THE GEOCHEMISTRY AND PETROLOGY OF KARROO BASALTS OF THE BARKLY EAST AREA, NORTH EASTERN CAPE

by

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DECLARATION

All work in this thesis is the original work of the author except where specific acknowledgement is made to the work of others.

signed : J. Pembert..........

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ABSTRACT

Sixty one basalt samples from the Drakensberg Subgroup in the Barkly East area were analysed for major elements and fourteen trace elements viz. Sr, Rb, Zr, Y, Nb, Zn, Cu, Ni, Co, V, Cr, La, Ce and Nd. These data confirm the tholeiitic nature of the Drakensberg Subgroup.

Geochemical differences in the major element compositions are small within the different units of the Drakensberg Subgroup. Small differences are also evident between these units. The trace element variation between the units and within the Lesotho Formation are more pronounced than the variation of the major elements.

The Lesotho Formation samples show a minor vertical increase in value for the top half of the Naudes Nek section in Fe, Ti, P, Zr, Nb, Y, La, Ce and Nd. A decrease in value from the same position in Mg, Ni and Co was observed. These patterns of variation are interpreted as representing low-pressure fractionation of plagioclase, olivine and clinopyroxene.

Differences between the units of the Drakensberg Subgroup are examined by using absolute trace element contents and interelement ratios. Ratios of incompatible elements differ for the different units leading to the suggestion that a heterogeneous mantle is the most likely explanation for these differences.

A unique unit of flows designated the Omega Formation is examined. The basal massive unit displays an unusual pattern of variation with height which suggests an origin through two different differentiation mechanisms.

The data from this thesis are compared with those of Cox and Hornung (1966) on the central Lesotho basalts, Bristow (1976) on the southern Lebombo basalts and Robey (1976) on the Karroo dolerites of the Eastern Cape. The geochemical comparison between the lavas of the Lesotho Formation in the Barkly East area, central Lesotho and the Karroo dolerites show no major differences. However the southern Lebombo basalts show an enrichment in Sr and depletion in Cr.

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INTRODUCTION

The purpose of this investigation is to contribute to the International Geodynamics Project, by providing new major and trace element data for the Drakensberg Subgroup lavas from the Barkly East area. This thesis is a continuation of the study of the Karroo dolerites and lavas by Robey (1976) and a geochemical comparison has been made between the dolerites (Robey, 1976) and the lavas analysed in this investigation.

In all 61 new major and trace element analyses are presented. Samples were collected from the lower Lesotho Formation along the Naudes Nek pass and from the basal volcanics in the area from Barkly East to Rhodes (Fig.1).

The major and trace element analyses were performed using a newly acquired Philips 1410 Spectrometer in the Rhodes University Geology Department. The setting-up of the X-ray techniques and calibration of the spectrometer under Prof. H.V. Eales and Dr. J.S. Marsh formed an integral part of this work.

A number of samples were collected from the basal lavas for K-Ar age dating by the $^{40}Ar\ ^{36}K$ vs $^{40}K\ ^{36}Ar$ isochron method. Two ages have been received to date:

Sample CLA 01 = 187,9 ± 5,6 m.y. (Drumbo Basalt Member)
Sample DBM 11 = 198,6 ± 7,6 m.y. (Donnybrook Basalt Member)

As the errors on the dates overlap it is assumed at present that these two samples are of similar age.

It is hoped that data from this study in conjunction with those from other areas of Karroo igneous activity will be of assistance in the unravelling of the geodynamics and fragmentation of Gondwanaland.

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INTRODUCTION

APPENDICES

1. PREVIOUS WORK

The majority of previous workers in the Barkly East area and Lesotho concentrated on mapping and general accounts of the geology. The initial work on the lavas of the Barkly East area and elsewhere in the North Eastern Cape was carried out by Du Toit (1903, 1904, 1905, 1910, 1911 and 1920) and consisted essentially of mapping, petrographical description and general discussion of field relationships. In his work Du Toit (1904, 1905) recognised an initial explosive eruptive stage in the Barkly East area as seen in the Belmore, Kelvin Grove and Broadford central vent-type structures associated with relatively abundant pyroclastic rocks. This initial stage was followed by voluminous outpourings of lava from fissure-vents to form the main lava pile of the area. Gevers (1927) described a cycle similar to that of Du Toit (1904, 1905) from his work in the Dordrecht area. The geology of Lesotho was described by Stockley (1947) who recognised a trachyte flow in the basal part of the succession followed by tholeiitic flood basalts with a few minor andesite flows.

Following on from the initial geochemical study of Walker and Poldevaart (1949), Cox (1970, 1972), Cox and Hornung (1966), Cox and Jamieson (1974), and Cox et al. (1967) have been responsible for much of the modern geochemical work on the volcanic rocks of the Karroo period. Although the bulk of their work has been on the Lebombo-Sabi area and other localities in Rhodesia, Cox and Hornung (1966) analysed 24 basalts from central Lesotho for major and some trace elements. Using this earlier work Cox et al. (1967) proposed a division of the Karroo basalts of southern Africa into Northern and Southern Provinces, based on their geochemistry. Cox (1972) published a review article where he considered all the volcanics of the Karroo as part of "a single unifying thermotectonic event postulated as initiating the disruption of Gondwanaland" which he referred to as "the Karroo Volcanic Cycle." The tectonics and vulcanism of the Karroo period were examined by Cox (1970) in relation to the breakup of Gondwanaland.

Rhodes and Krohn (1972) used the statistical approach of trend surface analysis to arrive at a model of Karroo vulcanism using the geochemical data of other workers. They find a correspondence between geochemical trend surfaces and the central Karroo structural basin and suggest that the separation of the Northern and Southern Provinces of Cox et al. (1967) is not valid.

The only age determinations for the Drakensberg subgroup prior to this study are those is that of Fitch and Miller (1971). They obtained an average age of 187 m.y. ± 7 m.y. using the K-Ar method.

The most recent published work on the Karroo volcanics of the Barkly East area by Lock et al. (1974) subdivides the volcanics using normal stratigraphic mapping techniques while Robey (1976) analysed eleven samples from the lower Barkly East basalts for major and trace elements.

2. STRATIGRAPHY AND FIELD RELATIONSHIPS

2.1 INTRODUCTION

The work of Lock et al. (1974) on the stratigraphy of the volcanics of the Barkly East area has been used extensively in this study of the Drakensberg Subgroup. It has been found in this study that the various members and formations as described and delineated by Lock et al. (1974) for the Drakensberg Subgroup exhibit distinctive geochemical characteristics.

They used lithostratigraphic units to name the rocks comprising the Karroo sequence;

Karroo Supergroup
- v) Volcanic Group = a) Lebombo Subgroup
  - b) Drakensberg Subgroup
- iv) Stormberg Group
- iii) Beaufort Group
- ii) Ecca Group
- i) Dwyka Group

In the regrouping of the Stormberg Series into the Stormberg Group, made up of sediments, and the "Volcanic Group" of lavas, they point out that the latter is an informal name to replace the older terms "Drakensberg and Lebombo Stages." In the Barkly East area the Drakensberg Subgroup was divided up into three formations on the basis of field relationships and stratigraphic height. Subsequent work has led to the recognition of another formation which is defined later in this text.

Stratigraphy of the Drakensberg Subgroup in the Barkly East Area

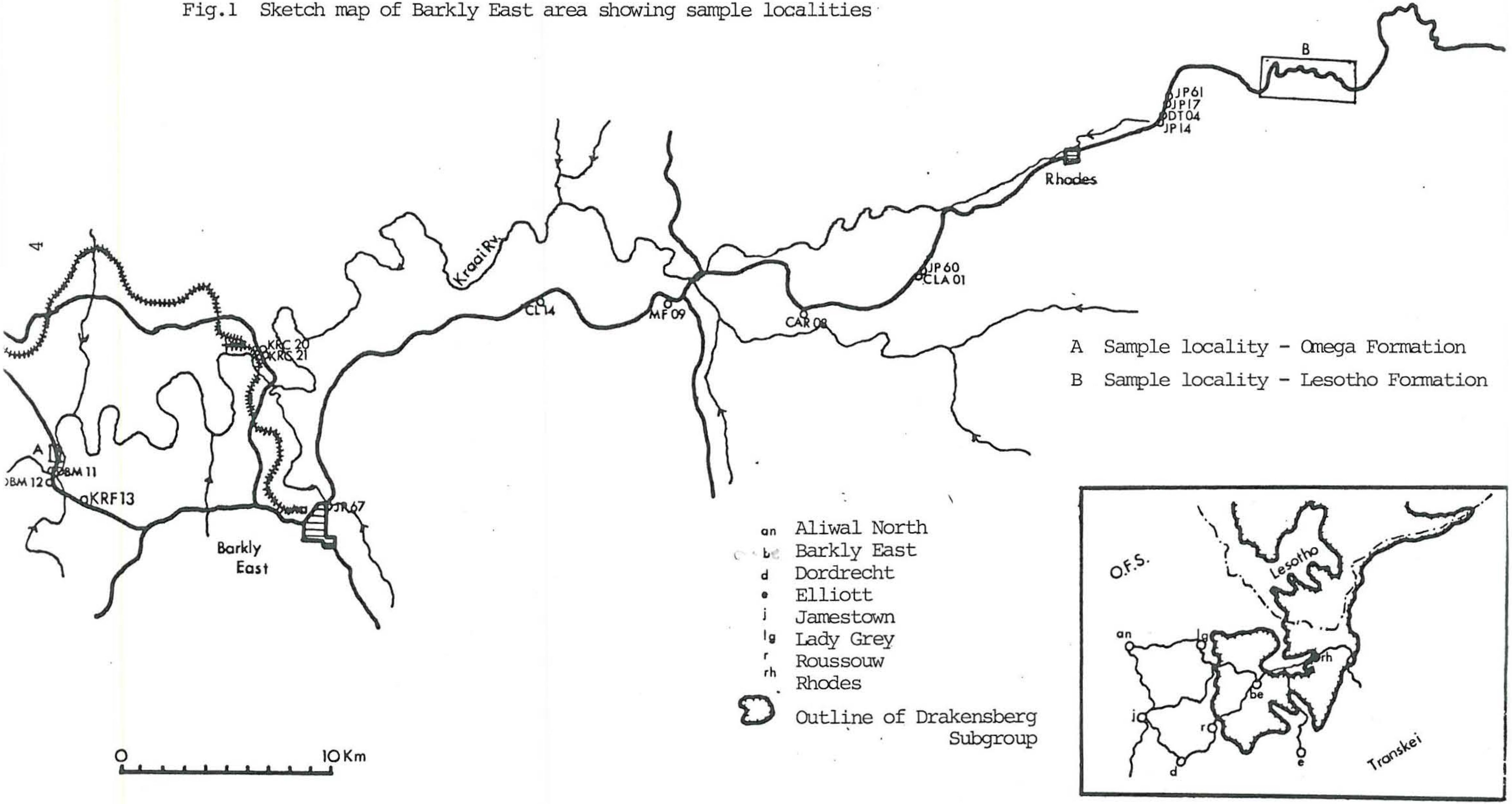
Verb ?

- iv) Lesotho Formation
- iii) Kraai River Formation
- ii) Omega Formation
- i) Moshesh's Ford Formation

2.2 THE MOSHESH'S FORD FORMATION

This formation incorporates the basal volcanics of the Barkly East area including the initial explosive stage of Du Toit (1904, 1905) and consists of the products of at least three known volcanic centres, i.e. Belmore, Kelvin Grove and Broadford.

Fig.1 Sketch map of Barkly East area showing sample localities



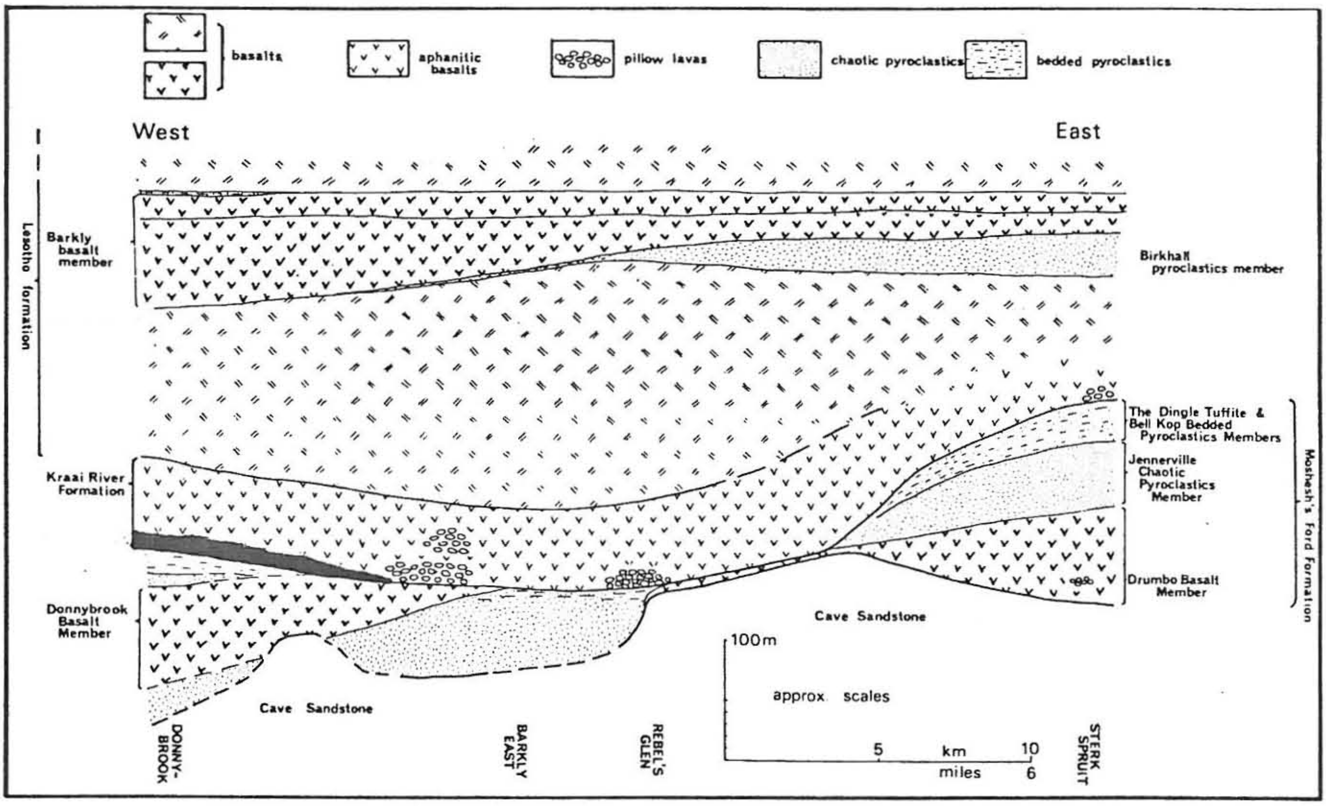


Fig.2 Summary of Stratigraphy - a west to east section (after Lock et al., 1974). Omega Formation added in black.

(fig.2). It consists of the following members:

7) Belmore Andesite Member
6) Bell River Andesitic Breccia Member
5) The Dingle Tuffite Member
4) Donnybrook Basalt Member
3) Bell Kop Bedded Pyroclastic Member
2) Jennerville Chaotic Pyroclastic Member
1) Drumbo Basalt Member

The Drumbo Basalt Member and the Donnybrook Basalt Member are important in this work in that they are the lowermost basalt lava flows of the Barkly East area. To the east of Barkly East the Drumbo Basalt Member is developed as a shield-shaped pile attaining a thickness of eighty metres in the type section. Lock et al. (1974) suggest that the Donnybrook Basalt Member, developed in the West of the area, originated from a separate centre of eruption, but from this study it has similar characteristics in the field and is petrographically and geochemically equivalent to the Drumbo Basalt Member. These two members are therefore treated as one unit in this study with their abbreviated form being Drumbo Member.

2.3 THE OMEGA FORMATION

Based on the geochemistry from this work and that of Robey (1976), the work of Minné (1974), and discussion with Dr. B.E. Lock, a unique unit consisting of several flows previously grouped with the Kraai River Formation, will now be designated, in an informal manner, the Omega Formation. Stratigraphically the Omega Formation is found between the Moshesh's Ford Formation and the Kraai River Formation. The type-section is found on the Lady Grey side of the Kraai River in the new road cutting for the Barkly East-Lady Grey tarred road. In addition to the type-section three other localities of outcrop have been identified:

a) Opposite the type-section on the Barkly East side of the Kraai River.
b) Below the type-section for the Kraai River Formation.
c) On the farm Savernake between these two localities.

The Omega Formation is approximately fifty seven metres thick and consists of thirteen flow units. (see fig.6). These units are:

a) A basal massive unit about thirty four metres thick.

b) Twelve overlying flows with thicknesses varying between one and two metres.

Robey (1976) analysed the base and top of the first thin unit overlying the massive unit, while the present study has concentrated on the massive unit.

2.4 THE KRAAI RIVER FORMATION

The Kraai River Formation underlies the 1800 metre peneplain in the Barkly East area. It consists of massive, tholeiitic, aphantic lavas with local development of pillows indicating locally aqueous conditions (Lock et al., 1974). In the type-section they report a thickness of 76 metres while on the farm Donnybrook it is 78 metres thick. The top of the Kraai River Formation is taken as the level where the mainly massive lavas give way to others which are thin and easily weathered. This assumed contact coincides with the level of the 1800 metre peneplain.

2.5 THE LESOTHO FORMATION

The name Lesotho Formation was proposed by Lock et al. (1974) for the thick sequence of lavas overlying the Kraai River Formation. It consists of up to 1300 metres of lava flows in the Mont Aux Sources region of north-eastern Lesotho, while in the Naudes Nek section examined in this study, a 600 metre section of the lower Lesotho Formation was systematically sampled. Flow thicknesses vary between one and thirty metres and Lock (pers.comm.) has mapped one prominent flow over a distance of at least 600 square kilometres. In the region of the farm Birkhall near Moshesh's Ford there occurs the Birkhall Pyroclastic Member which consists of thiry-seven metres of chaotic pyroclastics which resemble lahars (Lock et al., 1974).

3. SAMPLE TECHNIQUE AND SAMPLE LOCATIONS

3.1 INTRODUCTION

In this chapter the sampling position in the individual flows is examined in the light of preliminary geochemical work done in the Naudes Nek section. This is followed by a discussion on the sampling with regard to the area covered and the number of samples taken. The sample localities are given in detail in Appendix A.

3.2 MAJOR AND TRACE ELEMENT VARIATIONS WITHIN FLOWS

In an initial survey an attempt was made to determine the degree of variation of elements within single flows. The results of this survey allowed a decision to be made on a solution to the problem of where to sample a lava flow.
Three individual flows were sampled in the Naudes Nek section. These are numbered JP13 near the base, JP11 about halfway up and JP10 near the top of the sequence. Flows were sampled in four places with a basal sample, a sample a quarter way up, three-quarters way up and a top sample.

Amygdales were removed from all the samples, but in flow JP11 a duplicate sample with included amygdales was analysed from the top and basal levels to see what effect this had on the results. The top sample of flow JP13 was too weathered to warrant analysis.

On the basis of the major element pattern illustrated in Fig.3, it was decided to sample all flows as close to their base as possible. Two reasons can be given for this decision:

1) The major element abundances for the basal and topmost samples of each flow tend to be very similar but within the interior the composition varies erratically.
2) The base of a flow is easy to recognise and locate in the field.

Watkins et al. (1970) studied within-flow variations of major and trace elements in an Icelandic lava and found a general variation of about 5% (relative) for most major components other than SiO_2. They also found a strong positive correlation

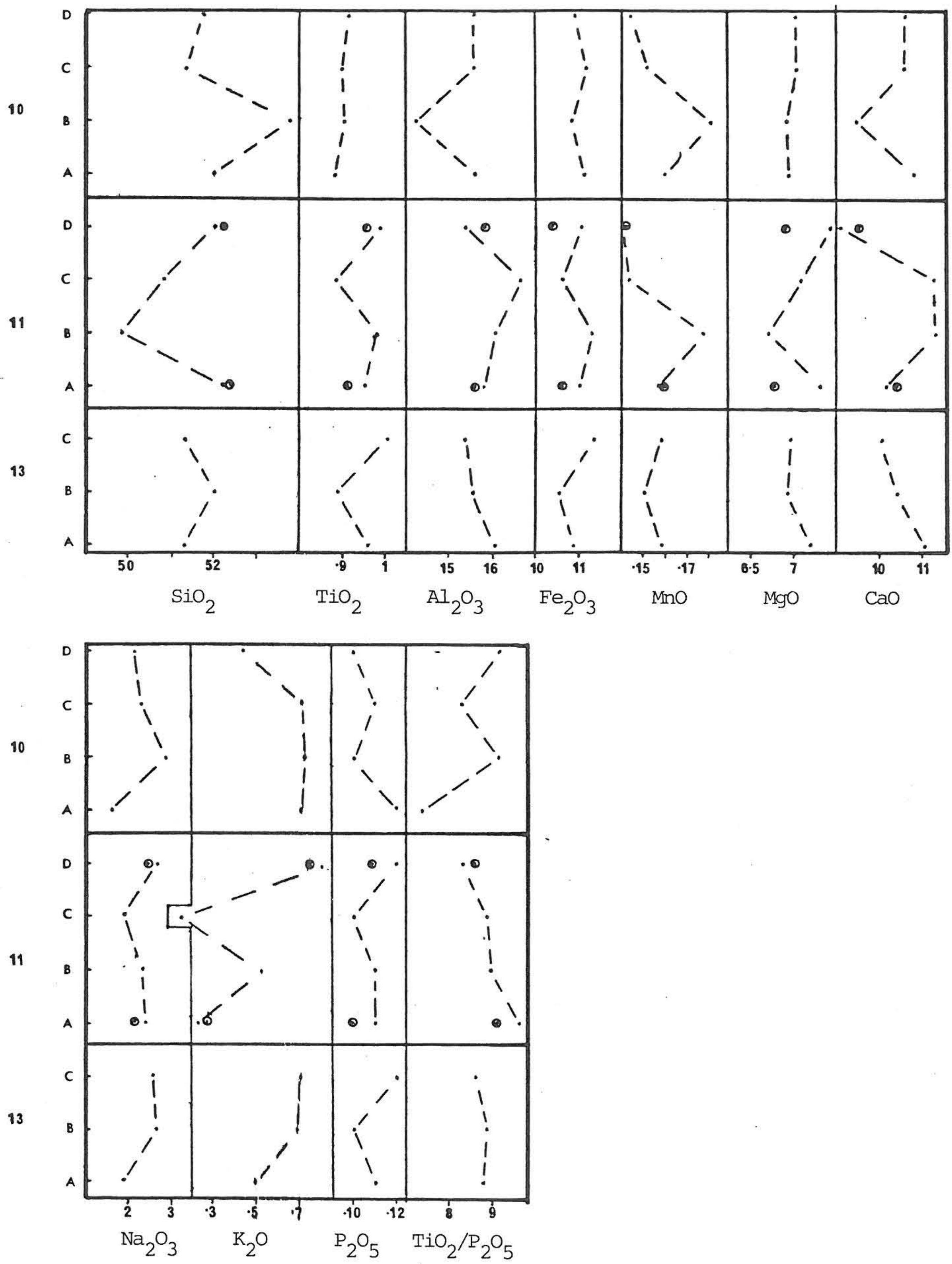


Fig.3 Major Elements from intralava sampling (LOI + H_2O^+ free data) (percentages)

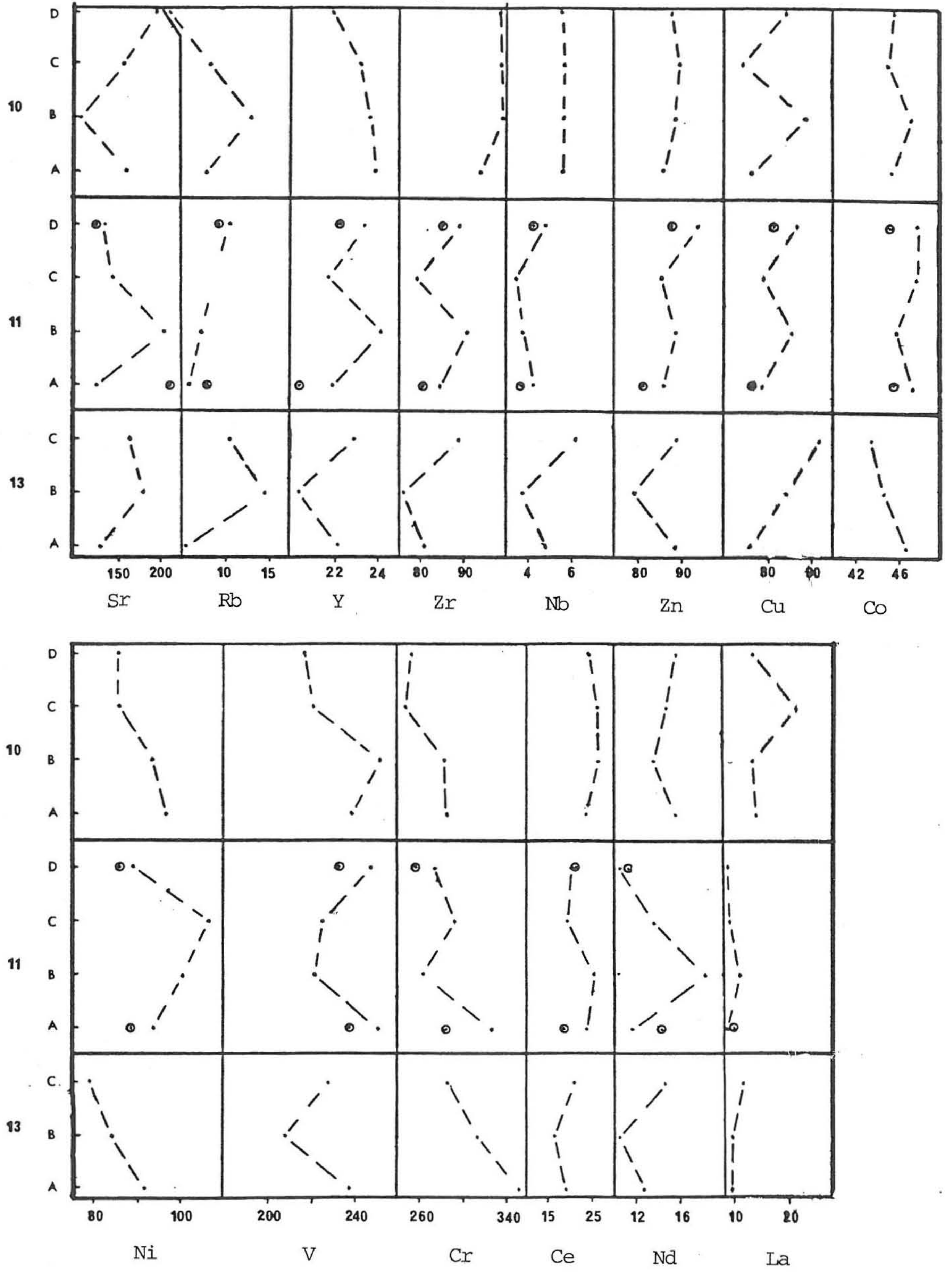


Fig.4 Trace Elements from intralava sampling (ppm)

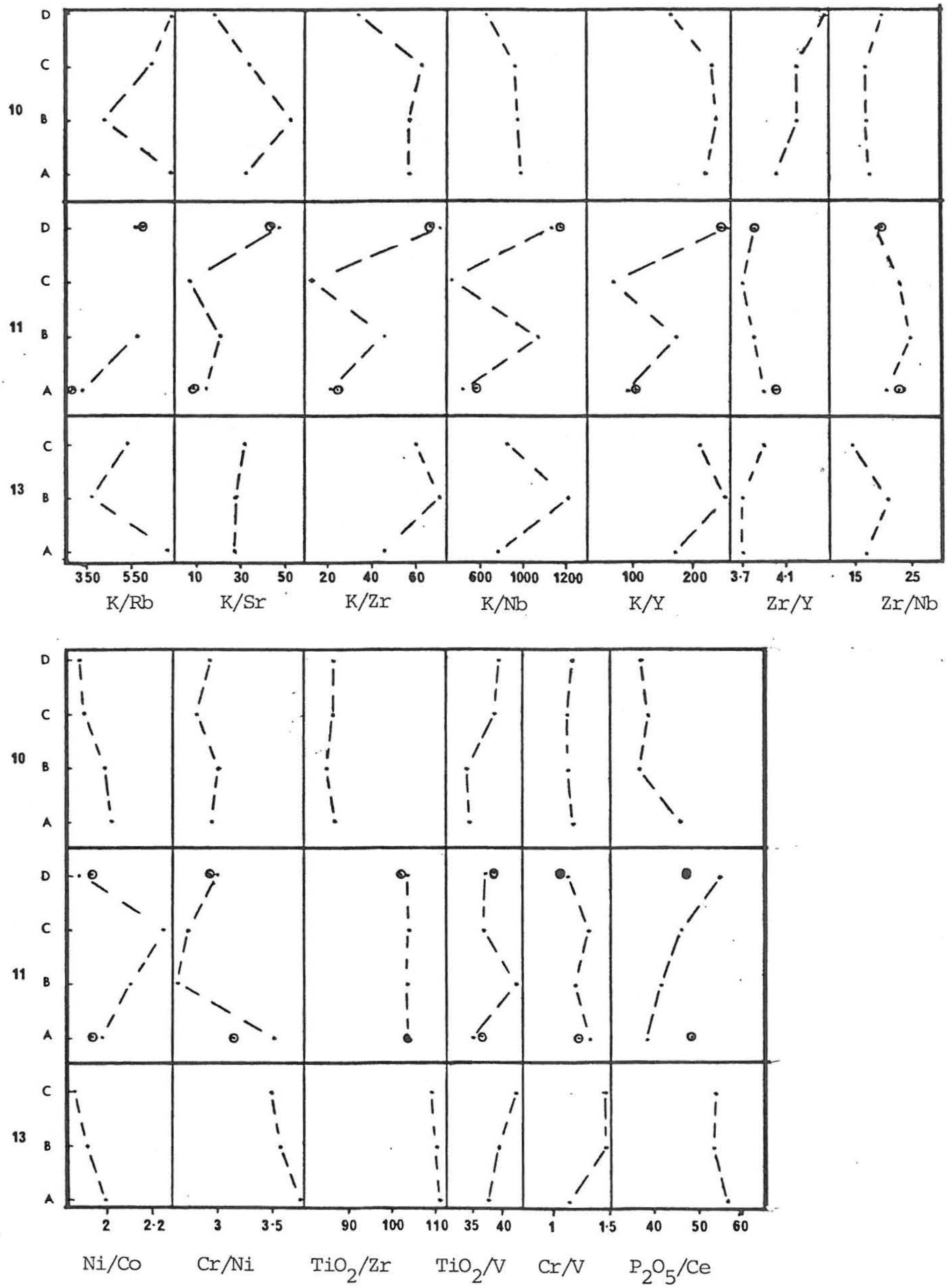


Fig.5 Interelement ratios from intralava sampling

between the following element pairs: K-Rb, Fe-Ti, Al-Ca, Ca-Na and Co-Ni. A negative correlation between Al-Fe and Al-Ti was observed. In Figs. 3 and 4 a positive correlation between Fe-Ti, Al-Ca, K-Rb and Cr-Ni as well as the incompatible elements Zr, Nb and Y is seen. Watkins et al. (1970) attribute most of the chemical variation to the non-random distribution of plagioclase and olivine phenocrysts. The rapid within-flow variation of the alkalies is attributed in part to laminar flow.

Hart et al. (1971) examined the problem of the alkalies and found that in a flow the outer surfaces are chilled rapidly and represent the original composition while the central region crystallizes more slowly until approximately 1% of the liquid remains. This liquid migrates upwards, creating an alkali-enriched layer and leaving an alkali-depleted layer behind. The close similarity between basal and top samples in this study supports the findings of Hart et al. (1971) but the two mid-flow samples have erratic contents of the alkali elements. In the crystallizing flow, the last liquid rich in alkalies and incompatible elements appears to have a random distribution within flow centres.

From this discussion it is apparent that there are two ways to produce a representative analysis from of a flow:

1) A number of samples can be taken through a flow and the results averaged.
2) The base or top of the flow can be sampled.

The ratios of various elements presented in Fig.5 provide significant information on their variation within flows. The ratio TiO_2/Zr is the most constant ratio through a single flow, remaining virtually the same from one sample to the next. Other ratios such as Zr/Y, Zr/Nb, and Cr/V are also relatively constant whereas the ratios with K tend to be erratic due to its large variation within flows, e.g. in flow JP11 K varies from 0,15% to 0,8%. Gunn et al. (1975) observed that ratios within flows are inconsistent for Na, K, Ba, Rb, Ti and Sr due to the migration of these elements.

The removal of the amygdales (see flow JP11, Figs.3, 4 and 5) leads to a slight difference in element content from those with them included. The amygdales tend to dilute the sample leading to an analysis with most elements falling below those of the sample with the amygdales removed. Of the major elements, K, Ca, Mn, Al and Si tend to have higher values in the samples with amygdales present but for the trace elements only Sr and Rb are higher.

The vesicle infillings are generally quartz, calcite and zeolites, which accounts for the higher values of Si, Al and Ca while the mobility of Rb, and the association of Sr with Ca results in their higher concentrations. The overall shift in concentration due to the presence of amygdales is however, a relatively minor one in comparison with the within-flow variations.

3.3 DISCUSSION ON SAMPLING

3.3.1 Drumbo and Donnybrook Basalt Members

As the establishing of the age of the earliest lava flows in the Barkly East area was one of the aims of this study, these two members were accordingly sampled as close as possibly to the Cave Sandstone - lava contact.
In all, nine samples were collected, with seven from the Drumbo Basalt Member and two from the Donnybrook Basalt Member. The sampling covers an area between the farm Druids Temple east of Rhodes and the new bridge across the Kraai River west of Barkly East. Fig.1 shows the sample positions while notes on their location are to be found in the appendix.

3.3.2 Omega Formation

The massive unit of the Omega Formation was sampled as a follow-up to Robey's (1976) sampling of the first overlying thin unit. In the diagrammatic sketch (Fig.6) the exact positions of samples JP1 to JP6 and KF10 as well as Robey's JR108a and b (Robey, 1976) are shown, while the general locality is seen on Fig.1.

3.3.3 Kraai River Formation

Four samples from the Kraai River Formation were collected in

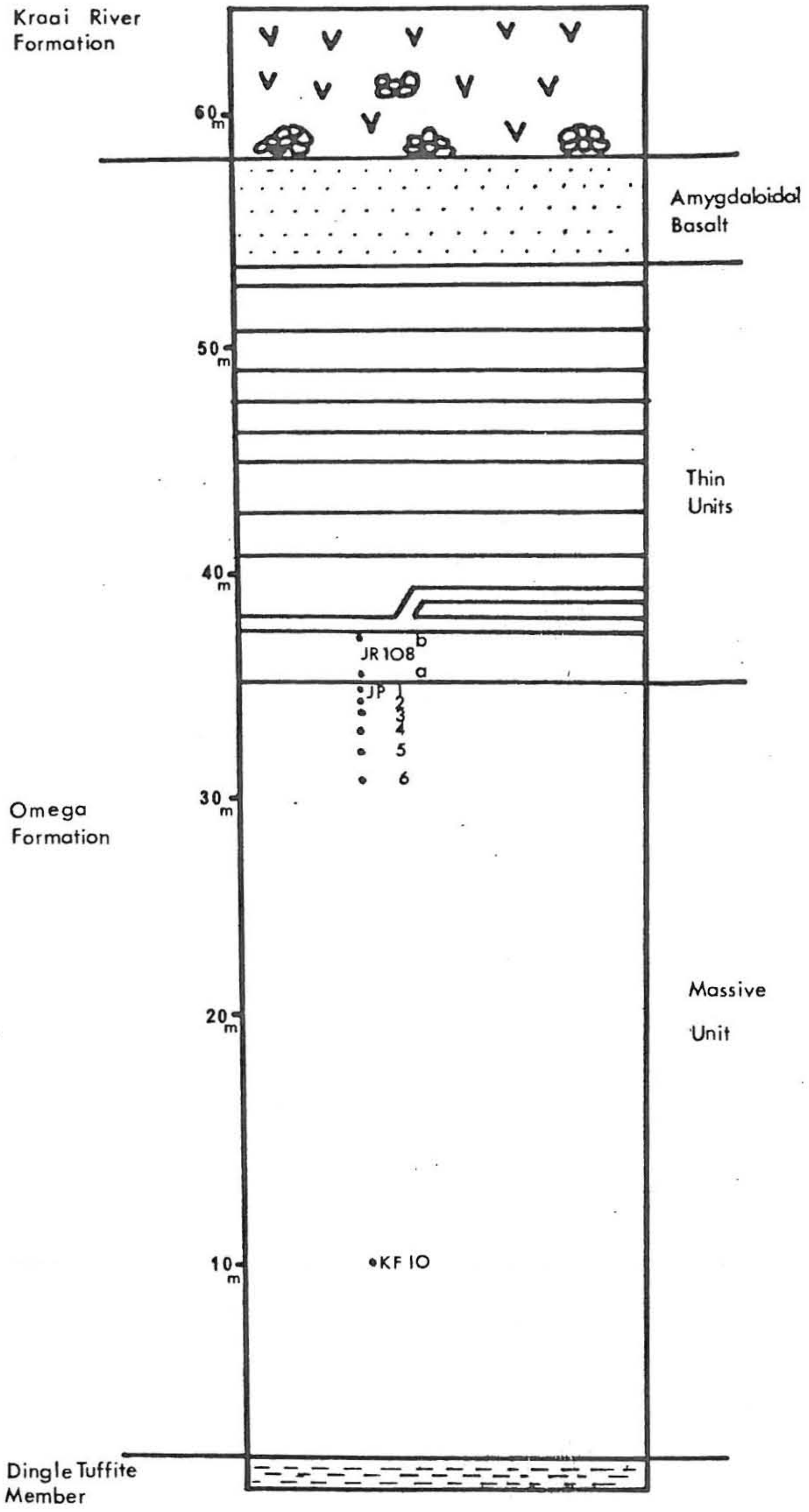


Fig.6 Diagrammatic sketch of Omega Formation showing sample positions

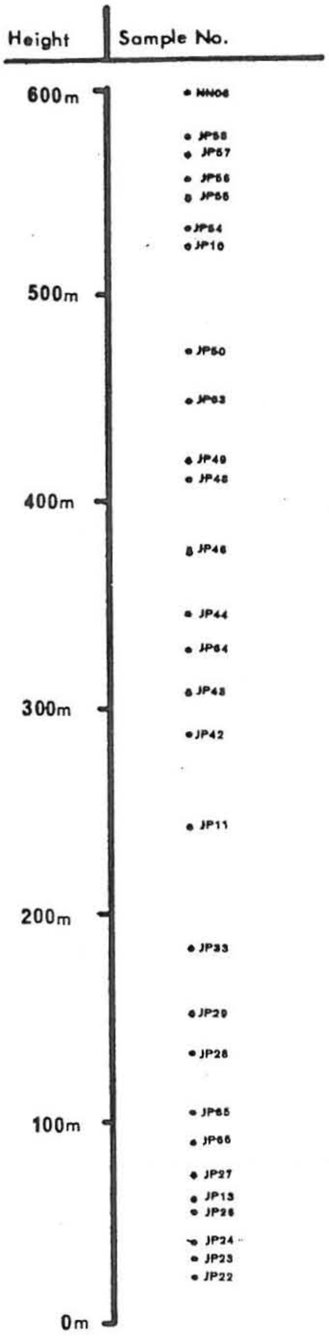


Fig.7 Diagrammatic sketch of sample position versus height for the Lesotho Formation

the general area of Barkly East. Two are from the type-section in the old Kraai River cuttings, one is from the new tarred road south of the Kraai River and one was collected close to Barkly East. The positions of these samples are plotted in Fig.1 and notes on their exact locations are given in the appendix.

