A PETROCHEMICAL INVESTIGATION OF THE SPITSKOP ALKALINE COMPLEX, EASTERN TRANSVAAL

by

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ABSTRACT

This study comprises a petrographical and mineralogical description of the rocks of the Spitskop Complex. Data on the chemical composition of the rock types and also on some of the minerals are presented.

The complex consists of a pyroxenite pipe near the perimeter of which is situated a composite ring-dyke of foyaite. Ijolite is present as dykes and sills in the pyroxenite and the carbonatite as a plug which is intrusive into the pyroxenite. The complex is surrounded by an aureole of umptekite, and xenoliths of gabbroic rocks and magnetitite are present in the complex. A plug and sill of latite inside the complex and dykes and cone sheets of latite and trachyte in the country rocks were encountered.

Profiles of eight core boreholes which were drilled to a depth of between 30 and 40 m into the complex, thirty two rock analyses, fifteen mineral analyses and variation diagrams of the chemistry of the clinopyroxenes are presented.

The borehole profiles indicate that the ijolite is intrusive into the pyroxenite in the form of sills and dykes. This feature is further confirmed by the nature of the outcrops to the west of the carbonatite.

The foyaite is subdivided into porphyritic, hypidiomorphic and trachytoidal textural varieties and the ijolite into hypidiomorphic and porphyritic varieties.

The chemical variation diagrams indicate that the clinopyroxenes of the alkaline rocks follow differentiation trends which are normal for alkaline complexes, whereas the trends of the clinopyroxenes of the theralites are similar to those usually found in layered intrusions.

From the geochemistry the following order of emplacement may be derived: pyroxenite - ijolite - foyaite, in cases where a low CO_2 pressure prevailed in the magma, and pyroxenite - ijolite - carbonatite in cases of a high CO_2 pressure.

The Upper Zone of the layered sequence of the Bushveld Complex is postulated as the source of the theralites, which are here interpreted as being xenoliths in the Spitskop Alkaline Complex, and a vertical displacement thereof of not more than a few hundreds of metres is suggested.

SAMEVATTING

Hierdie studie behels 'n petrografiese en mineralogiese beskrywing van die Spitskopkompleks. Gegewens oor die chemiese samestelling van die rotstipes asook van sommige van di minerale word aangebied.

Die kompleks bestaan uit 'n piroksenietpyp met 'n saamgestelde foyaietkringgang wat naby die buitenste rand daarvan geleë is. Ijoliet is teenwoordig as gange en plate in die piroksieniet en die karbonatiet as 'n intrusiewe prop in die piroksieniet. Die kompleks word omring deur 'n oureool van umptekiet en xenoliete van gabbroïese gesteentes en van magnetiet kom voor in die kompleks. 'n Latietprop en -plaat in die kompleks en gange en tregtergange van latiet en tragiet in die omringende gesteentes is opgemerk.

Profiele van agt kernboorgate met 'n diepte van tussen 30 en 40 m elk, twee en dertig gesteenteanalises, vyftien mineraalanalises en variasiediagramme van die chemie van die klinopiroksene word aangebied.

Die boorgatprofiele dui daarop dat die ijoliet intrusief is in die piroksieniet en dat dit daarin teenwoordig is as plate en gange. Hierdie kenmerk word bevestig deur die voorkoms van dagsome ten weste van die karbonatiet.

Die fojaiet word op grond van tekstuur onderverdeel in die porfiritiese, hipidiomorfe en porfiritiese tipes.

Die chemiese variasiediagramme toon dat die klinopiroksene van die alkaliese gesteentes differensiasieneigings volg wat ooreenstem met dié van alkaliese komplekse terwyl die klinopiroksene van die teraliete daarenteen neigings

volg wat normaalweg in gelaagde komplekse voorkom.

Van die geochemie kan die volgende inplasingsvolgorde afgelei word: In gevalle waar 'n lae CO_2 druk in die magma geheers het: pirokseniet - ijoliet - fojaiet, en pirokseniet - ijoliet - karbonatiet in gevalle mat 'n hoë CO_2 druk.

Die Bosone van die gelaagde opeenvolging van die Bosveldkompleks word as die bron van die teraliete, wat hier as xenoliete in die Spitskop Alkaliese Kompleks beskou word, voorgestel, en 'n vertikale verplasing van hoogstens 'n paar honderd meter word daarvoor gepostuleer.

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I. INTRODUCTION

A. General

The Spitskop Alkaline Complex is situated about 10 km south-east of the village Nebo in the Eastern Transvaal.

In the latter half of 1973 the Geological Survey carried out a core-drilling program in the Spitskop Complex during which eight holes were drilled. The holes had an average depth of about 35m and were drilled along two traverses at approximately right angles to each other and striking roughly east-west and north-south respectively (Map 1). The purpose of the drilling program was to test the possible nepheline reserves, which is of strategic importance because of the aluminium content of the mineral. During this time outcrop samples were also collected and the accuracy of existing maps of the complex was checked.

The maps of Strauss and Truter (1950) and of Verwoerd (1967, p30), were found to be correct as far as the contacts between the different rock units are concerned. Remapping of the complex was therefore considered to be unnecessary. At some places, however, the data obtained from the fieldwork and the drilling necessitated modifications to the existing maps. Map 1 (folder) is based on the maps mentioned above, and on a map compiled by Dr B.B. Hambleton-Jones of the Atomic Energy Board.

B. Previous work

The Spitskop Complex was discovered by Hall (1910), and in the same year Brouwer (1910) published a short petrographic description of some of the specimens collected by Hall. Shand (1921) published the first detailed description of the complex. He came to the conclusion that the carbonatite is a xenolith of the Transvaal Dolomite and that the foyaitic rocks are derivatives of the granitic or noritic magma of the Bushveld Complex which has been desilicified by reaction with the limestone or dolomite at depth.

Daly (1928, p766) concluded that the complex is younger than the Bushveld Complex and that it is therefore not related to the intrusion of the complex.

Hall (1932, p438) published a summary of the alkaline complexes of the Transvaal in which he concluded that the Spitskop alkaline rocks were not part of the igneous cycle of the Bushveld Complex and that the carbonatite was probably derived from the Transvaal System (Hall, 1932, p444-445).

Strauss and Truter (1950) carried out an excellent field and petrographic study of the complex. Some of their more important conclusions were:

(1) A magmatic origin was postulated for the carbonatite whereas Shand, Daly and Hall considered it to be xenolithic.

(2) The fayalite diorite and the theralites were regarded as fenites although the possibility of a magmatic origin of these rocks was not excluded (Strauss and Truter, 1950, p98).

(3) The central part of the complex, i.e., the part inside the umptekite and theralite, was regarded as consisting of ijolite with minor inclusions and intrusions of foyaite, carbonatite and pyroxenite (Strauss and Truter, 1950, p99), and was indicated as such on their generalised geological map (Strauss and Truter, 1950, p120).

Verwoerd (1964, 1966, 1967) suggested that the fayalite diorite and the other theralitic varieties resulted from the fenitisation of xenoliths of Bushveld gabbro (Verwoerd, 1967, p29). He also subdivided the carbonatite into the following compositional varieties: beforsite, sövite, and an intermediate variety, dolomitic sövite (Verwoerd, 1967, p29). He suggested a Late-Karoo age for the complex, based on similarities with the Shawa and Dorowa carbonatite complexes.

C. Techniques of investigation

Apart from ordinary microscopy in reflected and transmitted light, X-ray diffraction methods using iron filtered Co Kα radiation on a vertical goniometer, were used for mineral identification.

The mineral analyses were done on the JEOL automated electron microprobe of the Geological Survey. Pure oxide standards, developed by the laboratory of the Geological Survey, were used and the analyses were corrected by means of the Bence Albee correction procedures for inter-elemental effects (Bence and Albee, 1968). The standard error of the mineral analyses is estimated to be not more than about 5 per cent.

The rock analyses were supervised by the National Institute of Mineralogy. The major element analyses were done by General Superintendence Co. Limited of Johannesburg while the trace element analyses were done by the Geochemistry Department of the University of Cape Town. All elements were determined by X-ray fluorescence measurements except FeO, which was done volumetrically, and H_2O^-, H_2O^+ and CO_2 which were done gravimetrically. The calculation of the norms and the structural formulae were done by means of standard programmes used by the Geological Survey, and were run on an IBM 1470 and a PDP 8E computer.

D. Nomenclature

As the terminology of the alkaline rocks is not generally well known, a short review of the classification of the alkaline plutonic rocks, as proposed by the Subcommission on the Systematics of Igneous Rocks of the International Union of Geological Sciences (Streckeisen, 1974), is given here.

1. Plutonic rocks

As in the previous classification of the I.U.G.S. (Streckeisen, 1967), the classification is based on the QAPF double triangle (Fig. 1).

According to this classification the alkaline rocks are defined as those rocks which contain feldspathoids and/or alkali pyroxenes and/or alkali amphiboles (Streckeisen, 1974, p777).

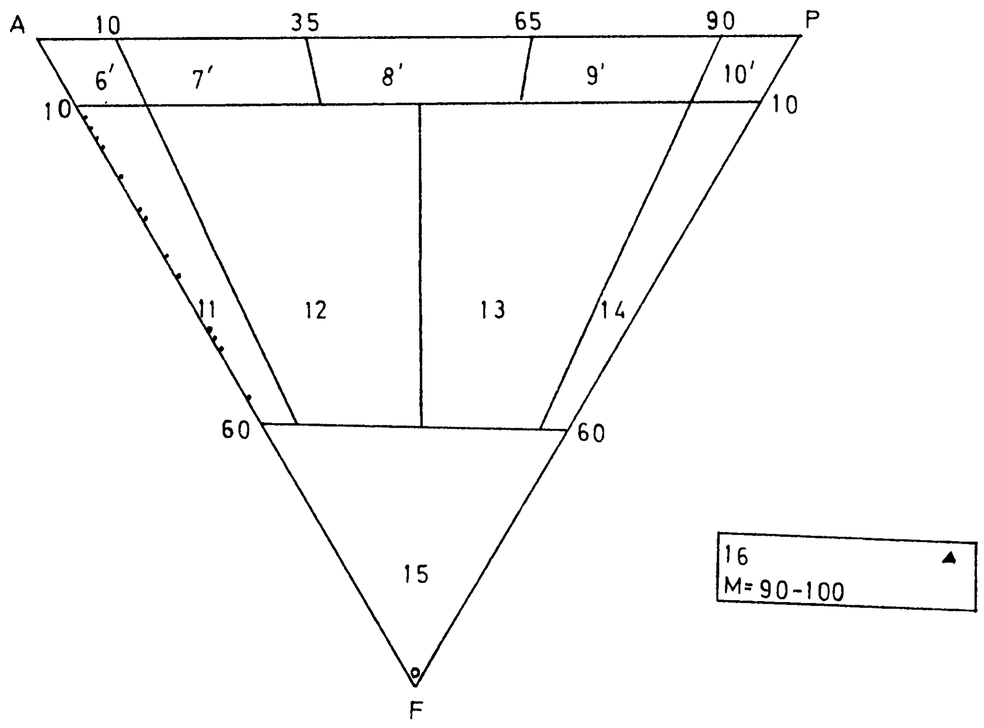
The alkaline rocks are represented in the APF triangle, which is subdivided into ten fields, from 6' to 15 (Streckeisen, 1974 and Fig. 1) and each of these fields is given a root name.

These root names are then modified to fit the specific rock. Thus, the root name of field II, "foid syenite" may be modified to nepheline syenite or even aegirine nepheline syenite depending on the feldspathoid and/or mafic constituents present.

Each of the fields in the triangle is subdivided further according to the mafic mineral content of the rocks and the prefix leuco- or mela-is used.

For field 15, that of the foidolites, special names are applied according to the nature of the feldspathoids, the mafic minerals, and the colour index. Thus the rocks containing no feldspar, but only nepheline and dark minerals,

Figure 1.- The classification of foid-bearing plutonic rocks (Streckeisen, 1974). Also indicated are some Spitskop alkaline rocks



6'	foid-bearing alkali-feldspar syenite
7'	foid-bearing syenite
8'	foid-bearing monzonite
9'	foid-bearing monzodiorite/monzogabbro
10'	foid-bearing diorite/gabbro
11	foid syenite
12	foid monzosyenite (≡ foid plagisyenite)
13	foid monzodiorite/monzogabbro (Both ≡ Essexite)
14	foid diorite (≡ Theralite)
15	foidolites
16	ultramafic rocks (ultramafitites)

▲ pyroxenite
● foyaite
○ ijolite

Spitskop alkaline rocks

for instance, may be named nepheline-foidolite or in the case of the Spitskop ijolites, nepheline-aegerine-foidolites, and are then subdivided as follows on the basis of the dark mineral content:

Dark mineral content	Name
0 to 30 per cent	urtite
30 to 70 per cent	ijolite
70 to 90 per cent	melteigite

In the same way the rocks of field 11, the foid syenites, are subdivided as follows:

Dark mineral content	Name
0 to 30 per cent	foid syenite
30 to 60 per cent	malignite
60 to 90 per cent	shonkinite

It is evident from Fig. 1 that rocks with less than 90 per cent mafic minerals (M) are classified on the basis of their felsic minerals, whereas rocks with M = 90 to 100 are classified on the basis of their mafic minerals.

It is therefore clear that the modal composition of rocks must be known to apply this classification.

The term 'foyaite', as used by Strauss and Truter (1950) for rocks consisting of feldspar, nepheline and clinopyroxene, is retained here rather than 'foid syenite', or the more specific 'nepheline syenite'. There are two reasons for this: to avoid a multitude of rock names as far as the Spitskop Complex is concerned, and to simplify the descriptive rock names. It is felt that the term 'hypidiomorphic foyaite' is less cumbersome than 'hypidiomorphic nepheline syenite', suggested by Streckeisen (1974, p778). The textural term 'trachytoidal' is used in this study for the texture in which the feldspar laths exhibit preferred orientation. This will prevent confusion between the term 'foyaite texture', which is sometimes used for the abovementioned texture, and 'foyaite' which is used here as a rock name. For the same reasons the term ijolite is retained when referring to the nepheline foidolites as a group, except in the chapter on the petrography, where the term nepheline foidolite is used to avoid confusion.

The terminology used for the gabbroic rocks is the same as that used by Molyneux (1974, p329-338) in describing the rocks of the layered sequence of the Bushveld Complex.

As nepheline present in the "theralites" (Strauss and Truter, 1950) is not considered to be primary constituent, the term 'gabbroic rocks' will rather be used for these rocks.

2. Hypabyssal rocks

To simplify the terminology of the hypabyssal rocks present at Spitskop, i.e. the rocks occurring as plugs, dykes and cone sheets, it was decided to adopt the nomenclature proposed by Streckeisen (1974, p161 and p181-191) for the volcanic rocks which is based on the QAPF double triangle, as is the case of the plutonic rocks.

Because of the small grain size of the Spitskop hypabyssal rocks, the C.I,P.W. normative minerals (Table IX) were used in the application of the classification. It was found that with the exception of one of the rocks, a trachyte, all the hypabyssal rocks may be classified as latite.

II. GENERAL GEOLOGY

A. Introduction

The Spitskop Alkaline Complex is situated near the eastern escarpment of the Pokwani Plateau and is intrusive into the granite and granophyre of the Bushveld Complex.

The complex is to a large extent covered by alluvium and outcrops are usually confined to stream beds and to a few isolated hills. The contacts between the different rocks are poorly exposed because of the alluvium cover and also because of the extreme weathering of most of the rocks.

