

GEOLOGY OF THE CENTRAL AND SOUTHERN DOMAINS  
OF THE KORAS GROUP, NORTHERN CAPE PROVINCE

by


Christopher Gerald Sanderson-Damstra, B.Sc. (Hons)

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Master of Science in the Department  
of Geology, Rhodes University  
Grahamstown.

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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: 

C.G. Sanderson-Damstra,  
Department of Geology,  
Rhodes University,  
Grahamstown.

September, 1982.

ABSTRACT

The Central and Southern Domains of the Koras Group, situated on the Doornberg Lineament, are the structurally preserved remnants of a once more widespread late-syntectonic cover sequence. Detailed examination of the field relationships, lithology and petrography together with new geochemical data (30 analyses) has resulted in the proposal of a new geological succession consisting mainly of two cycles of bimodal basaltic-rhyolitic volcanics with interbedded, immature conglomerates and lithic greywackes. These two cycles, named the Boomrivier and Leeudraai Formations, are overlain by the immature, polymictic orthoconglomerates and red arkosic sandstones of the Kalkpunt Formation. The first volcanic cycle commenced with the Lambrechtsdrif basaltic andesites and was followed, after a short hiatus, by the Swartkopsleegte rhyodacites. The second cycle comprises the Rouxville basalts and basaltic andesites and the Swartkop and Kenilworth rhyolites. Field evidence suggests that eruption of the rhyolitic and basaltic volcanics in the second cycle was contemporaneous.

Geochemically, the volcanics can be classified as an "average-K" to high-K, tholeiitic, subalkaline association which exhibits general similarities to other Southern African bimodal associations e.g., the tholeiitic lavas of the Wilgenhoutsdrif Group. The Koras Group is petrologically similar to the Sinclair Sequence which is presently considered to be its coeval equivalent, but the dominantly calc-alkaline character of the Sinclair rocks distinguishes them from the dominantly tholeiitic Koras lavas.

In a short literature review, the four main hypotheses for the petrogenesis of bimodal associations: liquid immiscibility, crystal fractionation, two-stage partial melting and separate magma sources, are described and the most feasible explanation for the origin of the Koras lavas is thought to be a "separate magma source" hypothesis in which two cycles of mantle-derived basalts and crustal-derived rhyolites were produced in a zone of high heat flow and erupted in an area of crustal weakness. The middle- or late-Proterozoic Koras Group was formed during unstable tectonic conditions, in a depositional setting that was probably controlled by late folding of the underlying pre-Koras sequences as well as the major strike-slip movement and subordinate dip-slip faulting in the Doornberg Lineament.

CONTENTS

	<u>PAGE</u>
ABSTRACT	<u>1</u>
List of figures	v
List of tables	viii
List of appendices	viii
List of maps in attached pocket	viii
1. INTRODUCTION	1
1.1 Regional Setting	1
1.2 Previous Geological Work	1
1.3 Physiography and Vegetation	3
1.4 Aim of the Present Study	5
2. GEOLOGICAL SUCCESSION	6
2.1 Subdivision of the Koras Group	6
2.2 Nomenclature	6
2.3 Comparison with Previous Work	11
3. PRE-KORAS SEQUENCES IN THE STUDY AREA	14
3.1 Historical Background	14
3.2 Sultanoord Group, Korannaland Sequence	15
3.3 Groblershoop Formation, Olifantshoek Sequence	15
3.4 Wilgenhoutsdrif Group	16
3.5 Granite-Gneiss	16
4. FIELD RELATIONSHIPS, LITHOLOGY AND PETROGRAPHY	17
4.1 Introduction	17
4.2 Boomrivier Formation	18
4.2.1 The Basal Sedimentary Member	18
4.2.1A Distribution and General Features	18
4.2.1B Central Domain	18
4.2.1C Southern Domain	19
4.2.2 Lambrechtsdrif Member	21
4.2.2A Distribution	21
4.2.2B Outliers	21
4.2.2C General Lithology	22
4.2.2D Petrography	26
4.2.3 Karos Member	27
4.2.3A Distribution	27
4.2.3B Conglomerates	27
4.2.3C Sandstones and Shales	28
4.2.3D Depositional Environment	29

4.2.4	Swartkopsleegte Member (Lower Quartz-Feldspar Porphyry)	30
4.2.4A	Distribution	30
4.2.4B	Lithology and Petrography	30
4.2.4C	Structural Banding : Igneous Flow Structure or Incipient Tectonic Foliation?	33
4.3	Leeudraai Formation	38
4.3.1	Ezelfontein Member	38
4.3.1A	Distribution	38
4.3.1B	Conglomerates and Sandstones	38
4.3.1C	Problematical Exposure of Quartz-Feldspar Porphyry at Ezelfontein Suid	39
4.3.1D	Depositional Environment	40
4.3.2	Rouxville Member	40
4.3.2A	Distribution	40
4.3.2B	Lithology and Petrography	42
4.3.2C	Associated Volcanic Breccias	44
4.3.2D	The Volcanic Environment	45
4.3.3	Quartz-Feldspar Porphyries of the Leeudraai Formation	48
4.3.3A	Distribution and Exposure	48
4.3.3B	Structure of the Swartkop Member Underlying the Swartkop Line of Hills	49
4.3.3C	Basal Glassy Quartz Porphyry (Kenilworth Member)	50
4.3.3D	Xenolith-bearing, Medium-grained, Quartz-Feldspar Porphyries (Kenilworth Member)	51
4.3.3E	Xenolith-bearing, Coarse-grained Quartz-Feldspar Porphyries (Swartkop Member)	52
4.3.3F	Rhyolite Ignimbrites	53
4.3.3G	Minor Interbedded Sedimentary Rocks	57
4.4	Kalkpunt Formation	59
4.4.1	The Kalkpunt Basin	59
4.4.2	Kalkpunt Conglomerates	59
4.4.3	Kalkpunt Sandstones	62
4.4.4	Depositional Environment	62
5.	STRUCTURAL GEOLOGY	65
5.1	Minor Folds in the Karos Member	65
5.2	Major Fold Structures	65
5.3	Faults	67
5.4	Regional Structural Setting	71
6.	GEOCHEMISTRY OF THE LAVAS	75
6.1	Introduction	75
6.2	Classification	76
6.3	Major and Trace Element Variation	85
6.4	Comparison with Previous Work	100
6.5	Comparison with the Sinclair Sequence	104
6.6	Comparison with the Wilgenhoutsdrif Group	109
6.7	Comparison with the Lavas of the Witwatersrand Triad	111

7.	ASSOCIATED INTRUSIVE ROCKS	113
7.1	Distribution and Correlation	113
7.2	Quartz-Feldspar Porphyry and Dolerite Dykes	113
7.2.1	Quartz-Porphyry Dykes on Leeudraai Farm	113
7.2.2	Quartz-Porphyry Dykes on Ezelfontein Noord	114
7.2.3	Straussburg-Rouxville Dyke Swarm	114
7.2.4	Dolerite Dykes (Southern Domain)	115
7.3	Granitic Rocks	116
8.	AGE, PETROGENESIS AND DEPOSITIONAL SETTING	117
8.1	Age of the Koras Group	117
8.2	Review of Hypotheses for the Origin of Bimodal Basaltic-Rhyolitic Lavas	119
8.2.1	Introduction	119
8.2.2	Liquid Immiscibility as a Process for producing Bimodal Basaltic-Rhyolitic Magmas	120
8.2.3	Crystal Fractionation	122
8.2.4	Two-stage Partial Melting of the Same Parent Material	122
8.2.5	Separate Magma Sources	125
8.2.6	Conclusion	125
8.3	Application to the Koras Lavas	126
8.4	General Depositional Setting	128
8.5	The Koras Group and Plate Tectonic Theory	131
9.	SUMMARY AND CONCLUSIONS	134
	APPENDICES	138
	ACKNOWLEDGEMENTS	156
	REFERENCES	157
	MAPS	

List of Figures

1.1	Locality maps showing the regional distribution and position of the three domains of the Koras Group and the position of the study area.	2
2.1	Generalized geological map illustrating the distribution of the three formations of the Koras Group.	9
4.2.1	Volcanic bombs in medium- to coarse-grained tuffaceous breccia of the Lambrechtsdrif Member.	24
4.2.2	Volcanic breccia of the Lambrechtsdrif Member.	25
4.2.3	Typical hyalopilitic texture of the basic lavas of the Lambrechtsdrif Member.	25
4.2.4	Streambank exposure of interbedded sandstone and shale of the Karos Member.	29
4.2.5	Subhorizontal structural banding on a weathered rock surface of fine-grained quartz-feldspar porphyry (Swartkopsleegte Mbr).	35
4.2.6	Structural banding manifest as a set of inclined, closely spaced parallel fractures in fine-grained Q-F porphyry of the Swartkopsleegte Mbr.	35
4.2.7	Weathered rock surface showing subvertical structural banding of fine-grained quartz-feldspar porphyry of the Swartkopsleegte Mbr.	36
4.2.8	Photomicrograph of altered zone or structural band and a microfault in quartz-feldspar porphyry.	36
4.2.9	Primary igneous flow structure cut by structural banding interpreted as incipient tectonic foliation produced during Koras folding.	37
4.3.1	Geology of the Koras Group at Leeudraai farm.	41
4.3.2	Differentiated lava flows consisting of a layered amygdaloidal flow top and less amygdaloidal basal part.	43
4.3.3	Downdip close-up view of a differentiated lava flow in Fig. 4.3.2	43
4.3.4	Hollow plagioclase laths that are box-shaped in cross-section, together with acicular plagioclase and opaque minerals in the hyalopilitic groundmass of Rouxville basalt.	46
4.3.5	Small within-flow breccia (Rouxville Mbr.) cemented with milky quartz.	46
4.3.6	Volcanic breccia near the base of the Rouxville Member at Karos Nedersetting.	47
4.3.7	Partially corroded, subhedral quartz phenocrysts set in the microcrystalline groundmass of the basal glassy porphyry (Kenilworth Member).	54

4.3.8	Embayed and corroded quartz set in a devitrified glassy to microcrystalline groundmass (Swartkop Member).	54
4.3.9	Strain lamellae and fractures in corroded quartz which is set in a microcrystalline groundmass (Swartkop Member).	55
4.3.10	Photomicrograph of part of a rounded, partially resorbed perthite-oligoclase intergrowth in coarse-grained quartz-feldspar porphyry of the Swartkop Member.	55
4.3.11	Polymineralic aggregate composed mainly of feldspar, quartz and opaque minerals.	56
4.3.12	Flow texture made up of welded glass particles in rhyolite ignimbrite of the Swartkop Member.	56
4.3.13	Volcaniclastic sedimentary rocks dipping to the left (north) at Karos Nedersetting.	58
4.4.1	Exposure of Kalkpunt conglomerate in the Swartkopsleegterivier.	61
4.4.2	Interbedded sandstone layers within the Kalkpunt conglomerate.	61
4.4.3	Possible relationship between major faults and the Kalkpunt basin.	63
5.1.1	Minor folds in micaceous sandstone and shale of the Karos Member.	66
5.1.2	Minor folds in the Karos Member.	66
5.1.3	Fault breccia of the Leeudraai-Kalkwerfputs fault on Leeudraai farm.	66
5.2	ERTS image illustrating major structural features and the distribution of the Central and Southern Domains of the Koras Group. (courtesy of NASA and of the N.P.R.L., C.S.I.R.)	68
5.3	Structural elements in the Koras Group and the adjoining pre-Koras sequences.	73
6.1a.	Alkalies-silica diagram.	77
6.1b.	Ol'-Ne'-Q' projection illustrating the subalkaline character of the Koras lavas.	77
6.2a.	AFM diagram illustrating the slight "iron enrichment trend" in the Rouxville Basalt Member and close grouping in the other three volcanic members.	78
6.2b.	Al <sub>2</sub> O <sub>3</sub> -normative plagioclase plot illustrating the tholeiitic character of the Koras lavas.	78
6.2c.	Jensen's (1976) diagram for distinguishing between tholeiitic and calc-alkaline lavas.	79
6.2d,e.	Comparison of the Koras lavas with various subalkaline (non-alkalic) volcanic rock series (from Miyashiro, 1974).	80
6.3a.	Plot of normative colour index versus normative plagioclase composition for the Koras lavas.	81

6.3b.	Nomenclature of volcanic rocks (excluding ultrapotassic rocks, after Cox et al., 1979, p.14).	81
6.3c	Q'-ANOR diagram for the Koras Lavas.	82
6.4.	An-Ab-Or projection illustrating the K-rich character of the Koras lavas.	84
6.5a-d	Major element variation diagrams (weight % oxides) using MgO as the abscissa.	88-91
6.6a-g	Trace element variation diagrams (in parts per million) using MgO (wt. %) as the abscissa.	92-98
6.7.	Selected interelement ratios for the Koras lavas.	99
6.8.	Comparison of the geochemical results of Grobler et al. (1977, p.171; top diagram) with the present study (bottom) on Mackenzie and Chappells (1972) potash vs. silica diagram.	101
6.9.	Generalized geological map illustrating the spatial relationship of the Sinclair Sequence, its correlatives and the Koras Group.	105
6.10.	Geological succession and evolutionary cycles of the Sinclair Group (after Watters, 1977).	106
6.11.	AFM-plot comparing the lavas and intrusives of the Sinclair Sequence (from Watters, 1974, p.115) with the Koras lavas.	107
6.12.	Comparison of the Koras lavas with the Sinclair Sequence on the diagram of Green (1973).	108
8.1.	The diopside-forsterite-silica system at $P(H_2O) = 20$ kbar (Kushiro, 1969, in Yoder, 1973, p.165).	123
8.2.	Generalized explanation for the petrogenesis of the Koras lavas.	127

List of Tables in the text

2.1 Geological Succession of the Koras Group.	7
2.2 A Comparison of the Geological Columns of the three Domains of the Koras Group.	8
2.3 Lithological Comparison of the Lambrechtsdrif Member Lavas and the Rouxville Member Lavas.	10
2.4 A Comparison of the Stratigraphic Columns for the Koras Group proposed by various authors.	13
6.1 Symbols Used to Represent the Koras Lavas.	75
6.2 Classification of the Koras Lavas	83
6.3 Chemical characteristics of the shoshonite association (from Morrison 1980, p.98)	100
6.4 Comparison of Trace Element Abundances (ppm) of the Koras Group with the Wilgenhoutsdrif Group.	109
6.5 Geochemical Comparison of the Swartkopsleegte and Lambrechtsdrif Members with Witwatersrand Triad Lavas.	112
8.1 A Summary of Age Determinations of rocks of the Koras Group.	118
8.2 Results of a Preliminary Geochemical Evaluation of the Tectonic Environment of the Koras Group using the Basaltic Lavas.	133

List of Appendices

1. Localities and Brief Descriptions of the Analyzed Samples.	138
2. Sample Preparation for Analysis.	142
3. X-Ray Fluorescence analysis.	142
4. Major Element Analyses ( $H_2O^-$ and L.O.I. included) and Trace Element Analyses.	145
5. Major Elements Analyses ( $H_2O$ -free, normalized to 100%) and CIPW Weight Percent Norms ( $Fe_2O_3 = TiO_2 + 1.5$ ).	149
6. CIPW Weight Percent Norms using $Fe_2O_3/FeO = 0.2$ .	153
7. Selected Interelement Ratios.	155

List of Maps in attached pocket

Map 1. Geology of the Koras Group at Karos village (1:10000).	
Map 2A. Geological map of the Central Domain of the Koras Group (1:50000).	
Map 2B. Geological map of the Southern Domain of the Koras Group (1:50000).	
Map 3. Generalized geological map of the Central and Southern Domains of the Koras Group (1:200000).	

## 1. INTRODUCTION

### 1.1. Regional Setting

The Koras Group is a sequence of volcanic and sedimentary rocks and associated intrusives of late Proterozoic age that are located in the northern Cape Province. Upington is the main town in the Northern Cape and is situated on the banks of the Orange River. The mildly deformed, unmetamorphosed Koras Group derives its name from the farm Koras which lies to the north of the Orange River and is about 40 kilometres east of Upington (Fig. 1.1). The names of the farm and the village Karos on the opposite bank of the Orange are spelt differently due to a historical misnomer.

The Group is distributed in an arcuate belt approximately 130 kilometres long and up to 35 kilometres wide. The regional outcrop area is divided into three domains as illustrated in Figure 1.1. Outliers and associated intrusive rocks are sporadically exposed throughout this area. The large Central Domain is roughly triangular in shape with Karos at its centre. The Southern Domain is a long, thin strip, the most southerly tip of which is about 20 kilometres west of Groblershoop. These two domains are geographically separate outcrop areas that have been found in this study to be the structurally preserved remnants of a once more widespread Koras Group. The Northern Domain is 50 kilometres north of Upington and was not included within the study area.

### 1.2. Previous Geological Work

The lavas, conglomerates and sandstones of the Koras Group were first described by Rogers (1908, p. 52-58) during a reconnaissance investigation along the north bank of the Orange River. This work was extended by Rogers and Du Toit (1910, p. 73-88) who investigated the Koras Group on the south side of the Orange River and subdivided it into sediments, basic lavas, and acid and intermediate lavas. Subsequently Le Roex (1943) mapped an area which included part of the Northern Domain of the Koras Group while part of the Central Domain was mapped for the Geological Survey by D.J. Simpson in 1944. Simpson wrote no report and left only an unpublished map.

The first complete mapping of the Koras Group was done by M.C. du Toit (1965) who subdivided the group into six stratigraphic units. Later the exposures north of the Upington - Olifantshoek road were mapped by Moen (1974) who also reinvestigated most of the area studied by Du Toit (1965). A. Kroner proposed a lithostratigraphic subdivision of the Koras succession based largely on the

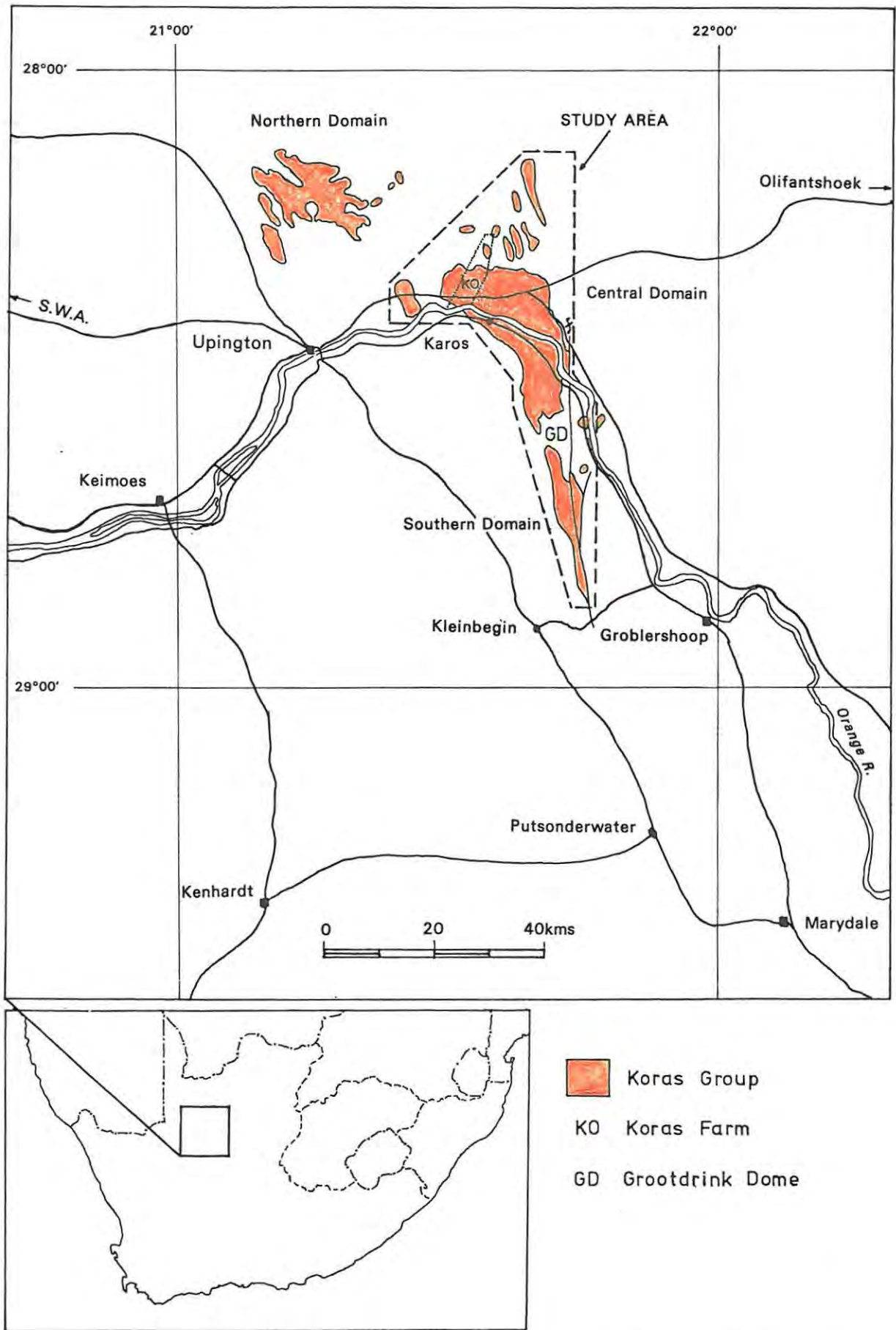


Figure 1.1. Locality maps showing the regional distribution and position of the three domains of the Karas Group and the position of the study area.

work of Du Toit (1965) and Moen (1974) and this was adopted by Grobler et al. (1977). Moen (1980) amended the stratigraphy and proposed the lithostratigraphic subdivision accepted by the South African Committee for Stratigraphy (1980, hereafter referred to as SACS). Comparisons of the stratigraphic columns and nomenclature as proposed by the numerous authors, a historical review and a summary of the previous geological work are also presented in SACS (1980).

Apart from these major contributions to the geology of the Koras Group a limited amount of research on the Group has been carried out by members of the Precambrian Research Unit of the University of Cape Town and this information is available in their annual reports (Vajner, 1974; Stowe, 1979).

Previous geochemical work has been carried out by Grobler et al. (1977) who indicate that the Koras Group is a calc-alkaline (shoshonite) association emplaced in a newly stabilized orogenic region. Other geochemical work includes that of Geringer and Botha (1976), Moen (in prep.) and Frick et al. (in prep.). Numerous age determinations have been calculated and these indicate an age of between 1000 Ma and 1200 Ma for the Koras Group (see Table 8.1, p.118).

The Koras Group, in the study area, unconformably overlies the Sultanaoord Group of the Korannaland Sequence, the Groblershoop Formation of the Olifantshoek Sequence, the Wilgenhoutsdrif Group and granite gneiss that is generally regarded as intrusive. These pre-Koras, early to middle Proterozoic sequences have recently been studied by Moen (1980), Van Zyl (1981) and Stowe (1980, 1981).

### 1.3. Physiography and Vegetation

From a point three kilometres southwest of Karos the western margin of the Koras Group is marked by the resistant quartzites of the Sultanaoord Group which build steep-sided hills and ridges. This band of quartzites, sometimes called the Kaaien Hills, is up to six kilometres wide and extends in a south-easterly direction to a point just east of Kleinbegin. The Koras porphyries and basalts build low rounded hills in the low-lying ground occupied by the Group. The Central and Southern Domains are separated by a cluster of quartzite hills and ridges that outline an elliptical area, the structure of which is that of an interference fold and is referred to as the Grootdrink dome. The centre of this dome is about five kilometres west of Grootdrink.

The Orange River is the main river in the area. Flowing in a north-westerly direction it passes to the east of the Southern Domain. It then turns west and crosses the southern part of the Central Domain. All other streams and rivers are ephemeral with steep gradients and beds of boulders and sand and flow directly into the Orange River.

The poor exposure of the Koras Group rocks south of the Orange River can be attributed to this ephemeral river action which has built up large deposits covering parts of the low lying areas occupied by the Koras Group. In addition, large talus slopes are developed below quartzite hills and these talus deposits obscure the relationship of the Koras Group to the underlying sequences. The Koras rocks have not produced good soils under the semi-desert climatic conditions and usually give rise to a rubble-strewn veld through which large in situ rocks protrude.

North of the Orange River the topography is generally flat and almost entirely covered by longitudinal Kalahari Group sand dunes that trend in a north-westerly direction. In this area the drainage pattern is poorly defined and drainage channels are best described as "vleis" which often terminate in pans. The exposures of quartz-feldspar porphyry and amygdaloidal basalt form low hills and koppies which protrude through the sand or are merely piles of rubble lying on the red sand with occasional rocks that appear to be in situ.

The flora reflects semi-desert conditions and most plants have xerophytic adaptations. Dense vegetation is localised along the Orange River. However, away from the Orange River, the boulder and rubble-strewn veld is sparsely covered with ubiquitous "driedoring" (*Rhigozum trichotomum*) and amongst other thorn trees the "swarthaak" (*Acacia detinens*) and "kameeldoring" (*Acacia erioloba*) are common particularly in dry river and stream beds. Aloes are common and occur singly or in clusters and "kraals" together with numerous other succulent species.

In the area around Karos "driedoring" (*Rhigozum trichotomum*) is more common on rubble-strewn basalt and porphyry exposures and less common on the calcrete-covered areas. This relationship is well-developed at the contact of basaltic andesite (Lambrechtsdrif Member) on the Wilgenhoutsdrif Group just to the west of Karos. This contact is poorly exposed, the exposures of basaltic andesite gradually giving way to more calcrete-rich veld. The change is accompanied by the disappearance of "driedoring" and increase in "perdebos" (*Monechma* sp.) and "skilpadbos" (*Zygophyllum microcarpum*).

#### 1.4. Aim of the Present Study

In an earlier investigation (Sanderson, 1979) the stratigraphic sequence proposed by Du Toit (1965), and used with minor amendments by later workers, was found to be controversial and it appeared that the sequence proposed by Rogers and Du Toit (1910, p. 74) was probably correct. Therefore the main objective of this study was to remap and examine the Koras Group in more detail and elucidate the stratigraphy of the group. To avoid duplication of the detailed work by Moen (in prep.) on the Northern Domain, it was decided that this study should concentrate on the Central and Southern Domains. In addition the new exposures of Koras rocks that had come to light (Moen 1974, 1980) were re-examined and interpreted in terms of the new geological succession proposed here.

The aim of the geochemical work is to support the stratigraphic study if possible, and to gain more insight into the geochemical nature of the lavas of the Koras Group.

## 2. GEOLOGICAL SUCCESSION

### 2.1. Subdivision of the Koras Group

The geological succession of the Koras Group is complicated by the presence of unconformities which do not, however, warrant the subdivision of the Group into two or more groups. This was first noted by Rogers (1908, p. 53): "Though there are two or more unconformities within this series, the members of it seem to be so closely related that it would at present introduce unnecessary complication to divide the group up into formal sub-divisions." Later, A.L. du Toit (1954, p. 5) exposed the problem and provided the key to understanding the geological succession of the Koras Group :

"The Koras Series is a fine illustration that formations composed largely of conglomeratic beds or of volcanic material are liable to great and sudden variation from point to point not only in the nature of their materials, but also in the thickness of the individual rock groups."

The Koras Group in the study area consists of nine alternating sedimentary and volcanic units whose lithologies and proposed lithostratigraphic names are presented in Table 2.1. The extent and occurrence of the members in the three domains is illustrated diagrammatically in Table 2.2. This table demonstrates that various members are missing from the geological succession in the different domains so that in no one domain is the full succession developed. In addition, certain members are better developed in some areas than in others.

The members of the Group make up three formations whose distribution is illustrated in Figure 2.1. In the Central Domain a distinct unconformity separates the Koras Group into upper and lower parts. The Boomrivier Formation is unconformably overlain by the Leeudraai and Kalkpunt Formations. The unconformity traverses the area from Leeudraai in the east, where it terminates against Wilgenhoutsdrif Group schists, to Kameelpoort in the west, where it joins the major unconformity separating the Koras Group from the Sultanaoord Group. This stratigraphic break probably represents a period of erosion or non-deposition while deposition of the Ezelfontein Member took place in the Southern Domain.

### 2.2. Nomenclature

Names used for formations and members are those defined by SACS (1980) except where the stratigraphic changes have made it necessary to use other names as proposed below.

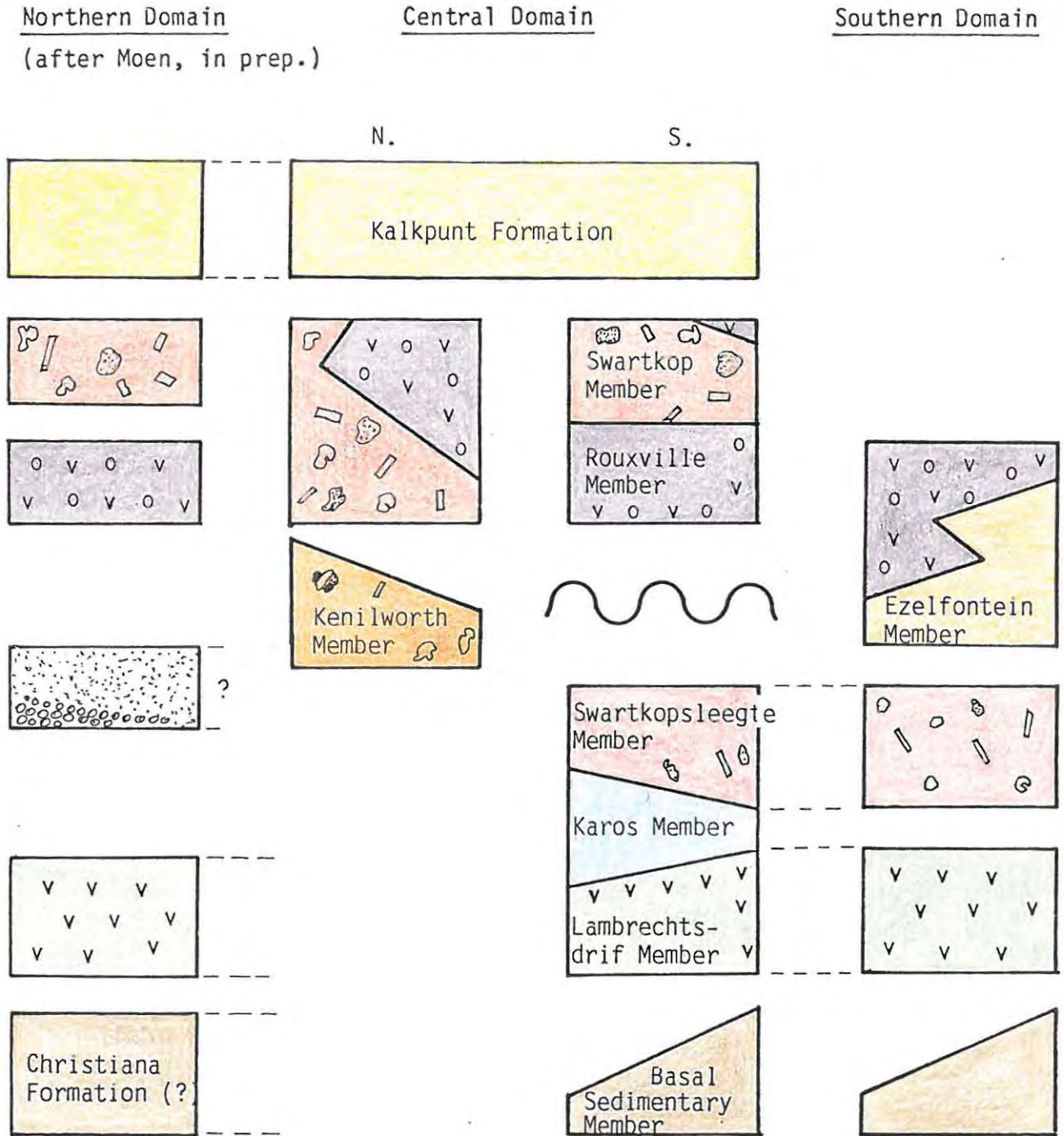
Table 2.1. Geological Succession of the Koras Group

ROCK TYPE	MEMBER	FORMATION
Red sandstone, conglomerate		Kalkpunt
Coarse-grained quartz-feldspar porphyry, ignimbrite, minor volcanoclastic rocks. (Rhyolite).	Swartkop (Upper Porphyry)	Leeudraai
Medium-grained quartz-feldspar porphyry, glassy quartz porphyry.	Kenilworth	
Amygdaloidal basaltic lava, minor interbedded sandstone and volcanic breccia. (Basalt to Basaltic Andesite).	Rouxville (Upper Basic Volcanics)	
Conglomerate, sandstone.	Ezelfontein	
Fine-grained quartz-feldspar porphyry, minor interbedded sandstone. (Rhyodacite).	Swartkopsleegte (Lower Porphyry)	Boomrivier
Conglomerate, micaceous sandstone, shale.	Karos	
Greenish-grey basaltic lavas, minor interbedded sandstone, volcanoclastic and pyroclastic rocks. (Basaltic Andesite).	Lambrechtsdrif (Lower Basic Volcanics)	
Conglomerate, quartzite.	Basal Sedimentary Member	

The basaltic rocks occur in two members, the upper basic volcanic member being named after the farm Rouxville in the western corner of the Central Domain where a 500m sequence of amygdaloidal basaltic lavas is exposed.

The Lambrechtsdrif Member comprises the lower basic volcanic rocks, as it is upon these rocks that the village of Lambrechtsdrif stands. The lithological characteristics of the two basaltic members are compared in Table 2.3. These lithological differences can be used to determine the stratigraphic position of outliers and other exposures of basic rocks where structural evidence is lacking.

Table 2.2. A Comparison of the Geological Columns of the three Domains of the Koras Group



N. - North of the Kalkpunt basin.  
S. - South of the Kalkpunt basin.

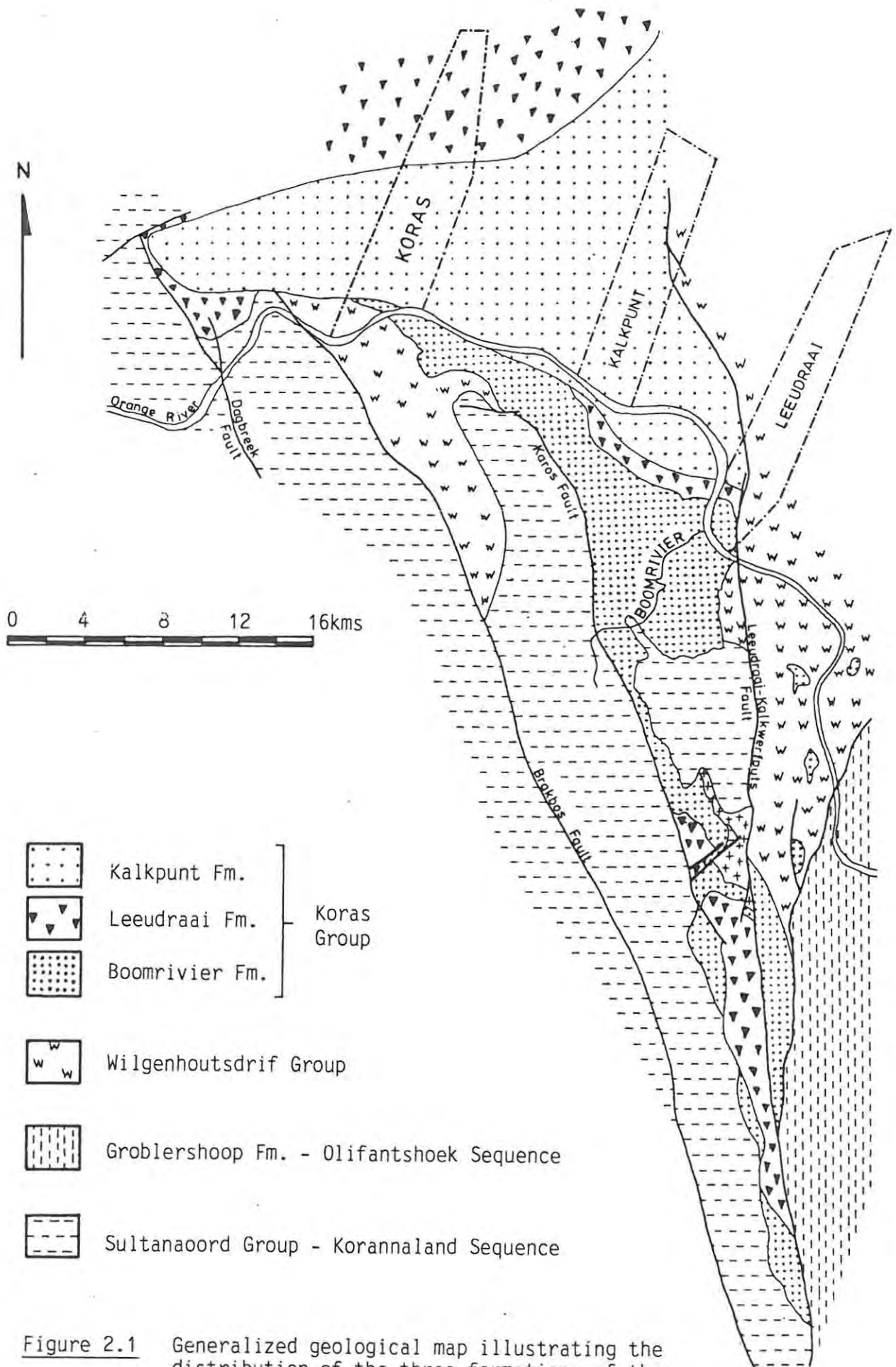


Figure 2.1 Generalized geological map illustrating the distribution of the three formations of the Koras Group.

Table 2.3. Lithological Comparison of the Lambrechtsdrif Member Lavas and the Rouxville Member Lavas

	<u>Lambrechtsdrif Member Lavas</u>	<u>Rouxville Member Lavas</u>
	Basaltic Andesites	Basalts to Basaltic andesites
Colour	Greenish-grey or grey; rarely dark grey.	Black, dark grey or purplish-brown; rarely grey. (Where not epidotized.)
Texture (Hand specimen)	Usually aphanitic; less commonly doleritic.	Usually aphanitic; rarely porphyritic.
Amygdales	Usually absent; where present they are sparse and white consisting of quartz and calcite.	Commonly present in abundance; sometimes in layers; amygdale fillings are epidote, quartz or calcite.
Alteration	Thin irregular veins of quartz and calcite are common while epidotization is rare	Often bright green in appearance due to epidotization.

The sedimentary member that overlies the Lambrechtsdrif Member in the Central Domain is named the Karos Member because the rocks are exposed around Karos Village on the farm Karos and on Karos Nedersetting (see map 2A). The Ezelfontein Formation in the Southern Domain is downgraded to member status.

The term Avondale Formation (SACS, 1980) which comprises the lower quartz-feldspar porphyries is replaced by Swartkopsleegte Member for the following reasons:-

- 1) The porphyries on the farm Avondale are not part of the lower porphyry unit but are interpreted, on the basis of lithology, to be part of the upper porphyry unit.
- 2) Swartkopsleegte is the name given to the valley between the Swartkop line of hills and the Kaaien Hills (Sultanaoord Group) and this valley is underlain by lower porphyry rocks. The name is also given to the stream that flows through the valley and is printed on the 1:50000 topographical map (2821BC).
- 3) No other town or farm names are available for the area south of the Orange River where the stratigraphic position of the lower porphyry member has been clearly determined.

In the area north of the Kalkpunt basin (Central Domain), Moen's (1980) lower porphyry phase is interpreted as a third major porphyry member and is named after the farm Kenilworth. The coarse upper phase (Moen, 1980) is correlated on the basis of lithology with the quartz-feldspar porphyries underlying the Swartkop line of hills and named the Swartkop Member, a name proposed by Moen (1974). Care should be taken to avoid confusion between the Swartkop Member (upper porphyry) and the Swartkopsleegte Member (lower porphyry).

The name Boomrivier Formation is proposed for the lower basic volcanics and lower porphyries and also includes the Karos Member and the Basal Sedimentary Member. The term Leeudraai Formation is retained for the upper porphyries but now also includes the upper basic volcanics as it is on Leeudraai that the interbedded relationship of porphyry and basalt is clearly exposed (Fig 4.3.1, p.41). In the Southern Domain the Leeudraai Formation includes the Ezelfontein Member (Table 2.1). The Kalkpunt conglomerates and red sandstones retain formation status.