3.3.4 Lesotho Formation

The Lesotho Formation was sampled along exposures provided by the Naudes Nek pass, now referred to in this text as the Naudes Nek section.

After the initial sampling to establish within-flow variations, the Lesotho Formation was sampled starting at the base close to the Naude Monument, 11½ km from Rhodes. In all, 43 samples from the basal portions of flows were collected. The sample positions were plotted in the field on aerial photographs (Job No.565, Strip No.15, Photograph Nos. 5375 and 5376) and then transferred to 1:50 000 topographic sheets of the area (3028CC Elands Height and 3027DD Rhodes). Heights were recorded in the field with a Paulin Precision Altimeter and checked against the 1:50 000 topographic sheets to give accurate locations through 600 metres of the Lesotho Formation.

In addition to these samples a further five were collected from the Naudes Nek section on a later excursion. After the thin sections had been studied 25 samples were chosen on their freshness, for chemical analysis. These 25 samples plus the three basal samples from the initial sampling experiment are plotted in the diagrammatic sketch Fig.7.

3.3.5 Miscellaneous Samples

Three further samples were collected from flows which do not form part of the Drakensberg Subgroup. One of these samples was from the basalt flow interbedded with Red Beds on the farm Siberia near Roussouw. This sample was taken from the base of the Waschbankspruit Pass on the Dordrecht - Barkly East road (sample SlB 03).

Two samples were collected on the farm Druids Temple, 4 km from Rhodes on the Naudes Nek road. These samples were at first thought to belong to the Drumbo Member but after their geochemical characteristics were established it became obvious that they were of an earlier episode related to the minor lava flows occuring within the Red Beds. In this area the Cave Sandstone/lava contact dips at 15° to the south-east, within what appears to have been a pre-lava valley. These early flows encountered aqueous conditions in the valley and formed pillow lavas while sediments were remobilised to crosscut the minor flows. The first flow of the Drumbo Member is thick and persistent and blankets these earlier flows. (Samples DT04 and JP14).

4. PETROGRAPHY

4.1 INTRODUCTION

The petrography of the Drakensberg Subgroup in the Barkly East area has been briefly examined by Lock et al. (1974) and Robey (1976) following on from the earlier work of Du Toit (1911). Walker and Poldervaart (1949) studied the Drakensberg Subgroup on a regional basis while Stockley (1947) and Cox and Hornung (1966) examined the lavas of central Lesotho.

4.2 DRUMBO AND DONNYBROOK BASALT MEMBERS

In all, nine rocks of the Drumbo Member were studied. Seven are from the Drumbo Basalt Member and two from the Donnybrook Basalt Member but as noted by Lock et al. (1974) the two members are petrographically indistinguishable.

The Drumbo Member lavas are hypocrystalline, phaneritic with intergranular to intersertal texture. In all specimens plagioclase occurs as zoned, subhedral laths 0,5 mm to 1 mm in length with compositions from An_{40}-An_{60}. Augite is subhedral to anhedral, generally having an ophitic relationship with plagioclase. Pigeonite is a common core to augite, being positively identified in the majority of rocks. Olivine is highly altered to either serpentine, iddingsite or bowlingite.

Petrographically the Drumbo Member differs from the rest of the Drakensberg Subgroup in the high percentage (approximately 15%) of glassy mesostasis. In the mesostasis crystallites occur and K-feldspar, quartz and apatite have been identified as well as iron-titanium oxides.

4.3 KRAAI RIVER FORMATION

The Kraai River Formation lavas are hypocrystalline, aphanitic-microgranular and porphyritic to glomeroporphyritic. Plagioclase occurs both as a groundmass mineral and as a phenocryst phase in subhedral lathlike form and is generally ophitically related to the pyroxenes. The composition of the plagioclase varies from An_{50} to An_{60}. Robey (1976) identified clinopyroxene only as a groundmass phase in the Kraai River Formation but from the specimens examined in this study augite is seen as a common phenocryst phase. In one rock (JP67) pigeonite occurs as cores to augite. Orthopyroxene (bronzite) occurs as phenocrysts up to 5 mm in length and usually poikilitically encloses plagioclase. Walker and Poldervaart (1949) identified a bronzite basalt in the Barkly East area and correlated it with the Hangnest-type dolerite in which bronzite occurs with augite and pigeonite. The alteration products of olivine were identified in one of the Kraai River Formation specimens. A small amount of glass and iron-titanium oxide also occurs in these rocks.

4.4 LESOTHO FORMATION

Thirty-six specimens of the Lesotho Formation were examined from the Naudes Nek section. These lavas appear to be very similar to those of the central Lesotho area studied by Cox and Hornung (1966).

The Lesotho Formation samples are hypocrystalline, aphanitic to phaneritic and intergranular to intersertal with some rocks having a glomeroporphyritic fabric. Plagioclase is subhedral, zoned and ophitically related to augite. Compositions vary from An_{50} to An_{70}. A number of positive identifications of pigeonite were made through the sequence. Cox and Hornung (1966) note that in central Lesotho pigeonite makes up a quarter of the total pyroxenes. Olivine is present in about a third of the flows examined, occuring as highly altered individual grains which are difficult to distinguish from glass. Glass is present in virtually all specimens with associated crystallites and iron-titanium oxides.

Vesicles are present and filled most commonly by zeolite minerals. Three zeolites have been identified from the Lesotho Formation in the Naudes Nek section by Anderson (1975). Heulandite occurs as amygdales and is associated with a green mineral tentatively identified as nontronite. Scolecite is found to a lesser extent as amygdales while laumontite is found solely in veins and as infillings in cracks.

4.5 OMEGA FORMATION

Fifteen specimens were studied from the massive unit of the Omega Formation. Nine of these were samples taken in the first 3 metres from the top down, while the rest were spread between 3 m from the base and 6 m from the top (Fig.8 a, b, c.).

Robey (1976) described the thin unit overlying the massive unit and a brief summary of his findings will be given here. The base of the thin unit is coarse grained with phenocrysts of plagioclase, and augite which has cores of pigeonite. Chlorophaeite is present and Robey (1976) suggests that this is an alteration product of olivine. Micropegmatite is a minor constituent found in interstices. The top of the thin unit consists of similar minerals but has abundant coarsely crystalline micropegmatite.

The top of the massive unit is marked by a plagioclase-rich zone with a network of plagioclase and clinopyroxene crystals (Fig.8). The zone is 5 mm thick while the plagioclase and clinopyroxene crystals are approximately 0,5 mm in size. Plagioclase is oriented parallel to the top of the flow. As a capping to the plagioclase-rich zone there is a layer rich in chlorophaeite while below it is the top of the relatively coarse holocrystalline massive unit.

In the top 20 cm the plagioclase encloses the clinopyroxenes poikilitically in samples C, D and E (Fig.8b). Augite has pigeonite as cores and rims and ranges in size from 0,5 to 5 mm with most augites being twinned. The clinopyroxenes in sample D are twinned and bent. From sample C to E the percentage of mesostasis and associated chlorophaeite and iron-titanium oxides increases rapidly from approximately 30% to over 70%. Sample JP3 shows a decrease in the amount of mesostasis but the medium grain size is retained.

In slides JP4 to JP6 (Fig.8c) a less coarse unit is seen than that overlying it. These three samples are holocrystalline, phaneritic and poikilophitic while plagioclase of 1 mm and clinopyroxene of up to 2 mm are present. Augite has pigeonite as cores and rims suggesting both an early and late stage of

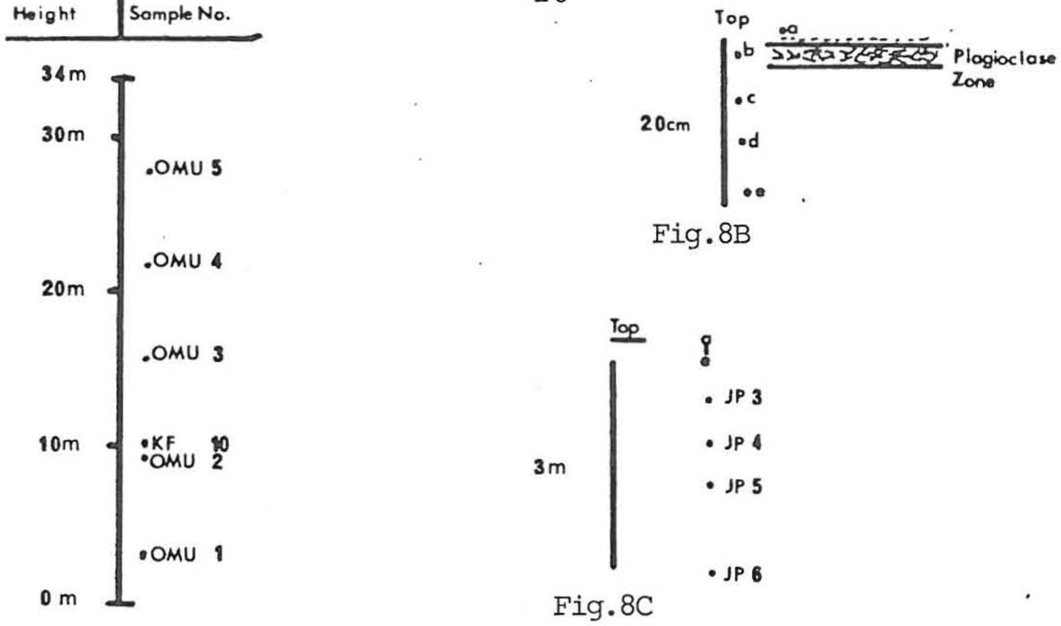


Fig.8A

Fig.8B

Fig.8C

Figs.8A-C Diagrammatic sketch of the positions of specimens from the Omega Formation studied petrographically

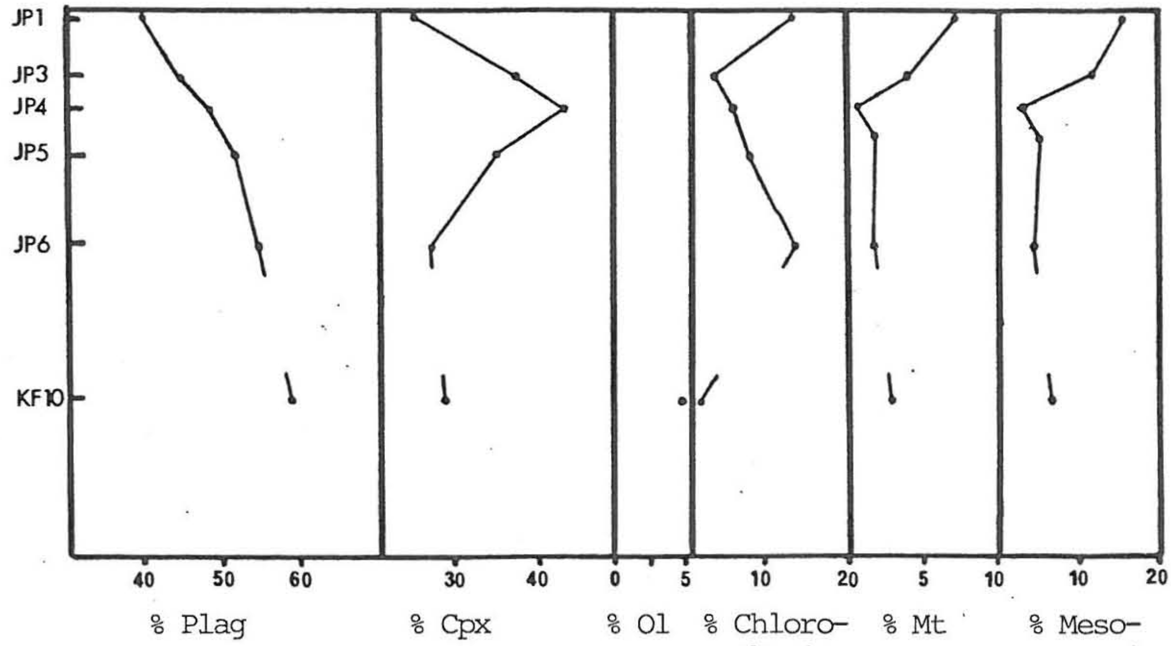


Fig.9 Modal counts in the Omega Formation

pigeonite crystallization. Chlorophaeite, mesostasis and iron-titanium oxide occur but in lesser amounts than in the overlying coarser unit.

Samples OMU5 to 1 were collected at 6-metre intervals from 3 metres above the base of the massive unit. These samples are an extension downwards of the JP4 - JP6 (Fig.8a) sequence. The textures and clinopyroxene-plagioclase relationships are similar to those of JP4 to JP6. In sample OMU1 (near the base) altered olivine is abundant but the amount falls off rapidly upwards.

Modal analysis was performed on six samples (JP1, 3, 4, 5, 6 and KF10) with approximately 600 point counts per slide. The diagrams (Fig.9) illustrate an increase in plagioclase downwards through the massive unit while clinopyroxene, chlorophaeite, magnetite and mesostasis show a change in concentration in the region of JP4.

Peacock and Fuller (1928) first described the mineraloid, chlorophaeite and since then its origin and composition have led to controversy.

Wilshire (1958) described chlorophaeite as a bright orange to dark green isotropic mineral which formed by deuteric alteration of mafic minerals. In a study of the mineralogy of Thingmuli, Easter Island, Carmichael (1967) found chlorophaeite as vesicle infillings and as an alteration product of glass. The work of Baragar et al. (1977) on chlorophaeite is perhaps the most comprehensive to date and suggests two varieties of the mineraloid exist:

1) Mg-rich variety coloured yellow to brown.
2) K-Fe-rich variety coloured in greens and deep red.

On this basis both varieties exist in the Omega Formation with the K-Fe-rich variety being dominant. On the basis of texture Baragar et al. (1977) interpret chlorophaeite as a primary low temperature mineral. The association of chlorophaeite and late-stage mesostasis in the Omega Formation supports this conclusion.

4.6 RED BEDS BASALT

The Red Beds Basalt from the farm Siberia is hypocrystalline and aphanitic with an intersertal texture. Plagioclase has an ophitic relationship to clinopyroxene and the augite is cored by pigeonite. Within the altered glass microlites and iron-titanium oxides are present. Trachytoid textures noted by Robey (1976) were not found in this specimen.

5. MAJOR ELEMENT CHEMISTRY OF THE DRAKENSBERG SUBGROUP LAVAS

5.1 INTRODUCTION

Major element compositions of samples from the Drakensberg Subgroup have been determined by Walker and Poldervaart (1949) (4 analyses), (Cox and Hornung (1966) (24 analyses), Lock et al. (1974) (4 analyses) and Robey (1976) (11 analyses). The samples of Cox and Hornung (1966) were collected in central Lesotho along the road from Leribe to Kao mine and from there to the summit of Thaba Bosiu. This sampling covered a stratigraphic section from the base to the top of the lavas. The samples analysed by Lock et al. (1974) and Robey (1976) represent the earliest lavas in the Barkly East area.

In this section 61 new major element analyses are presented for the Drakensberg Subgroup in the Barkly East area (Table 1). These samples were analysed by X-ray fluorescence using the sample preparation technique and corrections suggested by Norrish and Chappell (1969). Data reduction was done using computer programs, developed from their method and written in the Department of Geochemistry, University of Cape Town and adapted for use in the Geology Department at Rhodes University by Dr. J.S. Marsh.

All Fe was determined as Fe_2O_3 following the rationale of Norrish and Chappell (1969). Late-stage and secondary alteration have a critical effect on the normative calculation with an increasing Fe_2O_3/FeO ratio resulting in more magnetite being formed and therefore also quartz (Brooks, 1976). As the normative constituents form the basis of the classification of basalts proposed by Yoder and Tilley (1962) it is essential that the assumed Fe_2O_3/FeO ratio be as close as possible to that in the original magma. Brooks (1976) from a survey of the literature suggests a value for the Fe_2O_3/FeO ratio of 0,15 which is close to the value of 0,2 used in this work.

The major element data used in the following plots, diagrams and discussion are anhydrous values normalised to 100% (see Appendix b).

TABLE 1 : MAJOR AND TRACE ELEMENT ANALYSES OF THE DRAKENSBERG SUBGROUP

	JP 1	JP2	JP3	JP4	JP5	JP6	KF10	SIB03	JP14	DT04
SiO_2	52,70	51,5	52,97	51,33	51,16	51,21	50,22	49,73	49,79	51,66
TiO_2	1,39	1,17	1,02	0,69	0,73	0,78	0,86	1,04	0,94	1,07
Al_2O_3	12,68	13,32	14,62	15,48	15,35	15,89	14,85	14,69	15,55	15,61
x Fe_2O_3	12,76	12,16	10,81	9,54	9,78	9,96	11,00	11,26	9,09	10,44
MnO	0,17	0,18	0,16	0,15	0,15	0,15	0,17	0,15	0,14	0,15
MgO	5,24	5,69	6,26	7,58	7,28	7,34	9,24	5,43	5,69	5,91
CaO	9,20	9,80	11,17	11,52	11,42	11,05	10,03	9,22	9,95	10,15
Na_2O	2,46	2,54	2,63	2,35	2,43	2,31	2,28	1,57	2,19	2,47
K_2O	0,64	0,44	0,39	0,25	0,30	0,30	0,41	0,12	0,69	0,80
P_2O_5	0,35	0,29	0,24	0,22	0,23	0,21	0,08	0,10	0,08	0,09
L.O.I.	0,92	0,65	0,51	0,45	0,45	0,62	0,64	2,45	3,72	1,83
H_2O^+	2,51	1,95	1,28	1,72	1,56	2,14	0,53	4,53	1,19	0,60
TOTAL	101,03	99,69	102,05	101,28	100,83	101,96	100,34	100,28	99,01	100,77
Sr	190	194	196	192	193	197	184	274	213	215
Rb	15,1	9,0	8,9	5,6	6,1	6,9	7,2	n.d.	16,2	19,4
Y	39,3	29,2	25,6	20,6	21,2	21,3	21,5	25,7	23,9	26,85
Zr	159	106	91	65	70	72	79	124	104	121
Nb	8,1	3,5	3,7	3,1	2,7	2,9	1,8	1,85	4,7	5,8
Zn	106	96	82	68	69	72	81	91	77	73
Cu	131	122	102	83	81	88	77	79	79	82
Co	40	41	39	43	40	41	51	46	39	40
Ni	38	41	56	115	94	98	186	58	74	69
V	274	317	284	218	226	225	222	286	232	227
Cr	137	125	275	485	531	343	474	226	348	293
Ce	34	28	22	19	19	17	21	35	29	26
Nd	23	18	13	10	13	12	11	22	16	17
La	16	8	13	7	6	9	n.d.	12	9	14

x = All Fe determined as Fe_2O_3

n.d. = concentration below L.L.D.

JP 1-6 and KF10 - Omega Formation

SIB03 - Red Beds Basalt

JP14 and DT04 - From Farm Druids Temple

JP10a - NN06 - Lesotho Formation

JP17 - CL14 - Drumbo Member

JP67 - KRC21 - Kraai River Formation

Table 1 (cont'd.)

TABLE 1 (Cont'd). Drakensberg Subgroup

	JP10A	JP108	JP10C	JP100	JP11A	JP11AV	JP11B	JP11C	JP11D	JP11DV
SiO_2	48,08	50,02	48,38	48,37	48,23	48,47	47,60	47,55	48,41	47,85
TiO_2	0,81	0,85	0,89	0,86	0,89	0,85	0,94	0,83	0,93	0,88
Al_2O_3	14,45	13,22	14,63	14,66	14,45	14,78	15,87	15,62	14,39	14,84
Fe_2O_3	10,25	10,03	10,56	10,27	10,24	9,84	10,86	9,97	10,37	9,52
MnO	0,15	0,17	0,14	0,13	0,15	0,15	0,17	0,13	0,13	0,13
MgO	6,36	6,34	6,66	6,60	6,77	6,26	6,40	6,67	6,91	6,22
CaO	9,95	8,78	9,96	9,97	9,50	9,70	10,83	10,57	8,44	8,85
Na_2O	1,52	2,73	2,16	2,10	2,22	2,06	2,25	1,85	2,52	2,37
K_2O	0,65	0,69	0,68	0,41	0,22	0,25	0,50	0,13	0,74	0,69
P_2O_5	0,11	0,10	0,10	0,09	0,09	0,09	0,11	0,09	0,11	0,10
L.O.I.	7,17	7,02	5,63	5,70	6,75	6,94	3,05	6,09	6,97	7,17
H_2O^+										
TOTAL	99,50	99,94	99,75	99,18	99,50	99,38	98,57	99,48	99,92	98,59
Sr	167	107	161	197	127	214	205	150	134	128
Rb	7,6	13,5	8,6	4,6	5,6	7,8	7,3	n.d.	10,8	9,7
Y	23,8	23,5	23,3	21,9	22	20,4	24,1	21,6	23,4	22,3
Zr	94	99	98	98	85	82	92	80	88	85
Nb	5,5	5,9	6	5	4,2	3,6	3,6	3,5	4,9	4,4
Zn	87	88	89	88	87	84	88	86	94	88
Cu	77	89	73	84	78	77	86	78	87	82
Co	45	47	45	46	47	46	46	48	48	45
Ni	97	93	85	85	93	88	100	108	89	87
V	239	251	220	216	252	239	222	225	249	235
Cr	284	283	246	253	329	285	263	292	274	260
Ce	24	26	26	25	25	18	26	20	20	21
Nd	15	14	15	16	12	14	18	14	10	11
La	14	13	22	13	8	10	10	9	8	n.d.

Table 1 (cont'd.)

TABLE 1 (Cont'd.) Drakensberg Subgroup

	JP13A	JP13B	JP13C	JP22	JP23	JP24	JP26	JP27	JP28	JP29	JP33
SiO_2	47,94	49,10	48,71	47,95	49,58	48,33	50,84	49,87	52,23	49,80	49,20
TiO_2	0,90	0,84	0,98	0,90	0,92	0,93	0,88	0,90	0,99	1,09	0,85
Al_2O_3	15,00	14,68	14,63	15,06	15,13	14,95	14,04	15,04	15,03	13,51	15,80
Fe_2O_3	10,19	9,95	10,80	10,50	10,56	10,79	10,27	10,72	10,75	11,42	9,77
MnO	0,14	0,14	0,15	0,15	0,15	0,16	0,12	0,15	0,18	0,16	0,15
MgO	6,56	6,48	6,87	7,39	7,08	7,14	6,70	7,54	6,10	6,62	7,23
CaO	10,32	9,89	9,65	10,18	10,44	10,54	8,77	10,80	10,35	10,78	10,88
Na_2O	1,74	2,56	2,45	1,84	2,17	1,97	2,59	2,15	2,49	1,82	2,00
K_2O	0,46	0,64	0,66	0,54	0,59	0,53	0,89	0,46	0,70	0,79	0,40
P_2O_5	0,11	0,09	0,12	0,09	0,10	0,10	0,10	0,08	0,13	0,12	0.08
L.O.I.	6,36	4,92	5,16	1,54	0,91	1,38	1,58	0,80	0,40	3,19	1,37
H_2O^+				3,49	2,41	2,66	2,93	1,95	1,02	1,20	2,46
TOTAL	99,70	99,30	99,87	99,62	100,04	99,46	99,72	100,45	100,35	100,50	100,18
Sr	132	179	168	196	198	201	189	192	193	134	168
Rb	5,3	14,7	11,1	8,7	10,1	7,2	49,7	8	13,4	25,8	11
Y	22	20,5	23	22,6	23	24	23	22,3	30	30,1	22,5
Zr	81	76	90	87	86	88	83	77	119	99	80
Nb	4,9	3,8	6,3	5,6	6,1	5,4	4,5	3,5	4,7	4,9	2,6
Zn	88	80	90	80	88	88	89	76	79	86	82
Cu	76	85	92	75	85	124	81	81	78	91	84
Co	47	45	44	47	47	48	48	44	44	41	43
Ni	93	85	79	104	91	99	90	111	100	50	91
V	237	210	229	240	245	229	256	222	224	278	207
Cr	351	313	285	323	308	310	320	338	345	333	298
Ce	18	17	22	23	23	27	25	24	33	23	21
Nd	13	10	15	12	12	16	15	12	18	17	11
La	10	10	12	9	10	10	6	7	11	9	8

Table 1 (cont'd.)

TABLE 1 (Cont'd.) Drakensberg Subgroup

	JP42	JP43	JP44	JP46	JP48	JP49	JP50	JP54	JP55	JP56	JP57
SiO_2	48,70	47,06	49,55	46,61	49,15	49,10	49,09	49,40	49,80	48,87	49,41
TiO_2	0,87	0,81	0,86	0,81	0,90	0,89	0,91	0,86	0,94	0,94	1,03
Al_2O_3	15,60	15,75	15,14	15,13	14,92	15,39	14,87	15,13	15,03	15,41	14,82
Fe_2O_3	10,14	9,74	10,64	10,03	10,42	10,63	10,73	10,72	10,74	11,01	11,43
MnO	0,17	0,14	0,15	0,14	0,18	0,16	0,15	0,13	0,16	0,16	0,16
MgO	7,15	6,38	7,69	7,05	6,68	7,00	6,88	6,83	6,12	6,25	6,07
CaO	9,57	10,31	10,56	10,64	10,64	10,42	10,46	10,15	9,66	10,57	9,47
Na_2O	2,10	1,62	2,09	1,27	1,76	2,23	1,95	2,21	1,68	2,10	2,22
K_2O	0,93	0,68	0,23	0,19	0,15	0,63	0,65	0,72	0,65	0,36	0,89
P_2O_5	0,10	0,08	0,08	0,09	0,10	0,12	0,10	0,09	0,10	0,11	0,12
L.O.I.	1,75	3,38	0,67	4,210	1,31	0,78	1,15	1,45	3,92	3,08	2,77
H_2O^+	3,19	2,61	2,21	3,020	3,45	2,10	2,80	2,59	2,76	1,65	2,11
TOTAL	100,26	98,82	99,86	99,18	99,70	99,42	99,73	100,28	101,54	100,51	100,49
Sr	187	181	189	125	199	202	195	194	243	163	210
Rb	28,6	18	n.d.	7,1	n.d.	12,9	12,2	11	26,7	6,5	20,2
Y	22,2	19,7	22,4	21,4	24,4	23,7	25,9	24	24,2	24,7	25,6
Zr	84	78	82	87	97	95	105	98	105	102	108
Nb	3,8	3	2,4	4	5	4,9	4,5	5,3	4,9	4,7	5,4
Zn	72	79	81	81	82	89	83	91	92	93	97
Cu	82	74	79	79	85	80	85	77	95	85	86
Co	46	44	48	44	48	49	46	48	44	44	44
Ni	98	111	102	96	86	92	94	94	71	70	60
V	208	207	224	231	230	228	221	232	195	234	248
Cr	227	255	290	303	215	218	247	250	191	202	161
Ce	23	18	23	24	31	26	32	29	27	30	31
Nd	14	12	13	11	17	16	14	14	16	16	15
La	9	7	8	11	12	8	14	12	10	12	10

Table 1 (Cont'd.)

TABLE 1 (Cont'd.) Drakensberg Subgroup

	JP58	JP63	JP64	JP65	JP66	NN06	JP17	JP60	JP61	CLA01
SiO_2	50,22	50,56	51,22	51,21	50,90	49,36	51,37	52,86	52,44	52,34
TiO_2	1,01	0,89	0,85	0,94	0,93	1,00	1,05	1,06	0,99	1,04
Al_2O_3	14,82	15,40	15,44	15,23	15,12	15,33	15,45	15,29	15,61	15,21
Fe_2O_3	11,21	10,87	10,57	10,59	10,95	10,93	10,06	10,54	10,10	10,65
MnO	0,15	0,15	0,14	0,16	0,16	0,18	0,14	0,16	0,13	0,16
MgO	5,86	7,18	7,55	7,29	7,66	6,01	5,75	5,83	5,49	6,36
CaO	9,75	10,67	10,44	10,51	10,59	9,80	9,76	10,10	9,89	9,79
Na_2O	2,08	2,18	2,11	2,21	2,27	2,34	2,63	2,80	2,57	2,77
K_2O	0,87	0,62	0,34	0,49	0,49	0,35	1,09	1,12	1,06	1,09
P_2O_5	0,13	0,10	0,08	0,09	0,09	0,12	0,15	0,15	0,15	0,15
L.O.I.	3,09	0,79	0,93	0,39	0,50	3,20	0,66	0,76	0,66	0,39
H_2O^+	1,54	1,65	1,70	1,03	1,03	2,36	0,86	0,72	0,88	0,67
TOTAL	100,73	101,05	101,41	100,62	100,69	100,98	99,01	101,40	99,97	100,63
Sr	199	201	182	193	193	234	343	290	287	286
Rb	24	13,3	4,1	9,2	10,2	5,5	22,2	22,7	23,2	21,3
Y	25,4	23	21,4	23,4	24	24,3	26,4	27,1	26	26,6
Zr	106	93	80	77	77	104	153	156	153	154
Nb	5,6	4	2,7	2,7	3,4	4,6	16,4	16,6	15	16,5
Zn	94	87	86	76	69	83	83	88	76	93
Cu	99	80	75	75	67	88	78	77	58	77
Co	46	49	49	45	46	43	38	41	42	40
Ni	60	91	109	83	93	67	62	55	70	67
V	248	218	225	267	230	259	227	232	217	226
Cr	171	222	267	372	317	149	320	287	288	298
Ce	26	24	20	22	15	30	44	42	39	47
Nd	11	15	11	13	9	15	22	21	20	24
La	14	11	7	10	8	11	19	20	16	21

Table 1 (Cont'd.)

TABLE 1 (Cont'd.) Drakensberg Subgroup

	CAR08	MF09	DBM11	DBM12	CL14	JP67	KRF13	KRC20	KRC21
SiO_2	51,15	52,72	52,27	50,12	52,22	53,73	53,58	53,91	50,15
TiO_2	0,95	1,02	0,98	0,99	1,06	0,84	0,87	0,85	0,85
Al_2O_3	15,83	15,45	15,73	15,40	15,76	14,90	15,05	14,78	15,02
Fe_2O_3	9,84	10,57	10,26	9,56	9,92	9,86	9,89	9,89	9,79
MnO	0,13	0,15	0,15	0,14	0,15	0,14	0,15	0,14	0,15
MgO	5,64	5,80	6,41	5,88	5,60	6,64	6,48	6,31	6,53
CaO	10,50	10,11	9,92	10,07	10,27	9,59	9,84	9,87	10,64
Na_2O	2,33	2,50	2,50	2,18	2,46	2,25	2,03	2,37	1,96
K_2O	0,96	1,08	1,00	0,97	1,07	0,86	0,37	0,34	0,33
P_2O_5	0,14	0,15	0,14	0,14	0,16	0,09	0,09	0,09	0,09
L.O.I.	2,14	0,65	0,74	1,65	1,02	0,49	1,69	1,42	2,04
H_2O^+	1,22	1,29	1,12	2,91	1,41	1,32	1,43	0,97	2,37
TOTAL	100,82	101,49	101,22	100,01	101,08	100,70	100,85	100,94	99,91
Sr	309	297	303	308	334	191	210	199	229
Rb	19,3	20,8	19,6	18	21,5	28,3	10	32,8	8,5
Y	25	27	25,6	24,6	26,1	26,5	27,5	26,6	26,7
Zr	138	150	147	141	149	110	115	113	116
Nb	15,2	16,2	15	15,7	15,6	4,5	4,6	4,3	4,2
Zn	80	89	76	85	81	74	82	85	84
Cu	66	72	70	73	72	54	61	62	68
Co	38	40	41	39	38	39	40	40	43
Ni	67	67	80	71	61	46	48	42	54
V	201	224	214	213	204	229	251	245	256
Cr	300	297	325	288	251	276	272	278	297
Ce	42	48	40	42	37	39	37	37	33
Nd	21	24	20	19	20	19	23	20	19
La	16	21	18	18	17	16	16	17	17

5.2 CLASSIFICATION AS THOLEIITES

The classification scheme of Yoder and Tilley (1962) using the normative components has been used to classify the basalts of the Drakensberg Subgroup.

They recognise the following five basalt types:

1) Tholeiite (oversaturated) - normative quartz and hypersthene.
2) Tholeiite (saturated; hypersthene basalt) - normative hypersthene.
3) Olivine tholeiite (undersaturated) - normative hypersthene and olivine.
4) Olivine basalt - normative olivine.
5) Alkali basalt - normative olivine and nepheline.

The norms for the analysed samples of the Drakensberg Subgroup are presented in Table 2. Of the 61 samples, 59 can be classified as belonging to the oversaturated tholeiite type, having normative quartz and hypersthene. The other two are classified as olivine tholeiites, having normative hypersthene and olivine. One of these olivine tholeiites is from the base of the massive unit of the Omega Formation (sample KF10) with almost 5% olivine in the mode. The other (JP11B) is one of six samples from a single flow with the others all being oversaturated tholeiites. This sample has low SiO_2 and high Fe_2O_3 in comparison to the other samples which results in the appearance of olivine in the norm.

Kuno (1968) used the plot of ($K_2O + Na_2O$) vs SiO_2 to distinguish chemically between what he regards as three different magma types. Robey (1976) used this plot to identify the strongly tholeiitic nature of the Karroo dolerites. In Fig. 10 the Drakensberg Subgroup specimens are plotted as well as the field for the Karroo dolerites studied by Robey (1976). The Lesotho Formation specimens, with three exceptions, plot within the Karroo dolerite field and tholeiitic basalt field. The Kraai River Formation specimens fall well within the tholeiitic field while those of the Drumbo Member plot within the high alumina basalt field.

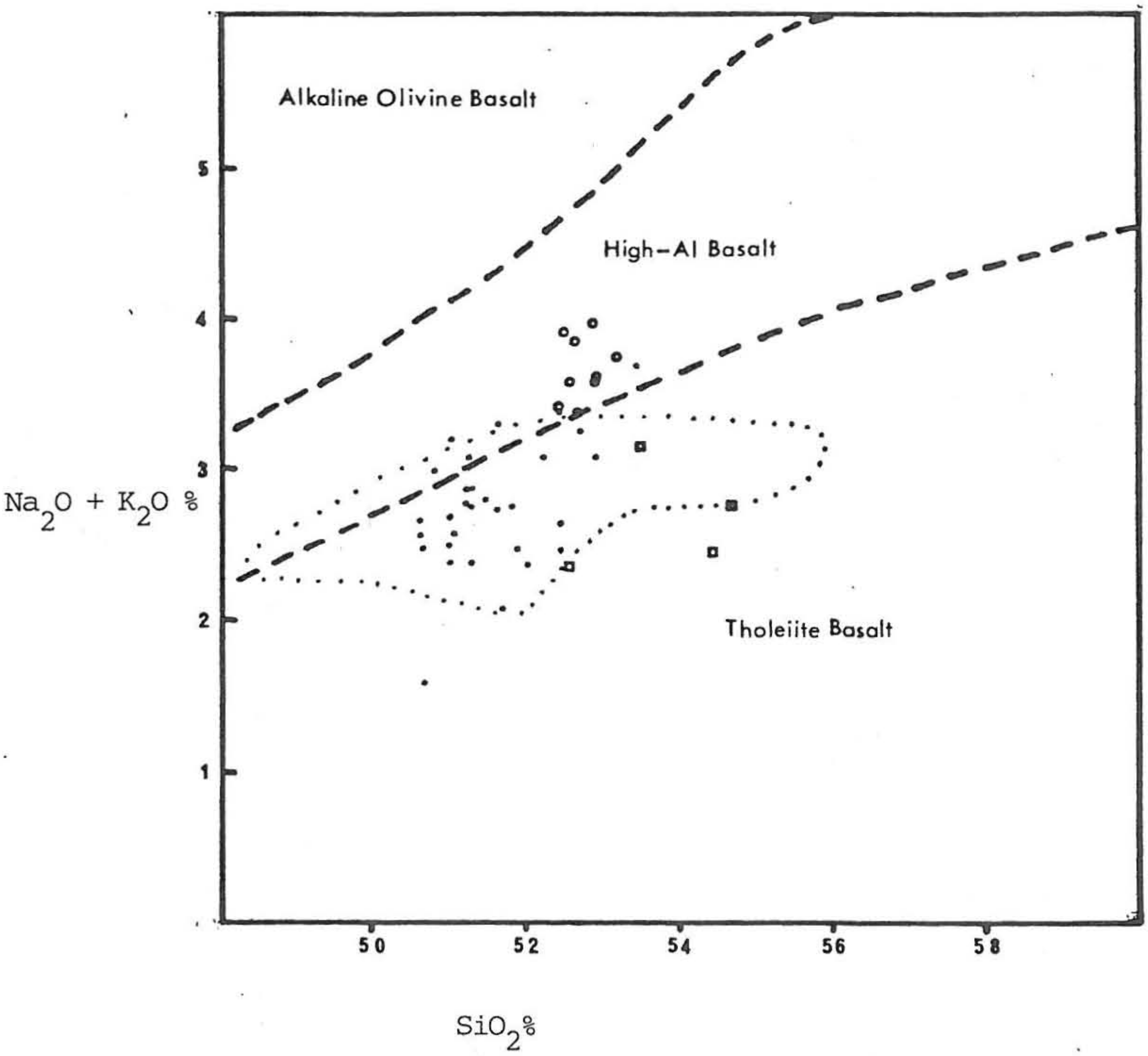


Fig.10 Alkali-silica diagram (after Kuno, 1968) for the Drakensberg Subgroup in the Barkly East area

○ Drumbo Member

□ Kraai River Formation

• Lesotho Formation

··· Dolerites (Robey, 1976)

In Kuno's classification of high alumina basalts (Kuno, 1968) an Al_2O_3 value of greater than 16,5% is considered definitive. The nine samples from the Drumbo Member have less than 16,5% Al_2O_3 and are not considered to be high alumina basalts. From the normative components the Drumbo Member samples are classified as oversaturated tholeiites which are relatively enriched in alkalies in contrast with the rest of the Drakensberg Subgroup. This results in the Drumbo Member samples plotting within the high alumina basalt field on the (K_2O + Na_2O) vs SiO_2 plot of Kuno (1968).