B. Field relationships

1. The xenolithic rocks

The gabbroic rocks and the magnetite breccia are considered to be xenoliths of gabbro, diorite, anorthosite and magnetite which were transported upwards from the layered sequence to their present position in the alkaline complex.

The gabbroic rocks, three major types of which were encountered during the investigation, occur at various places within the Spitskop Complex. The contacts between the different types, and also their contacts with the alkaline rocks, are nowhere clearly exposed and their mutual relationships had to be inferred.

Strauss and Truter (1950, p94) could not find a sharp contact between the gabbroic rocks and the white fenitised granite east of Eenzaamkop (H5 on the accompanying map), and they proposed a gradual transition between these two rock types. Owing to poor exposures the present author failed to locate either a sharp or a transitional contact.

The isolated occurence of gabbroic rocks in the south-eastern part of the complex (D7) seems to indicate a xenolithic origin for these rocks. At this locality the gabbro seems to be present as dyke-like body between foyaite dykes, although the exact relationship between these two rock types could not be established. It is noteworthly that no fenitised granite is present near this exposure of gabbroic rocks and the gabbro can therefore not grade into fenitised granite.

Gabbroic rocks were also encountered in borehole 5 (E8 Map 1 and Fig. 2). The presence of such rocks in this borehole indicates the extension of the body from south of Spitskop (F8) westwards (E8 Map 1). The possibility does exist, however, that the gabbro in borehole 5 is not part of the gabbro at Spitskop.

2. The Bushveld country rocks

According to Strauss and Truter (1950,p85) the Spitskop Complex is intrusive into Bushveld main granite and Bushveld granophyre. The granophyre is present as inclusions in the granite and is cut by numerous dykes and apophyses of the latter. Leptite was also described by Strauss and Truter (1950, p85) as occurring to the south of Spitskop (F9).

The country rocks and the alkaline rocks are always separated by a zone of fenitised granite.

3. The intrusive rocks

a. Pyroxenite

The largest part of the complex consists of pyroxenite which is present as a pipe-like body into which the foyaite and the ijolite seem to be intrusive.

The mineralogical composition of the pyroxenite varies at different localities and sporadic enrichments in biotite, apatite and magnetite are present. Examples of such enrichments are the biotite-rich pyroxenites in Rietfontein Spruit (D5 and E5) and in the south-western part of the complex (D7). These enrichments are very sporadic, as is evident from the fact that the biotite-pyroxenite was not encountered in borehole 3, which lies in the biotite-pyroxenite body postulated by Strauss and Truter (1950).

The pyroxenite weathers to a crumbly greenish aggregate in which only biotite can normally be identified megascopically. The contacts between the pyroxenite and the ijolite are usually sharply defined and may be attributed to the relatively high resistance of ijolite to weathering. In Rietfontein Spruit (E5) the soft pyroxenite is criss-crossed by dykes and sills of ijolite and the ijolite forms protruding ledges enclosing blocks of weathered pyroxenite. The same feature seems to be present in boreholes 3, 4, 6 and 7 (Fig. 2).

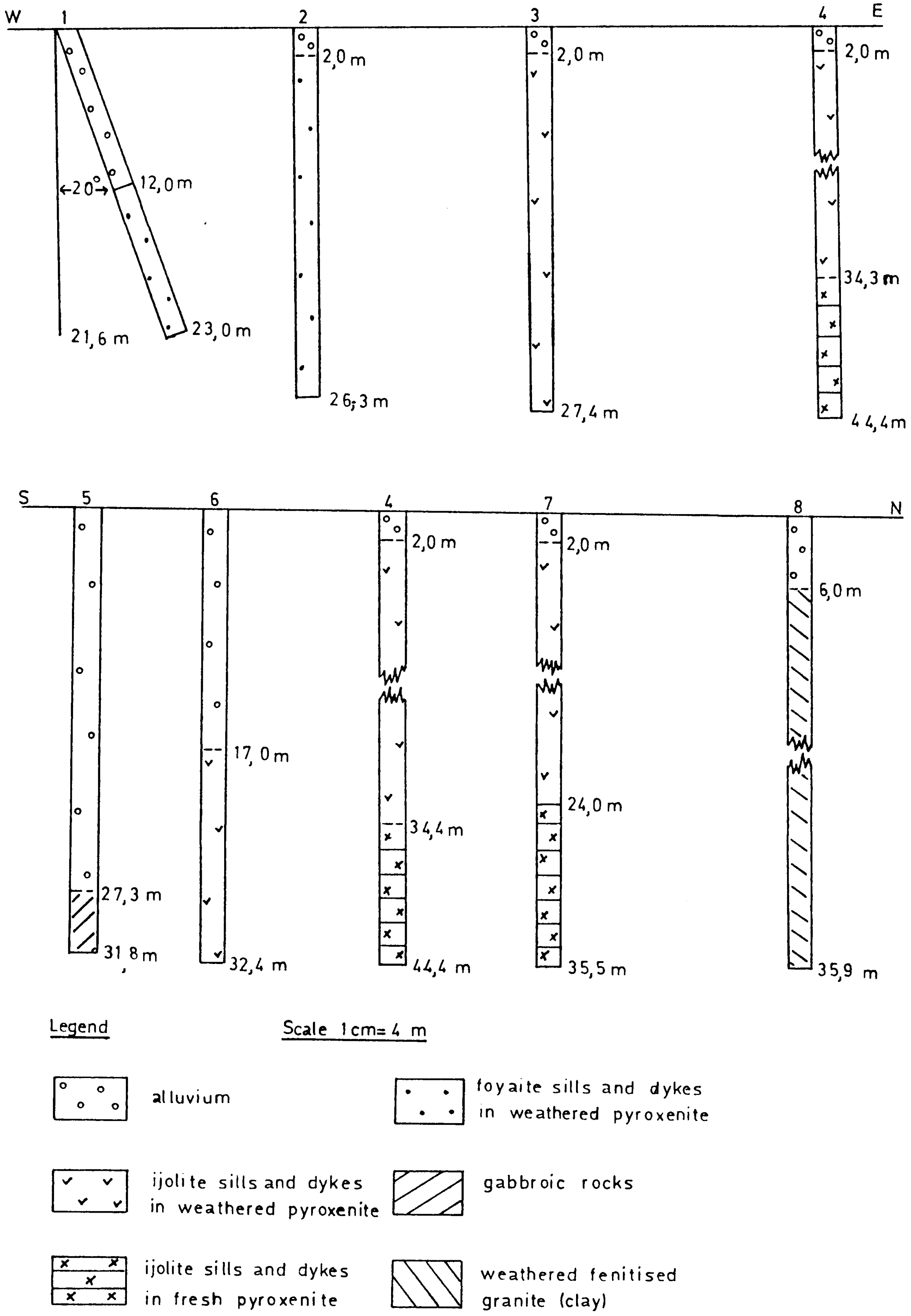
The contact between the pyroxenite and foyaite is not exposed, but the evidence from borehole 2 (Fig. 2) indicates the same relationship as that existing between the pyroxenite and the ijolite.

It is not clear whether the pyroxenite is in direct contact with the fenitised granite or not, as the contact between alkaline rocks and fenites is nowhere well exposed.

b. Foyaite

The foyaite is present as a composite ring-dyke around the central plug of pyroxenite. A pronounced thickening of the ring-dyke is evident around the carbonatite and in the vicinity of Spitskop and Eenzaamkop (F7,

Figure 2. Profiles of the boreholes drilled at Spitskop (1973 - 1974)



F8, G5, G6 and G7). This thickening has been interpreted as a subsidiary composite ring-dyke by Strauss and Truter (1950, p120). The interpretation is based on the foliation and dip of the foyaite in the area and is accepted as such in this study. On Map 1 the subsidiary foyaite ring-dyke is not distinguished as such for the reason of simplification.

Different textural varieties of foyaite were mapped by Strauss and Truter (1950), but it must be stressed that sharp contacts between the different varieties were not found during this investigation. It seems, however, that the ring-dyke consists of dykes of the different textural varieties which are intrusive into each other, and that it extends inwards into the pyroxenite in the form of sills and dykes, as indicated by the core from borehole 2 (Fig. 2).

Some large xenoliths of foyaite are present in the carbonatite (G6 and G7) but the outcrops are poor and the only signs of their presence are loose boulders.

c. Ijolite

Ijolite was encountered as dykes and sills in the pyroxenite at most of the localities indicated on Map 1. Exceptions to this are those to the east of the carbonatite (H7), in Spitskop (F8) and in Eenzaamkop (G6).

Verwoerd (1967, Folder 3) shows one inclusion consisting mainly of ijolite in the carbonatite. He mentions the possibility (1967, p31) that others which have been designated as foyaite may contain poorly exposed ijolite as well. The carbonatite is the youngest member of the complex, but some doubt remains about the age relationships of the ijolite and foyaite. The description of foyaite "enclosing big blocks and slabs of ijolite" (Verwoerd, 1967, p28) was apparently based on the map by Strauss and Truter (1950). This should be viewed with caution because much of what is now known to be underlain by pyroxenite was previously interpreted as ijolite. The possibility that the ijolite is intrusive into the foyaite of Spitskop (F8) and Eenzaamkop (G6) can therefore not be excluded.

Ijolite outcrops are present in most of the streams in the central and western parts of the complex. However, no convincing evidence could be found for the "central mass" of ijolite indicated by Strauss and Truter (1950, p99 and Fig. 3) in the central and western parts. The boreholes drilled in the area underlain by the so-called "central mass" of ijolite (boreholes 4, 6 and 7 in Fig. 2) all indicate a bulk composition of about 20 to 40 per cent ijolite and 60 to 80 per cent pyroxenite.

The ijolite which occurs to the east of the carbonatite (H6 and H7) has been interpreted as being nephelinised theralite (Verwoerd, 1967, p27) because of the presence of the magnetite breccia in the ijolite. However, the field evidence suggests that the magnetite is a xenolith which was brecciated by the intrusion of the ijolite or during its emplacement in the alkaline complex. Pyroxenite was not seen in this area but because of the alluvium cover its absence cannot be assumed.

It is not feasible to map the different textural varieties of the ijolite separately. The reason for this is that the ijolite is present as sills and dykes which intersect each other in many different directions and the different textural varieties can grade into each other in the same dyke or sill. Two or more varieties may even be present in one hand-specimen.

d. Carbonatite

In a comprehensive study Verwoerd (1967) distinguished four varieties of carbonatite at Spitskop. He mapped these separately and also made a radiometrical survey of the carbonatite. However, in the present investigation it was found that the contacts between these varieties are not always clearly recognisable on a weathered surface.

The carbonatite body is shaped like a plug and is situated to the south-east of the centre of the alkaline complex. In their geological cross-section Strauss and Truter (1950, Plate XXIII) indicated a central core of unexposed ijolite in the carbonatite, but no evidence of this could be found during the present investigation.

Intrusive contacts between the carbonatite and the surrounding alkaline rocks are characterised by apophyses penetrating the latter rocks. Good examples can be seen at the foot of Eenzaamkop (F6).

The carbonatite is generally well exposed but it is difficult to collect fresh samples owing to the deep weathering of the rocks and the absence of sharp projections on the outcrop surface.

4. The hypabyssal rocks

The fine-grained rocks, present as plugs and as dykes and cone sheets, are included under the term hypabyssal. They are apparently of later age than the rest of the alkaline rocks and occur for most part outside the Spitskop Complex proper, the exception being the latite plug and some agglomerate outcrops.

a. Latite and trachytic rocks

Latite and trachytic rocks are present in the form of cone sheets and radial dykes in the country rocks and fenitised country rocks surrounding the alkaline complex. The cone sheets and radial dykes are usually less than one metre thick and have sharp contacts with their host rocks. They have a brownish colour in hand specimen and exhibit a high degree of weathering. According to Strauss and Truter (1950, p108) the dips of the cone sheets increase from 15 degrees some distance away from the complex to from 70 to 80 degrees near the complex.

Two outcrops of latite are indicated on Map 1 (H6) inside the Alkaline Complex. The western one seems to be of plug shape, whereas the eastern one is apparently a sheet- or sill-like intrusion. Although both are indicated as being situated in ijolite, the exact relationships with the surrounding ijolite could not be determined because of the alluvium cover.

b. Agglomerate

Agglomerate was observed at three localities at Spitskop, two of which are situated inside the alkaline complex and one outside.

The agglomerate outside the complex (D10) is intrusive into the Bushveld granite and is plug-shaped. The one occurrence inside the complex is in the form of a dyke (G4). The other is situated to the east of the latite sheet (H6) and is not indicated on Map 1 because the relationship with the surrounding rocks is not clear. It was, in fact, only recognised as being an agglomerate during subsequent microscopical investigation.

5. Fenitised country rocks

The fenitised country rocks are divided into two main types, viz. the red fenitised granite and the white fenitised granite.

The fenitised granites form an aureole around the Spitskop Complex and there is a pronounced thickening of the aureole in the east (16 and 17). When both types are present at one locality (D8 and 17), the white fenitised granite is situated between the alkaline rocks and the red fenitised granite, which is then in contact with the Bushveld granite and granophyre. In cases where the red fenitised granite is absent (G8, H5 and C5), the white variety is in direct contact with the country rocks. The contacts between the two types of fenitised granite, and also their contacts with the country rocks, are gradational and nowhere sharp.

The contacts between the fenitised granites and the alkaline rocks are usually poor or completely covered by alluvium, and although Strauss and Truter (1950) indicated sharp contacts at two places (G7 and C5), these could not be found.

III. PETROGRAPHY

A. The xenolithic rocks

A large number of different xenolithic rocks were described by Strauss and Truter (1950, p94) and by Verwoerd (1964, p219 and 1966, p302), but only four types were encountered during this investigation. These four types seem to include most of those described by the abovementioned authors, and are mottled anorthosite (Figure 3), which resembles the mottled anorthosite of the Bushveld Complex (Strauss and Truter, 1950, p95), magnetite diorite (Figure 4), olivine diorite (Figure 5) and a magnetite breccia, which was not previously included with the theralites.

Except fot the magnetite breccia, these rocks are coarse-grained and have cumulate textures (Table I). The major constituent of these rocks, again with the exception of the magnetite breccia which may be described as a monomineralic rock, is plagioclase (Table II). Preferred orientation of the plagioclase grains is a characteristic feature of the gabbroic rocks, but this varies from extreme in the mottled anorthosite to indistinct in the olivine diorite.

Varying amounts of clinopyroxene, magnetite and olivine are present as additional minerals in the gabbroic rocks. Nepheline, soda-amphibole and zeolites occur as alteration products.

A characteristic feature of the gabbroic rocks is the presence of aureoles around some of the minerals constituting them, e.g. magnetite, olivine and plagioclase. These aureoles have been interpreted as being alteration haloes caused by the fenitisation of the rocks (Verwoerd,

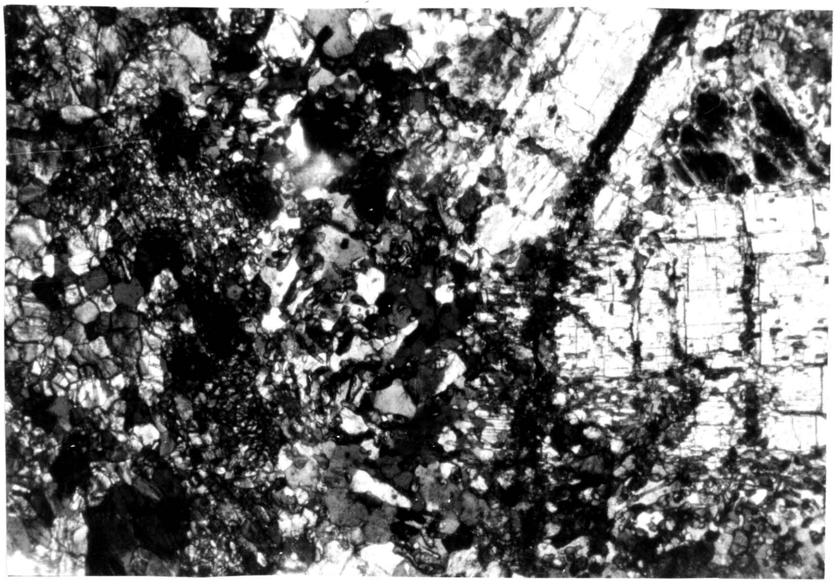


Figure 3. Mottled anorthosite: symplectitic texture and plagioclase; crossed nicols, x40.