### 2.3. Comparison with Previous Work

The first stratigraphic sequence proposed for the Koras rocks was that of Rogers and Du Toit (1910, see Table 2.4.). This sequence, although simplified, agrees with that of the present study. Rogers and Du Toit (op. cit.) recognised the presence of amygdaloidal basic lavas between the two porphyry units as well as the existence of basic lava below all the porphyries. The distribution of their lower basic lavas in the Central Domain is similar to that of the Lambrechtsdrif Member in this study. Their map is simplified as the porphyries and the intervening amygdaloidal lava are mapped as one unit termed "acid and intermediate lava". In addition, the interbedded nature of porphyry and amygdaloidal basic lava at Leeudraai (see Figure 4.3.1.) was first noted by Rogers (1908, p. 54) who wrote as follows :

"On Leeudraai this porphyry occurs in layers several feet thick interbedded with the amygdaloidal lava, dipping northwestwards under the Albany conglomerates."

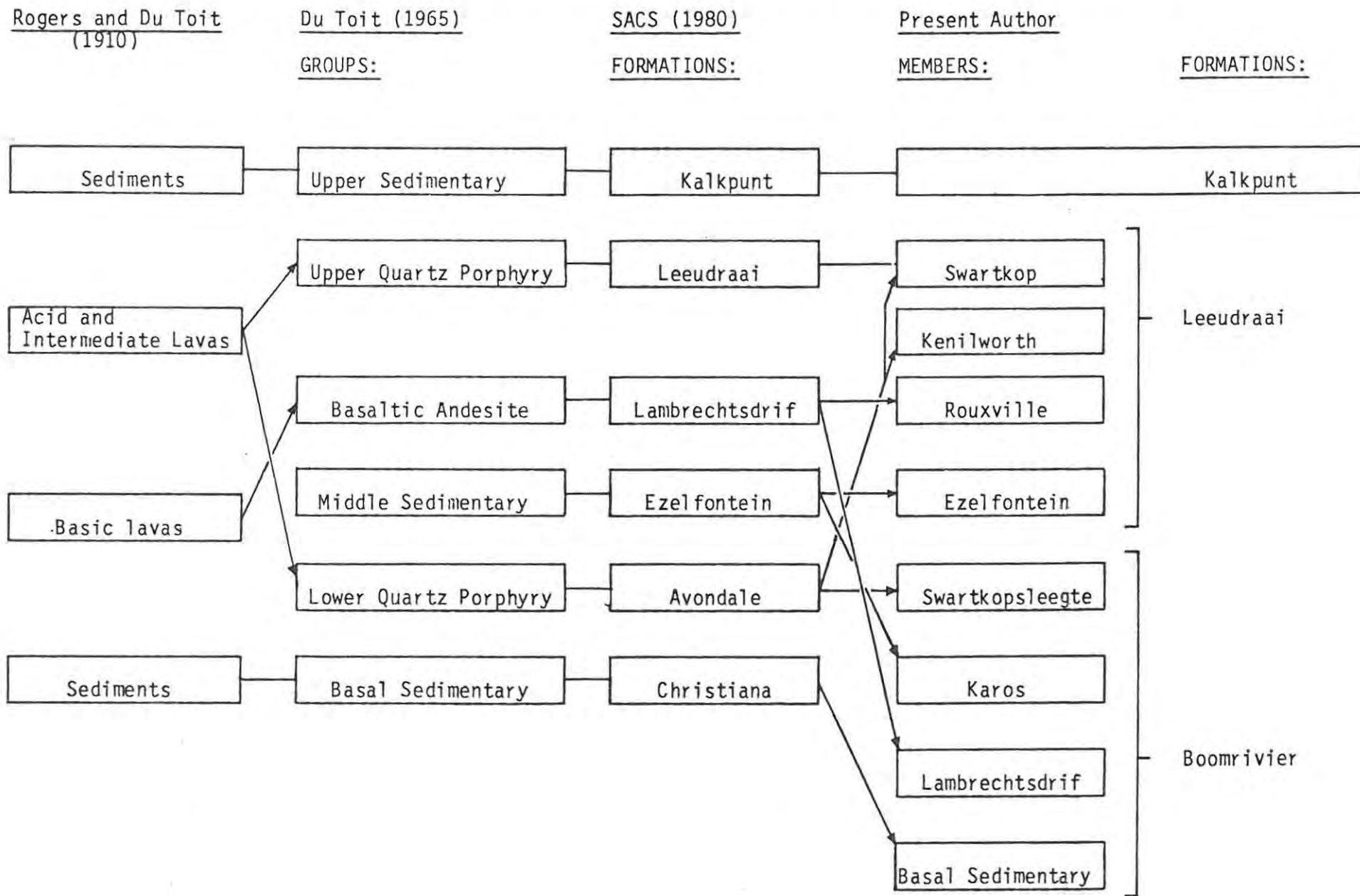
However it does appear that they (Rogers and Du Toit, 1910, p. 75-77) were unsure of the succession and some confusion existed because they described certain features which could not be located by Du Toit (1965, p. 33) or during the present study. This may be a result of base map inaccuracies and/or changes of farm boundaries and trigonometric reference points.

Du Toit (1965) divided the "Koras Formation" into six "groups" (Table 2.4.) and this subdivision has been used with minor amendments by all later workers and forms the basis of the stratigraphic nomenclature proposed by SACS (1980).

In summary, the following stratigraphic changes have been made by the present author:

- 1) The basaltic rocks have been separated into two members.
- 2) Sedimentary rocks in the Central Domain that were part of the Ezelfontein Formation (SACS, 1980) now make up the Karos Member.
- 3) Quartz-feldspar porphyries on Avondale and other farms in the northern part of the Central Domain are now part of the Leeudraai Formation.

Table 2.4. A Comparison of the Stratigraphic Columns for the Koras Group proposed by various authors.



### 3. PRE-KORAS SEQUENCES IN THE STUDY AREA

#### 3.1. Historical Background

The oldest rocks underlying the area have traditionally been referred to as the "Kheis Series, System or Group". Considerable controversy exists over the stratigraphic relationships of the "Kheis Group" and researchers from the Precambrian Research Unit, the Geological Survey, Upington and the University of Bloemfontein hold differing views on the stratigraphic and structural relationships between the pre-Koras sequences in this area. However, the details of the controversy are not the subject of this chapter and only the locality, present status, lithology and approximate age of the pre-Koras sequences in the study area is presented.

Rogers and Du Toit (1910) proposed the following threefold division of the Kheis Series :-

	Wilgenhoutsdrif Beds
Kheis Series	Kaaien Beds
	Marydale Beds

Vajner (1974) revised the classification and nomenclature of the "Kheis Group" in terms of the lithostratigraphic code :-

	Wilgenhoutsdrif Formation
Kheis Group	Kaaien Formation
	Groblershoop Formation
	Marydale Formation

The term Groblershoop Formation was introduced for part of the former Kaaien Formation. Malherbe (1978) reported that the Groblershoop Formation follows conformably on the Matsap Formation and thus for the first time incorporated rocks of the former Kheis Group into the Olifantshoek Sequence.

Although Smit (1977) largely upheld Vajners (op. cit.) subdivision, Moen (1976, 1980) introduced a number of new subdivisions and names, most important of which is the Sultanaoord Group which incorporates rocks of the former Kaaien Formation. Moen (1980) advanced evidence to show that the terms "Kheis" and "Kaaien" should be abolished. In addition the Wilgenhoutsdrif Formation has been upgraded to Group status (SACS, 1980).

The pre-Koras sequences have been subjected to three major phases of folding represented by the  $F_1$ ,  $F_2$  and  $F_3$  folds (Botha et al., 1977; Stowe, 1979; Moen, 1980). A fourth weak fold phase ( $F_4$ ) is recognized by Stowe (1979). Although there is disagreement over the existence, location and orientation of certain structural elements, there is, in general, a good correspondence between the phases of deformation as proposed by various authors.

### 3.2. Sultanaoord Group, Korannaland Sequence

These quartzites, quartz-sericite schists and phyllites build the hills and ridges along the western margin of the Central and Southern Domains as well as the hills of the Grootdrink Dome. In the Rooikoppies-Rouxville area the Sultanaoord Group is unconformably overlain by the basaltic lavas of the Rouxville Member while Lambrechtsdrif Member basalts overly the Sultanaoord Group around the Grootdrink Dome. According to Moen (1980) the overall structure of the Karos-Kleinbegin segment (Kaaie Hills) is in broad terms that of an antiform terminating in a northwest-plunging antiform near Karos. The Sultanaoord Group in the Rooikoppies-Rouxville area also exhibits complex folding and the Wilgenhoutsdrif Group is faulted down against these rocks.

U-Pb ages of 2100 Ma and 2400 Ma were reported (Nicolaysen, in SACS, 1980) on detrital zircons from a banded quartzite gneiss of the Dagbreek Formation which is part of the Sultanaoord Group. This indicates a probable maximum age for the formation (SACS, 1980).

### 3.3. Groblershoop Formation, Olifantshoek Sequence

The Southern Domain of the Koras Group is faulted against the Groblershoop Formation in the south-western part of the study area. Although there is a component of dip-slip faulting on the faults in this area, a considerable amount of strike-slip (wrench) faulting has occurred. The Groblershoop quartzites, sericitic quartzites and quartz-sericite schists have been subjected to low-grade metamorphism and the polyphase deformation has produced complex fold structures such as the Kalkwerf synform.

A minimum age for the Groblershoop Formation is given by an intrusive granite dated at  $1268 \pm 25$  Ma (Burger and Walraven, 1976, p. 325) while a minimum ( $^{40}\text{Ar} - ^{39}\text{Ar}$ ) age of 1780 Ma (Burger and Coertze 1974, p. 136), was obtained on an interbedded metalava.

### 3.4. Wilgenhoutsdrif Group

Moen (1980) has revised, subdivided and renamed the Wilgenhoutsdrif succession and suggested that it lies unconformably on both the Groblershoop Formation and the Sultanaoord Group:-

"The Wilgenhoutsdrif Group occurs between these two rock groups and overlies both while similar purple quartzite (Grootdrink/Kameelpoort quartzite) is developed on each contact. This relationship can be interpreted as a normal sedimentary unconformity or alternatively the purple quartzites may represent silicification zones along deformed and metamorphosed thrust planes of  $F_1$  age."

The Wilgenhoutsdrif Group can be divided into two parts. The lower part (Zonderhuis Formation) with the prominent and distinctive Grootdrink/Kameelpoort quartzite at its base comprises pelitic and psammitic schists with minor carbonate rocks, greenstone, ferruginous chert and serpentinite (Moen, 1980). In the predominantly volcanic upper part (Leerkrans Formation), Moen (1980) has identified two and possibly three, cycles of volcanicity which start with felsic lava, then basic lava and end with epiclastic sedimentation. Rocks of the Wilgenhoutsdrif Group occur mainly in two large areas separated by the overlying Koras Group. These areas are around the villages of Leerkrans in the west and Grootdrink in the east. Other exposures occur on Kaffirswart at the eastern, faulted margin of the Kalkpunt basin and on Jebeko in the northern corner of the study area.

Cornell (1975) obtained a Rb-Sr age of  $1148 \pm 48$  Ma on basic lava from the Wilgenhoutsdrif Group and argued that this figure closely approximates the age of extrusion. A U-Pb age of 1336 Ma has been determined on acid lava (Burger, in SACS, 1980).

### 3.5. Granite-Gneiss

Granite-gneiss in the study area outcrops in the Central Domain on Rooikoppies and in the Southern Domain on Ezelfontein, Buchberg Settlement and Kalkwerfputs. Smit (1977, p. 228 - 238) regards these gneisses as granitic intrusions that formed during the earliest ( $F_1$ ) major phase of folding. This is supported by Moen (1980, p. 204) who also views these granites as syntectonic ( $F_1$ ) intrusions. The gneiss at Rooikoppies has been interpreted as paragneiss by Von Backström (1964), but Moen (1980, p. 199) states that the igneous origin is quite clear and these granites are probably also syntectonic ( $F_1$ ) intrusives. According to Stowe (1981) all the gneisses in the study area are syntectonic ( $F_2$ ) intrusives and are part of the Straussburg suite (Stowe, 1981, p. 1).

#### 4. FIELD RELATIONSHIPS, LITHOLOGY AND PETROGRAPHY

##### 4.1. Introduction

In the following sections the field exposures and appearance in hand specimen and thin section of the Koras rocks in the study area are described. Some of the field exposures have been referred to directly and this has been done by means of a grid system on the maps provided e.g., (2A: H-11) indicates position H-11 on map 2A. In addition, hand specimen and thin section sample numbers are included where necessary to facilitate re-examination and further study.

Desert varnish similar to that described by Von Backström (1964, p. 11) is common on the weathered rock faces in the Koras Group throughout the study area. This shiny black surface feature is particularly frequent on the basic volcanic rocks and in the pitted surfaces of the quartz-feldspar porphyries as well as some conglomerates. Sandstones and shales are rarely covered with desert varnish. According to Von Backström (1964) desert varnish consists of a high proportion of manganese and ferric oxides which could be derived from the original rock and left as a residue on the rock face during weathering. This is also the view of Tricart and Cailleux (1964, in Cooke and Warren, 1973). According to Cooke and Warren (1973) numerous workers favour the idea that precipitation of desert varnish is helped by organic agencies which produce organic complexes that are very stable. However, Cooke and Warren (op. cit.) suggest that "it seems more likely that the source of much of the material is in weathered soil and debris surrounding the varnished surfaces and that the peculiar constitution of the varnish must be attributed to fractionation processes that occur during the movement of solutions to the rock surfaces". More recently, Elvidge and Moore (1979), who describe desert varnish composed of illite-montmorillonite (70%) and ferromanganese oxides (30%), believe that the materials for varnish formation are windblown and accreted to the rock surface. In their view much of the Fe and Mn enters the varnish as "soil formed ferromanganese coats on windblown clay particles" while some other materials common in desert soils e.g., sulphur, also accompany the major components into the varnish. The disagreement about the origin and formation of desert varnish as well as the disagreement about the environmental associations of desert varnish (Cooke and Warren, 1973) means that analyses of Koras varnish are required for an interpretation of its origin and geomorphological significance.

## 4.2. Boomrivier Formation

### 4.2.1. The Basal Sedimentary Member

#### 4.2.1A. Distribution and General Features

Basal sedimentary rocks are only locally developed in the Central and Southern Domains but a thick (1500m) sequence outcrops in the Northern Domain on the farm Christiana (G. Moen, pers. comm.). The locally developed deposits in the study area are typically interformational immature orthoconglomerates. Sandstones and quartzites are also known and have steep dips (65-80°) testifying to the folding that affected Koras rocks. The conglomerates are heterogeneous and compositionally reflect the nearest possible source e.g., on Ezelfontein Noord where conglomerates are exposed adjacent to granite-gneiss, the pebbles are almost entirely of granite-gneiss. At beacon 78, just west of an exposure of the Grootdrink quartzite, the pebbles and angular fragments making up this conglomerate are composed mainly of quartzite.

Basal sedimentary deposits are developed at the contact of pre-Koras rocks and Koras lavas and are often obscured and hidden by younger talus fans. However, a careful search of stream cuttings in the younger talus fans of the quartzite ridges that border the Koras Group has revealed that exposures of conglomerate mark an unconformable sedimentary contact for the base of the Koras where previously a fault had been inferred e.g., the south-western margin of the Southern Domain. In general, these heterogeneous sedimentary rocks which vary in thickness and extent can be interpreted as ancient talus fans and weathered rubble that fill depressions and hollows on the pre-Koras landscape.

#### 4.2.1B. Central Domain

The basal conglomerate exposed on Koras (2A: H-14) consists mainly of poorly sorted quartzite fragments (up to several tens of cms in diameter) that are angular to rounded. The conglomerate overlies phyllite and schist of the Wilgenhoutsdrif Group and is overlain by khaki-coloured shale and micaceous sandstone which is in turn overlain by greenish-grey basic lava of the Lambrechtsdrif Member. Moen (1980, p. 224) considered the possibility that these conglomerates belonged in the Christiana Formation but he included them in his Ezelfontein Formation. Du Toit

(1965, p. 39) regarded this exposure and those at beacon 78 in the Southern Domain "as troughs in the soft Wilgenhoutsdrif Series (now Group) which must have formed the floor of the Koras basin".

Two other rather poor exposures of conglomerate occur to the north of the Kalkpunt basin (2A: H-7 and P-1, P-2). The rubble consists mainly of poorly sorted quartzite. No Koras pebbles could be seen and on this basis the exposures are interpreted here as part of the Basal Sedimentary Member.

#### 4.2.1C. Southern Domain

The Southern Domain contains a slightly more varied collection of basal sedimentary rocks, the best known being those at Ezelfontein Noord (2B: S-28, S-29). These two exposures are of conglomerate which is composed of pebbles and large angular blocks (less than 1cm to tens of cms in diameter) of abundant granite gneiss and subordinate quartzite and schist. The fragments are rounded to irregular in shape and no bedding is visible. In the Ezelfonteinrivier the rocks are sheared and fractured. Minor amounts of aphanitic greenish-grey basic lava occur within the conglomerates at the dome-shaped northernmost exposure and appear to be interbedded with the conglomerate, indicating that eruption of Lambrechtsdrif lava commenced during deposition. Du Toit (1965) interpreted these rocks as sedimentary layers interbedded within his Basaltic-andesite Group and Lower Quartz-porphry Group.

On Buchuberg Settlement sporadic exposures of pebble-bearing quartzite occur along the contact between the Lambrechtsdrif Member and the underlying Wilgenhoutsdrif Group (2B: U-31, U-32). This contact has previously been interpreted as a major fault (Du Toit, 1965; Grobler et al., 1977; Moen, 1980) but is believed to be an unconformable sedimentary contact by the present author (see map 2B). Minor faulting may have occurred as vein quartz is present at one locality. These greyish-green to light brown, fine-grained, poorly-bedded quartzites are well-indurated and at places are fractured and traversed by numerous white quartz veins. Near the Kalkwerfslot they are interbedded with Lambrechtsdrif lavas. In a thin section (ES-18), the quartzite is composed mainly of quartz (90%) with minor amounts of feldspar and epidote as well as deformed chlorite and muscovite flakes. Quartz grains have undulose extinction and range in size from 0,1 mm to 0,4mm with an average size of 0,2 mm. Quartz grain boundaries are often sutured with a blastosammitic texture and occasional mortar structure. These textures indicate that the rock has

undergone a high degree of induration, possibly at low grades of metamorphism.

Numerous exposures of conglomerate and sandstone occur along the central part of the western flank of the Koras Group (2B: R-32, R-33, S-34, T-37). They are reddish-brown to khaki-coloured deposits and the pebbles in the conglomerates are well-rounded and composed of quartzite and schist. In one instance (T-37) an oligomictic conglomerate of schist fragments with the schistosity of the fragments orientated in all directions was observed. The presence of these rocks supports the view that this contact of the Koras Group is not a fault (Du Toit, 1965; Grobler et al., 1977) but rather an unconformable sedimentary contact. It has been suggested (J. Marsh, pers. comm.) that these conglomerates might be clastic wedges along faults that were active during Koras times and have subsequently been rejuvenated.

In the extreme south (2B;U-41, 42, 43) low hills and mounds of predominantly white to purplish quartzite rubble as well as quartz-sericite schist are regarded by Moen (1980, p. 227) as conglomerates of the Koras Group (Ezelfontein Formation). The fragments are generally angular, sometimes rounded and from one cm to several tens of cms in diameter. No pebbles or fragments of Koras rocks were seen amongst the rubble pile and therefore the material could represent conglomerates of the Basal Sedimentary Member, or possibly younger talus fan material.

A quartzite boulder conglomerate builds the hill on which beacon 78 stands (2B: V-30). Familiar darkly-weathered exposures of aphanitic greenish-grey basic lava occur below the hill on its western side and are outliers of the Lambrechtsdrif Member. The conglomerate is interpreted as a deposit of the Basal Sedimentary Member underlying the basic lava (see map 2B, section B1-B2). This is in agreement with Du Toit (1965, p. 39) and Moen (pers. comm.), who regards the rock as a talus fan deposit of Koras age.

A rather unusual outlier of darkly-weathering immature conglomerate is exposed next to the Orange river (2B: V-27). It consists of fragments of Wilgenhoutsdrif Group rocks as well as vein quartz, quartzite and gneiss, that are closely packed and completely variable in size (less than 5cm up to several tens of cm). Rogers and Du Toit (1910, p. 53) interpreted these rocks as volcanic breccias and gritty tuffs accompanying lavas of the Wilgenhoutsdrif Group although they considered the possibility that

the rocks were part of the Koras Group because of their undeformed state. Du Toit (1965, p. 23) interpreted the exposure as a volcanic neck of the Koras Group. The author is in agreement with Moen (1980, p. 227) who indicates that the rocks represent an outlier of Koras conglomerate. However, it is interpreted here as part of the Basal Sedimentary Member and not the Ezelfontein Member on the basis that no pebbles of Koras rocks could be detected in the conglomerate which overlies the Wilgenhoutsdrif Group.

#### 4.2.2. Lambrechtsdrif Member

##### 4.2.2A. Distribution

Lambrechtsdrif lavas outcrop in the Southern and Central Domains and Moen (in prep.) reports correlatives of these lavas in the Northern Domain. In the Central Domain there are exposures around Karos and near Witkop on Karos Nedersetting while the largest mass is in the Rooidraai-Lambrechtsdrif-Leeudraai area. An outlier underlies the village of Grootdrink and another is located on the opposite (east) bank of the Orange river on the farm Grootdrink.

In the Southern Domain on the west side of the Leeudraai-Kalkwerfputs fault, Lambrechtsdrif lavas outcrop in the north-eastern part of Ezelfontein Noord. This Member appears to thin out and is not developed further south. However, on the east side of the north-trending Leeudraai-Kalkwerfputs fault there is a large sliver-shaped mass of Lambrechtsdrif lava whose western margin adjoins the fault. The northern part of the eastern margin of this sliver overlies sporadically exposed basal sedimentary quartzites and the Wilgenhoutsdrif Group unconformably. The southern part of the eastern margin is faulted against the Groblershoop Formation.

##### 4.2.2B. Outliers

The position in the geological succession of the outliers described below cannot be determined from structural considerations alone and they are therefore interpreted as part of the Lambrechtsdrif Member on the basis of lithology. Further proof will have to be obtained from geochemical studies. The large mass of basic lava underlying Grootdrink village is poorly exposed and the rocks are badly fractured and weathered although fresh samples can be obtained from road cuttings. This outlier,

which was first examined by Du Toit (1965, p. 52), overlies the Wilgenhoutsdrif Group and has been carefully mapped by Moen (1980).

The outlier of aphanitic basic lava on the east bank of the Orange River opposite Grootdrink village builds two or three low, rounded hills that are partly covered by sand. In the east the outlier gives way to a calcrete-cemented gravel while the western and southern extremities are completely covered by sand dunes. To the north-east, however, the outlier is bounded by an area underlain by sand and soil with pebbles of banded ironstone and quartzite. In this area the base of the outlier is exposed in a stream that flows westwards into the Orange River. Basic lava can be seen exposed next to an immature polymictic conglomerate which overlies schistose quartzites and porphyries of the Wilgenhoutsdrif Group. The conglomerate consists of pebbles of schist, quartz porphyry, granite, quartzite and vein quartz and is slightly green due to epidotization. Near the eastern margin of the outlier a metre-wide exposure of khaki-coloured sandstone was found in a stream. These sandstones dip westwards at  $47^{\circ}$ , thus apparently underlying the outlier. The conglomerates and sandstones as well as the aphanitic appearance of the basic rocks testify to the probable extrusive character of the outcrop which has previously been interpreted as a large intrusive (Rogers, 1908, p. 53). Other outliers occur just south-west of beacon 78 (2B: V-30) and overlie basal sedimentary conglomerates and the Wilgenhoutsdrif Group.

#### 4.2.2C. General Lithology

Throughout most of the area of its outcrop the volcanic rocks of the Lambrechtsdrif Member have a uniform, aphanitic, greenish-grey appearance on fresh surfaces, while weathered surfaces are smooth and dark brown to shiny black. In places the rocks have sparsely distributed quartz and calcite amygdales which are white and circular in cross section and range in size from 1mm to 10mm. In large exposures and road cuttings joints and irregular fractures can be observed in these rocks. Thin veins of quartz and calcite fill the fractures. Exposures throughout the outcrop area are fairly good and fresh samples can be obtained quite easily.

In some places fine-grained, doleritic rocks were found and it could not be determined whether these dolerites were :-

- 1) comagmatic intrusives;
- 2) the more slowly cooled parts of thicker lava flows; or
- 3) younger intrusives.

In the area west of Wilgenhoutsdrif (2A: S-22) the Lambrechtsdrif Member is distinctly doleritic and is intimately associated with the quartzites (Wilgenhoutsdrif Group). This may well be an irregular dyke-like intrusive. The exposures of dolerite are irregularly interspersed with those of quartzite and schist and although no exposed contacts could be found, the exposures of dolerite and quartzite occur sufficiently close to give the impression that the dolerite has intruded the quartzite and schist.

Volcanic breccias and tuffs (Figs. 4.2.1, 4.2.2) are sporadically exposed throughout the outcrop area e.g., good exposures of volcanic breccia are present in the streambed 300 m downstream from the Ezelfontein Suid farmhouse. The breccias are usually made up of angular fragments although some rounded and irregular fragments that could be volcanic bombs are also present. Much of the material in the breccias probably represents the broken up parts of lava flows, possibly as a result of autobrecciation.

Brecciated andesite (cemented with calcite) and dolerite are exposed in places along the contact of the Lambrechtsdrif Member on the Wilgenhoutsdrif Group in the area south of Karos village. Quartz veins in the phyllites are common along this contact. Although there is no major fault along the contact zone, fault movement along minor faults has probably occurred in places as indicated on map 1.

In the field very little bedding or other features representing bedding were found within the member. In the area west of Karos Village some thin sandstones occur interbedded with the lavas, providing some evidence of the orientation of bedding. However, over most of its outcrop the orientation of this member must be interpolated, if possible, from the overlying and underlying sequences, but this has been done with care because lava flows are not always amenable to simple stratigraphic interpretation.

Numerous lineaments are visible on aerial photographs of the Lambrechtsdrif Member at Rooidraai and Ezelfontein Suid. These lineaments trend north-south and are about 50-75 m apart. Although the exact origin of the lineaments could not be determined in the field, the lineaments represent low-lying easily weathered zones and these could be caused by weaker rocks within the lavas such as volcanic breccias or they may be structural features such as faults or fracture zones.



Figure 4.2.1 Volcanic bombs in medium- to coarse-grained tuffaceous breccia of the Lambrechtsdrif Member (Locality: map 2B : U-35)

The failure to determine volcanic bedding and related features such as the thickness and extent of the lava flows and the relative spatial occurrence of breccias means that very little can be said of the volcanic environment in which the basaltic rocks of the Lambrechtsdrif Member were formed. However, it seems that the volcanic activity probably consisted mainly of relatively quietly extruded, possibly thick, basaltic to andesitic, undifferentiated lava flows that are represented by the greenish-grey, aphanitic, hyalopilitic and generally non-amygdaloidal rocks that can be seen today. This interpretation is also supported by the apparently minor proportions of breccias and tuffs within the member.

In the Karos area thin layers (up to 1 metre) of dolomite are sporadically exposed along the contact of the basic lava (Lambrechtsdrif Member) on Wilgenhoutsdrif phyllite and greenschist (1: A14-KK, A12-JJ). A discontinuous band of dolomite was also located within the lavas (1: A7-EE). Although these carbonate rocks are associated with the Lambrechtsdrif Member at Karos no exposures at other localities within the Karos Group are known.

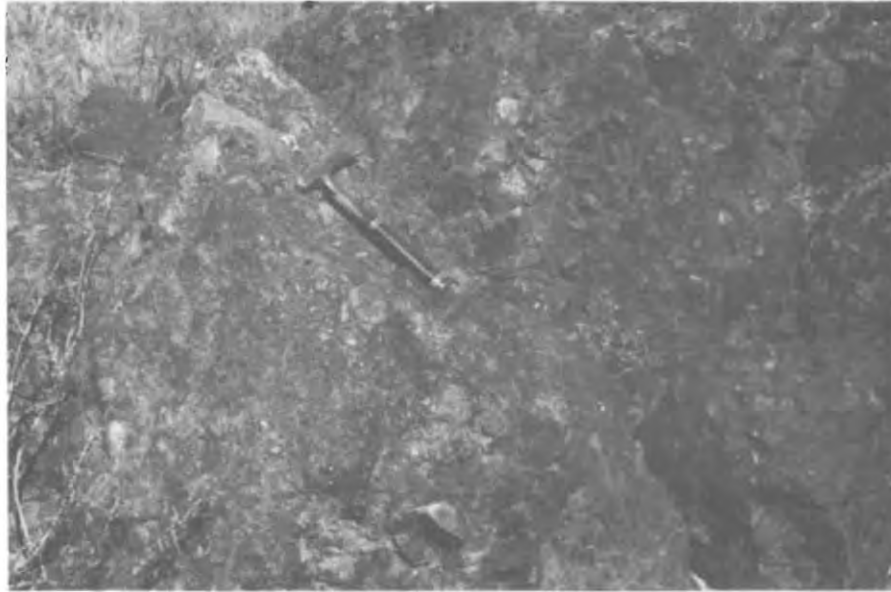


Figure 4.2.2. Volcanic breccia of the Lambrechtsdrif Member (Locality: VB on map 1 : A15 : KK)



0,25mm

Figure 4.2.3 Typical hyalopilitic texture of the basic lavas of the Lambrechtsdrif Member. This sample (CS-7) is composed of acicular, hollow plagioclase laths set in a brown glass (crossed nicols).

#### 4.2.2D. Petrography

The greenish-grey aphanitic lavas that make up the greater part of the Lambrechtsdrif Member are hypocrySTALLINE (40-50% devitrified glass) to holocrySTALLINE (no clearly visible glass). An increase in grain size accompanies this range in crystallinity. Hyalopilitic texture (Fig. 4.2.3) is the common fabric of these rocks with lesser amounts of sparsely porphyritic types, the phenocrysts being plagioclase and pyroxene (usually augite but orthopyroxene has also been identified) set in an intersertal or intergranular groundmass.

Plagioclase occurs as twinned, often saussuritized laths and acicular crystals that are frequently hollow (Fig. 4.2.3) and in the hyalopilitic rocks have a length of about 1/2mm or less. An attempt was made to determine the composition of the plagioclase using the microlite method (Heinrich, 1965, p. 362). However, this could not be done very successfully due to the hollow, often altered nature of the plagioclase laths, although the composition of some laths is in the calcic andesine - sodic labradorite range. Augite is typically finely granular (less than 0,3mm in diameter) or acicular (1/2mm in length) in the hyalopilitic rocks while the less common, slightly larger, subhedral grains are subophitic to ophitic. Other mafic minerals include rare orthopyroxene while a chloritized microphenocryst (probably a pyroxene) is occasionally present and in hand specimen appears as small (1/2mm) black specks. The proportion of the light to dark brown, weakly birefringent glass is variable (0-50%) and the weak birefringence is probably the result of devitrification although some alteration to epidote and chlorite has also occurred. In the glassy rocks opaque minerals are absent or are present as margarites and scapolites in the glass. Opaque euhedra are also present in some rocks. Minor amounts of microcrystalline quartz are commonly present in the groundmass and indicate that the rocks are slightly oversaturated with silica.

In conclusion, plagioclase is the dominant mineral with subequal to lesser amounts of augite and varying proportions of glass. This mineralogy, together with the texture and rock colour suggest that the lavas are petrographically best described as andesites or possibly basaltic andesites. The textures of the rocks indicate that the lavas cooled rapidly on extrusion with little or no pre-extrusive (porphyritic stage) crystallization.

### 4.2.3. Karos Member

#### 4.2.3A. Distribution

The conglomerates, sandstones and shales that make up this member are exposed in the Central Domain in the area around Karos (see Map 1) and on Karos Nedersetting in the area east of Lambrechtsdrif (see Map 2A). These sedimentary rocks were previously regarded as part of the Lower and Middle Sedimentary Groups (Du Toit, 1965) i.e., the Christiana and Ezelfontein Formations (Grobler et al., 1977). Moen (1980, p. 229) noted that certain basalts were present below the sandstones and conglomerates at Karos and regarded all of these rocks as part of the Ezelfontein Formation which he said contained basic lava at its base. Moen (op. cit., p. 224) indicated that the Christiana Formation was probably not developed in this area.

A detailed examination of the geology around Karos (Map 1) shows that the conglomerates and sandstones are all part of one unit, the newly proposed Karos Member. In contrast with the previous work, the Karos Member overlies basic lava (Lambrechtsdrif Member) and underlies porphyritic volcanics (Swartkopsleegte Member) in this area. This is in agreement with Rogers and Du Toit (1910, p. 74) who indicate on their map that the basic lava underlies the porphyry. Similarly, in the area just east of Lambrechtsdrif the sandstones and shales (Karos Member) overlie the basic lava (Lambrechtsdrif Member) and underlie the quartz-feldspar porphyries (Swartkopsleegte Member).

#### 4.2.3B. Conglomerates

The poorly bedded, polymictic conglomerates are localized to the Karos village area (map 1) and they do not appear to have any distinct relationship to the sandstones and shales e.g., always underlying or overlying them. They are interspersed with the sandstones and shales at irregular intervals and do not grade into the sandstones in any special way. The exposures of conglomerate often have a dark appearance due to desert varnish. They are composed of pebbles (usually 2-20 cms in diameter) of quartzite, granite, milky vein quartz, schist and gneiss set in a sandy matrix. As noted by Moen (1980, p. 229) pebbles of undeformed basic lava that are almost certainly derived from the Lambrechtsdrif Member can be seen in the conglomerates at some localities.

Karos Member conglomerate is exposed in the main (tarred) road cutting opposite the Karos shops. On the south side of the road the conglomerates can be seen overlying shales and sandstones and these overlie some weathered pebbles of undeformed basic lava. In addition there are sandstone beds and a small fault in the conglomerate. These sandstone layers are similar to those in the Kalkpunt conglomerates but are not a common feature of the Karos Member conglomerates.

#### 4.2.3C. Sandstones and Shales

The greenish-brown and khaki-coloured sandstones, siltstones and shales are commonly fractured and have a weak bedding cleavage defined by fine-grained micaceous minerals. The sandstones are usually distinctly micaceous with pink to grey feldspars, dark mafic minerals and rock fragments visible in hand specimen. Bedding is defined by alternating fine and coarse sand layers or by gravel and grit layers within the sandstones. Occasionally, alternating sandstone and shale layers can be seen.

The sandstones and shales in the area east of Lambrechtsdrif are only poorly exposed in river and stream beds. These exposures are commonly associated with calcrete which occurs as thin layers and irregular deposits on the bedding planes of the sandstones and shales. One exposure of the Karos Member/Lambrechtsdrif Member contact showed shale overlying weathered and fractured basic lava and dipping to the west at  $80^{\circ}$  (2A: Q-21).

The sandstones are composed of quartz grains, feldspar grains (microcline, perthite, plagioclase), muscovite flakes and metamorphic and volcanic rock fragments. This terrigenous material is set in a very fine-grained matrix. The grains are poorly sorted and rounded with a variable size (up to 1,5mm in diameter), and are therefore immature rocks that can be classified compositionally as lithic greywackes (Dott, 1964).

The exposures of pebble-bearing sandstone on Karos Nedersetting (2A: P-21) are of well-indurated rocks that could easily be called quartzites. They are composed of quartz, feldspar and rock fragments and the matrix has recrystallized to epidote, chlorite and clinozoisite (KA-700, KA-711). These poorly bedded rocks were mapped as a separate lithological unit during earlier investigations (Sanderson, 1979, 1980). However, due to their position between the Lambrechtsdrif and Swartkopsleegte Members they



Figure 4.2.4. Streambank exposure of interbedded sandstone and shale of the Karos Member. View is approximately down-dip. (Locality : map 2A : P-22)

can be interpreted as part of the Karos Member. Their high degree of induration and recrystallized matrix may be a result of contact metamorphism by the overlying quartz-feldspar porphyries.

A small exposure of sandstone occurs in the Boomrivier near the Rooidraai farmhouse (2A: Q-23). The sandstone is overlain by a Quaternary conglomerate that is cemented by calcrete. Calcrete is also present along the bedding planes of the sandstone as fist-sized lumps that transgress the bedding. The sandstone has a greenish to khaki-coloured appearance and is slightly micaceous, the flakes of muscovite being visible as pinpricks to 1mm-sized shiny specks.

#### 4.2.3D. Depositional Environment

It is very difficult to reconstruct the basin of the Karos Member mainly because of the folding and later faulting that have affected these rocks. The conglomerates and sandstones vary in thickness and extent and in places the Swartkopsleegte porphyry oversteps them and directly overlies the Lambrechtsdrif Member. The conglomerates and lithic greywackes are

immature rocks that were probably deposited as poorly developed alluvial fans in a rugged post-eruptive volcanic region, possibly also during unstable tectonic conditions. The presence of shales indicates that quiet conditions of sedimentation also prevailed at some times and places during the deposition. The khaki-brown to greenish appearance of the Karos Member rocks contrasts markedly with the red beds in the Kalkpunt Formation. This is interpreted to indicate rapid burial under reducing conditions. The composition of the conglomerates and sandstones indicates that the source area consisted of uplifted areas of basement metamorphic rocks, although some volcanic material was derived from the underlying Lambrechtsdrif Member.

#### 4.2.4. Swartkopsleegte Member (Lower Quartz-Feldspar Porphyry)

##### 4.2.4A. Distribution

The fine-grained quartz-feldspar porphyries of the Swartkopsleegte Member are exposed in the Southern Domain and the southern part of the Central Domain. According to G. Moen (pers. comm.), they are absent from the Northern Domain. The quartz-feldspar porphyries to the north of the Upington-Olifantshoek road are interpreted by Moen (1980, p. 225) as part of his Avondale Formation. However the porphyries in this area are interpreted by the present author as part of the Leeudraai Formation on the basis of lithology (section 4.3.3A).

A small outlier of quartz-feldspar porphyry on Buchuberg Settlement (2B: T-28) is regarded by G. Moen (pers. comm.) as part of the Koras Group. The outlier is interpreted here as part of the Swartkopsleegte Member on the basis of lithology, although the porphyry here is slightly coarser grained than the more typical Swartkopsleegte porphyries. Fine-grained, dark-brown and light-brown sandstones up to several metres thick occur at the base of the volcanics in this outlier which overlies Wilgenhoutsdrif Group schists.

##### 4.2.4B. Lithology and Petrography

The Swartkopsleegte Member consists mainly of quartz-feldspar porphyry which has light reddish brown to shiny black weathered surfaces that exhibit a pockmarked or pitted appearance due to the removal of quartz and feldspar crystals. On fresh surfaces, grey, glassy quartz (up to 2mm), pink to pale-grey feldspar (0,5 - 3mm) and sparse mafic minerals (up to

2mm) are set in an aphanitic groundmass that varies in colour from reddish-brown to greenish-grey. (In the field this change in groundmass colour was found to be a gradational feature and was not mapped.) Occasional large rounded feldspars, quartz and quartzite fragments (up to 4cm) are present.

The equidimensional quartz crystals are rounded and corroded with embayments and holes, are often fractured and have trails of dusty inclusions. Mantles of spherulitic quartz surround the crystals of quartz and are in optical continuity with them. The quartz grain boundaries are well-defined to fuzzy and have been described by Du Toit (1965, p. 42) as "lacy reaction rims". Quartz has undulose extinction indicating some crystal strain and at extinction positions, larger crystals exhibit lamellae that are interpreted as strain lamellae.

Feldspar generally occurs as rounded and corroded crystals with embayments and inclusions of apatite. They are equidimensional to tabular in outline and a few exhibit subhedral to euhedral shapes. In plane-polarized light, the feldspars are translucent and light-brown due to saussuritization which makes identification difficult and is often so severe that only the crystal outline remains. Simple, multiple and pericline-twinning is present in the feldspars which consist mainly of alkali feldspar and oligoclase.