5.3. MAJOR ELEMENTS IN THE DRAKENSBERG SUBGROUP

5.3.1 Introduction

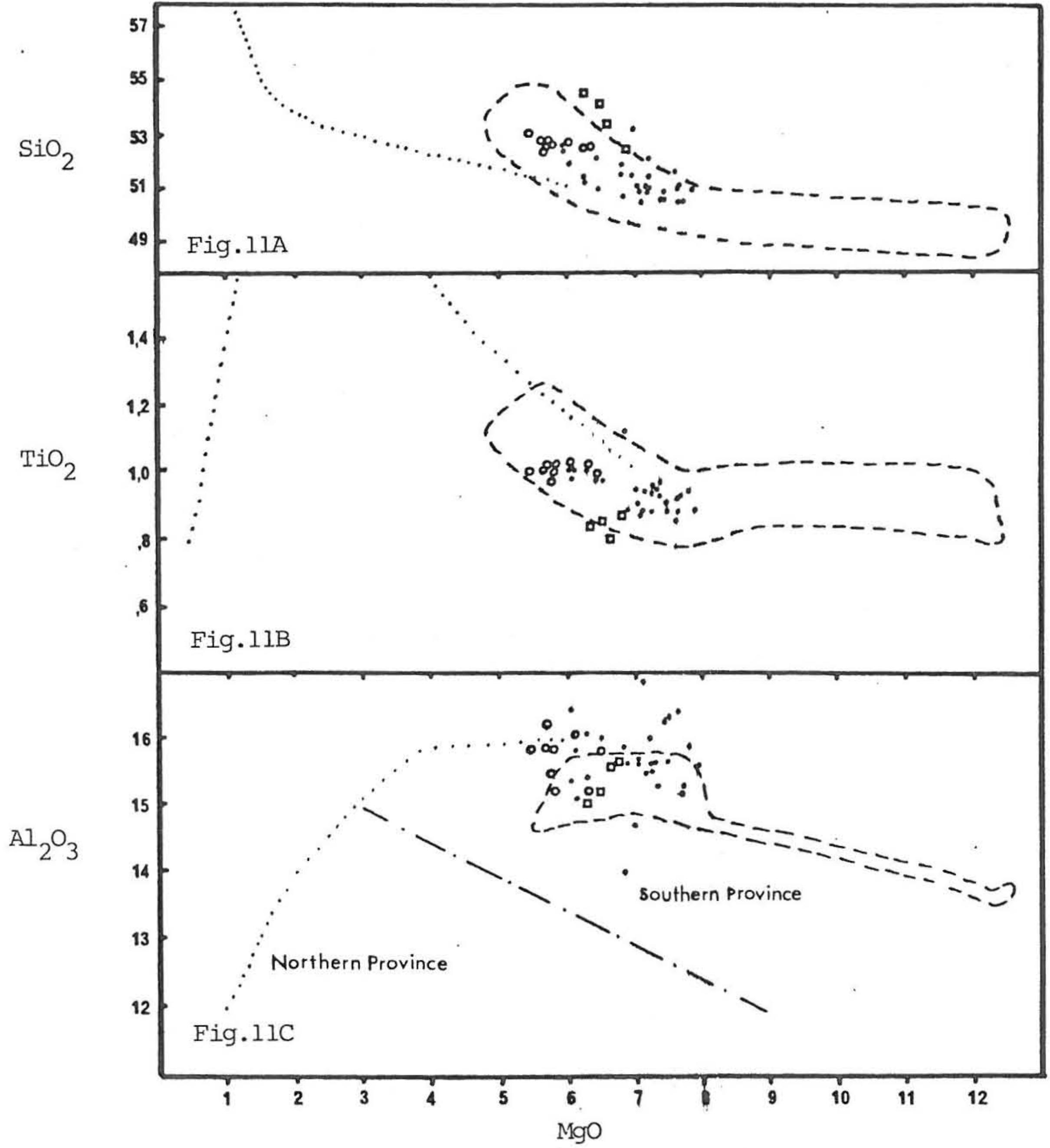
Cox et al. (1967) used MgO as the abscissa in oxide-variation diagrams in their comparison of the Northern and Southern Karroo Provinces. Robey (1976) used MgO in his study of the Karroo dolerites and lower Drakensberg Subgroup lavas. Wright (1974) has recommended the use of MgO as the abscissa in variation diagrams of ultramafic and basaltic rocks. Following the work of these authors MgO has been used in the oxide-variation diagrams in this work (Fig.11a to h). This has allowed a comparison to be made between the study of Karroo dolerites by Robey (1976) and that of the Drakensberg Subgroup by the writer.

The trend of differentiation of the Birds River Intrusion (Robey, 1976) is included in the diagrams as an indication of low-pressure fractionation trends of Karroo magmatism.

Considering the relatively undifferentiated nature of the Drakensberg Subgroup the major elements are discussed by comparison between the different units.

5.3.2 Comparison of Major-Elements within the Drakensberg Subgroup

The fields of the major elements in the Drakensberg Subgroup are presented in Figs.11a to h while the individual analyses are presented in Table 1. In summary, the differences and similarities are:



Figs.11 A-H Major element data for the Drakensberg Subgroup in the Barkly East area plotted against MgO%

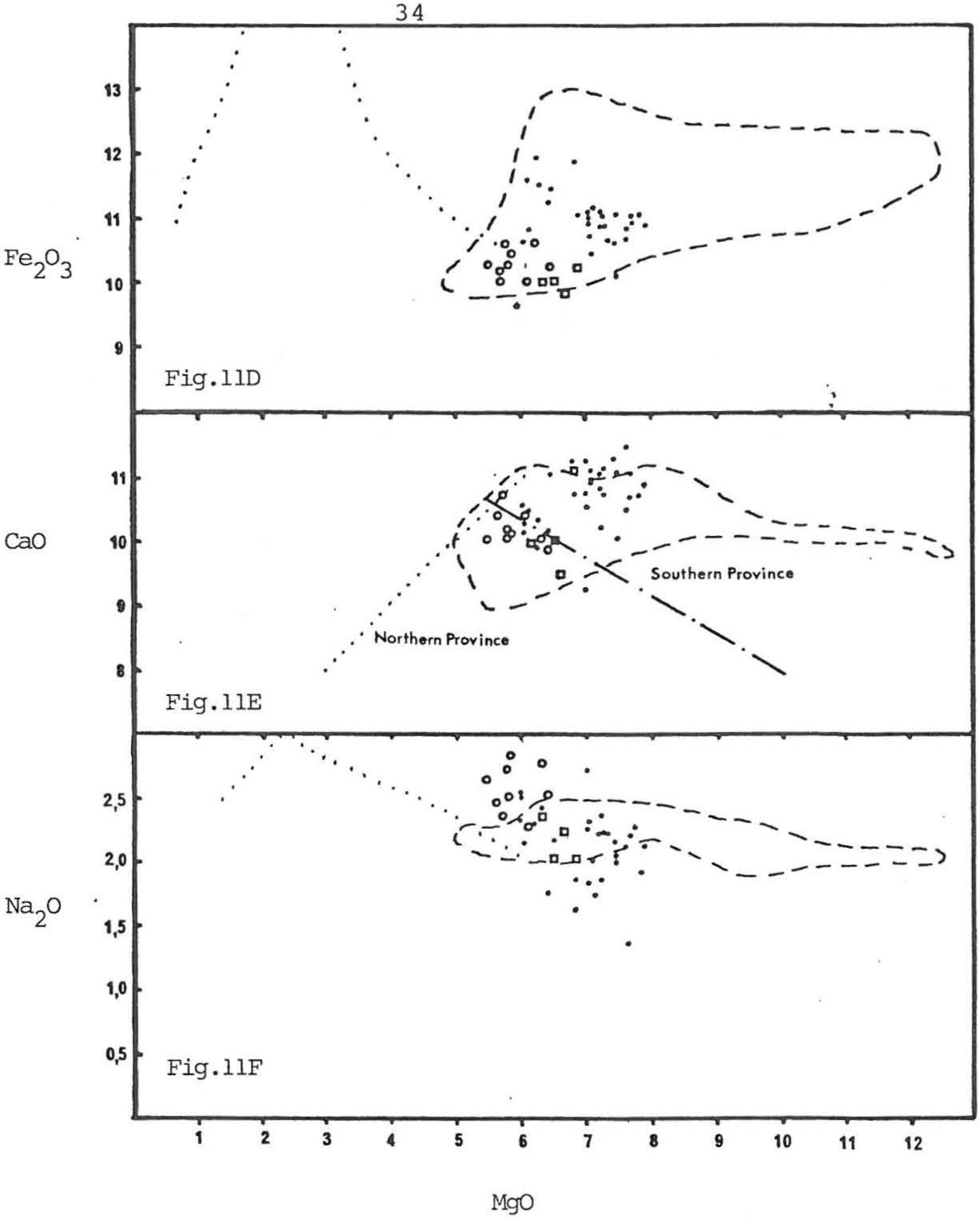
○ Drumbo Member

□ Kraai River Formation

• Lesotho Formation

--- Dolerites (Robey, 1976)

..... Birds River Intrusion (Robey, 1976)


Fe$_2$O$_3$
13
12
11
10
9
Fig.11D
CaO
11
10
9
8
Southern Province
Northern Province
Fig.11E
Na$_2$O
2,5
2,0
1,5
1,0
0,5
Fig.11F
1
2
3
4
5
6
7
8
9
10
11
12
MgO

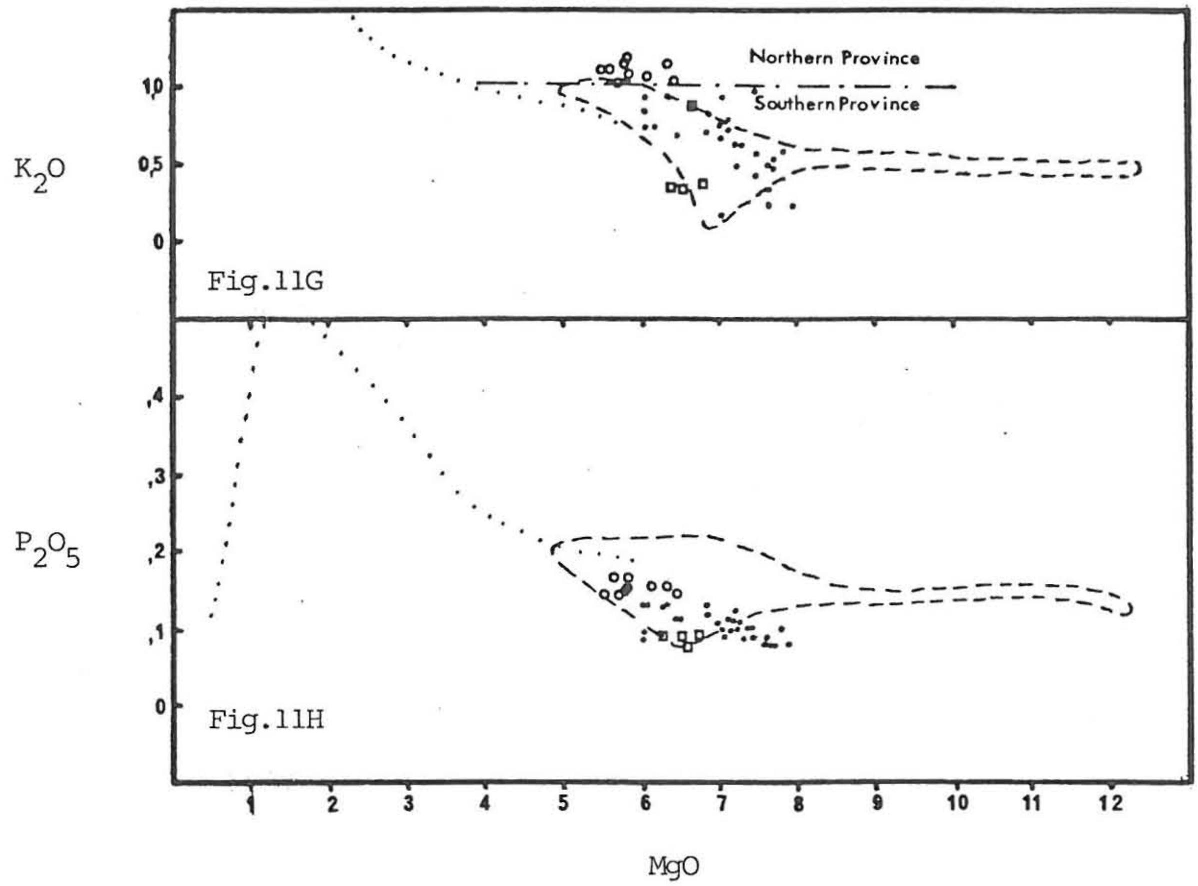


Fig.11G

Fig.11H

a) Lesotho Formation versus the Drumbo Member:
The Drumbo Member is - 1) enriched in - SiO_2, TiO_2, Na_2O, K_2O, P_2O_5
2) similar in - CaO, Al_2O_3
3) depleted in - MgO, Fe_2O_3

b) Lesotho Formation versus the Kraai River Formation:
The Kraai River Formation is -
1) enriched in - SiO_2
2) similar in - Na_2O, CaO, Al_2O_3
3) depleted in - P_2O_5, TiO_2, K_2O,Fe_2O_3, MgO

c) The Drumbo Member versus the Kraai River Formation:
The Kraai River Formation is -
1) enriched in - SiO_2, MgO
2) similar in - Al_2O_3, CaO, Fe_2O_3
3) depleted in - P_2O_5, TiO_2, K_2O, Na_2O

5.3.3 Comparison of the Drakensberg Subgroup and with Karroo Dolerites

In a general comparison of the Karroo dolerites of the Eastern Cape with the Drakensberg Subgroup lavas, the samples of the Lesotho Formation fall within the dolerite field for most of the major elements (Fig.11a to h). The alkalies and Al_2O_3 have a scatter about the dolerite field while P_2O_5 is consistently low. This difference in P_2O_5 is believed to be due to systematic analytical differences between Robey's data (Geochemistry Department, Univeristy of Cape Town) and these data (Rhodes University Geology Department).

The Drumbo Member specimens plot out of the dolerite field with respect to the alkalies and Al_2O_3 while SiO_2 of the Kraai River Formation samples is higher than that of the dolerites.

5.3.4 Discussion on K_2O in the Drakensberg Subgroup

Robey (1976) commented on the behaviour of K_2O in the Karroo dolerites with a general trend of increasing K_2O with differentiation but some of his dolerites have abnormally low concencentrations for their differentiation stage as indicated by MgO. From the behaviour of K_2O and related elements Ba and Rb, he concludes that factors other than crystal fractionation controlled major and trace element variations within the Karroo dolerites.

The Lesotho Formation samples have an erratic scatter of K_2O values in a manner similar to the dolerites with a range from 0,16% to 0,98% (Fig.11g). The samples of the Drumbo Member have high K_2O (average is 1,05% and range 0,99% to 1,13%). Three Kraai River Formation samples have values around 0,35% and another specimen has 0,87% K_2O.

The concentration of K_2O in the late stages of a crystallizing flow, and its high mobility, have been discussed in section 3.2. Jamieson et al. (1970) in their examination of K_2O and associated elements in tholeiitic basalts conclude that the K_2O content varies more or less independently of the fractionation processes controlling the concentrations of other elements. According to them significant K-enrichment processes are the degree of partial melting, magma and mantle wall-rock reaction and high pressure fractionation of eclogite.
In the case of Karroo tholeiites of Rhodesia, they propose that wall rock and/or an inhomogeneous mantle are responsible for the high K_2O contents.

The differences in K_2O within the Drakensberg Subgroup as well as within the Lesotho Formation confirm the ideas of Robey (1976) and Jamieson (1970) but the late-stage effects must also be considered as important factors in the control of K_2O content in tholeiites.

5.3.5 Major Element Variation with Stratigraphic Height in the Lesotho Formation

In Figs.12a to j, major elements have been plotted against stratigraphic height in the Lesotho Formation. Cox and Hornung (1966) used Fe/Mg as an indicator of the degree of fractionation and this, when plotted against height for their suite of samples from central Lesotho, showed a "slight tendency"

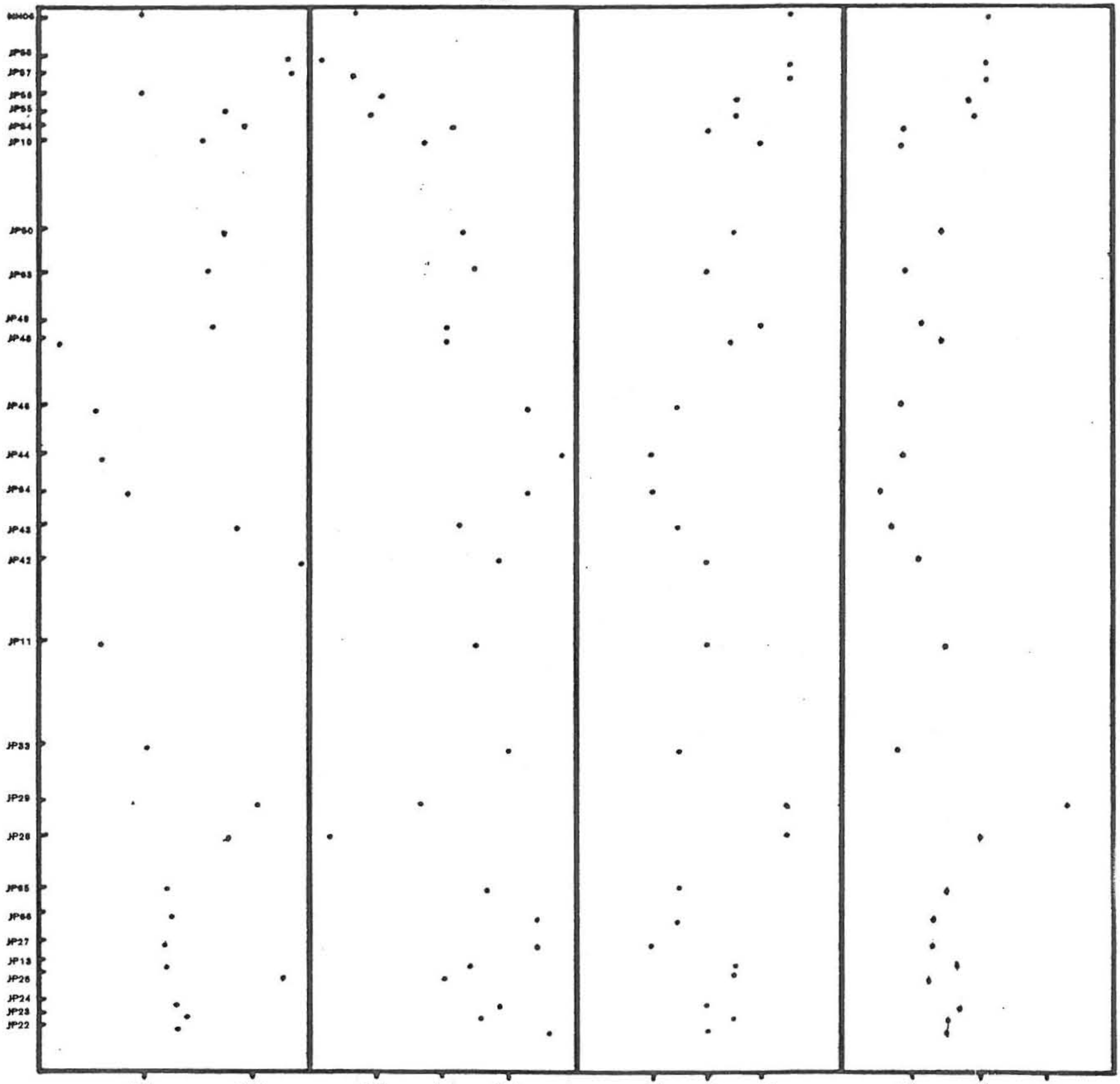


Fig.12.I K_2O Fig.12F MgO Fig.12J P_2O_5 Fig.12B TiO_2

Figs.12 A-J Major element data for the Lesotho Formation plotted against height

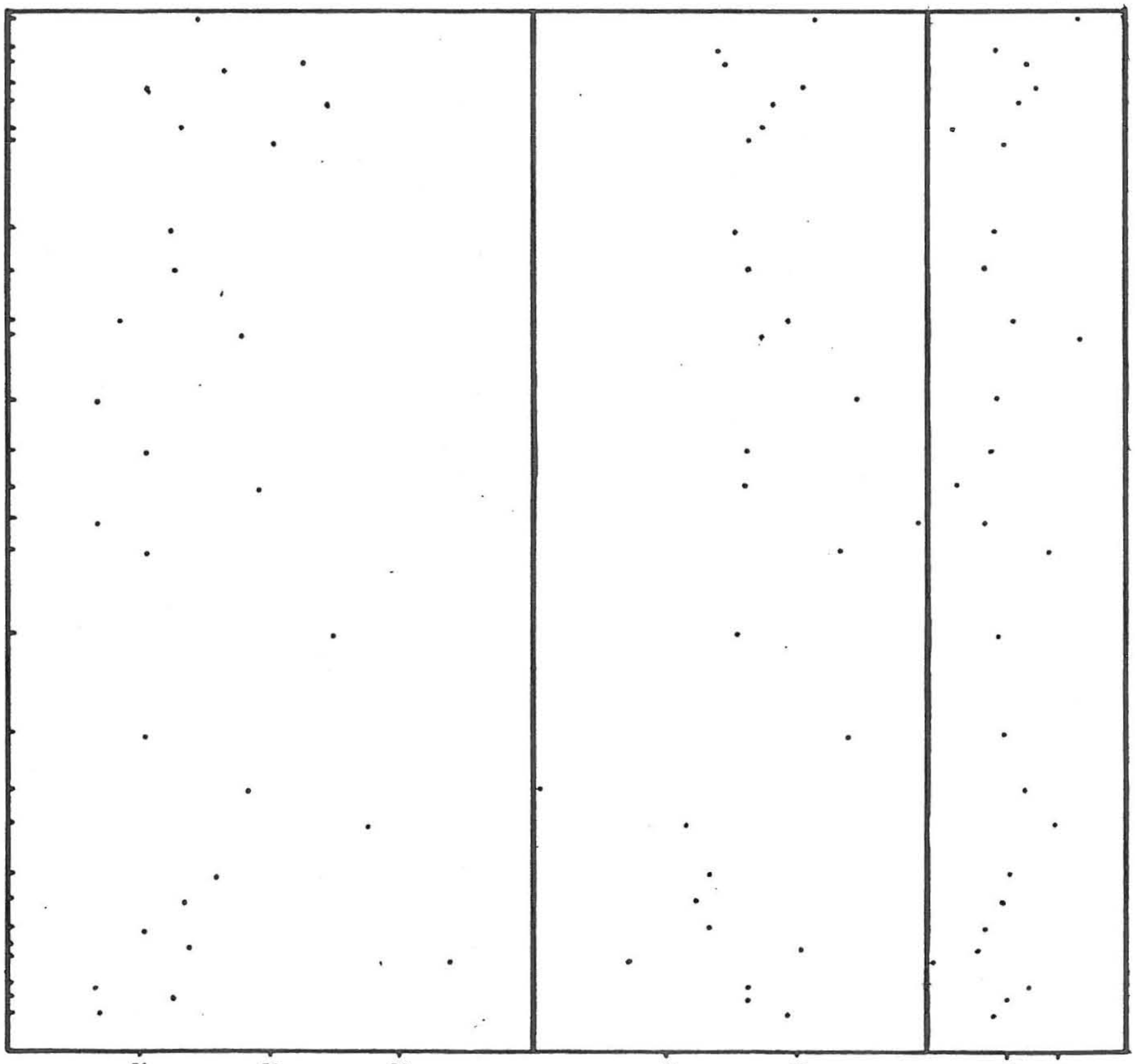


Fig.12A SiO$_2$

Fig.12C Al$_2$O$_3$

Fig.12E MnO

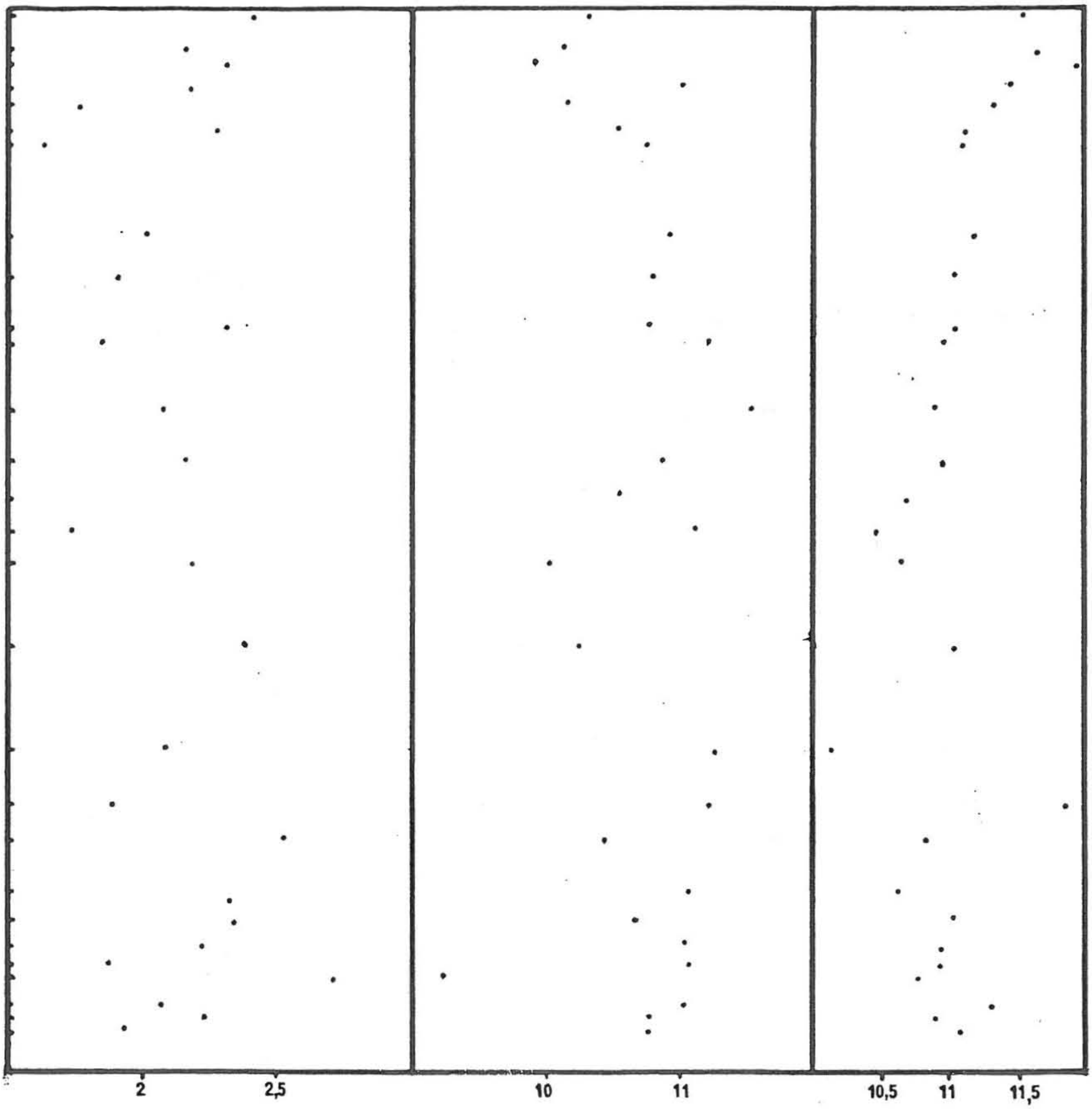


Fig.12H Na_2O Fig.12G CaO Fig.12D Fe_2O_3

towards increasing Fe/Mg with height.

The majority of the major elements from the Naudes Nek section do not define any distinctive trend with height, i.e., SiO_2, K_2O, Na_2O, CaO, Al_2O_3 and MnO. Fe_2O_3 and MgO show subtle but definite trends while those of P_2O_5 and TiO_2 are more subdued.

The Fe_2O_3-enrichment trend starts approximately half-way up the Naudes Nek section. From sample JP43 with 9,74%, Fe_2O_3 increases steadily to NN06 with 10,93%. In the lower half of the section Fe_2O_3 fluctuates around 11% but JP29 has an abnormally high concentration of 11,89%.

The MgO trend starts from halfway up the Naudes Nek section with depletion from JP44 with 7,67% MgO to NN06 with 6,01%. The most rapid decrease takes place in the topmost seven samples from JP54 with 6,83% MgO to JP58 with 5,86%. The basal part of the sequence has high MgO concentrations all above 7% while JP28 and JP29 have low MgO at 6,17% and 6,89% respectively.

P_2O_5 and TiO_2 have almost identical patterns when plotted against height. P_2O_5 and TiO_2 have an increase in value from halfway up the section while the lower half shows more erratic values. The enrichment is:

1) P_2O_5 - from JP44 with 0,08% P_2O_5 to NN06 with 0,12%

2) TiO_2 - from JP44 with 0,86% TiO_2 to NN06 with 1,00%

Samples JP28 and JP29 have high P_2O_5 at 0,13% while JP29 has the highest TiO_2 in the Naudes Nek section with 1,13%.

These trends, although not strong, do suggest that the increase in degree of fractionation with height recognised in central Lesotho (Cox and Hornung, 1966) is evident also in the Naudes Nek sequence.

5.3.6 Major Element variation with height in the Omega Formation

The Omega Formation as described previously (section 2.3), consists of the basal massive unit followed by a number of thin units, the first of which was studied by Robey (1976). The major elements from the massive unit have here been plotted against height to give an indication of variation in concentration with height.

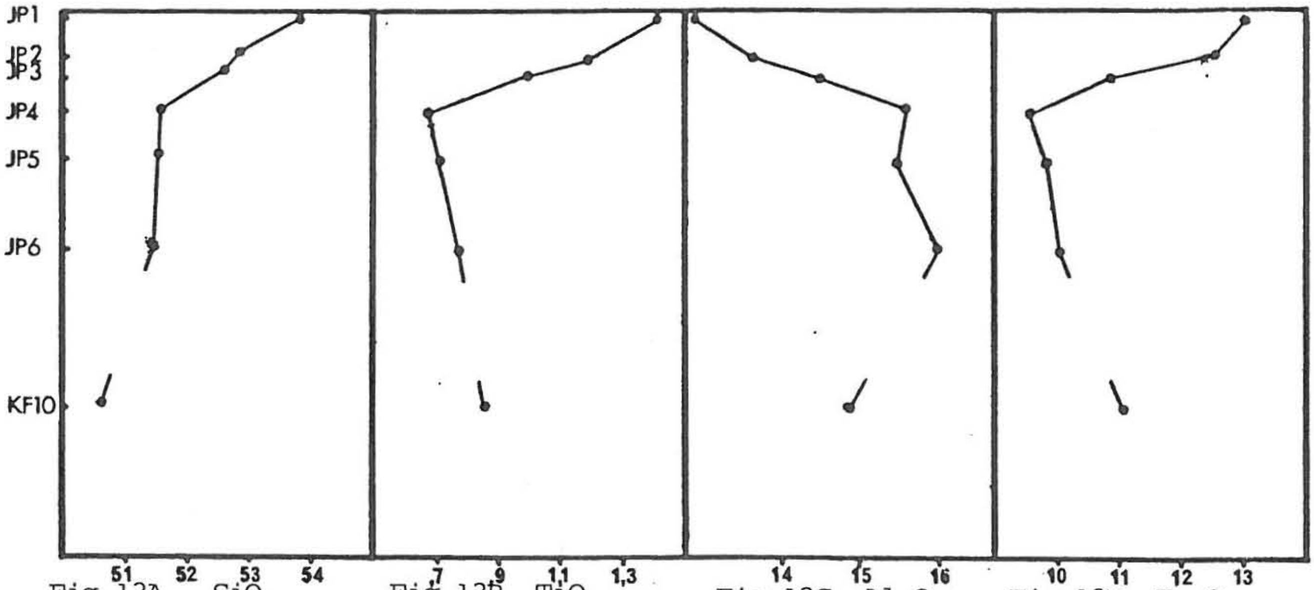


Fig.13A SiO_2

Fig.13B TiO_2

Fig.13C Al_2O_3

Fig.13D Fe_2O_3

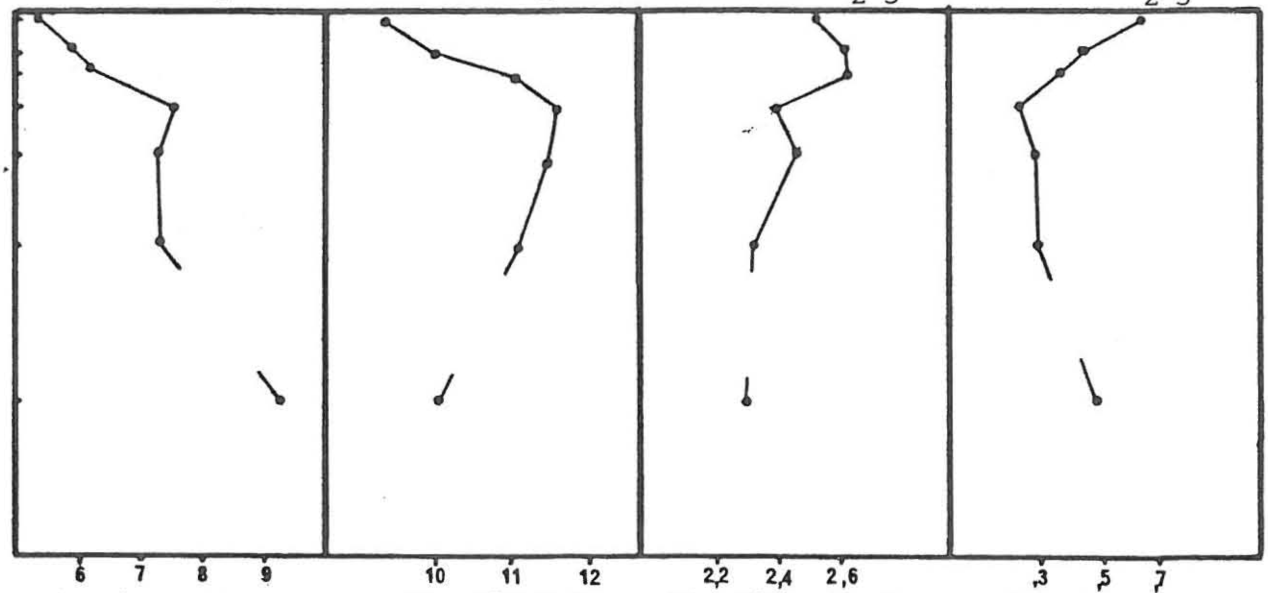


Fig.13E MgO

Fig.13F CaO

Fig.13G Na_2O

Fig.13H K_2O

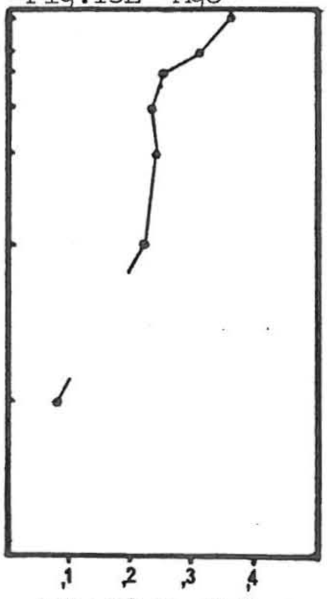


Fig.13.I P_2O_5

Figs.13 A-I. Major Element data for the massive unit of the Omega Formation plotted against height.

Figs.13 and 9 illustrate that both in terms of chemical data and modal data, the horizon depicted here by sample JP4 is one at which variation trends change rather abruptly.

1) K_2O, Fe_2O_3 and TiO_2 (Fig.13h, d and b) - these show a decrease from the top to JP4 and then an increase to the basal sample KF10.
2) MgO (Fig.13e) - increases to JP4, and then increases again to KF10 but with a more subdued slope.
3) SiO_2 and P_2O_5 (Fig.13a and i) - decrease from the top to KF10 with a change of slope at JP4.
4) CaO and Al_2O_3 (Fig.13f and c) - these increase to JP4 and then decrease to KF10. Al_2O_3 shows a slight increase at JP6 before decreasing to KF10.
5) Na_2O (Fig.13g) - exhibits an erratic pattern with a slight increase from the top to JP3 and then a decrease towards the base.

The uppermost part of the massive unit from JP1 to JP4 has a major element variation pattern similar to that of the differentiated Birds River Intrusion (Robey, 1976), i.e. - increasing SiO_2 and Fe_2O_3, decreasing MgO, CaO and Al_2O_3.

This suggests plagioclase, pyroxene and olivine have fractionated to varying degrees which is supported by the modes in Fig.9.

In the lower part of the massive unit the major element and mineralogical variation becomes contradictory. MgO increases downwards with olivine appearing in the mode of KF10. Plagioclase also increases downwards but clinopyroxene decreases. This suggests that the lower part of the unit has been affected by fractionation of plagioclase and olivine. The pattern is however contradicted by the increase of Fe_2O_3 and K_2O downwards which is seen in the mode by increasing magnetite and mesostasis.

From the major element variation pattern it appears that the massive unit has been acted on by two differentiation trends. The trace element variation pattern of the massive unit is examined in section 6.6 where this apparent dichotomy is discussed further and one possible model of differentiation is proposed.

5.4 NORMATIVE CHEMISTRY OF THE DRAKENSBERG SUBGROUP

5.4.1 Introduction

The normative chemistry (Table 2) of the Drakensberg Subgroup is discussed by comparison with the studies done by Cox and Hornung (1966) and Robey (1976). Cox and Hornung (1966) applied the method of Coombs (1963) which takes into account the major mineral phases of the tholeiitic basalt system. Robey (1976) compared the normative chemistry of the chilled Karroo dolerites and lower Barkly East lavas to that of the lavas of central Lesotho studied by Cox and Hornung (1966).

The method of plotting and projection has been discussed by Cox and Hornung (1966) and Robey (1976) while Coombs (1963) and O'Hara (1968) have looked at the theoretical considerations. A number of important features are:

1) In Fig.14 phase boundaries shown mark the junctions of the primary phase volumes of Fo, Di and En with that of An.
2) These phase boundaries mark a divariant equilibrium such as Fo + An + En + liq. They meet in the univariant point Fo + Di + En + An + liq. (X') at $1250^{o}C \pm 10^{o}C$ (Cox and Hornung, 1966) where the four phases and liquid are stable.
3) A higher Fe_2O_3/FeO ratio of 0,2 was used than that of Cox and Hornung (1966) but Robey (1976) recalculated their data using the value of 0,2.
   This results in a shift of their data towards the Q apex.
4) The line X'Y' is the divariant line along which En + Di and An + liquid coexist.

5.4.2 Discussion of Results

In Fig.14 the analyses of Cox and Hornung (1966) and those of the Drakensberg Subgroup from this study are plotted. The data of Cox and Hornung (1966) plots close to the trivariant surface of Fo + An + liq. and across the olivine-plagioclase control line. This leads them to conclude that in addition to olivine and plagioclase fractionation, pyroxene also had a control on the final composition of these lavas. Prior to the recalculation of their data using the higher Fe_2O_3/FeO ratio of 0,2, these lavas plotted across the thermal barrier Di-En.

As this barrier is effective at pressures greater than 10kb (Boyd and England, 1961) they suggest that the final compositions of the central Lesotho lavas were achieved at pressures less than 10kb to allow for the absence of this thermal barrier.

The chilled Karroo dolerites analysed by Robey (1976) plot within or close to the field defined by the central Lesotho lavas. The dolerites however, have a more variable phenocryst assemblage than the lavas with olivine, plagioclase and clinopyroxene being most common.

The lavas of the Lesotho Formation in the Drakensberg Subgroup of the Barkly East area have a greater scatter than those of central Lesotho and the chilled dolerites. An ophitic texture observed in most specimens suggests that plagioclase crystallization was followed by clinopyroxene and as the Lesotho Formation samples scatter across the olivine-plagioclase control line in a manner similar to the central Lesotho lavas, clinopyroxene fractionation besides that of olivine and plagioclase, must also have played a role in controlling the liquid compositions. As the Lesotho Formation lavas straddle the En-Di join, it is assumed, following the interpretation of Cox and Hornung (1966) that final equilibrium of the Lesotho Formation in the Barkly East area took place at less than 10 kb.
The basalts of the Drumbo Member plot within the field of the central Lesotho lavas of Cox and Hornung (1966) with one exception which plots over the Di-En join.

