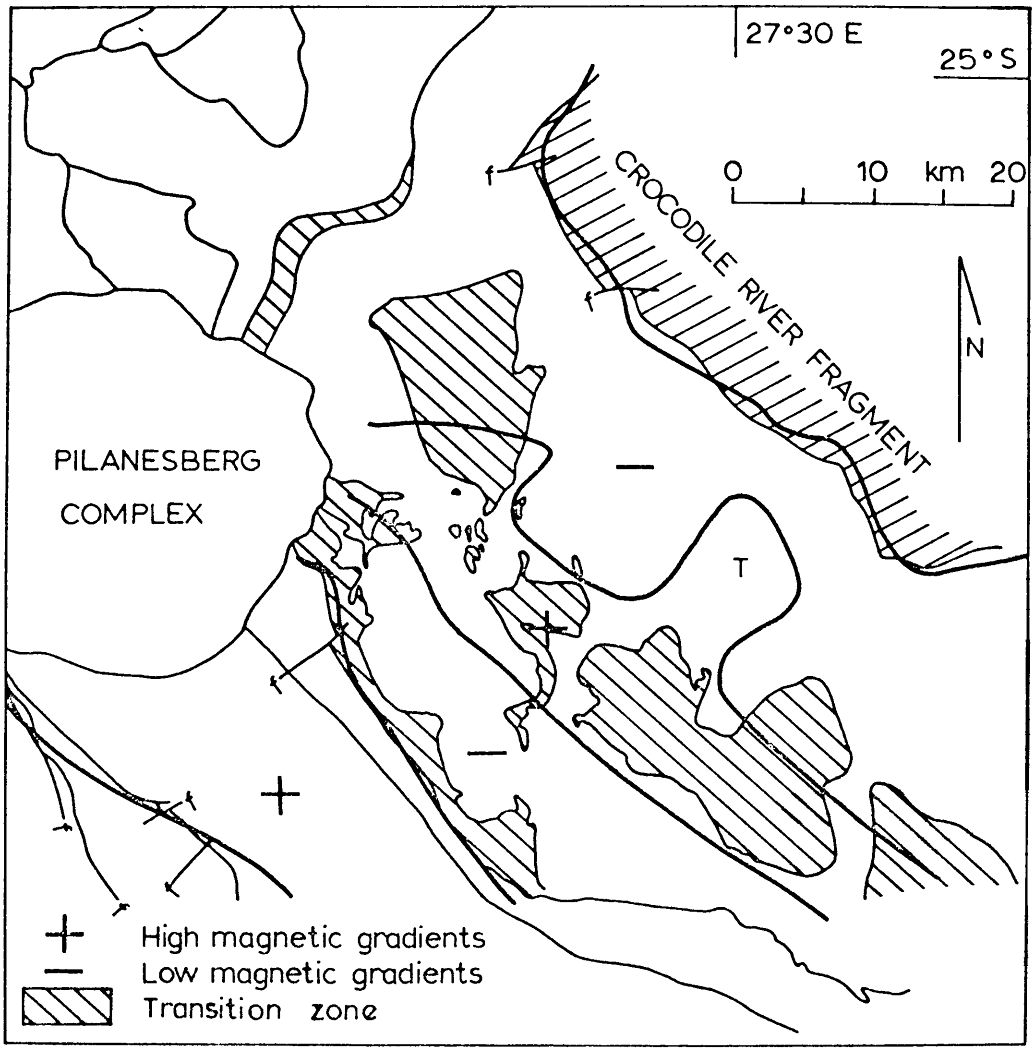


FIG. 26. LOCATION OF AREAS OF CONTRASTING AEROMAGNETIC PATTERNS

underlain by granite, the anomalies produced by the ferrogabbro would be much more severely attenuated by the increased thickness of acid rocks (transition zone plus Veekraal granite) and the pattern observed would be largely that of the granite itself.

7.1.3 GRAVIMETRIC EVIDENCE

Gravimetric evidence of the Bushveld Complex has led previous authors to suggest that the granite in the western Bushveld Complex may be relatively thin. This is concluded by Verwoerd (1967, p.97) and before him this view was expressed by P.J. Smit of the Geological Survey (unpublished manuscript), whose profiles across the Complex show the granite as a thin, flat sheet overlying the basic rocks of the Complex.

A qualitative interpretation of the available gravity data of the western Bushveld Complex was made and at a later stage, with the help of Dr. B.W. Darracott, then of the Geological Survey, a quantitative interpretation was made of the same data (Walraven and Darracott, 1976).

Fig. 27 depicts three gravity profiles constructed from the available gravity data together with a sketch map showing the location of the profiles. The data for the profiles were obtained from measurements made by Smit et al (1962) and the profiles are drawn along lines trending slightly east of north, more or less normal to the strike of the postulated fold axes. All three profiles show similar features. Approaching the granite from the southwest the values of the Bouguer anomalies increase steadily. The increase

continues.....

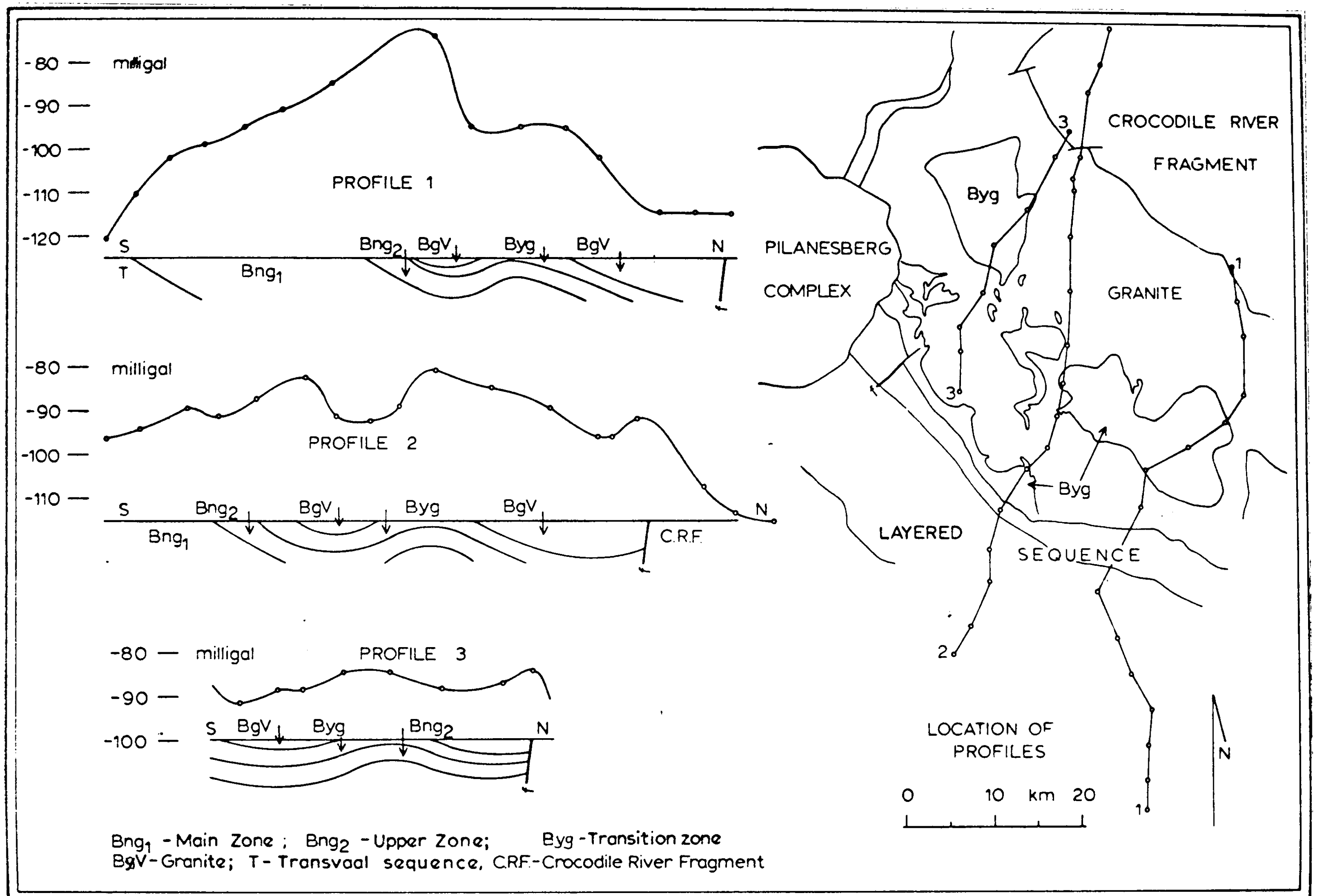


FIG. 27. OBSERVED BOUGUER ANOMALIES ALONG THREE PROFILES ACROSS THE WESTERN BUSHVELD COMPLEX

continues to a point beyond the contact of the layered sequence and the acid rocks before reaching a maximum. A minimum is then reached by the Bouguer anomalies while still over the granite and the anomaly values increase again as the central belt is approached. A second maximum is reached more or less over the central belt, and the Bouguer anomalies drop off again over the granite northeast of the central belt.

The Bouguer anomaly maximum observed over the central belt of granophyric rocks can be interpreted as being the result of either the presence of more dense rocks (basic rocks) closer to the surface, or a marked increase in the thickness of the more dense rocks at greater depth. Gravimetric considerations alone do not allow a distinction to be made between these alternatives, but the first is entirely consistent with the structural model.

The continued increase in the value of the Bouguer anomaly past the contact of the acid rocks and the layered sequence suggests a rapid increase in the thickness of the denser basic rocks at this point. This feature can also be explained by a sudden flattening of the dip of the layering, so that the basic rocks are shallower than expected, but this alternative is ruled out from geological observations. The increased thickness of basic rocks is probably also a structural feature and probably results from a steeper attitude of the layering, especially that of the Upper Zone which may have a discordant relationship with the underlying Main Zone. The increased thickness and discordance of the Upper Zone has a parallel in the suggested location of feeder pipes or feeder dykes of the Upper Zone close to the southwestern margin of the Bushveld granite (Coertze, 1974, p.45 and

Plate.....

Plate XIII).

In making a quantitative examination of the gravity data a simplified physical model based on the available geological data and the postulated structural model, was constructed along one of the profile lines shown in Fig. 27. The residual Bouguer anomalies along this profile were calculated by subtracting the estimated regional anomaly from the Bouguer anomalies. Expected residual anomalies were calculated from the simplified physical model and compared with the observed residual anomalies. The shape and dimensions of the physical model were then repeatedly modified until its computed gravity anomalies no longer differed significantly from the observed anomalies.

The profile line used for the quantitative interpretation corresponds to line 2 in Fig. 27. This line is sufficiently close to normal to the strike of the outcrops, and the lateral extent of the units is large enough in comparison to their depth extent, to allow the physical model to be regarded as a two-dimensional one. Fig. 28(a) shows the observed gravity anomalies along the profile line together with the assumed regional anomaly based on an average density of 2,70 g cm^{-3} of the rocks of the Transvaal sequence, which produce a gravity high relative to the older basement rocks. The main units used for the physical model are the acid rocks, the ferrogabbro of the Upper Zone and the remaining rocks of the layered sequence. The densities assigned to these units are based on values obtained from Smit and Maree (1966) and are as follows:

Acid rocks.....

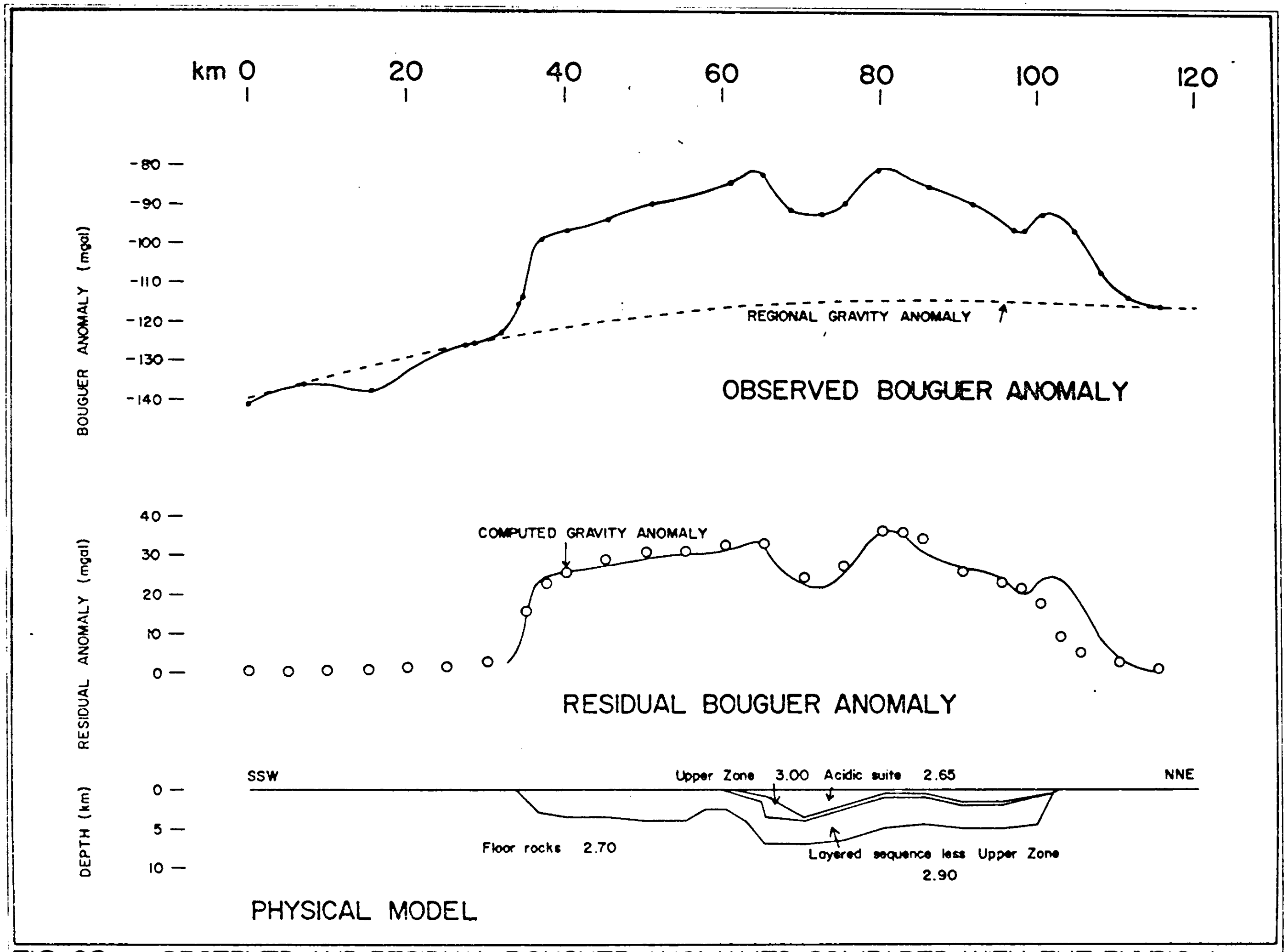


FIG. 28a. OBSERVED AND RESIDUAL BOUGUER ANOMALIES COMPARED WITH THE PHYSICAL MODEL AND THE GRAVITY ANOMALY COMPUTED THEREFROM