Figure 4. Magnetite diorite, symplectitic texture around magnetite in plagioclase, crossed nicols, x40.

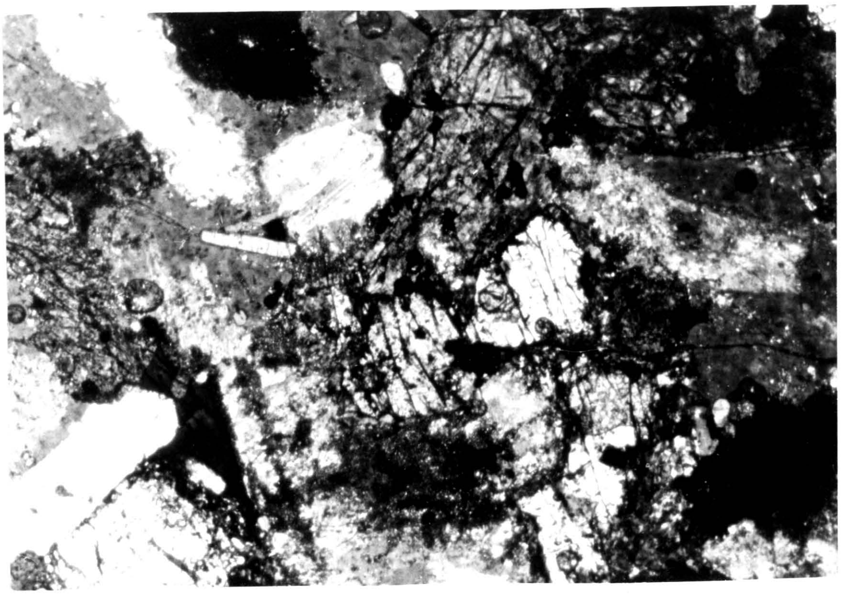


Figure 5. Olivine diorite, olivine (centre and apatite) surrounded by clinopyroxene and plagioclase crossed nicols, x40.

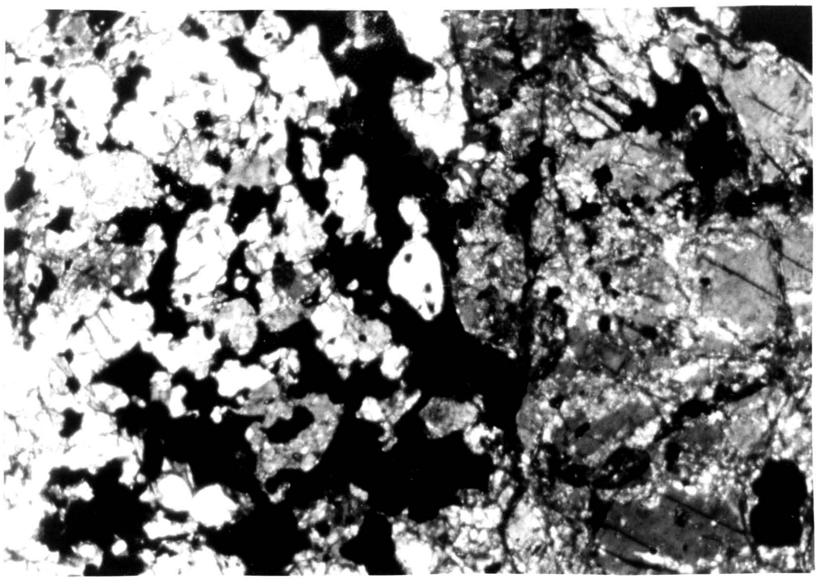


Figure 6. Pyroxenite consisting of clinopyroxene and magnetite grains; biotite surrounds magnetite, note layering (less magnetite to the right) crossed nicols, x40.

Table I. - Petrographic characteristics of the gabbroic rocks.

Rock variety:	Mottled anorthosite:	Magnetite diorite:	Olivine diorite:
Texture:	hypidiomorphic, symplectite at grain boundaries	hypidiomorphic, symplectite between magnetite and plagioclase	allotriomorphic
Plagioclase:	cumulus 2,5x0,5 mm An_{60}	cumulus 1,5-4,0x0,5-1,0 mm An_{40-55}	embayed variable grain size An_{50}
Clinopyroxene:	intercumulus variable grain size augite	intercumulus 1,0 mm ferro-augite	- variable grain size ferrohedenbergite
Magnetite:	-	intercumulus 1,0 mm	-
Olivine:	-	-	fayalite
Amphibole:	-	-	present

Table II. - The volumetric composition of the gabbroic rocks from the Spitskop Alkaline Complex.

Rock type: Sample No.:	Plagioclase:	Magnetite:	Clino-pyroxene:	Alteration products:	Amphibole:	Olivine:	Orthoclase:	Other:
Mottled anorthosite:								
DA99	30,92	-	2,17	66,91				
DA100	1,41	-	2,97	95,62				
Magnetite diorite:								
DA101	75,61	12,29	-	12,10				
DA121	80,26	4,91	7,07	7,76				
Olivine diorite:								
DA87	1,70	5,95	-	40,00	14,07	5,95	31,06	1,27

Note: Under alteration products all the mineral phases of the simplectitic haloes as well as the usual hydrothermal alteration products are included. In the case of DA87 the groundmass orthoclase, even though considered to be a metasomatic alteration product of plagioclase, is indicated separately.

1966, p304). However, exactly the same textures, even though the mineralogy may be slightly different, have been described in rocks of the Upper Zone of the layered sequence of the Bushveld Complex by Von Gruenewaldt (1971, p145), who called them "complex simplectitic textures".

Unfortunately the mineralogy of the simplectites could not be determined with the microprobe for the reason that the optical part of the instrument consisted only of reflected optics at the time of analyses. This made it nearly impossible to identify the various mineral phases in such a simplectite.

B. Bushveld country rocks

The acid country rocks into which the Spitskop Complex is intrusive are typical of the eastern part of the Bushveld Complex.

The granite consists of perthitic feldspar, quartz and mafic minerals and has a normal granitic texture, whereas the granophyre consists of the same minerals but displays typical graphic intergrowths of feldspar and quartz.

C. Intrusive rocks

1. Pyroxenite

The pyroxenite (Figure 6) is a melanocratic holocrystalline rock with a hypidiomorphic texture and consists of varying amounts of diopside, magnetite, apatite and biotite (Table III).

Table III. - The volumetric composition of the pyroxenite from the Spitskop Alkaline Complex.

Sample No.:	Clinopyroxene:	Biotite:	Apatite:	Magnetite:
DA98	81,1	5,7	0,3	12,9
DA113	67,7	11,7	tr.	20,6

The mineral grains constituting the pyroxenite can be subdivided into two groups on the basis of their grain sizes. The average diameter of one group of grains is about 3,5mm and that of the other is about 0,2mm. These two groups of minerals are present in separate, poorly defined layers which give a banded appearance to the rock. The bands are up to 5 mm thick and wedge out irregularly against each other. The banded structure of the pyroxenite is further enhanced by the fact that the fine-grained bands tend to contain more interstitial magnetite than the coarse-grained ones.

Alteration of the clinopyroxenes results in a schiller texture parallel to $\{010\}$ or to $\{100\}$ in the less altered grains, and to bleb-like intergrowths of chlorite and magnetite with no apparent orientation in the more altered grains.

Lamellar twinning along $\{100\}$, the lamellae of which are kinked in some grains, is common in the clinopyroxene.

Magnetite, apatite, biotite, ilmenite and pyrite are present in varying amounts and they all occur interstitially with respect to the clinopyroxene.

When both magnetite and biotite are present in an interstice, the biotite separates the magnetite from the clinopyroxene, which indicates that the biotite is later than the magnetite. Ilmenite and pyrite are also situated at the boundaries between the magnetite and the clinopyroxene. These minor minerals may, however, occasionally be the sole occupants of an interstice.

2. Foyaite

Three textural varieties of foyaite were recognised at Spitskop during the investigation, viz. trachytoidal (Figure 7), porphyritic (Figure 8) and hypidiomorphic (Figure 9).

Preferred orientation of feldspar laths is generally characteristic of the foyaite. Macroscopically it is pronounced in the porphyritic foyaite, less well developed in the trachytoidal, and nearly absent in the hypidiomorphic foyaite.

The foyaite is greenish in colour and varies from medium- to fine-grained for the trachytoidal variety, whereas the porphyritic and hypidiomorphic varieties are coarse grained. The petrography and volumetric compositions of the three varieties are compared in Tables IV and V.

The texture of the porphyritic and trachytoidal varieties is distinctly porphyritic, the only pronounced difference being in the grain size. In the former variety euhedral phenocrysts of alkali-feldspar are set in an equigranular groundmass of alkali-feldspar and nepheline, whereas in the latter variety alkali-feldspar laths form flow textures around nepheline phenocrysts. In both cases acicular clinopyroxene occupies the interstices between the feldspar and nepheline grains. The hypidiomorphic foyaite has a texture similar to that of the porphyritic variety except that the clinopyroxenes are usually present as squat laths rather than as needles, and that the phenocrysts, although larger than the groundmass feldspar grains, are sparsely developed.

Sphene, zircon, apatite, biotite, magnetite, plagioclase

Figure 7. Trachytoidal foyaite, feldspar laths showing flow texture around a nepheline phenocryst, crossed nicols, x40.

Figure 8. Porphyritic foyaite, perthitic feldspar laths with albite rims, intergranular nepheline, orthoclase and acicular clinopyroxene, crossed nicols, x40.

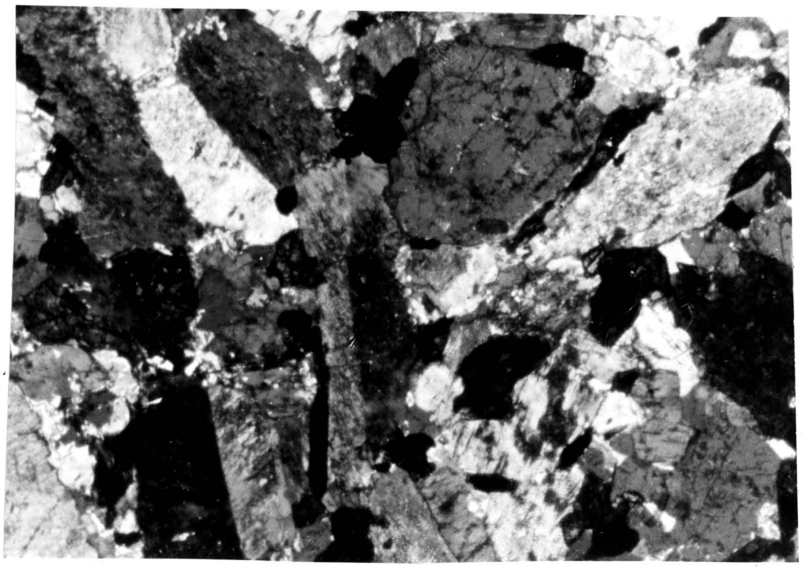


Figure 9. Hypidiomorphic foyaite, subhedral feldspar (perthitic), intergranular nepheline, orthoclase and clinopyroxene (squat), crossed nicols, x40.

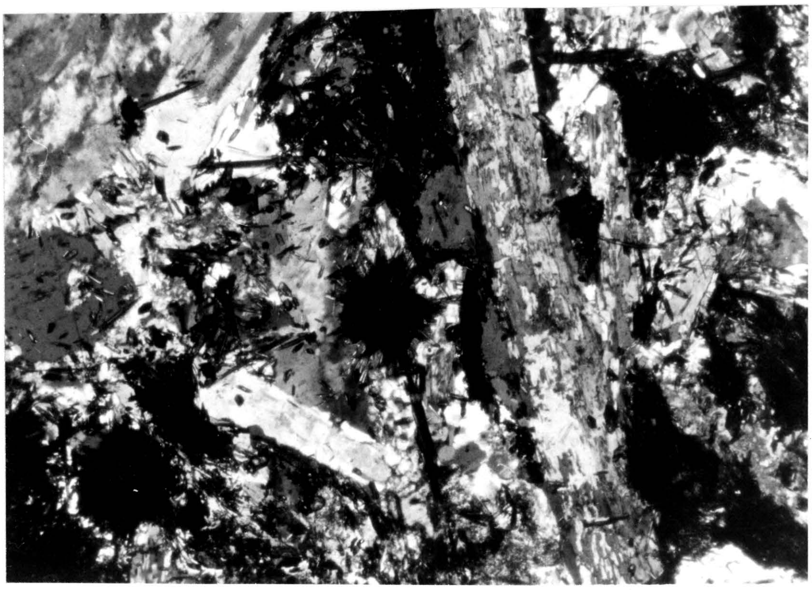


Figure 10 Clinopyroxene nodule (centre) in porphyritic foyaite, crossed nicols, x40.

Table IV. - Petrographic characteristics of the foyaite.

Textural variety:	Porphyritic:	Hypidiomorphic:	Trachytoidal:
A. Feldspar:			
1. Shape:	eu- to anhedral	sub- to anhedral	euhedral
2. Size (mm):	matrix: 0,5 phenocrysts: 4,0 x 1,0	0,5 x 2,5	1,0 x 0,15
3. Composition:	Or_{80} to Or_{96}	Or_{90} and Ab_{99}	-
4. Inclusions:	nepheline, clinopyroxene	clinopyroxene	-
5. Alteration products:	albite, sericite	sericite	-
6. Structure:	albite rims	twinned	twinned
B. Nepheline:			
1. Shape:	sub- to anhedral	sub- to anhedral	eu- to subhedral
2. Size (mm):	0,5	0,5	0,3 to 0,8
3. Composition:	$Ne_{79 - 83}$	-	-
4. Inclusions:	clinopyroxene	clinopyroxene	clinopyroxene, feldspar
5. Alteration products:	cancrinite, analcite	analcite	analcite
C. Clinopyroxene:			
1. Shape	euhedral, acicular	euhedral acicular to lath-shaped	anhedral
2. Size (mm):	0,3 x 0,03	0,5 x 0,03 to 0,1 x 0,01	0,25
2. Composition:	aegirine	aegirine	aegirine

Table V.- The volumetric composition of the foyaite from the Spitskop alkaline complex.