As with Robey's (1976) specimens of the Kraai River Formation, those from this study plot within the En + An + liq. field. A trend towards the Q apex is still apparent and as Robey (1976) suggested, "the residual liquids were moving across the trivariant surface En + An + liq. at the time of eruption and solidification." Three of the four samples of the Kraai River Formation lavas from this study as well as those examined by Robey (1976) had plagioclase and orthopyroxene as phenocryst phases. The lack of clinopyroxene led Robey (1976) to postulate that a rapid decrease in confining pressure prior to eruption reduced the clinopyroxene primary phase volume. In the other Kraai River Formation lava from this study, clinopyroxene in addition to

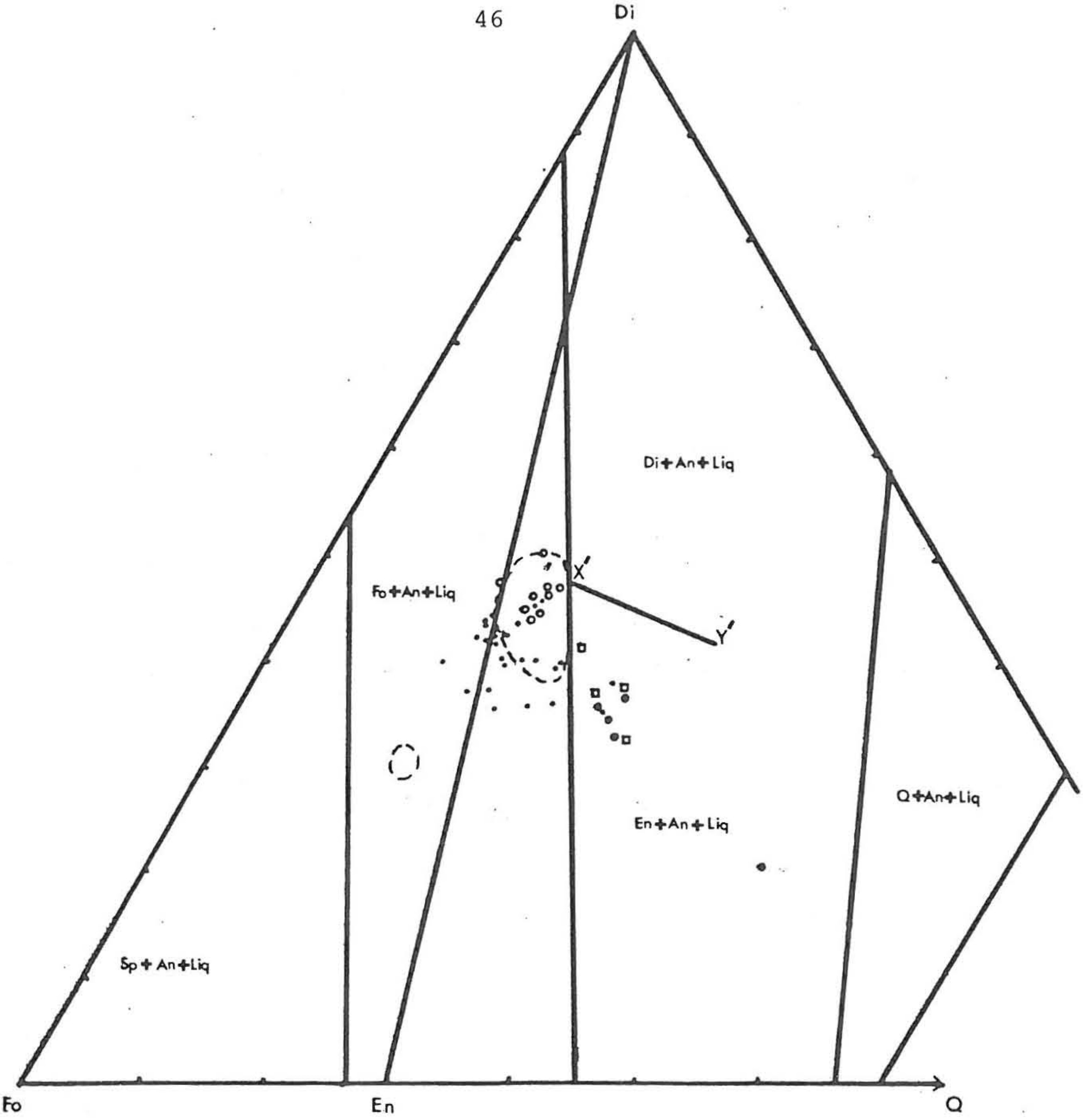


Fig.14 The Anorthite Projection of the Basalt System, An-Di-Fo-Q (after Cox and Hornung, 1966).

○	Drumbo Member
□	Kraai River Formation
•	Lesotho Formation
---	Field of central Lesotho basalts (Cox and Hornung, 1966)
●	Kraai River Formation (Robey, 1976)

plagioclase and orthopyroxene, is seen as a phenocryst-phase. In this case it appears that the residual liquids moved along the divariant line X'-Y' during equilibrium crystallization resulting in the presence of both orthopyroxene and clinopyroxene phenocrysts.

The normative chemistry of the Drakensberg Subgroup therefore confirms the patterns noted by Cox and Hornung (1966) and Robey (1976). Although the Drumbo Member and Kraai River Formation are different chemically from the Lesotho Formation, they do not fall on any control lines and their time relationships combined with their normative chemistry does not suggest a fractionation link.

TABLE 2. CIPW WEIGHT PERCENT NORM FOR THE DRAKENSBERG SUBGROUP

	JP1	JP2	JP3	JP4	JP5	JP6	KF10	JP10A	JP10B	JP10C	JP10D	JP11A	JP11AVA	JP11B	JP11C	JP11D	JP11DV	JP13A
AP	0,86	0,72	0,59	0,53	0,56	0,52	0,20	0,24	0,24	0,24	0,22	0,21	0,21	0,27	0,22	0,27	0,25	0,26
IL	2,68	2,26	1,90	1,31	1,39	1,47	1,63	1,55	1,62	1,63	1,66	1,67	1,61	1,81	1,58	1,75	1,69	1,71
OR	3,75	2,61	2,16	1,45	1,73	1,70	2,42	3,90	4,12	4,08	2,51	1,35	1,48	2,96	0,79	4,47	4,14	2,73
AB	21,60	22,45	22,55	20,31	21,14	19,92	19,51	13,04	23,28	18,44	18,00	18,99	17,64	19,49	15,81	21,45	20,40	14,87
AN	22,28	24,53	26,69	31,51	30,49	32,36	29,43	31,13	22,13	28,47	30,18	29,20	30,72	32,76	34,18	26,08	28,61	32,29
MT	2,93	2,78	2,42	2,15	2,21	2,24	2,46	2,31	2,23	2,36	2,30	2,29	2,20	2,44	2,24	2,33	2,14	2,23
DIEN	4,35	4,92	6,21	6,30	6,35	5,34	5,14	4,26	4,86	4,77	4,60	4,16	4,07	4,83	4,31	3,63	3,66	4,37
DIFS	5,00	4,92	4,99	3,80	4,12	3,47	2,89	3,26	3,66	3,50	3,32	2,93	2,97	3,80	3,01	2,56	2,59	3,16
DIWO	9,43	10,03	11,57	10,63	10,97	9,24	8,50	7,79	8,84	8,61	8,24	7,39	7,32	8,93	7,63	6,46	6,51	7,84
HYEN	8,63	9,47	9,45	12,77	11,89	13,00	15,32	11,73	10,80	12,23	12,09	12,91	11,79	9,61	12,63	13,61	12,07	12,10
HYFS	9,91	9,48	7,59	7,71	7,70	8,45	8,60	8,98	8,14	8,98	8,74	9,08	8,61	7,55	8,81	9,59	8,54	8,76
Q	7,64	5,19	3,38	1,08	1,01	1,68	0,00	4,55	2,98	1,00	2,35	3,02	4,38	0,00	2,63	0,81	2,11	3,25
FO							2,01							1,32				
FA							1,24							1,14				

AP - Apatite   IL - Ilmenite   OR - Orthoclase   AB - Albite   AN - Anorthite   MT - Magnetite   DIEN) DIFS) DIWO) Diopside

HYEN) HYFS) Hypersthene   Q - Quartz   FO) FA) Olivine

Table 2. (Cont'd.)

TABLE 2. (Cont'd.)

	JP13B	JP13C	JP22	JP23	JP24	JP26	JP27	JP28	JP29	JP33	JP42	JP43	JP44	JP46	JP48	JP49	JP50
AP	0,22	0,28	0,23	0,26	0,26	0,23	0,20	0,30	0,30	0,20	0,24	0,21	0,21	0,20	0,24	0,29	0,25
IL	1,59	1,87	1,77	1,79	1,79	1,70	1,74	1,90	2,07	1,64	1,70	1,62	1,68	1,59	1,77	1,72	1,79
OR	3,86	3,91	3,33	3,60	3,28	5,45	2,77	4,24	4,73	2,41	5,70	4,26	1,41	1,16	0,93	3,84	3,99
AB	22,01	20,97	16,30	19,05	17,24	22,87	18,74	21,41	15,68	17,49	18,50	14,32	18,25	11,23	15,65	19,56	17,18
AN	27,19	27,37	32,85	30,86	31,92	25,15	30,82	28,30	26,77	34,05	31,39	35,23	32,37	36,66	33,97	31,32	30,79
MT	2,23	2,39	2,44	2,42	2,48	2,37	2,41	2,42	2,58	2,21	2,33	2,24	2,44	2,33	2,45	2,44	2,47
DIEN	5,15	4,68	4,68	5,19	5,09	4,59	5,62	5,12	5,99	5,11	4,16	4,20	5,13	4,34	4,76	4,99	5,28
DIFS	3,65	3,51	3,10	3,63	3,59	3,30	3,67	4,23	4,79	3,22	2,80	2,89	3,33	2,90	3,56	3,56	3,86
DIWO	9,16	8,51	8,14	9,19	9,05	8,21	9,74	9,64	11,15	8,75	7,28	7,41	8,87	7,58	8,64	8,91	9,51
HYEN	11,44	11,97	14,65	12,93	13,44	12,75	13,77	10,20	10,76	13,34	14,17	12,99	14,76	14,13	12,58	13,06	12,50
HYFS	8,10	8,96	9,70	9,05	9,48	9,17	9,00	8,42	8,60	8,39	9,52	8,92	9,58	9,44	9,40	9,31	9,15
Q	0,42	0,37	1,22	1,08	0,96	2,58	0,69	3,40	3,35	1,77	0,40	2,17	1,29	4,03	4,69	0,21	2,03
FO																	
FA																	

Table 2. (Cont'd.)

TABLE 2. (Cont'd.)

	JP54	JP55	JP56	JP57	JP58	JP63	JP64	JP65	JP66	NN06	SIB03	JP14	DT04	JP60	JP61	CLA01	JP17
AP	0,23	0,27	0,27	0,30	0,30	0,25	0,19	0,20	0,21	0,28	0,24	0,20	0,22	0,35	0,35	0,35	0,38
IL	1,67	1,82	1,81	1,97	1,93	1,70	1,62	1,79	1,78	1,92	2,10	1,81	2,03	2,01	1,90	1,98	2,04
OR	4,39	3,87	2,13	5,41	5,22	3,72	2,03	2,93	2,95	2,09	0,69	4,16	4,73	6,62	6,39	6,59	6,64
AB	19,40	14,69	18,16	19,27	17,95	18,77	18,13	19,02	19,46	20,24	14,14	19,05	21,08	23,78	22,16	23,72	22,78
AN	30,13	31,97	32,23	28,58	28,94	30,93	31,74	30,80	30,07	31,04	34,45	31,26	29,09	25,68	28,40	25,99	27,61
MT	2,45	2,45	2,49	2,59	2,53	2,45	2,36	2,36	2,47	2,47	2,62	2,06	2,35	2,36	2,30	2,38	2,30
DIEN	4,97	3,79	4,59	4,08	4,24	5,18	4,88	5,73	5,39	3,94	2,76	4,41	4,67	5,25	4,53	5,04	4,79
DIFS	3,66	3,10	3,78	3,57	3,79	3,72	3,20	3,84	3,62	3,33	2,66	3,22	3,83	4,38	3,81	3,90	3,79
DIWO	8,98	7,12	8,64	7,87	8,25	9,27	8,46	10,01	9,42	7,50	5,54	7,93	8,77	9,93	8,59	9,26	8,88
HYEN	12,59	11,95	11,28	11,42	10,54	12,84	14,17	12,72	13,97	11,39	11,36	10,13	10,07	9,38	9,38	10,89	10,06
HYFS	9,28	9,76	9,30	9,99	9,43	9,22	9,29	8,53	9,39	9,62	10,93	7,40	8,26	7,81	7,90	8,43	7,97
Q	0,75	5,15	2,19	2,10	3,73	1,16	3,00	1,69	0,78	2,90	9,93	4,55	3,04	1,71	3,64	1,08	2,09
FO																	
FA																	

Table 2. (Cont'd.)

TABLE 2. (Cont'd.)

	CAR08	MF09	DBM11	DBM12	CL14	KRF13	KRC20	KRC21	JP67
AP	0,32	0,34	0,33	0,34	0,39	0,21	0,21	0,21	0,21
IL	1,82	1,93	1,84	1,93	2,01	1,65	1,61	1,64	1,60
OR	5,77	6,46	5,94	5,92	6,52	2,19	2,02	1,97	5,16
AB	19,98	21,38	21,37	19,22	21,13	17,43	20,19	17,18	19,31
AN	30,27	27,88	29,16	30,60	28,98	31,31	28,97	32,17	28,44
MT	2,20	2,36	2,28	2,19	2,20	2,22	2,21	2,25	2,21
DIEN	4,85	4,80	4,60	4,72	4,90	4,13	4,60	5,05	4,55
DIFS	3,81	4,07	3,35	3,46	3,90	2,94	3,37	3,57	3,15
DIWO	8,97	9,14	8,28	8,51	9,11	7,37	8,29	8,98	8,04
HYEN	9,58	9,66	11,63	10,56	9,20	12,23	11,24	11,71	2,23
HYFS	7,53	8,19	8,48	7,75	7,32	8,70	8,23	8,27	8,48
Q	2,74	3,14	2,00	3,10	3,31	8,52	7,63	4,90	6,13
FO									
FA									

of

6. TRACE ELEMENT CHEMISTRY IN THE DRAKENSBERG SUBGROUP

6.1 INTRODUCTION

61 analyses for 14 trace elements are presented and discussed. The elements Rb, Sr, Y, Zr, Nb, Cu, Ni, Zn, Co, Cr, V, La, Ce and Nd were determined, using X-ray fluorescence techniques.

Cox and Hornung (1966) published 22 determinations of 16 trace elements in the central Lesotho lavas. The majority of these determinations were obtained by optical spectrographic methods and as a result are not to be regarded as accurate or precise as those by modern X-ray fluorescence methods. Robey (1976) analysed 11 lavas from the Barkly East area for 11 trace elements and these data, in additon to those for his chilled Karroo dolerites and samples from the Birds River Intrusion, are used extensively in the following discussion.

The concept of the partition coefficient in this section is taken as the $\frac{\text{concentration of x in crystal}}{\text{concentration of x in co-existing liquid}}$

where x = trace element.

Arth (1976) has reviewed the behaviour of trace elements during magmatic processes and summarised the theoretical models based on expressions illustrating their behaviour during partial melting and fractional crystallization:

1) Equation for trace-element behaviour during fractional crystallization (from Arth, 1976) (phases are assumed to crystallize in constant proportions with constant partition coefficients)

$\frac{Cl}{Co} = F'^{(Ds-1)}$ where Cl = concentration in the differentiated liquid.

Co = concentration in the original melt.

F' = fraction of liquid remaining.

Ds = bulk partition coefficient.

2) Equation for bulk partition coefficient (from Arth, 1976):

$Ds=W^a K^{a/b}$ and $W^b K^{b/l}$ and .... etc. where-

W^a = represents the weight fraction of (a) in the precipitating phases.

K = solid/liquid partition coefficient.

3) Equation for partial melting (from Arth, 1976):

$$\frac{Cl}{Co} = \frac{1}{Do + F(1-P)}$$

where F = fraction of melting.

Co = initial trace element concentration of solid.

Cl = trace element concentration of liquid.

Do = bulk partition coefficient for starting assemblage.

$P = P^a K^{a/l} + P^b K^{B/l} + \ldots\ldots$ etc.

where P^a and P^b = fraction of liquid contributed by each phase during melting.

$K^{a/l}$ = solid - liquid partition coefficient for (a).

For simple modal melting (when percentage of each phase in the solid assemblage does not change during melting) i.e. P=D.

$$\frac{Cl}{Co} = \frac{1}{Do + F(1 - Do)}$$

The expressions above have been used, in addition to the previous evidence provided by the major elements, to assess the roles of fractional crystallization and partial melting in the Lesotho Formation in the light of the trace element evidence presented in this section.

6.2 INCOMPATIBLE ELEMENTS

6.2.1 Introduction and Theoretical Considerations

The incompatible elements are those which are enriched in the magma relative to the coexisting crystalline phases. In the tholeiitic basalt system under consideration the following incompatible elements have been determined: K, Nb, Rb, Zr, Y, La, Ce and Nd.

TABLE 3 : PARTITION COEFFICIENTS FOR Rb, La, Ce and Nb

Element	Plagioclase	Clinopyroxene	Orthopyroxene	Olivine	Apatite	Magnetite	Ilmenite
Rb	0,188-0,025[1]	0,284-0,013[1]	0,029[1]	0,0113[1]			
	0,05-0,23[2]	0,001-0,004[3]	0,004-0,08[2]				
La	0,069[4]	0,10[5]		0,0084[4]	8,6[4]	0,015[4]	0,098[4]
	0,280[5]						
Ce	0,062[4]	0,18[5]	0,031-0,038[7]	0,010[4]	11,2[4]	0,016[4]	0,11[4]
	0,215[5]	0,096[6]		0,009[6]			
	0,06[6]	0,020-0,646[7]		0,009[7]			
	0,062-0,295[7]						
Nd	0,028[4]	0,38[5]	0,034-0,058[7]	0,008[4]	14[4]	0,026[4]	0,14[4]
	0,170[5]	0,049-0,645[7]		0,010			
	0,023-0,199						

References

1. Philpotts and Schnetzler (1970)
2. Goodman (1972)
3. Shimizu (1974)
4. Paster et al. (1974)
5. Sun and Hanson (1976)
6. Shimizu and Arculus (1975)
7. Schnetzler and Philpotts (1970)

K has been discussed in section 5.3 on major element variation and section 3.2 on within-flow variation. Data relating to Y are presented on their own in section 6.3.

Presented in Table 3 are partition coefficients for Rb, La, Ce and Nd. The incompatible behaviour of these elements is illustrated by their partition coefficients being much less than unity for the common basaltic rock-forming minerals.

Although there is a lack of partition coefficient data for Nb and Zr in the literature, the incompatible behaviour of these elements in well established (Kesson, 1973; Erlank and Kable, 1976; and Flower, 1973). The three R.E.E. (La, Ce and Nd) have large partition coefficients for apatite, but, as apatite is a minor phase in tholeiitic basalts in general and has only been tentatively identified in the late-stage mesostasis of the Drumbo Member, it does not form a fractionating phase and these elements therefore behave incompatibly in all but late stages of crystallization.

a) Incompatible element ratios.

As a result of the exclusion of the incompatible elements from crystalline phases during melting and fractionation, the ratio between two incompatible elements should remain the same during these processes. The constancy of ratio of two incompatible elements can therefore be used as an indicator of consanguinity.

In a fractionation sequence incompatible element ratios can be used to demonstrate a fractionation link as shown by Flower (1973). Erlank and Kable (1976) have used differences in the ratio Zr/Nb to illustrate various degrees of depletion of the upper mantle (i.e. inhomogeneities in the mantle). They point out that large degrees of partial melting, such as that involved in the production of a tholeiite, are required to prevent any preferential partitioning of the incompatible elements.

b) Enrichment Factors

From the equation of trace element behaviour during fractional crystallization, the rate of enrichment of the incompatible elements in the fraction of liquid remaining should be the same.

This basic premise gives rise to the concept of the enrichment factor which is the ratio of the concentration of an element in the residual liquid over that in the original liquid. Enrichment factors for the incompatible elements in a fractionated sequence should be the same.

c) The incompatible behaviour of Ti and the TiO_2/Zr ratio. In the comparison of within-flow samples (section 3.2) it is shown that the ratio TiO_2/Zr is constant for any one flow whereas the ratios of other incompatible elements have values that are more scattered. Although clinopyroxene takes up Ti having a $D_{Ti} = 0,29$ (Duke, 1975), the effect of other phases results in a bulk partition coefficient that is very small. This apparently incompatible behaviour of TiO_2 can be illustrated using the data of Robey (1976) and the model of fractional crystallization for the Birds River Intrusion.

He used the compositions of clinopyroxene obtained by microprobe analyses by Eales and Booth (1974) which indicated an approximate $D_{Ti} = 0,5$. Robey's model can be used to calculate a bulk $D_{Ti} = 0.08$ which explains the incompatible behaviour of Ti. He illustrates this in his use of molar ratio diagrams where TiO_2 and P_2O_5 act incompatibly until a "very late stage of differentiation."

Kesson (1973) noted that there was a positive correlation between Ti and Zr in the fractionated Monaro volcanics while Sun and Nesbitt (1977) used Ti extensively as an incompatible element to discuss the heterogeneity and evolution of the mantle. From this discussion and the examples used it is apparent that in basaltic systems Ti can be treated as an incompatible element.

d) The relationship between Ce and P_2O_5.

Sun and Hanson (1975) studied the relationship between apatite and Ce during partial melting. They consider apatite to be a minor phase in the mantle, controlling the Ce content of the melt because of its high partition coefficient for Ce (Table 3). Because of the covariance of P_2O_5 and Ce, apatite is assumed to be non-residual in the mantle for primary alkali basalts and nephelinites (data from a number of sources) and the P_2O_5/Ce

ratio is constant for that particular melting episode.

6.2.2 Presentation of Data

The average and range for Rb, Zr, Nb, La, Ce and Nd in the Drumbo Member, Kraai River Formation and Lesotho Formation as well as the chilled Karroo dolerite and Kraai River Formation from the work of Robey (1976) are presented in Table 4. As the Lesotho Formation samples are differentiated the average is to be regarded with caution while the range gives an indication of the extent of variation of Rb, Zr, and Nb for the different units of the Drakensberg Subgroup, and allows a comparison with the data of Robey (1976). The three R.E.E. (La, Ce and Nd) are plotted against P_2O_5 in Fig.16 a-c. The various incompatible element ratios (Table 5) and derived histograms (Fig.17 a-f) are used to compare and contrast the different units of the Drakensberg Subgroup, while Robey's (1976) data are included where the element was determined. The data for the Lesotho Formation in the Naudes Nek section are presented by plotting element concentrations (Fig.18 a-e) and interelement ratios (Fig.19 a-e) against stratigraphic height.

6.2.3 Incompatible Elements in the Drakensberg Subgroup

A consideration of the various plots and histograms of the Drakensberg Subgroup shows differences in the incompatible element geochemistry for the Drumbo Member, Kraai River Formation and Lesotho Formation. These differences, together with those observed for the major elements and other trace elements, might be attributed to the following possible causes:

a) Variable degrees of crystal fractionation from a common parent.
b) Different degrees of partial melting.
c) A heterogeneous mantle source.

It is recognised that the oversaturated tholeiitic basalts under consideration here probably result from a complex interplay between melting and fractionation processes. If there were differences only in the degree of partial melting or degree of crystal fractionation from a common parent the in-

TABLE 4 : AVERAGES AND RANGES FOR Rb,Zr,Nb,La,Ce and Nd

Element	D.B.M.	K.R.F.	K.R.F. (Robey)	L.F.	DOLERITE (Robey)
Rb	21	20	17	13,9	13,6
	18-23	10-33	12-23	4-50	5,8-23
Zr	149	113	119	91	102
	138-156	110-116	103-158	77-119	75-158
Nb	15,7	4,4	5,7	4,4	7,5
	14,7-16,6	4,2-4,6	4,2-8	2,4-6,1	3,9-18,7
La	18	17		10	
	16-21	16-17		6-14	
Ce	42	37		25	
	37-48	33-39		15-32	
Nd	21	20		14	
	19-24	19-23		9-18	

TABLE 5 : AVERAGES AND RANGES FOR INCOMPATIBLE ELEMENT RATIOS

Ratio	D.B.M.	K.R.F.	K.R.F. (Robey)	L.F.	DOLERITE (Robey)
K/Rb	417	241	250	420	401
	380-433	86-317	122-322	148-714	229-514
Zr/Nb	9,4	25,8	21,2	21,8	16
	9-10,2	24,5-27,6	19,4-25,7	14-34,6	8-31
Zr/Y	5,7	4,2	4,5	3,9	3,9
	5,5-5,9	4,2-4,3	4,4-5,5	3,2-4,4	2,0-5,7
TiO_2/Zr	68	75	73	101	103
	65-71	73-76	54-80	83-122	84-132
P_2O_5/Ce	35	24		41	
	31-43	22-26		32-58	

Avg. = simple arithmetic average.

D.B.M. = Drumbo Member

K.R.F. = Kraai River Formation

L.F. = Lesotho Formation

(Robey) = Data from Robey (1976)

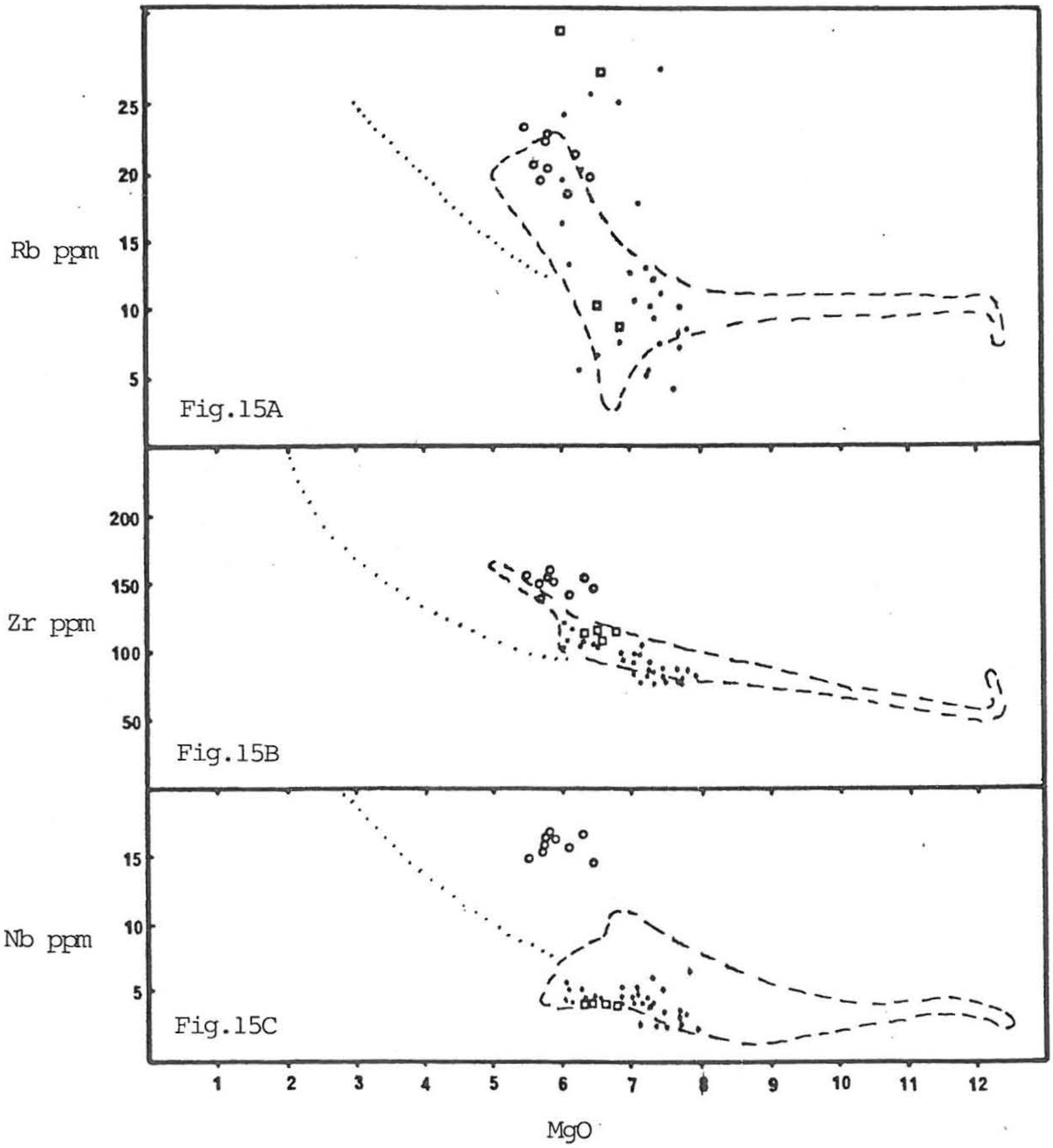
compatible element ratios would reflect these links (i.e. the incompatible element ratios would remain the same from one unit to the next).

The histograms (Fig.17 a-f) and averages (Table 5) illustrate the differences between the various interelement ratios for the incompatible elements. In Fig.17d the Zr/Nb ratios indicate the distinct and significant differences between the Kraai River Formation, Drumbo Member and Lesotho Formation samples. Their average values are respectively 25,8; 9,4; and 21,8. The TiO_2/Zr ratio (Fig.17e) separates the three units with the Drumbo Member having an average value of 68 compared with the Kraai River Formation value of 75 and the Lesotho Formation value of 101. The ratio Zr/Y (Fig.17c) is included to emphasize further the distinctions between these units of the Drakensberg Subgroup.

Several authors have commented on the use of, and variation in the K/Rb ratio. In section 3.2 on within-flow variations the large variability of the alkali elements is discussed. These variations are attributed to late-stage processes resulting from the migration of these mobile elements due to a filter pressing effect as well as to their being highly susceptible to leaching during weathering. Bell and Doyle (1971) have suggested that in a low-K magma (e.g. tholeiite) fractionation of olivine and pyroxene provide a mineralogical control on the whole-rock K/Rb, resulting in a variable ratio. This mineralogical control is here considered ineffective in the light of partition coefficient data, i.e.

$D^{olivine}_{K/Rb} = 0,99$ and $D^{clinopyroxene}_{K/Rb} = 1$ (Philpotts and Schnetzler, 1970)

which would suggest little control on this ratio being exerted by these minerals. Gast (1968) has pointed out that it would require vast amounts of olivine and pyroxene fractionation to change the K/Rb ratio. The work of Erlank and Hofmeyr (1966) showed that the dominant control of K/Rb is not provided by olivine or pyroxene (K/Rb = 200 to 300) but plagioclase (K/Rb greater than 300).



Figs.15 A-C Incompatible element data for the Drakensberg Subgroup in the Barkly East area plotted against MgO%

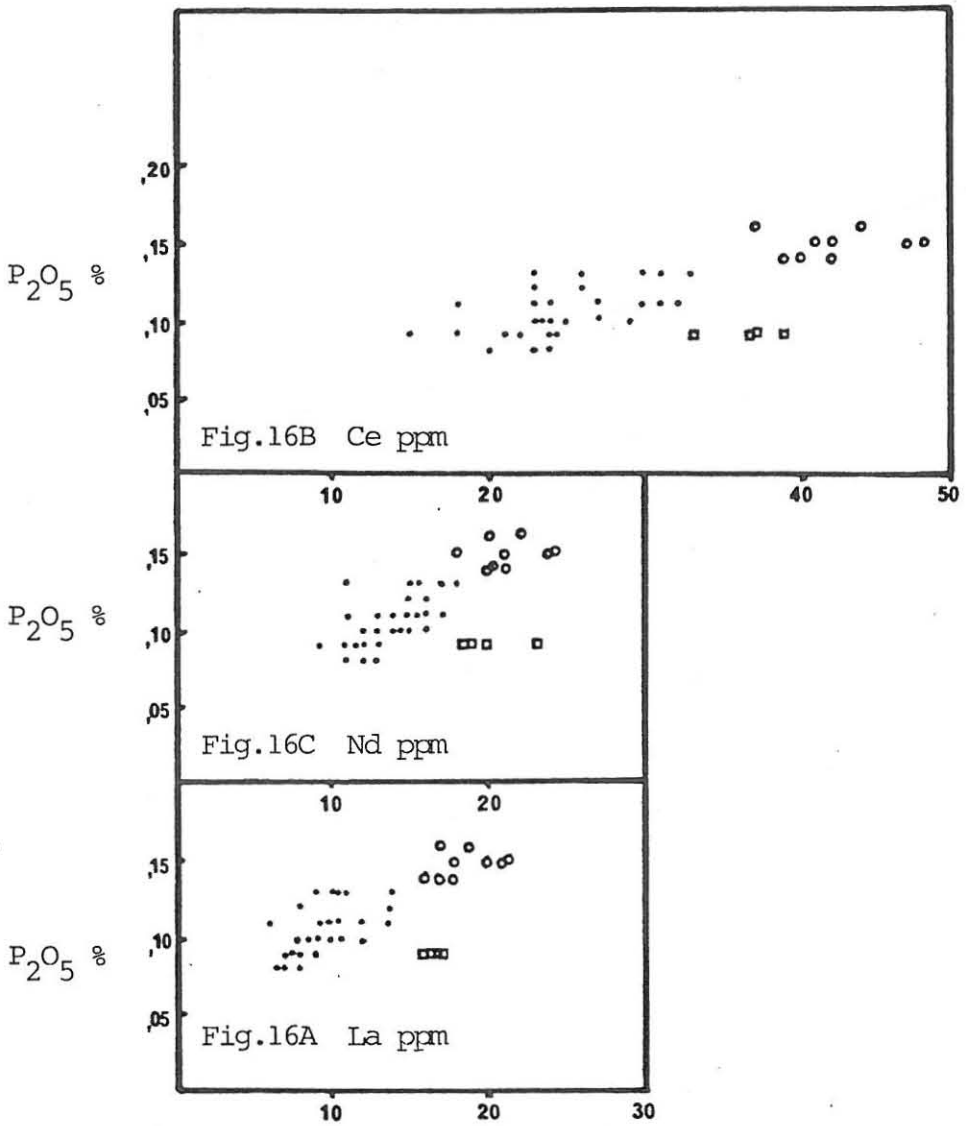
○ Drumbo Member

□ Kraai River Formation

• Lesotho Formation

--- Dolerites (Robey, 1976)

..... Birds River Intrusion (Robey, 1976)



Figs.16 A-C La, Ce and Nd for the Drakensberg Subgroup in the Barkly East area plotted against P_2O_5 %

- • Lesotho Formation
- ▫ Kraai River Formation
- ○ Drumbo Member

In the work of Danchin (1968) on the differentiated Losberg intrusion it is shown that the K/Rb ratio decreases with increasing K due to the exclusion of Rb from the plagioclase structure. The K/Rb ratios of the Drakensberg Subgroup have a wide variation but do show some grouping with the Drumbo Member specimens having a narrow range (Fig.17a) while the samples of the Lesotho Formation vary from 148 to 714. This large variation must result not only from the mineralogical controls but also from the alteration of these basalts due to weathering.

As Sun and Hanson (1975) consider apatite to be non-residual after the small degrees of partial melting normally assumed to be necessary to produce alkali basalts and nephelinites, it could be assumed that in the production of the tholeiites of the Drakensberg Subgroup apatite is also non-residual. If the plot of P_2O_5 versus Ce (Fig.18b) is examined, the line of constant ratio for the Lesotho Formation specimens does not go through the origin and neither do the lines for the samples from the Drumbo Member and Kraai River Formation. This indicates that the mineralogical source of P_2O_5 and Ce in the case of the Drakensberg Subgroup is residual in the mantle. As P_2O_5 acts as an incompatible element in basaltic systems the P_2O_5/Ce ratio would be the same for a magma generated in one particular melting and fractionation sequence. The histogram (Fig.17f) of the P_2O_5/Ce ratio and the averages (Table 5) illustrate the differences between the specimens from the Kraai River Formation, Drumbo Member and Lesotho Formation for this ratio. The plots of P_2O_5 versus La (Fig.16a) and Nd (Fig.16c) have a similar pattern for the different units of the Drakensberg Subgroup as that of the P_2O_5 versus Ce plot. This, in conjunction with the partition coefficients, illustrates the similar behaviour of these R.E.E.

The differences between the various incompatible element ratios, as well as the major element evidence, suggest that there is not a simple melting-fractionation link for the different units of the Drakensberg Subgroup. The most likely

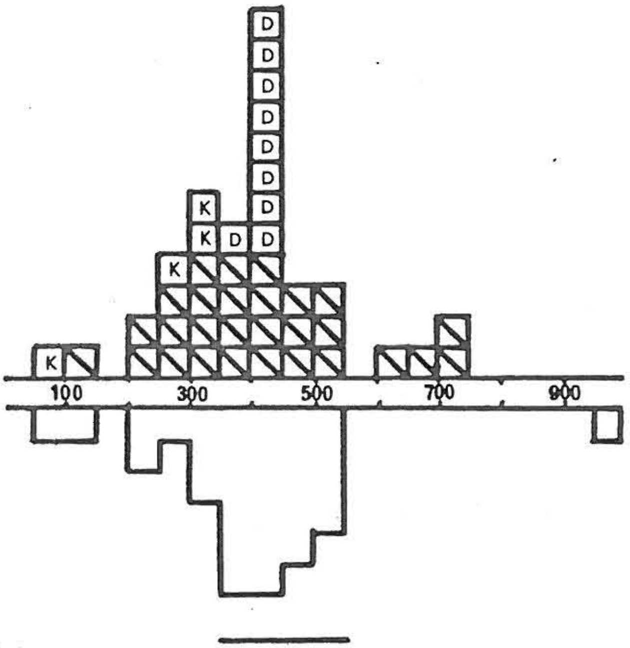


Fig.17A K/Rb

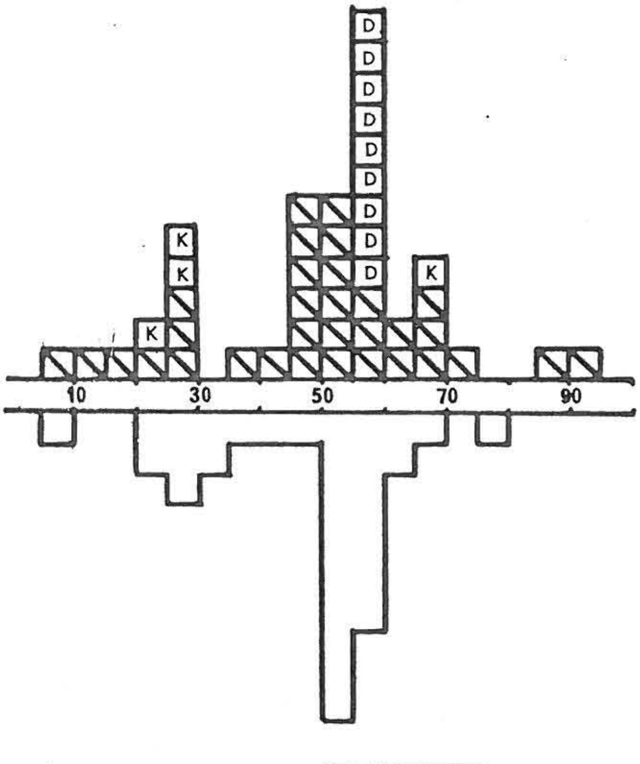


Fig.17B K/Zr

Figs.17 A-F Incompatible element ratios for the Drakensberg Subgroup in the Barkly East area and the Karroo Dolerites (from Robey, 1976).