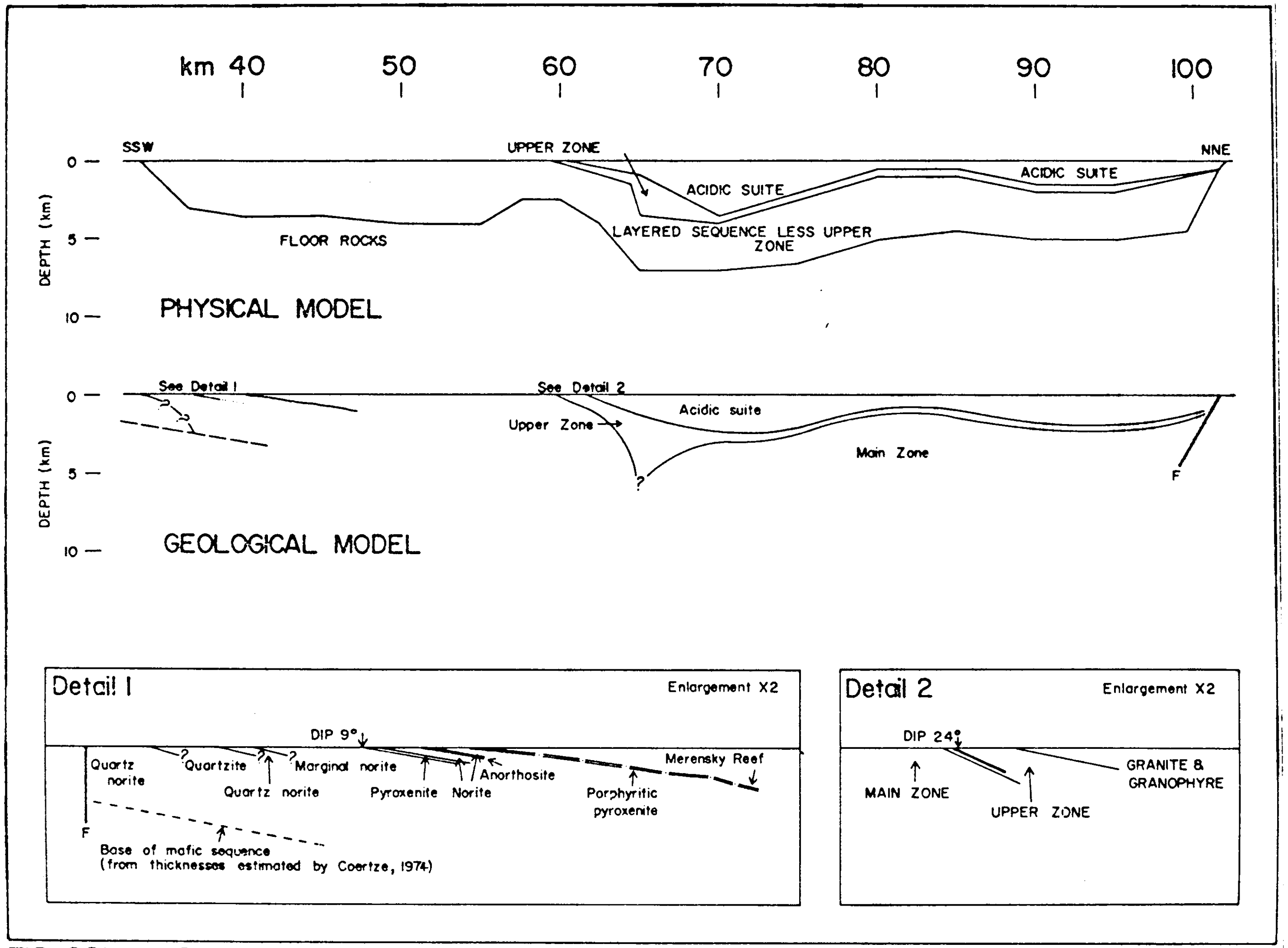


FIG. 28b. GEOLOGICAL DATA ON WHICH THE PHYSICAL MODEL IS BASED

Acid rocks: 2,65 g cm^{-3}
Upper Zone: 3,00 g cm^{-3}
Rest of Layered Sequence: 2,90 g cm^{-3}

In Fig. 28 (a) the final shape and dimensions of the physical model are shown together with the gravity anomalies that were computed from it and, for comparison,the observed residual anomalies. In Fig. 28(b) the proposed structural model has been included for comparison with the available geological data. The peak in the observed Bouguer anomaly at the northern end of the profile is believed to be related to the rocks of the Crocodile River Fragment, but since it does not affect the structural interpretation, no attempt is made to include it in the physical model.

The quantitative interpretation confirms the qualitative interpretation and in addition also suggests the following features: (1) the thickness of the layered sequence south of the contact with the acid rocks appears to be less than would be expected from the projection of the attitude of the layering at the southern extremity of the sequence, and (2) the attitude of the layered sequence near the contact with the acid rocks is possibly steeper than elsewhere. Both these features can be accounted for in the proposed structural model by an extension of the folding to the southwest, i.e. by adjoining another anticline and syncline to the southwestern syncline in the granite area (Fig. 24). The steeper attitude of the layering corresponds to the northern limb of the anticline and the flatter portion of the layered sequence would correspond to the northern limb of the syncline.

7.1.4.....

7.1.4 STRUCTURAL OBSERVATIONS

Evidence of possible tectonic activity during and after the intrusion of the layered sequence can be seen in the basic rocks of the Bushveld Complex north of Pilanesberg. As previously described in the section on the layered sequence, there are a number of transgressive lobes of ferrogabbro of the Upper Zone in this area. These are illustrated in Fig. 24 (see also Coertze, 1974, map in folder). A third transgressive lobe can be recognized by means of LANDSAT inagery, further north near the Crocodile River (Richards and Walraven, 1975).

Coertze (1974, p.97) interprets the relationship of the ferrogabbro to the older rocks to be the result of discordant intrusion to form two trough-like basins. The magnetitite layers in the Upper Zone are concordant with the outlines of the troughs and therefore support such a conclusion. The basinal shapes described by the magnetitite layers become shallower with increasing height in the Upper Zone. At the top of the Upper Zone, at the contact with the acid rocks, the basinal shape is very subdued.

Located between the two troughs of ferrogabbro is a remnant of the layered sequence which has not been transgressed and which shows the normal succession of basic rocks. At the southeastern end of this remnant, located at the southeast corner of the farm Syferkuil 9JQ (Fig.29), a large irregular outcrop of magnetitite is located within an arcuate layer of magnetitite which outlines the remnant of the older rocks. The shape of this outcrop is such that it could possibly have formed by the overturned minor

folding.....

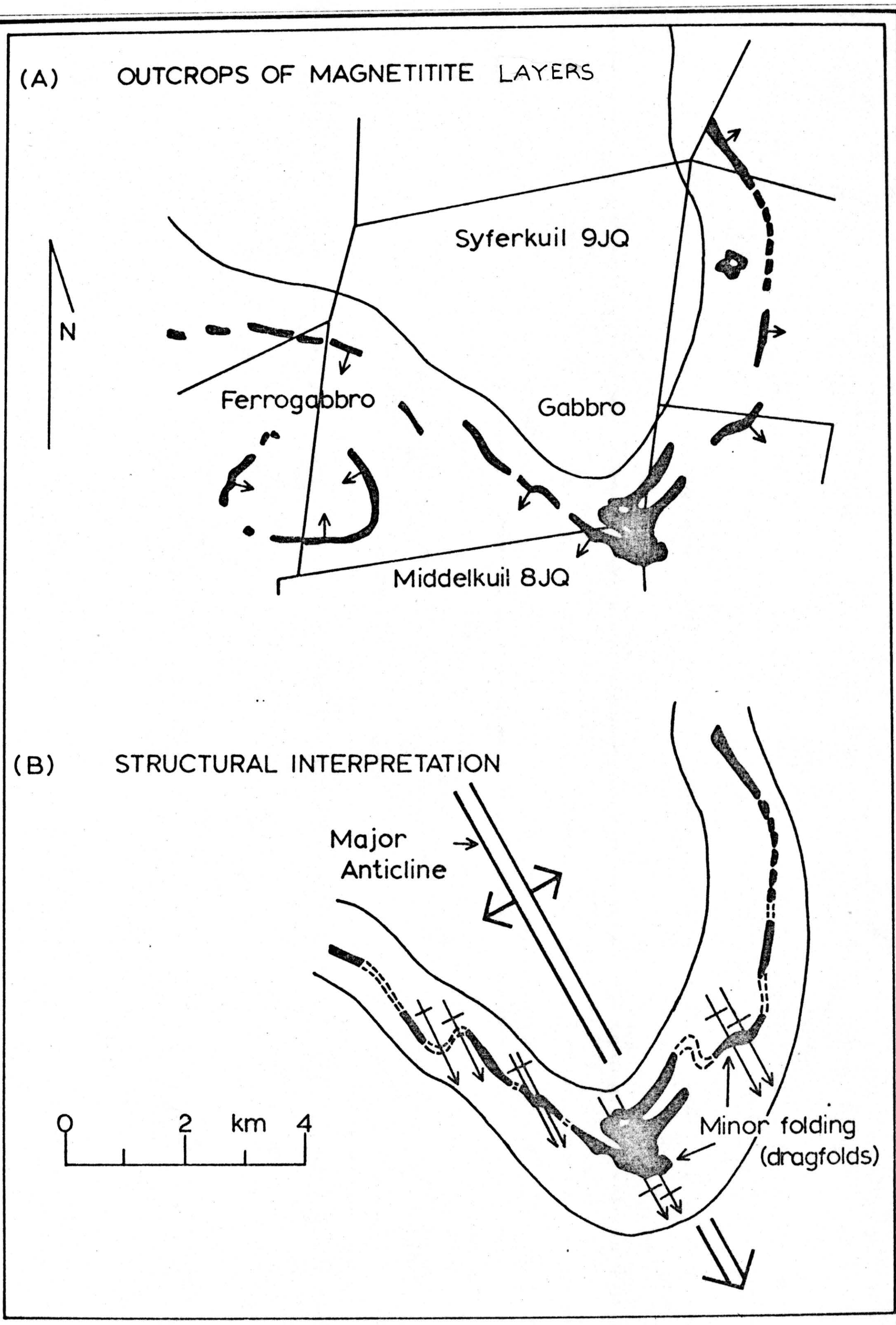


FIG. 29. DETAIL OF THE STRUCTURE IN THE MAGNETITITE LAYERS OF THE UPPER ZONE NORTH OF PILANESBERG AND THEIR INTERPRETATION

folding of two magnetitite layers at the nose of an anticline. The magnetitite layers located to the north and west of this outcrop have also been deformed in a manner consistent with minor folding developed in a large fold structure, viz., the development of moderately folded S-shaped drag folds on the southwestern limb of the anticline and the development of Z-shaped drag folds on the northeastern limb (Fig.29).

The shape of the magnetitite layers could therefore have resulted through folding to form an anticline located over the remnant of layered sequence rocks. The basinal shape of the magnetitite layers in the ferrogabbro in the transgressive lobes could similarly have resulted in part from the folding if synclinal axes were developed over the lobes.

7.1.5 CONCLUSIONS REGARDING THE STRUCTURAL MODEL

The structural model proposed for the western Bushveld Complex consists of northwest trending fold axes (Fig.24). The folds are located so that an anticline is situated over the central belt of granophyre and extends to the northwest to coincide with the remnant of layered sequence rocks between the transgressive lobes of ferrogabbro. Adjoining synclines are located over the transgressive lobes and over the Veekraal granite northeast and southwest of the central belt. Further fold axes are located to the southwest.

This model provides a unique solution for the observed distribution of rock types, especially the central and contact belts which are very similar to each

other.....

other and are believed to form part of the same stratigraphic horizon (Walraven, 1974b). The model also provides an acceptable explanation of the observed patterns on aeromagnetic maps of the area and is also perfectly consistent with the observed gravity anomalies. Although similar gravity anomalies would result from an elongated deep trough of basic rocks located at depth underneath the central belt of granophyric rocks, as might be expected if a feeder dyke of the Bushveld Complex were located here, such a trough would not be consistent with the aeromagnetic observations, nor could the distribution of rock types be explained as easily as in the proposed model. Finally some degree of support for the model is found also in the outcrop pattern of the magnetitite layers north of the Pilanesberg, which could represent minor fold structures.

7.2 JOINTING AND FAULTING

During the field work routine measurement of joint plane orientations was carried out. At each outcrop where joint planes were visible all the joint sets present were examined and a representative measurement made for each of the joint sets present in the outcrop. In this manner up to three sets of joints were normally recorded at most outcrops. The field data were subsequently plotted on orientation diagrams and grouped into subareas in an attempt to observe areal variations of the orientation of the joint planes. The results are illustrated in Fig. 30 where rose diagrams of the joint directions in each of the subareas are shown.

In.....

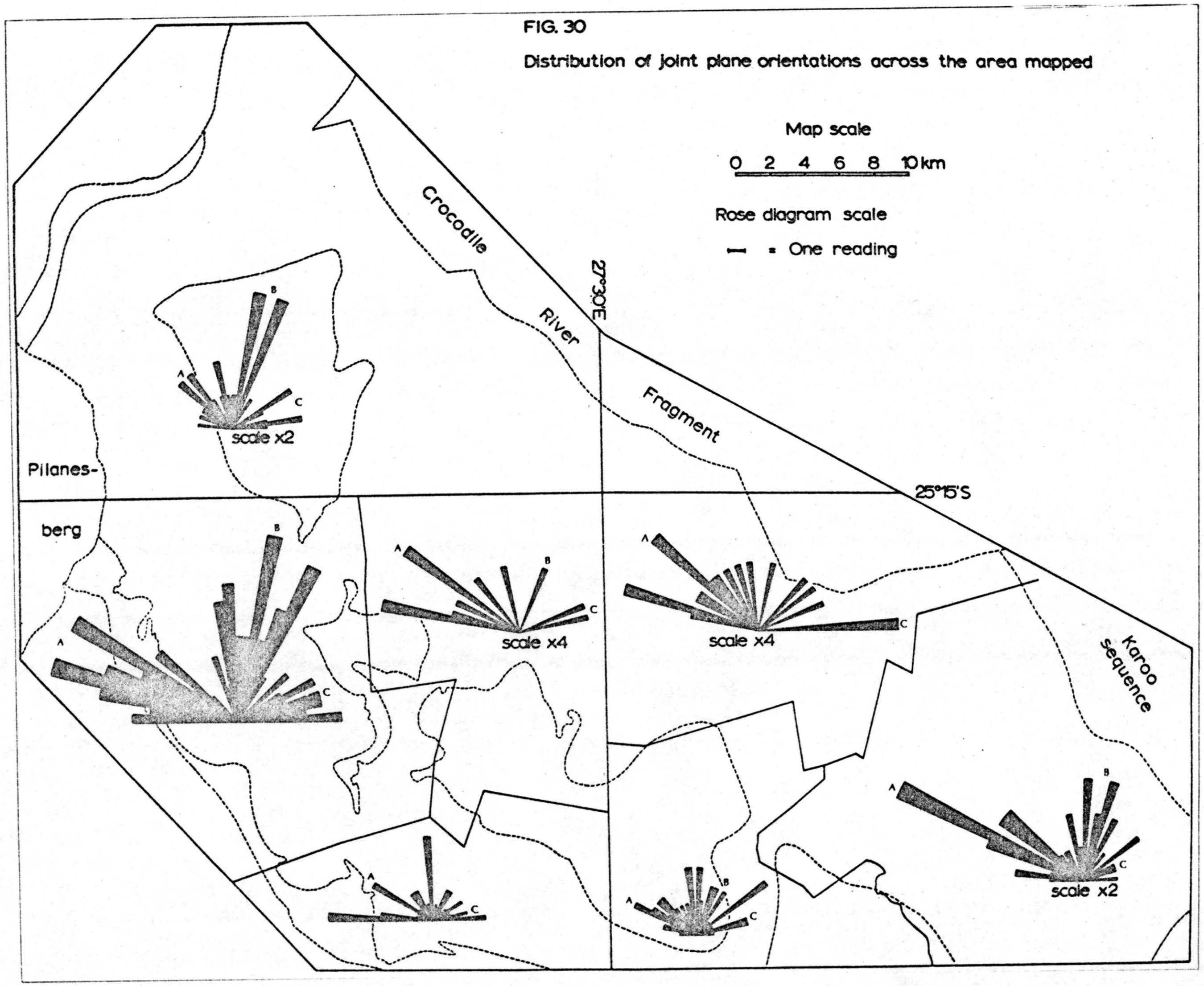


FIG. 30

Distribution of joint plane orientations across the area mapped

In the area as a whole there appear to be three joint systems. These are referred to as systems A, B and C. Two of the systems, A and B, are probably related to the same tectonic event. Joint system A consists of near-vertical joints having an average strike of 300 degrees. This direction is parallel to that of the diabase dykes which were probably intruded in the joints of this direction.