Mafic minerals are present in minor proportions and are usually completely altered to chlorite, epidote and opaque minerals. A partially chloritized augite is present in one of the analysed rocks (CS-13). Opaque minerals vary from tiny euhedra (less than 0,1mm) up to larger (1mm), partly corroded, grains that are set in the groundmass or associated with the mafic minerals. A common associate with the opaques is a bright reddish-orange alteration product believed to be a late-stage Ti-biotite (I.M. Reynolds, pers. comm.). The Ti-biotite is also present as tiny (less than 0,05mm) diamond-shaped to acicular crystals in the groundmass. Small (less than 0,5mm) euhedra of apatite, sphene and rare zircon are associated with opaques in the groundmass and are present as inclusions in feldspar, opaque minerals and the chloritized mafic minerals.

The minerals described above occur as discrete phases set in the groundmass and as parts of polymineralic aggregates that resemble rock fragments but could, in some cases, represent glomeroporphyritic arrangements of phenocrysts. The presence of quartzite particles and the

appearance of some of the polymineralic fragments indicate that at least part of the crystalline material in these porphyries is xenolithic in origin.

The groundmass in the porphyries consists of patches of microcrystalline quartz and feldspar as well as slightly darker areas of devitrified glass. The microcrystalline patches consist of a mosaic of quartz (up to 1mm) containing numerous microlites of feldspar. As noted by Grobler et al. (1977) the local green colour of the groundmass is caused by the presence of chlorite and epidote alteration products.

The proportions of crystals to groundmass is variable but the groundmass commonly accounts for 50-75% of the rock. Modal proportions are difficult to determine accurately due to the microcrystalline groundmass and the alteration of the feldspars. Proportions of quartz, alkali feldspar and plagioclase are estimated to be roughly subequal with mafic phases making up 10-15 % of the rocks. This estimate is in agreement with that of Grobler et al. (1977) although they indicate that plagioclase is in greater abundance than alkali feldspar but also that there are variations in modal proportions within the member. The porphyries can be classified mineralogically as rhyolites to dacites (Streckeisen, 1979).

The porphyritic texture of these oversaturated lavas can be interpreted in terms of a two stage cooling history. During the first stage, quartz, feldspar and mafic minerals crystallized at depth and this stage was terminated by partial resorption of the phenocrysts during the extrusive (rapid chilling) stage. The presence of xenoliths and xenocrysts in the porphyries can be interpreted in several ways as follows:-

- 1) Xenocrystal material may be relict, unmelted phases that are derived from the site of production of the magma. This possibility would suggest that the magmas are derived from a crustal granitic source.
- 2) The xenoliths and xenocrysts may be derived from the wall rocks during the passage of the magma from its site of production to its site of extrusion.
- 3) Xenolithic material may represent surface debris that was incorporated into the lavas during extrusion.

The retrograde chlorite and epidote alteration may have occurred at the time of extrusion by the prevailing heat and hydrous fluids in the volcanic environment or it could represent the onset of low grades of metamorphism during later burial.

The Swartkopsleegte porphyry is amygdaloidal in places and in the Karos area (1: A16-KK, A14-HH), a dark amygdaloidal feldspar porphyry is present at the base of the member. It consists of euhedral crystals of pink feldspar with green and white amygdales that are set in a dark-grey aphanitic groundmass. A similar quartz free, more mafic porphyry is present along the basal contact to the west of Karos (1: A18-JJ).

Minor amounts of sandstone are interbedded with the porphyries. In the Karos area (map 1) there are some poorly bedded pebbly sandstones which consist of quartzite and granite pebbles set in a quartz and feldspar matrix. At Ezelfontein Suid (2B: R-28) a thin band of sandstone, dipping at  $40^{\circ}$  to the south-west, marks the contact of porphyry on the underlying basic lava.

As with the Lambrechtsdrif Member there is very little data that could aid in reconstructing the volcanic environment in which the Swartkopsleegte Member was formed. The quartz-feldspar porphyries are interpreted to represent mainly lava flows which were interbedded with minor proportions of clastic sediments.

#### 4.2.4C. Structural Banding : Igneous Flow Structure or Incipient Tectonic Foliation?

A form of "structural banding" is a common feature throughout the Swartkopsleegte Member and is also manifest as sets of closely spaced parallel fractures (Figs. 4.2.5 to 4.2.9). On weathered surfaces the banding appears as light and dark weathered parallel lines or bands with a regular and planar habit (Fig.4.2.5) or irregular habit (Fig.4.2.9). The banding is accentuated by a concentration of desert varnish in the grooves on the weathered rock surfaces while the desert varnish is not as abundant on the ridges between grooves. The regular planar banding varies in width from a few millimetres to a few centimetres and there appears to be a complete variation from the regular planar type to the irregular type. In places the structural banding or parallel fractures are weakly curved giving the appearance that they have been weakly folded. The orientation of the regular planar type is entirely variable from sub-horizontal to sub-vertical and there appears to be no obvious trend in the orientation of the banding throughout the outcrop area.

On fresh surfaces the banding is manifest as light and dark layers and the dark layers can be traced to the grooves in the weathered surfaces. In thin section the slightly darker zones or bands have numerous linear to irregular or zigzagged fractures and are altered when compared to the relatively fresh lighter zones. Some movement along these microfractures and microfaults has taken place as indicated by the displaced parts of halved crystals. On an even finer scale, the fractures can be seen to be clearly defined cracks or are fuzzy microzones marked by opaques and chlorite. It seems that the darker bands which produce grooves on weathered surfaces are therefore more easily weathered planar weaknesses within the rocks.

The structural banding in the Swartkopsleegte Member has previously been regarded as flow structure (Du Toit, 1965, p. 42), flow bedding (Grobler et. al., 1977, p. 169) or flow banding (Moen, 1980, p. 225). During a previous investigation (Sanderson, 1979) the textural banding was also interpreted as a volcanic flow structure. However, the thin section studies of the regular planar banding which reveal microfractures, microfaults and retrograde alteration along parallel planar zones at regular intervals indicate that the bands are structurally produced features. It is suggested here that the regular planar banding is an incipient tectonic foliation or form of fracture cleavage that was produced during folding of the Koras Group (see chapter 5). The more irregular structures may also have been produced by this mechanism although some of them, at least, appear to be primary volcanic flow structures (see Fig. 4.2.9).



Figure 4.2.5. Subhorizontal structural banding on a weathered rock surface of fine-grained quartz-feldspar porphyry (Swartkopsleegte Mbr) which is also manifest as a set of parallel fractures (Locality: map 2A : M-18).



Figure 4.2.6. Structural banding manifest as a set of inclined closely spaced parallel fractures in fine-grained Q-F. porphyry of the Swartkopsleegte Mbr. (Locality: map 2A: L-16)

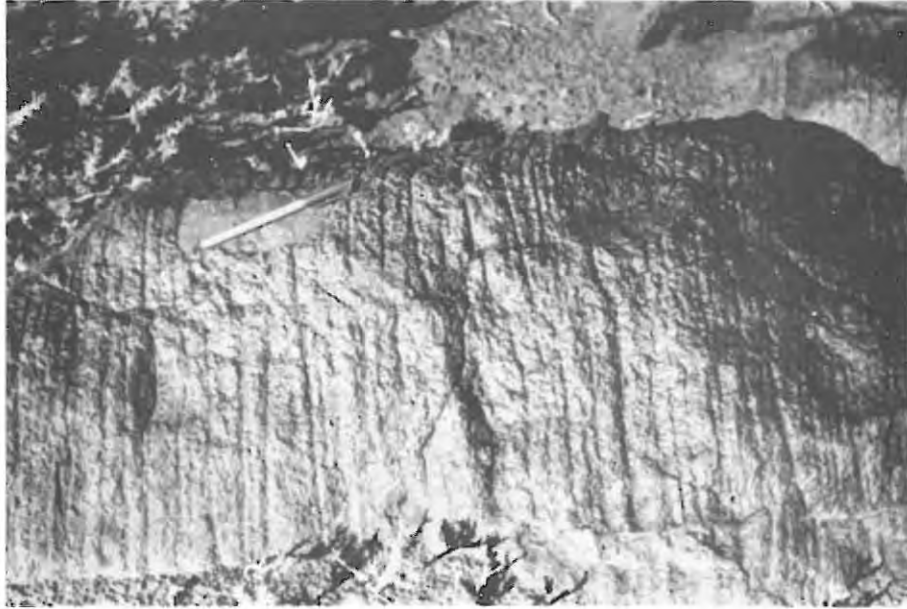


Figure 4.2.7. Weathered rock surface showing subvertical structural banding of fine-grained quartz-feldspar porphyry of the Swartkopsleegte Mbr. (Locality : map 2A : M-17)

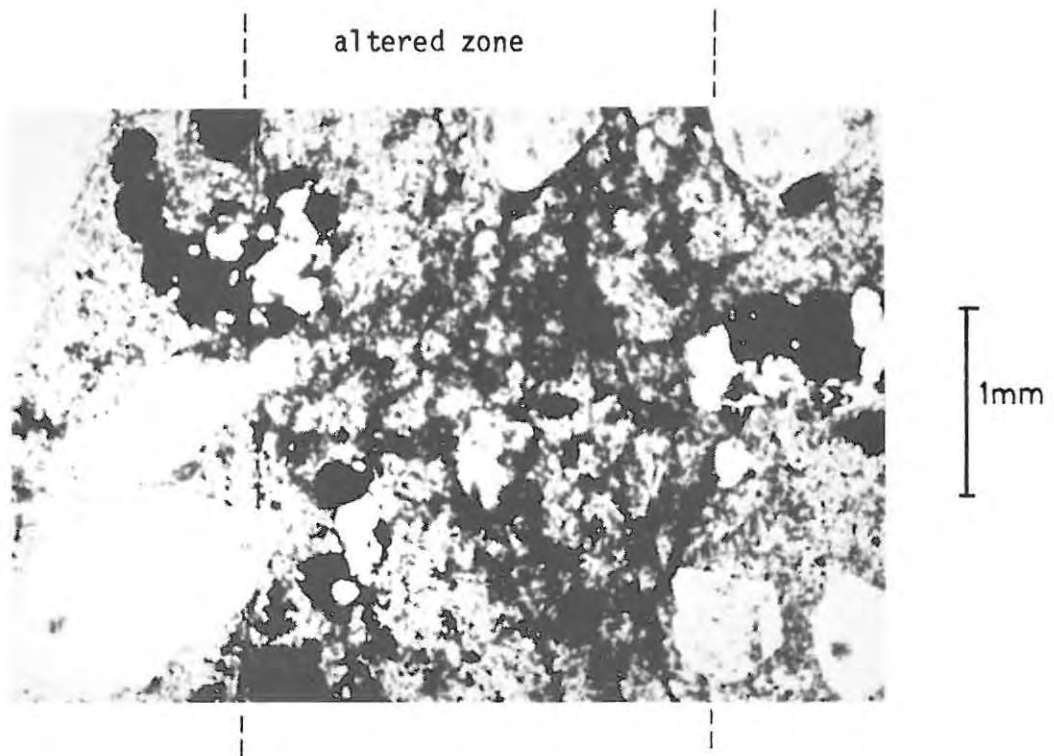
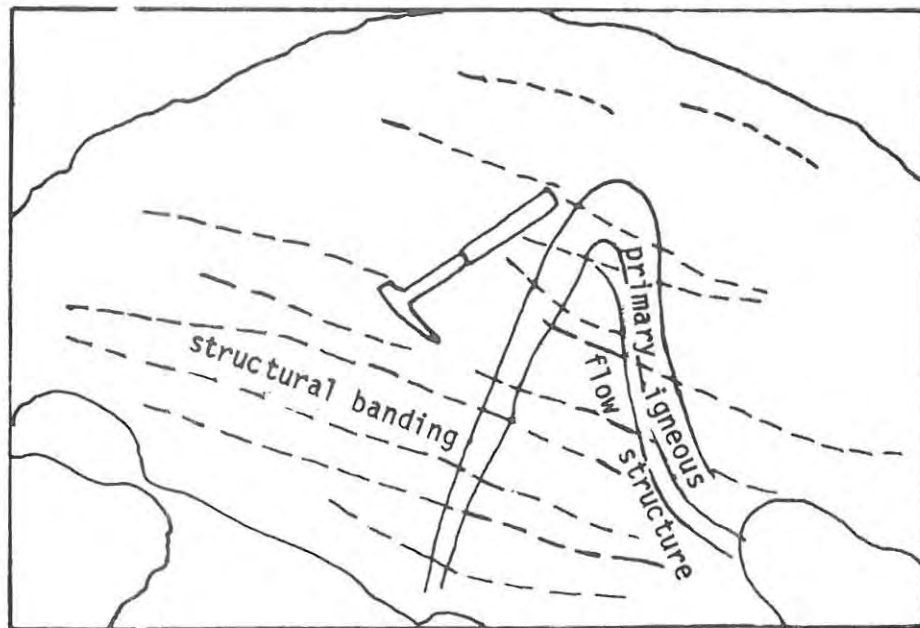


Figure 4.2.8. Photomicrograph of altered zone or structural band and a microfault in quartz-feldspar porphyry (Swartkopsleegte Mbr, sample KA-799, plane-polarized light).



Fig 4.2.9. Primary igneous flow structure cut by structural banding interpreted as incipient tectonic foliation produced during Koras folding (Locality : map 2A : M-17).

Interpretation of Figure 4.2.9.:



### 4.3. Leeudraai Formation

#### 4.3.1. Ezelfontein Member

##### 4.3.1A. Distribution

The Ezelfontein Member outcrops in the Southern Domain on Ezelfontein Noord, Ezelfontein Suid and Kalkwerfputs (Map 2B). The conglomerates and sandstones that make up this member are generally poorly exposed. Many of the exposures are surrounded by pebbles, cobbles and other rubble that are residual after weathering and removal of the matrix of the conglomerate. The moderate bedding dips ( $30^{\circ}$ - $55^{\circ}$ ) in this member define open fold structures which were mapped by Du Toit (1965, p. 50) who explained:

"Deformation of this group, like that for the two underlying groups took place by forces acting from the north-east, buckling the rocks into nearly NW-SE trending folds."

Du Toit (1965, Plate 1, Fig. 9) inferred a southeast-plunging syncline on Ezelfontein Suid and the data obtained in this study are in agreement with this structure (see Map 3).

##### 4.3.1B. Conglomerates and Sandstones

The massive and poorly bedded conglomerates, the pebbly sandstones and the sandstones are generally similar to those of the Karos Member. However, the distinctive feature of the Ezelfontein conglomerate is the ubiquitous presence of pebbles of fine-grained quartz-feldspar porphyry derived from the Swartkopsleegte Member. These pebbles are often in such abundance that the conglomerate is oligomictic. Other pebble types include quartzite and milky vein quartz and less commonly, granite, gneiss and schist. In a few localities quartzite is the dominant pebble type. The pebbles are subangular to well-rounded and range in size from less than 1cm to more than 30cm in diameter. The matrix of the conglomerates usually consists of a fine-grained, light-brown to reddish-brown, arkosic sandstone. However, exposures of oligomictic quartz-feldspar porphyry conglomerate are set in a dark, sandy matrix that looks very similar to the porphyry pebbles. In some areas, sandstone layers similar to those in the Kalkpunt conglomerate are interbedded with the conglomerate. This sedimentary feature is more common here than in the older Karos Member conglomerates, and may indicate a more developed alluvial fan setting.

The sandstones are well-indurated and some of the finer-grained types have a weak bedding cleavage defined by fine-grained muscovite. The sandstones are composed of quartz, feldspar, metamorphic rock fragments, muscovite, chlorite and epidote set in an aphanitic matrix. These clastic terrigenous rocks are poorly sorted and grains are poorly rounded. They are therefore mineralogically and texturally immature and can be classified as lithic greywackes (Dott, 1964).

Sporadic exposures of basaltic lava occur within the Ezelfontein Member at Ezelfontein Suid and suggest that the lavas and sedimentary rocks are interbedded. Thus at Ezelfontein Suid there is probably a gradual transition from the sedimentary Ezelfontein Member to the Rouxville Basalt Member indicating that sedimentation and volcanism were contemporaneous during the transition.

#### 4.3.1C. Problematical Exposure of Quartz-Feldspar Porphyry at Ezelfontein Suid (Map 2B: S-32)

The exposure consists of boulders of fine-grained quartz-feldspar porphyry that can be equated with the Swartkopsleegte porphyries on the basis of lithology. The origin of this patch of porphyry which appears to be interbedded with the basic lava and conglomerates is obscure and could not be determined in the field due to the poor exposures. Several explanations are possible:-

- 1) The succession, porphyry-conglomerate-basic lava is duplicated by east-west faulting as suggested by Du Toit (1965).
- 2) A late lava flow of Swartkopsleegte porphyry was erupted and interbedded with the conglomerates and basic lava.
- 3) The porphyry is part of the Swartkop Member which does occur interbedded with basic lava at Leeudraai farm.
- 4) The exposure represents an intrusive porphyry.
- 5) The exposure represents an oligomictic boulder conglomerate of porphyry.

The author is of the opinion that explanation 5) is correct because oligomictic porphyry conglomerates are not uncommon in the Ezelfontein Formation and such a conglomerate is exposed along strike in the river bed to the west of the problematical exposure.

#### 4.3.1D. Depositional Environment

As for the Karos Member, the possible extent of the Ezelfontein repository cannot be determined because of the folding and faulting that has affected these rocks and has resulted in their limited present day distribution. However an environment similar to that for the Karos Member is envisaged for the Ezelfontein Member. The Ezelfontein conglomerates and sandstones were probably deposited as talus and alluvial fan deposits on a rugged volcanic landscape during continuing tectonic instability. A major contribution to the material in the conglomerates was made by the Swartkopsleegte Quartz Porphyry Member while a part of the source area almost certainly included the metamorphic basement sequences.

#### 4.3.2. Rouxville Member

##### 4.3.2A. Distribution

The Rouxville Member is the most widespread of all the members in the Koras Group. It has a significant outcrop area throughout the Central and Southern Domains and according to Moen (in prep.), Rouxville Member correlatives are also present in the Northern Domain. In the Central Domain on Karos Nedersetting a 300 m thick sequence of Rouxville basic lavas unconformably overlies lower Koras Group rocks. In the Rouxville-Rooikoppies area, the lavas unconformably overlies and are faulted against the Sultanaoord Group. Rouxville lavas together with volcanic breccias and minor interbedded sedimentary rocks are also exposed in the extreme north of the Central Domain and poor exposures are present near the new main road at Kaffirswart and near the village of Wilgenhoutsdrif. In the Southern Domain the Rouxville Member outcrops sporadically from Ezelfontein Noord in the north to Sandlaagte in the south.

An interesting feature of this member is its association with the quartz-feldspar porphyries of the Swartkop Member at the margins of the Kalkpunt basin. On the south side of the basin at Karos Nedersetting the basic lava underlies the porphyries. At the north side of the basin the bulk of the basic lava apparently overlies the porphyries although minor exposures at Duikerrand and Koras give the impression that the lavas are interbedded. The solution to the problem is provided at Leeudraai where the basic lava and quartz-feldspar porphyry are interbedded (Fig 4.3.1) and were first described by Rogers (1908, p. 54).

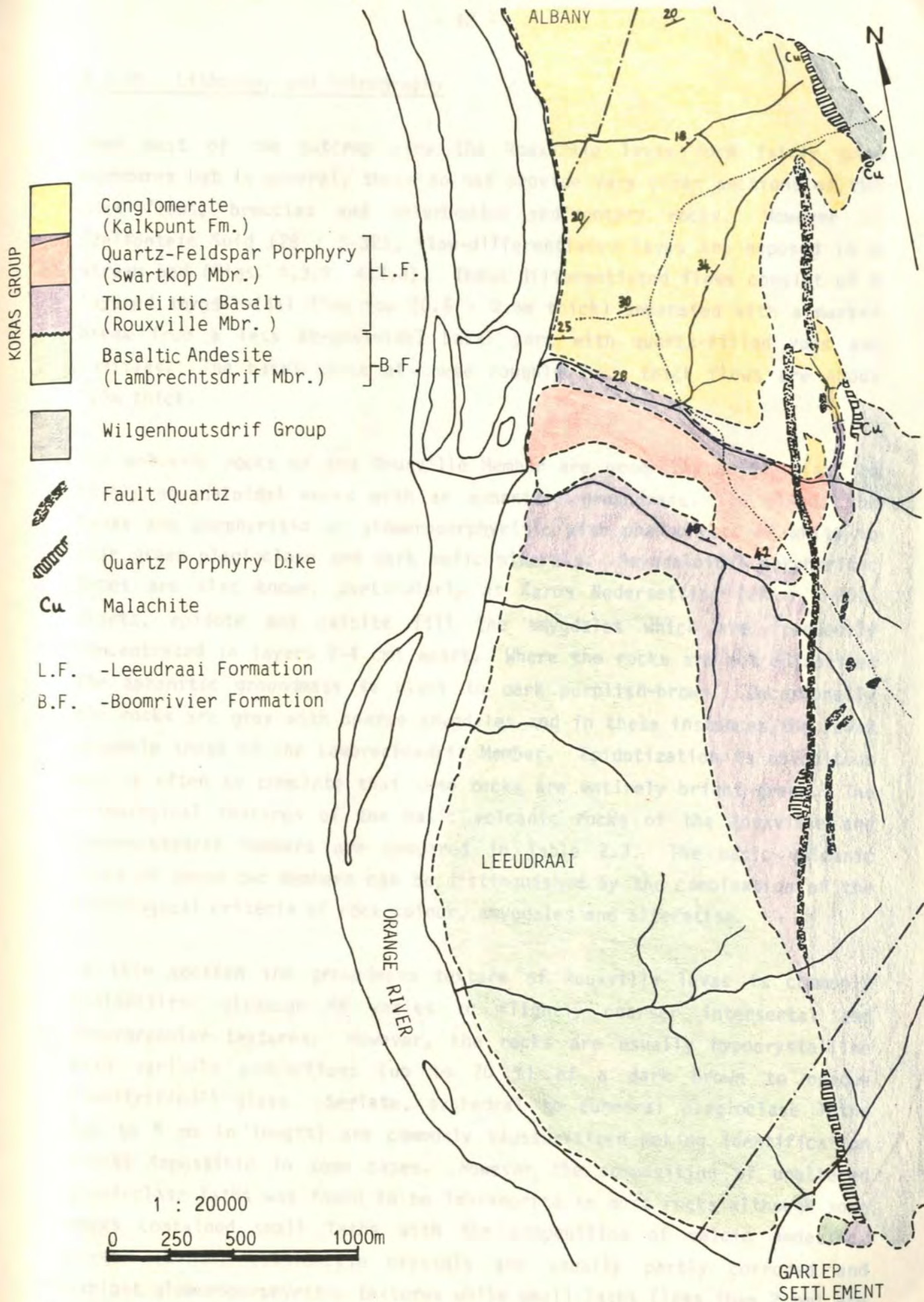


Figure 4.3.1 Geology of the Koras Group at Leeudraai farm.

#### 4.3.2B. Lithology and Petrography

Over most of the outcrop area the Rouxville lavas form fairly good exposures but in general, these do not provide very clear sections of the lava flows, breccias and interbedded sedimentary rocks. However at Ezelfontein Suid (2B : S-32), flow-differentiated lavas are exposed in a stream bed (Figs. 4.3.2, 4.3.3). These differentiated flows consist of a layered amygdaloidal flow top (0.5 - 0.6m thick) separated with a marked break from a less amygdaloidal basal part with quartz-filled vugs and cavities. The basal parts of these roughly 2m - thick flows are about 1,5m thick.

The volcanic rocks of the Rouxville Member are generally amygdaloidal to highly amygdaloidal rocks with an aphanitic groundmass. In places the lavas are porphyritic or glomeroporphyritic with phenocrysts of white to pale green plagioclase and dark mafic minerals. Amygdaloidal porphyritic types are also known, particularly at Karos Nedersetting (2A : R-20). Quartz, epidote and calcite fill the amygdales which are frequently concentrated in layers 2-4 cms apart. Where the rocks are not epidotized the aphanitic groundmass is black to dark purplish-brown. Occasionally the rocks are grey with sparse amygdales and in these instances the lavas resemble those of the Lambrechtsdrif Member. Epidotization is ubiquitous and is often so complete that some rocks are entirely bright green. The lithological features of the basic volcanic rocks of the Rouxville and Lambrechtsdrif Members are compared in Table 2.3. The basic volcanic rocks of these two members can be distinguished by the combination of the lithological criteria of rock colour, amygdales and alteration.

In thin section the groundmass texture of Rouxville lavas is commonly hyalopilitic although it varies to slightly coarser intersertal and intergranular textures. However, the rocks are usually hypocristalline with variable proportions (up to 70 %) of a dark brown to opaque (devitrified?) glass. Seriate, subhedral to euhedral plagioclase laths (up to 5 mm in length) are commonly saussuritized making identification almost impossible in some cases. However the composition of unaltered plagioclase laths was found to be labradorite in most rocks although some rocks contained small laths with the composition of calcic andesine. Larger (2-5mm) plagioclase crystals are usually partly corroded and exhibit glomeroporphyritic textures while small laths (less than 2 mm) are usually dispersed throughout the groundmass with occasional directive textures and are sometimes hollow (Fig. 4.3.4).



Figure 4.3.2. Differentiated lava flows consisting of a layered amygdaloidal flow top and a less amygdaloidal basal part. The lava flows are about 2m thick and the view is almost downdip (Locality : map 2B : S-32).

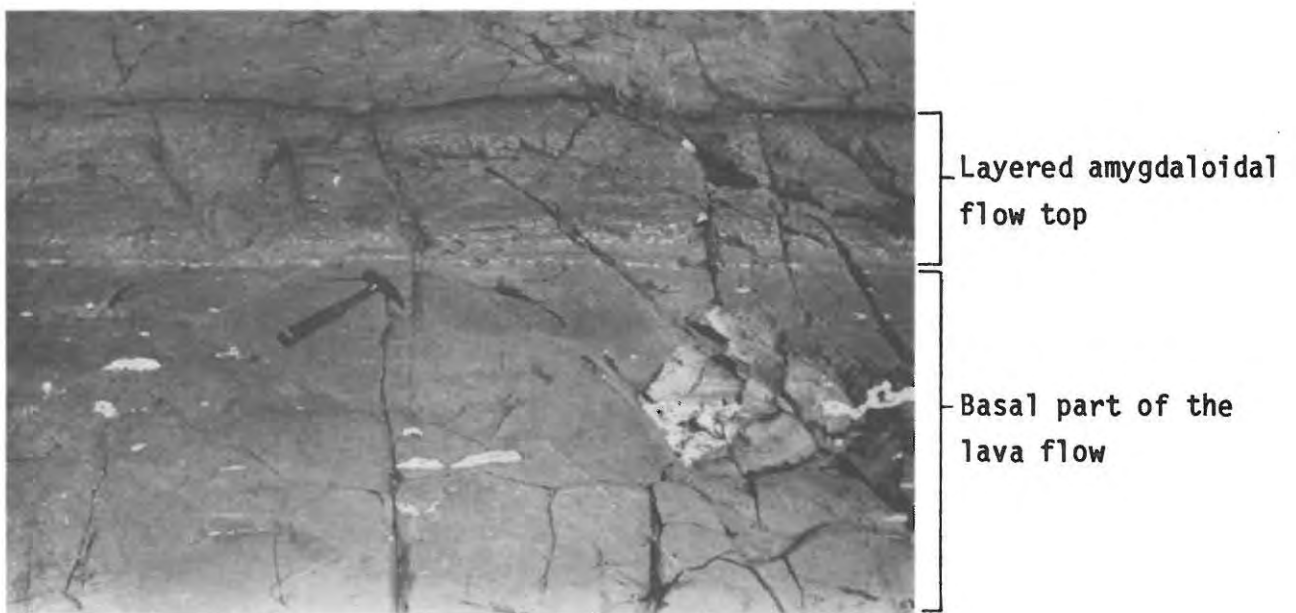


Figure 4.3.3. Downdip close-up view of a differentiated lava flow in Fig. 4.3.2.

The common mafic mineral is granular to elongate, anhedral to subhedral augite (usually less than 1 mm in length) which is sometimes subophitic and partly chloritized. Mafic phenocrysts (augite ?) that are up to 4 mm in length are present in CS-24 and are completely altered to chlorite and opaque phases. Accessory opaque minerals vary from larger euhedra (up to 1 mm) to skeletal arborescent crystals in the dark brown glass. Brown to reddish-brown Ti-biotite is generally associated with the opaques and sometimes with augite. Other accessory minerals include quartz, apatite and K-feldspar in the interstitial glassy mesostasis. Epidote and chlorite are present in the groundmass and the amygdalae.

The dominance of labradorite means that the lavas can be classified as basalts although the presence of some andesine might indicate that some of the rocks are andesites. In addition, the presence of minor amounts of quartz in the groundmass suggests that the rocks are slightly oversaturated with silica. The seriate nature of the plagioclase is interpreted to indicate continuous nucleation and crystallization possibly just before and just after extrusion. The larger glomeroporphyritic plagioclase crystals may have crystallized just before the extrusion of the magma and come together to form clusters during the extrusive event.

The Rouxville Member also has minor proportions of conglomerates and sandstones that are interbedded with the volcanic rocks. To the west of the farm house on Ezelfontein Noord the interbedded conglomerates and pebbly sandstones are massive and poorly bedded polymictic rocks that are poorly exposed. In places there are monomictic conglomerates that are composed of rounded pebbles of Rouxville lava. In the Central Domain on Karos Nedersetting (2A : R-20), well-bedded sandstones occur at the unconformable basal contact of the Rouxville Member on the Lambrechtsdrif Member, and dip at moderate angles to the north. Some red sandstones are interbedded with the lavas on the opposite bank of the Orange River at Leeudraai while at Rouxville the interbedded sedimentary rocks are also fine-grained reddish-brown sandstones, not dissimilar to the Kalkpunt sandstones.

#### 4.3.2C. Associated Volcanic Breccias

Volcanic breccias are sporadically exposed throughout the outcrop area and commonly consist of blocky to angular and irregular-shaped fragments with an aphanitic light brown to reddish-brown matrix. At places within the lavas this aphanitic matrix material is also present in irregular

fractures and in rounded to irregular cavities that resemble amygdales. In thin section the matrix consists of very fine-grained quartz fragments with epidote as well as finer microcrystalline material. In one thin section (AVD-11) the matrix is irregularly interspersed with highly epidotized lava fragments and gives the impression that the breccia formed by reaction of a lava with a muddy sediment.

Some volcanic breccias (Figs. 4.3.5, 4.3.6) are partially or completely cemented by milky quartz with some cavities and vugs between the lava fragments. In these breccias the amygdales consist of milky quartz and the lavas are occasionally partly epidotized. This type of breccia probably represents a within-flow breccia, the fragments of which are the broken up parts of lava flows.

#### 4.3.2D. The Volcanic Environment

Mild folding and faulting of the Rouxville Member together with post-Koras erosion has resulted in widely distributed, disjointed outcrops and this limits any attempts to reconstruct the volcanic environment. The lavas were clearly poured out over a large area which includes the outcrops that can be seen today and probably covered most of the underlying members of the Koras Group together with parts of the adjoining areas. The lava extrusions are envisaged as forming relatively thin flows, some of which are differentiated. The highly amygdaloidal nature of the lavas indicates a substantial gas content in the magmas and probably resulted in considerable amounts of explosive activity with the accompanying fragmentation or autobrecciation of some lava flows. A minor amount of sedimentation continued throughout the volcanic event as evidenced by the interbedded conglomerates and sandstones.



Figure 4.3.4. Hollow plagioclase laths that are box-shaped in cross-section, together with acicular plagioclase and opaque minerals in the hyalopilitic groundmass of Rouxville basalt (sample CS-24, crossed nicols).

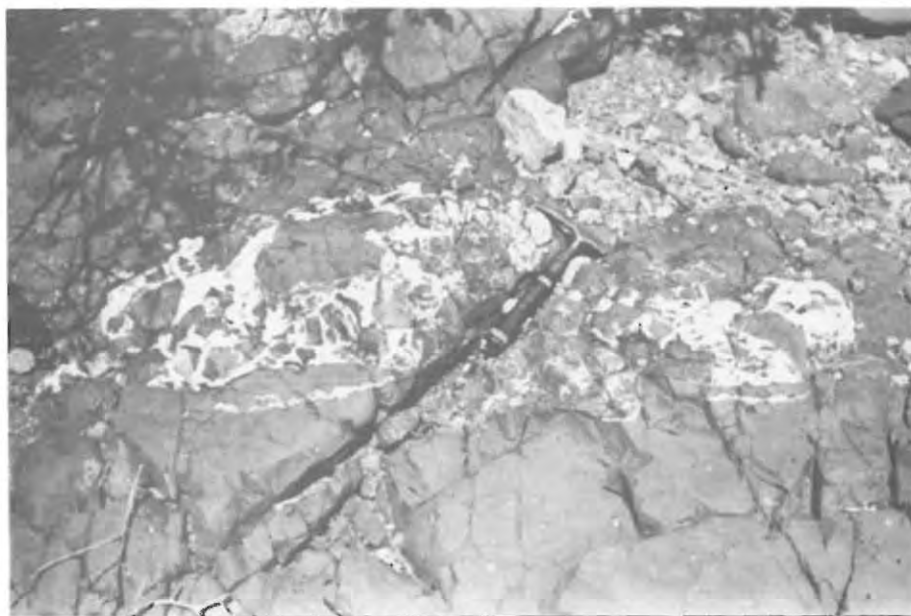


Figure 4.3.5. Small within-flow breccia (Rouxville Mbr) cemented with milky quartz. (Locality : map 2B : S-32)



Figure 4.3.6. Volcanic breccia near the base of the Rouxville Member at Karos Nedersetting. (map 2A : R-20).

### 4.3.3. Quartz-Feldspar Porphyries of the Leeudraai Formation

#### 4.3.3A. Distribution and Exposure

The coarse-grained, xenolith-bearing, quartz-feldspar porphyries of this formation outcrop in the Central Domain and are exposed on Koras, Avondale, Adeisestad, Kenilworth and Geelkoppan with some rather poor exposures on Jebeko and Kaffirswart. The best exposures are those on Karos Nedersetting and Leeudraai where the coarse-grained, xenolith-bearing porphyry builds a line of hills which includes Swartkop (see map 2A). Moen (in prep.) reports correlatives of these rocks in the Northern Domain where coarse-grained porphyries are overlain by red sandstones of the Kalkpunt Formation. Apart from two dykes, no lithologically similar rocks are present in the Southern Domain.

The porphyries exposed in the Koras-Avondale-Geelkoppan area were first mapped and described by Moen (1974, 1980), who regarded them as part of his Avondale Formation. Moen (1980) noted that the porphyries were mainly of two types (an upper and a lower type), with minor exposures of a third glassy type near the old farmhouse on Geelkoppan (G.P. at 2A : M-3). He correlated the lower type with the lower porphyry member south of the Orange River and regarded the upper type as a coarse-grained phase stratigraphically at the top of his Avondale (lower porphyry) Formation. However, he notes that the Swartkop Member on Karos Nedersetting (upper porphyry) cannot be distinguished from the coarse phase (upper type) of the Avondale Formation in the north (Moen, 1980, p.233).

This similarity was also noted by Rogers (1909, p. 54) and Du Toit (1965, p. 58), and the present author correlates the upper coarse-grained phase of Moen (1980) with the porphyry underlying the Swartkop line of hills, on the basis of lithology (section 4.3.3E). The lower porphyry of Moen (1980) in the north is regarded as a third major porphyry type distinct from the Swartkopsleegte porphyries or the coarse-grained xenolith-bearing porphyry of the Swartkop Member. This third major porphyry type has been mapped as a separate unit (medium-grained quartz-feldspar porphyry of map 2A i.e., Kenilworth Member), and is tentatively regarded as forming the basal part of the Leeudraai Formation in this area.

The lithological characteristics of the porphyries which are distinguished by their types of xenoliths and general grain size are described in the sections that follow. Further evidence for the correlation of the

porphyries must be obtained from geochemical studies although the xenolith-bearing porphyries may not be amenable to geochemical correlation because chemical variation will reflect, in part, the extent of incorporation of xenolithic material and the variation of xenolith types.

#### 4.3.3B. Structure of the Swartkop Member Underlying the Swartkop Line of Hills

A few geologists have considered the possibility that the Swartkop Member on Karos Nedersetting and Leeudraai which builds the Swartkop line of hills is an intrusive sheet or sill (Rogers and Du Toit, 1910, p. 84; Moen, 1980, p. 234). S.J. Malherbe of the Geological Survey, Upington (pers. comm.) interprets the feature as a sill that intruded Koras rocks at the edge of the Kalkpunt basin during the time of deposition of the conglomerates in the basin. However, these porphyries are interpreted here as a sequence of volcanic lava and ignimbrite flows on the basis of the following data:

- 1) Pebbles of coarse-grained quartz-feldspar porphyry that can be matched with the Swartkop porphyry are present in the immediately overlying conglomerates.
- 2) Although the contacts are poorly exposed, they appear to be sedimentary contacts. The upper (northern) contact of the porphyry is a sedimentary contact marked by volcaniclastic sedimentary rocks composed of the underlying porphyry (2A : R-19).
- 3) Minor interbedded sandstones occur within the porphyries and are concordant with the sequence (2A : Q-19, T-20).
- 4) Rocks that are ignimbrites are interbedded with the porphyries (2A : P-19, T-20).
- 5) The porphyry is interbedded with basic lava (Rouxville Mbr) on Leeudraai.
- 6) Porphyries that can be matched with those under discussion (Rogers, 1908, p. 54; Du Toit, 1965, p. 58; Moen, 1980, p. 233; present author) underly conglomerates at the northern margin of the Kalkpunt basin and are also interbedded with the amygdaloidal basic lavas of the Rouxville Member.
- 7) Petrography. The rocks contain a devitrified glassy to microcrystalline groundmass throughout the exposure and this supports the view that these rocks were formed under subaerial extrusive conditions.

#### 4.3.3C. Basal Glassy Quartz Porphyry (Kenilworth Member)

These porphyries are exposed on Geelkoppan (G.P. on 2A : M-3) and are interpreted as the basal part of the Leeudraai Formation. They have an overall reddish-brown to dark maroon, siliceous, glassy to almost chertlike appearance and some are also streaky to mottled with diffuse light and dark coloured streaks and patches. They are sparsely porphyritic with rounded quartz and rounded to subhedral feldspar crystals that make up only 10 % or less of the rocks. They are generally brittle rocks with a subconchoidal fracture and brown weathered surfaces.

In thin section (AVD - 13, 15, 16) the groundmass is made up of a microcrystalline mosaic of irregularly-shaped quartz and feldspar (0.1 - 0.3 mm in diameter) with tiny inclusions of feldspar laths, opaques and quartz. Irregular fractures are distributed throughout the rock and are filled with opaque material, epidote and microcrystalline quartz. Displaced parts of fractured crystals indicate that minor movement has taken place along some of these fractures.

Quartz crystals are generally corroded and rounded with embayments and holes although a few are subhedral with hexagonal outlines (Fig. 4.3.7). They are usually fractured with the characteristic spindly, spherulitic haloes or mantles which are optically continuous. They have undulose extinction and exhibit strain lamellae. Alkali feldspar is the main feldspar type present and occurs as rounded to subhedral, fractured and altered crystals, that are in much less abundance than the quartz crystals, making up no more than a few percent of the rock. Some have a perthitic appearance and a few exhibit the typical crosshatch-twinned appearance of microcline. One or two crystals of mafic minerals altered to chlorite, epidote and opaque phases are present. Opaque minerals are present as corroded euhedra and cumulates in the groundmass. A few resorbed polymineralic aggregates that could be rock fragments or represent glomeroporphyritic texture are also present.

These silica-oversaturated rocks are regarded as volcanic in origin and can be classified according to Streckeisen (1979) as rhyolites. The porphyritic texture can be interpreted in terms of the traditional two-stage cooling history where the phenocrysts form during the first stage, possibly at depth, and the remainder of the magma is cooled rapidly upon extrusion to form the groundmass. Alternatively the crystals may represent relict phases that remained unmelted during the production of

the magma or are xenoliths and these possibilities are suggested by the presence of microcline, perthitic feldspars and some of the polymineralic aggregates.