D Drumbo Member
K Kraai River Formation
▧ Lesotho Formation
☐ Dolerites (Robey, 1976)
— Birds River Intrusion (Robey, 1976)

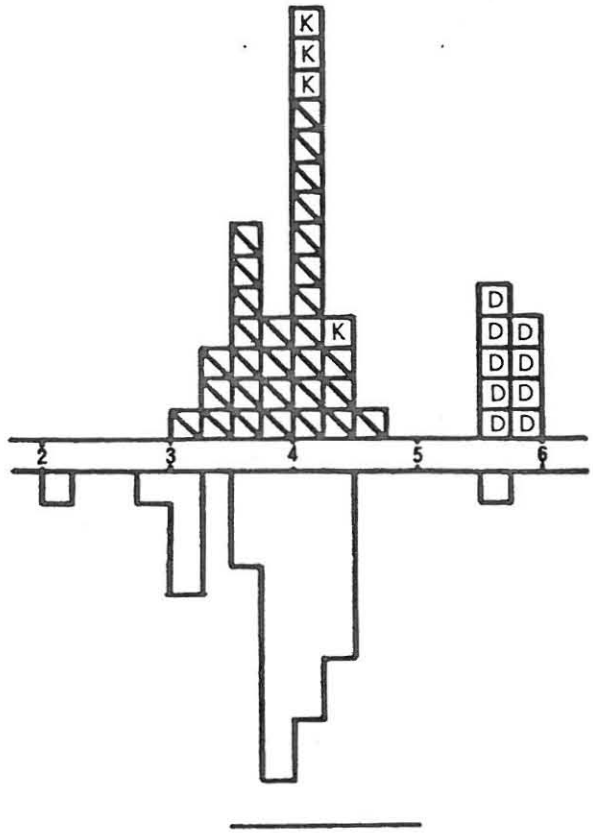


Fig.17B Zr/Y

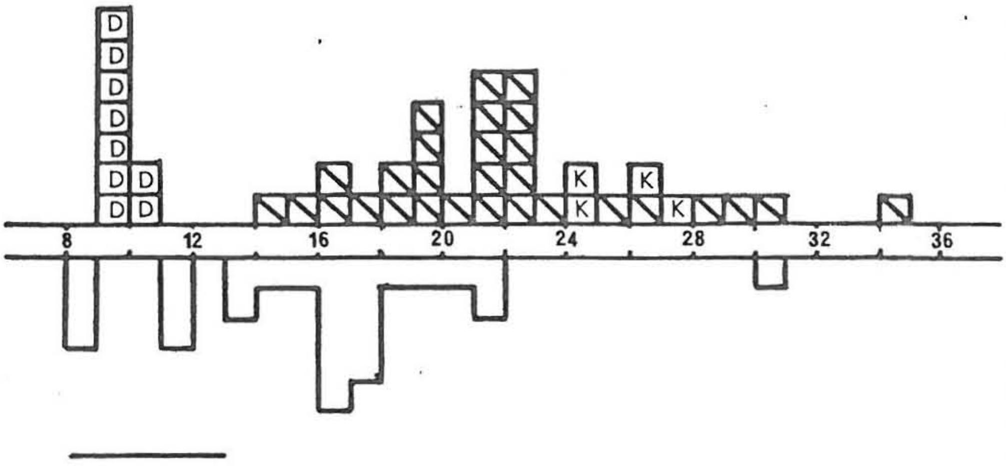


Fig.17D Zr/Nb

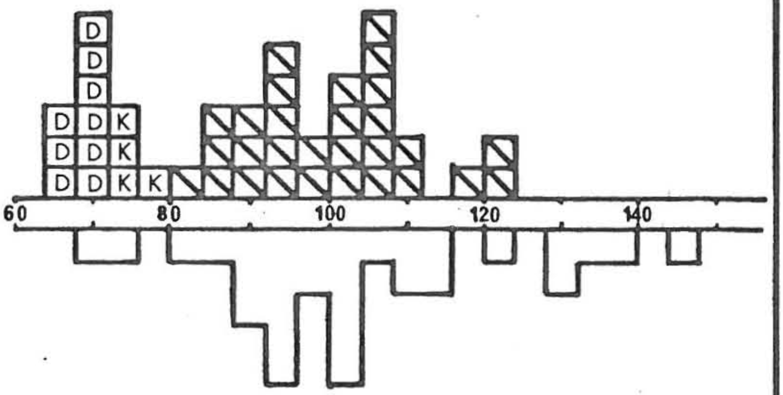


Fig.17E TiO_2/Zr

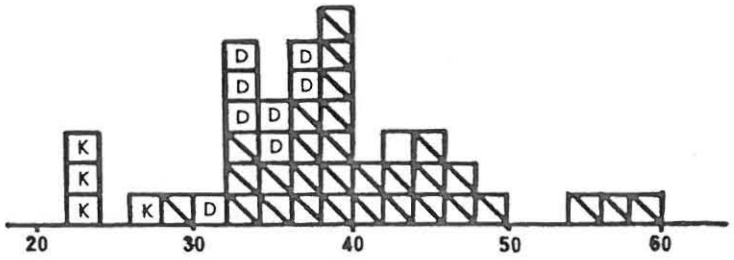


Fig.17F P_2O_5/Ce

reason for these differences, in the light of the present data, is a mantle source that is heterogeneous, resulting in different absolute amounts of the incompatible elements and different interelement ratios.

6.2.4 Incompatible Elements in the Lesotho Formation

In the plots of Zr, Rb, Nb and the total of La, Ce and Nd for the Lesotho Formation, against stratigraphic height (Fig.18 a-e) in the Naudes Nek section, an increase occurs from approximately halfway up the sequence. This increase in the incompatible elements with height is matched by increases in the major elements Ti, P and Fe and a decrease in Mg. With the supporting evidence from the transition elements, discussed in section 6.5.4, it is here proposed that the most likely cause of these trends in the Lesotho Formation is low-pressure fractionation. It is accepted that mantle and high pressure fractionation processes may have acted on these lavas but the observation of Ringwood (1975) that extensive low-pressure fractionation is well established for flood and mid-ocean-ridge basalts is supported by the major element chemistry in section 5.4 and by Cox and Hornung (1966).

The equation for fractional crystallization (section 6.1) has been used to calculate the amount of crystallization required to produce the enrichment seen in the incompatible elements. It must be emphasized that the initial and final liquids were arbitrarily taken to be those compositions depicted by samples JP43 and JP58. If electron microprobe data of the fractionating phases were available, accurate computer modelling of the differentiation might have been attempted. The aim of this exercise is to estimate in a qualitative way the amount of fractionation and the percentage of the various phases involved in the differentiation of the Naudes Nek section.

The following enrichment factors were calculated for the Naudes Nek section:

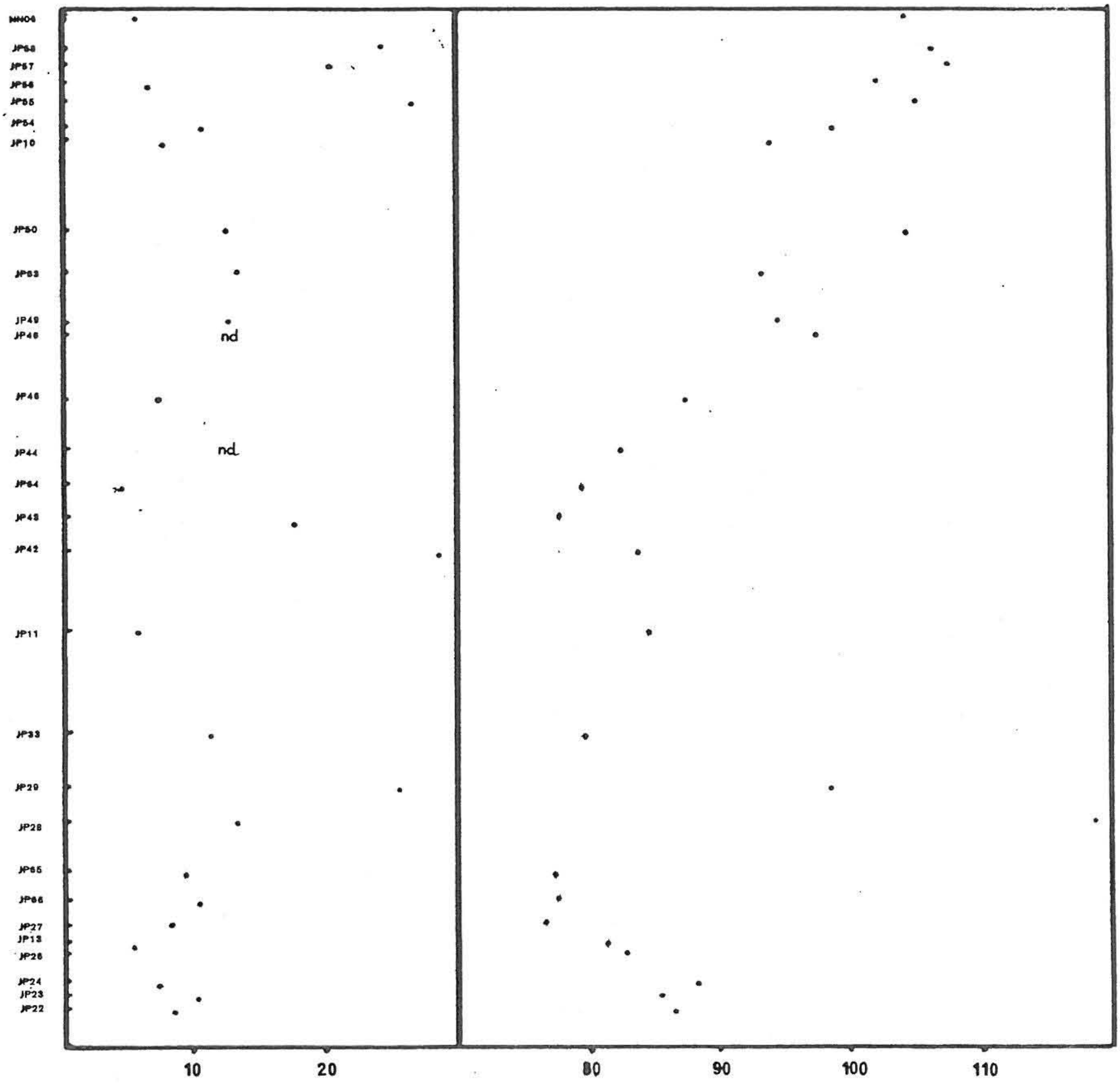


Fig.18A Rb ppm

Fig.18B Zr ppm

Figs.18 A-E Incompatible elements for the Lesotho Formation plotted against height

nd below Lower Limit of Determination

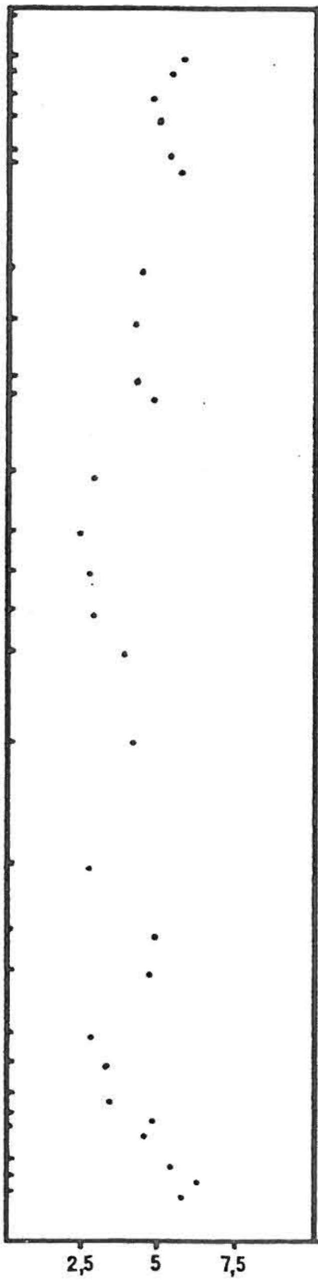


Fig.18C Nb ppm

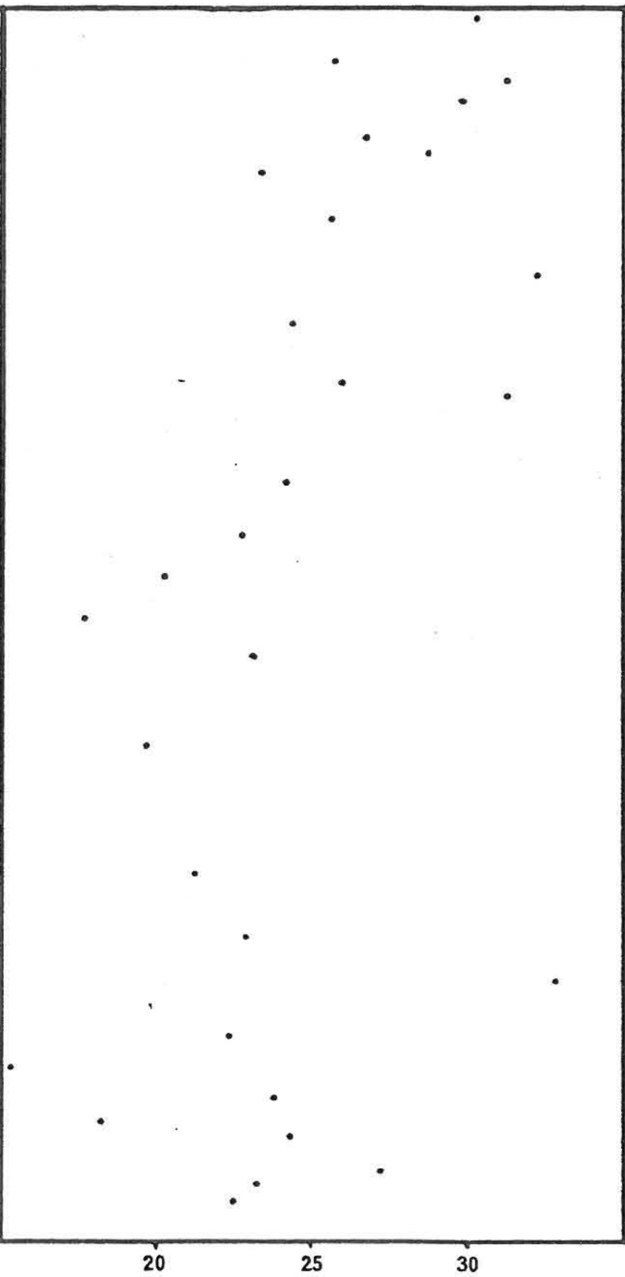


Fig.18D Ce ppm

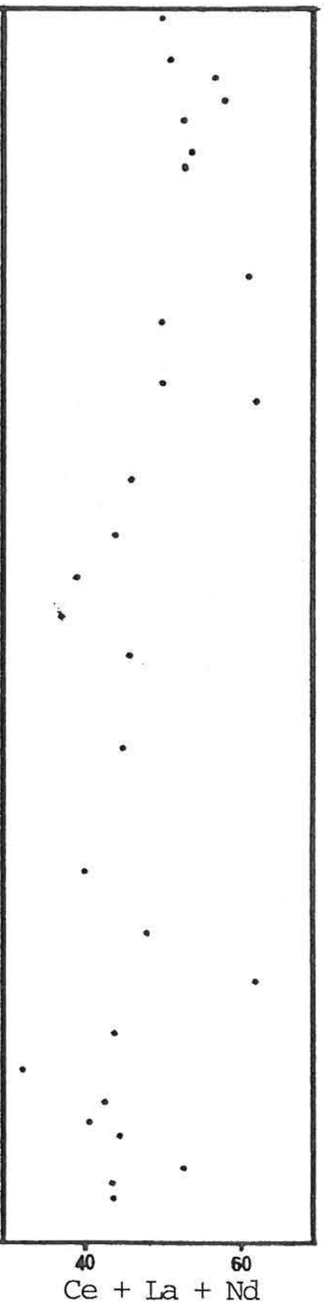


Fig.18E

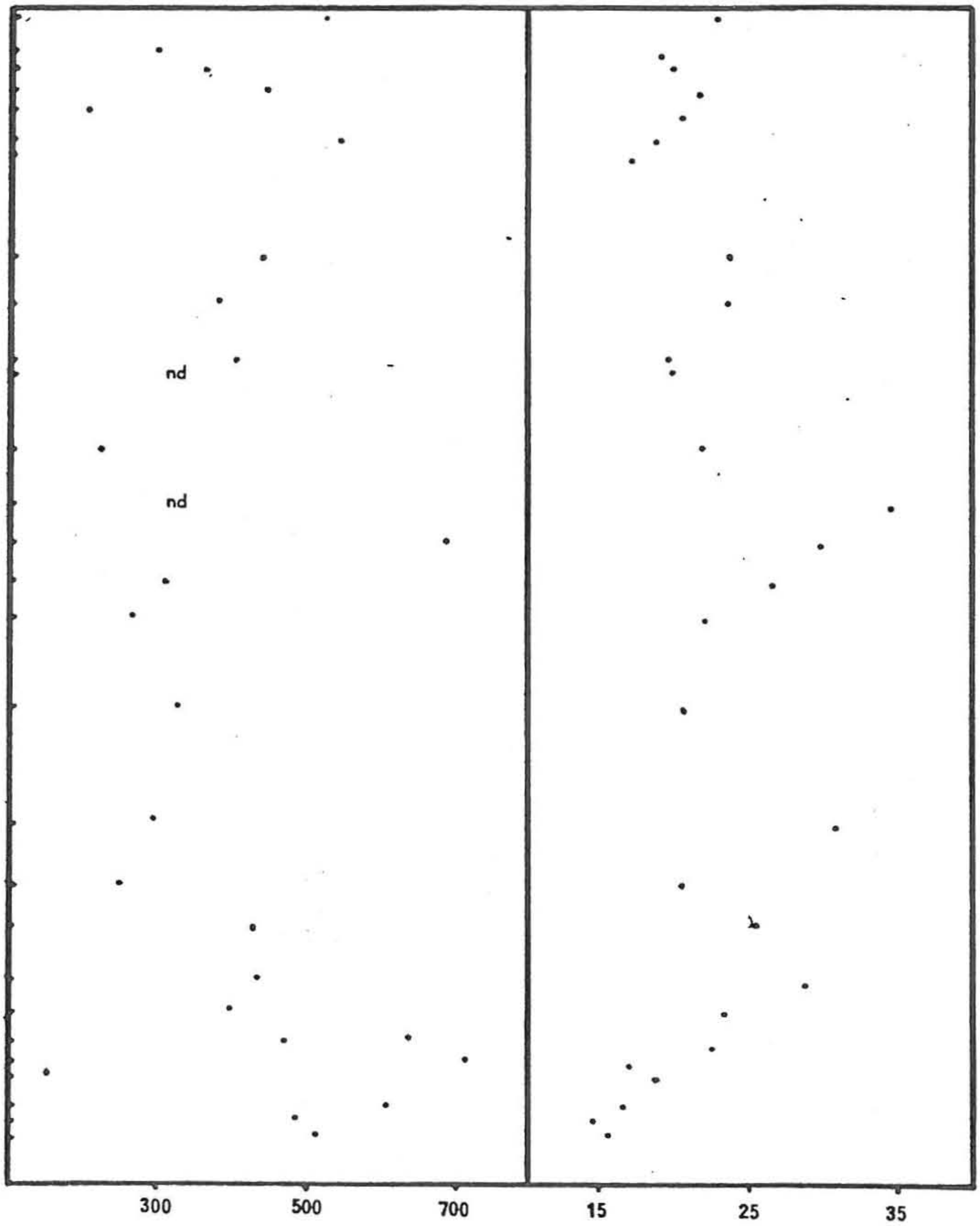


Fig.19A K/Rb Fig.19B Zr/Nb

Figs.19 A-E Incompatible element ratios for the Lesotho Formation plotted against height

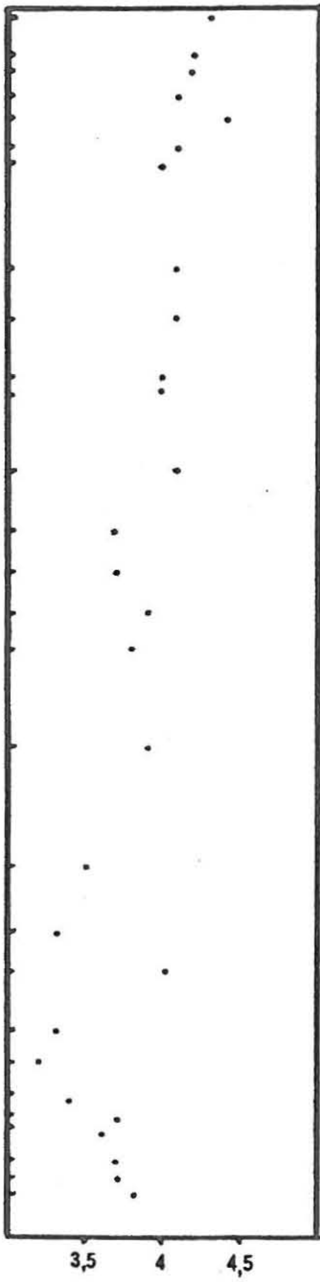


Fig.19C K/Y

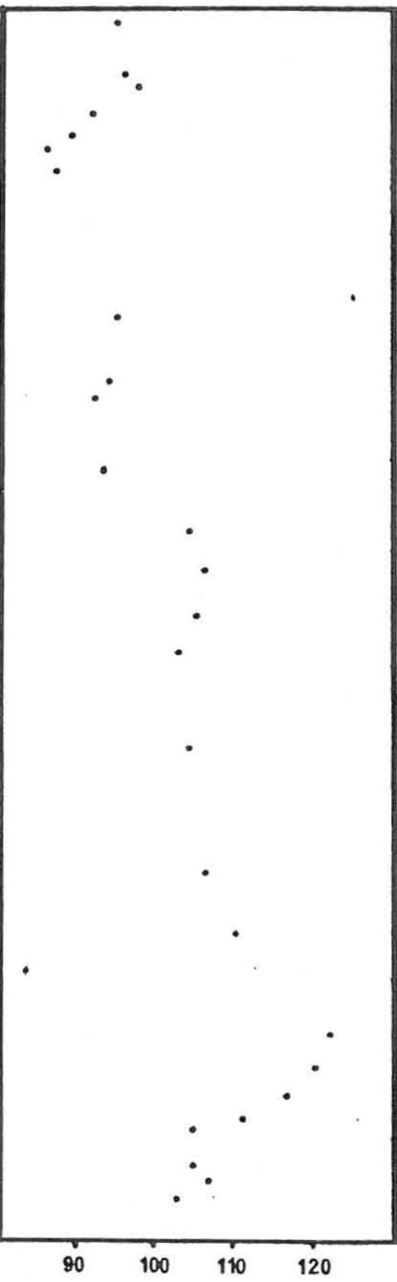


Fig.19D TiO_2/Zr

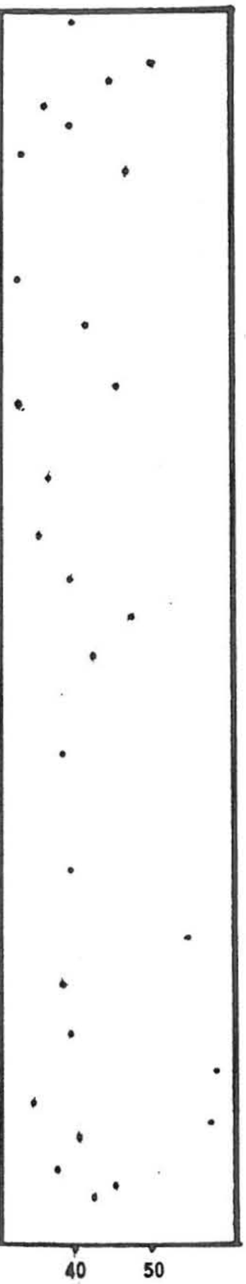


Fig.19E P_2O_5/Ce

Element	Enrichment Factor
Zr	1,36
Nb	1,87
Rb	1,34
Ce	1,44
Nd	1,24
La	1,90
K	1,28
Y	1,29
TiO_2	1,25
P_2O_5	1,52
Mean	1,45
Coefficient of variation	16,08%

If analytical accuracy is considered then the variation of the above factors is small and comparable with those from Réunion, (Zielinski, 1975). The mean of the enrichment factors may be used to calculate that approximately 30% crystallization was needed to produce the observed enrichments. This value has been used in the discussion of transition elements (section 6.5) to estimate the amount of the various phases undergoing fractional crystallization.

6.3 YTTRIUM

6.3.1 Introduction

According to Lambert and Holland (1974) Y behaves systematically in igneous rock series because of its incorporation in a predictable and uniform manner in Ca-bearing minerals. In size Y^{3+} falls between Fe^{2+} and Ca^{2+} but much closer to Ca^{2+}.

Lambert and Holland (1974) classified Ca minerals as either Y-acceptors or -rejectors depending on the Ca/Y ratio being greater or less than 2000. Y-rejector minerals are calcite, augite, plagioclase and kaersutite. Y-acceptors are hornblende, garnet, epidote, allanite, apatite and sphene while Ca-poor minerals are orthopyroxene, K-feldspar, micas and aegirine-augite. In igneous differentiation the ratio Ca/Y always decrease

falls but the extent of the fall varies and Lambert and Holland (1974) therefore define three general trends:

a) Standard or calc-alkali trend caused by clinopyroxene and plagioclase fractionation.
b) J-type or hornblende trend characterised by Y depletion with Ca-decrease caused by hornblende fractionation.
c) L-type or pyroxene trend with Y enriched relative to the J-type trend. This is caused by pronounced plagioclase and clinopyroxene fractionation.

6.3.2 Yttrium in the Rocks under review

Table 6 : YTTRIUM IN THE DRAKENSBERG SUBGROUP

	D.B.M.	K.R.F.	L.F.	K.R.F.(R)	Dolerite (R)
Average	25,6	26,8	23,6	26,6	25,7
Range	24,6 to 27,1	26,5 to 27,5	19,7 to 30,1	24,3 to 29	23,2 to 30,9

R = Robey (1966)
D.B.M. = Drumbo Member
K.R.F. = Kraai River Formation
L.F. = Lesotho Formation

The variation of the Y content in the different units of the Drakensberg Subgroup is shown in Fig.20. Diagrams showing Y versus height and Y versus CaO (as used by Lambert and Holland (1974)) are given in Fig.21 and Fig.22 respectively.

6.3.3. Discussion

Y does not appear to behave as a typically incompatible element in the Drakensberg Subgroup. In the Naudes Nek section the Y content does increase from the halfway stage but the enichment factor of 1,29 is below the mean for all the typical incompatible elements.

The plot of Lambert and Holland (1974) can be used as an indicator of fractionation patterns in the different units of the Drakensberg Subgroup. Although the trends are not as pronounced as those of the Birds River Intrusion or the Omega Formation, the Drumbo Member and Kraai River Formation have

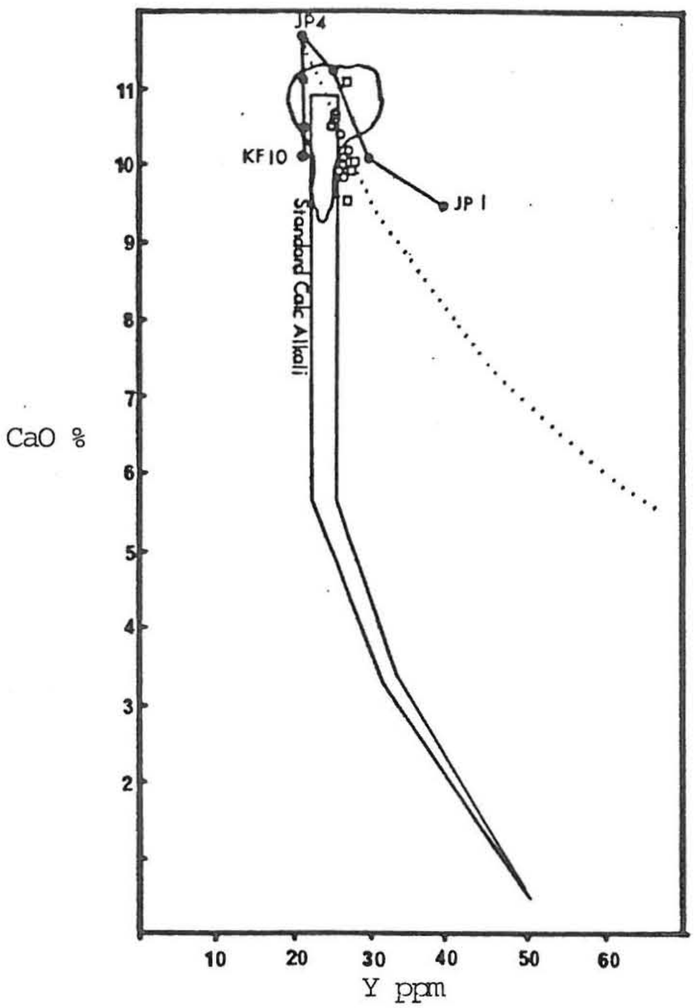


Fig.22 Yttrium plotted against CaO % (after Lambert and Holland, 1974)

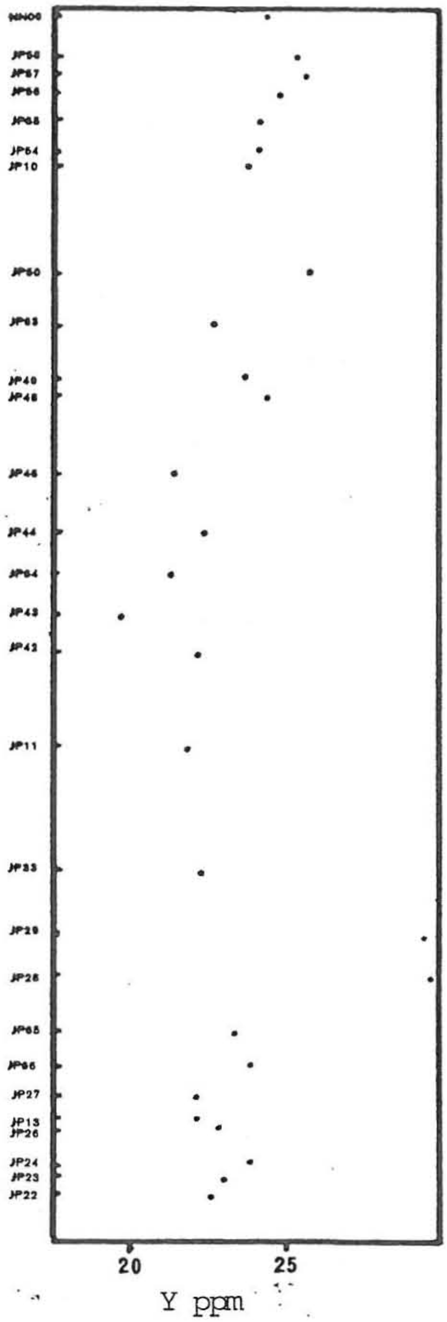


Fig.21 Yttrium plotted against height in the Lesotho Formation

- ° Drumbo Member
- ◻ Kraai River Formation
- — Lesotho Formation
- • Omega Formation
- .... Birds River Intrusion (Robey, 1976)

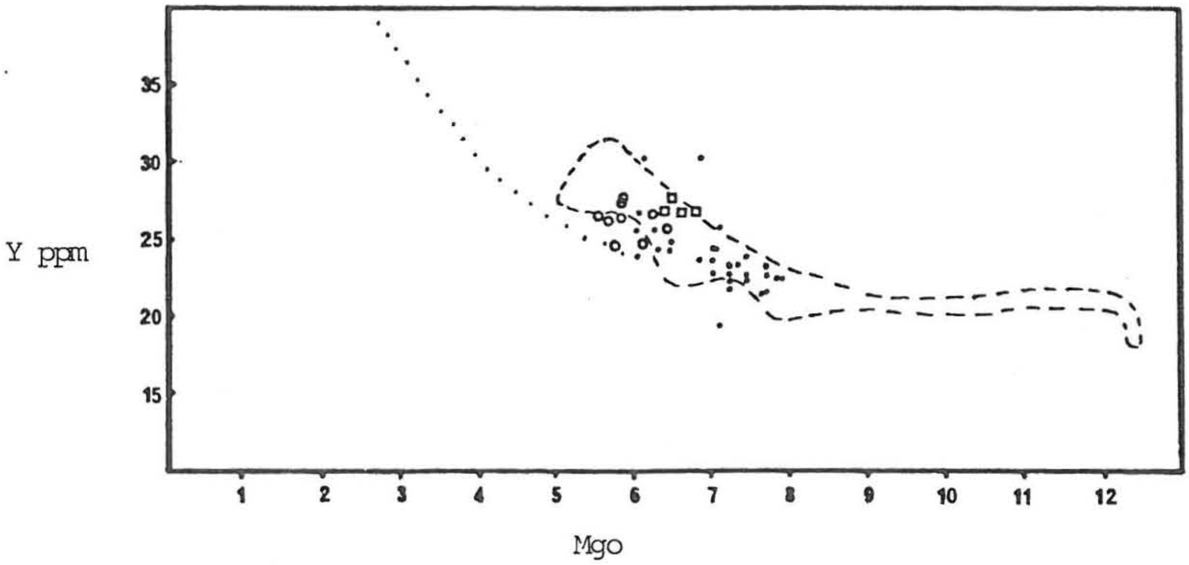


Fig.20 Yttrium plotted against MgO %

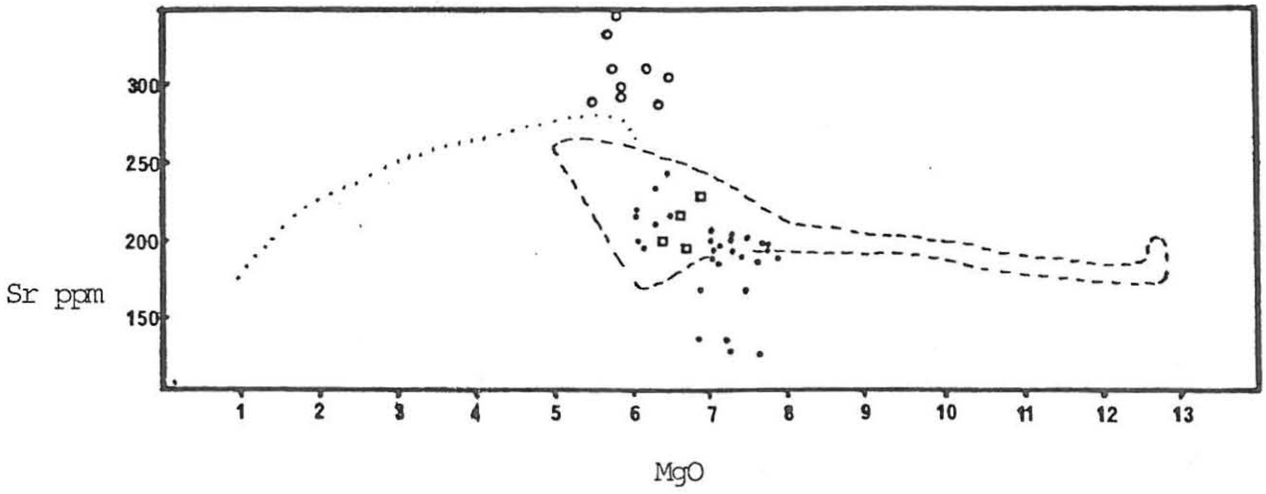


Fig.23 Strontium plotted against MgO %

● Drumbo Member

□ Kraai River Formation

• Lesotho Formation

\--- Dolerites (Robey, 1976)

····· Birds River Intrusion (Robey, 1976) weakly defined trends that fall between those of the standard calc-alkali and L-type trends. This pattern suggests clinopyroxene and plagioclase fractionation. The small degree of fractionation has apparently limited the variations in both Ca and Y and clearer definition of the trends cannot therefore be anticipated.

6.4 STRONTIUM

6.4.1 Introduction

In the tholeiitic basalt system the only phase with a partition coefficient greater than unity for Sr is plagioclase:

D^{Sr}_{plag} = 1,27 to 2,84 (Philpotts and Schnetzler, 1970)

D^{Sr}_{plag} = 7,0 for An_{30}, 5,4 for An_{45}, 3,8 for An_{60}, 2,3 for An_{75}, 1,5 for An_{90} (Korringa and Noble, 1971)

From the above it can be seen that the value of the partition coefficient also increases with increasing alkali content of the plagioclase. The experimental work of Sun et al. (1974) showed that with decreasing temperature the partition coefficient increases (from 1190°C to 1110°C D^{Sr}_{plag} increases from 1,525 to 2,123). The partition coefficients of olivine and pyroxene are well below unity:

D^{Sr}_{cpx} = 0,00187 to 0,516 (Philpotts and Schnetzler, 1970)
0,054 to 0,081 (Shimizu, 1974)

D^{Sr}_{ol} = 0,072 to 0,111 (Hart and Brooks, 1974)
0,00937 to 0,0185 (Philpotts and Schnetzler, 1970)

Considering these partition coefficients, separation of pyroxene and olivine would lead to an enrichment of Sr in the melt while plagioclase separation would reduce the Sr content of the residual melt. Taylor (1965), using Goldschmidt's Rules and the ionic radii of Ca and Sr, predicted that Sr would increase relative to Ca during fractionation. Brooks (1968) disagrees with this reasoning by pointing out that Ca is not only incorporated within the plagioclase structure but also

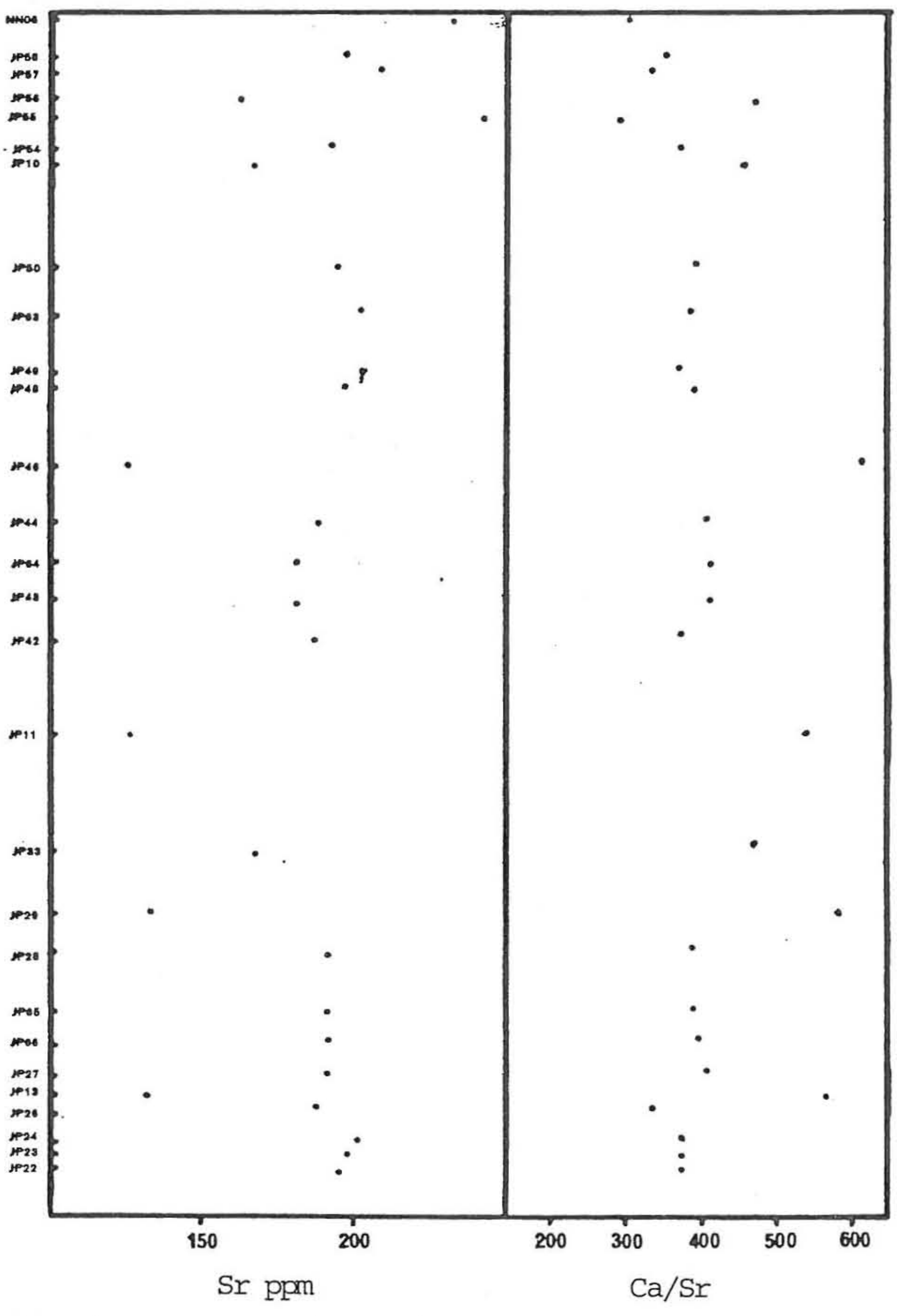


Fig.24 Strontium and the Ca/Sr ratio plotted against height
&
Fig.25 for the Lesotho Formation.

that of the pyroxenes. This means that the Ca/Sr ratio is controlled by the fractionating phases and not simply by the ease of entry into the plagioclase structure. In the differentiated Birds River Intrusion (Robey, 1976), the Ca/Sr ratio decreases from 326 to 210 with plagioclase, pyroxene and olivine fractionation.