The second system, B, is made up of joints striking between 010 and 050 degrees. Their distribution in the western Bushveld Complex does not appear to relate to other features but the orientation of this system and of system A suggests that they formed during periods of north-northeast directed stress which resulted in stress joints of system A and release joints of system B.

The distribution of the joints belonging to system C is very irregular. The joints are oriented between 072 and 083 degrees and approximate the strike of prominent aeromagnetic anomalies which can be seen on aeromagnetic maps of the area and which traverse the whole of Transvaal. The anomalies are related to basic dykes of Karoo age and the Elands River follows one of these dykes for a short distance from south of the Pilanesberg to the Vaalkop Dam. There seems little doubt that these dykes and the joints of system C are related.

Major faulting in the area has a strike of about 30 degrees west of north. The faults bounding the Crocodile River Fragment have this orientation as well as the faults forming the Brits graben. The latter can be traced as lineaments on aerial photographs for a considerable distance northward into the

Veekraal granite. The presence and orientation of quartz-filled tension gashes associated with the faults suggests that they were active after the intrusion of the granite and that they were caused by a stress pattern having a major stress component oriented between north and northeast. This is in agreement with the stress patterns suggested by the joint systems A and B and also with the direction of the major stress required to produce the northwest fold structures.

7.3 INTERPRETATION OF THE STRUCTURE

Geological, geophysical and structural observations in the western Bushveld Complex provide evidence for a structural model consisting of northwest striking anticlines and synclines. This evidence suggests that the approximate orientation of the major stress direction was northeast to southwest and the majority of the structural features observed in the western Bushveld appear to relate to this stress pattern.

Coertze, (1974, p.108) mentions alternating phases of stress and relaxation of stress which took place during and which partly controlled the intrusion of the layered sequence. Successive additions of magma to the Complex would have taken place during the phases of stress relaxation.

The joint systems in the Veekraal granite relate to this stress pattern; this indicates that these stresses were still active until after the intrusion of the granite. Therefore the cycle of tectonic activity to which these stresses belong took place over

a.....

a rather protracted time, i.e. at least from before the intrusion of the basic rocks of the Bushveld Complex until after the intrusion of the Veekraal granite, a period estimated to be at least 170 million years on the basis of available age dating. Because the diabase dykes also follow joints produced during this cycle of tectonism, it must be considered possible that the cycle was not yet finalized before their intrusion.

8 PETROGENESIS

A number of hypotheses have been presented in the past to explain the origin of the granophyric rock types. Von Gruenewaldt (1968, p.163; 1972, p. 126) considers the granophyre in the Tauteshoogte and Paardekop area and in the area north of Middelburg to be the result of melting of the roof rocks which consisted of acid lava of the Rooiberg Group. The magma thus formed would have intruded and crystallized as granophyre at a slightly higher level.

Such a mechanism is considered to be unlikely to have taken place in the western Bushveld Complex. In the eastern Transvaal the layered sequence intruded at the very top of the Pretoria Group, immediately below the Rooiberg Group. In the western Bushveld the lavas of the Rooiberg Group and the basic intrusives of the layered sequence were separated by the sedimentary rocks of the Rayton, Smelterskop and Leeuwpoort Formations. These intervening rocks would have prevented any melting of the acid lavas of the Rooiberg Group taking place so that the latter cannot be invoked as a source of granophyre magma in the western Bushveld Complex.

Published literature does not present a picture of universal agreement concerning the formation of granophyre and the development of its characteristic texture. Much of the confusion in the literature is probably caused by inconsistencies in the nomenclature, but even for those rocks which can be regarded as granophyre in the strict sense of the name, a number of different opinions have been advanced.

Mehnert (1968, p.194) notes that the origin of

graphic.....

graphic intergrowths (and of micrographic intergrowths) is as yet rather disputed and has been explained in various ways in the past. The classical interpretation is that it is an eutectic fabric resulting from the simultaneous crystallization of quartz and feldspar. Bygden (1904) arrived at this conclusion on the basis of the percentages of quartz and feldspar in graphic granite. Fersman (1915) described regular relationships between the crystallographic orientations of the quartz and feldspar of the intergrowths and consluded that it is a result of eutectic crystallization. Simpson (1962) suggests simultaneous crystallization from a vapour phase for the graphic granite from the Ramona district, California, whereas Leighton (1954) suggests non-eutectic crystallization from a granitic melt for the granophyre of a basic complex in northern Wisconsin.

Other suggestions for the formation of granophyre sensu stricto include the replacement of feldspar by quartz which grows along specific crystallographic directions within the feldspar (Drescher-Kaden, 1948) or metasomatic replacement of feldspar under a variety of petrogenetic conditions (Augustithis, 1973, p.35). Krokström (1932) considers that the granophyre associated with the Breven dolerite dyke did not form solely by eutectic crystallization, but may partly have formed by replacement and also by undercooling.

From the variety of opinions concerning the formation of granophyre it can only be concluded that there must be a number of ways in which such micrographic textures can develop. In the case of the Beestkraal granophyre contact relationships indicate that it intruded the transition zone after the formation of

the.....

the Zwartbank pseudogranophyre. The texture of the granophyre suggests that this rock formed by crystallization from a magma. The composition of the micrographic crystals from the centre outward is consistent with crystallization from a melt which lies in the feldspar field of the quartz-albite-orthoclase phase diagram. In Figure 31 a diagrammatic representation is given of the path which the melt is believed to have followed during crystallization of the granophyre. The first crystals to form from the melt are perthite. As these grow the melt becomes enriched in silica and its composition moves towards the quartz field of the diagram. When the cotectic line is reached, however, quartz does not immediately start to crystallize. Before crystallization of any phase can proceed, conditions must be reached under which the solid can exist stably (Stanton, 1972, p. 203). When the phase boundary is first reached any nuclei of quartz that might form would be small and therefore have a very high free energy per unit volume. Consequently there is a very strong tendency for such nuclei to go into solution again.

The only way in which the nuclei can avoid solution is by rapid growth to a size where the surface energy of the crystal is a much smaller proportion of its total energy and the free energy of the crystal is less than the free energy of the silica atoms in the melt. Such rapid growth will take place only under increased concentration gradients and crystallization of the quartz will therefore be delayed until such conditions are achieved, i.e., until the composition of the melt has moved some distance into the quartz field of the quartz-albite-orthoclase system

(Fig. 31).....

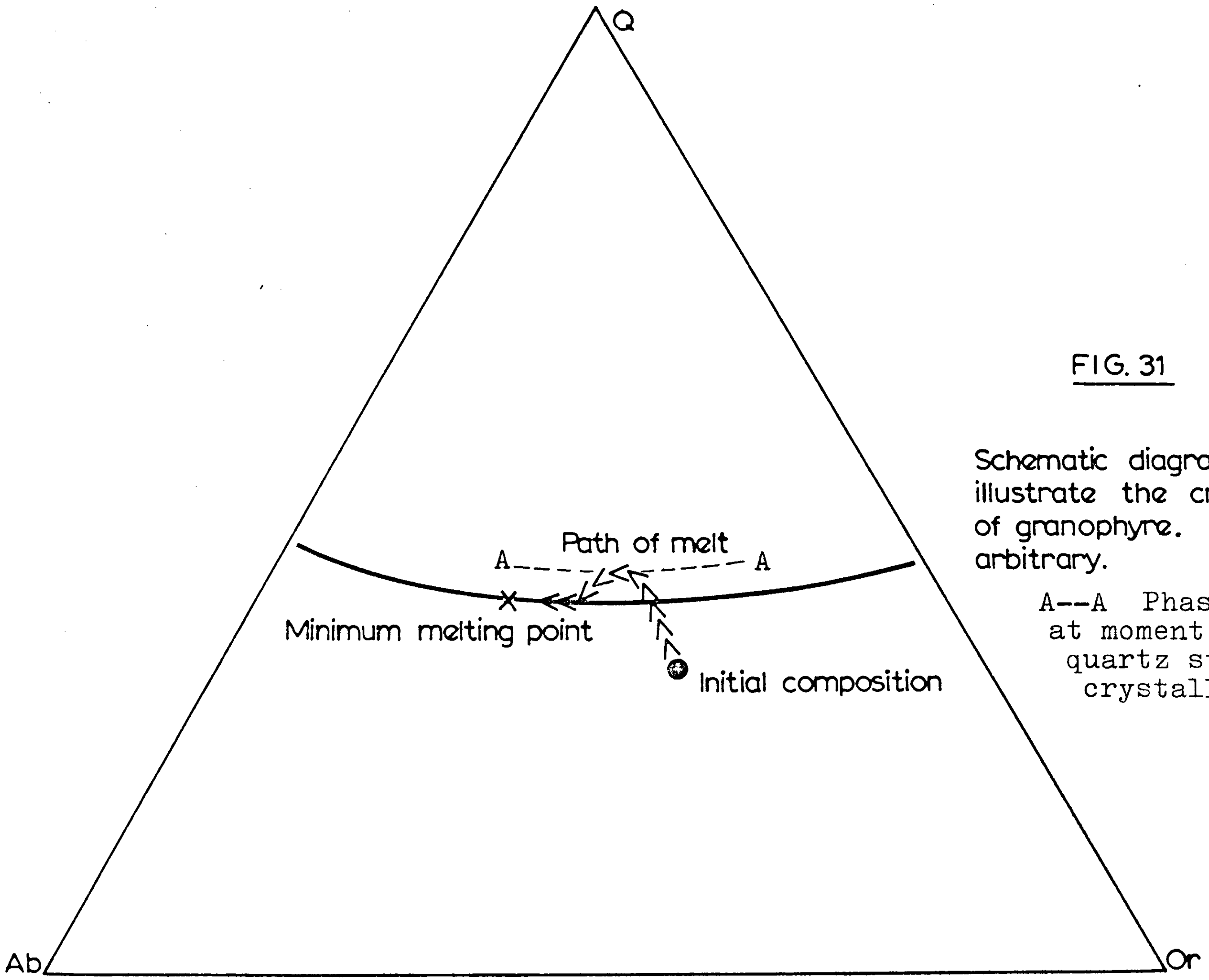


FIG. 31

Schematic diagram to illustrate the crystallization of granophyre. Scale is arbitrary.

A--A Phase boundary at moment at which quartz starts to crystallize.

(Fig. 31). This means that the melt has in fact become supersaturated with respect to SiO_2.

As a consequence of the supersaturation, the stage at which the melt crosses the cotectic line is represented in the micrographic crystals by a line located a small distance <u>inside</u> the boundary of the core and the mantle (Fig. 8). When the quartz does finally start to crystallize it does so rapidly and the ratio of quartz to feldspar is consequently higher until the excess SiO_2 has been used and the composition of the melt has moved back to a position on the cotectic line. From then on the quartz and feldspar crystallize simultaneously in the cotectic ratio of approximately 45 to 55, and the composition of the melt then changes towards the ternary minimum of the system.

Other investigations of granophyre and graphic granite (e.g. Simpson, 1962) have revealed that the quartz rods in the intergrowths are quite continuous. Although the rods become coarser away from the core, new ones are rarely started, confirming that nucleation of a new crystal is relatively difficult compared with further growth of an existing crystal.

Investigations of igneous complexes such as the Skaergaard (Wager and Brown, 1968) suggest that extreme differentiation of tholeiitic magma may result in the formation of an acid residue, rich in iron, sodium and potassium, from which granophyre could crystallize. In the western Bushveld both the lack of gradational contacts between the basic rocks and the granophyre as well as the relative proportions of these rocks suggest that such a mechanism was not operative in this case.

Two.....

Two alternative methods can be considered for the derivation of the granophyre magma. The first is that the magma was formed at shallow depths by melting of suitable material by means of the heat energy provided by the layered sequence. As noted at the start of this section, the lava of the Rooiberg Group cannot be considered as a suitable parent rock. Feldspathic sediments of the appropriate composition were almost certainly present in the roof rocks of the complex and the granophyre magma might have been derived from these.

The second alternative is that the granophyre magma was derived from a greater depth. No evidence is available to suggest at what depth the magma might have formed or by what method it was formed. Certain aspects of other basic rock-granophyre associations are of interest (Wager and Brown, 1968, pp.137, 515 and 518; McLeod, 1959, p.34). In many cases the acid rocks associated with the basic intrusions appear to have discordant relationships with the basic rocks and are not considered to have formed in situ, but to have derived at depth by fractional crystallization, e.g. the Somerset Dam layered intrusion (McLeod, 1959, p.34; Mathison, 1967, p.79).

Evidence abounds to suggest that the Beestkraal granophyre is not a marginal phase of the Veekraal granite. Intrusive contacts between the granophyre and the granite indicate that the granite intruded later. This is corroborated by the age determinations and is further supported by the chemical dissimilarity of the two rock types and by the existence of granophyre in the absence of granite in other localities in the Bushveld Complex (Von Gruenewaldt, 1972, p.121).

The.....

The textures of the Zwartbank pseudogranophyre and poikilogranite provide strong evidence that replacement of quartz by feldspar has taken place in these rocks (Fig. 10a, b and c). It is believed that the replacement relates to the formation of these rocks which are thought to have formed by a process of transformation from the roof rocks of the layered sequence by the heat from the basic intrusives.

Daly (1905, pp.195 and 209), in a review of some layered igneous bodies with granophyric and granitic portions, mentions several features similar to those observed in the Bushveld Complex. These include the presence of partly digested sedimentary xenoliths which are changed to "rocks similar to granophyre-granite", and the asymmetry of the arrangement in which the granophyric rocks occur only near the top of the basic body. Daly suggests the following contributory causes: (1) extensive assimilation at the the upper surface only, and (2) asymmetry due to density stratification of the magma composed of gabbro and digested sediment.

Examination of samples of the uppermost portion of the ferrogabbro of the Upper Zone (from bore-hole BK1) shows that these rocks contain an appreciable amount of hornblende as well as interstitial quartz which are not found in the remainder of the ferrogabbro. This may be the result of either assimilation of acid roof rocks or differentiation within the layered rock or by a combination of both. (Wager and Brown, 1968, p.240; Coertze, 1974, p.97).

In order to be able to produce the Zwartbank pseudogranophyre and poikilogranite, suitable parent rocks must have been available. Subgreywacke and

subarkose.....

subarkose form a large proportion of the strata in the upper part of the Pretoria Group (Visser, 1969, p.88) and their chemical composition is such that minor additions of sodium, potassium and iron would result in compositions similar to that of the Zwartbank rocks. These are therefore quite suitable roof rocks from which the pseudogranophyre and poikilogranite might have formed.

In the Zwartbank rocks the quartz has been replaced by perthite and orthoclase as well as by plagioclase. The replacement appears to have taken place by growth of the feldspar around as well as into the quartz grains. Therefore, although it is probably small, the process must involve a change in the bulk composition of the parent material.