#### 4.3.3D. Xenolith-bearing, Medium-grained, Quartz-Feldspar Porphyries (Kenilworth Member)

These porphyries are exposed at the northernmost parts of the farms Koras and Avondale and along the adjoining southeastern boundary of Kenilworth. They have been mapped as a separate unit termed "medium-grained quartz-feldspar porphyry" (map 2A), and together with the basal glassy porphyry, are interpreted as the lower part of the Leeudraai Formation in this area.

The characteristic lithological feature of this porphyry is the presence of rounded xenoliths (2mm-1cm in diameter) that are composed of roughly subequal amounts of fine- to medium-grained light grey feldspar and dark mafic minerals. These xenoliths resemble a basic igneous rock such as a gabbro or diorite. In thin section the xenoliths are composed of highly altered feldspar, chloritized and epidotized mafic minerals and opaque grains. The xenoliths, together with quartz and feldspar crystals are set in a groundmass that is partially epidotized in places and consists of a microcrystalline mosaic of quartz and feldspar with inclusions of tiny feldspar laths, quartz, opaques and accessory apatite. The groundmass is similar to that of the basal glassy porphyry (section 4.3.3C).

The rounded and embayed quartz crystals (1-5 mm in diameter) exhibit all the features typical of other quartz-feldspar porphyries in the Koras Group : corrosion, optically continuous spherulitic mantles, irregular fractures, undulose extinction and strain lamellae. Feldspars (1-6 mm in diameter) are corroded and rounded and due to their high degree of alteration their composition could not be determined.

These silica-oversaturated, porphyritic volcanic rocks are classified as rhyolites (Streckeisen 1979). The origin of the xenoliths is speculative, but their evenly distributed, ubiquitous presence throughout the exposures of the porphyry leaves the impression that they represent relict, unmelted phases from the site of production of the magmas.

4.3.3E. Xenolith-bearing, Coarse-grained Quartz-feldspar Porphyry  
(Swartkop Member)

This porphyry is characterized by the ubiquitous presence of partially resorbed, rounded fragments of pink feldspar (up to 2cm in diameter) which are interpreted as xenoliths. Rounded crystals of quartz and creamy-white feldspars are set, with the xenoliths, in an aphanitic reddish-brown groundmass. These rocks underlie the Swartkop line of hills on Karos Nedersetting and Leeudraai and also form a northeast-trending series of exposures from Koras in the east to Jebeko in the west (map 2A).

The basal contact of the coarse-grained porphyry on Karos Nedersetting is marked by porphyries that exhibit irregular flow structures on weathered surfaces. These flow structures are also exposed within the sequence. At Leeudraai the basal contact is exposed at the end of the Karos dam wall and is marked by volcanic breccias and some fine-grained sandstones.

Apart from very slight variations in the groundmass colour and the grain size there is very little change in the appearance of this porphyry throughout the outcrop area. The aphanitic reddish-brown to brown groundmass commonly makes up about 50-60% of the rocks and usually consists of a microcrystalline mosaic of quartz with tiny feldspar laths, opaque minerals and some devitrified brown glass. In some rocks the groundmass consists entirely of a devitrified cryptocrystalline to microcrystalline pale brown glass with numerous opaque crystallites.

Quartz crystals are rounded to well-rounded and corroded with embayments and holes (Fig. 4.3.8.). They are sometimes fractured and have occasional trains of dusty inclusions. They vary in size from less than 1mm up to 5mm. The larger quartz crystals have undulose extinction and exhibit strain lamellae (Fig. 4.3.9). Feldspars are subhedral to rounded and corroded, are sometimes fractured and are translucent and pale brown in plane polarized light due to alteration. Albite, carlsbad and pericline twin types are present. Some grains were found to be oligoclase in composition while many of the feldspars have a perthitic appearance. It is suggested that perthite and oligoclase are present in approximately equal proportions.

Mafic minerals, completely altered to epidote, chlorite and opaques are present in minor proportions (less than 10 %) as discrete phases in the groundmass or together with quartz and feldspar as resorbed polymineralic

aggregates (Fig. 4.3.11). The origin of these polymineralic aggregates is, as with other Karos porphyries, unclear because they appear to be relict or xenolithic rock fragments, but could in some cases, represent resorbed glomeroporphyritic aggregates. Opaque grains, apatite and rare zircon occur as accessory phases in the groundmass or are part of the polymineralic particles.

The feldspar ovoids that characterize these porphyries are large, altered perthitic feldspars with inclusions of plagioclase and quartz and rarely, of epidote and opaque grains (Fig. 4.3.10). The ovoids which commonly consist of one perthite crystal, but may consist of two or three perthite grains, are corroded and rounded with embayments, holes and corrosion tubes. The included feldspars are generally less altered and often in optical continuity with one another. The corrosion embayments are filled with devitrified glass, microcrystalline quartz, or granophyric quartz-feldspar intergrowths. Although much of the crystal material in these silica-oversaturated volcanic rocks is clearly relict or xenolithic in origin, their mineralogy suggests that they can be tentatively classified as rhyolites (Streckeisen, 1979).

Amygdaloidal quartz-feldspar porphyries are exposed on the Orange river bank just upstream from the Karos dam at Leeudraai (2A : S-20). At one place they outline a tight synclinal fold, several metres in height and wavelength, that is interpreted as a volcanic flow fold. These amygdaloidal lavas can also be seen in a ditch running next to the secondary (dirt) road at Karos Nedersetting (2A : R-20). The amygdales are 3-6 cm in diameter and are composed of concentrically-banded chalcedony with quartz crystals filling the cores completely or leaving small vugs and cavities.

#### 4.3.3F. Rhyolite Ignimbrites (I on map 2A)

Rocks interpreted as ignimbrites are exposed within the coarse-grained quartz-feldspar porphyries at Swartkop (2A : P-19), Leeudraai (2A : T-20) and Avondale (2A : M-8). Although they are interpreted as ignimbrites by the fragmental and streaky textures seen in thin section and some hand specimens, they can be easily recognized by their distinctive brick-red colour which is quite different to the usual reddish-brown appearance of the coarse-grained quartz-feldspar porphyries. In addition the rounded feldspar intergrowths that characterize the coarse-grained porphyry are sparse or absent from the ignimbrites.



Figure 4.3.7. Partially corroded, subhedral quartz phenocrysts set in the microcrystalline groundmass of the basal glassy porphyry (Kenilworth Member, sample AVD-16, plane-polarised light).



Figure 4.3.8. Embayed and corroded quartz set in a devitrified glassy to microcrystalline groundmass. (Swartkop Member, sample KA-501, crossed nicols).

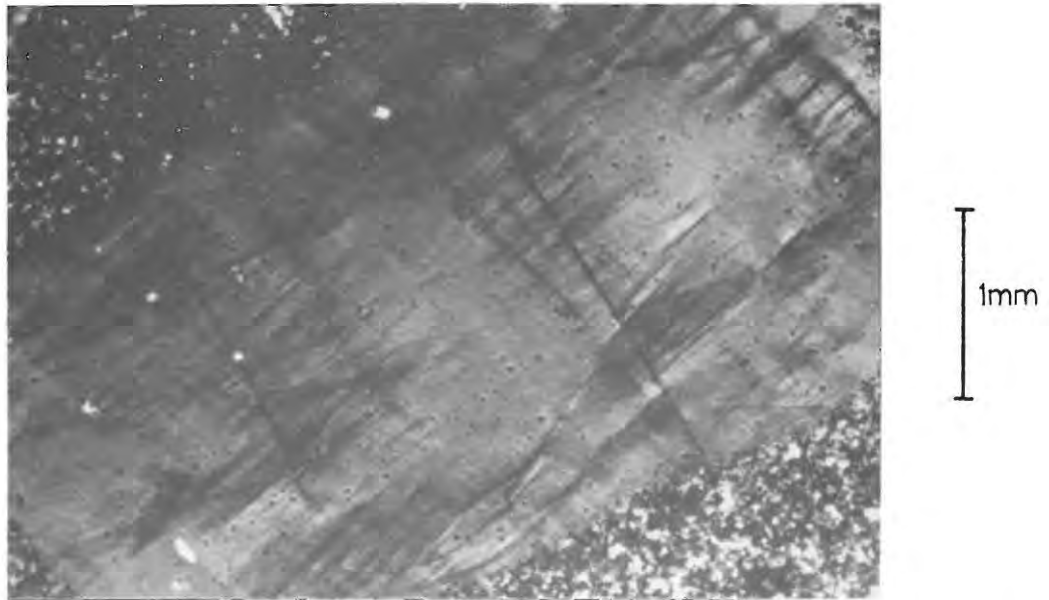


Figure 4.3.9. Strain lamellae and fractures in corroded quartz which is set in a microcrystalline groundmass (Swartkop Member, sample AVD-8, crossed nicols, quartz grain at near extinction position).



Figure 4.3.10. Photomicrograph of part of a rounded, partially resorbed perthite-oligoclase intergrowth in coarse-grained quartz-feldspar porphyry of the Swartkop Member (sample KA-23, crossed nicols). These feldspar ovoids are up to 2cm in diameter and characterize the porphyries of the Swartkop Member.



Figure 4.3.11. Polymineralic aggregate composed mainly of feldspar, quartz and opaque minerals. These resorbed rock fragments (glomeroporphyritic aggregates?) are common in all the quartz-feldspar porphyries of the Koras Group, particularly those of the Leeudraai Formation. (Swartkop Member, sample KA-429, crossed nicols).

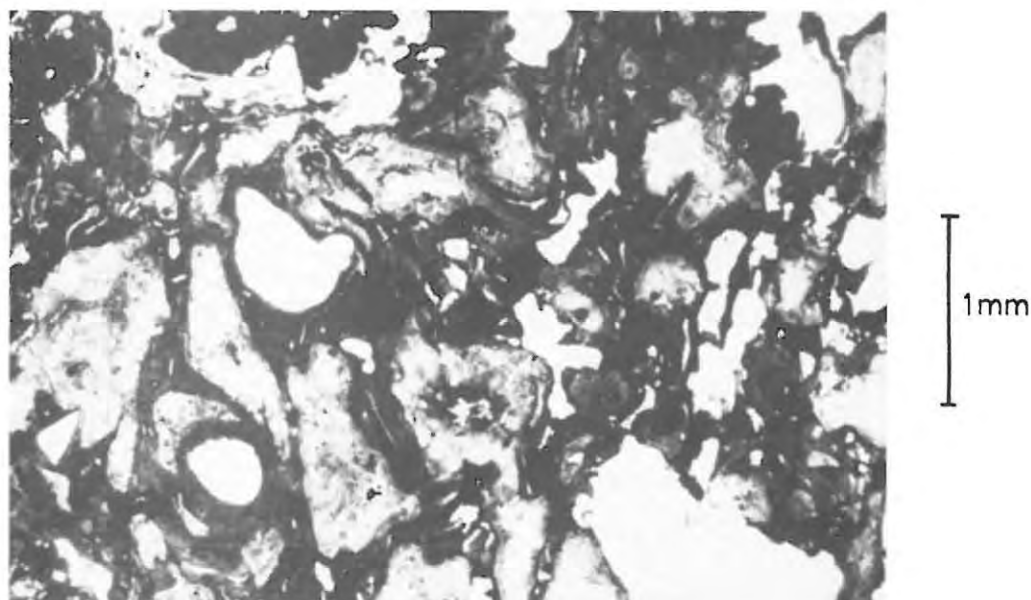


Figure 4.3.12. Flow texture made up of welded glass particles in rhyolite ignimbrite of the Swartkop Member (KA-565) Rounded quartz, feldspar and opaque minerals are also present. Individual particles are microcrystalline with a dark cryptocrystalline rim (plane polarized light).

The Swartkop ignimbrites (CS-27) are porphyritic with broken and rounded crystals of quartz and feldspar (generally 1-5 mm in diameter) that are set in a mottled to streaky, brick-red to orange-red groundmass of welded fragments. The mottles and streaky patches vary from less than 1 mm to several cms in diameter. The rocks are hard and compact with an uneven to subconchoidal fracture. On Avondale (2A : M-8) streaky ignimbrites (AVD-1) are present within an exposure of coarse-grained quartz-feldspar porphyry that forms a low rounded hill partly covered by Kalahari sand. These ignimbrites are porphyritic and have a purplish-brown to brick-red patchy and streaky appearance. They are similar to the Swartkop ignimbrites and are associated with breccias and other finer-grained fragmental rocks some of which are cemented with quartz.

In thin section (CS-22, KA-565, Fig. 4.3.12) the aphanitic groundmass exhibits a swirling or convoluted flow texture. The groundmass consists of orange-red to brown patches and irregular fragments of partially devitrified glass. Some of the particles have a cryptocrystalline rim with a microcrystalline, sometimes spherulitic core. The boundaries of the particles which appear to be welded together, are marked by lines of dusty opaque material.

Crystals of quartz, feldspar and mafic minerals have a similar appearance to those in the coarse-grained quartz-feldspar porphyries (section 4.3.3E). However, the ignimbrites have a greater proportion of broken crystal material. Accessory phases include apatite, opaques and reddish-brown Ti-biotite. These are usually associated with polymineralic particles that are similar to those described in section 4.3.3E.

The rocks are interpreted as ignimbrites on the basis of their welded, particulate, flow texture. Their mineralogical composition indicates they are oversaturated with silica and can be called rhyolite ignimbrites.

#### 4.3.3G. Minor Interbedded Sedimentary Rocks

Minor proportions of generally volcanoclastic sedimentary rocks (S on map 2A) are associated with the quartz-feldspar porphyries of the Leeudraai Formation. Near the main (tarred) road on Karos Nedersetting (2A : Q-19) there is an exposure of red sandstones which resemble the red sandstones in the Kalkpunt Formation. The rocks are well bedded, fine-grained sandstones with muscovite which is present as sparse shiny specks on fresh surfaces.

A poorly sorted and rounded volcaniclastic deposit (Fig. 4.3.13) occurs at the top of the Leeudraai Formation on Karos Nedersetting (2A : R-19). Du Toit (1965, p. 59) interpreted the rocks as agglomerates, while Moen (1980, p. 233) regarded the feature as an occurrence of volcanic breccias and tuffs. The rocks consist of subrounded to angular fragments of porphyry with a matrix of finer-grained and aphanitic material or are cemented with calcite. The rocks grade into the overlying Kalkpunt conglomerates and are interbedded with thin layers (less than 0.5 m) of mudstone (tuffs ?) which dip to the north at about  $40^{\circ}$ . An occurrence of similar volcaniclastic rocks is exposed at the southeastern corner of Geelkoppan although much of this material is cemented with quartz as well as calcite. Moen (1980, p. 226) suggests that some of these rocks may represent "welded pyroclastic deposits or autobreccias caused by the breaking up of a highly viscous flow".



Figure 4.3.13. Volcaniclastic sedimentary rocks dipping to the left (north) at Karos Nedersetting. (For scale, locate geopick at centre left. Locality : S on map 2A : R-20)

#### 4.4. Kalkpunt Formation

##### 4.4.1. The Kalkpunt Basin

The Kalkpunt Formation consists of a basal conglomerate which grades laterally into a fine-grained red sandstone. The conglomerate is exposed at the margins of the Kalkpunt basin, the eastern edge of which is faulted against schists and quartzites of the Wilgenhoutsdrif Group. The conglomerates overlie the interbedded lavas of the Swartkop and Rouxville Members conformably except in the area around Karos and Hoogland (map 2A) where they overlie lower Koras Group and Wilgenhoutsdrif Group rocks unconformably.

On Karos Nedersetting and Leeudraai the conglomerates are exposed in river and stream beds. The matrix of the conglomerate is easily weathered and removed so that over hills a polymictic debris of rounded pebbles from the underlying conglomerate is produced. Similarly, exposures of conglomerate at the northern margin of the basin are poor and consist of low hills of quartzite pebbles lying strewn amongst red dune sand with smaller amounts of other pebbles such as ironstone, chert and milky vein quartz. In the central part of the basin exposures of sandstone occur sporadically between the longitudinal sand dunes.

Various estimates of the thickness of the Kalkpunt Formation have been made. Du Toit (1965) indicated a thickness of 11,300 ft (3440 m) for the formation and a thickness of 1500 ft (450 m) for the conglomerate. Moen (1980, p. 235) estimated the thickness of the conglomerate to be more than 1000 m and the thickness of the exposed section of the basin to be more than 3000m. However, the author feels that these values are overestimates and that a maximum thickness for the exposed section of the basin is 1700m. This value is based on the geological sections accompanying map 2A. In a previous study (Sanderson, 1979) the thickness of the conglomerate at Swartkop was estimated to be about 600 m.

##### 4.4.2. Kalkpunt Conglomerates

The conglomerate is hard, well-indurated, generally dark reddish-brown and has a knobby appearance because the matrix is easily weathered and removed (Fig. 4.4.1). Compositionally the conglomerate is polymictic, the most abundant pebble type being quartzite (a variety of dark and light types) and fine-grained quartz-feldspar porphyry (Swartkopsleegte Mbr).

Pebbles of all the other Karas lavas as well as granite (usually a pink muscovite-bearing type in the Swartkop area), banded iron formation, sericite quartzite, schist, gneiss, phyllite, greenstone, conglomerate and sandstone are present. The pebbles are poorly sorted yet they are often well-rounded with moderate to good sphericity. They range in size from less than 1 cm to more than 40 cm but are usually 3-25 cm in diameter. Although the conglomerate is immature, it is well-packed, grain supported with less than 15 % matrix and can be called a polymictic orthoconglomerate. Minor variations of the conglomerate include oligomictic quartz-feldspar porphyry (Swartkopsleegte Mbr) conglomerate which occurs notably at Hoogland as well as a few other localities. On Karos Nedersetting close to the lower contact, there is a good exposure of conglomerate that has no matrix but is cemented by quartz (2A : R-19).

At the larger exposures the conglomerates give the appearance of being laid down in layers or beds that are 1/2 to 1 m in thickness and limited in extent to several metres. In addition, there are short, discontinuous, bedded sandstone layers and lenses that are similar but more distinct. In the Swartkopsleegterivier near Swartkop location (2A : P-19), an ancient channel roughly 2 m deep by 2 m wide is present within the conglomerate and is filled with conglomerate.

Sandstones that are interbedded with the conglomerate are well-indurated and purplish with bedding marked by alternating coarse and fine sand or darker and lighter coloured layers. These sandstones are composed of a variety of grain types. Most quartz is metamorphic (composite grains with undulose extinction) while microcline, perthite and a little plagioclase (variable in composition, but commonly oligoclase) are the feldspar types present. Rock fragments are mainly metamorphic (e.g., epidote-chlorite-quartz schist) but some basic volcanic rock fragments are also present. Opaque minerals occur as discrete grains and also as an alteration product of other minerals. Some chlorite is present. The matrix consists of very fine-grained material which is reddish-brown due to the presence of hematite or other iron oxides and this gives the rocks its purplish to reddish colour. In some cases calcite cement is present. The grains of these immature sandstones are poorly sorted and rounded with poor sphericity. They vary in size from 0.05 mm to 1 mm, the larger grains being quartz or metamorphic rock fragments. The rocks have 50-60 % quartz, approximately subequal amounts of feldspar and rock fragments, and therefore can be classified as lithic arkoses or feldspathic litharenites (Folk, 1968, in Blatt et al., 1972, p.311).



Figure 4.4.1. Exposure of Kalkpunt conglomerate in the Swartkopsleegterivier.  
(Locality : map 2A : P-18)



Figure 4.4.2. Interbedded sandstone layers within the Kalkpunt conglomerate.  
(Locality : map 2A : P-18)

#### 4.4.3. Kalkpunt Sandstones

The sandstones that underlie the central and greater part of the Kalkpunt basin are red, generally fine-grained (0.05 to 0.5 mm in diameter), almost aphanitic rocks and are mainly composed of very fine-grained quartz (75-80%). Feldspar, some metamorphic rock fragments, muscovite, epidote and opaque minerals are subordinate. The grains tend to be closely packed so that only a small amount of a very fine-grained matrix is present. Reddish-brown iron staining, which gives the rock its red colour occurs along grain boundaries and is probably hematite with other iron oxides. The sorting and sphericity of the grains is moderate, roundness is poor and the grains are well packed with four to six grain contacts. These submature sandstones can be classified as subarkoses or sub-litharenites (Folk, 1968, in Blatt et al., 1972, p.311).

The sandstones are well-bedded and display cross-bedding and ripple marks and contain mud chip conglomerates. In addition, graded bedding, planar cross-bedding and trough filling have been noted by Du Toit (1965) and Moen (1980), while Grobler et al. (1977, p. 169) report that shales occur locally toward the top of the succession. Planar crossbeds probably account for some of the anomalously high dip values in the sandstones. Although the exposures are very poor, limited current direction studies have been carried out south of the long axis of the basin by Du Toit (1965) and Grobler et al. (1977, Fig.2).

#### 4.4.4. Depositional Environment

The conglomerates of the Kalkpunt Formation were probably deposited as alluvial fans at the margins of the Kalkpunt basin that could have had a significantly greater distribution than the basin that can be seen today. The coarse clast-supported conglomerates indicate energetic transport by water. The poorly bedded to massive nature of the conglomerates and the rapidly increasing number of horizontally laminated sandstone beds support the view that the conglomerates were deposited in alluvial fans that possibly overlapped to form a coarse sheet at the margin of the Kalkpunt basin. Such conglomerates are usually laid down by sheet flood mechanisms and stream channels which are often difficult to distinguish (Rust, 1979).

Some of the short, discontinuous, horizontally bedded sandstone layers and lenses could represent sand-bars that formed during relatively quieter

periods of deposition in which a braided stream system with channels containing coarser material predominated. The sandstones within the basin are distal deposits whose red colouration may indicate a semi-arid palaeoclimate.

Coarse alluvial deposits are good indicators of sharp terrestrial relief caused by tectonic activity (Rust, 1979), and the thickness of the conglomerates points to a tectonically influenced setting. It is mooted here that folding made up a significant part of this tectonic activity so that the basin was continually deepened by horizontal NE-SW directed forces during deposition. This is supported by the steep dips of interbedded sandstones in the conglomerates from Hoogland in the west to Leeudraai in the east.

As suggested by Grobler et al. (1977) faulting may have played a significant role in the deposition of the Kalkpunt conglomerate. However, these faults could be well outside the limits of the present distribution of the Kalkpunt Formation as shown in Fig. 4.4.3. This view is supported by the conformable way in which the basal conglomerates overlie the interbedded lavas of the Swartkop and Rouxville Members.

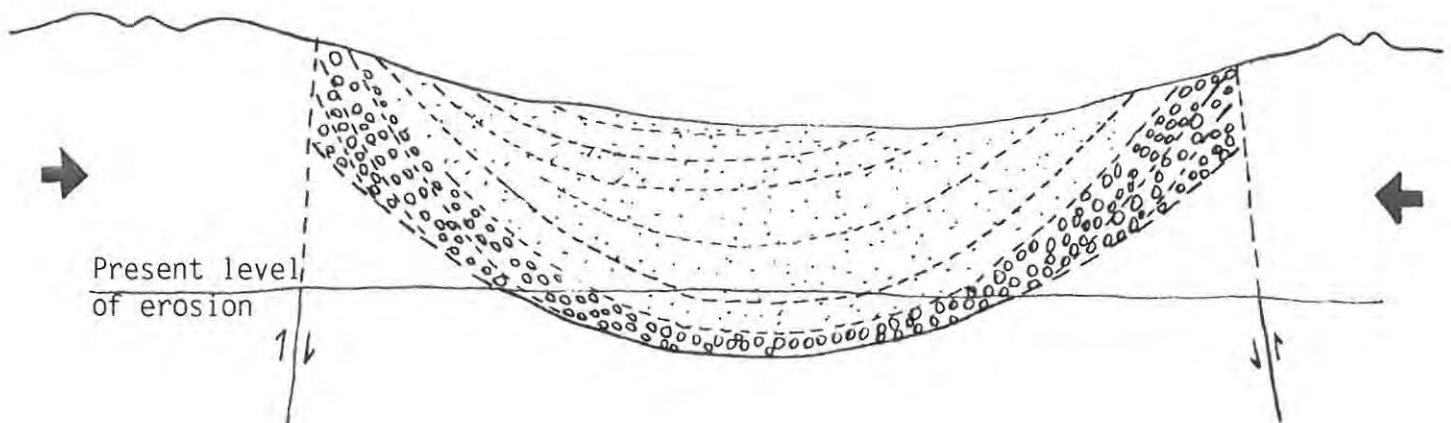


Figure 4.4.3. Possible relationship between major faults and the Kalkpunt basin.

The polymictic nature of the conglomerates suggests that there was a considerable variability of rock types in the source area. From the field and thin section studies one can conclude that metamorphic basement was eroded in the source area during the deposition of the Kalkpunt conglomerates and sandstones. Some basic and acid volcanic rocks of the Koras Group and probably the Wilgenhoutsdrif Group were also present in the source area. The banded ironstone pebbles are probably derived from the Griquatown Group. In addition, a proportion of the pebbles and cobbles was derived from older conglomerates and contributes considerably to the high degree of rounding of the pebbles. The presence of boulders of pre-existing conglomerates within the Kalkpunt conglomerates supports this view. This recycling feature was also noted by Grobler et al. (1977, p.173). The source area rocks described above almost certainly occurred in regions of high relief because fans form adjacent to such regions which are rapidly denuded to provide the sediment which builds the fans (Rust, 1979).

## 5. STRUCTURAL GEOLOGY

### 5.1 Minor Folds in the Karos Member

In the Karos area (map 1) upright minor folds are common in the sandstones and shales (Figs. 5.1.1, 5.1.2). The folds are disharmonic and folding varies in intensity depending on lithology. The fine-grained sandstones and shales have close chevron folds while folds in the coarser sandstones are close to open. To determine the axis of folding, 50 bedding measurements were taken at sub-areas where folds were well exposed. The structural data are attached to Map 1 and the sub-areas in which measurements were taken are represented by the fold axis arrows on map 1. The structural data indicate that the sandstones and shales are folded about south-east trending fold axes that plunge at angles between  $32^{\circ}$  and  $45^{\circ}$  except at sub-area F where the fold axis is roughly horizontal.

Minor folds were also seen in the sandstones and shales of the area to the east of Lambrechtsdrif (e.g., Sanderson, 1979, plate 3). However, these are not commonly seen due to the poor exposure and therefore no fold axis determinations with structural data were made here.

### 5.2 Major Fold Structures

The structure of the lower Koras Group around Karos village (map 1) is that of a large-scale synclinorium (wavelength  $\pm$  2.5 kms) plunging to the southeast as shown on map 3 and Figure 5.3. This view is based on the geology shown on map 1 and the structural data from the minor folds in this area. The wavelength of the folds making up the synclinorium is estimated to be 500-700 metres. It should be noted however that minor faults within the Koras Group are almost certainly present in this area because some brittle failure probably accompanied the folding but the exact position of minor faults is speculative. In addition the synclinorium is partially obscured by the unconformable way in which the Swartkopsleegte Member overlies the Karos and Lambrechtsdrif Members. In some areas (map 1) the Swartkopsleegte porphyries overlap the Karos sedimentary rocks and directly overlie the Lambrechtsdrif basic volcanics. The structure of the lower Koras Group at Karos Nedersetting (Map 2A) is that of a large-scale syncline (wavelength  $\pm$  3 kms) plunging to the northwest (see map 3 and Fig. 5.3).

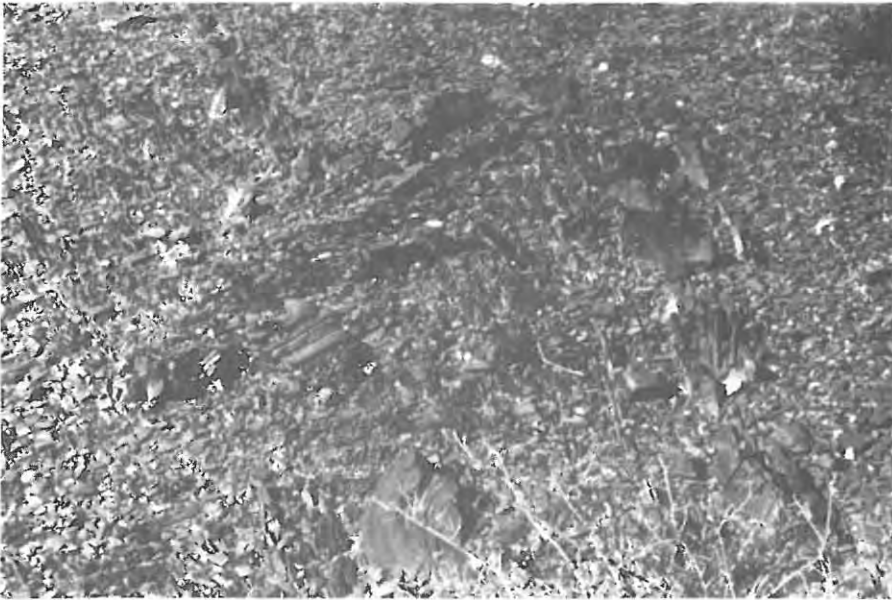


Figure 5.1.1

Minor folds in micaceous sandstone and shale of the Karos Member. (Locality structural subarea D on map 1).

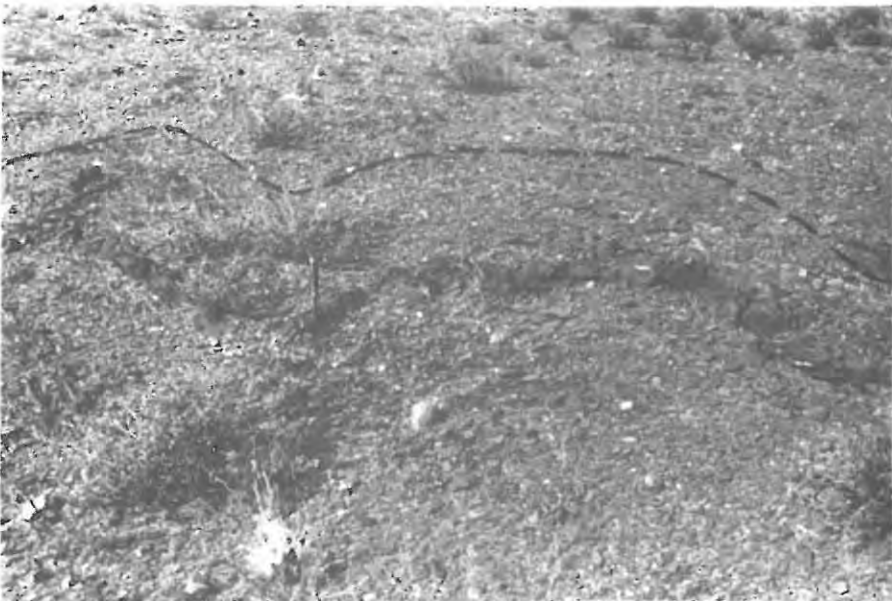


Figure 5.1.2

Minor folds in the Karos Member. (Locality : structural subarea D on map 1).

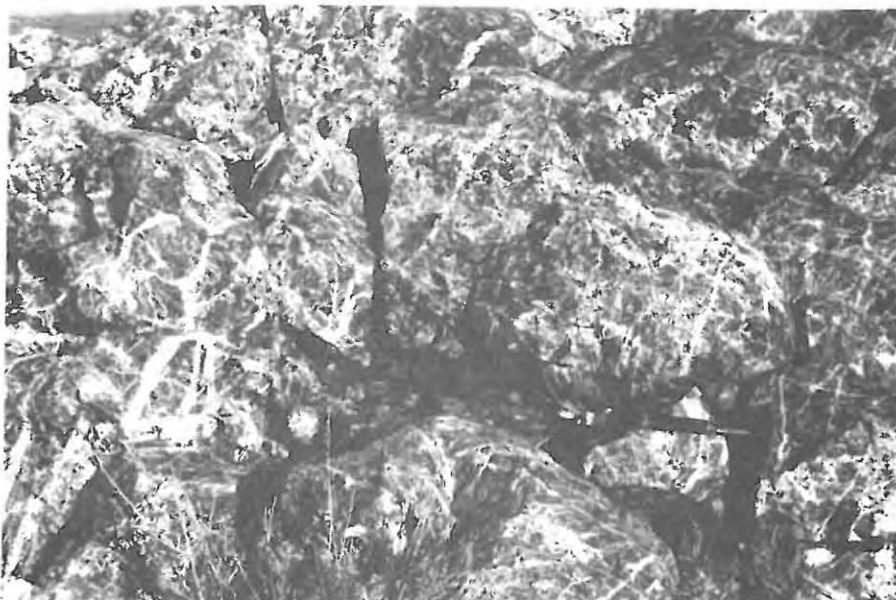


Figure 5.1.3

Fault breccia of the Leudraai-Kalkwerfputs fault on Leudraai farm (Locality : map 2A : T-19).

To account for the fold structures described above two phases of folding are proposed. These are labelled  $F_{1K}$  and  $F_{2K}$  to avoid confusion with the  $F_1$  to  $F_4$  fold phases in the pre-Koras sequences. The  $F_{1K}$  fold phase can be interpreted to be a result of compressional forces acting from the southwest and northeast as noted by Du Toit (1965, p. 35, p. 85). During the  $F_{2K}$  fold phase large-scale open folding about NE-trending axes has refolded the  $F_{1K}$  fold axes and probably accounts for the curved outcrop of the Leeudraai Formation in the Central Domain. In the Southern Domain the  $F_{1K}$  fold phase is represented by a single syncline plunging to the southeast.

The extent to which the Koras fold phases have affected the Kalkpunt basin is uncertain. The curved, roughly elliptical structural basin with its basin-edge conglomerates and inward-fining sequence is clearly depositional. However, the steep dips ( $50 - 70^{\circ}$ ) at the basin margins suggest that some infolding has taken place, probably during deposition, as suggested by Grobler et al. (1977, p. 173). In the Karos area, the folded lower Koras Group is unconformably overlain by the Kalkpunt Formation (see map 3). This suggests that in this area the lower Koras Group had been folded and had undergone some erosion before the onset of deposition of the Kalkpunt Formation. In other words the unconformity is a result of lower Koras Group folding, uplift and partial erosion, followed by Kalkpunt deposition.

### 5.3. Faults

The Koras Group is situated on a zone of major fractures, known as the Doringberg Lineament, which separates the southwest marginal part of the Kaapvaal craton from the multiply-deformed sequences of the Namaqualand Metamorphic Complex. The lineament comprises major shear faults e.g., the Doringberg and Brakbos faults as well as other faults for which local names have been introduced. According to Vajner (1974), the separation and offset of the geological features on both sides of the individual faults indicate right lateral (dextral), strike-slip and oblique-slip movement, and the total displacement in the lineament could amount to more than 50 kilometres. The Doringberg Lineament and the position of the Koras Group are well illustrated on ERTS imagery (Fig. 5.2).

In the study area there are numerous faults which can be recognized in the field by fault breccias and mylonites as well as quartz-porphyry dykes that have intruded the fault planes. The faults are also commonly associated with exposures of vein quartz. At places where the Koras Group is faulted against rocks of the underlying (pre-Koras) sequences, vein quartz is usually intruded

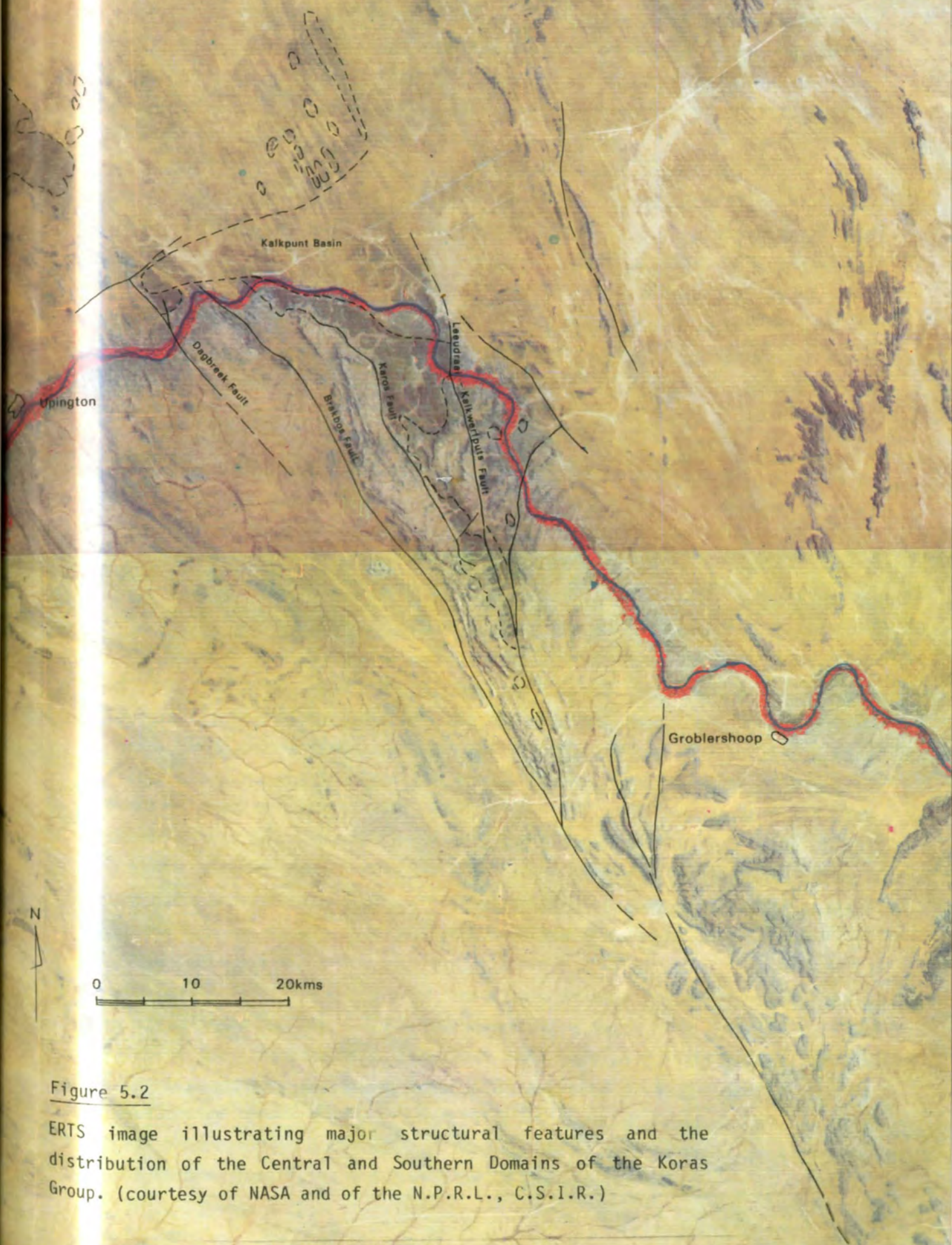


Figure 5.2

ERTS image illustrating major structural features and the distribution of the Central and Southern Domains of the Koras Group. (courtesy of NASA and of the N.P.R.L., C.S.I.R.)

into the phyllitic or schistose rocks. This feature is well-demonstrated along the Karos fault at Ezelfontein Noord where the Koras Group is faulted down against the Sultanaoord Group. Numerous veins and irregular masses of milky quartz (up to several metres in diameter) are intruded into quartz-sericite schists of the Sultanaoord Group.

The siliceous fault fillings and breccias (Fig. 5.1.3) in the Leeudraai-Kalkwerfputs fault at Leeudraai farm (see Fig. 4.3.1, p.41), form good linear features on air photographs. These reddish to white quartzitic rocks are irregularly traversed by milky quartz veins (1mm to 2cm in width) emphasizing the brecciated appearance (Fig. 5.1.3). Finer veins usually occur between the larger ones and in some places there are irregular cavities which are a few millimetres to several centimetres in diameter. Small quartz crystals can be seen in some cavities.

The Leeudraai-Kalkwerfputs fault is a major dextral strike-slip fault with an estimated strike-slip movement of about 20 kilometres. This interpretation is based on the following evidence:

1. On the east side of the fault the Lambrechtsdrif Member overlies basal members of the Wilgenhoutsdrif Group (phyllite, quartzite and schist unit; Moen, 1980). On the west side of the fault this relationship occurs to the north in the area just east of Rooidraai (map 2A : S-23,24).
2. In the northern half of Ezelfontein Noord (map 2B : R-28) the Lambrechtsdrif Member overlies the Sultanaoord Group and the granite-gneiss, and then pinches out (map 2B : S-29) so that further south, the fine-grained quartz-feldspar porphyries (Swartkopsleegte Member) directly overlie granite-gneiss (map 2B : S, T-31). The presence of the sliver-shaped mass of the Lambrechtsdrif Member, on the east side of the Leeudraai-Kalkwerfputs fault where it overlies the Wilgenhoutsdrif Group, cannot be explained by major dip-slip faulting because a matching sequence (Lamb. Mbr. on W.Gp.) does not occur on the west side of the Leeudraai-Kalkwerfputs fault.