6.4.2 Data Presentation - Strontium in the Rocks under Review

Table 7 : STRONTIUM AND THE Ca/Sr RATIO IN DRAKENSBERG SUBGROUP

	D.B.M.	K.R.F.	L.F.	K.R.F.(R)	Dolerite(R)
Sr					
Average	307	207	185	207	206
Range	287 to 343	191 to 229	125 to 233	183 to 236	168 to 264
Ca/Sr					
Average	235	345	406	336	397
	203 to 246	335 to 358	284 to 607	257 to 389	279 to 423

R = Robey (1966)
D.B.M. = Drumbo Member
K.R.F. = Kraai River Formation
L.F. = Lesotho Formation

Fig.23 shows Sr plotted against MgO for the different units of the Drakensberg Subgroup. Sr as well as the Ca/Sr ratio in the Naudes Nek section are plotted against height (Figs.24 and 25 respectively).

6.4.3 Discussion

If the increases in incompatible elements in the Lesotho Formation are due to fractionation, then with the regular occurrence of plagioclase as a phenocryst phase, the Sr content would be expected to decrease with height in the Naudes Nek section. The plot of Sr against height shows no such distinct decrease in Sr. An explanation for this behaviour of Sr is that fractionation of pyroxene and olivine has reduced the bulk partition coefficient of Sr in the rock to near unity.

In the Birds River Intrusion Robey (1976) noted a similar subdued depletion of Sr which he attributed to the concomitant fractionation of pyroxene and olivine.

The values of the Ca/Sr ratio in the Naudes Nek section are scattered but from sample JP43 to JP58 there is a decrease from 406 to 349. According to Brooks (1968) this would indicate not only plagioclase fractionation but also that of pyroxene.

As with the incompatible elements, the Sr content of the Drumbo Member is higher than that of the other units of the Drakensberg Subgroup. This could result from one or a combination of the following:

a) Fractionation of olivine and pyroxene, assuming a homogeneous mantle.
b) If fractionation of plagioclase, olivine and pyroxene took place to a similar extent as in the other units then either an inhomogeneous mantle or smaller degrees of partial melting could be involved.

In the light of the discussion in the previous section (6.2) it is suggested that the most likely cause of the high Sr of the Drumbo Member is heterogeneity of the mantle source. As with the incompatible elements, the particular source area appears to have been enriched, or less depleted, in Sr.

6.5 TRANSITION ELEMENTS

6.5.1 Introduction and Theoretical Considerations

The transition elements, (V, Cr, Co and Ni with Cu and Zn being included although they are not strictly transition elements) in contrast to the incompatible elements, behave in a compatible manner within a fractionating magma in that they generally enter into the crystal structure of the common rock forming minerals. On the melting of a mantle source the transition metal ions tend to be retained in the crystalline phases.

As the behaviour of the transition elements does not entirely

TABLE 8 : PARTITION COEFFICIENTS FOR TRANSITION ELEMENTS

Element	Olivine	Clino-pyroxene	Ortho-pyroxene	Plagio-clase	Magnetite
Zn	0,95[1]				
	0,73-1,1[2]				
Cu	0,37-1,05[2]	0,17-0,87[3]		0,19[3]	1,3-2,3[3]
	0,11[4]			0,17[4]	
	0,02-0,039[8]				
Co	1,9-4,5[5]	1,7-4,7[3]	3,4-9,2[3]		6,2-11[3]
	3[1]	0,68-1,22[9]			
	3,1[6]	1,0-1,7[10]			
	2,8-4,2[8]				
	3,6-6,3[10]				
	2,75-4,44[9]				
Ni	10[1]	5,6-8,4[3]			19[3]
	3,6-12[2]	1,42-2,11[9]			
	13,2-18,6[5]	1,2-10			
	13,5-15,9[7]				
	8,3-23,5[8]				
	8,63-18,54[9]				
	7,0-4,8[10]				
V	0,02-0,09[10]	0,94-4,1[3]	0,5-2,3[3]		24-63[3]
		0,22-2,31[10]			
Cr	1,2-3,1[8]	0,75-32[3]	0,65-23[3]		27-58[3]
	3,1-10[2]	8-36[10]			
	1,5-5,2[1]				

References

1. Gunn (1971)
2. Flower (1973)
3. Ewart et al. (1973)
4. Bougault et al. (1974)
5. Henderson and Dale (1970)
6. Paster et al. (1974)
7. Häkli and Wright (1967)
8. Leeman and Scheidegger (1976)
9. Dale and Henderson (1976)
10. Duke (1976)

TABLE 9 : O.S.P.E. FOR TRANSITION ELEMENTS

Cr^{3+}	37,7 k cal. $mole^{-1}$
Ni^{2+}	20,6 " "
Co^{2+}	7,4 " "
Cu^{2+}	15,6 " "
V^{3+}	12,8 " "
Zn	0 " "

(from Burns, 1970)

TABLE 10 : AVERAGE AND RANGES FOR THE TRANSITION ELEMENTS

	Zn	Cu	Co	Ni	V	Cr
D.B.M.	83	71	40	67	218	295
	76-93	58-78	38-41	55-80	202-232	251-325
K.R.F.	81	61	41	48	245	281
	74-85	54-68	39-43	42-54	228-256	272-297
L.F.	84	83	46	89	233	271
	69-97	67-124	41-49	50-111	195-278	149-373
K.R.F.	80	60	35	47	233	271
(Robey)	76-83	47-67	29-39	33-54	189-242	121-255
DOLERITE	84	93	42	78	239	243
(Robey)	75-105	82-118	34-58	44-271	192-261	125-651

D.B.M. = Drumbo Member
K.R.F. = Kraai River Formation
L.F. = Lesotho Formation

(Robey) = Data from Robey (1976)

conform to the empirical rules of Goldschmidt (1937) and Ringwood (1955) they have been treated by Burns and Fyfe (1964) according to crystal field theory. In silicate melts transition metal ions enter either the tetrahedral or octahedral sites but these authors point out that in the crystalline phases it is energetically more favourable for the transition elements to enter the octahedral sites and that they are rarely found in the tetrahedral sites. This relative preference of the transition elements can be expressed as the octahedral site preference energy (O.S.P.E.) which is the difference between the crystal field stabilization energies of the octahedral and tetrahedral sites in the silicate minerals. The O.S.P.E. gives an indication of the relative affinity of the transition elements for an octahedral site in a silicate mineral and can be used to predict the order of uptake into the crystallizing phases:

Ni > Cu > Co > Fe > Mg > Zn for M'' ions
Cr > Mn > V > Ti > Fe > Sc for M''' ions (from Burns and Fyfe, 1964)

A. Nickel

As Ni has a high O.S.P.E. (Table 9) through crystal field effects it is rapidly depleted in the melt by crystallizing phases such as olivine and clinopyroxene (see Table 8). Henderson and Dale (1970) have shown a linear relationship between the partition coefficients and O.S.P.E. for Fe^{2+}, Co^{2+}, and Ni^{2+} for olivine and suggest that crystal field effects are dominant in determining the partition coefficients for olivine. This relationship is questioned by Leeman and Scheidegger (1976) who found a correlation between log D and the ionic radius but also point out that factors other than the O.S.P.E. and ionic radius are important in the uptake of Ni into the olivine structure.

In olivine and orthopyroxene Ni occupies the M1 site through its crystal field stabilization energy while in clinopyroxene the M1 site is distorted leading to a lower partition coefficient for Ni (Burns, 1969).

B. Chromium

Cr, with its high O.S.P.E. (Table 9), is rapidly depleted in the coexisting melt mainly through its enrichment in clinopyroxene. In augite Cr^{2+} is enriched in the M2 site due to a deficiency of Ca ions in the clinopyroxene structure while in the orthopyroxene structutre Cr^{3+} is enriched in the M1 site while Cr^{2+} occupies the M2 site (Burns, 1970).

Duke (1976), using his experimental work, has discussed the unexpected enrichment of Cr in olivines. As there are no obvious spinels in his material he suggested that too-rapid cooling led to a metastable state with no exsolution of Cr-spinels. Flower (1973) and Leeman and Scheidegger (1976) both obtained a partition coefficient greater than unity for Cr in olivine with the latter expressing some doubt as to the olivine being free of Cr-spinel despite a detailed examination. As the M1 site of olivine is distorted, Burns (1969) has suggested that the easily oxidised Cr^{2+} ion is stabilized in it, thereby explaining the appearance of Cr in olivine that is Cr-spinel-free. In Robey's (1976) study of the Karroo dolerites picotite was found in olivines from olivine-rich dolerites with Cr contents in the region of 780 ppm. It is considered unlikely that the presence of Cr-rich phases in olivines has been missed in the basalts of the Drakensberg Subgroup because of the low Cr contents of these rocks in comparison with the olivine-rich dolerites. From this discussion it must be assumed that Cr is present in olivine but to a lesser degree than in pyroxene.

C. Cobalt

valence

The O.S.P.E. for Co is low in comparison with Cr and Ni resulting in its relatively subdued entry into olivine and pyroxene (see Table 8). As a result of the crystal field stabilisation energy of Co, Burns (1970) predicts enrichment in the M1 sites in olivine while in orthopyroxene Co^{3+} is enriched in M1 sites and Co^{2+} in M2 sites. In clinopyroxene Co enters the M2 position to a limited degree.

valence

D. Copper

Although Cu has a relatively high O.S.P.E. it is not readily accepted into the structures of olivine and pyroxene, but is enriched in the melt until the end stages of fractionation. Burns (1970) has suggested that this behaviour of Cu is due to the Jahn-Teller distortion which Cu produces in its coordination polyhedra. During differentiation of basic magma at Skaergaard an immiscible phase rich in Cu and S separated at a late stage to deplete the melt in Cu (Wager and Brown, 1968). Walker (1970) reports a similar behaviour of Cu in the Palisade sill. This immiscible phase was found to separate when Cu had enriched to about 500 ppm. In the Birds River Intrusion Cu increases from 71 ppm to 165 ppm with differentiation before declining in the late stages to 60 ppm (Robey, 1976). No Cu sulphides were identified and Robey (1976) suggests that the late-stage crystallization of Na-plagioclase and magnetite resulted in this depletion of Cu.

E. Zinc and Vanadium

Zn has zero O.S.P.E. and according to Flower (1973) behaves in an unpredictable way in the Anjoun and Grande Comore lavas. The behaviour of V is also little understood. Duke (1976) noted its preference for clinopyroxene while Ewart et al. (1973) found that the partition coefficients for the pyroxenes can be greater than unity. V has a large partition coefficient in magnetite which will result in its rapid depletion following separation of this phase. This was noted by Robey (1976) in the case of the Birds River Intrusion but Zn behaved incompatibly, being progressively enriched in the melt.

F. The Cr/Ni and Ni/Co Ratios

According to Gunn (1971) the Cr/Ni ratio will vary depending on whether olivine or pyroxene is the dominant fractionating phase. As olivine has a greater partition coefficient for Ni than for Cr and pyroxene the reverse, with olivine fractionation the Cr/Ni ratio should increase while with pyroxene fractionation it should decrease. He illustrates this with data from the Kilauea lavas which resulted from olivine fractionation and have a Cr/Ni ratio which increases from 1,4 to 2,95 with fractionation. The Makaopuhi lavas whose composition variation is controlled by pyroxene fractionation have a decreasing Cr/Ni ratio from 2,7 to 1,6.

The Cr/Ni ratio has been used by Leeman (1976) to establish possible mantle source compositions for the McKinney Basalts. A pyroxenite mantle source would yield a melt depleted in Cr relative to Ni and would therefore have a low Cr/Ni ratio (0,10 to 0,33). A peridotitic source would yield a higher value (2,41 to 6,71) because of olivines retention of Ni. They use R.E.E. data to support these ideas and suggest that low pressure fractionation does not disrupt the ratio to an extent too great for a decision on the source composition to be made.

In a fractionating basaltic system Ni will be depleted in the residual liquid at a faster rate than Co because of the greater partition coefficients olivine and pyroxene have for Ni. As a result of the rapid Ni depletion the Ni/Co ratio should fall during fractionation in a basaltic system.

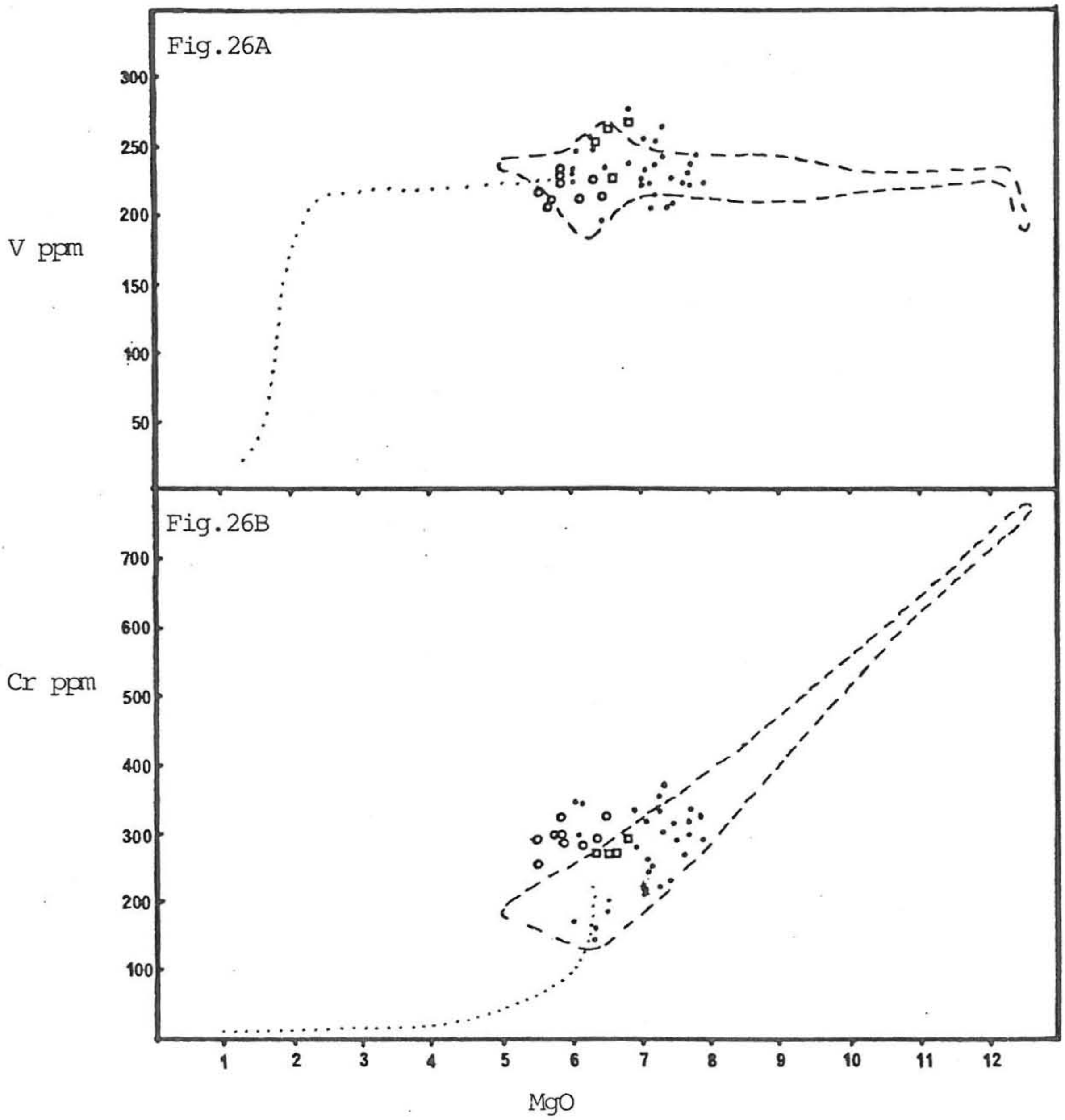
6.5.2 Data Presentation

The transition element content of the Drakensberg Subgroup are presented in Table 1 and the averages and ranges as well as Robey's (1976) data for the Kraai River Formation and chilled dolerites are presented in Table 10. The MgO variation diagrams are plotted in Figs.26 a-f. In the Naudes Nek section the transition elements as well as the ratios Cr/Ni and Ni/Co are plotted against height (Figs.27 a-h). These two ratios are also plotted as histograms in Figs.28 a and b.

6.5.3 Transition Elements in the Drakensberg Subgroup

The conclusions that may be drawn from Table 10 and Figs.28 a-f are as follows:

a. The Zn contents of the different units are very similar (approximately 80 ppm) and with one exception fall within Robey's (1976) dolerite field.



Figs. 26 A-F Transition elements for the Drakensberg Subgroup in the Barkly East area plotted against MgO %

○ Drumbo Member

▫ Kraai River Formation

• Lesotho Formation

--- Dolerites (Robey, 1976)

..... Birds River Intrusion (Robey, 1976)

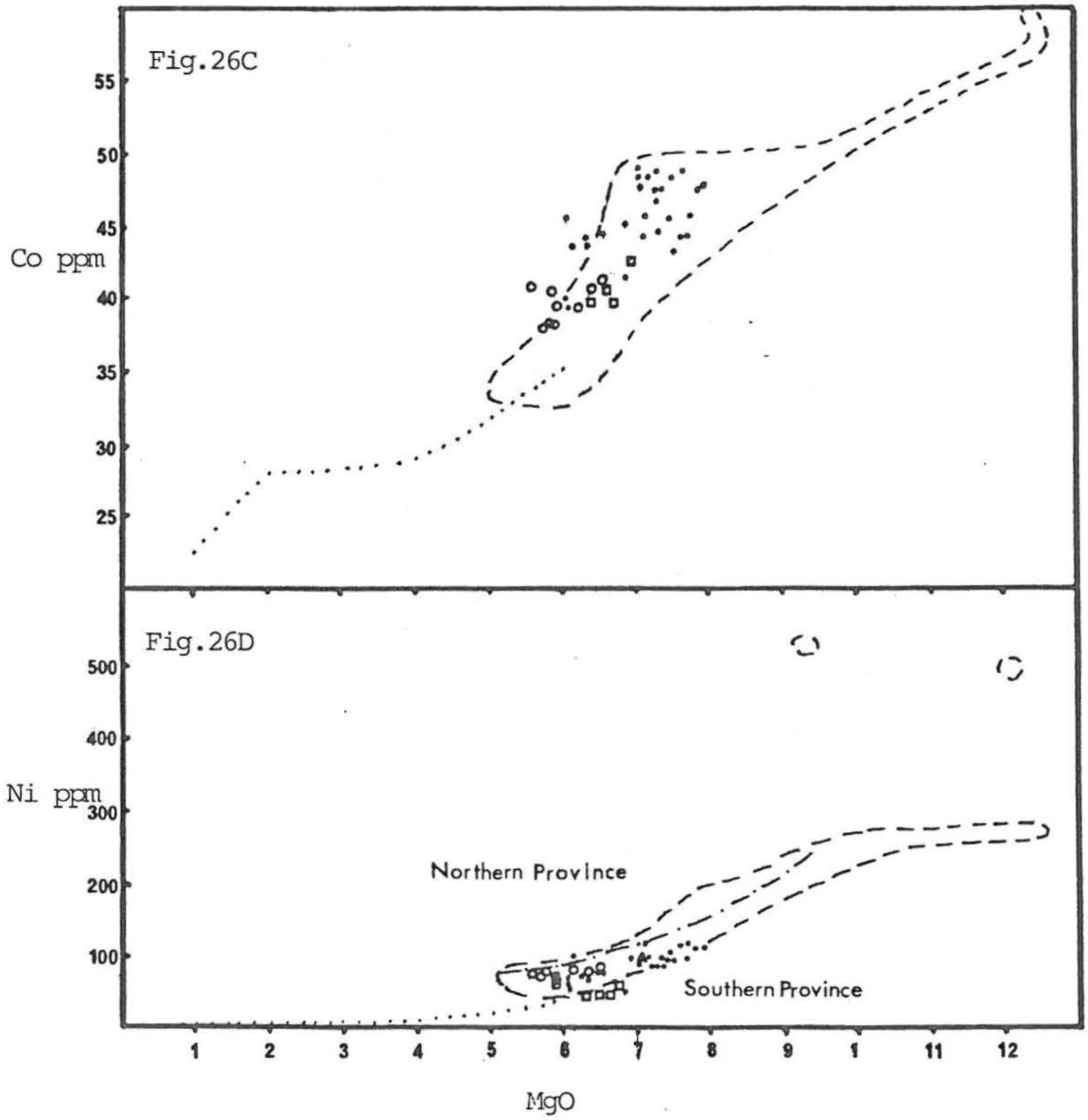


Fig.26C
Co ppm
55
50
45
40
35
30
25
Fig.26D
Ni ppm
500
400
300
200
100
Northern Province
Southern Province
1
2
3
4
5
6
7
8
9
1
11
12
MgO

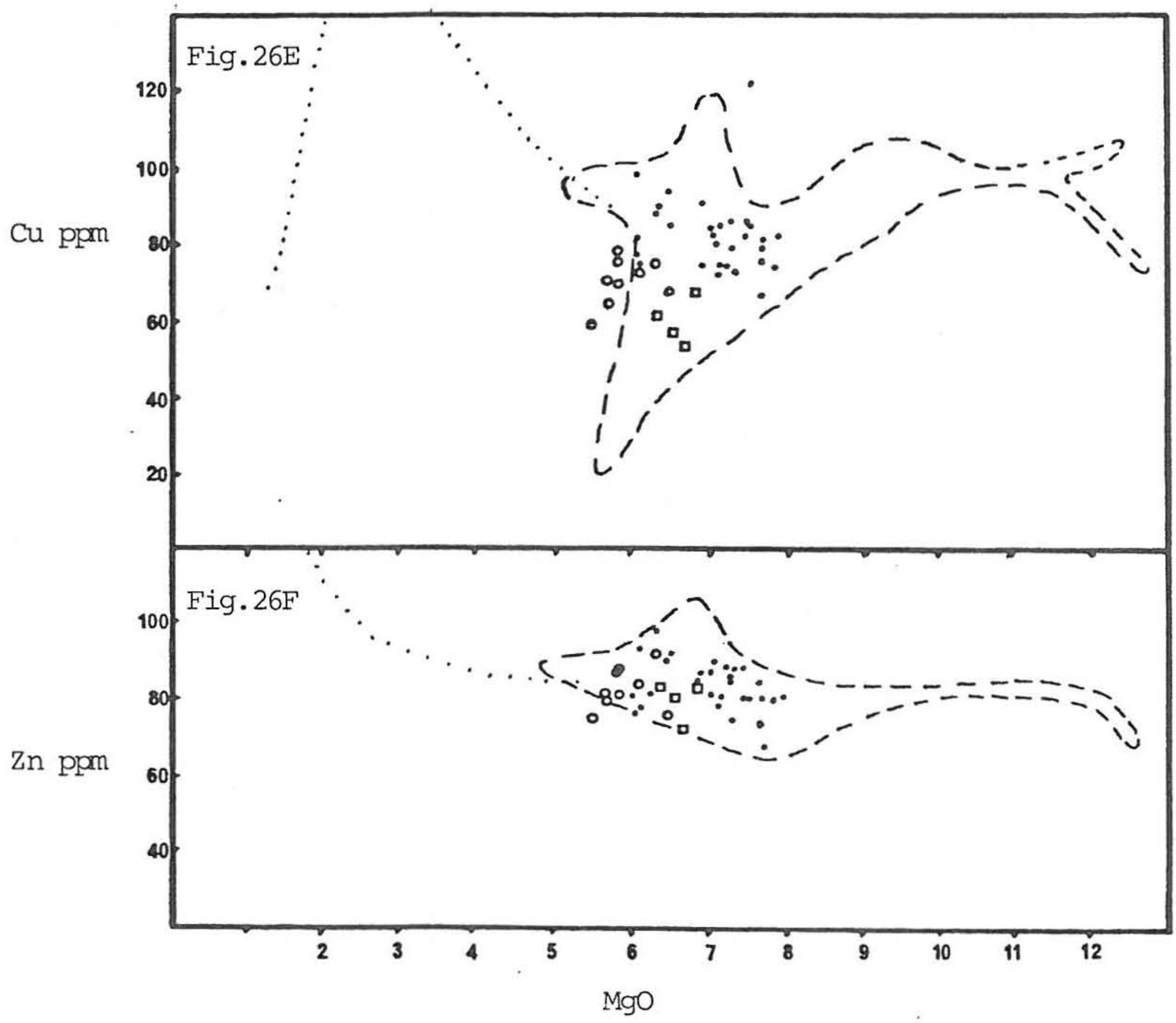


Fig.26E

Fig.26F

b. Cu in the Drumbo Member and Kraai River Formation is slightly lower than that of the Lesotho Formation. The majority of the Drumbo Member samples plot out of the dolerite field.

c. The Co contents of the Drakensberg Subgroup have a small range (38 to 49 ppm) but the averages of the Drumbo Member and Kraai River Formation are lower than that for the Lesotho Formation.

d. The Kraai River Formation has a substantially lower Ni content than the Drumbo Member and Lesotho Formation. The average for the Drumbo Member is lower than that for the Lesotho Formation but for similar MgO contents the Drumbo Member and the Lesotho Formation have the same Ni contents. A possible explanation for the lower Ni contents of the Kraai River Formation is that it is the only unit with orthopyroxene phenocrysts and their fractionation plus olivine and clinopyroxene would lead to a more rapid Ni depletion than that seen in the other units.

e. The V contents of the different units are similar with the range for the Lesotho Formation overlapping both those of the Drumbo Member and Kraai River Formation.

f. Cr has a similar pattern of variation to that of V with no distinct differences between the units.

In the Drakensberg Subgroup the Cr/Ni ratio can be used to predict the nature of the original source material of the basalts in the manner of Leeman (1976). As the Cr/Ni values of the Drakensberg Subgroup are all well above 2 it is assumed that the mantle source was of peridotitic composition.

6.5.4 Transition Elements in the Lesotho Formation

The transition elements in the Lesotho Formation allow the differentiation exhibited in the upper half of the Naudes Nek section to be investigated in more detail. Using the Cr, Ni and Co data it is possible to establish what the likely