There are three alternative processes that can account for the SiO_2 which has been replaced: (1) it could be removed from the rock, possibly by upward migration into the overlying strata or by lateral migration into less siliceous parts of the roof rocks, (2) it could form overgrowths on other, smaller quartz grains in the rock, or (3) it could combine with introduced material to form feldspar.

Of these possibilities the second one is discarded because no overgrowths have been observed on the quartz grains in either the pseudogranophyre or the poikilogranite. The first alternative, if operating alone, would result in a bulk decrease in the volume of the parent rocks; similarly the third alternative would result in a bulk increase in volume. Table 9 shows the average composition of the Zwartbank rocks compared to that of some possible parent materials from which they might have formed. Feldspathic

quartzite.....

quartzite from the roof rocks to the northeast of the Crocodile River Fragment (column II) has a composition rather similar to the average Zwartbank rocks, although the Al_2O_3 content is slightly high. The average composition shown in column III has been obtained by combining the composition of subgreywacke, subarkose and arkose from the Rayton Formation (Visser, 1969, p.100) with that of the average shale (Pettijohn, 1957, p.344) in a ratio representing the relative proportions of these rock types in the succession.

TABLE 9

CHEMICAL COMPOSITION OF SEVERAL ALTERNATIVE PARENT MATERIALS FOR THE ZWARTBANK ROCKS

	I	II	III	IV
SiO_2	74,09	73,08	74,14	72,83
TiO_2	0,24	0,48	0,44	0,34
Al_2O_3	11,66	14,29	12,48	11,14
Fe_2O_3	1,61	0,82	2,68	1,18
FeO	1,54	0,28	1,64	2,36
MgO	0,13	0,30	1,50	2,18
CaO	0,93	0,60	1,82	1,94
Na_2O	3,36	3,46	1,24	2,74
K_2O	4,91	5,73	3,80	3,48

I Average composition of Zwartbank pseudogranophyre and poikilogranite (analyses in Appendix 2)

II Feldspathic quartzite, northeast of the Crocodile River Fragment (Visser, 1964, p.203)

III Average composition of Pretoria Group sediments from the Magaliesberg Quartzite Formation upwards (excluding orthoquartzite, feldspathic quartzite and non-clastic sediments; see text for further details)

IV Average composition of analysed sedimentary xenoliths in area mapped (Appendix 2)

Orthoquartzite and feldspathic quartzite are the rock types forming the majority of the sedimentary xenoliths and have been left out of consideration. Non-clastic sediments and lava have also been left out since they are volumetrically unimportant; the non-clastic xenolith on Potgietershoogte 134JQ

suggests.....

suggests that these rocks were also not involved in the transformation process.

The average composition thus obtained is lower in Na_2O and slightly higher in MgO and Fe-total content than the composition of the Zwartbank rocks. Although considerable uncertainty must exist in these comparisons, they do confirm the presence of suitable parent rocks forming the roof of the layered sequence from which the Zwartbank rocks may gave been formed and furthermore they suggest that little or no change in the SiO_2 and Al_2O_3 contents was needed to form the Zwartbank rocks.

Discrepancies in the Na_2O content of parent rocks and products suggest some addition of Na_2O during the transformation, probably in the form of an acid, alkali-rich liquid derived from the basic rocks. Since there are no indications of a consequent increase in the SiO_2 content of the transformed rocks, it would appear that some SiO_2 was also lost from these rocks during the transformation process.

Simple recrystallization of the parent rocks to form the pseudogranophyre and poikilogranite is not thought to have taken place. Such a possibility is precluded firstly by the limited availability of parent rocks of the same chemical composition as the product rocks and secondly because the quartz-feldspar intergrowths in the pseudogranophyre represent a higher-energy state than the texture of the parent rocks.

A close relationship between sedimentary rocks and the Zwartbank pseudogranophyre is indicated by the inclusion of partly assimilated quartzite pebbles in the pseudogranophyre. These are interpreted as

being.....

being the remnants of strongly deformed sedimentary strata (brecciated, as seen in some of the sedimentary xenoliths) in which all but the very quartz-rich sediments have been transformed.

Chemical data also provide indications of a relationship between the Zwartbank rocks and the sedimentary rocks. Cluster analysis shows that these rocks resemble each other by not grouping together at low values of the distance function, i.e., both are more variable in their chemical composition than either the Veekraal granite or the Beestkraal granophyre.

Van Rooyen (1950) has ascribed a metamorphic origin to pseudogranophyre in the area north of Potgietersrus. He considers the rock, which closely resembles the"Rooiberg pseudogranophyre" described by Strauss and Truter (1944, p.70), to represent an altered feldspathic quartzite of the Pretoria Group.

Both the pseudogranophyre as well as the poikilogranite are believed to have formed by a similar transformation process. The different textures seen in these rocks are thought to reflect differences in the grain size of the parent rocks. Figure 32 is a diagrammatic representation of the transformation process acting on fine- and coarse-grained parent rocks. Growth of feldspar crystals A to D has, in the coarse-grained rock, resulted in the production of a pseudographic texture while in the fine-grained rock a poikilitic texture is formed.

Grain size measurement of the Zwartbank rocks suggests that half a millimetre is the approximate size above which quartz grains tend to be embayed and penetrated by the growing feldspar crystals. Quartz grains below this size tend to be only slightly

rounded.....

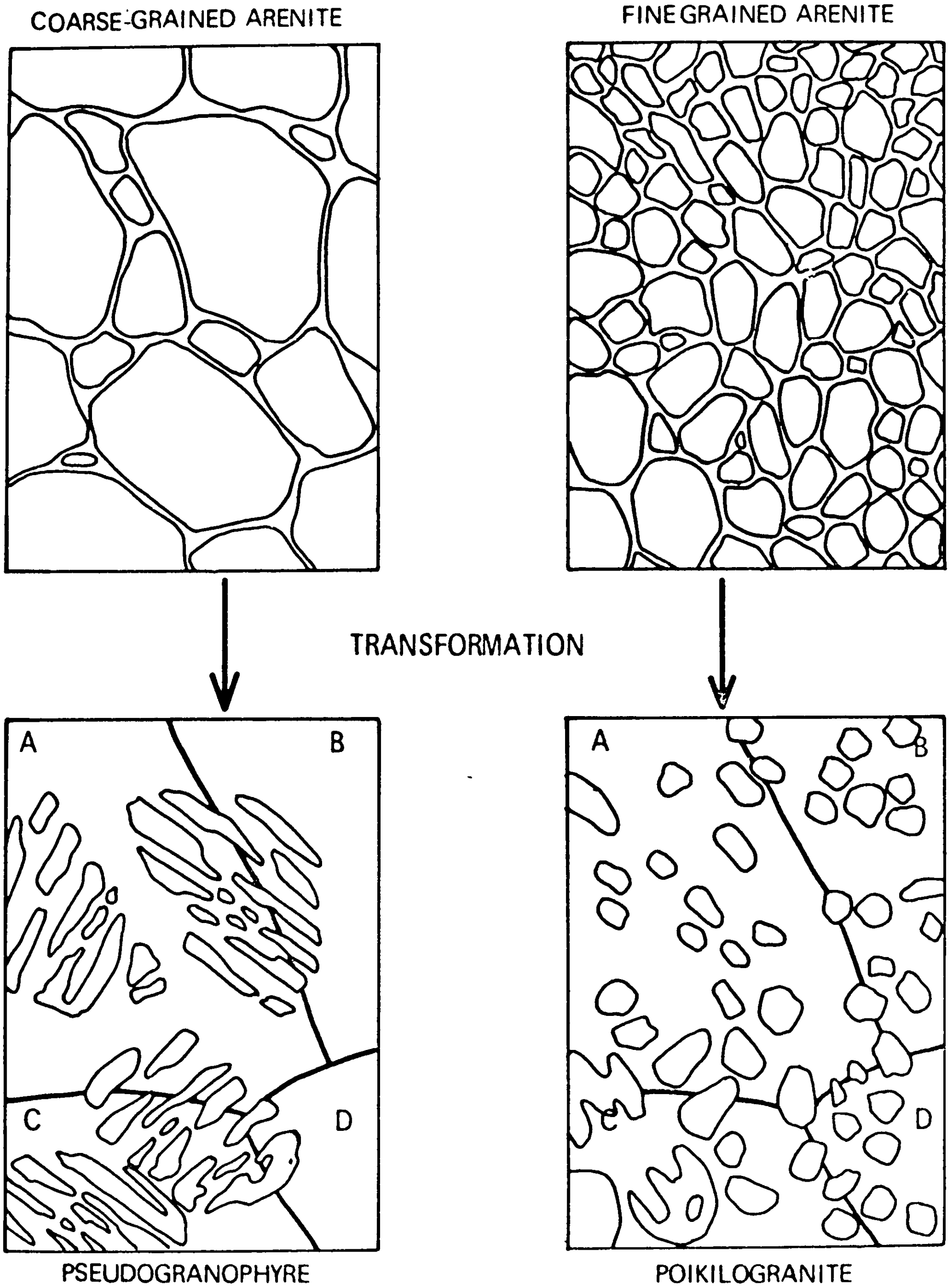


FIG. 32. SCHEMATIC REPRESENTATION OF THE TRANSFORMATION PROCESS

GROWTH OF FELDSPAR CRYSTALS A TO D RESULTS IN THE FORMATION OF A PSEUDOGRAPHIC OR A POIKILITIC TEXTURE DEPENDING ON THE GRAINSIZE OF THE PARENT ROCK rounded during the feldspar growth. As noted in section 4.2.2.2 the pseudogranophyre and poikilogranite are completely gradational and various proportions of both textures are found in individual rocks.

As shown by the statistical analyses as well as by the quartz-albite-orthoclase and AFM diagrams, the metasedimentary rocks of the xenoliths are chemically distinct from the other rock types of the transition zone. The source of the sedimentary rocks was very probably the upper part of the Pretoria Group which formed a part of the roof during the intrusion of the layered sequence of the Bushveld Complex. In the western Transvaal the rocks that form the floor of the Bushveld Complex are predominantly the strata of the Magaliesberg Quartzite Formation. Furthermore the layering of the Complex is generally conformable to the underlying sedimentary strata and no evidence of any major transgression of the floor rocks is seen. It is therefore reasonable to suppose that the Magaliesberg Formation also forms the floor of the Bushveld Complex in the area under consideration. Consequently the roof rocks of the Complex consisted of those strata of the Pretoria Group that were overlying the Magaliesberg Formation: the equivalents of the Rayton Formation east of Pretoria and the Leeuwpoort and Smelterskop Formations in the Rooiberg area.

As shown in Table 2 (section 4.1.1), suitable quartzite beds from which the sedimentary xenoliths could have been derived are present in these formations. The xenolith on Potgietershoogte 134JQ, which contains non-clastic strata, provides additional support for this choice of parent formations for the xenoliths because similar non-clastic sediments consisting of alternating chert and limestone beds are found in the Rayton Formation (Table 2 and Visser, 1969, p.94).

9 SUMMARY AND CONCLUSIONS

Field work in the area north of Rustenburg and Brits has demonstrated the existence of a transition zone separating the rocks of the layered sequence below from the Veekraal granite above. Age determinations and contact relationships indicate that the Veekraal granite is younger than and intrusive into the rocks of the transition zone. Consequently an upper portion of the transition zone, separating the Veekraal granite and the roof of the Bushveld Complex, must have existed at the top of the Veekraal granite prior to its removal by erosion.

A number of rock types make up the transition zone. Quantitatively the most important of these rock types are the Beestkraal granophyre and the Zwartbank pseudogranophyre and poikilogranite. Microgranite and metasedimentary rocks make up the remainder of the transition zone. Intrusive lobes of Veekraal granite are also found within the transition zone. These represent downward offshoots from the main body of Veekraal granite overlying the transition zone.

Field and contact relationships, age determinations and major as well as trace element chemistry provide conclusive evidence that there is no genetic relationship between the granite and the rocks of the transition zone. The Veekraal granite is younger than, has sharp intrusive contacts with, and differs considerably chemically from the other rock types. Significant chemical differences exist between the Veekraal granite, the granophyric rocks and the metasediments (e.g. statistical analyses, section 6.2).

Chemical differences also exist between the

Veekraal.....

Veekraal granite in the lower part of the granite sheet and the granophyric rocks as well as between the lower and upper parts of the granite sheet. Samples from the lower part of the granite sheet form a separate cluster in the cluster analysis and also occupy the same area on the AFM diagram as the granite samples from bore-hole BK1, which are very near to the base of the granite sheet. This area on the AFM diagram is separate from the area occupied by the granite samples from the upper part of the granite sheet and samples of the granophyric rocks. Plots of chemical content versus depth of the bore-hole samples show consistent differences between the major element chemistry of the granite and the other rock types.

There can be little doubt that the lowermost granite intersection in bore-hole BK1 has been contaminated by material incorporated from the ferrogabbro of the Upper Zone. As was shown in Figure 19, a number of major elements and the anorthite content of the plagioclase in the granite exhibit gradual changes towards the contact with the ferrogabbro, but have sudden, sharp changes at the contact itself. In addition, support for this conclusion is found in the presence of inclusions of partly assimilated "mottles" of ferrogabbro within the lowermost granite intersection.

A summary of the geological history is illustrated in Figure 33. The events are as follows:

A. Before the intrusion of the Bushveld Complex the Pretoria Group was overlain by acid lavas of the Rooiberg Group.

B. Intrusion of the basic magma of the layered

sequence.....

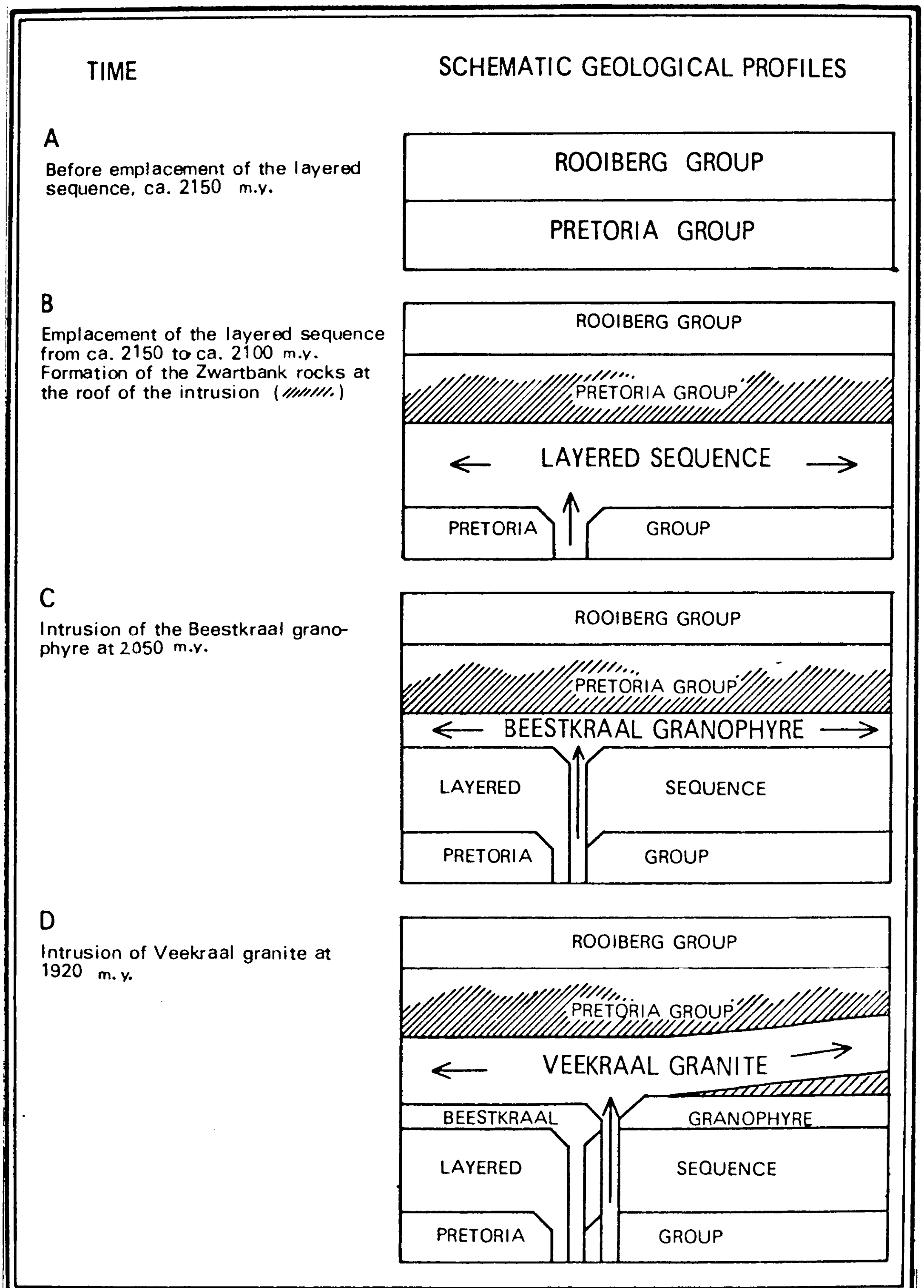


FIG. 33. SCHEMATIC GEOLOGICAL HISTORY OF THE WESTERN BUSHVELD COMPLEX

sequence took place at a stratigraphic level corresponding to the top of the Magaliesberg Quartzite Formation. The final basic intrusion (ferrogabbro of the Upper Zone) took place at about 2100 m.y.