Thus the large sliver-shaped mass of the Lambrechtsdrif Member in the Southern Domain is believed to have been moved south along the fault from the Central Domain. The Swartkop Member at Leeudraai farm (map 2A : T-20) bends into the Leeudraai-Kalkwerfputs fault and this is interpreted as fault drag caused by the 20-kilometre wrench fault movement along this major fault. The direction of dip-slip movement is problematical because there appears to be downthrow to the east at some localities and downthrow to the west at others.

The Karos fault is another major fault which has affected the Koras Group and considerable dip-slip movement has taken place with downthrow on the eastern side. This is particularly well shown at Ezelfontein Noord (map 2B : R-30) where an almost complete section of the Koras Group in this area is downfaulted against Sultanaoord Group schists. The nature of the terminations at Karos and Ezelfontein Suid are unclear. A horizontal dextral displacement of approximately 10 kilometres has been suggested by Stowe (1980, Table 3) but no evidence could be found to corroborate this estimate.

The Brakbos fault, which is one of the largest faults in the Doringberg lineament is a major dextral strike-slip fault and has a component of dip-slip faulting with downthrow in the east (Vajner, 1974; Pretorius, 1974). In the study area the Brakbos fault is covered by sand as it extends towards the Kalkpunt Formation which it does not appear to have affected to any major extent. Some faulting of the Kalkpunt Formation may have taken place but due to the sand cover, any interpretation is speculative. Stowe (1981) has estimated the horizontal displacement of the Brakbos fault to be 15 kilometres. According to Moen (1980, p. 173) "its displacement is calculated at about 2000m at Leerkrans, yet it does not affect the Koras Group".

The Dagbreek fault is a major dextral strike-slip fault and has a horizontal displacement of 16,4 kilometres, as estimated by C. van Zyl (in Stowe, 1981). In addition a significant component of dip-slip faulting with a downthrow on the east can be inferred in the Rouxville area where the Rouxville Member is downfaulted against the Sultanaoord Group.

From the above it is clear that in this part of the Doornberg Lineament there has been major dextral strike-slip movement together with a step-like arrangement of dip-slip faulting, the western blocks being upthrown relative to those on the east. The progressive stepping-up of the terrane on the southwestern sides of successive faults in the Doornberg Lineament was proposed by Pretorius (1974), who suggests that the Namaqua Metamorphic Complex has been considerably elevated relative to the Kaapvaal Craton.

The orientation of the fault planes could not be determined but various suggestions have been made by other authors:

1. Grobler et al. (1977, p. 174) and Botha et al. (1977, p.105) consider that the faults were mainly normal faults and controlled Koras deposition in a series of grabens with intervening horsts.
2. Stowe (1980, p.32, Fig. 9) suggests that the faults are reverse faults.

3. Moen (1980, p. 174) is of the opinion that "the widespread mylonitization, strong deformation and sporadic occurrence of crush conglomerate along certain faults particularly the Brakbos, may indicate high-angle reverse faulting rather than normal block faulting in at least some cases. The reverse faults may have acted as a stress-release mechanism after the  $F_2$  event, and may also be related to the widespread intrusion of late- to post- $F_2$  granites as well as the extrusion of the Koras lavas."

#### 5.4. Regional Structural Setting.

The Koras Group has traditionally been regarded as an undeformed post-tectonic sequence whose deposition and preservation are the result of rifting and block faulting. However it is suggested here that folding, as well as faulting, has played a significant role in the preservation of the Central and Southern Domains of the Koras Group. According to Grobler et al. (1977) the Koras rocks were deposited in "graben-like repositories in a newly stabilized orogenic region shortly after the cessation of the last period of folding." In this view the synclinal structures first noted by Du Toit (1965) are "interpreted as basins formed by a combination of sediment transport from different directions into graben-like repositories and continued movement along the normal faults defining the grabens" (Grobler et al., 1977, p. 173).

A clue to the regional structural setting of the Koras Group was provided by the late Dr V. Vajner (1974, p. 17) who suggested the possibility that the Koras Group had been folded during the last ( $F_4$ ) phase of folding of his Kheis Group:

"The Koras tectonism is characterized by a generally mild deformation of primary layering along west-northwesterly and northwesterly axes. The deformation pulses probably accompanied and partly followed the accumulation of individual members of the Koras sequence as demonstrated by several unconformities within the succession. The magnitude and importance of these unconformities is not yet fully understood. Similarities in trend and geometry between the  $F_4$  structures in the pre-Koras basement and the WNW-trending macroscopic folds in the Koras indicates the influence of the Kheis basement architecture upon the deformation of its Koras sedimentary cover."

In an attempt to relate the deformation in the Koras Group to that in the pre-Koras sequences, the major structural elements in the pre-Koras sequences as determined by Moen (1980, p. 157) and Stowe (1979, p. 28) are shown in Figure 5.3, together with the structural trends and fold directions in the

Koras Group. This structural map shows that the lower Koras  $F_{1K}$  and  $F_{2K}$  fold directions are roughly parallel to the  $F_2$  and  $F_3$  fold directions in the underlying sequences. This could be interpreted to mean that the Lower Koras Group was deformed during the Namaqua tectogenesis. In this view the onset of deposition of the Koras Group occurred just prior to or shortly after the  $F_2$  phase of folding commenced and deposition in this syntectonic cover sequence continued during the Namaqua Event. Lower Koras Group rocks were moderately folded by the  $F_2$  deformation as can be seen in the Karos Member. Middle Koras rocks are less affected as shown by the open syncline in the Ezelfontein Member. Finally the Kalkpunt basin with a long dimension that trends northwest may reflect deformation that occurred during the  $F_4$  phase. The major dextral faulting associated with the  $F_4$  phase was probably instrumental in producing uplifted areas of source rocks for the Kalkpunt basin in a manner suggested in Figure 4.4.3.

Alternatively it has been suggested that the stress field operative during the Namaqua Event continued for some time so that late, residual stresses of the Namaqua Event are represented by the Koras Group folds. In this interpretation the late  $F_4$  event with associated dextral wrench faulting is responsible for the Koras fold structures as suggested by Vajner (1974, p. 17).

A consideration of the age of the folding events provides some, if inconclusive, evidence on the relationships of the various fold phases. Botha et al. (1977) estimated an age of 1200-900 Ma for their  $F_1 - F_3$  folding events. Similar age estimates for the Namaqua fold phases have been considered by Moen (1980) although Moen (op. cit.) estimates an age of 1300 Ma for the  $F_1$  event. According to Stowe (1981) the Namaqua Event, overprinted as  $F_2$ ,  $F_3$  and  $F_4$  folds took place across the south of the Kaapvaal Craton and the Kheis Tectonic Province during the period 1400 - 1000 Ma. The currently proposed age of the Koras Group: 1200 Ma, Botha et al. (1980); 1100 Ma, Stowe (1980); 1000 Ma, Moen (1980) suggests that the Koras Group was formed during the Namaqua Event and that it is therefore a syntectonic, albeit late syntectonic, cover sequence. However, Botha et al. (1977) consider that an age of 900 Ma is more appropriate if the Koras Group is to postdate their last ( $F_3$ ) phase of folding in "Kheis" rocks. In addition other discrepancies exist, for example, Joubert (1981, p. 688) writes:

"Rather surprisingly these (Koras) rocks, of which an acid lava was dated at  $1280 \pm 50$  Ma, in places lie on granite similar to others dated at  $\pm 1200$  Ma." Clearly then, the age determinations in the area are contradictory and require some detailed attention and explanation. Any discussion of the ages of various fold phases is still speculative although broad time periods are

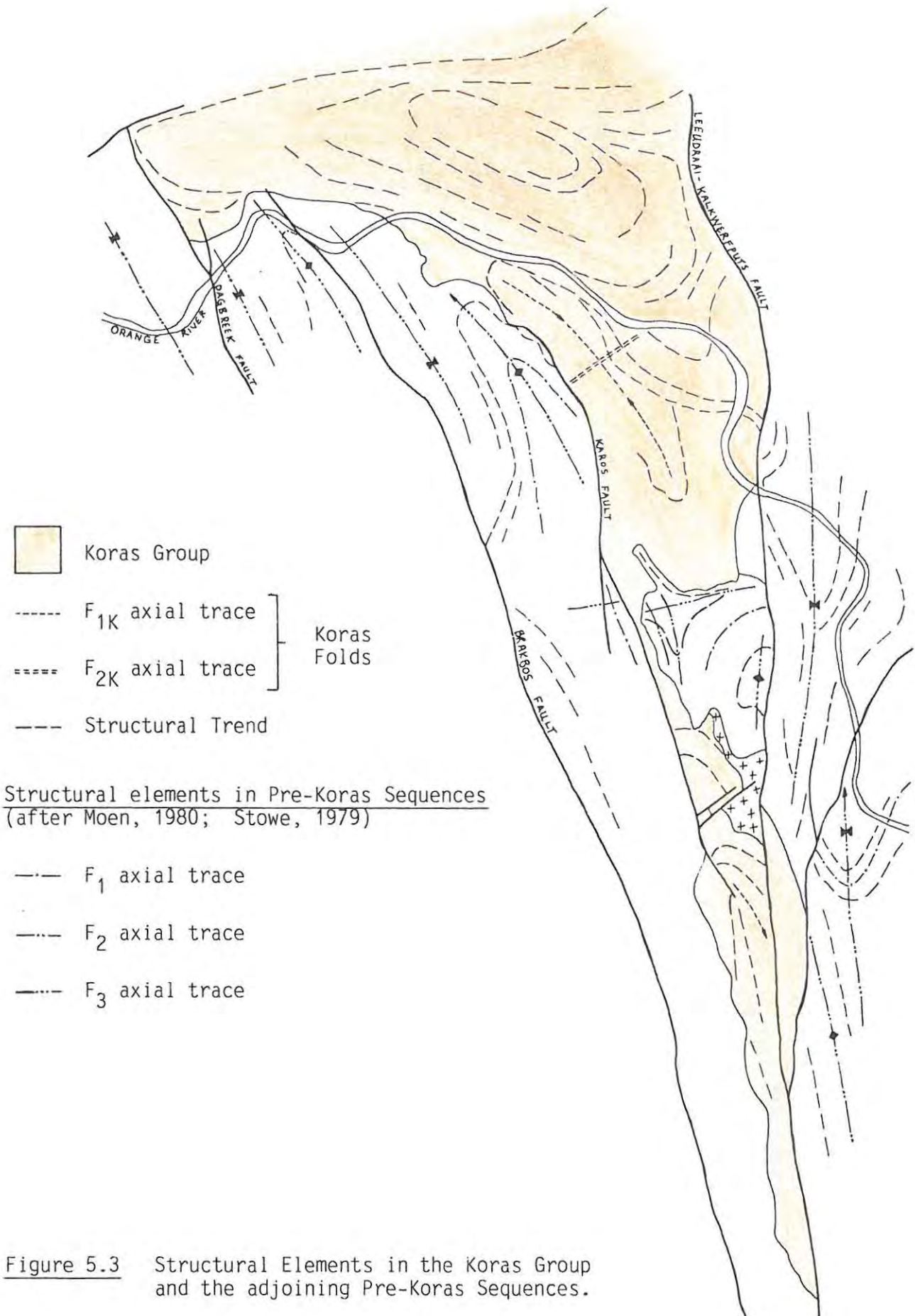


Figure 5.3 Structural Elements in the Koras Group and the adjoining Pre-Koras Sequences.

emerging. Further discussion of ages obtained from rocks of the Koras Group is continued in section 8.1.

During the late stages of the Namaqua Event, the area under consideration was traversed by numerous faults and fault zones (Stowe, 1981). These faults have affected Koras rocks significantly so that they were definitely operative on a major scale during post-Koras times. Botha et al. (1977) believe that the faults were active before, during and after Koras deposition. Two sets of faults, which represent two ages of faulting, postdate the  $F_2$  folding event of the pre-Koras sequences (Botha et al., 1977; Moen, 1980). The earliest set of faults is northwest striking and includes the major faults described in section 5.3. These are dextral wrench faults with components of downthrow to the east. The second set displaces the first set and has an easterly to northeasterly strike (Botha et al., 1977; Moen, 1980); some of these have sinistral displacements (Stowe, 1981).

In conclusion it is postulated that the Koras Group was deposited and folded during the late stages of the Namaqua Event although the deposition of the Kalkpunt red beds, at the top of the Koras succession, probably occurred towards the end of the major period of northwest-trending, strike-slip faulting. This synorogenic, albeit late synorogenic, deposition created unconformities within the sequence as suggested by Vajner (1974, p. 17). The late large-scale faults which dissect the area have resulted in considerable uplift in the west and major dextral wrench movement along the Doornberg lineament. Thus the Central and Southern Domains of the Koras Group are the infolded and downfaulted erosional relicts of a once more widespread late-syntectonic cover sequence.

## 6. GEOCHEMISTRY OF THE LAVAS

### 6.1. Introduction

Major and trace element analyses for thirty volcanic rocks of the Koras Group are presented. In addition, two amygdaloidal basalts (CS-25,26) of the Rouxville Member in the Central Domain were analysed twice, i.e., with and without the amygdales, so that the effect of the amygdales on the analyses could be examined. Localities and short petrographic descriptions of the analysed samples, sample preparation procedures and analytical techniques are presented in appendices 1 to 3. The analytical results are listed in appendix 4 but unless specified otherwise the major element data used are anhydrous values normalized to 100% (appendix 5). All Fe was determined as  $\text{Fe}_2\text{O}_3$  and in the norm calculation (appendix 5) the formula of Irvine and Baragar (1971) was used to determine the  $\text{Fe}_2\text{O}_3/\text{FeO}$  values which are listed in column A of Table L, appendix 7.

$$\% \text{Fe}_2\text{O}_3 = \% \text{TiO}_2 + 1.5 \text{ (Irvine and Baragar, 1971, p.526).}$$

In keeping with the previous work in this department e.g., Pemberton (1978), Mitchell (1980), norms calculated using  $\text{Fe}_2\text{O}_3/\text{FeO} = 0.2$  are also provided (appendix 6).

The symbols used to represent the Koras lavas are the same for all the graphical plots and are presented in Table 6.1.

Table 6.1. Symbols Used to Represent the Koras Lavas

Solid symbols	—	Central Domain
Hollow symbols	—	Southern Domain
+	—	Swartkop Member
▲ △	—	Rouxville Member (amygdale-free analyses)
◻	—	Analyses CS-25A, CS-26A (amygdales not extracted)
■ □	—	Swartkopsleegte Member
● ○	—	Lambrechtsdrif Member
⊗	—	Analysis CS-10

## 6.2. Classification

The classification scheme of Irvine and Baragar (1971) as well as some other diagrams have been used to classify the basaltic lavas and quartz-feldspar porphyries of the Koras Group. Irvine and Baragar's (op.cit.) classification scheme is essentially non-genetic and is based on analyses of rocks that are Precambrian or Cenozoic in age and are from several dozen different localities or environments.

Two diagrams are used to distinguish between alkaline and subalkaline volcanics (Figs. 6.1a, 6.1b), and both plots indicate clearly that the Koras lavas represent a subalkaline association. Subalkaline rocks are further classified as tholeiitic or calc-alkaline on the commonly used AFM-diagram (Fig. 6.2a) and the  $Al_2O_3$  - normative plagioclase plot (Fig. 6.2b). Jensen's (1976) cation plot (Fig. 6.2c), Miyashiro's (1974) diagrams (Figs. 6.2d,e) and Green's (1973) diagram (Fig. 6.11, p.108) have also been used for the tholeiitic/calc-alkaline distinction. The results suggest that the Koras lavas are best classified as a tholeiitic association and indicate a slight "iron-enrichment trend" in the Rouxville basalts (triangular symbols, Figs. 6.2a,c). It should be noted, however, that the Lambrechtsdrif lavas are clearly transitional tholeiitic/calc-alkaline rocks with minor compositional variation, but their low  $Al_2O_3$ -contents (average = 14.85%, S.D. = 0.20; see Fig. 6.2b), and slightly high FeO and  $TiO_2$  concentrations (Figs. 6.2c,e) supports the general classification as tholeiitic.

Following Irvine and Baragar (1971), further classification within a suite or association of volcanic rocks is made using a normative colour index-normative plagioclase diagram as shown in Figure 6.3a. The classification diagrams of Cox et al. (1979, p.14), and Streckeisen and Le Maitre (1979) are also used. The results from the three chemical classification diagrams as well as the modal classification (Streckeisen, 1979) and names suggested by the present author are listed in Table 6.2. The Lambrechtsdrif lavas, which have a close grouping, are clearly transitional rocks between basalt and andesite and are best described as basaltic andesites. The Swartkopsleegte quartz-feldspar porphyries which also exhibit a close grouping, are transitional rocks between dacite and rhyolite and the name rhyodacite is proposed following the suggestion of Streckeisen (1979) and Streckeisen and Le Maitre (1979) that the term "rhyodacite" is not applied to any specific field within classification diagrams but should be used for transitional rocks between dacite and rhyolite. The Rouxville lavas do not exhibit the close grouping typical of the other members and are best described as basalts to basaltic andesites while the Swartkop quartz-feldspar porphyries can be classified as rhyolites.

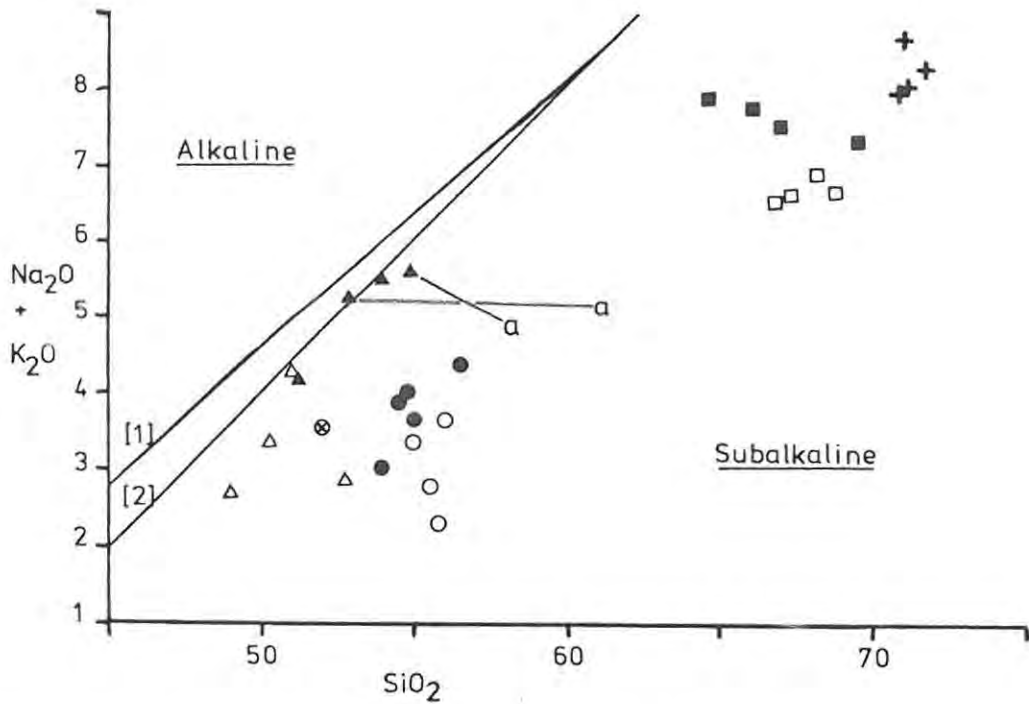


Figure 6.1a. Alkalies-silica diagram with dividing lines proposed by (1) Irvine and Baragar (1971), and (2) MacDonald (1968). (Plots in wt. %).

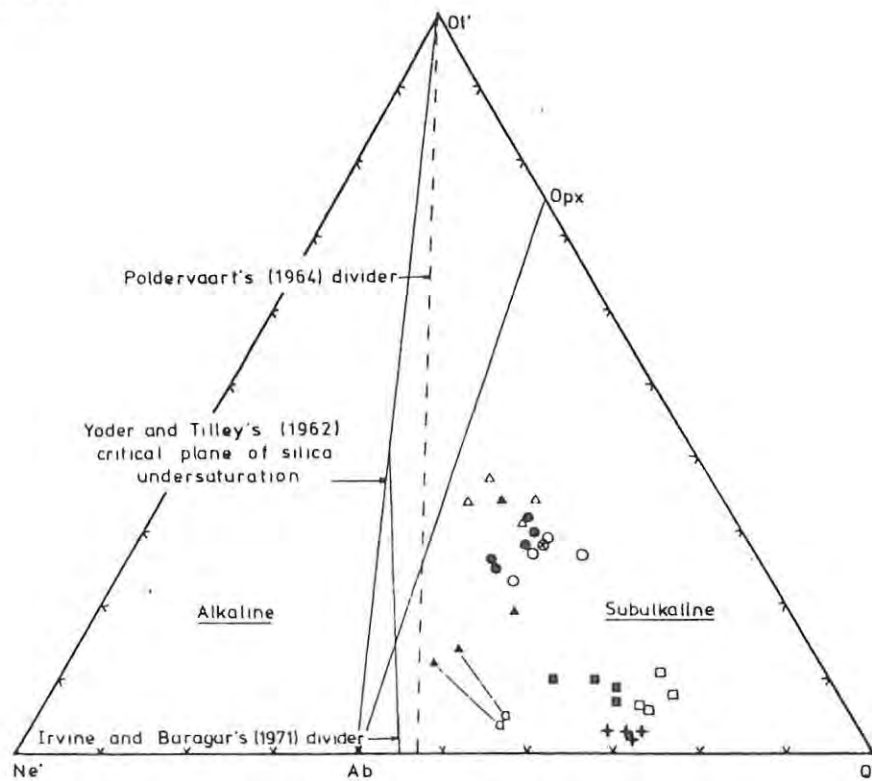


Figure 6.1b.  $\text{O}1'$ - $\text{Ne}'$ - $\text{Q}'$  projection illustrating the subalkaline character of the Koras lavas (Plots in % cation equivalents based on the cation norm).

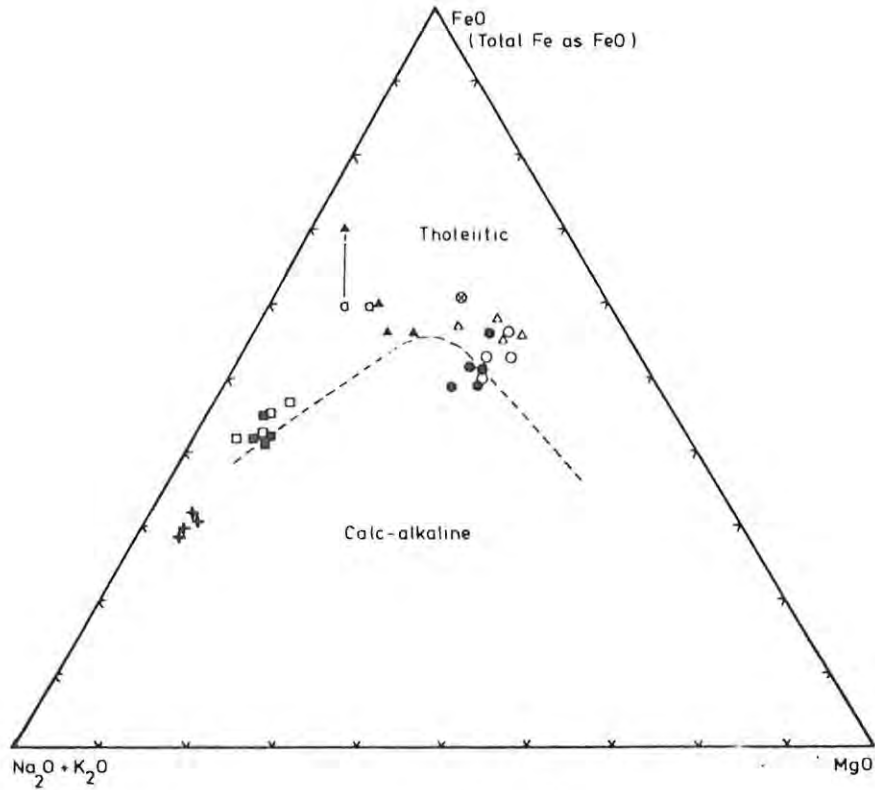


Figure 6.2a. AFM diagram illustrating the slight "iron enrichment trend" in the Rouxville Basalt Member and close grouping in the other three volcanic members.

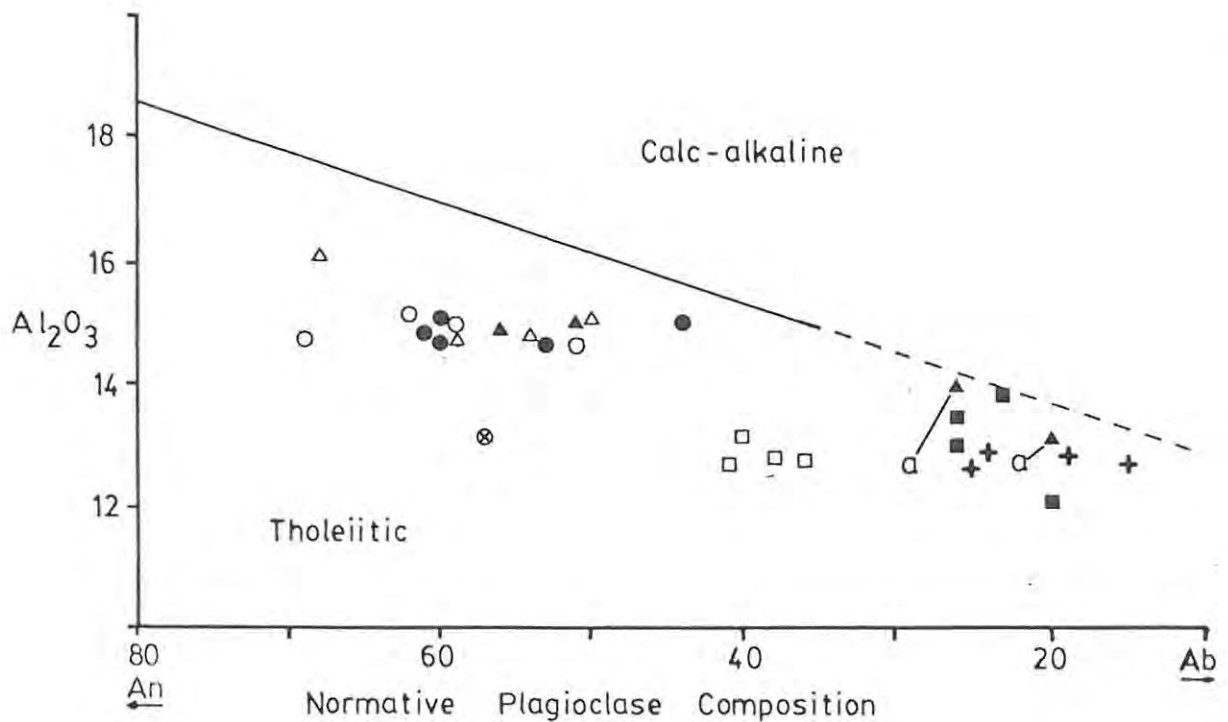


Figure 6.2b. Al<sub>2</sub>O<sub>3</sub>-normative plagioclase plot illustrating the tholeiitic character of the Koras lavas.

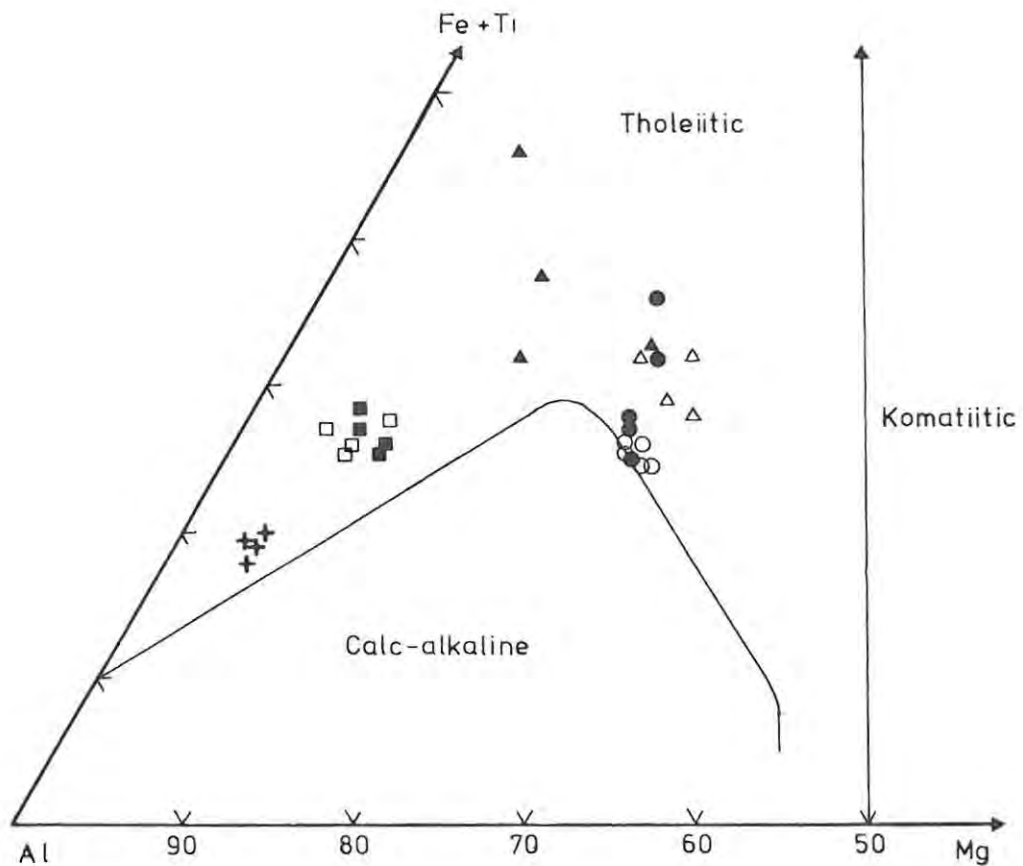
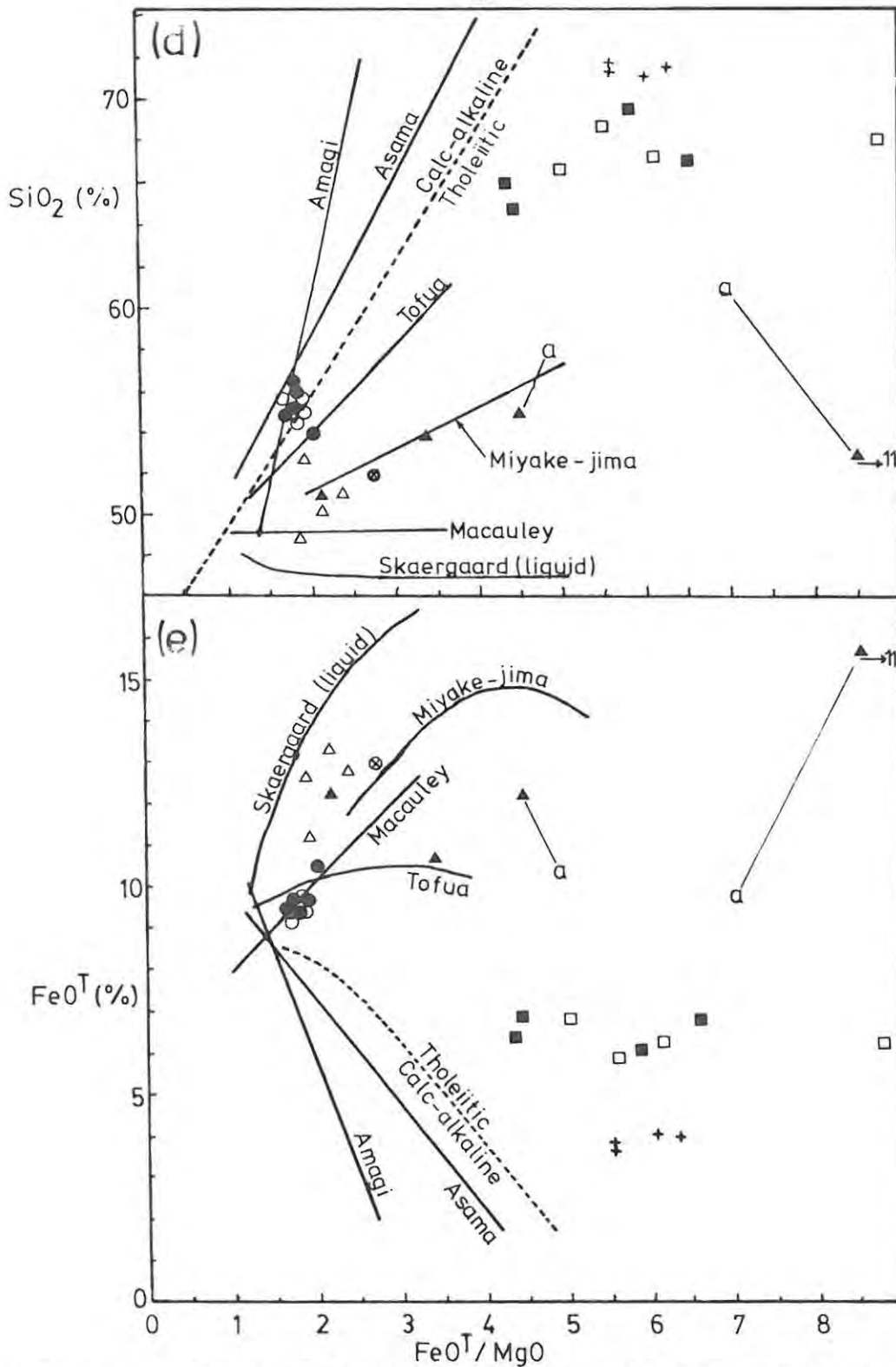


Figure 6.2c. Jensen's (1976) diagram for distinguishing between tholeiitic and calc-alkaline lavas. This plot, together with Fig. 6.2b supports the view that the Koras Group represents a tholeiitic association.

Finally, Irvine and Baragar (1971) suggest approximate guidelines for distinguishing between K-rich, "average" and K-poor lavas (Fig. 6.4). This plot clearly emphasizes the generally K-rich character of the Koras lavas although the tholeiitic basaltic andesites of the Rouxville Member (CS-25, 26) are Na-rich. Thus on the basis of the analytical results of this study (thirty analyses), the Koras lavas are classified as an "average-K" to K-rich, tholeiitic, subalkaline association consisting of bimodal basaltic-rhyolitic volcanics.



Figures 6.2d,e.

Comparison of the Koras lavas with various subalkaline (non-alkalic) volcanic rock series (from Miyashiro, 1974). The diagrams suggest that the Rouxville basaltic lavas ( $\Delta\blacktriangle$ ) and the quartz-feldspar porphyries ( $\square\blacksquare+$ ) are tholeiitic while the Lambrechtsdrif basaltic Lavas ( $\circ\bullet$ ) are transitional tholeiitic/calc-alkaline rocks.

Amagi volcano, Izu-Bonin Arc in Japan (Kurasawa, 1959).  
 Asama volcano, Northeast Japan Arc (Aramaki, 1963).  
 Tofua Island, Tonga Arc (Bauer, 1970; Baker et al., 1971; Bryan et al., 1972).  
 Miyake-jima volcano, Izu-Bonin Arc, Isshiki (1960, 1964).  
 Macauley Island, Kermadec Arc (Brothers and Martin, 1970).  
 Skaergaard intrusion (Wager and Brown, 1967).

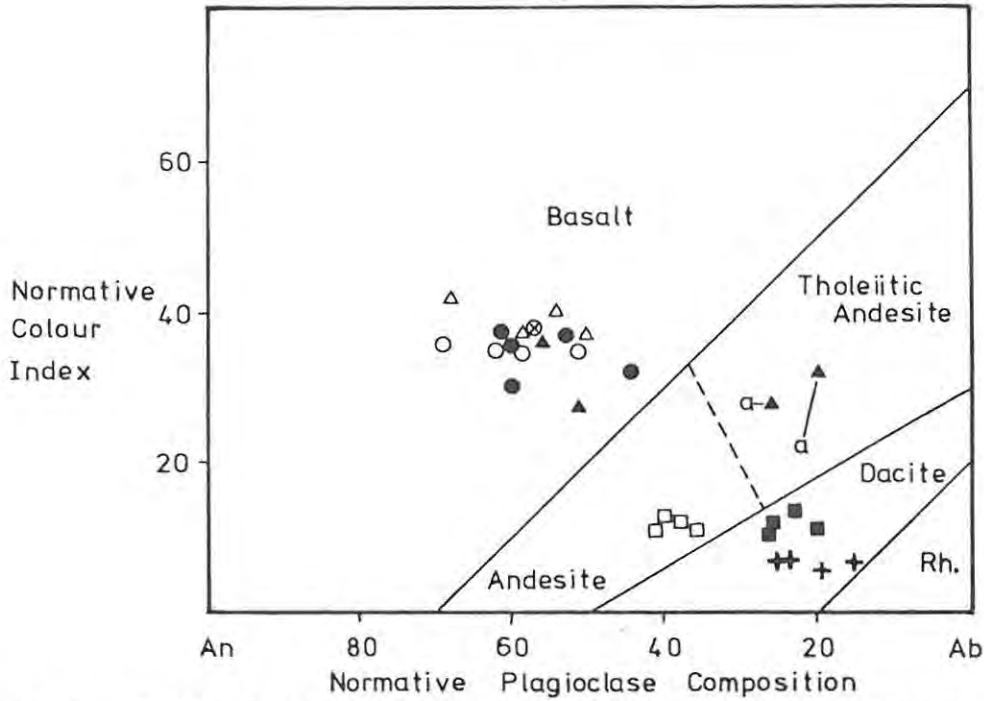


Figure 6.3a. Plot of normative colour index versus normative plagioclase composition for the Koras lavas using the dividing lines proposed by Irvine and Baragar (1971). (Plots in % cation equivalents).

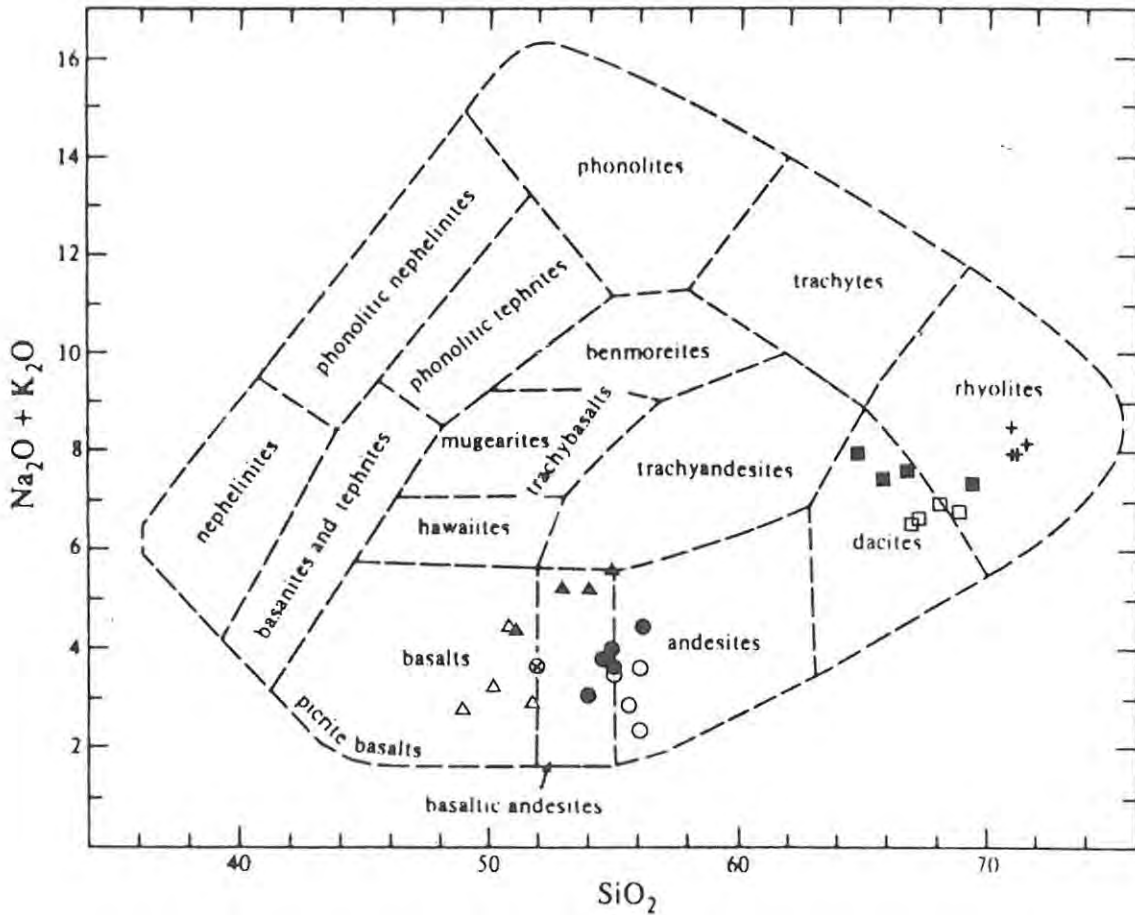


Figure 6.3b. Nomenclature of volcanic rocks (excluding ultrapotassic rocks, after Cox et al., 1979, p.14). The diagram illustrates the generally close grouping within individual members of the Koras Group and provides the best agreement with the modal classification. (Plots in wt. %).