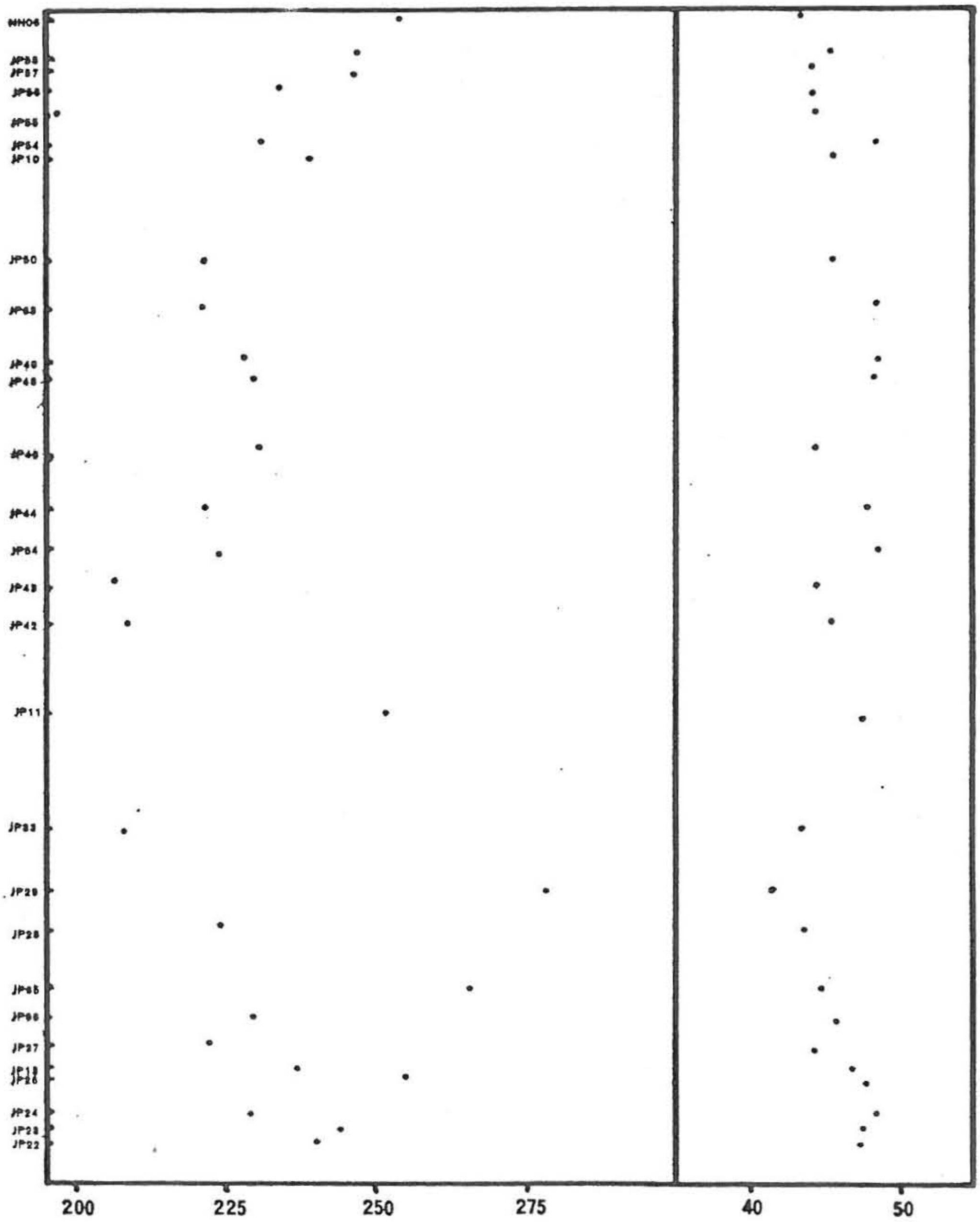


Fig.27A V ppm

Fig.27C Co ppm

Figs.27 A-H Transition elements for the Lesotho Formation plotted against height

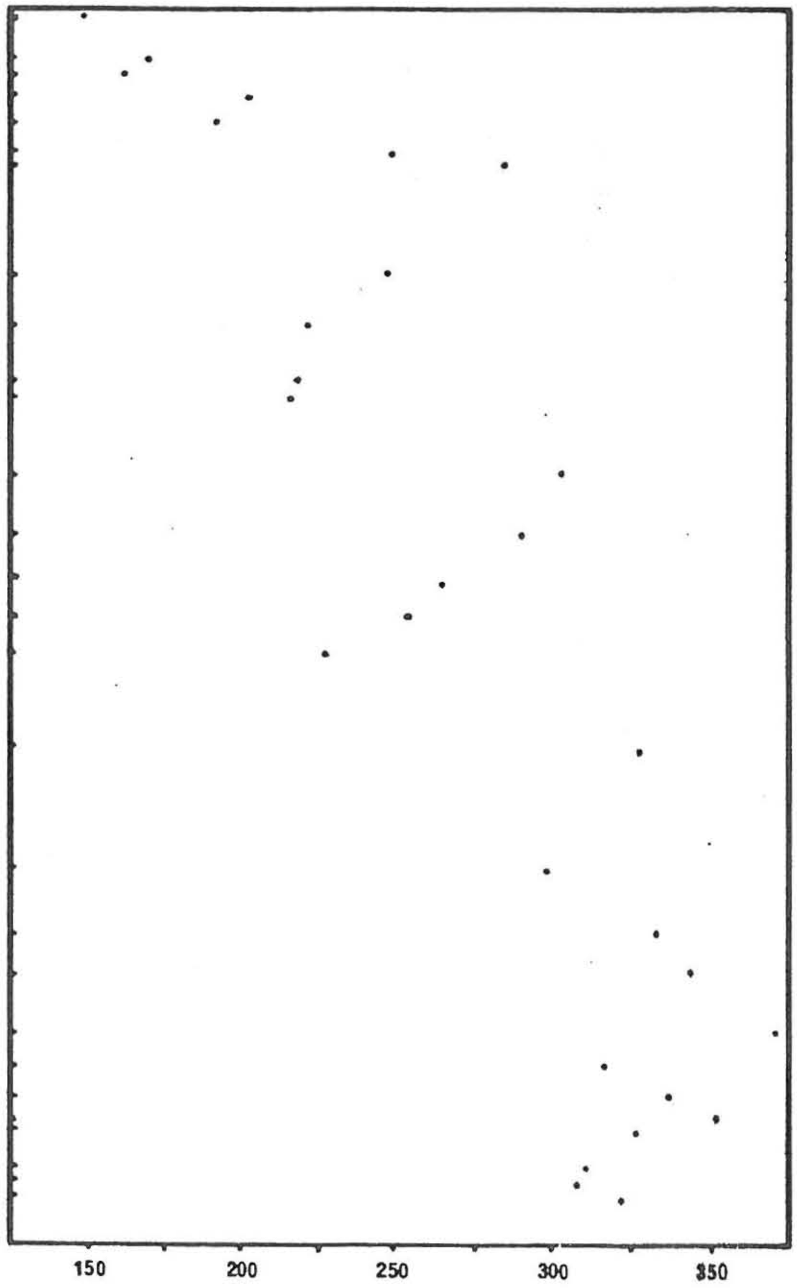


Fig.27B Cr ppm

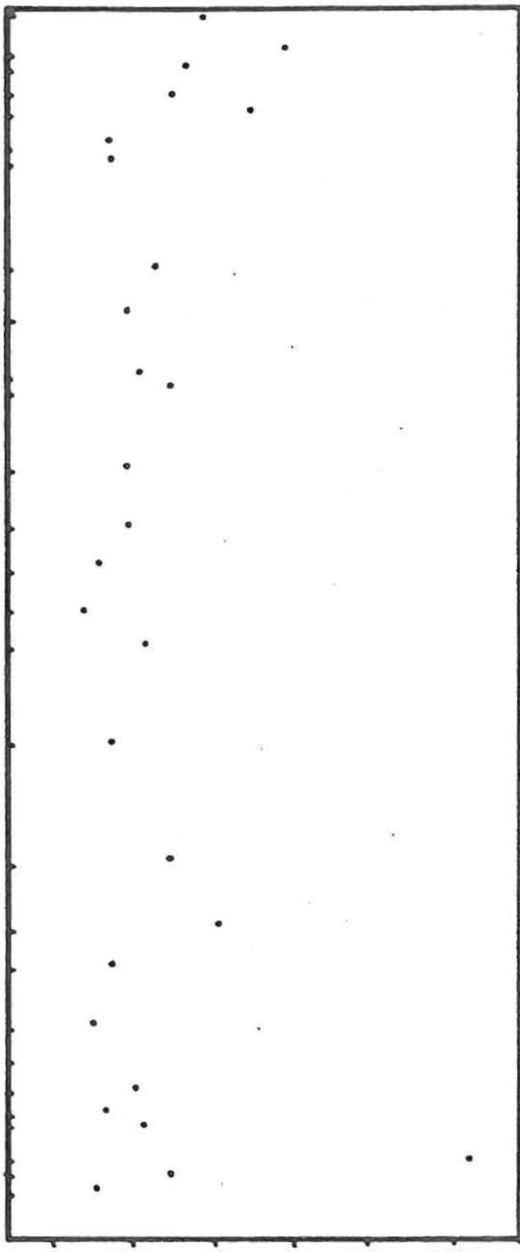


Fig.27E Cu ppm

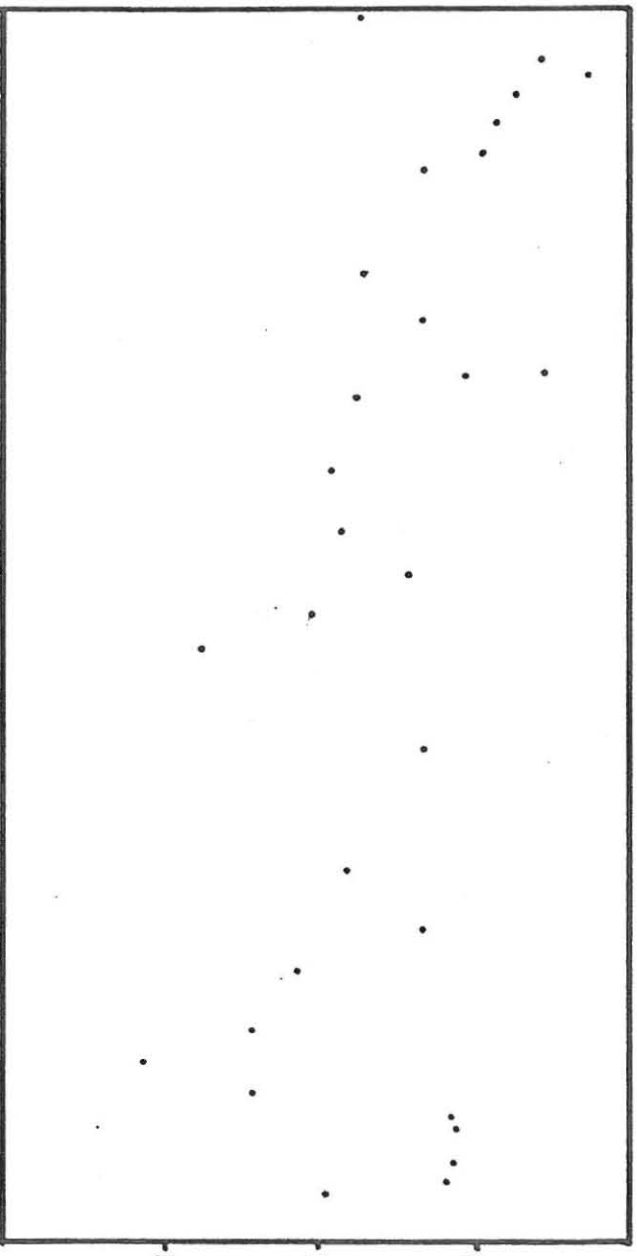


Fig.27F Zn ppm

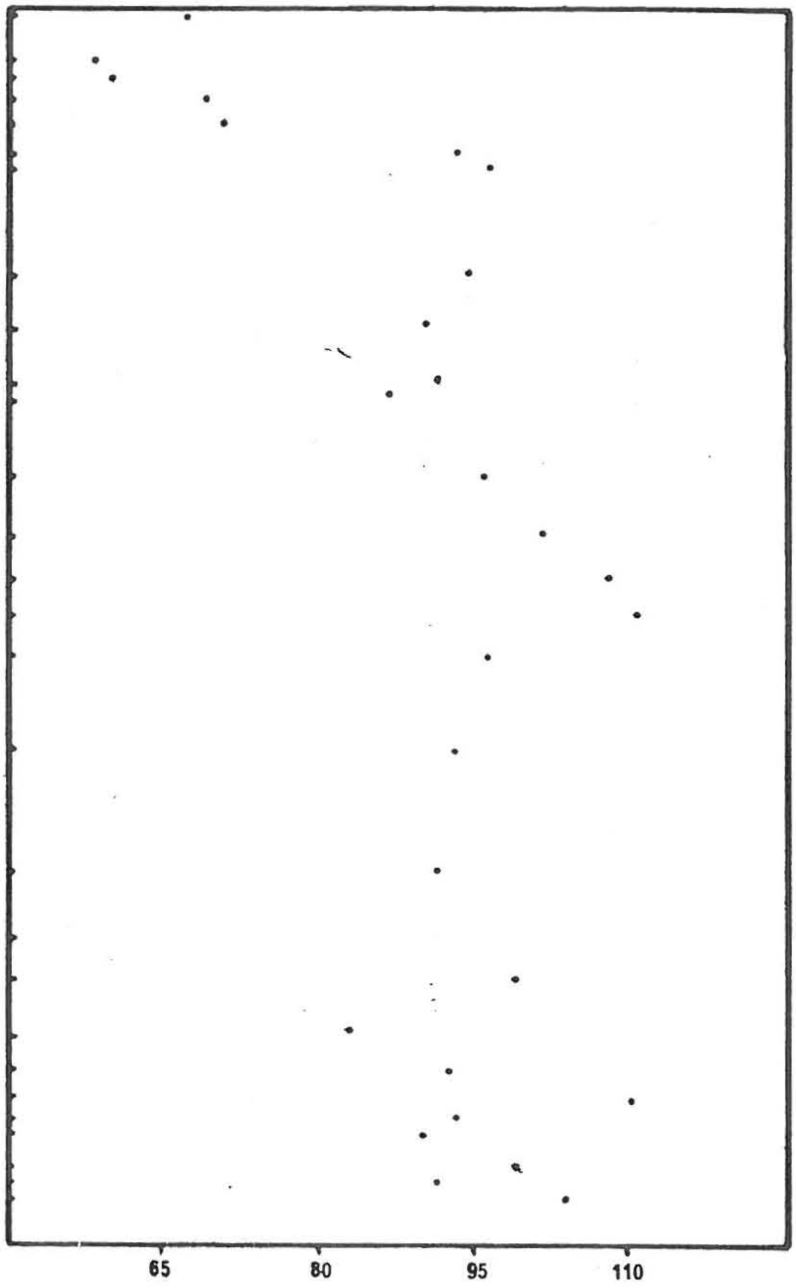


Fig.27D Ni ppm

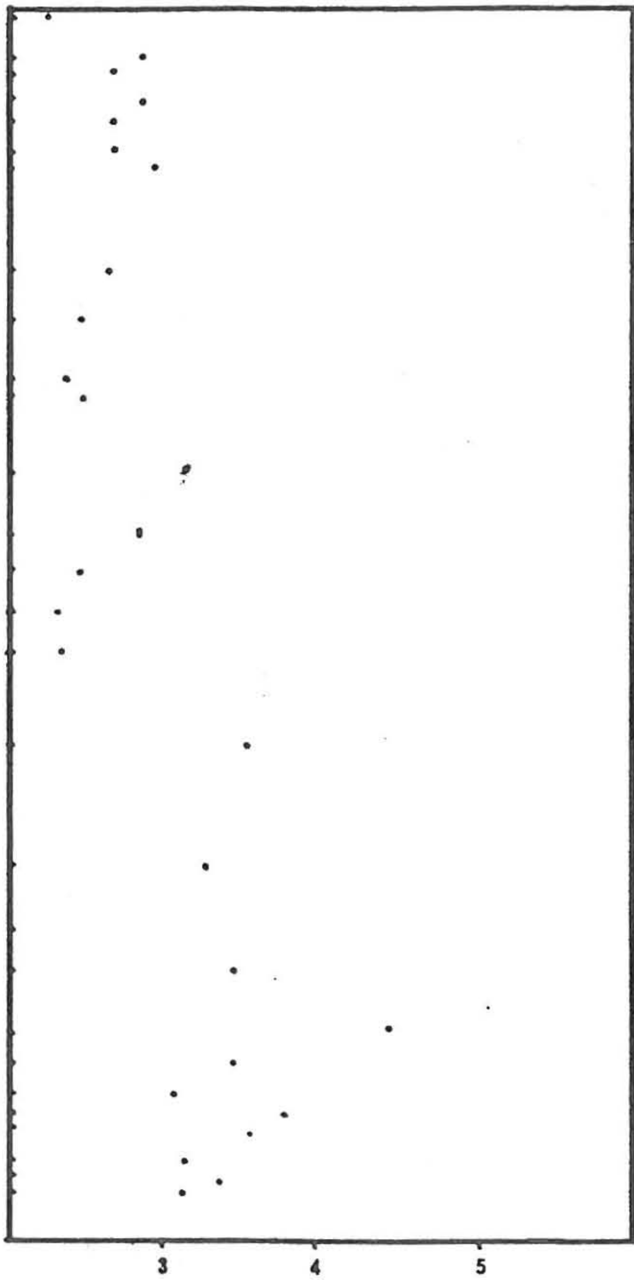


Fig.27G Cr/Ni

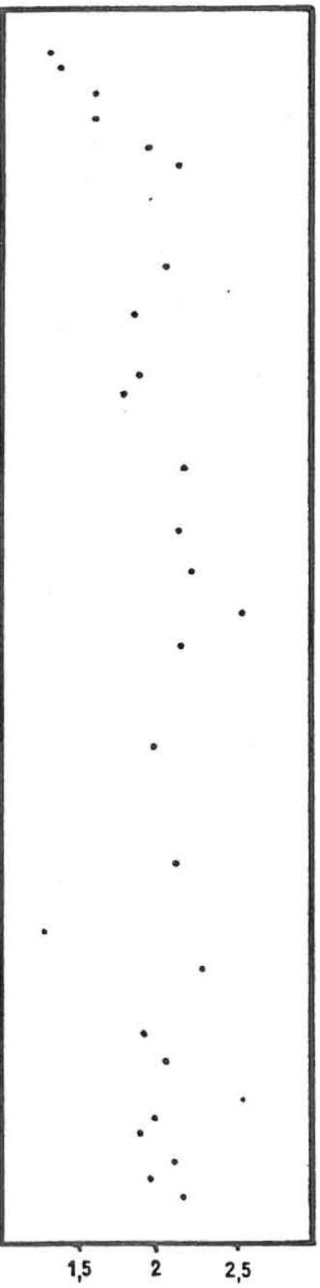


Fig.27H Ni/Co

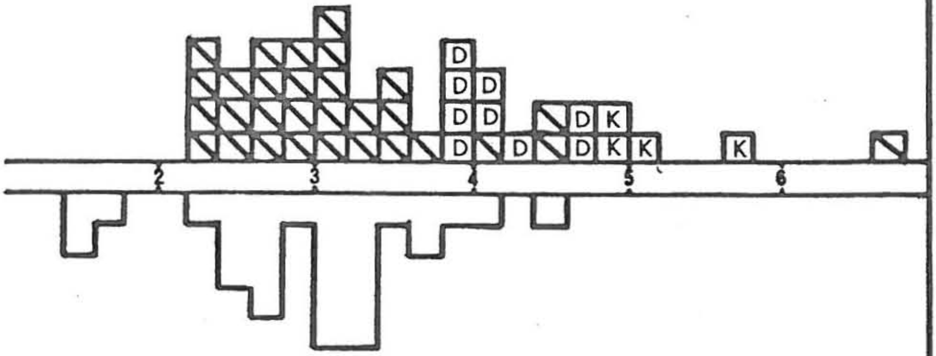


Fig.28A Cr/Ni

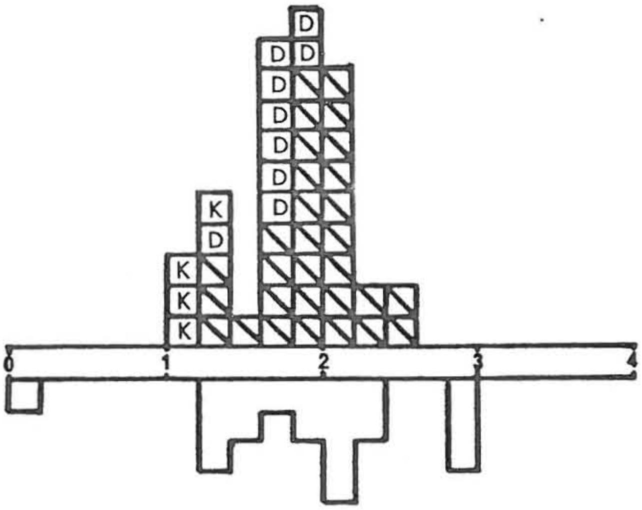


Fig.28B Ni/Co

Figs. 28 A-B Transition element ratios for the Drakensberg Subgroup in the Barkly East area and Karroo Dolerites (from Robey, 1976).

D Drumbo Member
K Kraai River Formation
▧ Lesotho Formation
□ Dolerites (Robey, 1976)

fractionating phases were, and to estimate approximate proportions of these phases in the fractionating assemblage.

From the base of Naudes Nek to an horizon halfway up the sequence, the Ni content (Fig.27d) remains relatively constant (approximately 95 ppm). Ni then decreases from JP43 at 111 ppm to JP48 at 86 ppm, remains constant up to JP10 (about three-quarters the way up the section) and then decreases rapidly to the top of the succession with JP58 having 60 ppm. This decrease in Ni values is not considered to be attributable to varying degrees of partial melting. This mechanism would require melts to be produced with the degree of partial melting varying from approximately 10% to 90%. The decrease of Ni with height is regarded, rather, as being indicative of olivine fractionation at low pressures.

Cr in the Naudes Nek section (Fig.27b) decreases from the base to the top in an erratic manner, from a high value of 373 ppm near the base to 149 ppm at the top. Halfway up the section the Cr content increases from JP42 with 227 ppm to JP46 with 302 ppm. In the uppermost quarter of the section Cr matches Ni with a rapid decrease from 284 ppm to 149 ppm. The overall decrease of Cr with height suggests that pyroxene was also an important fractionating phase.

The plot of Co versus height (Fig.27e) shows no distinct trend but rather a grouping around an average of 46 ppm. The dominant plagioclase fractionation in the Birds River Intrusion resulted in the Co content remaining constant until the late stages when Ti-magnetite became a primary fractionating phase (Robey, 1976). In the Naudes Nek section the constancy of Co values is probably the result of the bulk partition coefficient for Co for the fractionating assemblage being close to unity.

In the Naudes Nek section the trends of variation for Cu, Zn and V are similar. Their values in the lower half of the section are erratic whereas in the upper half the values increase in a similar manner to the incompatible elements. Although Zn and Cu have partition coefficients close to unity for olivine, and V partition coefficients greater than unity for the pyroxenes, their bulk partition coefficient must be very much less than unity to account for the enrichment of these elements. This suggests that plagioclase is an important phase in the fractionation assemblage.

The section (6.2.4) on the incompatible elements in the Naudes Nek section established the following two points:

1. The lavas in the upper half of the Naudes Nek section show an increase in incompatible element contents with height. This is ascribed to low-pressure fractionation.
2. Using the enrichment factors it was calculated that approximately 30% crystallization took place, taking JP43 as the initial liquid and JP58 as the final liquid.

Using the figure of 30% crystallization, the equation describing trace element behaviour during fractional crystallization, and these analytical data for Cr, Ni and Co, it is possible to calculate the bulk partition coefficients for these three elements. From these the approximate proportions of olivine, clinopyroxene and plagioclase in the fractionating assemblage can be obtained in a semi-quantitative way. It must once again be emphasized that these calculations are not a quantitative statement but merely an exercise to establish the approximate proportions of the phases involved in the differentiation of the upper part of the Naudes Nek section.

a. Partition Coefficients used in the Calculations

$D^{Ni}_{plag} = 0,001$ $D^{Cr}_{plag} = 0,001$ $D^{Co}_{plag} = 0,001$

$D^{Ni}_{cpx} = 1,5$ $D^{Cr}_{cpx} = 12$ $D^{Co}_{cpx} = 2$

$D^{Ni}_{ol} = 15$ $D^{Cr}_{ol} = 1,5$ $D^{Co}_{ol} = 3$

The values of the partition coefficients above were selected from those in Table 8.

b. <u>Bulk partition coefficients</u> (calculated using equation 1 in section 6.1)

$$D^{Ni}_{bulk} = 2,7$$

$$D^{Cr}_{bulk} = 2,1$$

$$D^{Co}_{bulk} = 0,9$$

c. Using equation 2 in section 6.1 the following proportions of the fractionating phases have been calculated.

15% olivine + 15% clinopyroxene + 70% plagioclase gives:

$$D^{Ni}_{bulk} = 2,6$$

$$D^{Cr}_{bulk} = 2,0$$

$$D^{Co}_{bulk} = 0,8$$

If a D^{Sr}_{plag} of 1,5 is used, a D^{Sr}_{bulk} of unity is obtained for the proportions of the fractionating assemblage proposed above. This D^{Sr}_{plag} is slightly low for the An_{60} to An_{70} of the Lesotho Formation, but in the light of the accuracy of the present calculations it is not considered unreasonable.

From these estimates it appears that the Ni, Cr and Co bulk partition coefficients can be obtained by the fractionation of about 30% of the liquid present halfway up the Naudes Nek section in the proportion 15% olivine, 15% clinopyroxene and 70% plagioclase.

The Cr/Ni ratio can be used to estimate the dominance of either olivine or clinopyroxene at various stages in the fractionation of the lavas of the Lesotho Formation in the Naudes Nek section.

The ratio is reasonably constant except for four samples from JP43 to JP46 where the ratio increases from 2,3 to 3,1. According to Gunn (1971) this indicates the dominance of olivine over clinopyroxene as a crystallizing phase for that part of the sequence. The proportions of olivine and clinopyroxene as crystallizing phases are equal for most of the top half of the Naudes Nek sequence - in accordance with the calculations above. The Ni/Co ratio falls with fractionation from 2,52 to 1,55 as predicted in section 6.5.1(f).

6.6 OMEGA FORMATION

6.6.1 Introduction

The field relations and major element geochemistry of the massive unit of the Omega Formation have been discussed in the previous section 2.3 and 5.3.6 respectively. As the theoretical behaviour of the trace elements has already been examined the following discussion will be restricted to the variation in the trace elements of the massive unit and the support they offer to a suggested model of differentiation. Modal analysis was performed on six slides from the massive unit to allow a comparison between mineraology and geochemistry to be made.

The trace element concentrations (Figs.29 a-n), interelement ratios (Figs.30 a-f) and modes (Fig.9, section 4.5) are plotted against height to show vertical differentiation within the massive unit. A distinct break in the pattern of variation is present between samples JP4 and JP5 as is the case with the major elements.

6.6.2 Incompatible Elements

The incompatible elements in the massive unit show similar patterns of variation when plotted against height:

1. A marked upwards increase between JP4 and the top.
2. A smaller increase downwards from JP4 to KF10.

An exception to this pattern of variation is Nb which decreases rapidly from JP1 to JP2 but then remains virtually constant with low values that are very close to the lower limit of determination and are therefore suspect.

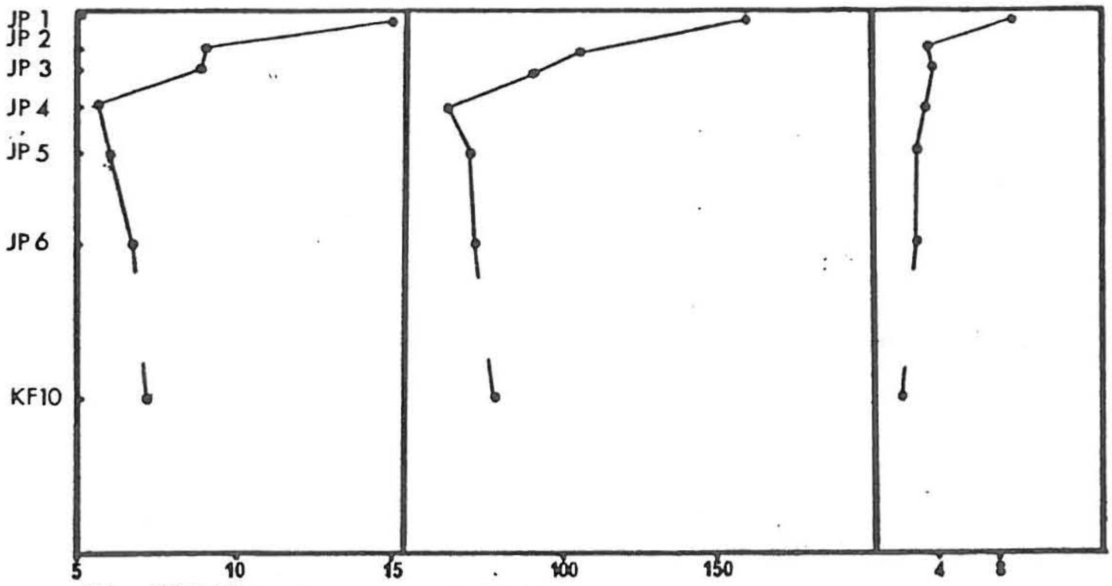


Fig.29A Rb ppm Fig.29B Zr ppm Fig.29C Nb ppm

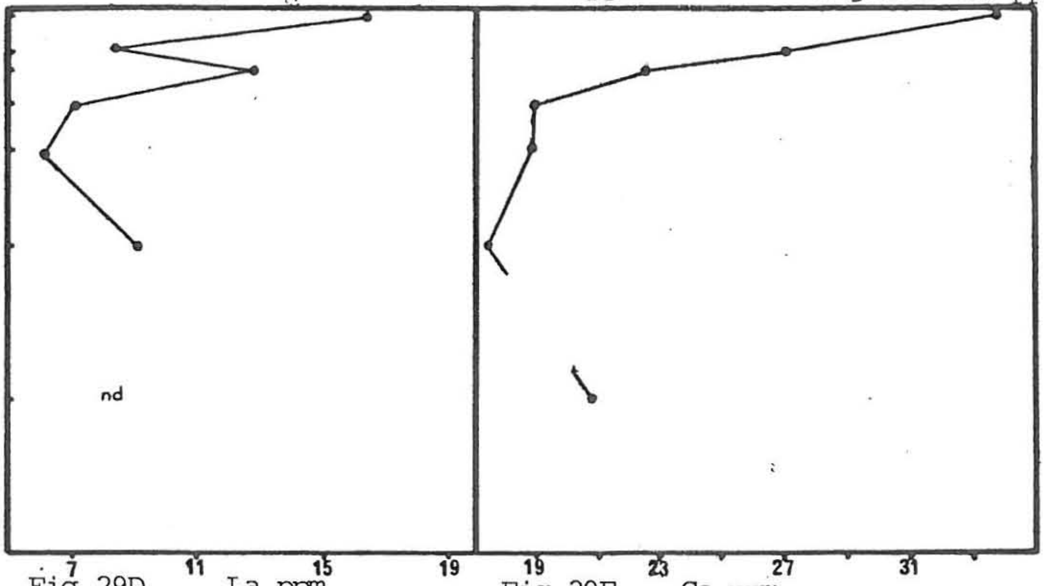


Fig.29D La ppm Fig.29E Ce ppm

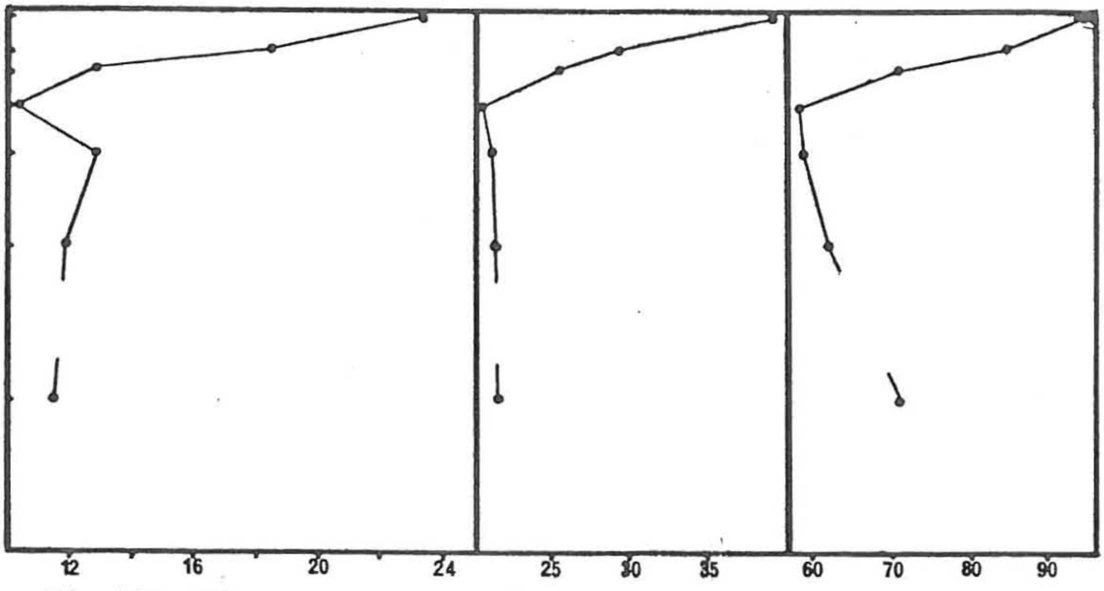


Fig.29F Nd ppm Fig.29G Y ppm Fig.29H Zn ppm

Figs.29A-N Trace element data for in the massive unit of the Omega Formation plotted against height

nd below Lower Limit of Determination

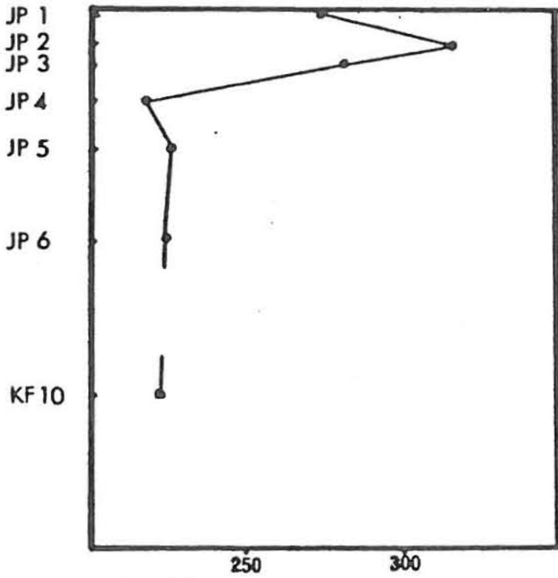


Fig.29.I V ppm

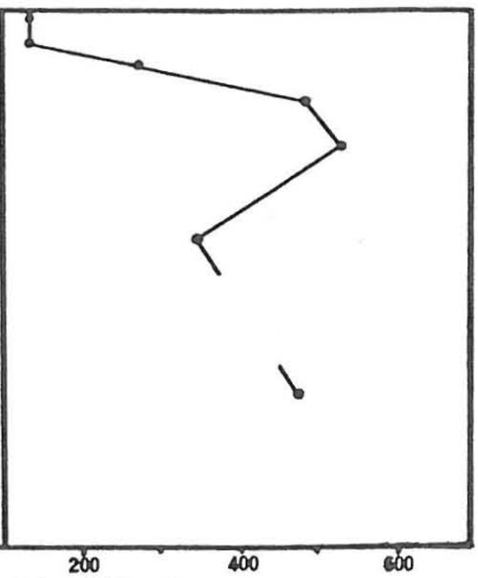


Fig.29J Cr ppm

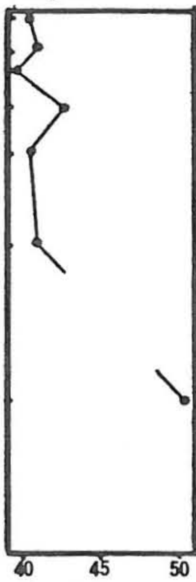


Fig.29K Co ppm

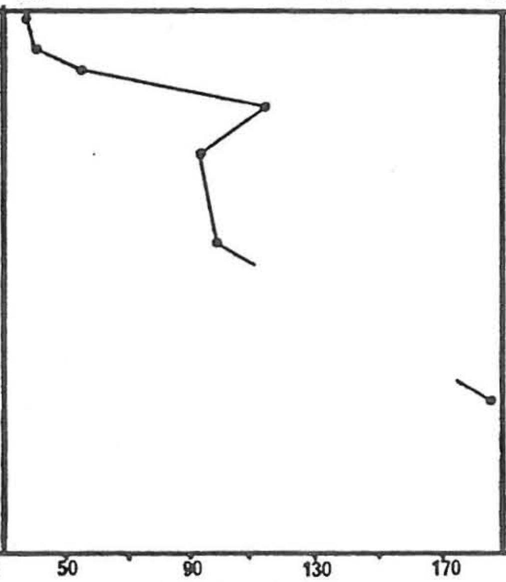


Fig.29L Ni ppm

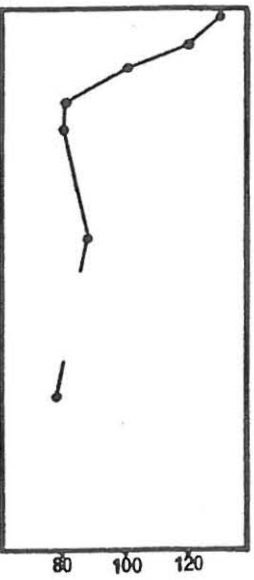


Fig.29M Cu ppm

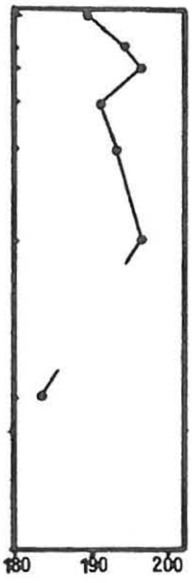


Fig.29N Sr ppm

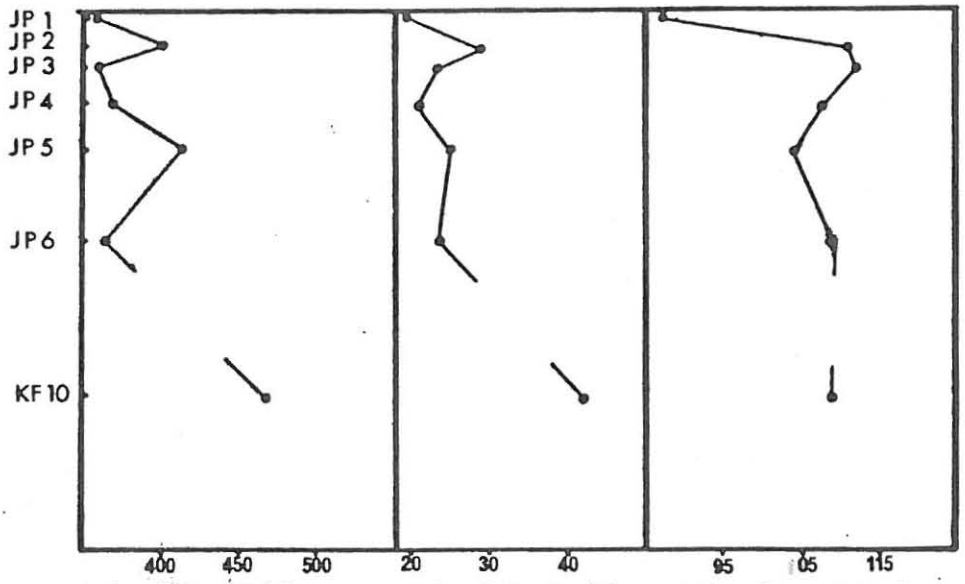


Fig.30A K/Rb Fig.30B Zr/Nb Fig.30C TiO_2/Zr

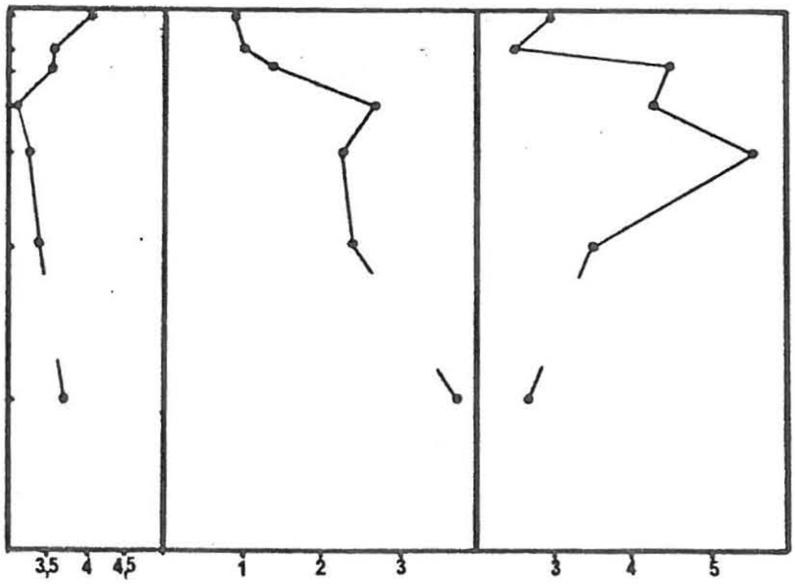


Fig.30D Zr/Y Fig.30E Ni/Co Fig.30F Cr/Ni

Figs.30 A-F Interelement ratios for the massive unit of the Omega Formation

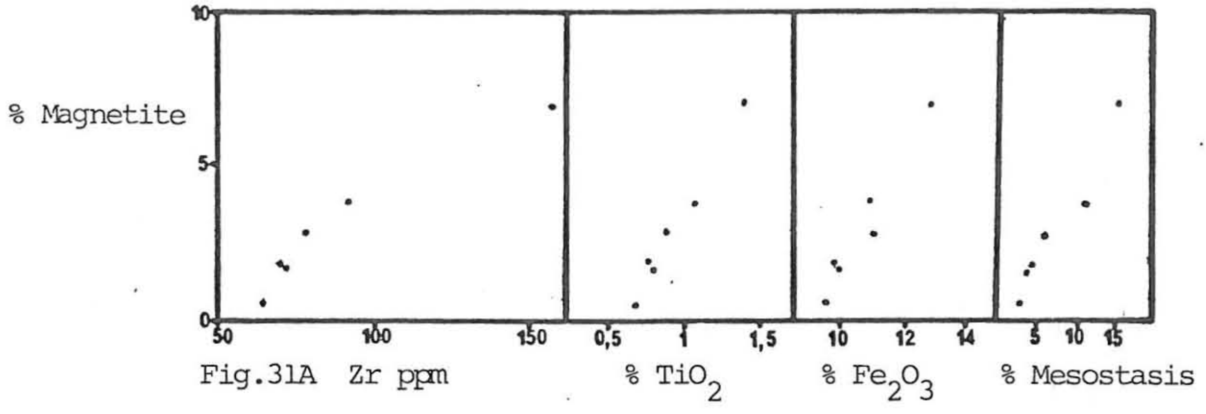


Fig.31A

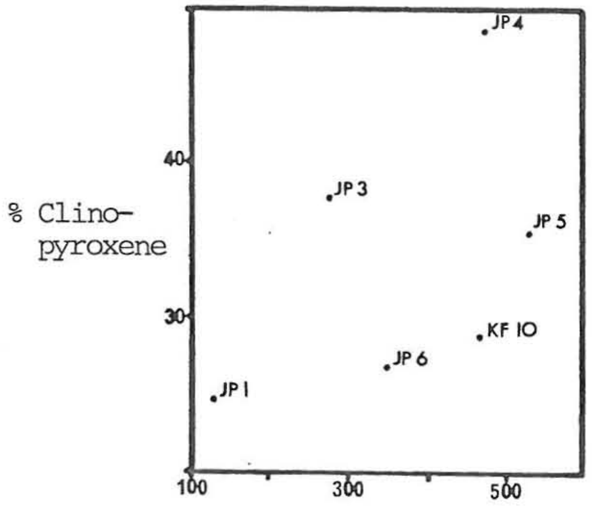


Fig.31B

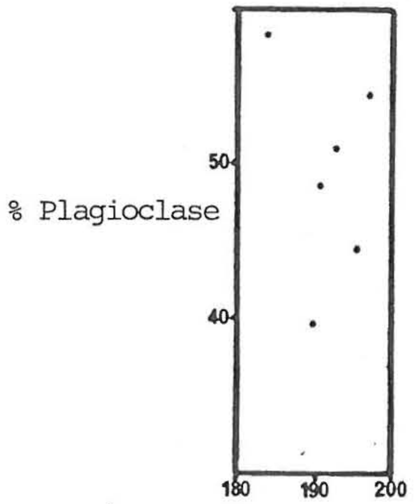


Fig.31C

Figs.31 A–C Modal data for the massive unit plotted against Zr, TiO_2, Fe_2O_3, Mesostasis %, Cr and Sr.

The incompatible elements have a good positive correlation with the modal values for magnetite and the mesostasis, which are amongst the last phases to crystallize. In the plot of TiO_2 and Fe_2O_3 against the precentage magnetite the expected linear correlation is obtained (Fig.31a). The variation of the incompatible elements (Figs.29 a-g) and the positive correlation of magnetite and mesostasis (Fig.11) support the major element evidence in that the massive unit appears to have been affected by two trends of differentiation.

The incompatible element ratios are not as constant as those for the other units of the Drakensberg Subgroup. The Zr/Nb ratio is considered to be unreliable because of the very low Nb contents of the massive unit. Ratios involving K are erratic and K/Rb varies from 353 to 468. The Zr/Y ratio increases upwards and downwards from JP4 while TiO_2/Zr is reasonably constant except for JP1 which is very low.

6.6.3 Yttrium

The Ca O versus Y plot (Fig.22) illustrates the two apparent differentiation trends in the massive unit. From JP4 to the top sample JP1, an L-type trend is found and downwards, from JP4 to KF10 a trend similar to the Standard calc-alkali trend is present.

6.6.4 Strontium

The Sr content of the massive unit varies from 184 ppm to 196 ppm with no apparent trend. In the plot of Sr against plagioclase (Fig.31c) there is no increase in Sr with increase in plagioclase content. This behaviour of Sr, similar to that of Sr in the Lesotho Formation, must result from the bulk partition coefficient of the fractionating assemblage being unity for Sr.

6.6.5 Transition Elements

The three transition elements Ni, Cr and Co provide further evidence which assists in explaining the pattern of differentiation in the massive unit.

The Ni content of the massive unit increases from the top to JP4, decreases between JP4 and JP5 and then increases to the basal KF10. Olivine is present in KF10 and decreases rapidly from the base upwards (Fig.9).

Cr increases in content downwards to JP5, decreases to JP6 and then increases to KF10. Clinopyroxene when plotted against height (Fig.9) and Cr (Fig.31b) shows the mineralogical control of clinopyroxene on Cr from the top to JP4. From JP5 to KF10 however, the anomalous overall enrichment in Cr for the percentage clinopyroxene present is suggestive of the presence of another phase rich in Cr.

The Co content remains fairly constant down to JP6 but then increases with the increase in olivine. It is probable that a bulk partition coefficient of unity was effective down to JP6 after which the increase in olivine to KF10 resulted in the enrichment of Co.

Zn appears to behave as an incompatible element having a similar enrichment pattern to the incompatible elements. Cu and V increase upwards from JP4 but tend to remain constant below that level. In the uppermost sample V decreases but as TiO_2 and Fe_2O_3 (elements with which V would be expected to associate) increase this behaviour of V is puzzling.

The Ni/Co ratio increases downwards but between JP4 and JP5 a break in slope is present. The Cr/Ni ratio increases from the top to JP4 and decreases from JP5 to KF10.

6.6.6. Conclusion

A number of features have emerged from this discussion of the trace elements in the massive unit:

1. The incompatible elements show an apparent dichotomy by increasing both upwards and downwards from the region of JP4 and JP5.
2. The CaO/Y plot (Fig.22) suggests that from JP1 to JP4 plagioclase and pyroxene dominated fractionation but from JP4 to KF10 more subdued plagioclase and pyroxene fractionation was active.

3. The Sr content suggests that plagioclase, pyroxene and olivine fractionation took place.
4. The Co/Ni ratio increases from the top to JP4 indicating pyroxene fractionation dominant over olivine but from JP5 to KF10 the ratio decreases suggesting that olivine fractionation was dominant over pyroxene.

From these points it is apparent that the massive unit has undergone fractionation with what appears to be two trends of differentiation. Kennedy (1931) and McCallien (1932) have described similar composite flows which Bhattacharji (1967) suggests result from flow differentiation. The concept of flow differentiation as proposed by Bhattacharji (1964) and proved experimentally by him in a later paper (Bhattacharji, 1967) can be used to explain some of the puzzling features of the massive unit.

Flow differentiation occurs in a rising magma column as a result of a velocity gradient across the column with the central portion having a greater velocity than the sides. As a result the central portion will be able to carry more higher-density, crystalline material than the sides, and will sweep early-formed phenocrysts into the central portion. The effect of this action will produce a magma that is differentiated mineralogically and chemically.

If the features of the massive unit resulted solely from flow differentiation then it would be expected to have a core enriched in Mg, Cr, Ni and Co, grading outwards into more evolved material. The enrichment of the incompatible elements and late-formed phases towards the top and base is in agreement with an origin through flow differentiation but the base and not the core is enriched in Mg, Cr, Ni and Co. This enrichment of Cr, Ni and Co and the modal data for plagioclase and olivine indicate that some degree of <u>in situ</u> crystal settling under gravity must have taken place.

Therefore in a qualitative way the differentiation of the massive unit can be explained as follows: on rising, phenocrystal olivine and plagioclase were concentrated in the faster rising core. Clinopyroxene started crystallizing at a later stage and on extrusion continued to crystallize while olivine, plagioclase and early formed clinopyroxene settled.