Textural type: Sample No.	Alkali-feldspar:	Clinopyroxene:	Nepheline:	Accessory minerals:	Nomenclature: (Streckeisen, 1974)
Trachytoidal:					
DA26	45,6	11,9	40,9	1,6	Nepheline syenite
DA36	36,4	54,6	8,0	1,0	Malignite
DA37	33,2	29,0	37,8	tr.	Nepheline syenite
DA43	33,1	42,1	24,8	tr.	Malignite
DA50	48,4	31,0	14,1	6,5	Malignite
DA66	43,9	39,0	8,3	8,8	Malignite
DA82	33,7	49,5	13,7	3,1	Malignite
Porphyritic:					
DA3	56,8	35,2	7,4	0,6	Malignite
DA24	39,4	17,3	38,3	5,0	Nepheline syenite
DA45	48,9	20,3	25,8	5,0	Nepheline syenite
DA46	60,7	10,3	23,1	5,9	Nepheline syenite
DA51	49,4	36,1	10,5	3,9	Malignite
DA59	19,8	49,2	24,9	6,1	Malignite
Hypidiomorphic:					
DA49A	60,3	16,8	17,2	5,7	Nepheline syenite
DA49B	64,4	22,9	11,7	1,0	Nepheline syenite
DA52	47,8	19,5	28,4	4,3	Nepheline syenite

and a blueish soda-amphibole, probably arfvedsonite, are the accessory minerals of the foyaites.

Strauss and Truter (1950, p105) distinguished a fourth variety of foyaite for which they used the term "nodular foyaite". These nodules (Figure 10) consist of rosettes of euhedral clinopyroxene needles about 1,0 mm long which are arranged radially around a core of squat, anhedral grains of clinopyroxene. These nodules are here regarded as the result of accidental crystallisation around phenocrysts, and as they are present in all the varieties of foyaite, this distinction does not seem to be justified.

3. Nepheline Foidolite

The nepheline foidolites are subdivided into the porphyritic (Figure II) and the hypidiomorphic (Figure 12) varieties. These two textural varieties of nepheline foidolite may further be subdivided into urtite, ijolite and melteigite an the basis of their volumetric compositions (Table VI). The nepheline foidolite at Spitskop varies from reddish, medium-grained urtites to melanocratic fine-grained melteigites. The petrographical characteristics are summarised in Table VII.

The nepheline foidolites consist essentially of nepheline and clinopyroxene, the latter occupying the interstices between the nepheline grains along with the common minor minerals such as apatite, sphene, zircon and in some cases magnetite.

In the porphyritic nepheline foidolite inclusions of clinopyroxene are common in the euhedral grains of nepheline and are present as needle- or lath-shaped grains, apparently arranged parallel to a specific crystallographic

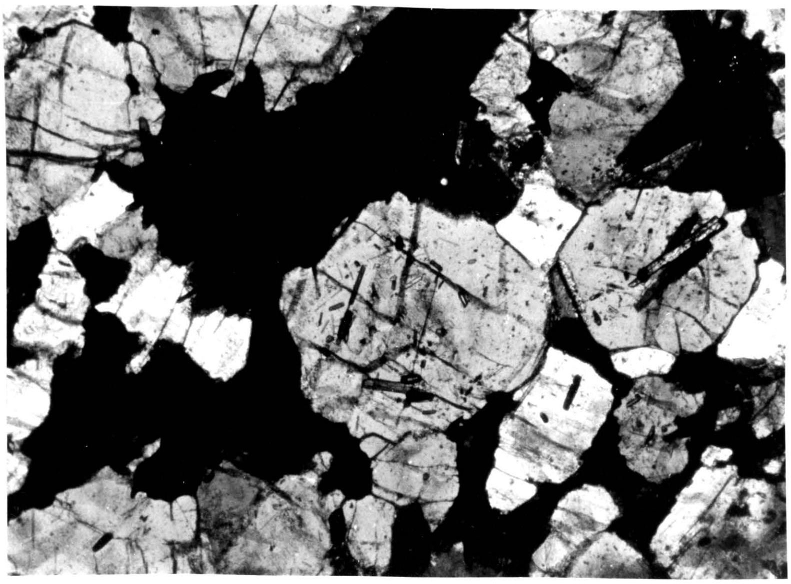


Figure 11. Porphyritic ijolite consisting of nepheline phenocrysts with inclusions of clinopyroxene and also intergranular clinopyroxene, crossed nicols, x40.

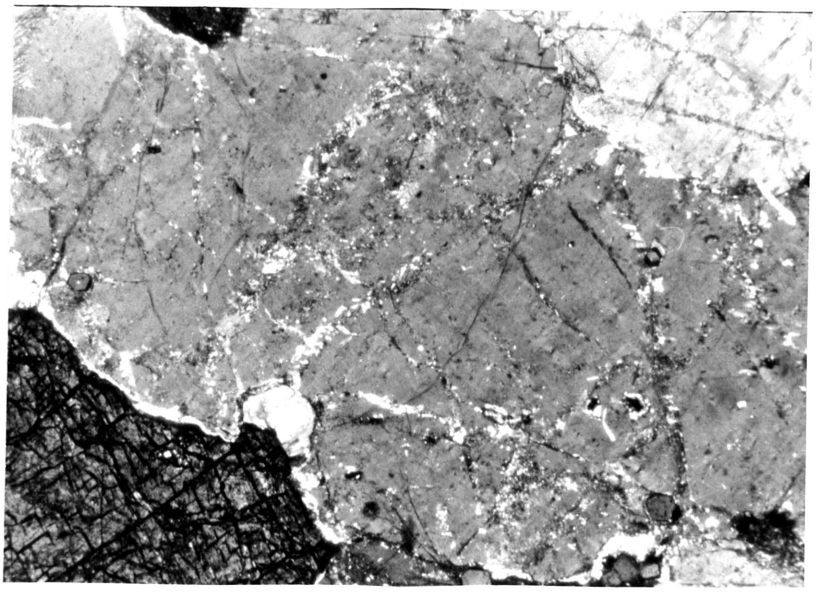


Figure 12 Hypidiomorphic ijolite consisting of anhedral nepheline and intergranular clinopyroxene, crossed nicols, x40.

Table VI. - The volumetric composition of the nepheline foidolites from the Spitskop alkaline complex.

Textural type:	Nepheline:	Pyroxene:	Accessory:	Nomenclature (Streckeisen,1974)
Porphyritic				
DA5	50,0	36,8	13,2	ijolite
DA28	60,2	34,3	5,5	ijolite
DA30	62,3	35,9	1,6	ijolite
DA31	68,6	28,9	2,5	urtite
DA83	47,6	50,8	1,6	ijolite
DA88	52,9	43,5	3,6	ijolite
DA107	32,7	63,3	4,0	ijolite
DA110	71,5	17,3	11,2	urtite
DA123	31,0	59,0	10,0	ijolite
Hypidiomorphic				
DA25	66,6	28,0	5,4	urtite
DA39	66,6	30,5	2,9	ijolite
DA40	78,9	19,6	1,5	urtite
DA41	45,8	51,0	3,2	ijolite
DA42	66,3	30,5	3,2	ijolite
DA47A	63,4	32,5	4,1	ijolite
DA47C	51,4	41,0	7,6	ijolite
DA49C	66,7	30,8	1,9	ijolite
DA54	84,9	14,5	0,6	urtite
DA60	64,3	34,9	0,8	ijolite
DA97	90,2	9,2	0,6	urtite
DA116	76,1	17,3	6,6	urtite

Table VII. - Petrographic characteristics of the nepheline foidolite.

Textural variety:	Porphyritic:	Hypidiomorphic:
A. Nepheline:		
1. Shape:	eu- to subhedral	anhedral
2. Size (mm):	0,2 to 2,0	5,0
3. Composition:	Ne_{81-85}	-
4. Inclusions:	clinopyroxene	apatite, clinopyroxene
5. Alteration products:	cancrinite	cancrinite
6. Structure:	secondary overgrowths	-
B. Clinopyroxene:		
1. Shape:	eu- to anhedral	eu- to subhedral
2. Size (mm):	0,2-0,5 x 0,5-2,0	length: 0,25 - 7,00
3. Composition:	aegirine-augite	aegirine-augite
4. Alteration:	none	schillerisation

direction, probably $\{10\bar{1}0\}$.

Nepheline is altered to cancrinite along cracks and grain boundaries in the hypidiomorphic variety, and clinopyroxene is irregularly altered to magnetite and chlorite (schillerisation).

4. Carbonatite

Verwoerd (1967, p33) subdivided the carbonatite into two main varieties, viz. sövite and beforsite, but he also recognised intermediate varieties such as "dolomitic sövite". Sövite has calcite as its major constituent, whereas beforsite contains mainly dolomite. According to Verwoerd (1967, p33), the calcite is replaced by magnesiodolomite in the dolomite sövite, in which case relics of calcite partially replaced by dolomite along grain boundaries and cleavage directions are present.

The beforsite consists of crystals with cores of iron-bearing magnesiodolomite surrounded by rims of parankerite (Verwoerd, 1967, p35).

D. Hypabyssal rocks

1. Latitic and trachytic rocks

The latitic and trachytic rocks from outside the Alkaline Complex are reddish-brown and contain macroscopically distinguishable phenocrysts of analcite pseudomorphous after nepheline. Microscopically phenocrysts of various minerals can be distinguished in these rocks, viz. analcite, feldspar, clinopyroxene, apatite and nepheline. The analcite phenocrysts have an average diameter of about 0,25 mm whereas the diameter of the others is about 0,15 mm.

Some of the dykes contain only analcite as phenocrystal phase, but X-ray diffractograms of the whole rocks indicate that the other minerals mentioned above are also present. It therefore seems as if the mineralogy of all the dykes and cone sheets is similar, the only major differences being their respective grain sizes and degrees of crystallinity.

The latite from inside the Spitskop Alkaline Complex is a greenish, fine-grained rock with numerous amygdales. Under the microscope the amygdales are seen to consist of analcite and chlorite grains set in an aphanitic groundmass. Analcite is usually present as acicular grains pointing towards the centre of the amygdale, the core of which consists of a mossaic of analcite grains, thus forming a druse.

Small phenocrysts of feldspar were distinguished in the groundmass, although the identification is based only on the lath-shape of the phenocrysts and on polysynthetic twinning.

2. Agglomerate

The agglomerate occurring within the alkaline complex (H6 and G4) is a greyish coloured rock in which fragments of perthitic feldspar may be recognised. On the other hand, the material from the calcareous diatreme (D10) looks quite different. It consists of a calcareous groundmass in which numerous rock fragments such as carbonatite, granite and the various alkaline rocks can be distinguished.

E. Fenitised country rocks

Strauss and Truter (1950, p86) distinguished two varieties of fenitised acid rocks, viz. "red fenites" and "white fenites", for which they also used the term "umptekites". Both these varieties are derived from the Bushveld granite and the Bushveld granophyre surrounding the complex.

This subdivision of the fenitised granites is based entirely on the colour of the varieties in the field. The colour, however, is dependent on the degree of recrystallisation of the reddish perthitic orthoclase of the Bushveld rocks. Thus, in the red fenitised granite, where no recrystallisation of the feldspar is evident the rock has a reddish colour, whereas in the white fenitised granite the feldspar is recrystallised to white perthite and the red colour is destroyed.

The red fenitised granite is characteristically pock marked by vugs on weathered surfaces but on freshly broken surfaces these vugs are seen to be filled with ochre. Apparently the vugs originally contained clinopyroxene which had replaced quartz during fenitisation and which in turn was altered to ochre. The general texture of the red fenites is the same as that of the Bushveld country rocks from which they were derived, viz. granitic and porphyritic.

In the white fenitised granite the original texture of the rocks was destroyed by the recrystallisation of the feldspar. The white fenitised granite, representing the final stage of fenitisation, is a hypidiomorphic rock with a slightly larger grain size than the rock from which it was derived.

IV. MINERALOGY AND MINERAL CHEMISTRY

A. Introduction

As clinopyroxene is the only mineral which occurs in all the alkaline and xenolithic rocks at Spitskop, its chemical composition is an obvious parameter for determining differentiation trends in the possible rock suites. Fifteen analyses of clinopyroxenes are presented here and form the basis of the chemical variation diagrams and the subsequent discussion.

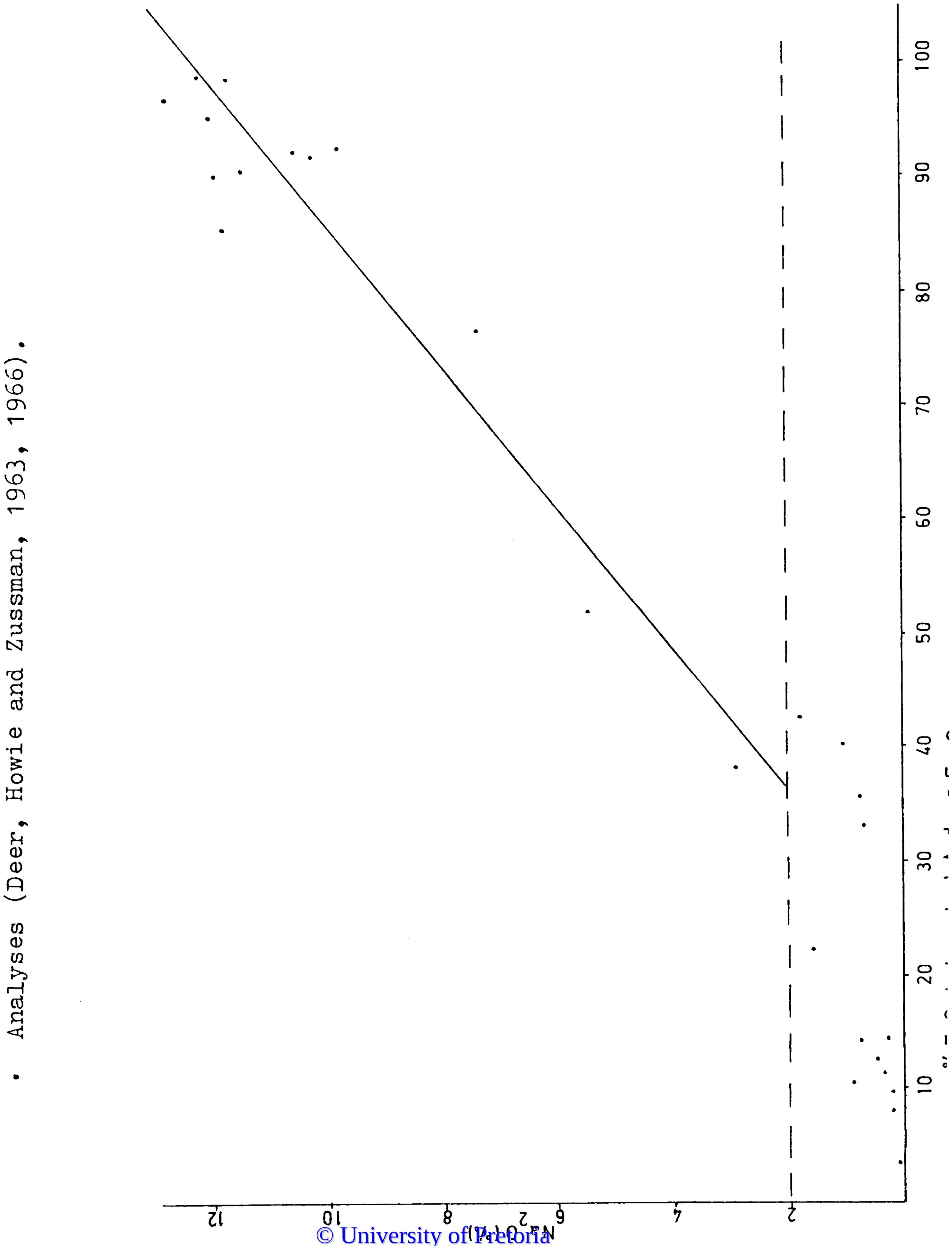
Because of the fact that iron is analysed as Fe with the microprobe and then calculated as FeO, and also because the values of both FeO and Fe_2O_3 must be known to calculate the structural formulae of the clinopyroxenes, a way of recalculating the total iron (as FeO) to give FeO and Fe_2O_3 values, had to be devised.