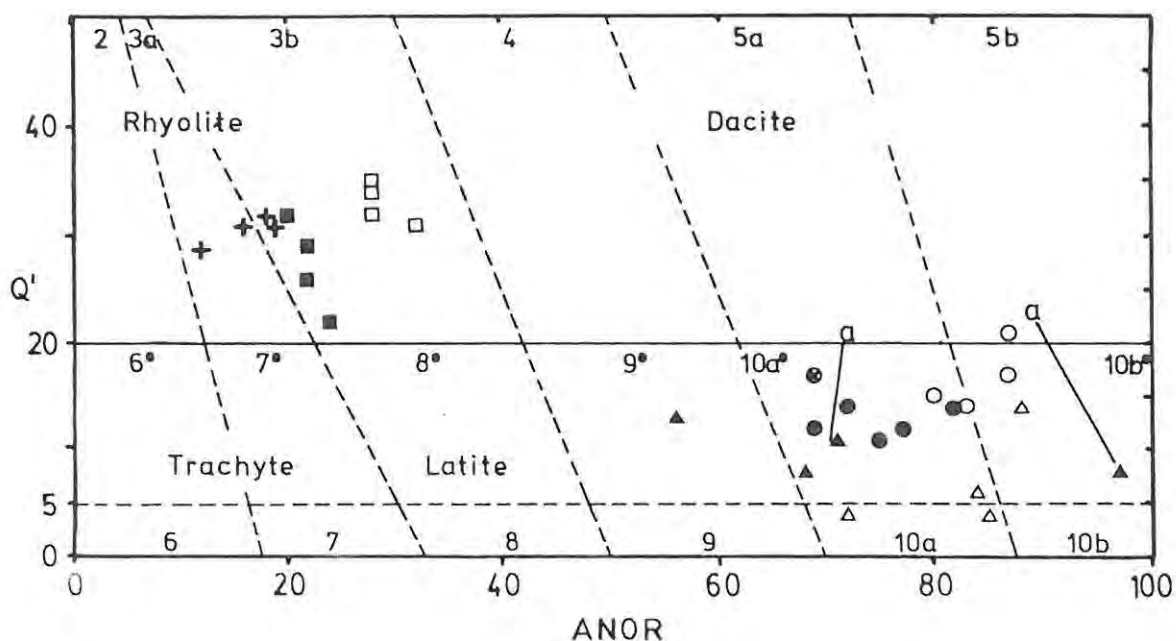


Figure 6.3c. Q'-ANOR diagram (after Streckeisen and Le Maitre, 1979) for the Koras lavas showing the normative fields 2, 3a, 3b, etc., which correspond approximately to the fields 2, 3a, 3b, etc., of the modal QAPF diagram of Streckeisen (1979).

$$Q' = (Q/Q + Or + Ab + An) \times 100$$

$$ANOR = (An/An + Or) \times 100$$

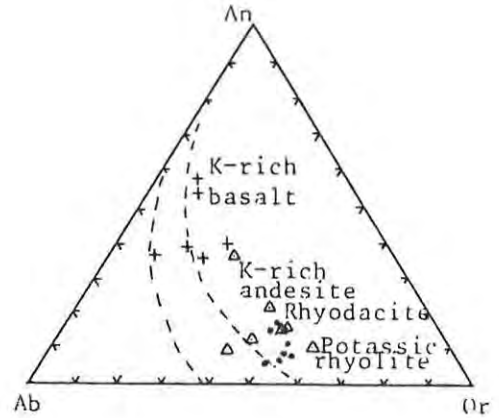
Plots in % normative minerals (Barth-Niggli molecular norm). Fields 9 to 10 include basalts and andesites which are distinguished by Streckeisen (1979) using 52% SiO<sub>2</sub> as the divider. By this criterion Lambrechtsdrif lavas are all andesites while Rouxville lavas are basalts to andesites (see Fig. 6.3b).

Table 6.2. Classification of the Koras Lavas

	LAMBRECHTSDRIF MEMBER	SWARTKOPSLEEGTE MEMBER	ROUXVILLE MEMBER	SWARTKOP MEMBER
Modal classification (Streckeisen, 1979) See chapter 4.	basalts to andesites	dacites to rhyolites	basalts to andesites	rhyolites
Irvine and Baragar (1971), Fig. 6.3a.	basalts	andesites/ dacites	basalts to tholeiitic andesites	dacites
Cox et al. (1979), Fig. 6.3b.	basaltic andesites to andesites	dacites to rhyolites	basalts to basaltic andesites	rhyolites
Streckeisen and Le Maitre (1979), Fig. 6.3c.	andesites	rhyolites	basalts to andesites	rhyolites
Present author, on the basis of the above results.	basaltic andesites	rhyodacites	basalts to basaltic andesites	rhyolites

Key for Inset Diagram

- + Basaltic Rocks
- △ Lower Porphyry (Swartkopsleegte Mbr.)
- Upper Porphyry (Swartkop Mbr.)



KEY

- + Swartkop Member
- △ Rouxville Member
- CS-25A, 26A
- Swartkopsleegte Mbr.
- ● Lambrechtsdrif Mbr.
- ⊗ CS-10

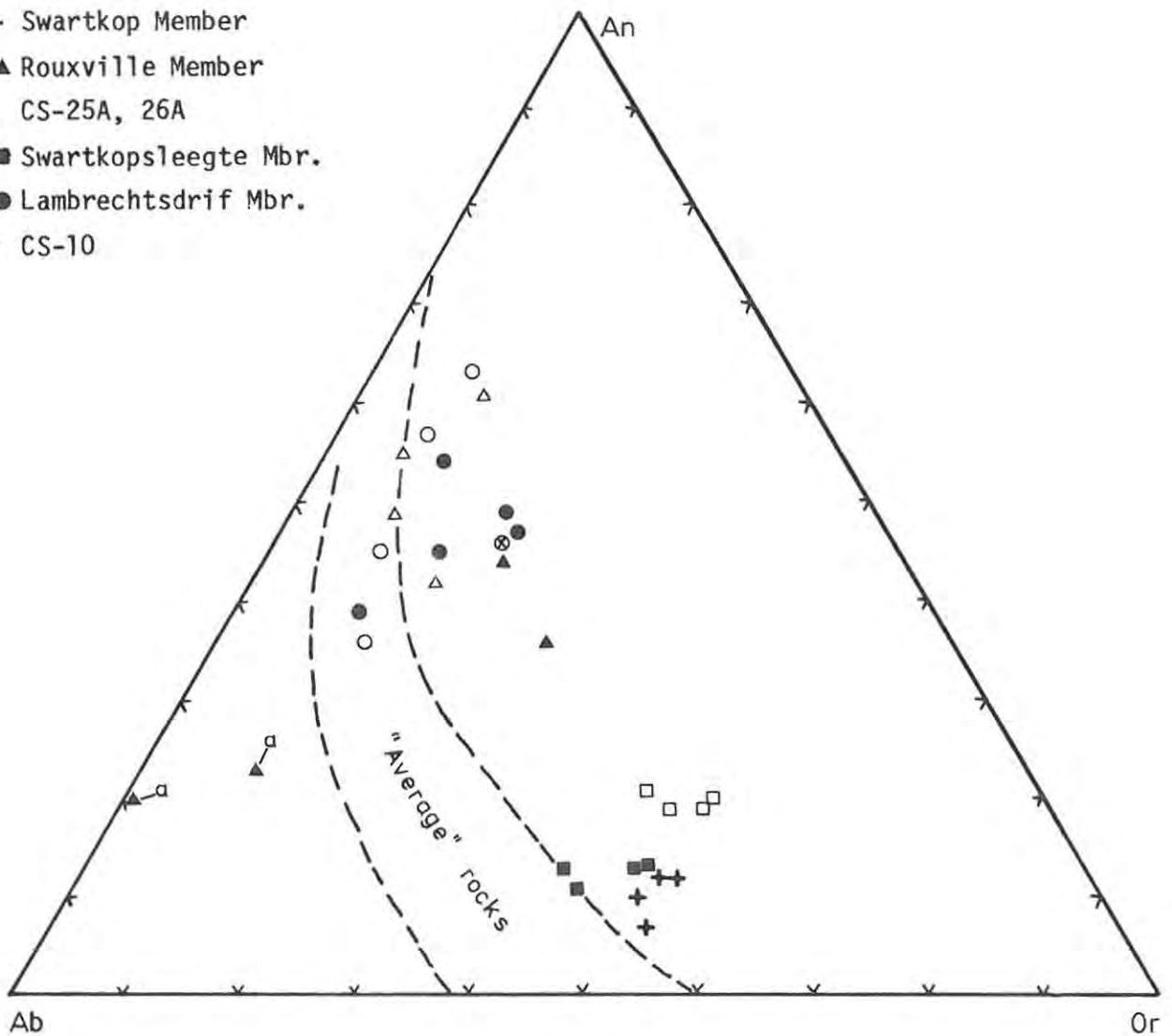


Figure 6.4. An-Ab-Or projection illustrating the K-rich character of the Koras lavas, with the exception of the tholeiitic basaltic andesites (CS-25,26) of the Rouxville Member which are Na-rich. Similar results were obtained by Grobler et al. (1977, p.171) whose diagram is included for comparison (inset diagram; plots in % cation equivalents; after Irvine and Baragar, 1971)

### 6.3. Major and Trace Element Variation

Major element variation diagrams (Figs. 6.5a-d) and trace element variation diagrams (Figs. 6.6a-g) are presented for the Koras lavas, and together with the classification plots these diagrams illustrate several important features.

The basaltic andesites of the Lambrechtsdrif Member (CS-1 to 9, hollow and solid circular symbols) exhibit a close grouping on all diagrams as one would expect from an inspection of the analyses. Thus the average of the nine samples (appendix 4) provides a geochemical "fingerprint" for the member.

The Swartkopsleegte rhyodacites also exhibit a close grouping on all diagrams. Samples from the Central Domain (solid squares) and the Southern Domain (hollow squares) are generally similar in major and trace element chemistry with the exception of CaO and Na<sub>2</sub>O. Central Domain samples have slightly lower CaO and slightly higher Na<sub>2</sub>O when compared to their Southern Domain correlatives. This has resulted in their separation into two groups on diagrams that use normative plagioclase as an abscissa, e.g., Figs. 6.2b, 6.3a.

Although the Fe<sub>2</sub>O<sub>3</sub> - MgO plot (Fig. 6.5b) for the Rouxville lavas is somewhat scattered, the basalts to basaltic andesites of this member exhibit a weak "iron- enrichment trend" (Figs. 6.2a,c) which is accompanied by increasing contents of Si, Ti, Na and P, and decreasing amounts of Mg, Al and Ca. The more basic endmembers of the "trend" are from the Southern Domain while the Central Domain samples are more evolved rocks within the Rouxville Member e.g. CS-25, 26 have 53-55% SiO<sub>2</sub> with low MgO (1,4-2,8%), and high Fe, Na, Ti and P contents. However, further samples are required to establish that there is a definite, continuous differentiation trend within the member, to outline the possible trend clearly and to support further the lithostratigraphic correlation of the Rouxville Member between the domains. Trace element patterns also indicate the possibility of a differentiation trend in the Rouxville Member and, in general these are a reflection of the major element variation. Rb has a similar pattern to K, Sr mimics Ca weakly, while Zr, Y, Nb, La, Nd, Ce exhibit the typical behaviour of incompatible elements and are similar in their behaviour to P<sub>2</sub>O<sub>5</sub>. Cr, Co and Ni decrease in concentration with decreasing MgO and V, Cu and Zn exhibit fairly constant to slightly erratic behaviour.

The basic rocks of the Rouxville Member can be distinguished from those in the Lambrechtsdrif Member by their higher Ti, Fe, P, Y, Ni, Zn, La, Nd, and Ce contents and lower Cu concentrations.

The Swartkop Member samples (CS-27-30) exhibit a close grouping and this suggests very limited chemical variation within these lavas on Karos Nedersetting.

Amygdale-inclusive analyses (CS-25A, 26A). The amygdales in CS-25A consist mainly of quartz and calcite and those in CS-26A are almost entirely of quartz. As one would expect the resultant effect is one of dilution of most components of the analyses with the exception of those components that make up the amygdales. Thus  $\text{SiO}_2$  increases in both samples while CaO increases in CS-25A. The decrease in CaO and increase in  $\text{K}_2\text{O}$  in CS-26A, relative to CS-26, may be a result of minor secondary alteration or possibly minor heterogeneity in the sample material. All other major elements decrease in concentration. Rb mimics K, while Sr exhibits an inverse relationship with Ca. The limited data precludes any interpretation of this Ca-Sr relationship except to say that CS-26A may have undergone slight secondary alteration. All other trace elements decrease in concentration. The results reaffirm the work of Pemberton (1978, p.13) and emphasize the need to remove amygdales during sample preparation, although for general purposes, a small amount of amygdale contamination can be tolerated.

Analysis CS-10. On the major and trace element variation diagrams and the classification plots, sample CS-10 does not fall within the close group of nine sample points of the Lambrechtsdrif Member. CS-10 has chemical characteristics that are similar to those of the Rouxville Member Lavas e.g., high  $\text{P}_2\text{O}_5$  and  $\text{TiO}_2$ , and on most variation diagrams falls within the "trend" exhibited by the Rouxville Member. It is therefore suggested that the sample was probably collected from a small dyke or fissure intrusion of the Rouxville Member, in the Lambrechtsdrif Member, which was not identified in the field due to the poor exposure in the area. Mineralogically, sample CS-10 also differs from the more typical Lambrechtsdrif lavas in having phenocrysts of orthopyroxene compared to the usual aphanitic plagioclase-augite assemblages. Petrographic comparison with the Rouxville lavas is difficult because of the commonly amygdaloidal, aphanitic to porphyritic nature of these lavas and the presence of altered mafic phenocrysts (pyroxene?) in some samples e.g., KA-720.

Interelement Ratios. Selected interelement ratios are presented in Appendix 7 and Fig.6.7. Together with the variation diagrams these ratios show that the lava members of the Koras Group are geochemically distinct units and it is suggested that they are not related by any simple fractionation process. However, a detailed geochemical investigation of the inter-member

relationships of the Koras lavas is beyond the scope of this study and would require more whole rock analyses, as well as mineral analyses. In addition, such an investigation would be subject to the following limitations:

1. The Rouxville lavas have been shown to be flow-differentiated (Fig. 4.3.2) and some within-flow sampling would be required to determine the effects of flow-differentiation on chemical composition. Pemberton (1978, p.8) suggests, from work on Karoo basalts, that samples should be collected from as near the base of the flow as possible. (Concerning further analytical work on the basaltic lavas of the Rouxville Member, it will be essential to ensure that non-epidotized samples are used and that, as far as possible, all amygdales are removed).
2. The Koras quartz-feldspar porphyries contain numerous crustal xenoliths which suggests that:
  - (a) the porphyries are crustal melts, and the xenoliths represent relict, unmelted phases, or
  - (b) the porphyries are contaminated with crustal material and as such it will be very difficult to determine their uncontaminated composition.

However the most dominant feature of the Koras Lavas is their bimodal basaltic-rhyolitic composition and their petrogenesis is thus discussed in chapter 8 in the light of hypotheses for the origin of bimodal associations.

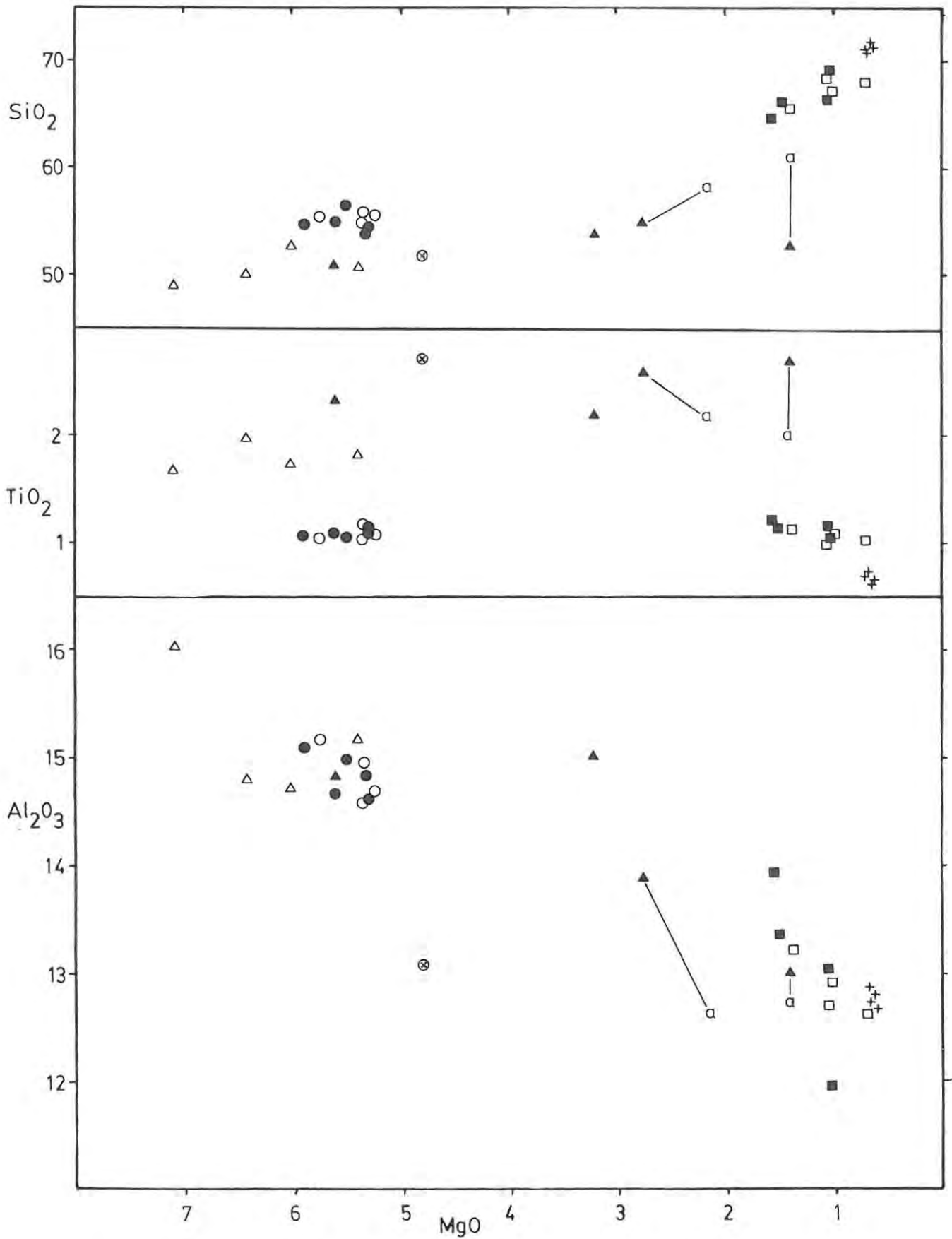


Figure 6.5a. Major element variation diagrams (weight % oxides) using MgO as the abscissa.

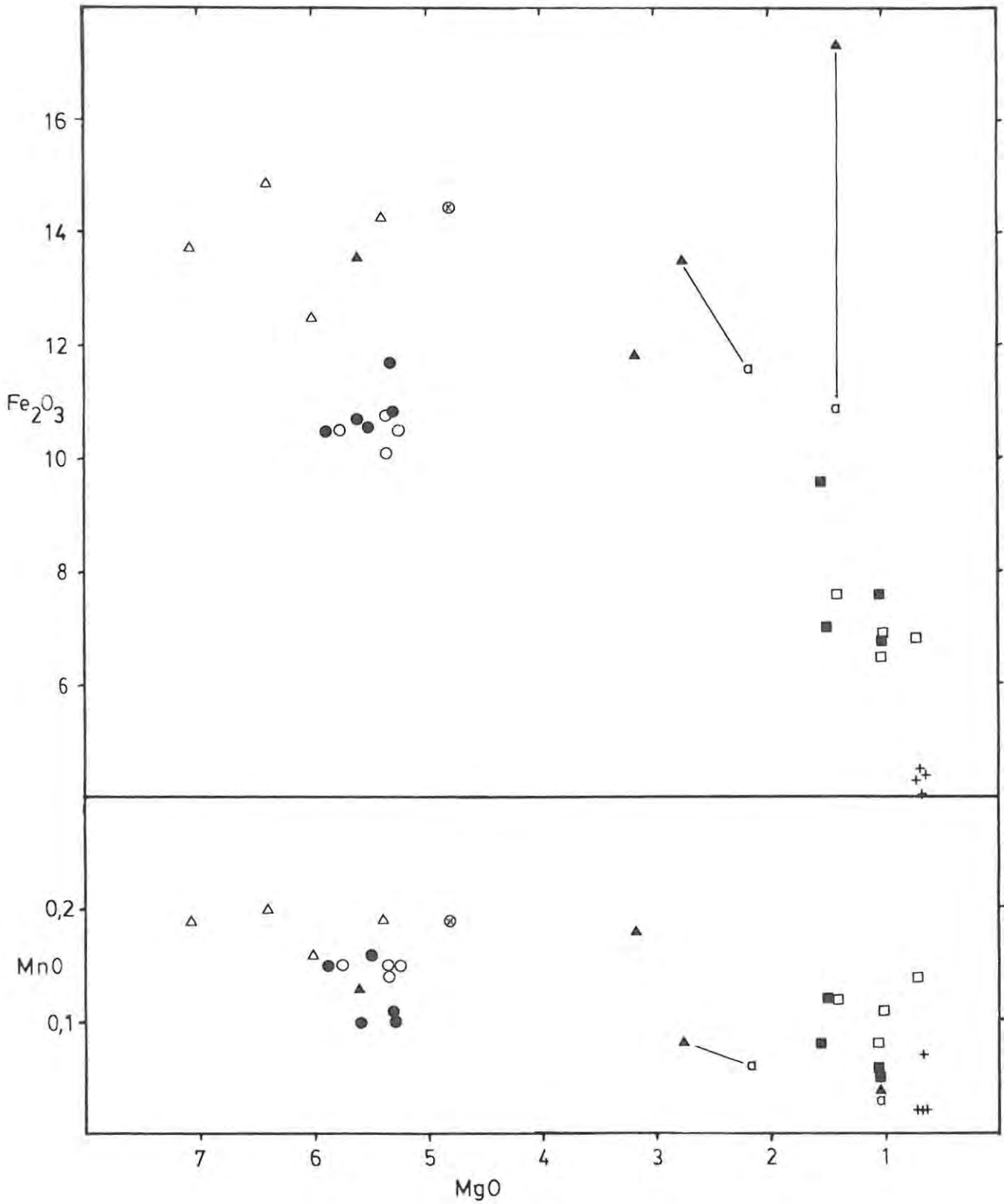


Figure 6.5b. Major element variation diagrams (weight % oxides) using MgO as the abscissa.

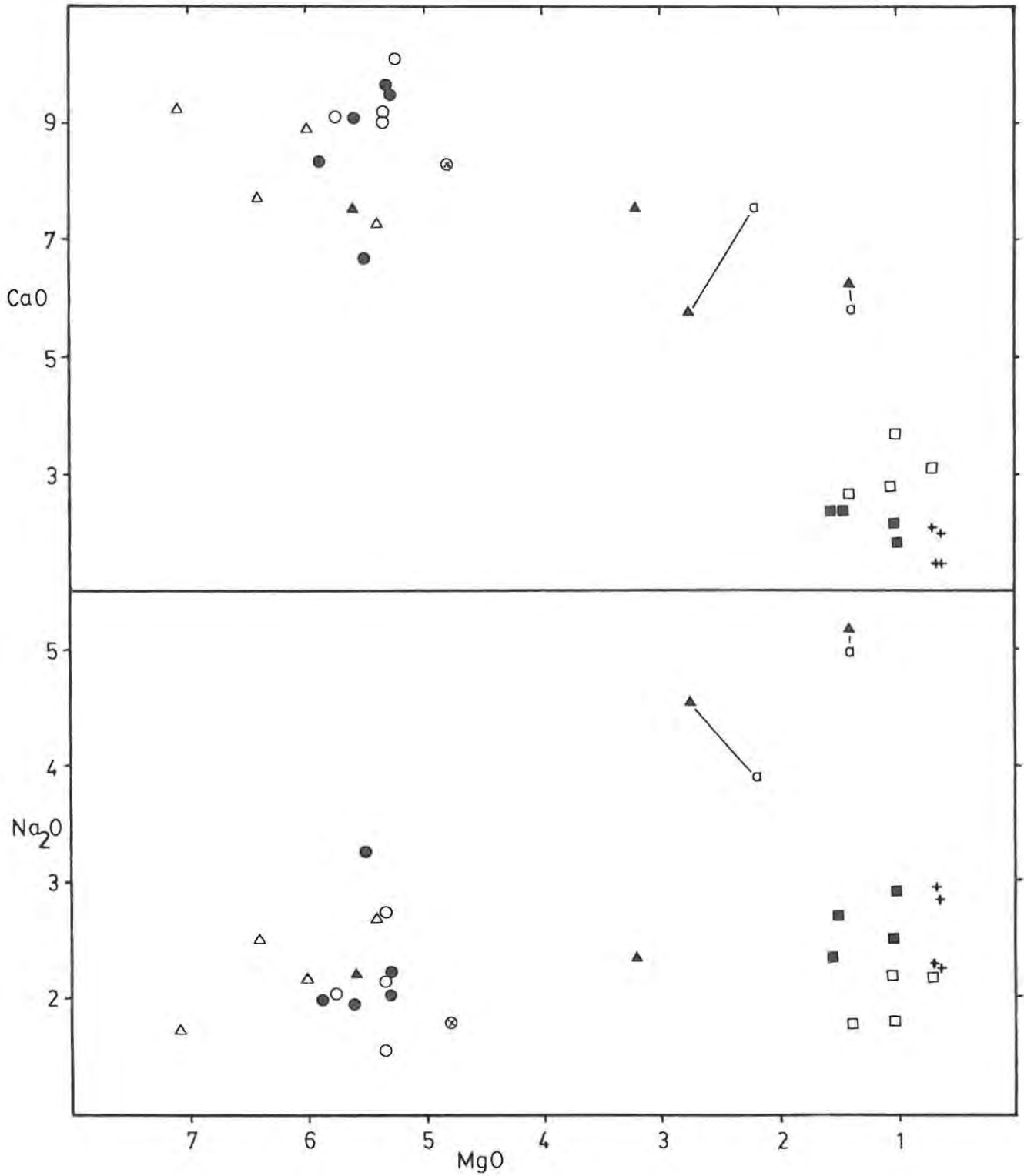


Figure 6.5c. Major element variation diagrams (weight % oxides) using MgO as the abscissa.

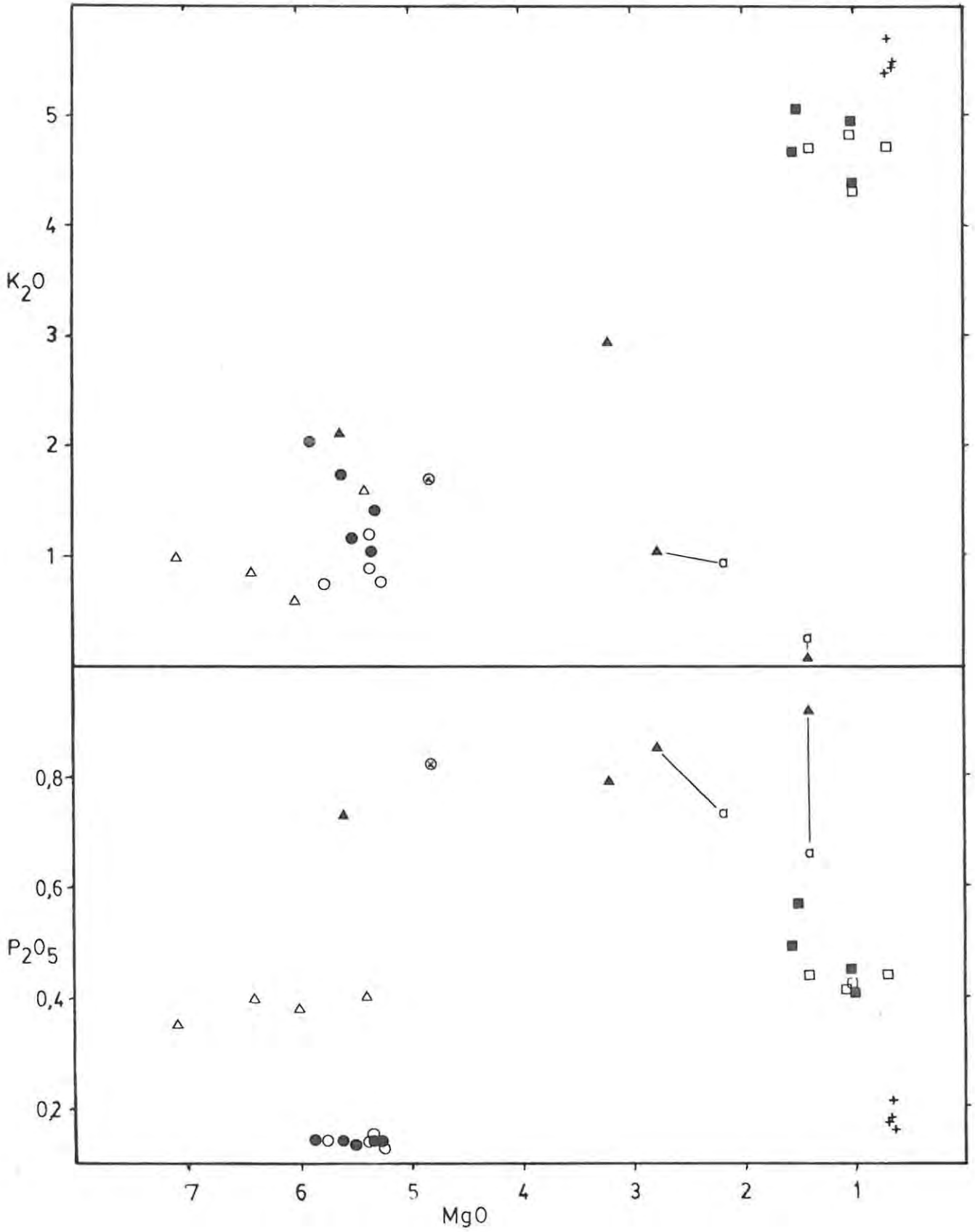


Figure 6.5d. Major element variation diagrams (weight % oxides) using MgO as the abscissa.

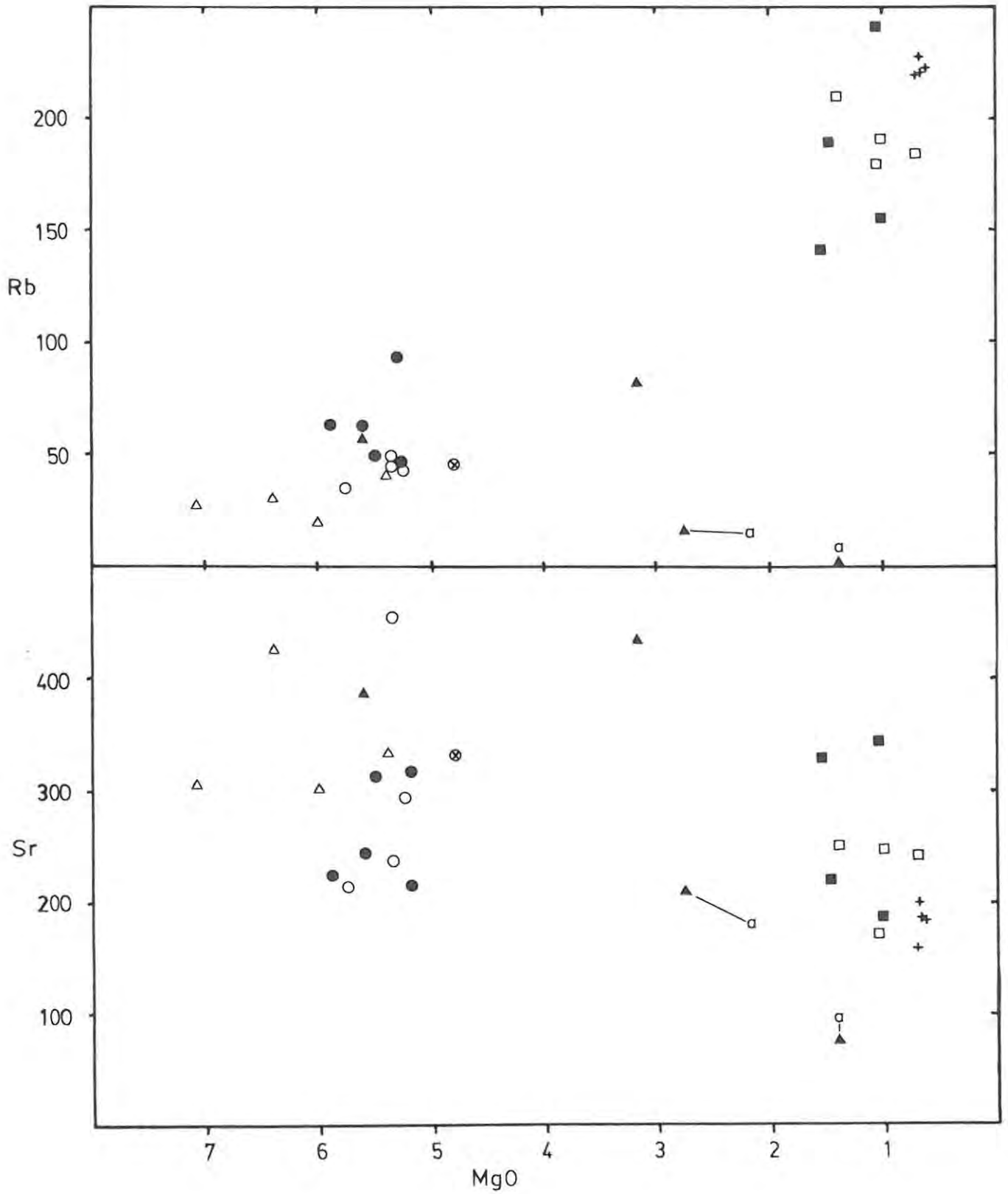


Figure 6.6a. Trace element variation diagrams (in parts per million) using MgO (wt.%) as the abscissa.

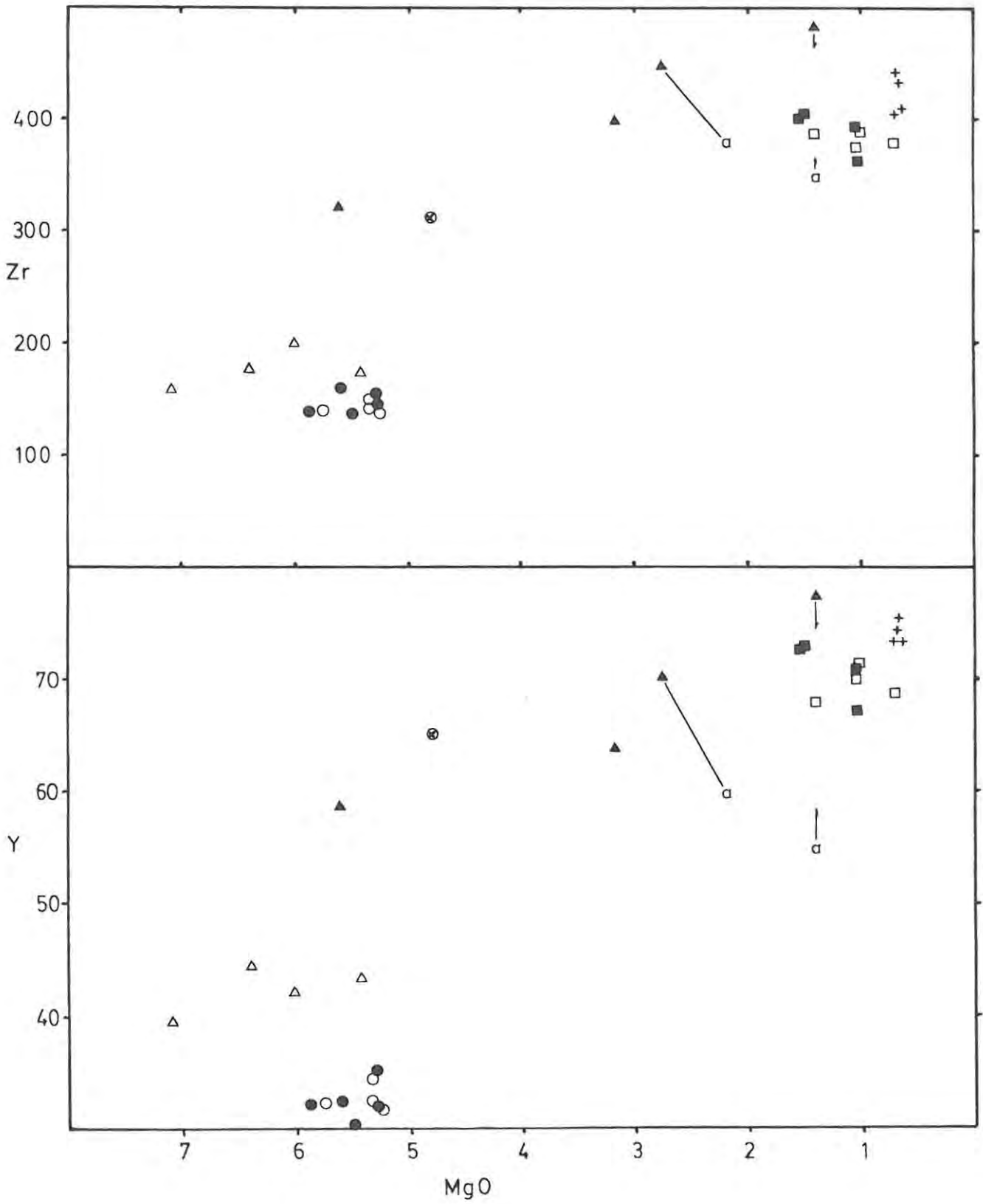


Figure 6.6b. Trace element variation diagrams (in parts per million) using MgO (wt.%) as the abscissa.