In this way, utilizing a two stage process of differentiation, the following features can be explained:

1. The increase of the incompatible elements both upwards and downwards.
2. The two fractionation trends with olivine dominance below JP4 and clinopyroxene above.

It is appreciated that there are a number of pitfalls to this model but in the light of the data presently available this seems to be the most likely explanation of an unusual situation. Further analyses to fill in between JP6 and KF10 and microprobe work on the mineral phases in planned by other members of the Rhodes University Geology Department. Once this work is completed, computer modelling of this differentiation process will allow a more quantitative statement to be made.

6.7 TRACE ELEMENTS IN THE RED BED BASALTS

The table below allows a comparison between two samples from the Red Beds Basalt. JR88 is a sample collected and analysed by Robey (1976) while S1B/O3 is from the present study. Agreement is generally good with the major differences being between the Cu, Cr and Co values. These differences could result from a sampling bias or inter-laboratory discrepancies.

	JR88	S1BO3
Sr	239	274
Rb	below LLD	-
Y	28	26
Zr	122	124
Nb	2.3	1.9
Zn	95	91
Cu	92	79

	JR88	S1BO3
Co	36	46
Ni	51	58
V	255	286
Cr	163	226
Zr/Nb	53	67
TiO_2/Zr	94	84
Ni/Co	1,42	1,25
Cr/Ni	3,2	3,5

A comparison with trace element data from the other units of the Drakensberg Subgroup illustrates the differences between the units. The incompatible elements, in particular K and Rb, have lower values than in the other units. The Zr and Nd contents are higher than those of the Lesotho Formation while the Y content is the same as that in the other units. Sr concentrations in the Red Beds Basalt falls between that of the Drumbo Member and the Lesotho Formation.

The concentrations of the transition elements are slightly higher than those of the Lesotho Formation for equivalent MgO contents, but slightly less than or equal to, the Drumbo Member.

The TiO_2/Zr is similar to the other units while Zr/Nb is high. Transition element ratios fall within the ranges defined by the other units.

From this discussion is appears that the Red Beds Basalt has affinities with both the Drumbo Member and Lesotho Formation. The incompatible elements are not as enriched as those of the Drumbo Member but the transition elements and Sr have similar values. The high Zr/Nb value is indicative of a distinct magma for the Red Beds Basalt but with only one analysis and the very low Nb content this cannot be substantiated.

6.8 TRACE ELEMENTS IN SAMPLES JP14 and DT04

As these two samples are, stratigraphically, from the earliest lavas in the Rhodes-Naudes Nek area, they were thought to belong to the Drumbo Member. The geochemistry of the two samples however, separates them from the overlying Drumbo Member.

The incompatible elements as well as Y, Sr and Ni are on the same trend of differentiation as the Lesotho Formation samples. Incompatible element ratios as well as Ni/Co fall within the ranges defined by the Lesotho Formation. The Cr/Ni ratio value falls between that of the Drumbo Member and Kraai River Formation.

These two samples have affinities with the Lesotho Formation yet are separated from this formation by the overlying Drumbo Member. More detailed sampling and geochemical data are required to establish the relationship of these basalts to the rest of the Drakensberg Subgroup.

7. COMPARISON WITH OTHER COMPOSITIONAL DATA OF KARROO BASIC ROCKS

7.1 INTRODUCTION

Data from various workers on Karroo-age lavas and intrusions are displayed in Table 11. As Robey (1976) has already compared his data with that of Walker and Poldervaart (1949), Nockolds and Allen (1956) and Cox et al. (1967), the present comparison will be restricted to the data of Cox and Hornung (1966) from central Lesotho, and that of Bristow (1976) from the southern Lebombo basalts.

The Karroo dolerites studied by Robey (1976) have been used in a comparative way throughout this present work, leading to the conclusion that the Lesotho Formation and chilled dolerite fields are coincident in most cases and therefore their chemical compositions are similar. Robey (1976) noted the relatively low SiO_2 and K_2O of the Karroo dolerites in comparison with those from Antarctica and Tasmania. The same observation holds for the basalts of the Lesotho Formation, but not for those of the Drumbo Member, which has high K_2O, or for those of the Kraai River Formation, with high SiO_2.

7.2 DRAKENSBERG SUBGROUP FROM CENTRAL LESOTHO

The normative chemistry of the central Lesotho basalts studied by Cox and Hornung (1966) has been discussed in section 5.4. Table 11 allows a comparison of the averages of the major elements and trace elements from the central Lesotho area and Barkly East area. The major elements of the central Lesotho basalts are very similar to those of the Lesotho Formation from the Barkly East area. Na_2O and K_2O are higher in the central Lesotho area and Al_2O_3 is lower.

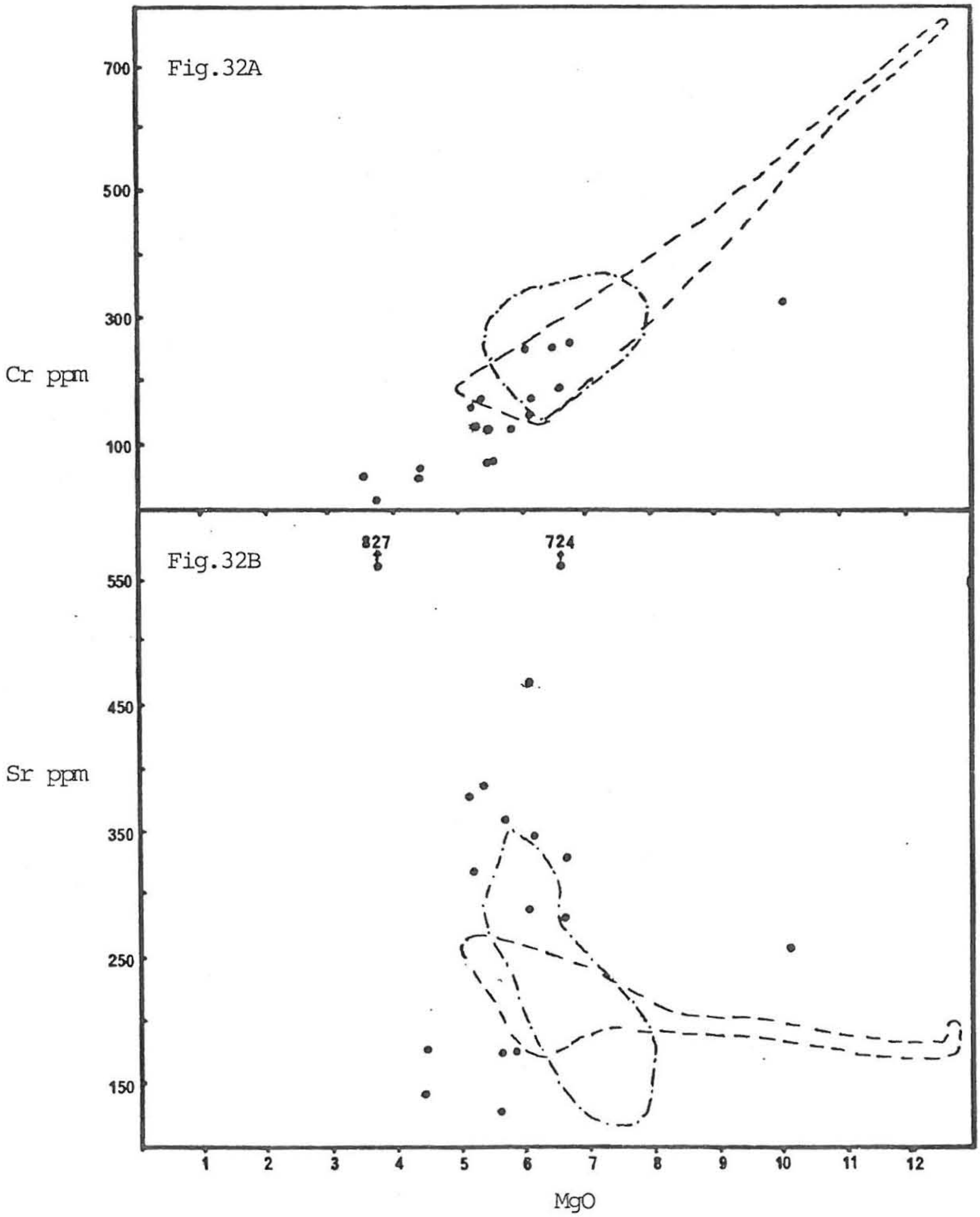
A comparison of trace element data from Table 11 shows that the basalts of the Lesotho Formation from the present study have similar Sr, Y, Zr and Ni values but Rb, Nb, V and Cr are lower and Co higher than for basalts of the central Lesotho. As these differences are not systematic it is possible that the use of the optical spectrograph for the analyses of most of the trace elements has led to results which are less precise than

TABLE 11 : DATA ON KARROO-AGE LAVAS AND INTRUSIONS

	A	B	C	D	E	F	G	H	I
SiO_2	52,58	53,8	53,9		51,8	51,96	53,23	54,43	52,33
TiO_2	1,00	,6	,7		1,13	1,00	1,04	0,88	1,28
Al_2O_3	15,47	15,5	16,1		14,8	15,83	15,83	15,42	14,53
Fe_2O_3	1,71^x	,8	,8		3,92	1,65^T	1,60^T	1,55^T	11,49
FeO	8,69^x	8,5	7,4		7,26	8,54	7,99	7,71	
MnO	,18	,1	,1		,17	,17	,15	,15	,16
MgO	6,63	6,7	7,0		7,1	7,20	5,99	6,82	5,62
CaO	10,69	11,2	11,1		10,57	10,82	10,30	10,36	8,63
Na_2O	2,27	1,7	1,8		2,40	2,14	2,59	2,22	2,50
K_2O	,61	1,0	1,0		,74	0,58	1,08	,49	,69
P_2O_5	,17	,1	-		,13	0,11	,15	,09	,26
Ba	220			204	233				325
Sr	206			164	213	185	307	207	344
Rb	13,6			11	29	13,9	21	19,9	17,7
Y	27,7			22	23	23,6	25,6	26,8	26,6
Zr	102			91	109	91	149	113	127
Nb	7,4			-	11,6	4,4	15,7	4,4	4,1
Zn	84			-	-	84	83	81	92
Cu	93			-	-	83	71	61	89
Co	41,7			39	34	46	40	41	49
Ni	78			80	73	89	67	48	79
V	239			220	300	233	218	245	245
Cr	243			335	317	271	295	281	137
La						9,8	18	17	
Ce						25	42	37	
Nd						14	21	20	

x = FeO calculated assuming $Fe_2O_3/FeO = 0,15$
T = " " " $Fe_2O_3/FeO = 0,20$

A = Avg. chilled Karroo dolerite (Robey, 1976)
B = Avg. chilled Tasmanian dolerite (McDougall, 1962)
C = Avg. chilled Antarctic dolerite (" ")
D = Avg. Karroo dolerite (Nocholds and Allen, 1956)
E = Avg. Lesotho basalt (Cox and Hornung, 1966)
F = Avg. Lesotho Formation (This study)
G = Avg. Drumbo Member (This study)
H = Avg. Kraai River Formation (This study)
I = Avg. southern Lebombo basalt (Bristow, 1976)



Figs.32 A-B Cr and Sr plotted against MgO % for the Drakensberg Subgroup in the Barkly East area, Karro Dolerites (Robey, 1976), and southern Lebombo basalts (Bristow, 1976).

-·-·- Drakensberg Subgroup

--- Dolerites (Robey, 1976)

● southern Lebombo basalts (Bristow, 1976) those from X-ray fluorescence techniques.

7.3 SOUTHERN LEBOMBO BASALTS

The southern Lebombo basalts studied by Bristow (1976) appear to be more differentiated than the basalts of the Lesotho Formation from the Barkly East area. In comparison with the Lesotho Formation basalts from this study, the southern Lebombo basalts have higher concentrations of SiO_2, TiO_2, Na_2O, K_2O and P_2O_5 but lower Al_2O_3, MgO and CaO.

The most apparent difference between the trace elements from the southern Lebombo basalts and those of the Drakensberg Subgroup in the Barkly East area is in the elements Sr and Cr. These differences are illustrated in Fig.32a and b respectively, while the averages (Table 11) show Sr for the southern Lebombo basalts to have a higher value than for the Drakensberg Subgroup lavas and Cr has a lower value. The incompatible elements Rb, Zr and Nb have similar levels to those of the Kraai River Formation, but K, Ti and P are higher in the southern Lebombo basalts.

From this general comparison it appears that the geochemistry of the southern Lebombo basalts is similar to that of the Drakensberg Subgroup except for the differences in Sr and Cr.

7.4 NORTHERN AND SOUTHERN KARROO PROVINCES

Cox et al. (1967) divided the Karroo basalts and dolerites into two provinces on the basis of their differing chemistry. The Northern Province is characterised by enrichment in K, Ti, P, Ba, Sr and Zr, by factors of approximately two to four in comparison to the Southern Province. The Northern Province includes all the Rhodesian Karroo basalt and dolerite localities while the Southern Province encompasses the basalts of Lesotho, Swaziland, southern Lebombo and the Karroo dolerites.

The boundary line for the two provinces (Cox et al., 1967) is indicated by a dashed line in Fig.11c, e, g and 26d. In figure 11c the higher Al_2O_3 content of the Southern Province is confirmed by the data from the Drakensberg Subgroup lavas.

The plot of CaO vs MgO (Fig.11e) however, indicates that a number of Lesotho Formation, Kraai River Formation, and most of the Drumbo Member samples plot within the Northern Province field. In the K_2O vs MgO (Fig.11g) plot, the Drumbo Member specimens fall almost entirely within the Northern Province field. In the plot of Ni vs MgO (Fig.26d), the Drakensberg Subgroup lies within the Southern Province field.

Although some samples from the Drakensberg Subgroup plot within the Northern Province field, this study supports the broad geochemical differences noted by Cox et al. (1967). It is of interest to note however that the Drumbo Member with its plots in the Northern Province field is also enriched in Ti, P, Sr, Zr and Nb but not to the same degree as the Northern Province basalts.

8. GEODYNAMIC CONSIDERATIONS

The geochemistry of the Drakensberg Subgroup studied in this project forms a part of a larger investigation into the Karroo volcanics and intrusives of southern Africa and as such the geodynamic aspects of the present study will have to be viewed with regard to the overall results at the end of the International Geodynamics Project. At present the results from this study can be discussed in a general manner with regard to the tectonothermal event which resulted in the fragmentation of Gondwanaland.

With reference to the fragmentation of Gondwanaland there appears to have been sporadic igneous activity starting early in the Karroo period. Glass shards and laumontite have been reported from the Ecca Group by Wilson (1974) and Elliott and Watts (1974). Martini (1974) has found ashbeds and greywackes rich in volcanic material in both the Ecca Group and Beaufort Group. Volcanism only became widespread late in the Karroo sedimentary cycle with the earliest recognised lava being reported in the Red Beds (Lock et al. 1974).

The onset of the Karroo volcanic and intrusive period is correlated by Cox (1970) with a postulated convective uprise of mantle material responsible for the fragmentation of Gondwanaland. The Central Karroo and Lebombo volcanism is regarded as the earliest Karroo activity and the lowermost Drakensberg Subgroup lavas in the Barkly East area have been dated at ± 190 my. (CLA01=188 my ± 5,6 my and DBM = 199 ± 7,6 my). Scrutton (1973) has related these volcanics to the formation of the Indian Ocean but Cox (1970) proposes that the main fragmentation of the southern continents took place in the Cretaceous. In this he is supported by the work of Seidner and Miller (1975) who date the age of extrusion of the Kaoko and Serra Geral basalts at 130 my which they associated with the rifting of the Atlantic Ocean. Cretaceous volcanism from the south east of Africa is known from Lupata (Mozambique) and Madagascar while the Deccan Traps lavas of India are of late Cretaceous age (Cox, 1970).

The fragmentation of Gondwanaland has been considered by Cox (1972) in relation to a single unifying thermotectonic event. He postulates that the cycle began with the rise of a potassic-rich picritic magma from depths of approximately 500 km under what is now Rhodesia. Overlying and peripheral to this body of magma, a zone of tholeiitic magma was generated. Carmichael et al. (1974) has however pointed out that the broad similarities between oceanic and continental basalts indicate a similar source process with these magmas being generated in the depth range of the low-velocity layer. To overcome the latent heat of melting required to form a magma it is necessary to move material as conduction alone, as suggested by Cox (1972), cannot supply enough heat. Material moves upwards by a density differential between it and the surrounding upper mantle and its buoyancy increases as it rises, leading to melting (Verhoogen, 1970). From this it could be suggested that convection led to the uplift and tension associated with the fragmentation of Gondwanaland.

Briden and Gass (1974) have correlated within-plate magmatic and metamorphic activity in Africa with those periods in which the apparent polar wonder path did not move. They suggest that the Karroo magmatic activity which corresponds with a lack of movement of the proto-Africa continent for 200 my to 100 my resulted from the stationary plate being positioned over a heat source which then had a long period to produce recognizable effects in the upper crust. Therefore at the time of the Karroo volcanic and intrusive period, Africa was stationary, resulting in a vast amount of magmatism in southern Africa which Cox (1970) has described as one of the most spectacular volcanic episodes the earth has ever seen. From this discussion, however, a number of questions arise - the answers to which are not readily available at present:

1. What process resulted in the rise of temperature in the region of the low velocity layer which led to the large magmatic episode and eventual fragmentation of Gondwanaland? Anderson (1975) has suggested that deep mantle

chemical plumes arising from original chemical inhomogeneities can supply the necessary energy to the upper mantle to fuel convection, uplift, tension and melting.

2. What was the relationship between the older Central Karroo and Lebombo volcanics associated with tensional tectonics and the eventual formation of the Atlantic Ocean, Kaoko and Serra Geral basalts, the Indian Ocean and the younger volcanics associated with it?

3. The differences in the geochemistry of the units of the Drakensberg Subgroup have been ascribed to mantle inhomogeneities. The question arises as to the scale of these inhomogeneities in a vertical and horizontal sense in the mantle. Accepting the evidence of Carmichael et al. (1974) that the low-velocity zone is the origin of basaltic melts, it must be postulated that there is a lateral heterogeneity to explain differences such as those between the Northern Province (Cox et al., 1967), southern Lebombo basalts (Bristow, 1976), and the Barkly East area basalts. The differences in the lavas of the Barkly East area suggest that there is also a vertical inhomogeneity because of their close spatial relationship.

The geochemical data presented in this study will be viewed in association with that from other areas of Karroo magmatism at the end of the International Geodynamics Project. This overall view of the geochemical evidence in combination with geophysics will allow the geodynamic aspects of the fragmentation of Gondwanaland and the related magmatism to be unravelled.

9. CONCLUSIONS

The following conclusions result from this study of the Drakensberg Subgroup and the comparisons with related Karroo igneous activity. These conclusions are presented in point form and may, with further work in the area, require modification.

a. Of the total 61 rocks analysed, 59 are quartz and hypersthene normative oversaturated tholeiites and 2 are olivine tholeiites. This illustrates the tholeiitic character of the Drakensberg Subgroup in the Barkly East area.

b. Following an initial survey of the major element variation through a single lava flow, it was decided that all samples would be taken as close to the base of the flows as possible. The trace element analyses from these samples were examined in conjunction with the major elements. This led to the suggestion that the last liquid to crystallize (rich in incompatible elements) would be affected by a filter pressing mechanism resulting in an erratic distribution within the flow.

c. In the An-projection of the basalt system Fo + An + Di + Q the samples of the Drumbo Member plot within the field of Cox and Hornung's (1966) analyses of samples from central Lesotho. The specimens of the Lesotho Formation have a larger spread than those of the Drumbo Member. The Kraai River Formation samples plot within the En + An + liquid field and define a trend towards the Q apex.

d. The differences in incompatible element geochemistry between the samples of the Drumbo Member, Kraai River Formation and Lesotho Formation are ascribed to an inhomogeneous mantle and the possibility of a fractionation link or different degrees of partial melting is regarded as unlikely in the light of the data from this study. The major element and transition element geochemistry support this suggestion.

e. The pattern of variation of the incompatible elements, Fe enrichment, depletion of Cr, Ni and Mg and the behaviour of Sr and Co suggest that the lavas of the upper half of the Naudes Nek section have been differentiated by the fractionation of olivine, clinopyroxene and plagioclase. Calculations using the enrichment factors and bulk partition coefficients suggest that approximately 30% crystallization of the liquid took place with the separation of minerals in the proportion of about 15% olivine, 15% clinopyroxene and 70% plagioclase.

f. The samples of the Kraai River Formation have a similar petrography to that of the Hangnest-type dolerite but the latter are enriched in K, Ti, Zr and Cr and depleted in Ni, V and Cu (Hangnest dolerite data from Le Roux, 1976).

g. A two-stage process of differentiation has been proposed for the massive unit of the Omega Formation. In the first instance the upwelling magma is flow differentiated in the manner proposed by Bhattacharji (1964) and once flow had stopped gravity settling of the early formed phases occurred. In this way the major and trace element variation patterns for this unit can be explained.

h. In the major element variation diagrams the fields for the Lesotho Formation and chilled dolerites are coincident for all elements with the exception of Al, P and Na. The Drumbo Member is enriched in K, Ti and Na and Al in comparison to the dolerites. The Kraai River Formation is enriched in Si in comparison to the dolerite.

i. The basalts of the southern Lebombo (Bristow, 1976) appear to be enriched in Si, Ti, Na, K and P but depleted in Ca, Al and Mg in comparison to those of the Lesotho Formation. In comparison to all members of the Drakensberg Subgroup, the southern Lebombo basalts are enriched in Sr and depleted in Cr.

j. From this study a number of areas of future research can be suggested:

1) More chemical and microprobe data from the massive unit of the Omega Formation are needed to help clarify the unusual pattern of compositional variation.
2) A more detailed geochemical study of the Kraai River Formation has been completed recently as an honours project by P. Barree in the Rhodes University Geology Department, but requires further extension.
3) The Drumbo Member needs to be sampled vertically through the sequence on both the western and eastern sides of Barkly East to establish any patterns or trends with changes in stratigrahic height.
4) The lavas in the vicinity of the farm Druids Temple need to be examined in more detail in the field and laboratory to establish their position and relationship in the stratigraphy of the Drakensberg Subgroup in the Barkly East area.
5) Finally, the areal extent of the Drumbo Member and Kraai River Formation needs to be investigated by further sampling and geochemistry.

APPENDIX A

SAMPLE LOCALITIES

1) DRUMBO AND DONNYBROOK BASALT MEMBERS

CLA-01 and JP60	Two samples from massive columnar jointed flow on farm Claremont on road between Moshesh's Ford and Rhodes. Samples ± 1 metre from basal contact and ± 17 km from Moshesh's Ford. Drumbo Basalt Member. 27° 52.7'E 30° 51.6'S
CAR-08	Coarse basalt ± 2 metres above cave sandstone on farm Carbury ± 11 km from Moshesh's Ford on way to Rhodes. Drumbo Basalt Member. 27° 50.3'E 30° 51.6'S
MF-09	Coarse basalt from massive columnar jointed flow overlying Cave sandstone. Sample on farm Moshesh's Ford 27 km from Barkly East on Moshesh's Ford road. Sample ± 5 metres above cave sandstone. Drumbo Basalt Member. 27° 45.8'E 30° 51.7'S
JP17	Coarse basalt on farm Druids Temple ± 4 km from Rhodes on Naudes Nek road. First massive flow overlying pillow lavas. Drumbo Basalt Member. 27° 59.9'E 30° 46.7'S
JP61	Coarse basalt ± 1 km further on towards Naudes Nek from JP17. Drumbo Basalt Member. 28° 00.3'S 30° 46.5'S
CL14	Coarse basalt on farm Cloverley. 22 km from Barkly East on way to Moshesh's Ford. Sample ± 4 metres above cave sandstone. Drumbo Basalt Member. 27°42'E 30° 52'S

DBM11	Coarse basalt ± 10 metres below sandstone layer 15,5 km from Barkly East on new road to Aliwal North on north side Kraai River. Donnybrook Basalt Member. 27° 27.8'E 30° 57.4'S
DBM12	Coarse basalt. Sample taken ± 150 metres south of bridge over Kraai River and ± 25 metres above river level. Donnybrook Basalt Member. 27° 27.7'E 30° 57.6'S

2) OMEGA FORMATION

The specific localities of the seven Omega Formation samples are as described in the previous section and as seen in Fig.6 27° 27.8'E 30° 56.8'S to 30° 57.2'S.

3) KRAAI RIVER FORMATION

KRF13	Massive aphanitic basalt. Above Omega Formation 11 km from Barkly East on the new road to Aliwal North. 27° 29.8'E 30° 58.2'S
KRC20 KRC21	Massive aphanitic basalts ± 7 km from Barkly East in old Kraai River cuttings on farm Lynndale. 2 samples ± 100 metres apart half way up the Northern side of the cuttings. 27° 34.2'E 30° 53.5'S
JP67	Coarse basalt ± 1 km from Barkly East on the road to Moshesh's Ford. Sample from quarry just about pillow lavas. 27° 35.6'E 30° 57.5'S

4) LESOTHO FORMATION

As described in the previous section on sampling, and as seen on map (Fig.1) and Fig.7.
28° 03.4'E to 28° 05.5'E, 30° 45.3'S to 30° 45.7'S

5) OTHER SAMPLES

SIB03	Red Beds Basalt on farm Siberia. North of Roussouw on roadpass through Waschbankspruit on road from Dordrecht to Barkly East. 27° 17'E, 31° 08'S
DTO4	Both samples on farm Druids Temple ± 4 km from Rhodes. Samples from lowest point on road just below pillow lavas. 28° 00.1'E 30° 46.9'S

APPENDIX B. L.O.I. and H_2O^+ free Major Element Analysis

	JP1	JP2	JP3	JP4	JP5	JP6	KF10	JP10a	JP10b	JP10c	JP10d	JP11a	JP11av	JP11b	JP11c
SiO_2	53,94	52,96	52,74	51,68	51,64	51,53	50,64	52,08	53,83	51,41	51,75	52,50	52,43	49,83	50,91
TiO_2	1,42	1,20	1,02	0,69	0,74	0,78	0,87	0,88	0,92	0,91	0,92	0,96	0,92	0,99	0,89
Al_2O_3	12,97	13,72	14,58	15,62	15,53	16,03	14,98	15,65	14,23	15,54	15,69	15,58	15,99	16,61	16,73
Fe_2O_3	13,04	12,56	10,80	9,63	9,90	10,06	11,10	11,10	10,80	11,22	10,99	11,04	10,65	11,37	10,67
MnO	0,18	0,19	0,16	0,15	0,16	0,15	0,17	0,16	0,18	0,15	0,14	0,16	0,16	0,18	0,14
MgO	5,35	5,83	6,21	7,61	7,33	7,36	9,34	6,89	6,82	7,07	7,06	6,77	7,30	6,70	7,14
CaO	9,42	10,09	11,14	11,63	11,56	11,15	10,11	10,77	9,45	10,58	10,67	10,24	10,49	11,33	11,30
Na_2O	2,51	2,62	2,63	2,37	2,35	2,33	2,30	1,65	2,94	2,29	2,24	2,40	2,23	2,36	1,98
K_2O	0,63	0,44	0,37	0,24	0,29	0,29	0,48	0,70	0,72	0,71	0,44	0,24	0,27	0,52	0,14
P_2O_5	0,36	0,31	0,25	0,23	0,24	0,22	0,08	0,12	0,10	0,11	0,10	0,10	0,10	0,11	0,10

Appendix B. (Cont'd.)

APPENDIX B. (Cont'd.)

	JP11d	JP11dv	JP13a	JP13b	JP13c	JP14	JP17	JP22	JP23	JP24	JP26	JP27	JP28	JP29	JP33	JP42
SiO_2	52,08	52,33	51,36	52,03	51,43	52,92	52,71	50,69	51,26	50,66	53,40	51,04	52,79	51,82	51,06	51,09
TiO_2	1,00	0,96	0,96	0,89	1,04	1,00	1,08	0,95	0,95	0,97	0,92	0,93	1,00	1,13	0,88	0,91
Al_2O_3	15,48	16,23	16,07	15,56	15,45	16,53	15,85	15,96	15,64	15,66	14,75	15,39	15,19	14,05	16,40	16,36
Fe_2O_3	11,16	10,41	10,92	10,54	11,40	9,66	10,32	11,10	10,91	11,31	10,79	10,98	10,86	11,89	10,14	10,64
MnO	0,14	0,14	0,15	0,16	0,15	0,15	0,15	0,16	0,16	0,17	0,13	0,15	0,18	0,17	0,16	0,18
MgO	7,43	6,80	7,22	6,87	6,93	6,04	5,81	7,81	7,32	7,48	7,04	7,72	6,17	6,89	7,50	7,45
CaO	9,08	9,68	11,06	10,48	10,19	10,57	10,01	10,76	10,80	11,04	9,21	11,05	10,46	11,22	11,29	10,04
Na_2O	2,71	2,58	1,87	2,72	2,58	2,33	2,70	1,94	2,24	2,06	2,72	2,20	2,51	1,90	2,07	2,20
K_2O	0,80	0,75	0,49	0,68	0,70	0,75	1,12	0,57	0,61	0,56	0,93	0,47	0,71	0,82	0,41	0,98
P_2O_5	0,12	0,11	0,11	0,10	0,12	0,09	0,16	0,10	0,11	0,10	0,11	0,08	0,13	0,13	0,09	0,10

Appendix B. (Cont'd.)

APPENDIX B. (Cont'd.)

	JP43	JP44	JP46	JP48	JP49	JP50	JP54	JP55	JP56	JP57	JP58	JP63	JP64	JP65	JP66
SiO_2	50,59	51,09	50,69	51,80	50,86	51,25	51,33	52,49	51,03	51,68	52,26	51,27	51,91	51,62	51,34
TiO_2	0,87	0,89	0,88	0,95	0,92	0,95	0,89	0,99	0,98	1,07	1,06	0,90	0,86	0,95	0,94
Al_2O_3	16,96	15,61	16,45	15,72	15,94	15,53	15,72	15,84	16,09	15,50	15,42	15,62	15,63	15,35	15,24
Fe_2O_3	10,49	10,97	10,90	10,98	11,01	11,20	11,13	11,32	11,49	11,95	11,66	11,02	10,70	10,67	11,05
MnO	0,15	0,16	0,16	0,19	0,16	0,16	0,14	0,17	0,17	0,17	0,16	0,15	0,14	0,16	0,16
MgO	7,17	7,93	7,67	7,04	7,04	7,19	7,10	6,45	6,53	6,34	6,09	7,28	7,64	7,35	7,73
CaO	11,10	10,89	11,57	11,21	10,79	10,92	10,54	10,18	11,03	9,91	10,15	10,82	10,57	11,10	10,68
Na_2O	1,74	2,15	1,38	1,85	2,31	2,03	2,30	1,77	2,19	2,32	2,16	2,22	2,14	2,23	2,29
K_2O	0,73	0,24	0,21	0,16	0,65	0,67	0,75	0,69	0,37	0,93	0,91	0,63	0,34	0,49	0,50
P_2O_5	0,09	0,08	0,09	0,11	0,12	0,11	0,10	0,11	0,11	0,13	0,13	0,10	0,08	0,09	0,09

Appendix B. (Cont'd.)

APPENDIX B. (Cont'd.)

	NN06	SIB03	DT04	JP60	JP61	CLA01	CAR08	MF09	DBM11	DBM12	CL14	JP67	KRF13	KRC20	KRC21
SiO_2	51,48	53,30	52,53	52,91	53,23	52,57	52,49	52,96	52,60	52,57	52,92	53,57	54,49	54,76	52,52
TiO_2	1,05	1,12	1,09	1,06	1,01	1,05	0,98	1,03	0,99	1,04	1,07	0,84	0,88	0,87	0,98
Al_2O_3	16,14	15,74	15,88	15,30	15,88	15,28	16,24	15,52	15,83	16,13	15,97	15,69	15,30	15,05	15,73
Fe_2O_3	11,56	12,07	10,62	10,55	10,32	10,69	10,09	10,62	10,33	10,02	10,06	9,82	10,06	10,04	20,25
MnO	0,19	0,16	0,15	0,16	0,14	0,16	0,13	0,15	0,13	0,15	0,15	0,14	0,15	0,14	0,15
MgO	6,34	5,67	6,01	5,83	5,55	6,39	5,79	5,82	6,45	6,17	5,68	6,64	6,59	6,32	6,84
CaO	10,33	9,89	10,32	10,11	10,03	9,83	10,77	10,15	9,99	10,55	10,41	9,60	10,01	10,00	11,14
Na_2O	2,44	1,69	2,51	2,81	2,63	2,79	2,39	2,51	2,52	2,29	2,50	2,25	2,07	2,40	2,06
K_2O	0,36	0,12	0,81	1,13	1,08	1,10	0,99	1,09	1,00	1,02	1,09	0,87	0,37	0,35	0,34
P_2O_5	0,13	0,11	0,09	0,15	0,14	0,15	0,14	0,15	0,14	0,15	0,16	0,09	0,09	0,09	0,09

APPENDIX C

The whole rock chemical analyses were performed in the Rhodes University Geology Department using a Philips 1410 Spectrometer and X-ray fluorescence procedures. These procedures were set up under the supervision of Prof. H.V. Eales and Dr. J.S. Marsh.

The samples were initially crushed by a hand-worked rock splitter and all visible amygdales were removed. A Herzog swing mill crushed the samples to ± 120 mesh size using a manganese steel container and then five grams of this powder were ground to ± 300 mesh size by hand with an agate mortar and pestle. Powder briquettes were made using approximately four grams of the fine-crushed powder. Duplicate fusion discs were prepared by the method of Norrish and Hutton (1969).

The elements Si, Al, Fe, Mn, Ti, K, Mg, Ca and P were analysed on the fusion discs and Na, Sr, Rb, Zr, Nb, Y, La, Ce, Nd, Zn, Ca, Ni, Co,Cr, and V were determined on the powder briquettes. Mass absorption coefficients for the trace elements were calculated from the major element analyses using Heinrich's values.

H_2O^- was determined gravimetrically by heating the samples at 110°C for 6 hours. In a similar manner LOI was determined by igniting the sample overnight in a furnace at 950°C. FeO was not determined separately and all Fe is stated as Fe_2O_3. A value of 0,2 for the Fe_2O_3/FeO ratio was used in the norm calculations.

The trace element data were processed using computer programs written in the Department of Geochemistry, U.C.T. and adapted for use at Rhodes University. The major element program was written in the Rhodes University Geology Department by Dr. J.S. Marsh. Corrections were made for matrix effects, deadtime, position factors and spectral line interference. The working curves were calculated using international rock standards (AGV-1, GSP-1, BCR-1, G-2, NIM-N, NIM-P, NIM-G and NIM-D). Analytical conditions for the major and trace element analyses are shown in Table A and the averaged lower limits of determinations in Table B.

TABLE A. ANALYTICAL CONDITIONS

MAJOR ELEMENTS

	Fe	Mn	Ti	Ca	K	P	Si	Al	Mg	Na
Tube	Cr	----	----	----	----	----	----	----	----	----
Kv	55	----	----	----	----	----	----	----	----	----
mA	40	----	----	----	----	----	----	----	----	----
Counter	flow	----	----	----	----	----	----	----	----	----
Collimator	fine	coarse	fine	----	----	coarse	----	----	fine	----
Crystal	LIF 200	----	----	----	----	Ge	PET		TLAP	
Counting Time On Peak (sec.)	20	40	10	10	10	20	40	40	200	100

TRACE ELEMENTS

	Sr	Rb	Zr	Y	Nb	Zn	Cu	Ni	Co	Cr	V	La	Ce	Nd
Tube	W	----	----	----	----	----	----	----	----	----	----	----	----	----
Kv	55	----	----	----	----	50	----	----	55	----	----	----	----	----
mA	40	----	----	----	----	40	----	----	40	----	----	----	----	----
Counter	Scintillation				----	flow + scint-flow			----	----	----	----	----	----
Collimator	fine	----	----	----	----	----	----	----	----	----	----	----	----	----
Crystal	LIF220	----	----	----	----	----	----	----	----	----	----	----	----	----
Counting Time On Peak (sec.)	200	----	----	----	----	----	----	----	----	----	----	----	----	----

TABLE B. AVERAGE LOWER LIMITS OF DETERMINATION (L.L.D.) AND ERRORS OF DETERMINATION

1. MAJOR ELEMENTS - Avg. absolute error and percentage error are for calibration curves using international rock standards.

	Av. L.L.D.	Avg.absolute error	Avg. % error
Fe	0,023%	0,10	1,79
Mn	0,027	0,02	9,54
Ti	0,010	0,02	3,74
Ca	0,014	0,04	1,46
K	0,007	0,02	0,77
P	0,031	0,02	6,47
Si	0,077	0,28	0,48
Al	0,057	0,12	0,82
Mg	0,117	0,12	1,70
Na	0,020	0,05	1,78

2. TRACE ELEMENTS

	Av. L.L.D.	Avg. absolute error
Sr	1,40 ppm	0,70 ppm
Rb	1,40	0,45
Y	1,40	0,44
Zr	1,50	0,55
Nb	1,55	0,45
Zn	1,50	0,65
Cu	2,30	6,50
Ni	1,60	0,70
Co	3,00	0,80
V	4,00	1,20
Cr	2,70	1,30
La	6,0	1,50
Ce	11,50	2,90
Nd	6,50	1,60

$$\text{L.L.D.} = \frac{6.0}{Ip/m} \times \frac{Ib}{T}$$

where Ip = peak intensity
Ib = background intensity
T = total counting time
m = counts per sec. per % of element

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ERRATA: The following references should be omitted from the list: BHATTACHARJI, S., and SMITH, C.H., 1964
BESWICK, B.E., 1976

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ERRATA

PAGE 1, LINE 13
For GEVERS (1927) read GEVERS (1928)

PAGE 8, SECTION 3.2, LINE 9
Add Fig. 3,4, 5 illustrate these sample positions with major and trace element chemistry plus various interelement ratios.

PAGE 8, SECTION 3.2, LINE 23
For WATKINS (1970) read WATKINS *et al* (1971)

PAGE 14
For Fig. 6 read: Diagrammatic sketch of Omega Formation showing sample positions JP 1-6, KF 10 and JR 108 a and b.

PAGE 20
For Fig. 8 a-c read:
Fig. 8 a is a diagrammatic section of the whole of the massive unit of the Omega Formation showing various sample positions against height.
Fig. 8 b shows the top 20 cm of the massive unit with sample positions a to e.
Fig. 8 c shows the top 3 m of the massive unit with sample positions a to e and JP 3 to JP 6.

PAGE 33
Add to the explanation to Fig. 11 A - H: Northern and Southern Province of Cox *et al* (1967) referred to later in text (SECTION 7.4).

PAGE 53
Under 3) insert "equilibrium" before "partial melting"

PAGE 54
In heading for TABLE 3 read Nd for Nb

PAGE 55, LINE 21
Insert "essentially" between "remain" and "the"

PAGE 62, LINE 1
For DANCHIN (1968) read DANCHIN and FERGUSON (1968)

PAGE 63
Figure 17 A - F should commence "Histogram showing ..."

PAGE 74
Add to Fig. 20 and Fig. 23 after "MgO%": "for the Drakensberg Subgroup in the Barkly East area".

PAGE 94
Fig. 28 A - B should commence "Histogram showing ..."

PAGE 114, LINE 29
Correct SEIDNER to read SIEDNER