There is a correlation between the Na_2O values of the clinopyroxenes and the Fe_2O_3:FeO ratio and a curve was therefore drawn by using values published by Deer, Howie and Zussman (1963, p82-84 and p114-123) for the aegirine-augite series and for augite (Figure 13).

The assumption that Na_2O varies linearly with Fe_2O_3:FeO is based on the crystal chemistry of the augite-aegirine solid solution series because there is a coupled substitution of $NaFe^{3+}$ for $Ca(Fe^{2+}Mg^{2+})$ ignoring the minor rôles of K, Al, Mn, Ti, Cr.

The object of the curve (Figure 13) is to deduce a rapid ratio in which the total Fe (as FeO) can be subdivided so as to facilitate the calculation of an approximate formulae. The structural formulae is not intended to be an end in itself, but rather a means

Figure 13. - Diagram used to subdivide total Fe into FeO and Fe_2O_3 before the calculation of the structural formulae of the aegirine-augite clinopyroxenes from microprobe analyses.



to evaluate the "usuability" of a microprobe analysis when studying differentiation trends. For such a purpose it is felt that the approximation that Na_2O can be used to proportion the total iron, is valid.

Because of the scatter of points below 2 per cent Na_2O (Figure 13), it was decided not to proportion the total iron for clinopyroxenes with Na_2O below this value and all the iron was left as FeO for the calculation of the structural formulae.

When calculating the Fe_2O_3:FeO ratio, the Na_2O value of the analysed grain is plotted on the vertical axis and the amount of FeO to be recalculated to Fe_2O_3 (by multiplying with 1,1114) is read off on the horizontal axis. Note that this curve van only be applied to augite and aegirine-augite.

The abnormally high values of Fe, Mg, Mn, Cr and Ni for some of the minerals may be attributed to erroneous background extraction techniques, which may result in too high nett peaks. The absolute values of the mineral analyses are, however, not important in this study as the analyses are only used to determine differentiation trends, in which case a relative error of up to 10% for Ca, Mg, Na and Fe is acceptable.

B. Clinopyroxene

The clinopyroxenes in the alkaline rocks investigated all exhibit pleochroism in shades of green. No zoning was noticed and twinning was observed in the aegirine-augite of the hypidiomorphic ijolite. The twin plane is $\{100\}$ and twinning is usually simple, but lamellar twinning is

Table VIII. Mineral analyses of some min p

Sample No.	SiO_2	Al_2O_3	TiO_2	MgO	total iron	MnO	Cr_2O_3	NiO	CaO	Na_2O	K_2O	Total
Clinopyroxene in pyroxenite												
DA113	50,32	3,30	1,49	12,58	3,44	0,04			26,22	0,06		97,45
DA119	51,38	2,21	1,13	14,34	6,04	0,21			22,16	1,23	0,05	99,06
Clinopyroxene in porphyritic foyaite												
DA52	50,91	1,41	0,44	5,54	20,06	0,49	0,11	0,23	13,50	7,44	0,06	100,19
DA102	51,18	1,12	0,58	4,36	22,14	0,48	0,16	0,24	11.93	8,04	0,10	100,33
Clinopyroxene in hypidiomorphic foyaite												
DA24	50,90	1,34	0,75	3,46	23,05	0,64	0,12	0,26	6,82	12,15	0,04	99,53
DA84	51,67	1,40	0,66	1,98	25,30	0,51	0,12	0,24	6,62	11,02	0,05	99,57
Clinopyroxene in trachytoidal foyaite												
DA36	52,08	1,66	1,64	0,26	27,28	0,35	0,10	0,18	1,61	15,18	0,05	100,39
DA51	51,61	1,23	1,16	2,20	25,28	0,60	0,09	0,25	6,67	11,12	0,05	100,26
Clinopyroxene in hypidiomorphic ijolite												
DA42	51,57	2,14	0,74	12,38	10,12	0,32	0,07	0,23	20,46	1,76	0,06	99,85
DA60	51,09	1,32	0,62	11,95	10,31	0,38	0,11	0,17	22,17	1,14	0,04	99,30
Clinopyroxene in porphyritic ijolite												
DA30	50,69	1,19	0,35	4,59	22,46	0,68	0,08	0,23	15,06	5,08	0,06	100,67
DA108	50,96	1,17	0,83	9,83	14,67	0,39	0,06	0,23	19,76	1,81	0,04	99,75
Clinopyroxene in mottled anorthosite												
DA99	54,37	0,36	0,11	13,60	6,92	0,86			24,68	0,02	0,02	100,94
Clinopyroxene in magnetite diorite												
DA121	50,32	2,46	0,18	9,51	15,74	0,40	0,11	0,29	19,99	1,17	0,11	100,29
Clinopyroxene in olivine diorite												
DA87	48,08	0,94	0,16	0,88	27,80	0,51	0,23	0,26	18,64	1,70	0,05	99,26
Alkali-feldspar in porphyritic foyaite												
DA52	65,88	18,25	0,21	0,07	0,68	0,22	0,11	0,15	0,03	1,91	11,83	99,34
DA102	64,26	18,27	0,12	0,10	0,27	0,17	0,14	0,17	0,06	0,40	15,16	99,12
Alkali-feldspar in hypidiomorphic foyaite												
DA84	66,04	21,06	0,01	0,11	0,29		0,17	0,19	0,03	3,70	8,54	100,14
Alkali-feldspar in trachytiodal foyaite												
DA36	61,72	17,11	0,08	0,06	0,29	0,20	0,16	0,20	0,06	1,23	17,31	98,42
DA51	65,93	19,37	0,08	0,06	0,20	0,17	0,12	0,16	0,06	13,67	0,15	99,97
Plagioclase in magnetite diorite												
DA121	54,42	31,21	0,09	0,10	0,24	0,19	0,15	0,17	6,91	5,99	0,34	99,81
Plagioclase in olivine diorite												
DA87	56,98	30,97	0,09	0,11	0,15	0,18	0,14	0,23	7,02	3,50	0,21	99,58
Nepheline in porphyritic ijolite												
DA30	43,69	32,40	0,08	0,04	1,28	0,18	0,08	0,17	0,10	17,29	4,61	99,92
DA108	43.74	32,74	0,08	0,09	1,17	0,18	0,10	0,15	0,07	15,61	5,51	99,44
Nepheline in porphyritic foyaite												
DA52	44,43	31,69	0,07	0,06	0,88	0,19	0,13	0,26	0,12	16,94	5,18	99,95
DA102	43,89	32,15	0,09	0,11	0,84	0,20	0,15	0,18	0,06	15,80	6,59	100,06
Olivine in olivine diorite												
DA87	28,65			0,44	68,76							97,85

Total Fe calculated as FeO
For structural formulae the total iron was proportioned into FeO and
Fe_2O_3 as explained in the text.

Struotural formulae.

Sample No.	Si	Al	Ti	Mg	Fe^{+++}	Fe^{++}	Mn	Cr	Ni	Ca	Na	K	O
DA113	1,905	0,147	0,042	0,710		0,109	0,001			1,063	0,004		6
DA119	1,928	0,098	0,032	0,802		0,190	0,007			0,891		0,002	6
DA52	1,929	0,063	0,013	0,313	0,445	0,191	0,016	0,003	0,007	0,548	0,547	0,003	6
DA102	1,930	0,063	0,013	0,246	0,520	0,183	0,015	0,005	0,007	0,485	0,591	0,005	6
DA24	1,917	0,059	0,021	0,194	0,722	0,004	0,020	0,004	0,008	0,275	0,887	0,002	6
DA84	1,046	0,062	0,019	0,111	0,737	0,060	0,016	0,004	0,007	0,267	0,805	0,002	6
DA36	1,938	0,073	0,046	0,014	0,849		0,011	0,003	0,005	0,064	1,095	0,002	6
DA51	1,933	0,054	0,033	0,123	0,737	0,055	0,019	0,003	0,008	0,268	0,808	0,002	6
DA42	1,944	0,095	0,021	0,696		0,319	0,010	0,002	0,007	0,826	0,129	0,003	6
DA60	1,948	0,059	0,018	0,679		0,329	0,012	0,003	0,005	0,906	0,084	0,002	6
DA30	1,936	0,054	0,016	0,261	0,398	0,319	0,022	0,002	0,007	0,615	0,376	0,003	6
DA108	1,964	0,053	0,024	0,565		0,472	0,013	0,002	0,007	0,816	0,135	0,002	6
DA99	2,004	0,016	0,003	0,747		0,213	0,027			0,975	0,001	0,001	6
DA121	1,935	0,116	0,005	0,545		0,507	0,013	0,003	0,009	0,824	0,087	0,005	6
DA87	1,987	0,046	0,005	0,054		0,951	0,016	0,005	0,008	0,825	0,136	0,003	6
DA52	11,915	3,944	0,029	0,018		0,104	0,030	0,015	0,022	0,006	0,680	2,767	32
DA102	11,959	4,008	0,017	0,028		0,042	0,027	0,021	0,025	0,012	0,144	3,599	
DA84	11,795	4,434	0,001	0,029		0,043		0,024	0,027	0,006	1,281	1,946	32
DA36	11,829	3,866	0,012	0,017		0,046	0,032	0,024	0,031	0,012	0,457	4,232	32
DA51	11,700	4,053	0,011	0,016		0,030	0,026	0,017	0,023	0,011	4,704	0,034	
DA121	9,760	6,599	0,012	0,027		0,036	0,029	0,021	0,025	1,328	2,083	0,078	32
DA87	10,090	6,466	0,012	0,029		0,022	0,027	0,020	0,033	1,332	1,202	0,047	32
DA30	8,416	7,358	0,012	0,011		0,206	0,029	0,012	0,026	0,021	6,458	1,133	32
DA108	8,446	7,453	0,012	0,026		0,189	0,029	0,015	0,023	0,014	5,844	1,357	
DA52	8,554	7,193	0,010	0,017		0,142	0,031	0,020	0,040	0,025	6,324	1,272	32
DA102	8,475	7,319	0,013	0,032		0,136	0,033	0,023	0,028	0,012	5,916	1,624	
DA87	0,992			0,022		1,992							4

Table VIII Cont.: - Grouping of constituents.

Sample No.	Z	X+Y	X
Clinopyroxene:			
DA113	2,00	1,98	
DA119	2,00	1,95	
DA52	2,00	2,08	
DA102	2,00	2,06	
DA24	2,00	2,11	
DA84	2,00	2,04	
DA36	2,00	2,10	
DA51	2,00	2,04	
DA42	2,00	2,05	
DA60	2,00	2,05	
DA30	2,00	2,01	
DA108	2,00	2,02	
DA99	2,00	1,98	
DA121	2,00	2,05	
DA87	2,00	2,05	
Theoretical	2,00	2,00	
Feldspar:			
DA52	15,86		3,47
DA102	15,97		3,78
DA84	16,23		3,26
DA36	15,70		4,72
DA51	15,75		4,77
DA121	16,36		3,52
DA87	16,54		2,61
Theoretical:	16,00		4,00
Nepheline:			
DA30	15,77		7,91
DA108	15,90		7,51
DA52	15,75		7,88
DA102	15,79		7,82
Theoretical:	16,00		8,00

Z=Si+Al (For clinopyroxene=Si(+Al+Ti+Fe^{3+})Deer, Howie and Zussman, 1966, p106)

X = Mg + Ca + Na + K

X + Y = All elements except Z

Table VIII Cont. – Sample localities

DA4	latite	latite plug		(H6)
DA24	hypidiomorphic foyaite	Spitskop Spruit west of junction		(H6)
DA30	porphyritic ijolite	Rietfontein Spruit		(D5)
DA36	trachytoidal foyaite	Eenzaam Spruit		(H6)
DA42	hypidiomorphic ijolite	west of latite plug		(H6)
DA51	trachytoidal foyaite	at corner post		(C6)
DA52	porphyritic foyaite	near white fenite		(C5)
DA56	granite	west of borehole		(B6)
DA59	hypidiomorphic foyaite	near stream junction		(C4)
DA60	hypidiomorphic ijolite	at junction of spruits		(F6)
DA69A	porphyritic ijolite	in spruit west of pyroxenite outcrop		(E7)
DA72	trachytoidal foyaite	south-west corner of H7		(H7)
DA76	granite	east of white fenite		(I6)
DA77	agglomerate	in west draining stream		(I6)
DA80	fenitised granite	in south-west draining stream		(I6)
DA84	hypidiomorphic foyaite	east of latite sheet in stream		(H6)
DA85	fenitised granite	in south-west draining stream		(I6)
DA86	latite	cone sheet east of latite sheet		(H6)
DA87	olivine diorite	in stream east of latite sheet		(H6)
DA89	latite	latite sheet		(H6)
DA90	agglomerate	calcareous diatreme		(D10)
DA90A	granite	near calcareous diatreme		(D10)
DA94	latite	radial dyke in granite		(B5)
DA96	trachyte	just west of DA94		(B5)
DA99	mottled anorthosite	stream east of borehole 7		(G5)
DA102	porphyritic foyaite	stream east of borehole 7		(G4)
DA103	magnetite diorite	stream east of borehole 7		(G6)
DA105	latite	stream east of borehole 7		(G4)
DA108	porphyritic ijolite	Spitskop Spruit near fenite		(H7)
DA113	pyroxenite	borehole 4, 43,4m	– The only fresh pyroxenite found during this investigation.	(E6)
DA115	pyroxenite	borehole 4, 39,7m	–	(E6)
DA116	hypidiomorphic ijolite	borehole 4, 39,0m		(E6)
DA119	pyroxenite	borehole 4, 34,1m	–	(E6)
DA121	magnetite diorite	borehole 5, 33,6m		(E8)
DA124	hypidiomorphic ijolite	borehole 6, 25,0m		(E7)

Figure 14.- Ca-Mg-Fe diagram with trends of clinopyroxenes for the Spitskop alkaline and gabbroic rocks

△	pyroxenite	
•	hypidiomorphic	foyaite
×	porphyritic	
v	trachytoidal	
◻	hypidiomorphic	ijolite
∘	porphyritic	
F	olivine diorite	
M	mottled anorthosite	
G	magnetite diorite	
⟶	gabbroic trend	
- - →	alkaline trend	

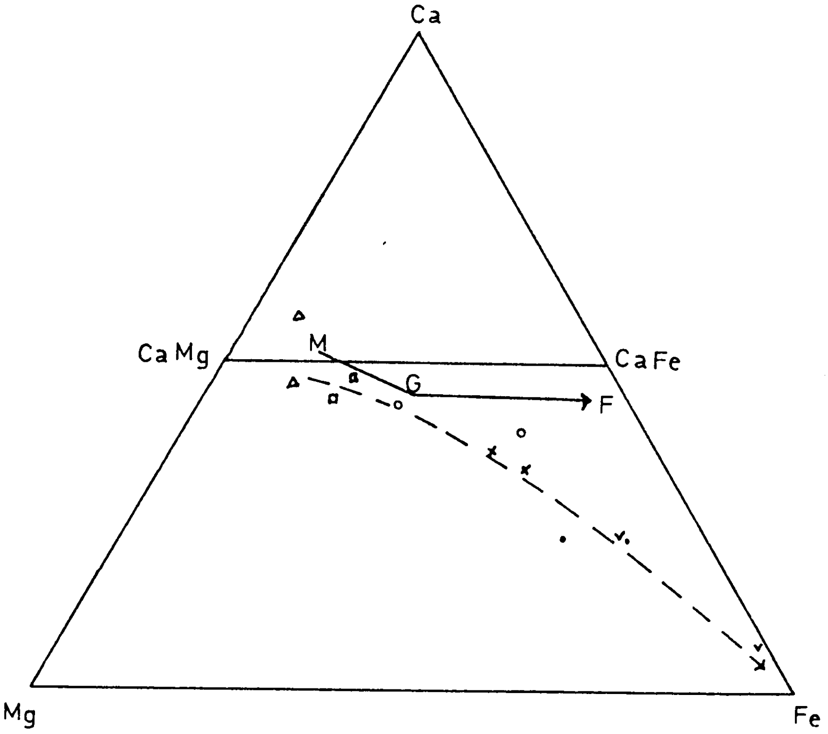


Figure 15.- Na-Mg-Fe diagram with trends of clinopyroxenes for the Spitskop alkaline and gabbroic rocks