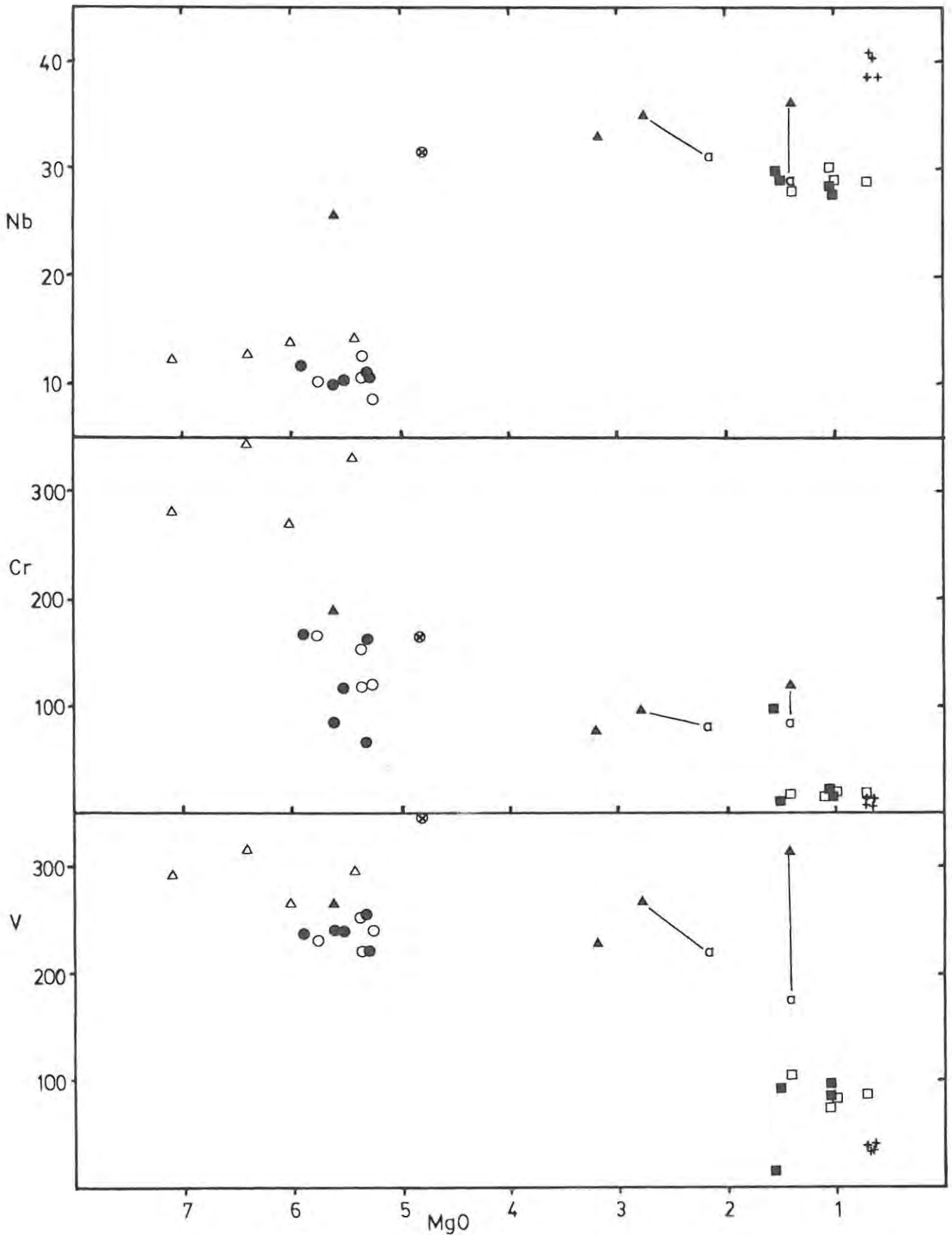


Figure 6.6c. Trace element variation diagrams (in parts per million) using MgO (wt.%) as the abscissa.



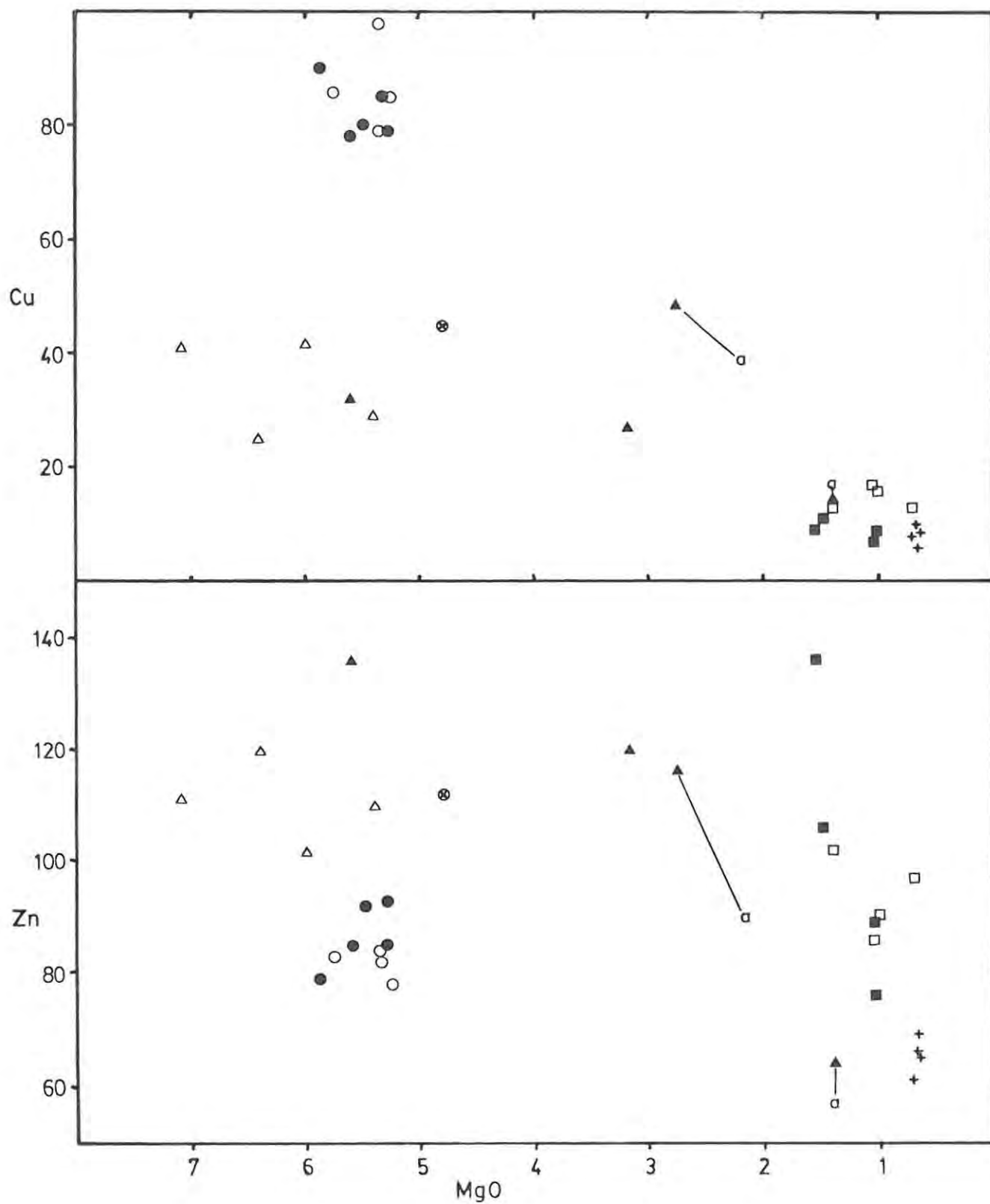


Figure 6.6e. Trace element variation diagrams (in parts per million) using MgO (wt.%) as the abscissa.

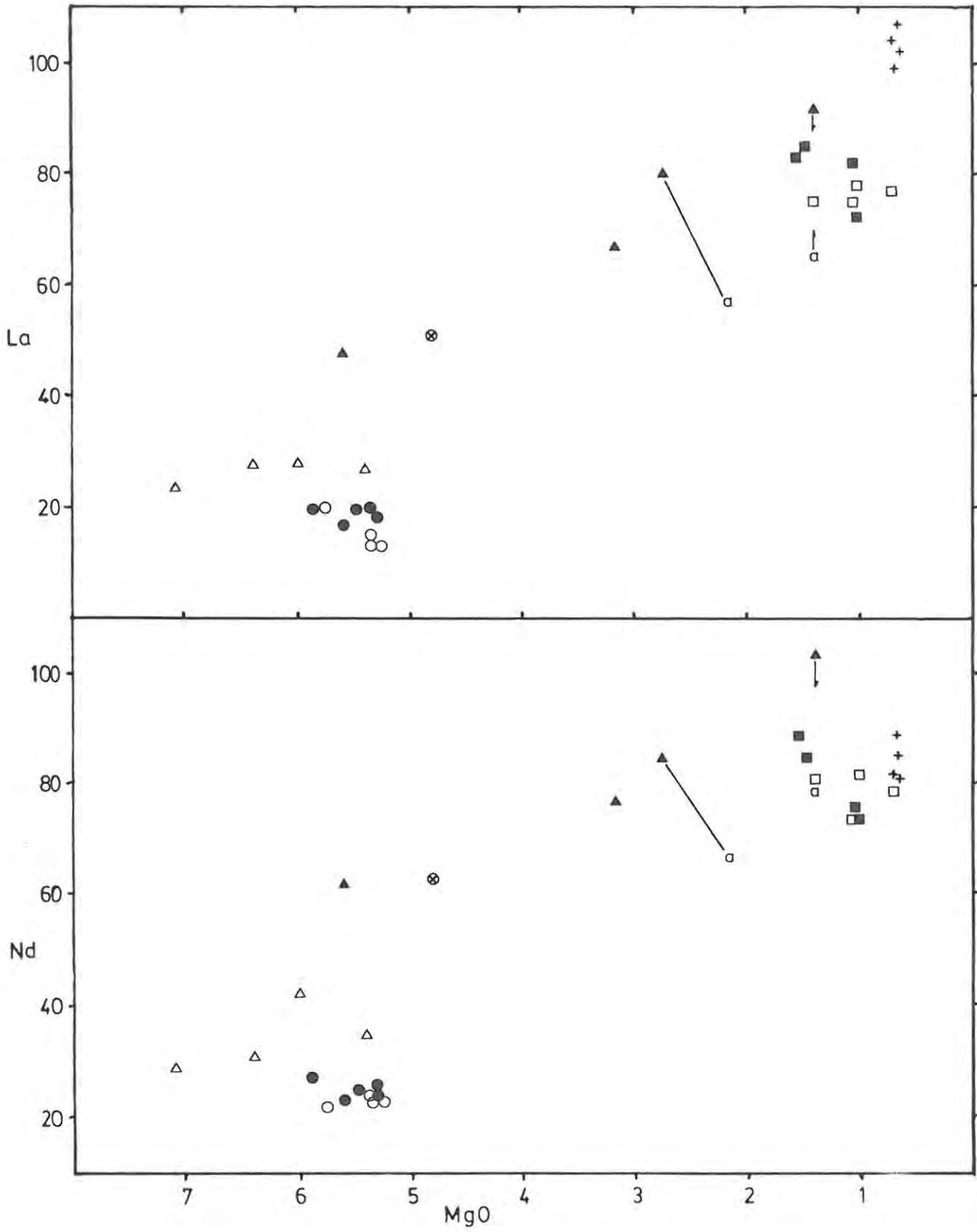


Figure 6.6f. Trace element variation diagrams (in parts per million) using MgO (wt.%) as the abscissa.

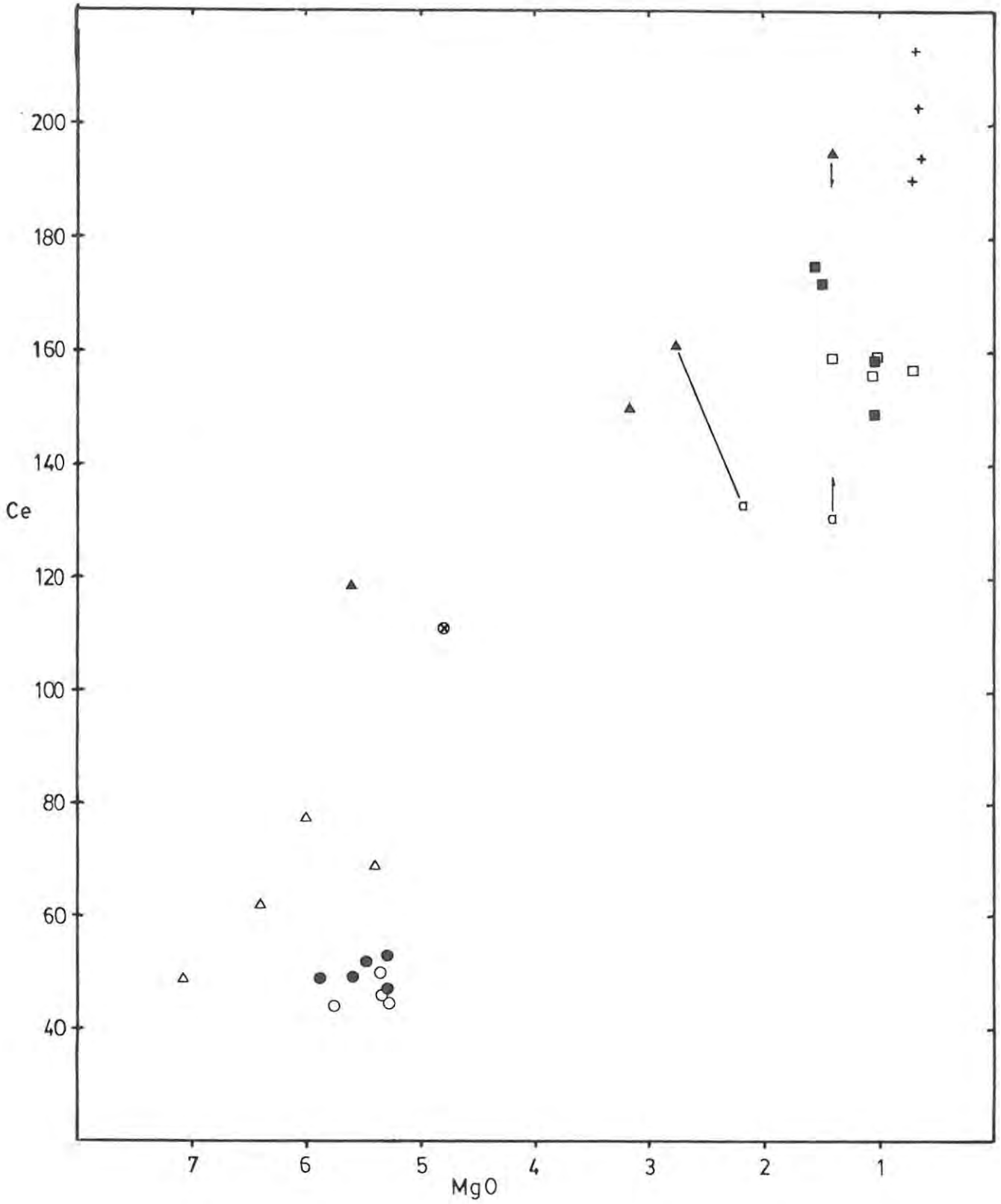


Figure 6.6g. Trace element variation diagram (in parts per million) using MgO (wt.%) as the abscissa.

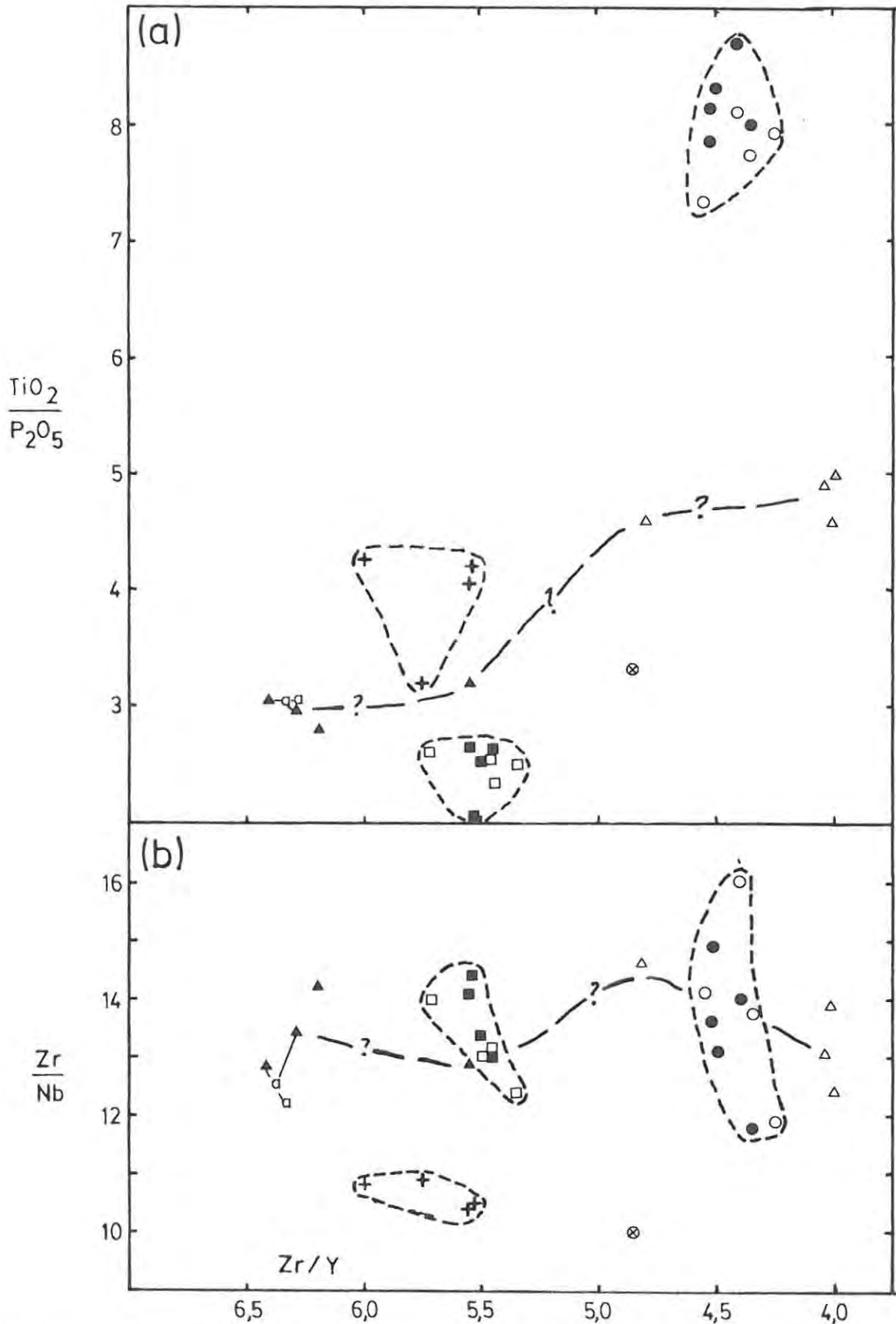


Figure 6.7. Selected interelement ratios for the Koras Lavas. The elongation of some fields is probably the result of low concentrations of certain elements in the particular volcanic units, e.g., the elongation of the Lambrechtsdrif Mbr. field in (b) is probably the result of the low concentrations of Nb (av. = 10.6; S.D. = 1.1) in this member, compared to Zr (av. = 144; S.D. = 6). The dashed line joining Rouxville Member samples outlines the possible "trend" in this unit.

#### 6.4 Comparison with Previous Work

On the basis of the stratigraphic succession of Du Toit (1965) and the work of Smit (1977), Grobler et al. (1977) proposed that the Koras lavas represent a shoshonitic, calc-alkaline association, and were emplaced in a newly stabilized orogenic region shortly after the cessation of the last period of Namaqua folding. Although Grobler et al. (1977) and the present study are in agreement that the Koras lavas are an "average-K" to high-K, subalkaline association (see Figs. 6.4, 6.8), the present study differs in that the Koras lavas are classified here as a tholeiitic association. In addition, the structural data of this study based on a newly proposed stratigraphic succession suggests that the Koras Group represents the erosional relicts of a late-syntectonic cover sequence that formed during the late stages of the Namaqua Event. Comparison of the geochemical work of Grobler et al. (1977) and the present study indicates that similarities exist, however, there are differences on the interpretation of the analytical data and the graphical plots. This problem can only be resolved by further, more detailed, geochemical work based on the newly proposed stratigraphic succession. In this regard, papers that are in preparation (Frick et al., in prep., and Moen, in prep.) should be most illuminating.

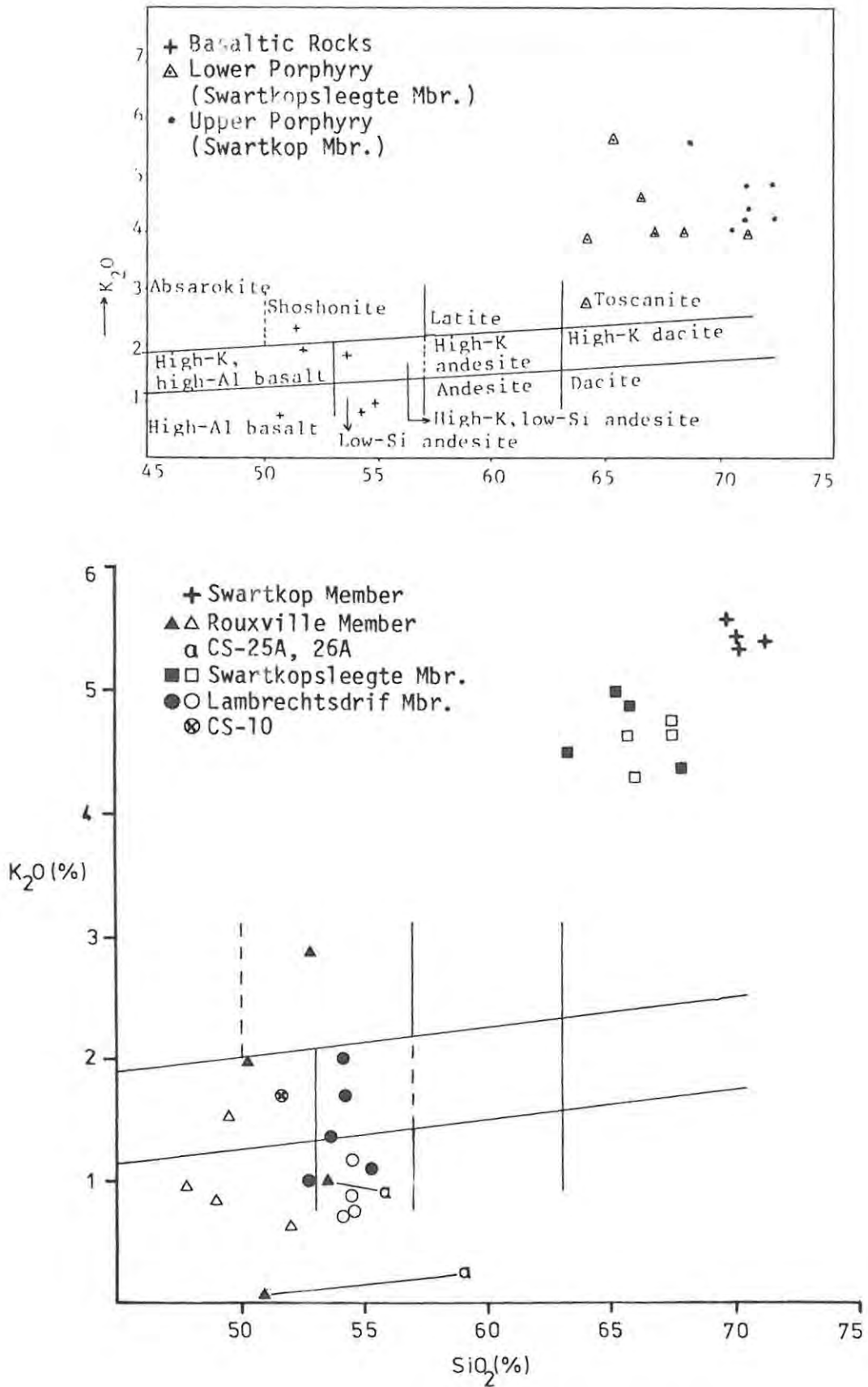
Further consideration of the possible shoshonitic affinities of the Koras lavas is desirable because:

1. The Koras lavas appear to be generally K-rich rocks.
2. Some Koras samples plot in the shoshonite field on Mackenzie and Chappell's (1972) potash vs. silica diagram (see Fig. 6.8).
3. Shoshonitic rocks are characteristic of specific tectonic environments.

In a recent review, Morrison (1980) describes the characteristics (see Table 6.3) and tectonic setting of the shoshonite rock association.

Table 6.3 Chemical characteristics of the shoshonite association (from Morrison 1980, p.98)

- (1) Basalts near-saturated in silica (i.e. rarely have normative Ne or Q)
- (2) Low iron enrichment (flat trend on AFM)
- (3) High total alkalis ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$  greater than 5%)
- (4) High  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  (greater than 0.6 at 50%  $\text{SiO}_2$ , greater than 1.0 at 55%  $\text{SiO}_2$ )
- (5) Steep positive slope on  $\text{K}_2\text{O}$  versus  $\text{SiO}_2$  at low  $\text{SiO}_2$  (less than 0.5 at 45-57%  $\text{SiO}_2$ , but zero or negative at greater than 57%  $\text{SiO}_2$ )
- (6) Enrichment in P, Rb, Sr, Ba, Pb, light rare earth elements (in accord with potassium enrichment)
- (7) Low  $\text{TiO}_2$  (less than 1.3%)
- (8) High but variable  $\text{Al}_2\text{O}_3$  (14-19%)
- (9) High  $\text{Fe}_2\text{O}_3/\text{FeO}$  (greater than 0.5)



**Figure 6.8.** Comparison of the geochemical results of Grobler et al. (1977, p.171; top diagram) with the present study (bottom) on Mackenzie and Chappells (1972) potash vs. silica diagram. The similarity of the results is obvious and although some basaltic rocks plot in the shoshonite field, the general chemical characteristics of the Koras lavas do not conform with those of the shoshonite association as proposed by Morrison (1980, p.98).

Comparison of the chemical characteristics of the Koras lavas with those proposed by Morrison (1980, p.98) for the shoshonite association (Table 6.3) shows the following:

1. The basaltic rocks of the Koras Group are all distinctly quartz-normative:  
Lambrechtsdrif Member, average Q = 9.88, S.D. = 2.04  
Rouxville Member, average Q = 5.93, S.D. = 2.71
2. The Lambrechtsdrif Member exhibits a close grouping and no Fe-enrichment or calc-alkaline trend is discernable, however, the Rouxville Member exhibits a weak "Fe-enrichment trend".
3. Total alkali content in the Koras basaltic lavas is generally less than 5% (see Fig. 6.1a).
4.  $K_2O/Na_2O$  values:

<u>Lambrechtsdrif Mbr.</u>			<u>Rouxville Mbr.</u>		
Sample	SiO <sub>2</sub>	K <sub>2</sub> O/Na <sub>2</sub> O	Sample	SiO <sub>2</sub>	K <sub>2</sub> O/Na <sub>2</sub> O
CS-1	54.80	1.02	CS-19	48.90	0.57
CS-2	54.52	0.57	CS-20	50.28	0.33
CS-3	54.04	0.50	CS-21	52.80	0.30
CS-4	54.98	0.88	CS-22	51.07	0.58
CS-5	56.51	0.36	CS-23	51.04	0.92
CS-6	55.70	0.51	CS-24	53.90	1.25
CS-7	55.92	0.33	CS-25	54.89	0.22
CS-8	54.99	0.55	CS-26	52.89	0.01
CS-9	55.41	0.36	(CS-10)	51.98	0.90

In general it can be seen that the Koras basaltic lavas do not exhibit the high  $K_2O/Na_2O$  values characteristic of the shoshonite rock association.

5. The Koras lavas represent a bimodal basaltic-rhyolitic association so that discussion of slopes on a potash vs. silica diagram (Fig 6.8) with the limited data from this study is speculative.
6. Compared to the averages for shoshonitic rocks (Morrison, 1980, p.102) Lambrechtsdrif basaltic andesites have low P, Sr and similar Rb, La, Ce, Nd contents; Rouxville basalts have low Rb, Sr, similar P and high La, Ce, Nd concentrations.
7. Although the Lambrechtsdrif basaltic andesites have low TiO<sub>2</sub> contents (average = 1.10, S.D. = 0.05), the Rouxville basalts to basaltic andesites are typified by high TiO<sub>2</sub> (greater than 1.6%; see Fig. 6.5a; average = 2.14, S.D. = 0.37).

8. The Koras basaltic lavas generally have low  $Al_2O_3$  contents ( $\pm 15\%$ ; see Fig. 6.5a), which results in their classification as tholeiitic rocks on Fig. 6.2b.

Lambrechtsdrif Member average  $Al_2O_3 = 14.85\%$ , S.D. = 0.20

Rouxville Member average  $Al_2O_3 = 14.69\%$ , S.D. = 0.84.

9. All Fe was determined as  $Fe_2O_3$ .

The name shoshonite is used for a rock association that has been defined on the basis of major element chemistry and as such the Koras lavas do not, in general, exhibit the chemical characteristics of shoshonitic lavas. In addition, the shoshonite association has chemical features in common with both the calc-alkaline and alkali-olivine basalt associations but diagrams used in section 6.2 suggest that the Koras lavas are best classified as a tholeiitic association.

Shoshonitic basalts and basaltic andesites typically have abundant phenocrysts of olivine (Morrison, 1980, p.103). No olivine has been identified in the Koras basaltic lavas and their oversaturated character suggests that it would be unlikely to occur. In addition, phenocrysts of clinopyroxene and plagioclase (labradorite) are common in shoshonitic basaltic lavas and are also present in some Koras basalts but these phenocrysts are common in most basalt associations and are not diagnostic. Further mineralogical comparison is difficult because the Koras basaltic lavas are generally non-porphyrific, aphanitic, glassy rocks.

According to Morrison (1980, p.103) "there is a consistent relationship in time and space between the various rock associations in young orogenic areas and the shoshonite association represents a specific tectonic regime". Shoshonitic rocks in evolved orogenic settings e.g., the Andes, tend to be the youngest volcanic suite and occur above the deeper part of the subduction zone. However, evidence for a subduction zone in the region during Koras times is speculative and the Koras lavas are believed to represent a continental late-orogenic cover sequence. It is suggested that the Koras lavas do not represent a shoshonitic association.

### 6.5. Comparison with the Sinclair Sequence

The Sinclair Sequence of southern S.W.A./Namibia (Fig. 6.9) consists of interbedded volcanic, volcanoclastic and clastic rocks which are intruded by granite, syenite, basic to intermediate bodies and felsic and basic dykes. On the basis of lithological similarity and similar age limits, this sequence has been correlated with the Koras Group by Truter (1949, p.1x), Du Toit (1965, p.98) and Grobler et al. (1977, p.174), and is presently considered to be the coeval equivalent of the Koras Group by SACS (1980). However, considerable work on the Sinclair Sequence and the Koras Group remains to be done before any detailed correlation can be made. According to Miller (1980, p.1), mapping and geochemical study of the Sinclair Sequence have been carried out on a reconnaissance basis only. In addition, the characteristics and mutual relationships between each volcanic and plutonic event need to be investigated in detail in order to quantify the source regions and earth processes that produced the Sinclair Sequence. As with the Koras Group, detailed geochronological work is required to date the whole Sinclair event and to trace the geochronological history across the contact between Sinclair and Namaqua rocks (Miller, 1980).

The Sinclair Sequence consists of three evolutionary cycles of deposition (Fig. 6.10), each cycle consisting of basic lava, rhyolitic lava and immature sedimentary rocks, and in this respect, it is quite similar to the Koras Group which comprises two cycles of bimodal basaltic-rhyolitic lavas and associated greywackes and arkoses. However, geochemically the Sinclair lavas are mainly calc-alkaline, often shoshonitic, and thus differ from the predominantly tholeiitic Koras Lavas (Fig. 6.11).

Two major structural trends dominate the Sinclair Sequence and although structural correlation over 500km is speculative, these trends are similar to the two structural trends seen in the Koras Group i.e. the first is northwesterly/westnorthwesterly and is expressed by bedding strike and major faults; the second N/NE trend has displaced the Guperas and Auborus Formations in large horst and graben structures and is paralleled by numerous dyke swarms.

Thus the Koras Group is petrologically similar to the Sinclair Sequence although geochemical differences between the respective lavas exist. However, the conclusion reached here, that the Koras Group represents a late-syntectonic cover sequence which formed during the Namaqua event is similar to the

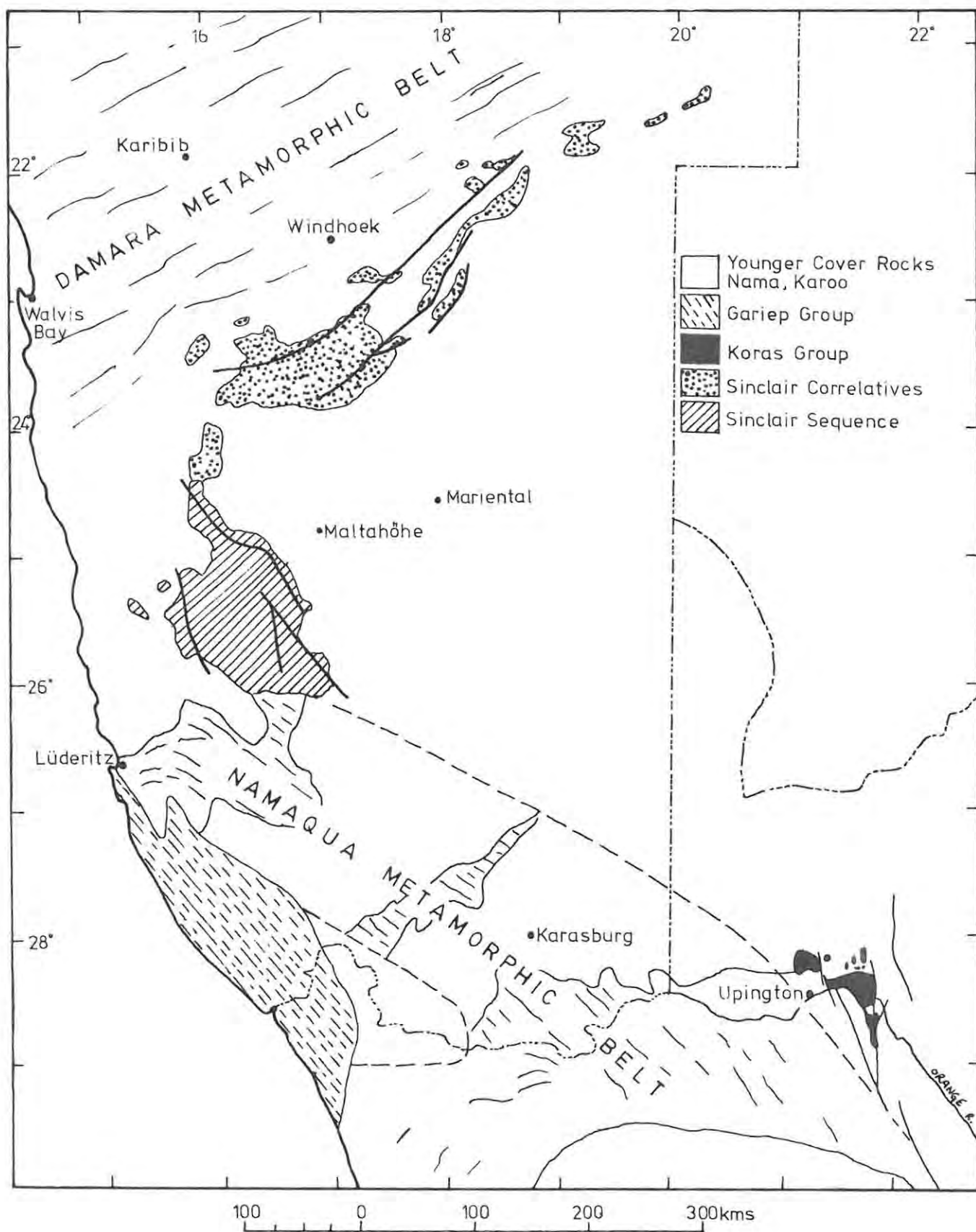


Figure 6.9. Generalized geological map illustrating the spatial relationship of the Sinclair Sequence, its correlatives and the Koras Group.

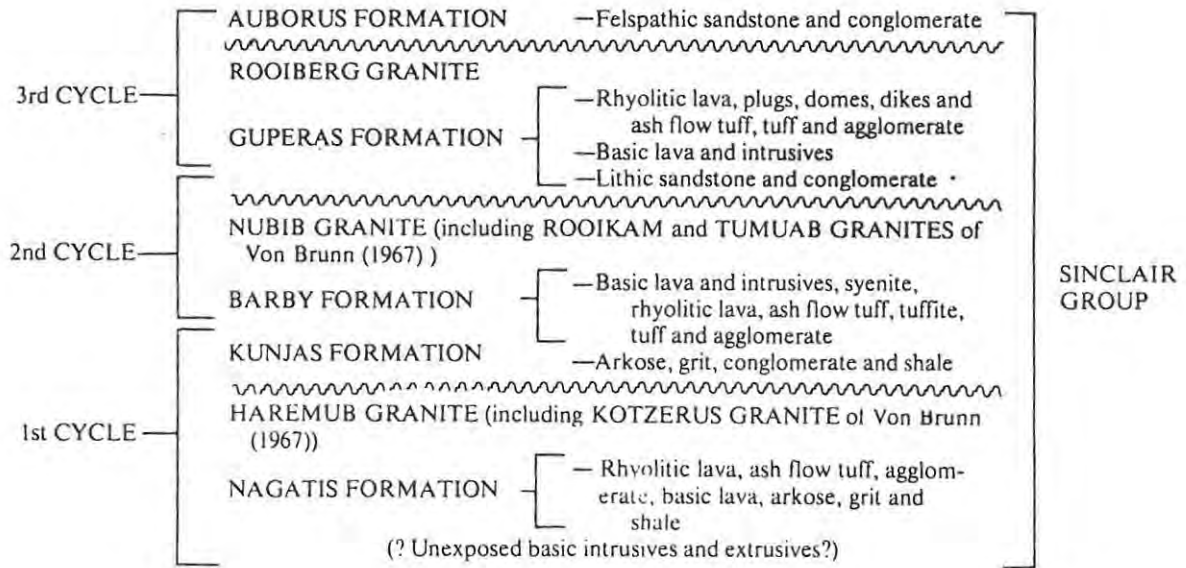
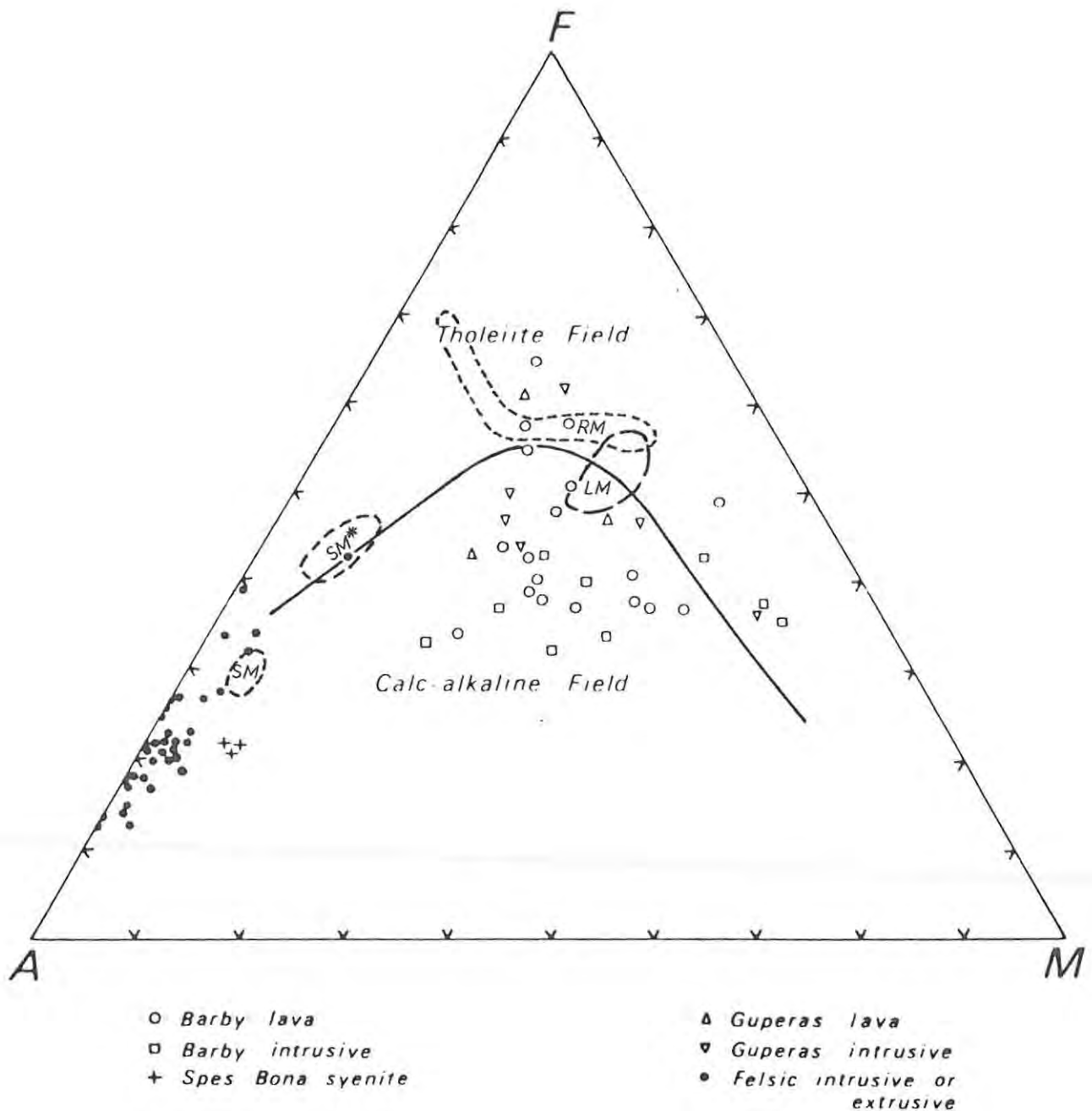


Figure 6.10. Geological succession and evolutionary cycles of the Sinclair Group (after Watters, 1977)

explanation provided by Miller (1980, p.23) for the Sinclair Sequence:

"Several major faults in the Helmeringhausen area parallel this (early NW-WNW) trend. This obviously indicates a strong basement structural control during the Sinclair event. The orientation of the Excelsior mylonite belt parallel to this trend could be taken as an indication that it is a feature with a long history, i.e., that it is primarily a feature of syntectonic Namaqua age (despite its present late- to post-tectonic expression) and that the Sinclair event is directly related to and is the surface expression of the Namaqua event. Sinclair rocks are thus preserved on the edge of the Namaqua orogen."