During the emplacement of the basic magma varying degrees of transformation of the roof rocks occurred. Relatively pure quartzites were mainly recrystallized but many of the rocks of the Rayton Formation, including subgreywacke, subarkose and other rock types were affected to the extent that they were transformed into the Zwartbank pseudogranophyre and poikilogranite. The original grain size of the transformed rocks played a part in the texture produced during the transformation process.

The transformation process involved replacement of quartz by feldspar, and took place under the influence of the heat energy and was aided by volatiles provided by the basic rocks. During the transformation process a limited amount of material, mainly in the form of alkalies, was added to the roof rocks which probably also lost relatively small amounts of SiO_2.

C. After the intrusion of the basic rocks and the formation of the Zwartbank rocks, intrusion of an acid magma took place at about 2050 m.y. This magma crystallized to form the Beestkraal granophyre the characteristic texture of which is the result of cotectic crystallization of quartz and feldspar. The origin of the granophyre magma cannot be determined with certainty.

D. Intrusion of the Veekraal granite took place at

about.....

about 1920 m.y. The granite intruded into the transition zone and consequently another, stratigraphically higher part of this zone must have overlain the granite prior to its removal by erosion.

E. Intrusion of diabase dykes took place some time after the consolidation of the Bushveld rocks. Subsequent to this the intrusion of various carbonatite veins and dykelets and of east-west trending dolerite dykes took place.

Tectonic activity was evidenced at various stages during the intrusion of the Bushveld Complex and probably to some extent controlled the intrusive phases of the Complex. The predominant structural elements are oriented in a northwest-southeast direction and the resulting structure consists of northwest oriented fold axes. An anticlinal fold axis underlies the central belt of the transition zone. The rocks of the central belt are regarded as a lateral continuation of the contact belt which has been folded into its present position and is exposed on the crest of an anticline. If this structural model is correct, the basic rocks of the layered sequence are situated at a comparatively shallow depth below the central belt.

10 ACKNOWLEDGEMENTS

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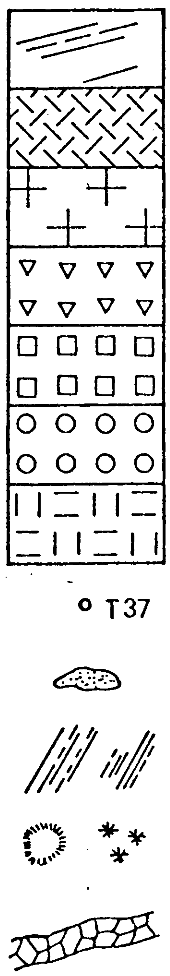
APPENDIX 1. LOG OF BORE-HOLE BK1.

Location:	Bierkraal 120 JQ, 25°27,5'S 27°20,0'E
Drillers:	Department of Water Affairs
Total depth:	1680 m
Inclination:	Vertical

NOTE This log covers only the upper portion of the bore-hole, from zero to 450 m, which is the portion of interest to this thesis.

LEGEND



Quartzite, showing bedding traces

Diabase

Veekraal granite

Beestkraal granophyre

Zwartbank pseudogranophyre

Zwartbank poikilogranite

Ferrogabbro of the Upper Zone

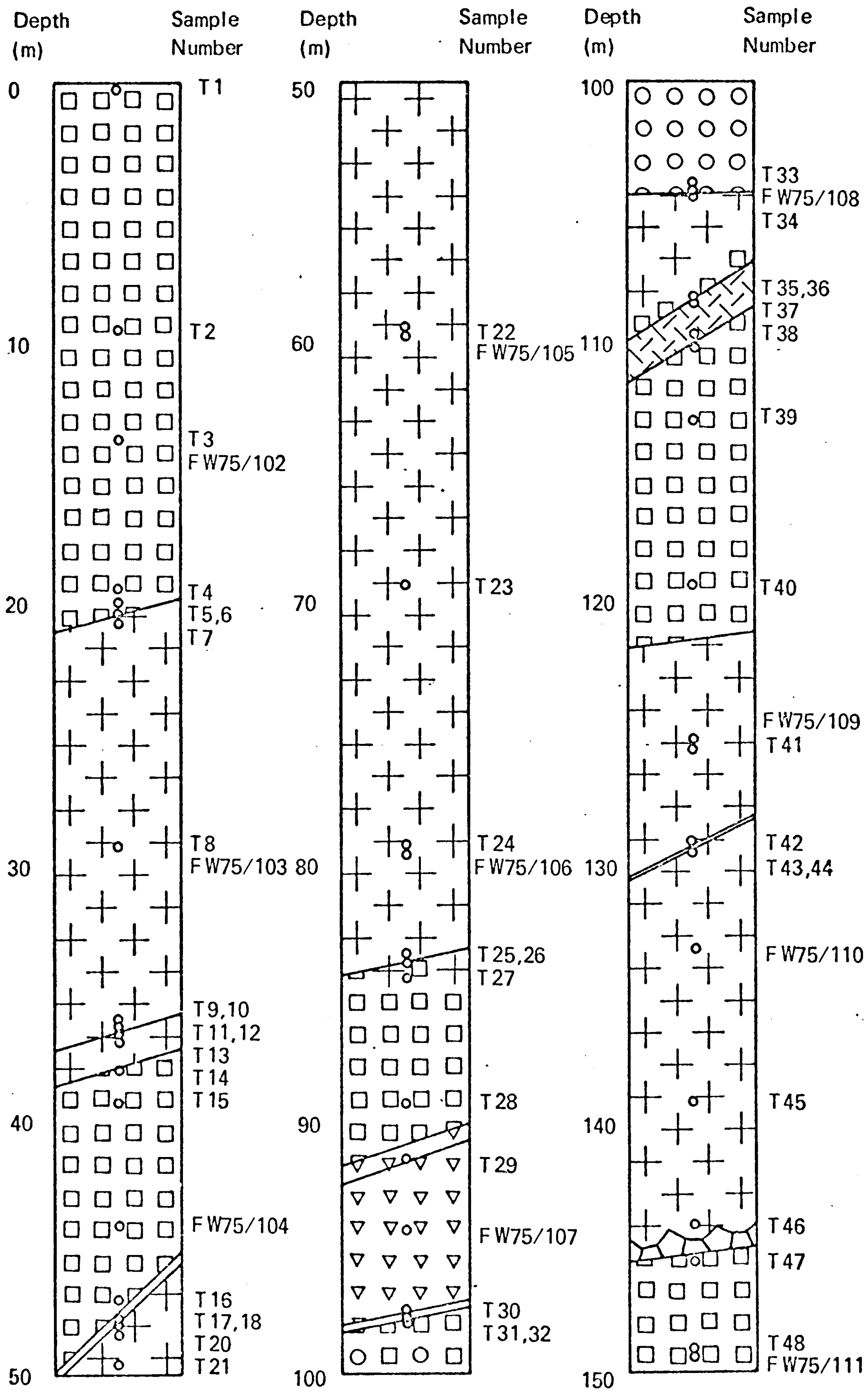
Location of sample for thin section or analysis