▲ pyroxenite

foyaite:
- • hypidiomorphic
- × porphyritic
- ⌄ trachytoidal

ijolite:
- ▫ hypidiomorphic
- ∘ porphyritic

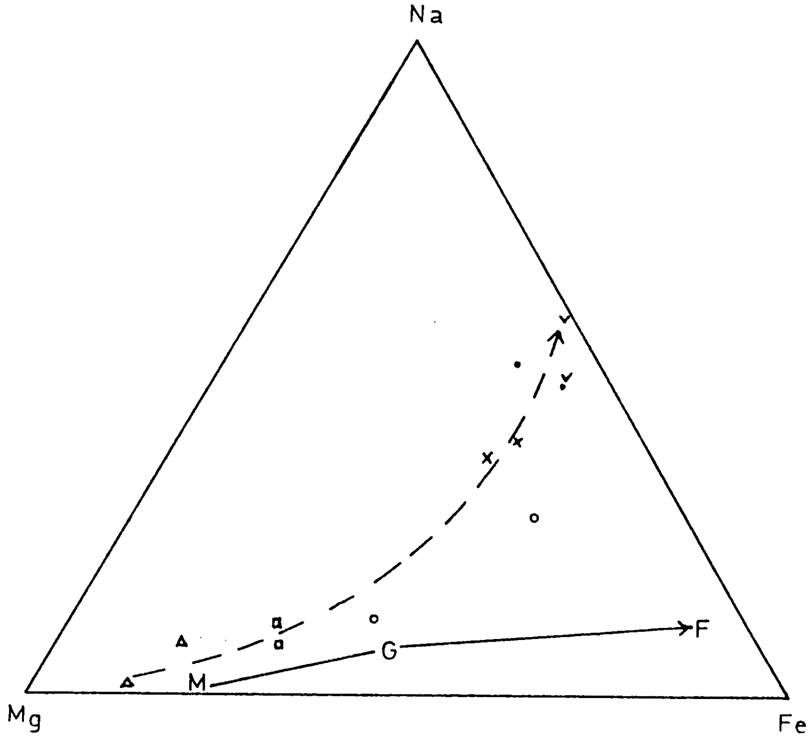
F olivine diorite

M mottled anorthosite

G magnetite diorite

⟶ gabbroic trend

- - → alkaline trend



also sporadically encountered.

The chemical composition of the clinopyroxenes (Table VIII) expressed in terms of Ca+Mg+Fe (atomic per cent) and Na+Mg+Fe (atomic per cent) are shown in Figs. 14 and 15 respectively. The alkaline clinopyroxenes from the Spitskop Complex follow the same trends as those from other alkaline complexes, according to the data given by Aoki (1964, p1208 and 1210).

In the Ca+Mg+Fe diagram (Fig. 14) the trend is towards enrichment in Fe at the expense of Ca and Mg. If this trend is considered to be continuous, it goes through the following rock-types in the sequence indicated: pyroxenite, hypidiomorphic ijolite, porphyritic ijolite, porphyritic foyaite, hypidiomorphic foyaite and, as the last differentiate, trachytoidal foyaite.

The Na+Mg+Fe diagram (Fig. 15) shows the same sequence of differentiation as that indicated by Figure 14, except that in this case the enrichment is towards the Na+Fe tie-line showing that the final pyroxene to crystallise was aegirine (Fig. 15).

Also indicated in the above-mentioned ternary diagrams (Figs. 14 and 15)are three analyses of clinopyroxenes from the gabbroic rocks. It is evident that these clinopyroxenes follow a trend which differs from that of the clinopyroxenes in the alkaline rocks. For the gabbroic rocks the trend on the Ca+Mg+Fe diagram (Fig. 14) is towards the Ca+Fe tie-line at the expense of Mg, whereas the trend for the alkaline rocks is towards iron enrichment at the expense of the other two components. In the case of the Na+Mg+Fe diagram (Fig. 15) the trend for the gabbroic rocks again differs from that of the alkaline rocks in that the trend is towards iron enrichment, whereas the trend in the alkaline rocks is towards enrichment in both iron and sodium. The clinopyroxenes of the gabbroic rocks are therefore members of the diopside hedenbergite solid solution series, whereas those of the alkaline rocks belong to the augite aegirine-augite series.

C. Nepheline

Nepheline is a major constituent of both the ijolite and the foyaite of the Spitskop Complex. Four analyses of nepheline are presented here. Two of these are of nepheline in the porphyritic ijolite and two of nepheline in the porphyritic foyaite (Table VIII). It is evident that the composition of the nepheline is approximately constant, at least for the two rock types concerned. When the atomic ratios of Na and K in the nepheline analyses are calculated to 100 per cent, the sodium on the Na+K tie-line of a Na+K+Si diagram varies between 78,5 and 85,1 per cent.

It was not possible to achieve good analyses of nepheline in the other rock types because it is usually altered to some degree to either cancrinite or analcite.

D. Alkali feldspar

Two analyses each of alkali feldspar in the porphyritic and the trachytoidal foyaite and one of that in the hypidiomorphic foyaite are presented in Table VIII.

The alkali feldspar in the porphyritic foyaite is orthoclase with an albite content which varies between 3,8 and 19,7 mol per cent, whereas the alkali feldspar in the hypidiomorphic foyaite has a cryptoperthitic composition and contains 39,6 mol per cent albite.

Two different alkali feldspars were found in the trachytoidal foyaite, the one being orthoclase with 9,7 mol per cent albite and the other almost pure albite containing only 0,7 mol per cent orthoclase. This feature may be interpreted in two ways. There could be two different alkali feldspars present in the rock, or the feldspar could be a perthite of which the two phases were analysed separately. Under the optical microscope, however, it was not possible to identify any perthite, mainly because of the small size of the grains, even under high magnification.

The calcium content of the alkali feldspar in the Spitskop foyaite is consistently low when compared with other alkali feldspars (Deer, Howie and Zussman 1966, pp300-301). The anorthite content is only about 0,3 mol per cent.

E. Plagioclase

Plagioclase is present as a major constituent only in the gabbroic xenoliths at Spitskop. Two analyses of plagioclase are given in Table VIII, one of plagioclase in the olivine diorite and the other of that in the magnetite diorite. That the analyses are not of a good quality, is evident from the structural formulae, in that Ca+Na+K+Mg which should total 4, is not close enough to that figure. This can be explained by the fact that all the plagioclase grains encountered in this investigation showed signs of alteration and that the analyses are therefore not of pure plagioclase.

From these analyses one can, however, estimate the compositions of the two grains as far as anorthite contents

<u>Table IX</u>. Chemical analyses and C.I.P.W. norms of the Spitskop rocks.

																Trace elements (ppm)								
Sample No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O^-	H_2O^+	CO_2	P_2O_5	Total	Nb	Zr	Y	Sr	Rb	Ba	Ce	Nd	La
Pyroxenite																								
DA113	40,23	2,64	3,58	12,12	7,50	0,17	12,38	17,59	0,57	1,04	0,15	0,69	0,40	0,18	99,24	13	129	22	433	29	137	43	26	14
DA115	40,32	2,50	5,32	10,88	7,12	0,18	10,78	16,95	2,57	0,90	0,11	1,22	0,68	0,19	99,72	14	137	16	340	15	121	23	17	
DA119	38,68	2,63	5,53	12,41	7,05	0,21	9,31	17,74	2,22	0,57	0,22	1,39	0,63	1,14	99,73	9	103	20	532	18	253	38	25	13
Latite																								
DA4	49,26	0,91	14,86	2,16	7,84	0,13	7,24	8,57	3,38	0,79	0,68	3,19	0,19	0,16	99,36		79	22	697	22	175	22	13	8
DA86	47,94	1,03	15,31	3,61	7,28	0,15	6,84	9,47	1,82	1,09	2,33	2,38	0,13	0,18	99,56		85	26	306	25	2617	17	15	9
DA89	49,32	0,93	14,98	3,35	6,94	0,15	6,73	11,23	2,18	0,52	1,10	1,69	0,17	0,19	99,48		74	27	210	8	171	20	11	9
DA94	43,92	1,27	17,70	7,09	3,68	0,23	2,97	8,35	4,39	2,98	0,18	3,79	1,93	0,61	99,09	26	154	31	1399	98	784	43	22	24
DA105	48,87	0,94	14,86	3,25	6,61	0,14	7,67	8,44	2,87	1,16	0,99	3,45	0,05	0,17	99,47		73	25	1089	38	1438	15	13	8
Trachyte																								
DA96	50,68	0,85	18,81	5,22	1,79	0,18	1,21	4,18	6,80	4,24	0,37	0,38	0,72	0,29	99,12	37	235	25	877	103	2362	34	19	20
Porphyritic foyaite																								
DA52	51,18	0,60	19,17	4,08	2,01	0,09	1,37	4,93	9,42	4,42	0,22	1,08	0,25	0,55	99,37	29	386	9	355	91	1014	13	11	7
DA102	47,57	1,08	18,34	6,00	2,60	0,18	1,07	5,73	9,64	3,47	0,28	1,88	0,99	0,35	99,18	37	192	15	835	78	1380	49	23	21
Hypidiomorphic foyaite																								
DA59	51,36	0,51	18,32	6,92	1,09	0,14	0,20	1,50	11,14	4,90	0,20	2,61	0,28	0,03	99,20	3	221	10	583	111	1033	13	6	8
DA84	49,12	0,83	18,41	4,11	2,44	0,14	0,51	3,05	11,91	4,66	0,19	1,69	2,36	0,06	99,48	12	159	12	1224	118	1811	17	13	8
Trachytoidal foyaite																								
DA36	53,60	0,72	17,91	7,47	1,02	0,12	0,07	0,67	9,66	5,10	0,18	2,58	0,14	0,03	99,27	7	222	9	388	121	425	13	6	7
DA51	50,37	0,70	18,25	5,37	1,58	0,16	0,59	3,52	11,73	4,03	0,24	1,67	1,24	0,21	99,66	19	167	10	810	94	1199	19	13	11
DA72	54,95	0,69	16,62	8,98	0,94	0,12	0,11	0,90	10,11	2,29	0,28	2,86	0,16	0,04	99,05	8	533	9	452	58	234	13	6	7
Porphyritic ijolite																								
DA30	44,18	0,95	23,46	4,02	2,63	0,13	1,12	4,97	13,57	2,98	0,18	0,81	0,12	0,19	99,31	29	107	8	287	46	31	15	12	8
DA69A	44,18	1,14	18,44	4,21	2,65	0,15	3,07	9,35	10,89	3,02	0,18	0,72	0,67	1,30	99,97	34	159	35	707	39	67	93	46	40
DA108	42,18	1,32	21,04	3,95	3,81	0,14	2,99	8,25	11,46	3,16	0,08	0,32	0,34	0,84	99,88	13	91	13	435	50	22	32	19	13
Hypidiomorphic ijolite																								
DA42	42,51	0,31	20,71	2,46	1,90	0,08	4,18	10,07	10,31	3,81	0,39	0,97	0,37	1,38	99,45		40	10	540	56	289	25	14	16
DA60	45,17	0,39	15,72	3,92	3,67	0,16	4,63	12,31	8,81	2,80	0,13	0,78	0,35	1,11	99,95	3	62	17	487	40	1768	52	29	23
DA116	41,22	1,39	17,95	4,00	3,03	0,19	2,18	12,14	6,93	2,31	0,25	3,84	1,58	2,41	99,42	55	186	82	1753	16	216	238	122	112
DA124	46,50	0,23	14,27	3,99	3,78	0,18	5,76	11,83	9,20	2,24	0,11	0,41	1,00	0,09	99,59		13	9	466	14	367	13	8	8
Magnetite diorite																								
DA99	46,23	0,11	26,48	0,49	1,30	0,06	1,44	13,32	6,64	0,90	0,09	0,79	1,25	0,19	99,29	4	16	6	375	16	176	12	5	7
DA103	50,11	0,05	28,00	0,37	0,67	0,04	0,17	12,22	4,88	1,10	0,12	1,13	0,37	0,12	99,35		3		454	11	281	11	5	7
Granite																								
DA56	74,53	0,29	11,79	1,87	1,01	0,08	0,06	0,65	3,70	4,68	0,28	0,34	0,31	0,02	99,61	16	369	266	79	162	71	234	197	203
DA76	72,00	0,41	11,89	2,07	2,30	0,08	0,13	1,18	3,59	4,91	0,37	0,48	0,20	0,03	99,64	14	602	32	140	146	2109	101	43	60
DA90A	75,18	0,39	12,30	1,02	0,14	0,05	0,27	0,10	2,73	6,19	0,31	0,57	0,17	0,10	99,52	38	315	30	34	187	619	133	54	71
Fenitised granite																								
DA80	62,12	0,33	16,53	3,67	0,86	0,11	0,40	1,79	6,28	5,68	0,31	0,41	0,44	0,16	99,09	25	151	18	613	81	4273	26	15	15
DA85	60,94	0,63	14,80	4,61	2,16	0,14	0,29	2,64	6,43	5,66	0,18	0,19	0,25	0,12	99,04	21	252	15	546	98	2525	21	15	14
Agglomerate																								
DA77	56,88	0,47	13,35	4,94	0,30	0,13	0,54	5,38	0,31	11,45	0,48	0,81	4,31	0,04	99,39	31	765	29	55	112	188	134	54	72
DA90	37,60	0,73	8,61	2,30	5,34	0,18	4,49	13,76	0,20	6,92	0,23	1,35	16,51	0,98	99,20	53	143	102	409	182	768	51	27	24

<u>C.I.P.W. Norms</u>.