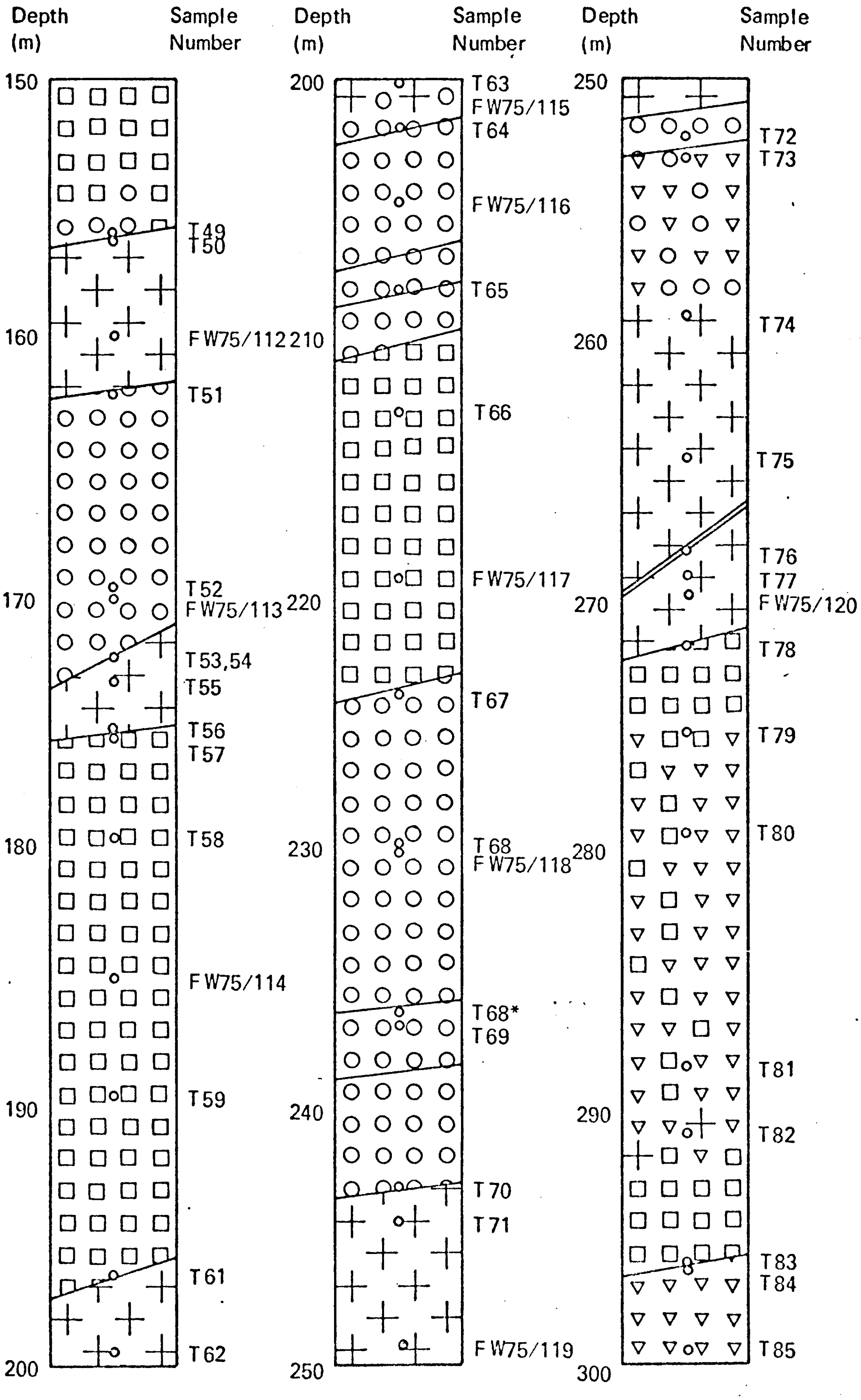
Sedimentary inclusion

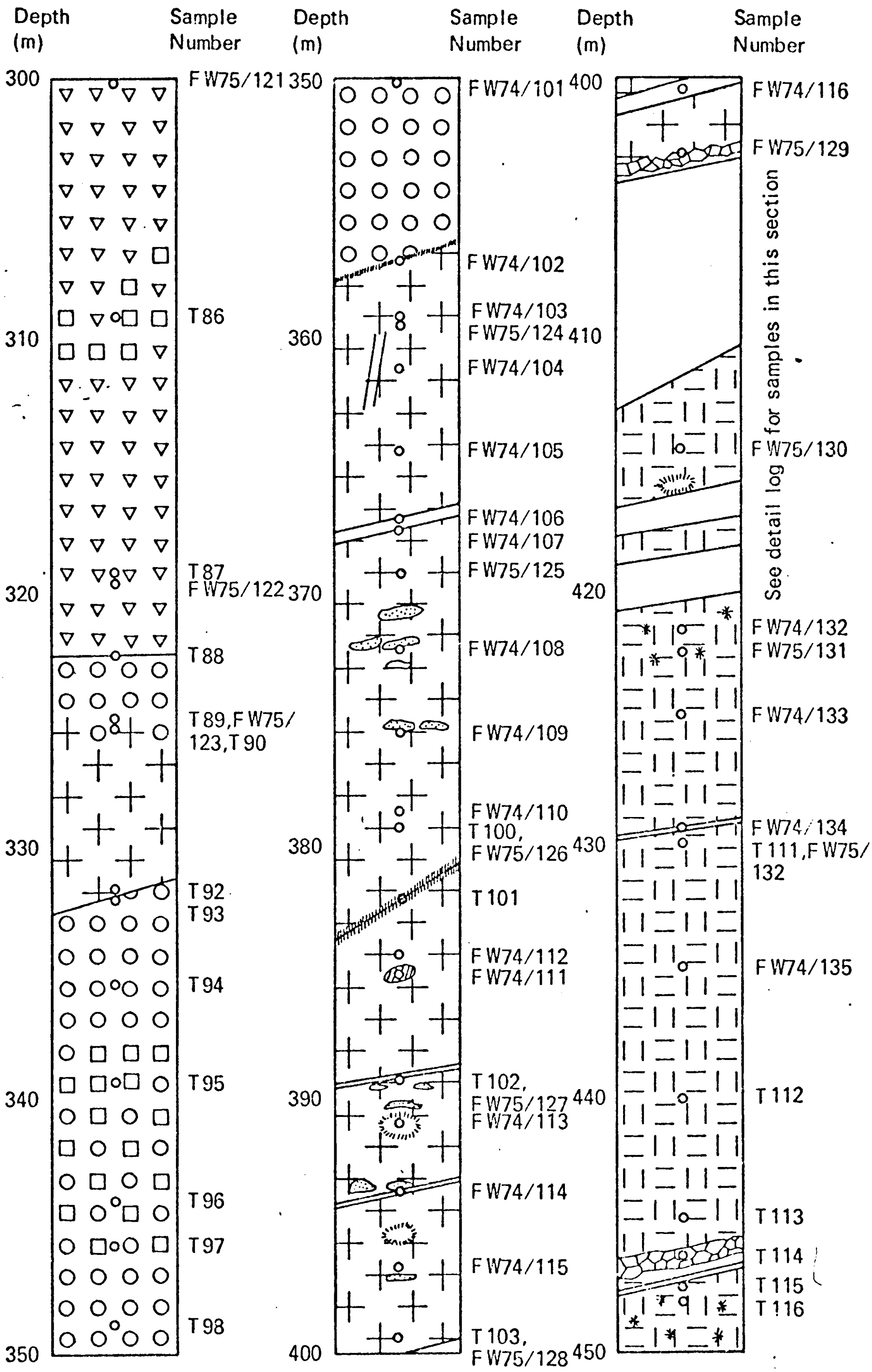
Joint and fracture traces

Inclusion of basic rock, large and small mottle

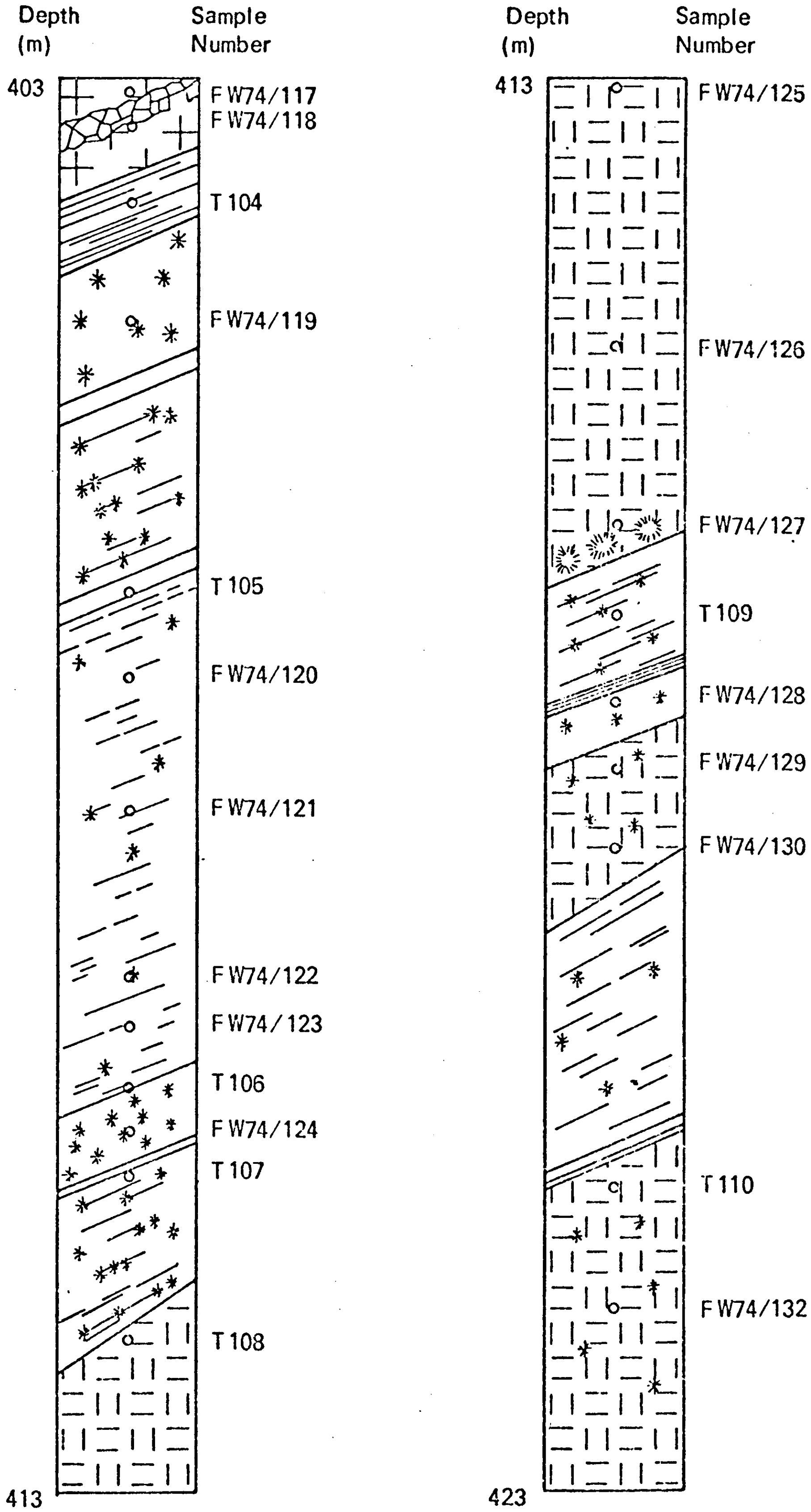
Pegmatite


Depth (m)
Sample Number
Depth (m)
Sample Number
Depth (m)
Sample Number
0
10
20
30
40
50
T1
T2
T3
FW75/102
T4
T5,6
T7
T8
FW75/103
T9,10
T11,12
T13
T14
T15
FW75/104
T16
T17,18
T20
T21
50
60
70
80
90
100
T22
FW75/105
T23
T24
FW75/106
T25,26
T27
T28
T29
FW75/107
T30
T31,32
100
110
120
130
140
150
T33
FW75/108
T34
T35,36
T37
T38
T39
T40
FW75/109
T41
T42
T43,44
FW75/110
T45
T46
T47
T48
FW75/111


Depth (m)
Sample Number
150
T49
T50
160
FW75/112
T51
170
T52
FW75/113
T53,54
T55
T56
T57
180
T58
FW75/114
190
T59
T61
T62
200
Depth (m)
Sample Number
200
T63
FW75/115
T64
FW75/116
T65
210
T66
220
FW75/117
T67
230
T68
FW75/118
T68*
T69
240
T70
T71
FW75/119
250
Depth (m)
Sample Number
250
T72
T73
260
T74
T75
T76
T77
270
FW75/120
T78
T79
280
T80
T81
290
T82
T83
T84
T85
300


Depth (m)
Sample Number
300
310
320
330
340
350
F W75/121
T 86
T 87
F W75/122
T 88
T 89, F W75/ 123, T 90
T 92
T 93
T 94
T 95
T 96
T 97
T 98
Depth (m)
Sample Number
350
360
370
380
390
400
F W74/101
F W74/102
F W74/103
F W75/124
F W74/104
F W74/105
F W74/106
F W74/107
F W75/125
F W74/108
F W74/109
F W74/110
T 100,
F W75/126
T 101
F W74/112
F W74/111
T 102,
F W75/127
F W74/113
F W74/114
F W74/115
T 103,
F W75/128
Depth (m)
Sample Number
400
410
420
430
440
450
F W74/116
F W75/129
See detail log for samples in this section
F W75/130
F W74/132
F W75/131
F W74/133
F W74/134
T 111, F W75/ 132
F W74/135
T 112
T 113
T 114
T 115
T 116

Bore-hole BK1. Detail log of section from 403 to 423 m.



APPENDIX 2. RESULTS OF CHEMICAL ANALYSES

Analysts: National Institute for Metallurgy.

Methods: X-ray fluorescence:

SiO_2, Al_2O_3, Fe_2O , MgO, CaO, K_2O, TiO_2, P_2O_5, MnO, BaO, ZrO_2, Sn, Rb_2O and SrO

Atomic absorbtion spectroscopy:

Co and Zn

Volumetric:

FeO

Gravimetric:

CO_2, H_2O+, and H_2O-

Colorimetric:

F

LOCALITY AND MAP REFERENCE OF ANALYSED SPECIMENS

PART 1. Veekraal granite.

Specimen number	Map reference	Farm name
A75	H6	Veekraal 221JQ
A77	G6	Veekraal 221JQ
A79	G5	Klipplaat 217JQ
A81	G4	Syferkuil 208JQ
A87	G5	Waterval 220JQ
A112	G4	Tinnie 218JQ
A132	H5	Rietgat 224JQ
A133	H6	Elba 223JQ
A147	Outside area shown on map	
FW173A	A4	Klipfontein 60JQ
FW190	A4	Buffelsfontein 85JQ
FW199A	A4	Buffelsfontein 85JQ
A231	C2	Rhenosterspruit 28JQ
A232	C2	Rhenosterspruit 28JQ
A233	C2	Vygeboomspruit 29JQ
FW248A	B5	Zwartbank 121JQ
FW215	B5	Rietspruit 83JQ
A250	D3	Legkraal 68JQ
A252	D3	Zandsloot 71JQ
A255	C3	Legkraal 68JQ
A256	C3	Zeekoegat 67JQ
FW256	B6	Bierkraal 120JQ
FW261	B6	Bierkraal 120JQ
A310	C1	Makayskraal 18JQ
FW317	D5	Schietfontein 130JQ
FW347	A4	Klipfontein 60JQ
FW350	A4	Klipfontein 60JQ
FW354	A4	Klipfontein 60JQ
FW433	D5	Klipplaat 129JQ
FW470	Outside area shown on map	

PART 2. Beestkraal granophyre

Specimen number	Map reference	Farm name
FW22	E6	Welgevonden 202JQ
FW31	E5	Yzerfontein 31JQ
FW68	G6	Hartebeestpoort C 419JQ
FW144	E6	Beestkraal 199JQ
FW196	A5	Buffelsfontein 85JQ
FW313	D5	Welgevonden 131JQ

PART 3. Zwartbank pseudogranophyre

Specimen number	Map reference	Farm name
FW72	F6	Zanddrift 212JQ
FW73	F6	Zanddrift 212JQ
FW297	C5	Zandfontein 124JQ
FW388	C4	Klipplaat 77JQ
FW416	D5	Klipkopspruit 127JQ

PART 4. Metasediment

Specimen number	Map reference	Farm name
FW143	E5	Beestkraal 199JQ
FW258	B6	Bierkraal 120JQ
FW283	C5	Zandfontein 124JQ
FW295	C5	Zwartbank 121JQ
FW391	D4	Vaalkop 76JQ
FW422	D5	Klipplaat 129JQ
FW459A	C5	Klipkopspruit 127JQ
FW508	C6	Kafferskraal 133JQ

PART 1. CHEMICAL ANALYSES OF VEEKRAAL GRANITE

	A75	A77	A79	A81	A87	A112	A132	A133	A147
Major elements (percent)									
SiO_2	73.61	73.28	73.85	74.02	72.79	74.43	73.31	72.39	83.88
TiO_2	0.28	0.34	0.27	0.30	0.34	0.24	0.30	0.37	0.12
Al_2O_3	12.22	12.54	12.49	12.34	12.33	12.27	12.93	12.67	8.81
Fe_2O_3	0.46	0.68	0.84	0.91	0.99	0.84	0.75	0.76	0.43
FeO	2.13	2.61	2.28	2.43	2.49	2.04	2.10	3.00	0.16
MnO	0.04	0.06	0.05	0.05	0.04	0.04	0.04	0.06	0.00
MgO	0.29	0.30	0.05	0.08	0.15	0.20	0.06	0.19	0.03
CaO	1.30	1.31	1.00	1.05	1.15	0.89	1.04	1.24	0.19
Na_2O	3.54	3.31	3.40	3.37	3.89	4.04	3.83	3.25	3.21
K_2O	5.06	4.96	4.95	4.72	4.70	4.39	4.95	4.79	2.84
H_2O+	0.38	0.43	0.42	0.45	0.33	0.32	0.44	0.70	0.25
H_2O-	0.16	0.07	0.12	0.14	0.15	0.15	0.02	0.03	0.02
P_2O_5	0.04	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.02
CO_2	0.33	0.00	0.10	0.08	0.12	0.00	0.10	0.19	0.07
Total	99.84	99.84	99.94	99.92	99.96	99.84	99.94	100.03	99.91
Trace elements (ppm)									
Zr	315	351	312	340	356	301	309	356	87
Co	18	31	30	30	26	29	31	30	25
Ba	1099	1364	914	931	931	803	999	1308	417
Sr	57	118	54	53	49	36	58	79	21
F	410	350	880	800	550	80	350	530	25
Rb	42	44	52	46	43	37	49	43	24
Sn	5	5	5	5	5	5	5	5	5
Zn	31	83	49	46	32	19	26	63	12
CIPW Norm (excluding H_2O and others)									
Q	29.84	30.42	31.71	32.67	28.76	31.07	28.84	30.29	53.87
Or	29.97	29.38	29.34	27.97	27.85	26.00	29.33	28.38	16.82
Ab	29.95	28.00	28.76	28.51	32.91	34.18	32.40	27.49	27.15
An	2.51	4.76	4.22	4.62	2.30	2.39	3.49	5.89	0.93
Di	3.25	1.43	0.12	0.00	2.63	1.73	1.27	0.00	0.00
Hy	2.21	3.80	3.20	3.51	2.28	2.34	2.30	4.86	0.07
Mt	0.66	0.98	1.21	1.31	1.43	1.21	1.08	1.10	0.17
Il	0.53	0.64	0.51	0.56	0.64	0.45	0.56	0.70	0.22
Total	98.92	99.41	99.07	99.15	98.80	99.37	99.27	98.71	99.23
Mesonorm (Barth)									
Mt	0.49	0.73	0.90	0.94	1.06	0.89	0.80	0.79	0.37
Ti	0.60	0.73	0.56	0.62	0.73	0.51	0.64	0.78	0.25
Ap	0.10	0.12	0.09	0.12	0.12	0.10	0.12	0.12	0.05
Or	30.58	26.40	26.53	24.95	27.81	24.87	27.59	24.38	16.85
Ab	32.51	30.35	30.42	30.17	35.75	36.89	34.99	29.21	29.06
An	0.20	4.60	3.70	3.77	0.49	1.53	3.28	4.48	0.37
Q	28.14	30.77	33.43	34.55	27.45	30.11	28.35	33.38	52.54
Bi	0.00	5.66	4.20	4.55	0.99	2.41	3.47	6.32	0.11
C	0.00	0.00	0.19	0.33	0.00	0.00	0.00	0.54	0.40
Hy	7.12	0.64	0.00	0.00	5.60	2.69	0.76	0.00	0.00
Di	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.01	100.00	99.99	100.01	100.00	100.00	100.00	99.99	100.01

PART 1 Continued.