Sample No.	Q	C	or	ab	an	lc	ne	nc	ac	ns	di	hy	wo	ol	cs	mt	il	hm	ru	ap
DA113					6,66	4,81	0,03	0,96			60,83			1,84	0,39	17,07	5,01	0,34		0,42
DA115					4,62	4,17	7,38	1,63			58,45		0,58		0,56	15,77	4,74			0,44
DA119			3,36	2,25	7,42		4,88	1,51			50,01		3,71			15,78	4,99	1,52		2,68
DA4			4,66	26,33	24,24			0,45			14,04	15,08		5,42		3,13	1,72			0,37
DA86	3,33		6,44	13,84	31,21			0,31			11,83	20,25				5,25	1,95			0,42
DA89	3,65		3,07	16,41	30,63			0,40			19,32	16,10				4,85	1,76			0,44
DA94	3,36		17,61	14,14	31,99			4,64			4,23	5,43				8,92	2,41	0,93		1,43
DA105			6,85	23,68	24,55			0,12			13,06	16,96		2,88		4,71	1,78			0,40
DA96			25,06	32,37	12,83			1,73			4,67			0,59		3,89	1,61	2,53		0,68
DA52			26,12	20,56			28,94	0,60	2,39		7,69		4,60			4,71	1,13			1,29
DA102			20,50	22,81	2,79		25,43	2,38			5,74		6,66			5,83	2,05	1,97		0,82
DA59			28,96	9,14			31,31	0,67	20,02	0,28	3,74		1,19				0,96			0,07
DA84			27,54	20,44			26,17	5,68	3,42		4,52		3,84			4,24	1,57			0,14
DA36			30,14	24,46			21,27	0,33	14,38		0,37		1,10			1,59	1,36	1,40		0,07
DA51			23,81	17,12			29,42	2,98	11,47		4,82		4,24			2,03	1,32			0,49
DA72			13,53	51,17			11,68	0,38	9,58		0,59		1,43			1,42	1,30	4,68		0,09
DA30			2,73			11,66	56,38	0,28	8,18		10,75		4,33			1,72	1,80			0,44
DA69A			11,24			5,17	42,27	1,61	5,38		18,97		5,81			3,40	2,16			3,06
DA108						14,64	49,10	0,81	1,99		20,54		0,63		2,55	4,72	2,50			1,98
DA42					1,32	17,65	44,86	0,89			20,37			1,37	4,24	3,56	0,58			3,25
DA60			0,86			12,29	35,36	0,84	4,48		33,21		5,22			3,43	0,74			2,61
DA116			13,65	12,45	21,04		14,81	3,80			12,30		3,22			5,79	2,63			5,68
DA124			5,51			6,05	33,01	2,40	4,39		40,06		3,39			3,58	0,43			0,21
DA99			5,31	13,09	47,70		15,27	3,01			11,33		1,32			0,71	0,20			0,44
DA103			6,50	26,78	53,59		5,46	0,89			2,63		1,31			0,53	0,09			0,28
DA56	36,20	0,22	27,66	27,61	3,09			0,74								2,66	0,55			0,04
DA76	30,97		29,02	27,99	3,09			0,48			2,23					3,00	0,77			0,07
DA90A	36,66	1,56	36,58	21,07				0,40									0,40	1,01	0,17	0,23
DA80	4,53		33,57	47,89	2,92			1,05			2,14		0,89			2,17	0,62	2,17		0,37
DA85	1,89		33,45	44,61				0,60	5,99		3,60		3,34			3,67	1,19			0,28
DA77	11,99	0,74	67,67		0,57			0,53				1,34				0,02	0,89	4,91		0,09
DA90	28,17	16,36	40,90					0,34				1,99				3,33	1,38			2,31

are concerned, and they were found to be about 52 and 38 mol per cent An for the plagioclase from the olivine diorite and the magnetite diorite respectively.

These values correspond to values for plagioclase from the Upper Zone of the layered sequence of the Bushveld Complex (Molyneux, 1974, p335-336).

F. Other minerals

One analysis of olivine in the olivine diorite is presented in Table VIII. The fayalite content of this olivine is 98,91 mol per cent, which falls within the range defined by Molyneux (1974, p336).

Magnetite, apatite, zircon, biotite and soda-amphibole are present in varying amounts as accessory minerals in the Spitskop rocks. Only in the magnetite breccia is magnetite a major constituent.

Two different soda amphiboles were found during the investigation. One is present in foyaite and is pleochroic in shades of blue. It has an estimated $2V_\alpha$ of 20 degrees and is probably arfvedsonite. The other soda amphibole is present in the mottled anorthosite. It is pleochroic in shades of brown and has a $2V_\alpha$ of more than 100 degrees. A microprobe analysis indicated that the mineral is pargasite, which agrees with the optical data.

Traces of minerals containing rare earth elements were encountered during the microprobe analyses but were not investigated owing to their small grain size, which made identification of the minerals impossible when working with reflected light, which was the only optics available at the time on the microprobe.

G. Conclusions

The chemical composition indicates that the clinopyroxenes of the alkaline rocks follow the normal differentiation trend observed in alkaline rocks (Aoki, 1964, p1208 and 1210). It is also evident that the clinopyroxenes of the gabbroic rocks follow a trend similar to that of clinopyroxenes in layered intrusions such as Skaergaard (Aoki, 1964, p1208 and 1210) and the Bushveld Complex (Atkins, 1969, p239).

This fact, and also the compositions of the plagioclase and olivine, suggest that the gabbroic rocks are closely related to the layered sequence of the Bushveld Complex. They must therefore be regarded as xenoliths originating from the underlying layered sequence of the Bushveld Complex, and not as theralites.

V. PETROCHEMISTRY

A. Introduction

The purpose of the petrochemical investigation was to construct chemical variation trends which could be used as a basis for unravelling the origin of the various alkaline rocks of the Spitskop Complex.

Thirty two chemical analyses of the different rock types and their C.I.P.W. norms are presented in Table IX. The sample localities are listed in Table VIII.

B. The major elements

The Spitskop alkaline rocks van be classified as miaskitic alkaline rocks on the basis of their Al_2O_3 contents which exceed their values of Na_2O+K_2O. (Sørensen 1974, p23).

The felsic index of the alkaline rocks is plotted versus the mafic index (Simpson, 1954, p238) in Figure 16. According to this diagram it appears that the various foyaites represent the most differentiated silicate rocks of the complex, and of these the trachytoidal foyaite appears to be more differentiated than the porphyritic foyaite, whereas the hypidiomorphic foyaite occupies an intermediate position.

The ijolite appears to contain less iron than the foyaite for a specific felsic index. The hypidiomorphic ijolite appears to follow a trend in which the felsic index decreases for an increasing mafic index while the trend of the porphyritic ijolite has an increase in the felsic index for increasing mafic indices, as is the case with the foyaite.

According to Figure 16 the direction of maximum variatior

Figure 16. - Diagram of the felsic index versus the mafic index for the Spitskop alkaline rocks.

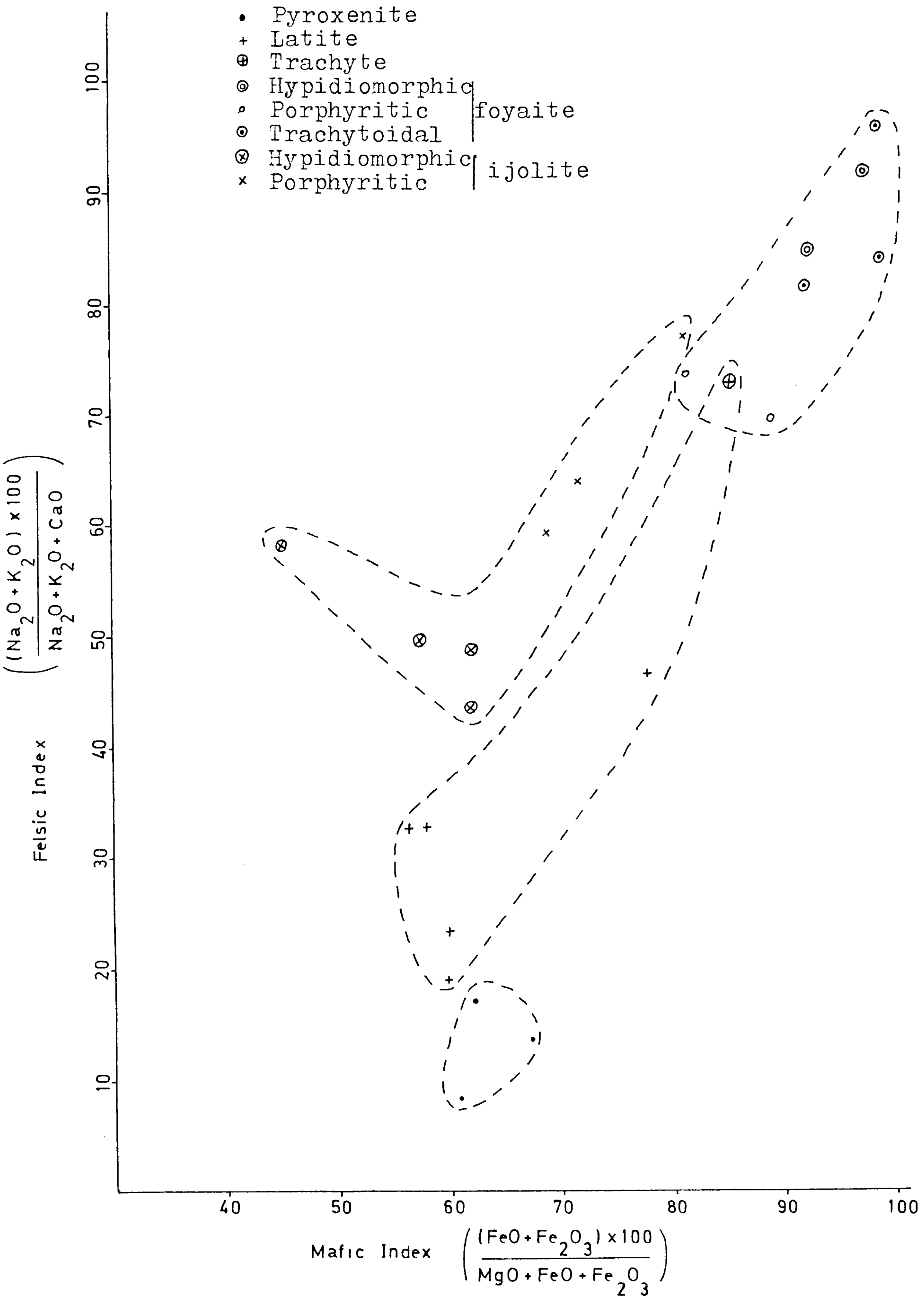
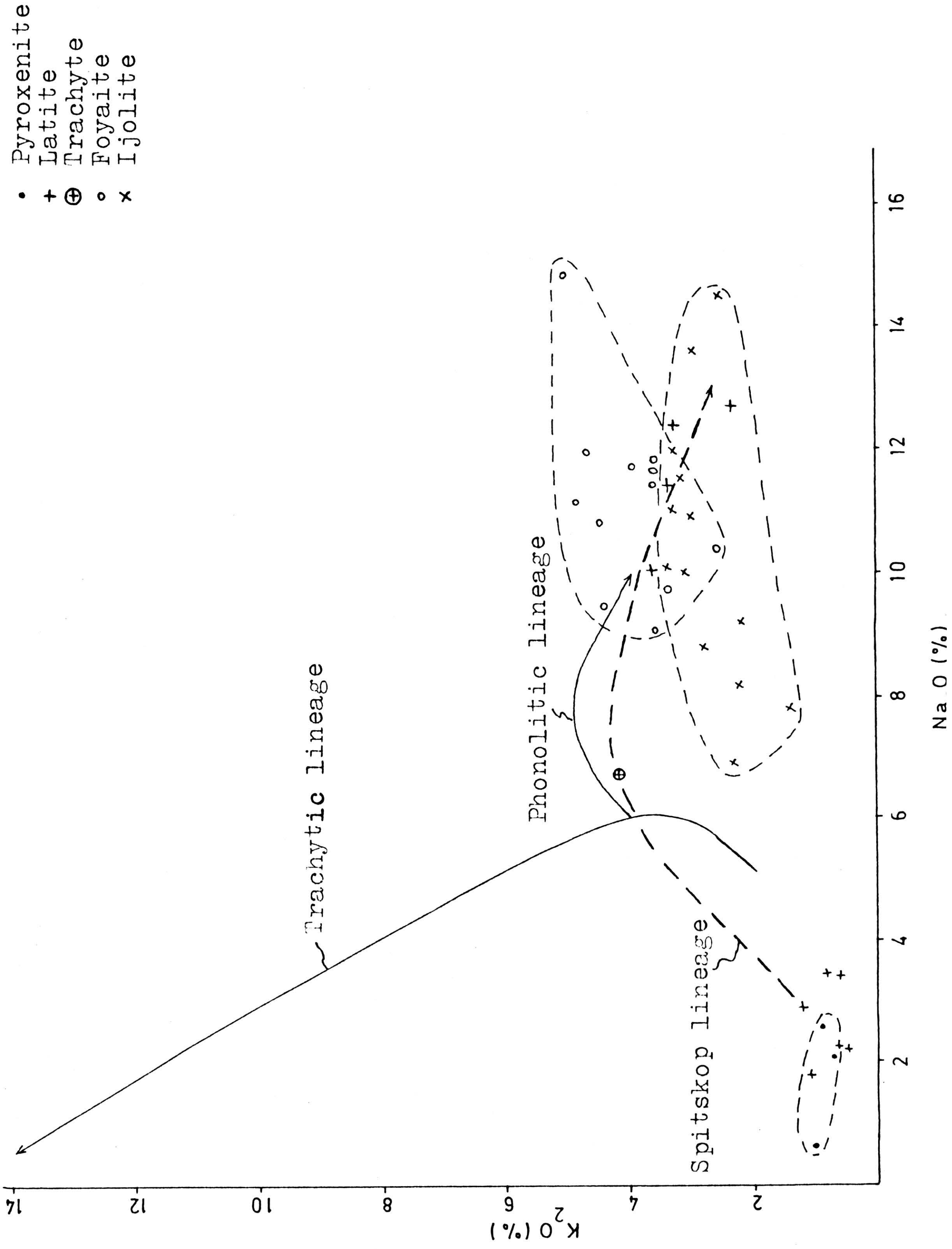


Figure 17. - Diagram of K_2O versus Na_2O for the Spitskop alkaline rocks.



and consequently the trend according to which the fractionating magma may have fractionated, is similar to that of the porphyritic ijolites and the foyaite and may represent the differentiation of the primary magma during the fractionation of the alkaline rocks.

According to Simpson (1954, p241) the composition of the early cumulates of a fractionating magma will lie on the negative continuation of the fractionation trend of the magma. Since the hypabyssal rocks are the closest approximation of the composition of the fractionating silicate magma, the pyroxenite, which lies along the negative continuation of the trend of the hypabyssal rocks could then be interpreted as the earliest cumulates.

According to Rock (1976, p97), the concentration of CO_2 in an alkali basalt magma can influence the fractionation trend of the magma considerably. A high CO_2 concentration in the magma could lead to the crystallisation of carbonatite, nephelinite, pyroxenite and ijolite, whereas a low CO_2 concentration in the magma could result in the fractionation of nepheline syenite (foyaite).

According to the K_2O/Na_2O diagram (Figure 17), a definit differentiation trend can be constructed for the hypabyssal rocks, which would closely approximate the fractionation trend of the crystallising alkaline magma. On this diagram the trachytitic and phonolitic lineages of King and Sutherland (1966) and Frick (1975,p212), are compared with the trend obtained for the hypabyssal rocks from Spitskop.