	FW173A	FW190	FW199A	A231	A232	A233	FW248A	FW215	A250
Major elements (percent)									
SiO_2	71.91	70.46	72.91	74.91	75.58	68.86	70.20	71.97	72.00
TiO_2	0.37	0.48	0.37	0.40	0.17	0.55	0.45	0.39	0.34
Al_2O_3	12.91	12.88	12.23	13.26	13.29	13.28	12.81	12.37	12.77
Fe_2O_3	1.13	1.32	0.97	0.43	0.48	2.58	1.13	1.33	2.19
FeO	2.77	3.72	3.06	0.96	0.22	3.27	3.98	3.11	1.79
MnO	0.12	0.12	0.10	0.05	0.02	0.08	0.12	0.08	0.10
MgO	0.16	0.03	0.26	0.32	0.38	0.21	0.24	0.28	0.32
CaO	1.16	1.52	1.25	1.17	0.32	1.65	1.50	1.27	0.74
Na_2O	3.20	3.31	3.09	6.35	4.92	3.11	3.32	2.93	3.21
K_2O	5.34	4.75	4.79	1.21	4.05	4.71	5.07	4.95	5.04
H_2O+	0.58	0.62	0.52	0.48	0.39	0.77	0.74	0.77	0.77
H_2O-	0.01	0.04	0.05	0.09	0.01	0.17	0.01	0.07	0.14
P_2O_5	0.05	0.06	0.05	0.08	0.03	0.11	0.05	0.06	0.05
CO_2	0.09	0.14	0.12	0.08	0.07	0.11	0.10	0.05	0.19
Total	99.80	99.94	99.92	99.88	99.87	99.91	99.90	99.85	99.99
Trace elements (ppm)									
Zr	398	554	398	441	74	515	520	422	375
Co	23	27	19	38	31	18	15	23	29
Ba	1685	2062	1749	513	1272	1949	1408	1644	1283
Sr	125	136	100	61	63	136	79	129	79
F	25	25	530	120	170	150	450	25	230
Rb	52	43	45	14	36	37	52	48	53
Sn	5	5	5	5	5	5	5	5	5
Zn	95	98	103	29	22	70	140	108	68
CIPW Norm (excluding H_2O and others)									
Q	28.45	27.53	31.69	30.38	30.12	27.50	25.79	30.95	31.44
Or	31.64	28.14	28.38	7.17	24.05	27.90	30.05	29.33	29.87
Ab	27.07	28.00	26.14	53.72	41.62	26.31	28.09	24.79	27.15
An	5.17	6.36	5.44	4.13	1.68	8.07	5.11	6.07	3.62
Di	0.72	1.30	0.56	1.07	0.00	0.00	1.89	0.33	0.00
Hy	3.79	4.57	4.75	1.11	0.94	3.64	5.31	4.64	1.90
Mt	1.63	1.91	1.40	0.62	0.29	3.74	1.63	1.92	3.17
Il	0.70	0.91	0.70	0.75	0.32	1.04	0.85	0.74	0.64
Total	99.17	98.72	99.06	98.95	99.02	98.20	98.72	98.77	97.79
Mesonorm (Barth)									
Mt	1.18	1.39	1.06	0.44	0.49	2.72	1.22	1.40	2.31
Ti	0.77	1.01	0.82	0.82	0.35	1.15	0.97	0.82	0.71
Ap	0.12	0.14	0.12	0.18	0.07	0.26	0.12	0.14	0.12
Or	28.05	23.87	25.44	5.23	22.62	24.71	26.06	25.39	28.11
Ab	28.66	29.83	24.07	55.64	43.40	28.14	30.70	26.44	29.01
An	4.06	5.41	4.76	3.70	0.74	5.54	4.32	4.50	2.12
Q	31.24	31.19	36.46	31.08	30.32	31.02	27.20	34.27	33.08
Bi	5.50	6.84	6.92	2.79	1.42	5.34	7.67	6.42	3.07
C	0.41	0.35	0.35	0.13	0.58	1.19	0.00	0.61	1.40
Hy	0.00	0.00	0.00	0.00	0.00	0.00	1.24	0.00	0.00
Di	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.99	100.02	100.00	100.00	100.00	100.00	100.00	100.00	100.00

PART 1 Continued.

	A252	A255	A256	FW256	FW261	A310	FW317	FW347	FW350
Major elements (percent)									
SiO_2	75.31	76.65	75.37	74.00	71.95	67.16	68.27	72.44	70.80
TiO_2	0.21	0.26	0.26	0.38	0.35	0.56	0.59	0.35	0.43
Al_2O_3	12.08	12.89	12.16	11.30	12.75	12.94	13.01	12.56	12.52
Fe_2O_3	1.48	0.41	0.53	0.96	0.68	2.50	1.63	0.67	2.92
FeO	0.72	0.26	1.60	2.96	3.11	3.04	4.70	3.18	1.74
MnO	0.03	0.02	0.04	0.09	0.10	0.11	0.13	0.08	0.07
MgO	0.26	0.21	0.25	0.26	0.18	0.24	0.23	0.05	0.42
CaO	0.24	0.37	0.77	1.23	1.28	2.11	1.87	1.40	1.09
Na_2O	3.19	5.72	3.44	3.24	3.32	3.30	3.26	3.47	1.90
K_2O	5.31	2.57	4.70	4.73	5.20	4.05	4.65	4.76	6.01
H_2O+	0.72	0.29	0.50	0.57	0.51	1.17	0.94	0.55	1.28
H_2O-	0.14	0.16	0.11	0.01	0.03	0.21	0.03	0.01	0.06
P_2O_5	0.02	0.05	0.03	0.03	0.03	0.10	0.11	0.04	0.04
CO_2	0.09	0.00	0.00	0.00	0.08	2.15	0.36	0.07	0.45
Total	99.80	99.80	99.80	99.80	99.88	101.95	100.16	99.87	100.25
Trace elements (ppm)									
Zr	288	304	263	458	444	491	534	417	48
Co	21	43	0	26	34	26	24	31	27
Ba	670	605	1085	2038	1524	1965	1565	1829	2279
Sr	22	26	57	111	79	143	100	122	186
F	1100	25	370	550	500	750	550	390	25
Rb	48	27	46	54	53	37	51	49	59
Sn	5	5	5	5	5	5	5	5	5
Zn	47	47	60	98	106	112	112	88	110
CIPW Norm (excluding H_2O and others)									
Q	35.78	32.46	34.37	32.86	27.90	26.78	24.68	29.18	33.44
Or	31.46	15.23	27.85	28.04	30.82	23.99	27.56	28.21	35.62
Ab	26.99	48.39	29.10	27.41	28.09	27.92	27.58	29.35	16.07
An	0.44	1.69	3.71	2.34	4.57	8.63	7.19	4.67	5.91
Di	0.00	0.00	0.00	3.36	1.51	1.16	1.35	2.07	0.00
Hy	0.64	0.52	2.77	3.13	4.43	2.80	6.42	3.91	1.25
Mt	1.81	0.16	0.76	1.39	0.98	3.62	2.36	0.97	4.23
Il	0.22	0.29	0.49	0.72	0.66	1.06	1.12	0.66	0.81
Total	97.34	98.74	99.05	99.25	98.96	95.96	98.26	99.02	97.33
Mesonorm (Barth)									
Mt	1.56	0.42	0.55	1.03	0.73	2.68	1.71	0.72	3.12
Ti	0.44	0.53	0.54	0.82	0.75	1.20	1.23	0.75	0.91
Ap	0.05	0.12	0.07	0.07	0.07	0.24	0.26	0.10	0.10
Or	30.88	14.32	26.04	27.71	27.77	21.28	21.76	25.90	34.67
Ab	28.84	50.42	30.51	29.93	30.60	30.37	29.40	31.99	17.44
An	0.30	0.53	2.65	0.10	4.28	7.93	6.39	3.97	3.58
Q	35.72	32.17	35.41	31.79	28.64	30.77	29.57	29.42	35.70
Bi	1.14	0.95	3.77	1.68	6.04	5.20	9.36	4.77	2.63
C	1.07	0.54	0.46	0.00	0.00	0.33	0.31	0.00	1.75
Hy	0.00	0.00	0.00	6.36	1.12	0.00	0.00	2.38	0.00
Di	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	99.99	100.00	100.00	100.00	100.00	99.99

PART 1 Continued.

	FW354	FW433	FW470
Major elements (percent)			
SiO_2	71.33	72.17	74.48
TiO_2	0.39	0.38	0.27
Al_2O_3	12.54	12.06	12.17
Fe_2O_3	3.18	2.80	0.89
FeO	1.45	0.65	2.21
MnO	0.10	0.11	0.04
MgO	0.32	0.40	0.00
CaO	0.99	1.05	0.92
Na_2O	2.80	3.12	3.60
K_2O	4.92	5.56	4.80
H_2O+	0.97	0.94	0.41
H_2O-	0.22	0.01	0.01
P_2O_5	0.00	0.07	0.03
CO_2	0.00	0.74	0.08
Total	99.21	99.95	99.29
Trace elements (ppm)			
Zr	0	269	378
Co	25	30	33
Ba	1853	1172	1107
Sr	197	25	58
F	190	25	240
Rb	46	41	61
Sn	5	5	5
Zn	117	38	93
CIPW Norm (excluding H_2O and others)			
Q	33.53	30.48	32.14
Or	29.15	32.93	28.47
Ab	23.69	26.39	30.45
An	5.05	2.49	2.88
Di	0.00	1.96	1.50
Hy	0.79	0.10	2.17
Mt	3.87	1.36	1.29
Il	0.74	0.72	0.51
Total	96.82	96.43	99.41
Mesonorm (Barth)			
Mt	3.38	1.52	0.95
Ti	0.83	0.80	0.58
Ap	0.00	0.16	0.07
Or	28.66	32.05	27.23
Ab	25.56	28.24	33.02
An	3.61	3.26	2.41
Q	35.06	31.60	31.38
Bi	1.45	1.71	2.78
C	1.45	0.65	0.00
Hy	0.00	0.00	1.58
Di	0.00	0.00	0.00
Total	100.00	100.00	100.00

PART 2. BEESTKRAAL GRANOPHYRE

	FW22	FW31	FW68	FW144	FW196	FW313
Major elements (percent)						
SiO_2	74.09	74.01	73.57	73.84	75.09	76.07
TiO_2	0.22	0.21	0.23	0.21	0.30	0.21
Al_2O_3	11.77	12.12	11.77	11.93	12.09	10.67
Fe_2O_3	1.88	1.49	3.07	2.25	0.75	2.28
FeO	1.33	1.40	0.40	1.30	1.51	0.38
MnO	0.06	0.08	0.02	0.08	0.03	0.06
MgO	0.04	0.21	0.11	0.09	0.11	0.16
CaO	1.02	0.53	0.21	0.64	1.26	0.34
Na_2O	3.52	3.08	3.59	3.04	5.32	2.43
K_2O	5.13	5.21	5.49	5.34	2.30	5.79
H_2O+	0.15	0.84	0.49	0.82	0.53	0.73
H_2O-	0.09	0.11	0.09	0.11	0.06	0.07
P_2O_5	0.04	0.02	0.04	0.02	0.02	0.21
CO_2	0.12	0.19	0.22	0.21	0.14	0.10
Total	99.46	99.65	99.68	99.67	99.64	99.60
Trace elements (ppm)						
Zr	352	369	335	346	398	330
Co	10	21	16	29	26	34
Ba	1155	1059	1188	112	434	1300
Sr	63	58	42	59	95	41
F	600	10	10	450	1140	300
Rb	53	48	49	51	17	51
Sn	43	14	20	4	13	18
Zn	73	82	25	77	34	102
CIPW Norm (excluding H_2O and others)						
Q	32.29	34.04	31.41	34.15	32.67	39.22
Or	30.40	30.87	32.53	31.64	13.62	34.30
Ab	29.78	26.05	29.91	25.72	45.01	20.55
An	1.14	2.84	0.00	2.78	2.32	0.57
Di	1.44	0.00	0.64	0.00	2.74	0.00
Hy	0.00	1.66	0.00	0.56	0.57	0.39
Mt	2.72	2.15	0.69	3.26	1.08	0.82
Il	0.41	0.39	0.43	0.39	0.56	0.39
Total	98.18	98.00	95.61	98.50	98.57	96.24
Mesonorm (Barth)						
Mt	2.02	1.57	0.08	2.37	0.80	0.90
Ti	0.47	0.44	0.49	0.44	0.64	0.45
Ap	0.10	0.05	0.10	0.05	0.05	0.50
Or	31.09	29.58	32.77	31.14	13.82	34.39
Ab	32.42	27.96	32.84	27.53	48.56	22.22
An	1.20	1.76	0.00	2.30	1.45	0.00
Q	30.66	35.31	31.80	34.72	30.47	39.34
Bi	0.00	2.47	0.45	1.10	0.00	0.72
C	0.00	0.86	1.46	0.34	0.00	1.47
Hy	0.00	0.00	0.00	0.00	2.73	0.00
Di	1.96	0.00	0.00	0.00	1.49	0.00
Total	99.92	100.00	100.00	100.00	100.01	100.00

PART 3. ZWARTBANK PSEUDOGRANOPHYRE AND POIKILOGRANITE

	FW72	FW73	FW297	FW388	FW416
Major elements (percent)					
SiO_2	73.78	74.28	73.77	72.21	73.54
TiO_2	0.25	0.22	0.20	0.30	0.22
Al_2O_3	11.59	11.92	11.74	11.71	11.81
Fe_2O_3	2.12	2.33	1.38	0.90	2.09
FeO	1.43	0.98	2.19	2.95	0.92
MnO	0.05	0.04	0.08	0.07	0.09
MgO	0.26	0.07	0.12	0.14	0.16
CaO	0.42	0.43	0.95	1.75	0.64
Na_2O	3.28	3.29	3.12	3.41	2.84
K_2O	5.31	5.33	5.12	5.17	5.74
H_2O+	0.59	0.43	0.68	0.65	0.84
H_2O-	0.23	0.11	0.12	0.08	0.11
P_2O_5	0.05	0.02	0.02	0.03	0.03
CO_2	0.14	0.10	0.01	0.29	0.47
Total	99.50	99.60	99.51	99.79	99.97
Trace elements (ppm)					
Zr	347	388	332	318	308
Co	10	8	26	23	26
Ba	1067	1131	1075	1123	1316
Sr	31	54	57	58	62
F	900	850	800	600	450
Rb	44	50	49	44	59
Sn	15	11	4	19	4
Zn	53	105	171	74	58
CIPW Norm (excluding H_2O and others)					
Q	33.10	33.83	32.99	28.25	33.54
Or	31.45	31.58	30.34	30.63	34.02
Ab	27.75	27.83	26.39	28.85	24.02
An	1.23	1.73	2.92	1.36	2.56
Di	0.16	0.00	1.25	6.23	0.40
Hy	1.12	0.17	2.36	1.42	0.21
Mt	3.07	2.65	2.00	1.30	2.63
Il	0.47	0.41	0.37	0.56	0.41
Total	98.35	98.20	98.62	98.60	97.79
Mesonorm (Barth)					
Mt	2.24	2.29	1.49	0.97	2.17
Ti	0.53	0.46	0.43	0.65	0.47
Ap	0.12	0.05	0.05	0.07	0.07
Or	30.44	31.50	30.08	31.39	33.94
Ab	29.79	29.74	28.94	31.45	25.88
An	0.83	1.22	2.03	0.00	2.20
Q	33.82	33.96	32.15	26.67	34.31
Bi	2.06	0.34	1.88	0.00	0.79
C	0.17	0.43	0.00	0.00	0.18
Hy	0.00	0.00	2.95	5.22	0.00
Di	0.00	0.00	0.00	3.49	0.00
Total	100.00	100.00	100.00	100.00	100.00

PART 4. METASEDIMENTARY ROCKS

	FW143	FW258	FW283	FW295	FW391	FW422	FW459A	FW508
Major elements (percent)								
SiO_2	96.28	61.19	61.79	63.04	58.35	76.37	90.34	75.31
TiO_2	0.08	0.74	0.13	0.23	0.70	0.39	0.11	0.31
Al_2O_3	1.84	17.67	10.43	14.67	15.43	12.72	4.61	11.77
Fe_2O_3	0.04	4.08	1.52	1.43	0.96	0.24	0.02	1.17
FeO	0.14	4.10	4.46	3.31	5.78	0.26	0.17	0.68
MnO	0.01	0.20	0.19	0.09	0.08	0.02	0.02	0.04
MgO	0.06	2.61	6.16	2.46	5.04	0.09	0.40	0.60
CaO	0.04	1.57	6.61	2.25	2.38	1.19	0.55	0.89
Na_2O	0.08	1.07	2.33	2.46	5.59	5.47	1.87	3.11
K_2O	0.79	3.29	4.95	8.23	2.86	2.37	1.33	3.99
H_2O+	0.26	2.82	0.85	1.16	0.99	0.33	0.31	0.79
H_2O-	0.01	0.11	0.12	0.16	0.04	0.14	0.08	0.12
P_2O_5	0.01	0.13	0.04	0.05	0.02	0.03	0.02	0.18
CO_2	0.10	0.08	0.16	0.06	0.46	0.10	0.01	0.26
Total	99.74	99.82	99.90	99.80	100.20	99.84	99.75	100.00
Trace elements (ppm)								
Zr	178	188	201	149	145	315	118	157
Co	29	42	13	16	18	42	29	29
Ba	115	890	674	827	173	207	185	1733
Sr	5	135	39	69	45	133	47	190
F	10	10	1850	400	7500	10	570	10
Rb	12	44	41	78	91	12	9	26
Sn	4	4	4	4	4	12	14	4
Zn	3	108	47	61	119	30	36	41
CIPW Norm (excluding H_2O and others)								
Q	92.55	33.80	9.32	8.01	0.56	33.37	73.14	39.41
Or	4.69	19.51	29.32	48.77	17.05	14.02	7.87	23.62
Ab	0.67	6.05	19.71	20.81	47.29	46.28	15.82	26.31
An	0.16	7.26	3.35	4.65	6.26	3.16	0.25	3.81
Di	0.00	0.00	22.68	5.09	0.00	0.48	1.59	0.00
Hy	0.26	9.81	11.47	8.33	21.36	0.00	0.40	1.49
Mt	0.05	5.91	2.20	2.07	1.39	0.00	0.02	1.43
Il	0.15	1.40	0.24	0.43	1.32	0.60	0.20	0.58
Total	98.53	83.74	98.29	98.16	95.23	97.91	99.29	96.65
Mesonorm (Barth)								
Mt	0.05	4.42	1.51	1.52	1.00	0.25	0.02	1.24
Ti	0.18	1.60	0.26	0.49	1.46	0.82	0.24	0.65
Ap	0.03	0.32	0.09	0.12	0.05	0.07	0.05	0.43
Or	4.62	10.63	27.00	47.11	0.00	14.11	8.27	22.25
Ab	0.76	9.96	19.95	22.40	50.00	49.49	17.52	28.30
An	0.00	4.34	0.00	0.00	7.91	3.14	0.00	1.95
Q	92.86	41.23	7.98	8.75	9.21	31.08	71.09	40.72
Bi	0.52	15.25	0.00	3.52	28.34	0.00	0.00	2.65
C	0.99	12.24	0.00	0.00	0.00	0.00	0.00	1.81
Hy	0.00	0.00	27.83	16.09	1.92	0.14	1.61	0.00
Di	0.00	0.00	14.43	0.00	0.00	0.89	1.20	0.00
Total	100.00	100.00	100.00	100.00	100.00	99.99	100.00	100.00

PART 5. CHEMICAL ANALYSES AND NORMS OF SAMPLES FROM BOREHOLE BK1

	PW75/102	103	104	105	106	107	108	109	110
Major elements (percent)									
SiO_2	73.95	71.96	74.40	72.23	73.23	73.92	74.68	72.19	71.48
TiO_2	0.24	0.35	0.21	0.38	0.33	0.31	0.24	0.38	0.39
Al_2O_3	11.83	12.62	11.90	12.38	12.30	11.85	12.05	12.56	12.62
Fe_2O_3	0.92	0.66	0.62	0.96	0.32	0.62	0.66	0.67	0.74
FeO	2.62	3.75	2.82	3.34	3.61	3.10	2.38	3.76	4.03
MnO	0.06	0.08	0.07	0.09	0.08	0.06	0.04	0.09	0.12
MgO	0.05	0.08	0.02	0.08	0.04	0.05	0.09	0.05	0.08
CaO	0.99	1.38	0.98	1.37	1.28	1.14	0.95	1.43	1.52
Na_2O	3.46	3.32	3.39	3.25	3.37	3.54	3.48	3.35	3.38
K_2O	4.71	4.87	4.85	4.69	4.67	4.53	4.39	4.59	4.69
H_2O+	0.61	0.38	0.43	0.58	0.47	0.52	0.45	0.44	0.56
H_2O-	0.04	0.04	0.03	0.07	0.03	0.05	0.03	0.06	0.05
P_2O_5	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.03
CO_2	0.00	0.19	0.00	0.19	0.12	0.00	0.18	0.07	0.11
Total	99.50	99.69	99.50	99.69	99.62	99.50	99.68	99.57	99.61
CIPW Norm (excluding H_2O and others)									
Q	32.35	28.64	32.40	30.45	30.64	31.89	33.93	29.66	28.09
Or	27.83	28.78	28.66	27.72	27.60	26.77	25.94	27.12	27.72
Ab	29.27	28.09	28.68	27.49	28.51	29.95	29.44	28.34	28.59
An	2.84	5.15	2.93	5.34	4.64	3.06	4.29	5.68	5.41
Di	1.72	1.32	1.60	1.11	1.34	2.12	0.25	1.08	1.71
Hy	2.97	5.40	3.64	4.48	5.35	3.77	3.59	5.44	5.65
Mt	1.33	0.95	0.89	1.39	0.46	0.89	0.95	0.97	1.07
Il	0.45	0.66	0.39	0.72	0.62	0.58	0.45	0.72	0.74
Total	98.76	98.99	99.19	98.70	99.16	99.03	98.89	99.01	98.98
Mesonorm (Barth)									
Mt	0.99	0.71	0.66	1.01	0.34	0.67	0.69	0.70	0.80
Ti	0.52	0.75	0.45	0.80	0.71	0.66	0.50	0.80	0.84
Ap	0.05	0.07	0.05	0.07	0.07	0.07	0.05	0.07	0.07
Or	27.00	25.02	27.30	23.69	23.95	25.28	22.98	22.36	23.97
Ab	31.98	30.63	31.20	25.56	31.04	32.62	31.23	29.99	31.21
An	1.81	5.05	1.94	5.25	4.44	1.84	3.72	5.52	5.02
Q	31.68	29.75	31.87	33.43	31.50	31.42	35.87	33.02	29.20
Bi	2.64	7.28	3.33	6.50	6.97	3.51	4.72	7.50	7.25
C	0.00	0.00	0.00	0.04	0.00	0.00	0.23	0.06	0.00
Hy	3.33	0.74	3.20	0.00	0.99	3.92	0.00	0.00	1.65
Di	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.01	99.99	100.00	100.00	100.01

PART 5 Continued

	PW75/111	112	113	114	115	116	117	118	119
Major elements (percent)									
SiO_2	74.15	72.19	74.54	74.39	73.54	71.30	74.42	76.00	73.19
TiO_2	0.23	0.38	0.23	0.24	0.30	0.43	0.23	0.17	0.33
Al_2O_3	11.91	12.31	11.81	11.79	11.86	12.66	11.84	11.77	12.10
Fe_2O_3	0.62	0.83	0.49	1.06	0.61	0.63	0.31	0.48	0.55
FeO	2.82	3.76	3.03	2.45	3.18	4.18	2.75	2.16	3.61
MnO	0.06	0.10	0.07	0.06	0.08	0.10	0.06	0.05	0.09
MgO	0.02	0.03	0.06	0.05	0.05	0.13	0.29	0.08	0.05
CaO	1.00	1.39	0.92	1.03	1.19	1.43	1.09	0.69	1.20
Na_2O	3.57	3.53	3.23	3.45	3.48	3.25	3.16	3.21	3.47
K_2O	4.69	4.62	4.71	4.71	4.66	4.76	4.54	4.86	4.63
H_2O+	0.48	0.57	0.48	0.56	0.35	0.64	0.84	0.44	0.43
H_2O-	0.04	0.07	0.02	0.06	0.05	0.08	0.05	0.03	0.05
P_2O_5	0.02	0.03	0.02	0.02	0.03	0.03	0.02	0.01	0.03
CO_2	0.08	0.11	0.15	0.00	0.22	0.09	0.07	0.00	0.15
Total	99.69	99.80	99.84	99.69	99.91	99.78	99.76	99.69	99.84
CIPW Norm (excluding H_2O and others)									
Q	31.78	28.96	33.61	33.02	31.23	28.19	34.00	35.61	30.51
Or	27.72	27.30	27.83	27.83	27.54	28.13	26.83	28.72	27.36
Ab	30.20	29.86	27.32	29.19	29.44	27.49	26.73	27.15	29.35
An	2.62	4.10	3.81	2.77	2.98	5.90	4.71	3.35	3.76
Di	1.96	2.31	0.54	1.95	2.42	0.88	0.48	0.00	1.76
Hy	3.40	4.62	4.76	2.42	3.82	6.48	4.99	3.58	4.98
Mt	0.89	1.20	0.71	1.53	0.88	0.91	0.44	0.69	0.79
Il	0.43	0.72	0.43	0.45	0.56	0.81	0.43	0.32	0.62
Total	99.00	99.07	99.01	99.16	98.87	98.79	98.61	99.42	99.13
Mesonorm (Barth)									
Mt	0.66	0.89	0.52	1.14	0.66	0.66	0.32	0.49	0.59
Ti	0.49	0.82	0.48	0.51	0.64	0.90	0.48	0.35	0.71
Ap	0.05	0.07	0.05	0.05	0.07	0.07	0.05	0.02	0.07
Or	26.82	25.03	24.00	27.57	26.49	22.66	22.61	25.91	24.46
Ab	32.88	32.55	29.03	31.77	32.13	29.17	28.92	28.75	31.95
An	1.28	2.94	3.61	1.47	1.38	5.36	4.43	2.75	3.05
Q	31.00	29.09	36.04	31.79	30.64	32.22	36.53	37.07	30.95
Bi	2.57	4.81	6.18	1.56	2.93	8.74	6.55	4.41	5.76
C	0.00	0.00	0.09	0.00	0.00	0.21	0.11	0.24	0.00
Hy	4.24	3.81	0.00	4.13	5.07	0.00	0.00	0.00	2.46
Di	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.99	100.01	100.00	99.99	100.01	100.00	100.00	100.00	100.00

PART 5 Continued

	FW75/120	121	122	123	124	125	126	127	128
Major elements (percent)									
SiO_2	71.79	74.12	74.27	74.48	66.55	66.34	64.13	63.44	60.21
TiO_2	0.45	0.23	0.24	0.28	0.66	0.73	0.80	0.83	0.97
Al_2O_3	12.67	12.17	12.03	11.98	13.98	13.63	14.03	14.43	15.46
Fe_2O_3	1.04	0.31	0.85	0.76	1.18	0.70	0.86	0.89	1.13
FeO	3.48	2.17	2.17	2.28	5.98	6.89	7.85	8.35	9.42
MnO	0.12	0.07	0.07	0.05	0.15	0.17	0.18	0.20	0.24
MgO	0.24	0.25	0.22	0.15	0.26	0.05	0.05	0.07	0.08
CaO	1.12	0.89	0.90	0.95	2.54	2.76	3.49	3.78	4.50
Na_2O	3.33	3.18	3.18	3.42	3.57	3.76	3.92	4.28	3.84
K_2O	4.33	4.72	4.80	4.49	3.88	3.91	3.42	2.77	2.93
H_2O+	0.92	0.88	0.79	0.56	0.89	0.64	0.72	0.51	0.69
H_2O-	0.05	0.03	0.04	0.06	0.03	0.05	0.07	0.03	0.03
P_2O_5	0.04	0.02	0.03	0.02	0.06	0.08	0.08	0.11	0.12
CO_2	0.11	0.19	0.18	0.14	0.12	0.08	0.08	0.15	0.10
Total	99.69	99.88	99.87	99.83	99.81	99.77	99.77	99.84	99.79
CIPW Norm (excluding H_2O and others)									
Q	30.91	33.93	33.85	33.85	21.41	19.59	16.45	15.16	11.43
Or	25.59	27.89	28.37	26.53	22.93	23.11	20.21	16.37	17.31
Ab	28.17	26.90	26.90	28.93	30.20	31.81	33.16	36.21	32.48
An	5.29	4.28	4.26	4.07	10.66	8.76	10.59	11.98	16.29
Di	0.00	0.00	0.00	0.44	1.36	3.91	5.52	5.38	4.66
Hy	5.60	3.68	3.56	3.33	9.12	9.22	9.90	10.91	12.93
Mt	1.50	1.17	1.23	1.10	1.71	1.01	1.24	1.29	1.63
Il	0.85	0.43	0.45	0.53	1.25	1.38	1.51	1.57	1.84
Total	97.91	98.28	98.62	98.78	98.64	98.79	98.58	98.87	98.57
Mesonorm (Barth)									
Mt	1.09	0.85	0.90	0.80					
Ti	0.94	0.49	0.51	0.58					
Ap	0.09	0.05	0.07	0.05					
Or	21.12	24.99	25.55	23.65					
Ab	30.08	28.68	28.65	30.74					
An	3.70	3.48	3.41	3.59					
Q	34.29	36.03	35.86	35.72					
Bi	7.40	4.82	4.66	4.66					
C	1.27	0.61	0.40	0.20					
Hy	0.00	0.00	0.00	0.00					
Di	0.00	0.00	0.00	0.00					
Total	100.00	100.00	100.00	100.00					

THE MESONORM IS NOT SHOWN FOR THE SAMPLES BEYOND FW75/123, AS THESE ROCKS ARE BASIC AND THE MESONORM IS NOT USED IN THIS THESIS

PART 5 Continued

	FW75/129	130	131	132	133	134	135	136	137
Major elements (percent)									
SiO_2	57.65	50.22	46.89	45.68	53.35	49.57	46.12	45.97	40.20
TiO_2	1.21	1.58	1.92	2.23	0.64	1.49	1.90	1.93	2.84
Al_2O_3	14.55	11.51	11.66	11.35	17.14	11.16	13.08	12.46	11.55
Fe_2O_3	1.51	1.61	1.22	1.53	1.04	1.08	1.64	1.58	3.10
FeO	12.57	20.08	21.24	22.11	12.25	21.90	22.11	22.18	22.69
MnO	0.27	0.41	0.40	0.37	0.31	0.45	0.46	0.41	0.36
MgO	0.08	0.25	0.62	2.26	0.23	0.44	0.64	1.67	4.17
CaO	6.05	8.51	8.59	8.39	7.97	8.97	9.53	8.78	9.13
Na_2O	4.39	3.05	2.89	2.89	3.73	2.81	2.86	2.92	2.34
K_2O	0.61	1.04	0.84	0.83	1.26	0.78	0.74	0.61	0.39
H_2O+	0.76	0.90	0.69	0.80	1.37	0.90	0.14	0.51	0.75
H_2O-	0.02	0.05	0.06	0.03	0.05	0.02	0.05	0.02	0.06
P_2O_5	0.12	0.37	0.56	0.92	0.19	0.31	0.50	0.60	1.94
CO_2	0.07	0.19	0.21	0.22	0.21	0.06	0.00	0.19	0.24
Total	99.86	100.05	100.07	100.08	100.07	99.92	99.86	100.05	100.10
CIPW Norm (excluding H_2O and others)									
Q	10.15	1.01	2.87	0.00	0.00	0.00	0.00	0.00	0.00
Or	3.60	6.14	7.44	4.96	4.90	4.61	4.37	3.60	2.30
Ab	37.14	25.80	31.55	24.45	24.45	23.77	24.19	24.70	19.79
An	18.20	14.64	26.30	16.36	15.54	15.53	20.67	19.09	19.86
Di	9.82	22.36	10.64	20.00	17.50	23.90	20.67	18.02	10.97
Hy	15.32	22.45	16.14	25.62	10.59	25.61	5.48	8.83	5.26
Mt	2.18	2.33	1.50	1.76	2.21	1.56	2.37	2.29	4.49
Il	2.29	3.00	1.21	3.64	4.23	2.82	3.60	3.66	5.37
Ol	0.00	0.00	0.00	0.95	16.96	0.39	17.03	17.50	26.12
HAp	0.28	0.87	0.44	1.32	2.17	0.73	1.17	1.41	4.57
Total	98.98	98.60	98.09	99.07	98.55	98.92	99.55	99.10	98.73