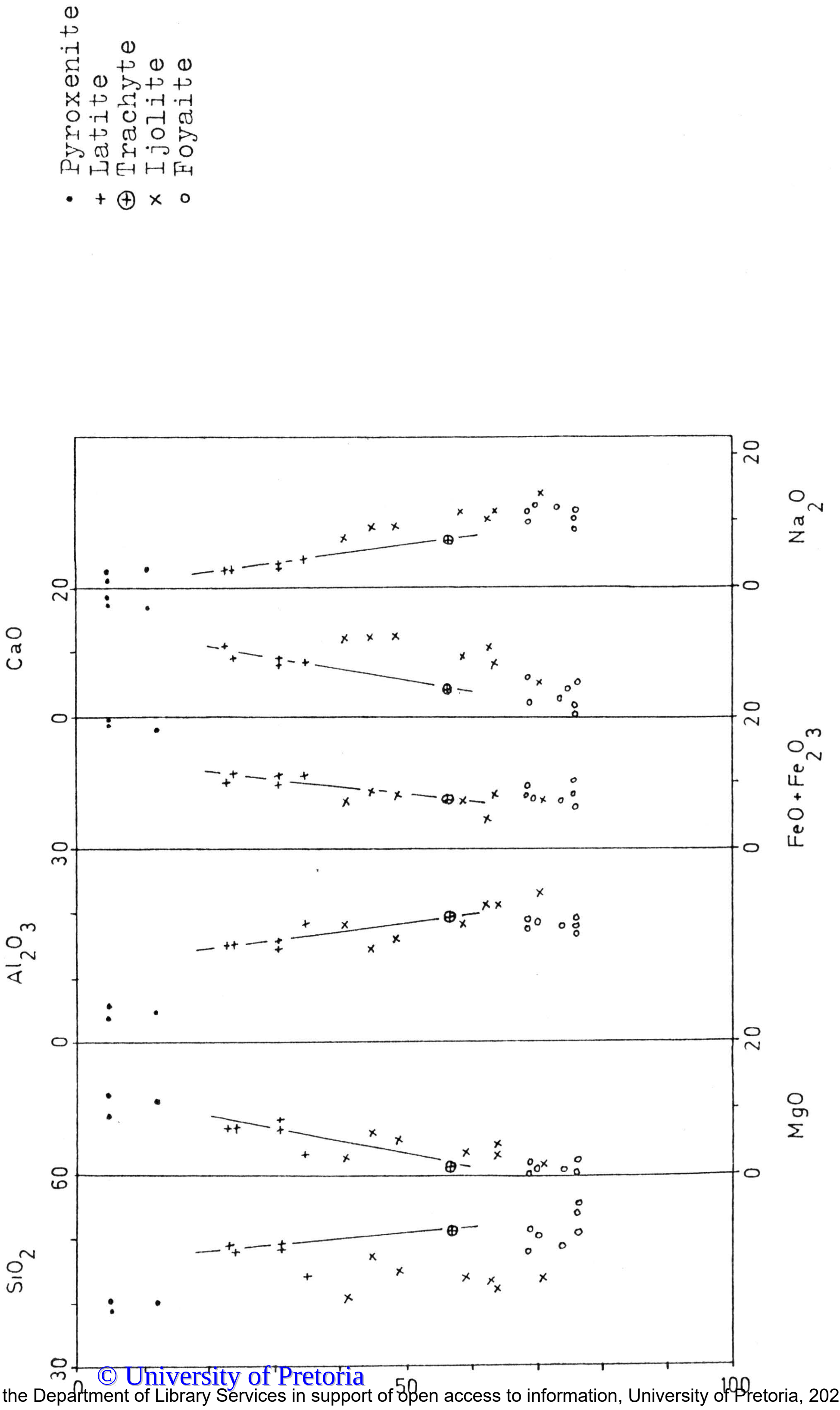
Both the analyses obtained in the present investigation and those published by Strauss and Truter (1950, p110, 112 and 113) are shown in Figure 17. From this diagram it is clear that the primary magma for the hypabyssal rocks was basaltic in composition and fractionated along the phonolitic lineage, i.e. enrichment in Na_2O with respect to K_2O.

This diagram also shows that the pyroxenite, which is the most undifferentiated of the Spitskop rocks, is likely to represent the first crystallate to have fractionated from this primary magma. According to the diagram both the ijolite and the foyaite could have fractionated from the magma during its differentiation along the phonolitic lineage.

The data thus indicate that an alkaline magma initially fractionated clinopyroxene and this was followed either by orthoclase, plagioclase and nepheline (foyaite) and then nepheline (ijolite) or by nepheline (ijolite) only. According to Rock (1976, p97), the latter sequence would be the sequence associated with high CO_2 pressure, whereas the former sequence would represent the fractionation of an alkali basalt magma under conditions of low CO_2 pressure. As no field evidence is available to indicate which dykes are related with which plutonic rock-type it is not possible to tell which crystallisation sequence was followed.

There is, however, still the carbonatite which has to fit into the fractionation sequence and as the phase relations published by Wyllie (1966) exclude the possibility of considering calcite and dolomite as the last fractionation phases, the carbonatite had to form during the

Figure 18. – Diagram of DI versus some of the major elements for the Spitskop alkaline rocks.



phonolitic line of liquid differentiation. According to Koster van Groos and Wyllie (1973) the carbonatite can form as a consequence of a high CO_2 pressure in a phonolitic magma The mechanism which they proposed requires that all the Ca^{2+}, which would form the anorthite molecules in plagioclase, would combine with the CO_2 to form a carbonatite magma which would be immiscible with a silicate magma. Should this reaction be the cause of the formation of the carbonatite magma, it is clear that the crystallisation of the foyaite would be suppressed and the fractionation sequence would be pyroxenite, ijolite and carbonatite, as was proposed by Rock (1976, p97).

On the other hand, a magmatic lineage from which no carbonatite exsolves, would yield the sequence pyroxenite, foyaite and ijolite (Rock, 1976, p97). According to the evidence in Figure 17 it is therefore clear that both mechanism must have been operating at the Spitskop Alkaline Complex.

In Figure 18 the differentiation index (DI), as proposed by Thornton and Tuttle (1960, p664) is plotted versus some of the major element concentrations of the alkaline rocks. The DI is based on the residua system in petrology, viz., the system $SiO - KAlSiO_4 - NaAlSiO_4$, and the DI is defined in terms of the normative minerals (C.I.P.W.) as:

$$DI = Q + ab + or + ns + lc$$

The differentiation trends indicated in Figure 18 with full lines represent the differentiation trends of the hypabyssal rocks, and it is proposed here that the positions of the alkaline rocks are controlled by the mineral phases in them. Thus the low alumina values of the pyroxenite relative to the other alkaline rocks are the result of the absence of alumina-bearing minerals, such as nepheline and feldspar, in it. Furthermore the ijolites have a higher alumina value than the foyaites because of the higher Al:Si ratio of the nepheline (1:1), which is the major alumina-bearing mineral in the ijolite, than that of the alkali feldspar (1:3), which is a major constituent of the foyaite.

It is evident that both the foyaite and the ijolite could have fractionated from the magma represented by the hypabyssal rocks, but it is not possible to establish whether both of the mechanisms, high or low CO_2 pressure, or only one are present on the basis of the diagrams presented in Figure 18.

It must be pointed out, however, that the DI is only strictly applicable to the differentiation of a magma, and not to that of cumulates of minerals fractionating from such a magma. The differentiation trends observed for the alkaline rocks in Figure 18 must therefore be viewed with caution and must be related to those observed for the hypabyssal rocks.

C. The trace elements

In Figure 19 the trace element concentrations of the alkaline rocks (this study) along with the Ba and Sr concentrations of the carbonatite (Verwoerd, 1967, p39) are plotted versus the DI. A value of zero for the DI is allotted to the carbonatite for the reason that CaO and MgO, which make up most of the carbonatite as carbonates, are not part of the residua system on which the DI is based.

It must be pointed out at this stage that there is a good correlation between the values of the trace elements achieved in this study and those obtained by optical sprectrographic methods by Liebenberg (1964) for some of the alkaline rocks. From the diagrams in Figure 19, however, it is evident that tha ijolite plotting at DI = 40,09 does not correlate with the other ijolites and the trace element concentrations must be assumed to be erroneous.

From the diagrams of Ba and Sr respectively versus DI, the following tentative conclusions may be drawn:

1. A differentiation trend can be drawn for both Ba and Sr which will run through the fields of the pyroxenite, the hypabyssal rocks, the ijolites and the foyaites. Average values for the abovementioned rock types would also increase in the sequence listed. These trends could be evidence of the low CO_2 pressure mechanism.

2. It is also evident that the concentration of Ba and Sr is relatively high in the carbonatite and low in the ijolite and that the hypabyssal rocks occupy an intermediate position between the two. This feature is what one would expect when a magma, represented by the hypabyssal rocks, exsolves into two magmas. The one exsolved magma may contain a high concentration of an element, which must then result in the other exsolved magma having a low concentration of the element, and with the primary magma having an intermediate concentration between the two exsolved magmas. This feature could be interpreted as evidence of the high CO_2 pressure model.

In the cases of the other trace elements there is no evidence of the high CO_2 pressure model, but this is the result of not having analyses of the carbonatite and also because it is not possible to establish which of the ijolites resulted from which of the two models.

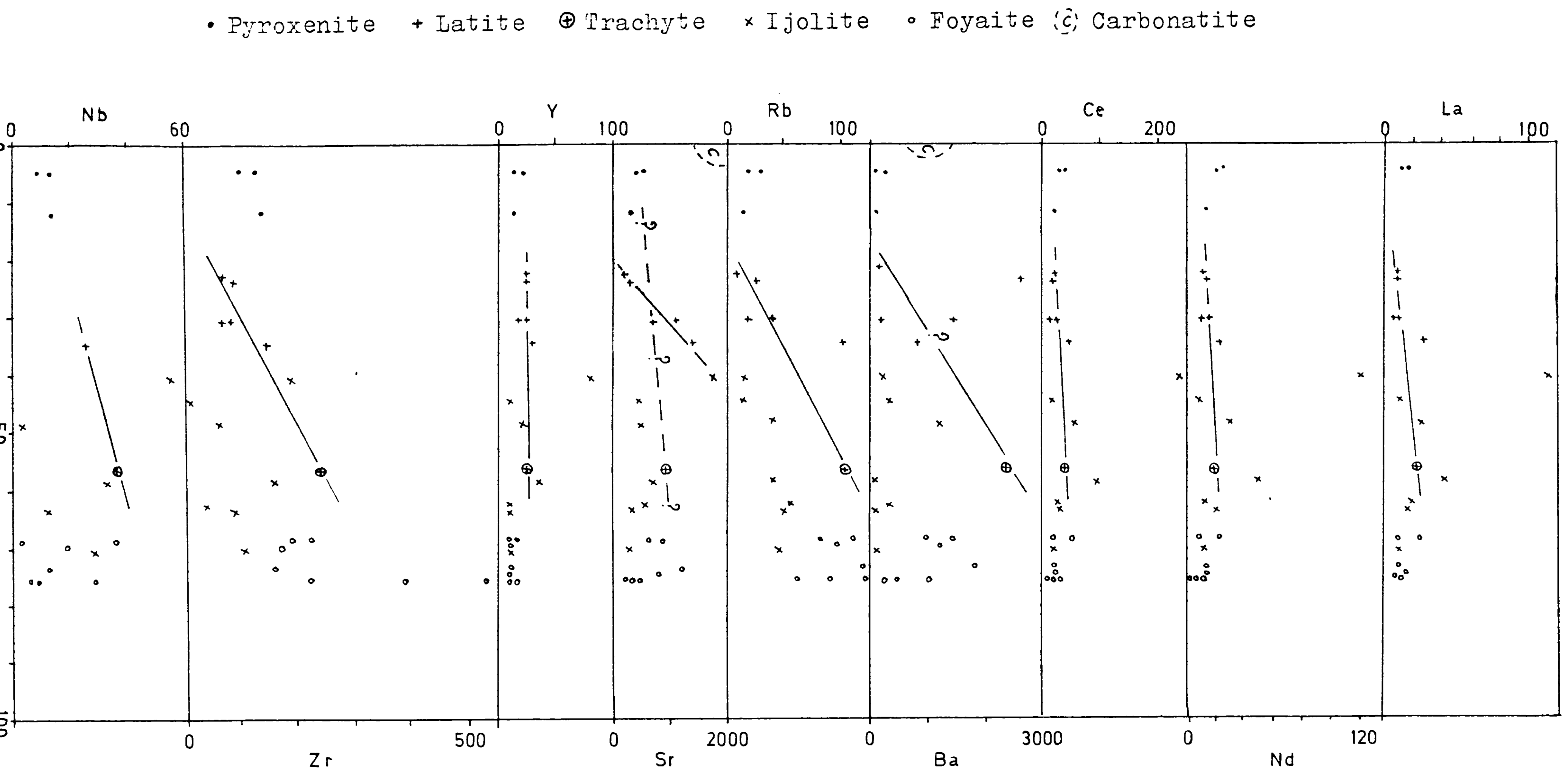
D. Conclusions

It can be concluded that the primary magma, which had a basaltic or alkaline basaltic composition, differentiated along a phonolitic lineage. The first mineral to fractionate from the magma was clinopyroxene. Two models have to be used to explain the further course of the crystallisation of the alkaline rocks and the carbonatite.

In the first model the fractionation of the clinopyroxene continued, but under conditions of low CO_2 pressure, firstly alkali feldspar, plagioclase and nepheline fractionated from the magma to give the foyaite, and secondly only nepheline fractionated along with the clinopyroxene to give ijolite.

In the second model the fractionation of the clinopyroxene also continued, but at a certain stage in the course of the differentiation, conditions of high CO_2 pressure was established. At this stage the primary magma unmixed into a silicate magma, low in calcium, and a carbonatite magma high in calcium. The silicate magma crystallised as ijolite with low calcium, strontium and barium values, whereas the carbonatite magma crystallised carbonatite high in calcium, barium and strontium.

<u>Figure 19</u>. - Diagram of DI versus some trace elements for the Spitskop alkaline rocks.



VI. SUMMARY AND CONCLUSIONS

A. The alkaline rocks

The alkaline rocks of the Spitskop Alkaline Complex is subdivided into hypabyssal rocks (latite and trachyte) and plutonic rocks (pyroxenite, foyaite, ijolite and carbonatite) on the basis of texture and mode of occurrence. The foyaite is further subdivided into the porphyritic, hypidiomorphic and trachytoidal varieties and the ijolite into the hypidiomorphic and porphyritic varieties on the basis of texture.

The ijolite is here interpreted as sills and dykes which are intrusive into a central pipe of pyroxenite, as opposed to the interpretation of a central mass of ijolite containing bodies of pyroxenite and theralite (Strauss and Truter, 1950).

A basaltic magma which differentiated along a phonolitic trend is postulated as the primary magma and the evolution of the alkaline rocks is explained with two models. In the first model pyroxenite,foyaite and ijolite crystallised under conditions of low CO_2 pressure, whereas in the second model unmixing of the primary magma occurred at an unknown stage during the differentiation of the magma. The two exsolved magmas were a carbonatite magma and a silicate magma which crystallised as carbonatite in the case of the former and ijolite in the case of the latter.

B. The xenolithic rocks

The theralites of Strauss and Truter (1950), the olivine diorite and the magnetite breccia are interpreted here as xenoliths in the alkaline complex. Because of the secondary nature of the nepheline in the theralites, the term "gabbroic rocks" is suggested, at least for those rocks with a gabbroic or dioritic composition, and it is suggested that the term "theralite" be discontinued.

The chemical variation trend of the clinopyroxenes of the gabbroic rocks is similar to those of layered intrusions, whereas that of the alkaline rocks is typically alkaline. The variation trends and the composition of the plagioclase and olivine in these gabbroic rocks indicate that they are xenoliths from the Upper Zone of the layered sequence of the Bushveld Complex, which underlies the Spitskop Alkaline Complex.

The chemical variation trends of the clinopyroxenes indicate a sequence of formation for the gabbroic rocks which is comparable with that of the Upper Zone of the layered sequence, viz. mottled anorthosite followed by magnetite diorite followed by olivine diorite. The alteration rims around certain minerals in the gabbroic rocks are interpreted as symplectitic textures inherent to the rocks of the Upper Zone, which may or may not have been altered by fenitisation in the alkaline rocks.

The magnetite breccia in the alkaline complex is grouped under the xenolithic rocks because of its spatial distribution in the complex, which is similar to that of the gabbroic rocks, and because of the presence of magnetite seams in the Upper Zone of the layered sequence.

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