- S.M. - Swartkop Member (rhyolites)
- R.M. - Rouxville Member (basalts to basaltic andesites)
- S.M.\* - Swartkopsleegte Member (rhyodacites)
- L.M. - Lambrechtsdrif Member (basaltic andesites)

Figure 6.11. AFM-plot comparing the lavas and intrusives of the Sinclair Sequence (from Watters, 1974, p115) with the Koras lavas.

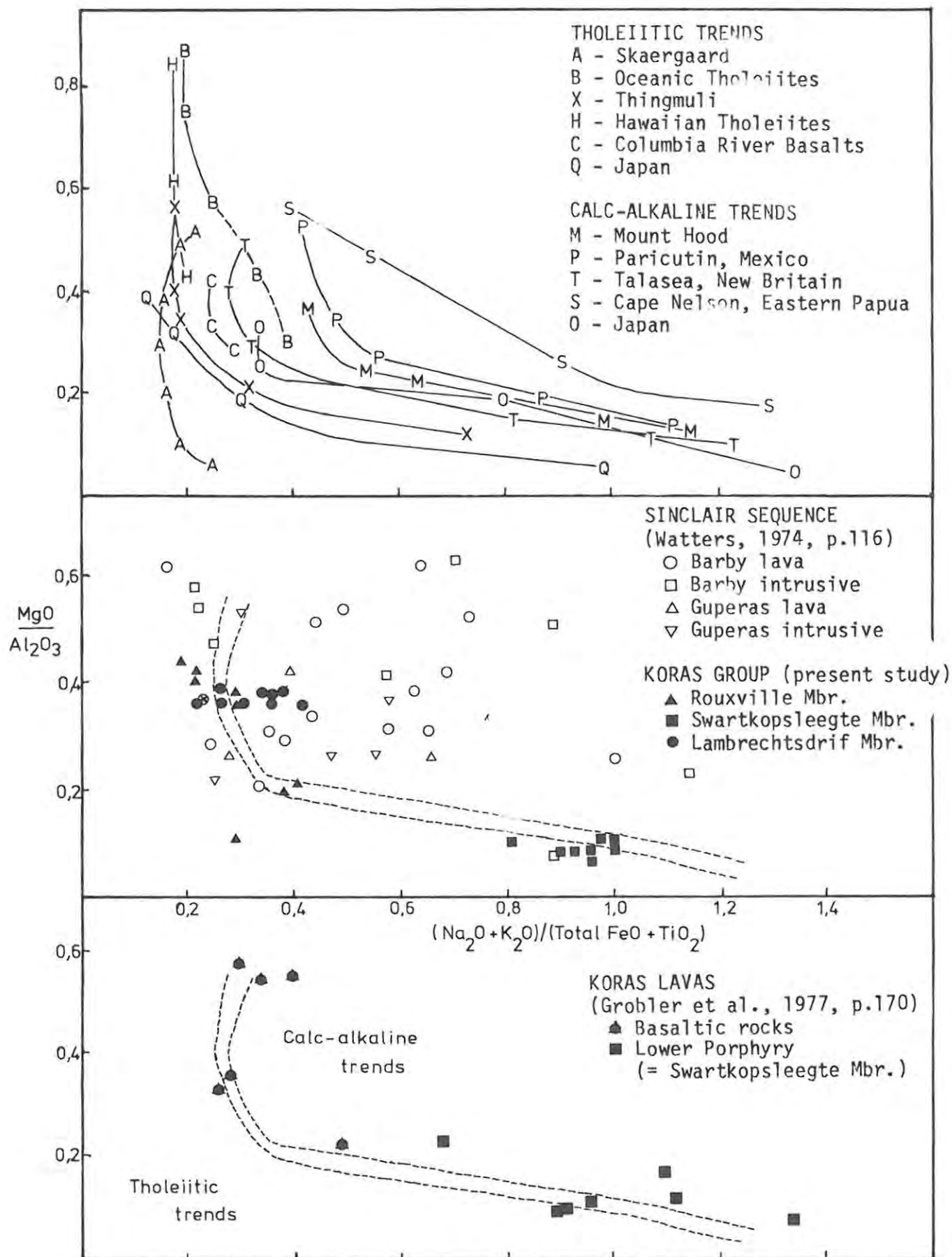


Figure 6.12.

Comparison of the Koras lavas with the Sinclair Sequence on the diagram of Green (1973). The approximate boundary of the tholeiitic and calc-alkaline fields is drawn from Green's diagram (top).

## 6.6 Comparison with the Wilgenhoutsdrif Group

The "spatial, lithological and petrogenetic similarity" between the Koras Group and the underlying deformed and metamorphosed Wilgenhoutsdrif Group has been noted by Moen (1980, p.245):

"No intraformational unconformities could be recognized in the Wilgenhoutsdrif, but the two successions are similar in the ratio of felsic to basic lava, and to some extent also the type of sediments that intersperse the volcanics. In both cases the volcanic activity was not widespread; in fact both successions are of relatively small areal extent and apparently formed under tectonically unstable conditions".

The subalkaline, tholeiitic lavas of the Wilgenhoutsdrif Group consist of two or three bimodal cycles of low-K to "average-K" basalts and low-K to high-K, peraluminous (up to 1-2% normative corundum) rhyodacites (quartz-feldspar porphyries), and are thus similar to the Koras lavas. Trace element averages are compared in Table 6.4. The Lambrechtsdrif Member differs from the Wilgenhoutsdrif basic lavas by having higher Rb, Cr and V contents and lower Nb concentrations while the Rouxville Member has higher Rb, Zr, Y, Nb, Cr, V and lower Cu values when compared to the Wilgenhoutsdrif basic lavas. Koras quartz porphyries have significantly higher Rb, Sr, Zr, Y, Nb and lower Cr and Ni concentrations.

TABLE 6.4. Comparison of Trace Element Abundances (ppm) of the Koras Group with the Wilgenhoutsdrif Group

	LMA	RMA	WGB	S.D.	S1MA	SkMA	WGR	S.D.
Rb	53,2	34,1	9	7	186,8	223,2	67	49
Sr	279	310	257	141	250	183	78	31
Zr	144	296	144	53	387	424	255	117
Y	32,6	54,9	31	5	70,3	74,3	46	11
Nb	10,6	22,1	19	8	28,8	39,6	20	7
Cr	127	212	70	69	16	10	55	28
V	237	281	121	28	93	36	27	20
Co	50	52	47	17	19	21	27	13
Ni	64	90	78	24	20	11	30	17
Cu	84	32	85	40	12	8	6	3
Zn	85	111	95	23	98	65	47	26

LMA - Lambrechtsdrif Member average (9 analyses)

RMA - Rouxville Member average (8 analyses)

WGB - Wilgenhoutsdrif Group basic lavas (average of 17 analyses from Moen, 1980)

S1MA - Swartkopsleegte Member average (8 analyses)

SkMa - Swartkop Member average (4 analyses)

WGR - Wilgenhoutsdrif Group rhyodacites (quartz-feldspar porphyries; average of 14 analyses from Moen, 1980)

S.D. - Standard deviations of Wilgenhoutsdrif Group averages.

Although there is a general absence of intermediate volcanics in the Wilgenhoutsdrif Group, Moen (1980 p.141) proposes a qualitative crystal fractionation model which suggests that the Wilgenhoutsdrif volcanics could possibly be related to a single parent magma. However, he (op.cit., p.153) does not rule out the possibility that the Wilgenhoutsdrif rhyodacites could have originated as separate magma by partial or complete melting of crustal material. Finally Moen (1980) proposes a plate tectonic model to account for the geotectonic history of the region:-

"The Wilgenhoutsdrif Formation is situated in a zone characterized by prominent faults and numerous, though small, ultramafic intrusions, and is overlain by undeformed lava and sediments of the Koras Group. It would thus seem to occur in a zone of crustal weakness which persisted for a considerable time. A geotectonic model, accounting for these features in terms of plate tectonics postulates the Wilgenhoutsdrif Group to have developed in the early stages of a collision between two continental plates, during which time the ultramafics were emplaced and the tholeiitic lavas were extruded. After cessation of the ensuing deformation, the geosuture remained as a zone of deeply penetrating faults and abnormal heat flow, which gave rise to the Koras volcanics".

### 6.7. Comparison with the Lavas of the Witwatersrand Triad.

The Koras Group has been correlated lithologically with the Dominion Group by Visser (1959, p.xxvi) and with the Ventersdorp Supergroup by Rogers and Du Toit (1910, p.73) and Le Roex (1943, p.2). Truter (1949, p.lx) correlated the Koras Group with the Zoetlief Group which is presently believed to be of Dominion Group/Lower Ventersdorp Supergroup age (SACS, 1980). Although radiometric age determinations of the Koras Group and its immediately underlying sequences (Wilgenhoutsdrif Group; Sultanaoord Group) yield younger ages than those determined for the above cratonic sequences, it is of interest in view of the above lithological correlations to compare the Koras lavas with those of the Witwatersrand triad on the basis of geochemistry. A unifying general feature is that both associations are subalkaline, are "average-K" to K-rich with tholeiitic affinities, and consist of cyclic, bimodal basaltic/andesitic and rhyodacitic lavas.

The results of a comparison with Witwatersrand triad volcanics from the Klerksdorp area indicate that the Rouxville and Swartkop Members of the Leeudraai Formation are not similar to any of the lava units of the Witwatersrand triad in this area. However, the Swartkopsleegte Member (Boomrivier Fm.) is similar to the Makwassie Formation in the Ventersdorp Supergroup. The Makwassie Formation exhibits a fairly close grouping (17 analyses) for most elements and the average is presented in Table 6.5 together with the Swartkopsleegte average. The Lambrechtsdrif Member is similar to some of the Dominion basic lavas as well as the Alberton Formation (Klipriviersberg Group). The basic lavas of the Dominion and Klipriviersberg Groups exhibit considerable within-group geochemical variation as well as between-group similarities (M.P. Bowen, pers.comm.).

Clearly, similar processes of magma generation, probably involving similar source rocks, have probably operated at different times in the region and thereby produced geochemically similar lavas. This explanation conforms with the presently accepted age relationships of the region and seems plausible because of the frequent occurrence of bimodal basalt-rhyolite volcanics through time in Southern Africa, e.g., Zoetlief Group, Wilgenhoutsdrif Group, as well as in other regions of the earth's crust. Further discussion on the origin of bimodal volcanism is continued in section 8.2.

TABLE 6.5. Geochemical Comparison of the Swartkopsleegte and Lambrechtsdrif Members with Witwatersrand Triad Lavas.

	SMA	MFA	S.D.	LMA	AFA	S.D.	DGB	S.D.
SiO <sub>2</sub>	67,30	64,56	3,91	55,21	55,40	1,61	57,24	1,90
TiO <sub>2</sub>	1,12	1,22	0,18	1,10	1,07	0,05	1,02	0,18
Al <sub>2</sub> O <sub>3</sub>	12,99	14,46	1,51	14,85	14,95	0,66	14,56	0,85
Fe <sub>2</sub> O <sub>3</sub>	7,12	7,62	1,98	10,69	11,44	0,67	11,79	1,84
MnO	0,09	0,09	0,03	0,13	0,13	0,02	0,15	0,02
MgO	1,15	2,43	1,27	5,47	5,12	0,78	3,91	1,13
CaO	2,65	3,34	1,55	8,96	7,19	1,45	6,70	1,20
Na <sub>2</sub> O	2,43	3,02	1,30	2,24	3,40	0,94	3,08	0,62
K <sub>2</sub> O	4,71	2,72	1,96	1,21	1,13	0,60	1,28	0,83
P <sub>2</sub> O <sub>5</sub>	0,45	0,52	0,07	0,14	0,16	0,01	0,26	0,07
Nb	29,2	32,4	5,1	10,8	5,5	1,2	6,5	1,0
Zr	393	535	79	147	116	16	153	12
Y	71,4	71,6	8,2	33,2	22,2	1,57	26,5	2,6
Sr	254	621	688	284	393	184	512	184
Rb	19,0	89,2	64,9	54,2	39,4	23,2	32,9	21,9
Zn	100	112	32	87	85	8	105	18
Cu	12	14	5	86	92	17	54	15
Ni	20	25	6	65	158	30	49	23
Co	19	22	5	51	61	4	58	7
Cr	16	22	6	129	124	105	18	15
V	94	107	19	241	184	12	276	91
La	79	93	24	17	12	3	22	3
Ce	164	193	43	46	30	5	46	7
Nd	81	92	28	24	14	3	25	4

SMA - Swartkopsleegte Member average (8 analyses)

MFA - Makwassie Formation average (17 analyses)

S.D. - Standard deviation

LMA - Lambrechtsdrif Member average (9 analyses)

AFA - Alberton Formation average (19 analyses)

DGB - Dominion Group basic lavas (average of 13 analyses selected from 72 analyses; samples with similar Zr and Ce contents to the Lambrechtsdrif Member were selected).

The major element analyses are volatile-free and recalculated to 100%. Trace element concentrations are adjusted to the volatile free analyses. The data for the Witwatersrand triad volcanics of the Klerksdorp area were obtained with permission from M. Bowen (in prep.) and T. Bowen (in prep.).

## 7. ASSOCIATED INTRUSIVE ROCKS

### 7.1. Distribution and Correlation

In the Upington-Groblershoop area various undeformed intrusive rocks such as quartz-porphry dykes, dolerite dykes, granites and syenites are regarded as intrusive equivalents of the Koras Group (Du Toit, 1965; Geringer and Botha, 1976; Smit, 1977; Grobler et al., 1977; Moen, 1980; Van Zyl, 1981). Although it is possible to simply correlate any relatively undeformed intrusive with the Koras Group, certain field and lithological evidence as well as age determinations are required to show that the intrusives are associated with the tectonothermal event that produced the Koras lavas. Geochemical evidence, particularly trace element geochemistry, together with isotope geochemistry, if possible, is needed to show comagmatic relationships. In this chapter all the relatively undeformed intrusive rocks that could be associated with the Koras Group are briefly described and discussed. No evidence is led here to show comagmatic relationships and to date, the only published attempt to show such relationships is the work of Geringer and Botha (1976).

### 7.2. Quartz-Feldspar Porphyry and Dolerite Dykes

#### 7.2.1. Quartz-Porphry Dykes on Leeudraai Farm

(Figure 4.3.1, p41; map 2A : T-19, 20, 21)

Medium-grained quartz-feldspar porphyry dykes are intruded along the Leeudraai-Kalkwerfputs fault on Leeudraai farm. These porphyries are reddish-brown and are fractured and veined with malachite filling the fractures at some localities. In thin section (LD-27, LD-32) the porphyries consist of corroded and strained quartz, corroded and altered feldspar and epidotized mafic minerals set in a microcrystalline to partially devitrified groundmass. Opaques and apatite are associated with the epidotized mafic minerals and some epidote is also present in the groundmass. These porphyries are generally similar in texture and mineralogy to the quartz-feldspar porphyries of the Koras Group, but are not, in the opinion of the present author, specifically similar to the quartz-feldspar porphyries of any particular member of the Koras Group.

The dykes are intruded into the fault zone between Koras rocks and the Wilgenhoutsdrif Group and are therefore probably all post-Koras in age. These dykes are probably not intrusive equivalents of the Koras lavas and

may represent a period of minor magmatic activity during post-Koras times where quartz-porphyry was intruded into areas or zones of structural weakness such as the Leeudraai-Kalkwertputs fault. Alternatively these porphyries may have been produced at depth as a result of movement along the Leeudraai-Kalkwerfputs fault and are localized dykes.

#### 7.2.2. Quartz-Porphyry Dykes on Ezelfontein Noord

Three northeasterly striking dykes were encountered at or near Ezelfontein Noord in the Southern Domain. The porphyry dykes to the east and west of the Ezelfontein Noord farmhouse (map 2B : S-29, R-29) are poorly exposed, xenolith-bearing, medium- to coarse-grained quartz-feldspar porphyries that are brown to grey-brown in colour and are generally similar in appearance to the porphyries of the Leeudraai Formation. In thin section (EN-25, -26, -32), they are composed of corroded and strained quartz crystals, altered and corroded feldspars, chloritized mafic minerals, xenoliths and resorbed rock fragments (glomeroporphyritic aggregates?). This medium to coarse-grained crystalline material is set in a microcrystalline groundmass composed of quartz, feldspar laths, chlorite and opaques.

The dyke at the north of Ezelfontein Noord (map 2B : Q-28) appears to be an inclined sheet dipping to the northwest at a moderate angle. The dyke rocks are resistant and form piles of slightly rounded boulders which protrude above the adjacent terrain underlain by volcanic rocks of the Lambrechtsdrif Member. On fresh surfaces, these fine-to medium-grained rocks are speckled white, yellow, brown and black, with an overall light greyish-brown appearance. In thin section (EN-6) corroded and strained quartz crystals, corroded and altered feldspars (some of which are perthitic) and chloritized mica are set in a granophyric groundmass with accessory epidote, chlorite, sphene, opaque minerals and apatite. The quartz and feldspar that are set in the granophyric groundmass are texturally similar to those set in the microcrystalline groundmass of the Swartkopsleegte porphyries. This microgranite dyke may well be a feeder to the Swartkopsleegte porphyries in this area, however, major and trace element geochemical data are required to substantiate this statement.

#### 7.2.3. Strausburg-Rouxville Dyke Swarm

In the area from Strausburg village in the east, across the Orange River to Rouxville farm in the west, numerous quartz-feldspar porphyry and

dolerite dykes with a dominant northeast-trending strike intrude granite-gneiss (map 2A : B-16) and the Sultanaoord Group. The dykes have been described by Du Toit (1965, p.58) and Moen (1980, p.233) who both noted that the quartz-feldspar porphyries are similar in texture and mineralogy to those of the Swartkop Member. Although the groundmass of the dyke rocks is fine-grained and aplitic compared to the aphanitic reddish-brown groundmass of the Swartkop porphyries, the dyke porphyries are, in the opinion of the present author, very similar to the porphyries of the Swartkop Member. The dykes which vary in width from less than a metre to more than 20 metres contain irregular to rounded xenoliths of fine-grained to aphanitic basic rocks as well as some gneiss fragments. Some of the dolerites have large (up to 2cms) rounded and corroded feldspars (xenoliths?) that protrude like warts from the desert-varnished, weathered surfaces.

Moen (1980, p 174) noted that "there is a marked parallelism between the northeast trending faults and a swarm of dolerite and Koras dykes" and suggested that the faulting and dykes are associated and "occurred during a period of NW-SE tension". The strongly preferred northeast-southwest strike of "aplite dykes" in this area was also noted by Van Zyl (1981, p.32) who considered that some of the dykes "may in fact be quartz-porphyry dykes related to the acid volcanics of the Koras Group". The Swartkop Member is interbedded with the basaltic lavas of the Rouxville Member and it is therefore suggested that the Strausburg-Rouxville dyke swarm, which consists of closely associated quartz-feldspar porphyries and dolerites, could represent the intrusive equivalent of the Swartkop and Rouxville Members.

#### 7.2.4. Dolerite Dykes (Southern Domain)

Two dolerite dykes are intruded into the Swartkopsleegte Member at Ezelfontein Noord (map 2B : R-29) and could possibly be intrusive equivalents of the Rouxville Member basalts in this area. Dolerites within the Lambrechtsdrif Member are discussed on p.22. In addition, relatively undeformed dolerite dykes intruded into the Wilgenhoutsdrif Group that are regarded by G. Moen (pers. comm.) as possible equivalents of the Koras Group were located on Buchberg Settlement (map 2B : U-27, V-27, V-29). The possibility that these dolerites are Karoo-age dykes also exists.

### 7.3. Granitic Rocks

Various post-tectonic (relative to the Namaqua Event) granitic rocks are regarded as plutonic equivalents of the Koras Group. A small (300m) circular syenite plug at Buchberg Settlement (map 2B : T-29) has been described and correlated with the Koras Group by Smit (1977, p.241). The plug is undeformed and intrudes granite-gneiss. Post-tectonic granites outside the study area occur near the farmhouse of Die Poort which is 5km east of Kleinbegin as well as in the area adjacent to, but west of the Brakbos fault. These granites are exposed on Hartbeesvlakte and Trooilapspan, northwest of Kleinbegin (Moen, pers. comm.). Granites in the southwestern corner of the farm Karos are regarded as post-tectonic intrusives by Stowe (1981), but it is unknown whether these are considered as equivalents of the Koras Group. According to Grobler et al. (1977, p. 169) a "non-foliated granite on Boks Puts 115 is considered a sub-volcanic equivalent of the acid Koras lavas".

In the Northern Domain the Blauwbosch granite is believed by Geringer and Botha (1976) to be an intrusive equivalent of the Koras Group. This interpretation is based on close field relationships that exist between the granite and the quartz porphyries as well as similarities in the major element geochemistry, and mineralogy. Although the Blauwbosch granite could well be associated with the tectonothermal event that produced Koras lavas, major element chemistry and mineralogy are insufficient to prove a consanguinous relationship between the granite and the quartz-feldspar porphyries. Trace element geochemistry, at least, is also required. In addition the correlation of the quartz porphyry on Steenkampspuits with the lower porphyry (Swartkopsleegte Member) by the absence of pyroxene is improbable because pyroxene (augite e.g., CS-13) has been found in the Swartkopsleegte porphyries of the Central Domain. Moen (in prepn.) correlates all the porphyries in the Northern Domain with the upper porphyries (Leeudraai Formation) in the Central Domain.

## 8. AGE, PETROGENESIS AND DEPOSITIONAL SETTING

### 8.1. Age of the Koras Group

The numerous age determinations of Koras Group rocks are presented in Table 8.1. The ages range from 1344 Ma to 976 Ma although most ages are within the wide range of 1000 - 1200 Ma. The Rb-Sr dates require reconsideration in view of the stratigraphy proposed here i.e., the division of the single basalt formation (Lambrechtsdrif Fm. of SACS, 1980) into two geochemically distinct, basalt members that are separated in time by sedimentation of the Karos Member (Central Domain), the extrusion of the Swartkopsleegte Quartz Porphyry Member and sedimentation of the Ezelfontein Member (Southern Domain). If the samples that were used for the Rb-Sr isochrons are all from one or all from the other of the two basalt members proposed here (Lambrechtsdrif or Rouxville), then the dates obtained will still be valid. If not, then the date obtained is under question because the primary assumption for a Rb-Sr isochron (i.e., that samples are from a geochemically related suite and have the same initial Sr-isotope composition) may not be fulfilled.

The wide range of U-Pb dates using quartz-feldspar porphyries (average age = 1140 Ma) has been questioned by Moen (1980, p.236) and could possibly be the result of inherited zircons. The zircons may be present in xenoliths or be unmelted phases left over during magma generation. According to Faure (1977) zircon is a very refractory mineral and may survive melting of pre-existing rocks. Burger and Walraven (1978) suggest that inherited zircon could be responsible for their higher ages and proposed that these should be disregarded. The xenoliths and resorbed rock fragments that can be seen in all the quartz-feldspar porphyries of the Koras Group (chapter 4), would support the view that inherited zircons are responsible for the wide range of U-Pb dates.

Thus evaluation of age determinations of the Koras Group indicates that some results are at present controversial and that a re-examination of the data is required. In addition, the quartz-feldspar porphyries are probably contaminated with crustal material or may, in fact, represent crustal -derived magmas with relict unmelted zircons so that U-Pb dating of zircons can only yield the most likely maximum age limit for the Koras Group.

TABLE 8.1. A Summary of Age Determinations of rocks of the Koras Group.

<u>Author</u>	<u>Rock Type</u>	<u>Formation</u> (previous author)	<u>Member</u> (this study)	<u>Method</u>	<u>Age</u>
Kroner et al. (1977)	basaltic-andesite	Florida Fm. (K0-4)	Rouxville Mbr. and/or Lambrechtsdrif Mbr.	Rb-Sr whole rock. 7 - point isochron	1176 + 9 Ma Ro = 0.70606 ± 0.00007
Barton (1979), quoted in Stowe (1981)		?		Rb-Sr	1170 Ma
Van Niekerk and Burger (1967)	quartz-feldspar porphyry	Upper and Lower Quartz Porphyry Members	Kenilworth Mbr. Swartkop Mbr. and/or Swartkopsleegte Mbr.	U-Pb	1085 ± 80 Ma
Geringer and Botha (1976)	granite	Intrusive equivalent of Koras quartz feldspar porphyry	Kenilworth Mbr. Swartkop Mbr. and/or Swartkopsleegte Mbr.	U-Pb	1054 Ma
Burger and Walraven (1976)	quartz-feldspar porphyry (SM-205)	Lower Porphyry Formation	Swartkopsleegte Mbr.	U-Pb	976 ± 20 Ma
	quartz-feldspar porphyry (SM-204)	Upper Porphyry formation	Swartkop Mbr.	U-Pb	1070 ± 20 Ma 1090 ± 20 Ma
Burger and Walraven (1978)	quartz-feldspar porphyry (HFM-428) (HFM-429)	Avondale Fm. (Moen, 1974): Upper phase Lower phase	Leeudraai Fm.: Swartkop Mbr. Kenilworth Mbr.	U-Pb	1148 ± 30 Ma 1313 ± 30 Ma 1344 ± 30 Ma
	granite porphyry (HFM-415)	Intrusive equivalent of Koras quartz-feldspar porphyry		U-Pb	1448 ± 30 1550 ± 40
Botha et al. (1979)	quartz-feldspar porphyry	Leeudraai Fm.	Swartkop Mbr.	U-Pb	1180 ± 74 Ma

## 8.2. Review of Hypotheses for the Origin of Bimodal Basaltic-Rhyolitic Lavas

### 8.2.1 Introduction

The contemporaneous or associated extrusion or intrusion of contrasting mafic and felsic magmas, with intermediate members absent or of negligible volume, is one of the oldest problems in petrology, and this relative paucity of intermediate rocks has often been described as the "Daly Gap" (Yoder, 1973). Walker and Skelhorn (1966) suggest that these "associations are so common that their understanding is likely to be of major significance in igneous petrogenesis". The brief review presented here is mainly concerned with bimodal basaltic-rhyolitic lavas as it is these rock types which are found in the Koras Group. However, some of these hypotheses can be applied to the alkaline rocks and also, in general, to intrusive bimodal associations.

Some general features of bimodal basaltic-rhyolitic associations recorded in the literature are listed below.

1. These associations are present in many volcanic provinces, from Archaean greenstone belt times to the present, in a wide variety of tectonic settings.
2. They are geochemically variable; the mafic mode may consist of olivine basalts, basalts, basaltic andesites or andesites; the felsic mode usually comprises trachytes, quartz trachytes, dacites or rhyolites.
3. There is usually a clear compositional break between the two modes, but in a few cases, intermediate rock types are sporadically developed. It would appear then that bimodal associations might grade into fully represented, differentiated suites.
4. The modes may be geochemically fairly uniform, homogeneous units as in the Island park caldera of eastern Idaho, U.S.A. (Hamilton, 1965), or they may be differentiated and exhibit short trends on variation diagrams e.g., the Tertiary volcanics of Eastern Queensland, Australia (Ewart et al., 1976).
5. The mafic mode may be more or less voluminous than the felsic mode or the two modes may be subequal in apparent volume. In other words, the modes vary in their relative abundance.
6. The modes can be extruded simultaneously and may be interbedded and/or mixed, or erupted sequentially, in either order, and may be separated by a short hiatus.
7. Almost every occurrence has its own characteristics; there are no distinct types but gradational relationships appear to exist e.g., Roobol, (1971).

In a short review, Yoder (1973, p.154) quotes numerous field and petrographic studies which show the contemporaneity of some bimodal magmas and he poses the question: "How are two magmas of such great contrast in composition generated and maintained at the same place, at the same time?" Examination of the literature on bimodal associations reveals that numerous explanations have been proposed. These are summarized below and discussed further in the sections that follow.

1. Liquid Immiscibility. Splitting of a basaltic parent magma which has been produced by partial melting in the mantle, followed by eruption of the separate, immiscible magmas.
2. Crystal Fractionation. The absence of intermediate members is explained by:
  - (a) lack of surface outcrop of intermediates possibly as a result of their occurrence as unexposed intrusives.
  - (b) sudden loss of volatiles in a hydrous fractionation process (Yoder, 1973, p.154).
  - (c) crustal contamination, e.g., Ewart et al., (1976). The evolved members of the fractionated suite are contaminated by crustal material and this produces a compositional gap.
3. Two-stage partial melting of the same parent material, e.g., Yoder, (1973).
4. Separate magma sources. Hypotheses in this category generally involve two melting episodes that are related to the same magmatic or geothermal event, but occur at separate source areas.

#### 8.2.2. Liquid Immiscibility as a process for producing Bimodal Basaltic-Rhyolitic magmas

Liquid immiscibility was proposed early in the development of petrology to explain the juxtaposition of rocks of quite disparate compositions, usually without intermediate types. Rocks such as basalt and rhyolite, and various pairs of dyke rocks were generally and conveniently assumed to have formed simply by the splitting of a formerly homogeneous magma into two immiscible magmas of contrasting composition, which would separate due to density differences (Roedder, 1979).

The Island Park caldera (Hamilton, 1965) is part of the Snake River - Yellowstone Province of intense Pliocene and Quaternary volcanism of olivine basalt and rhyolite. The rocks of the caldera are bimodal consisting of uniform olivine basalt and uniform highly silicic rhyolite. According to Hamilton (1965), the eruptive sequence and geometry of the lavas in the caldera suggest that the large magma chamber beneath the caldera contained

liquid rhyolite overlying liquid olivine basalt and he interpreted the occurrence in terms of liquid immiscibility:

"Several kinds of evidence indicate that the rhyolite of this and other bimodal volcanic provinces has formed by differentiation of basaltic magma. This differentiation can be explained in terms of an original tholeiitic basalt magma separating by liquid fractionation (liquid immiscibility) into rhyolite and olivine basalt liquids in the proportion of about 1 to 5. Such fractionation may possibly occur in the uppermost mantle or lower crust; there, rising tholeiitic magma might split into immiscible phases, one rich in volatiles and fusibles (rhyolite) and the other rich in refractories (olivine basalt), owing to instability of the initial homogeneous liquid caused by pressure decrease during ascent in a region of abnormally high thermal gradient."

Yoder (1973) argues against immiscibility as a general mechanism for the origin of bimodal associations because "the thermal and chemical properties of a conjugate rhyolitic magma would be most unusual compared with those of known rhyolitic magmas." In many cases, immiscibility has been rejected on petrographic, chemical and thermodynamic grounds, e.g., the composite dykes of Mount Desert Island, Maine, (Taylor et al., 1980).

In recent years experimental laboratory proof of liquid immiscibility has been found with geologically reasonable compositions and temperatures in a variety of silicate systems usually yielding a felsic alkali-alumino-silicate melt and a mafic melt rich in Fe, Mg, Ca and Ti (Roedder, 1979, p.47). Although relatively small changes in composition can initiate or eliminate immiscibility, it has been verified in such a wide range of rock compositions that it might be a general feature of many systems. This is supported by Philpotts (1976):

"The interpreted miscibility gap covers a wide range of compositions corresponding to intermediate rock types, which are typically less abundant than either more basic or felsic varieties. Immiscibility may, therefore, be an important petrogenetic process, one that could have played a major role in the development of the crust during early earth history".

However, according to Roedder (1979), the possible significance of metastable immiscibility in petrology, the limits under which silicate immiscibility occurs in compositions simulating natural rocks have yet to be investigated. One can conclude therefore that the evaluation of the relative importance of liquid immiscibility as a process for producing bimodal basaltic-rhyolitic

magmas must await the results of further research.

### 8.2.3. Crystal Fractionation

Although crystal fractionation is not a popular hypothesis for explaining the compositional variation in bimodal basaltic-rhyolitic associations, it has been inferred, e.g., Macauley Island, Kermadec Arc (Brothers and Martin, 1970), the Tertiary volcanics of Southern Queensland (Ewart et al., 1976) and the absence or relative paucity of data for intermediate members has been explained by various processes as suggested in section 8.2.1. Ewart et al. (op.cit.) propose that the rhyolites in Southern Queensland were derived by crystal fractionation from the basaltic magmas, but were modified by crustal contamination to produce a compositional gap. However, they did not rule out the possibility that the rhyolites may have been localized lower crustal melts which were modified by subsequent crystal fractionation.

By far the most serious objection to crystal fractionation hypotheses is the bimodal frequency distribution (Hamilton, 1965; Yoder, 1973). Yoder (op.cit.) suggests that, "in general, the volume of successive liquids and hence the rocks crystallized therefrom would be expected to decrease in a petrogenetic process controlled primarily by crystal fractionation. Furthermore, no gap or hiatus in liquid composition would be anticipated in an anhydrous crystal fractionation process. However, sudden loss of volatiles in a hydrous crystal fractionation process may produce major gaps in liquid composition".

Thus, although each association must be evaluated on its individual merits, the lack of a continuous differentiation trend in bimodal associations tends to limit the importance of crystal fractionation as a process for producing the compositional variation in these associations.

### 8.2.4. Two-stage Partial Melting of the Same Parent Material

Yoder (1973) assigns a dominant role to partial melting in the generation of bimodal rock associations and uses the data of Kushiro (1969) on the diopside-forsterite-silica system as an example to illustrate a possible mechanism for the generation of both magmas from a common parent (Fig. 8.1).

A parental magma (X) of quartz-normative composition is heated to 960°. Melting (in the presence of excess H<sub>2</sub>O) begins and yields an initial liquid

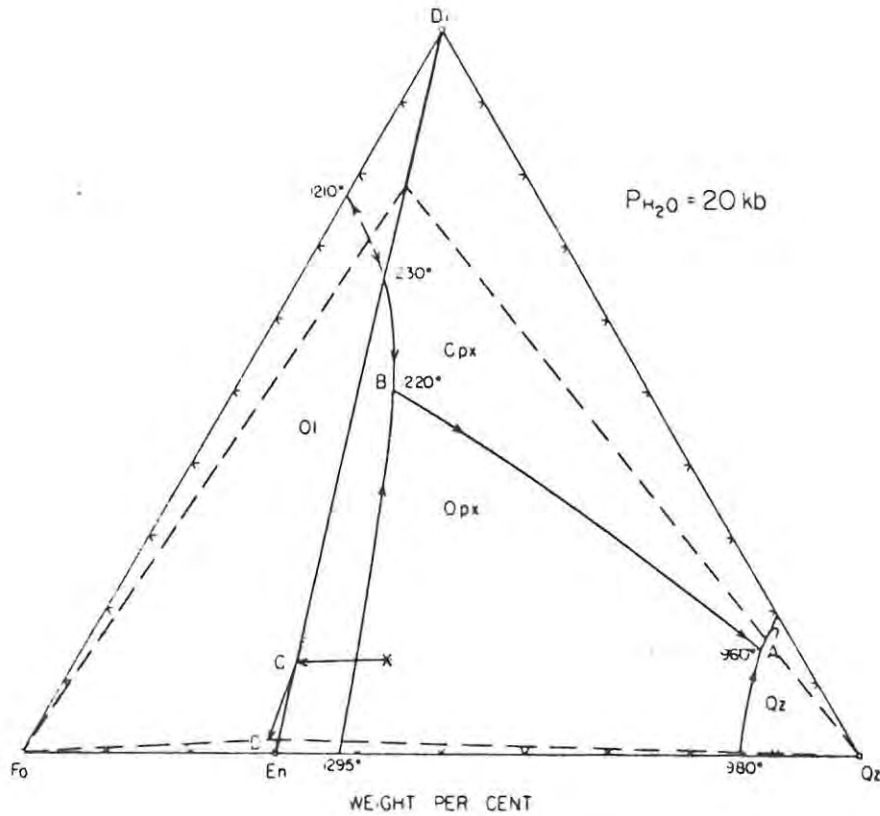


Figure 8.1. The diopside-forsterite-silica system at  $P(H_2O) = 20$  kbar (Kushiro, 1969, in Yoder, 1973, p.165). The X marks an assumed parental composition, and the arrows from it indicate the change of its composition resulting from continuous removal of liquids A and B with heating. The dotted lines are construction lines. Dashed lines indicate limits of three phase assemblages stable immediately below invariant point temperatures of A and B.

of composition A. Removal of the initial melt as soon as it is formed causes the bulk composition of the parent to move away from the liquid composition. Continuous isothermal removal of liquid A eventually causes the bulk composition to move to C. Alternatively the liquid may be left in equilibrium with the parental material and removed after all possible liquid is produced at  $960^{\circ}C$ . In either event the bulk composition of the remaining parental material has changed to a point on the Di-En join. Here the phase quartz of the parent material is exhausted and melting ceases after about 20% of siliceous liquid (rhyolitic magma) has been removed from the original bulk composition. This liquid may migrate up a fracture away from the site of generation, may be erupted or find a suitable reservoir.

Before the resumption of melting of the remaining parent material (C), it is

necessary to raise the temperature to 1220°C (point B). Continuous removal of liquid B in a similar way drives the bulk composition of the remaining parental material toward D where depletion of another major phase, diopside solid solution (Cpx) occurs. About 22% of parental material C has been removed as basic liquid B (andesitic magma) which may follow up the fracture behind the siliceous liquid A, occupy the same reservoir as liquid A, seek a separate reservoir or be erupted.

In an ideal situation, two homogeneous liquids have been removed from a common parent without the production of liquids of intermediate composition. Critical aspects of this hypothesis e.g., volume of parent material involved, are discussed by Yoder (1973, p.166) and will not be repeated here. However, as regards a heat source, Yoder suggests that the local source of heat for production of successive small batches of magma can possibly be provided by:

- (a) successive adiabatic decompressions of relatively small plates.
- (b) a convection cycle carrying new parental material within range of a fixed hot spot.
- (c) heat focusing and fluxing by volatiles in zones of lower pressure or tension (D.K. Bailey in Newall and Rast, 1970, p.177-186).

In passing, on the mechanism of eruption and magma mixing, Yoder (1973) writes: "Vesiculation of the magmas on pressure reduction as they rise to higher levels in the crust may initiate the explosive eruptive phase. Some mixing may take place during the turbulent period of simultaneous eruption while mechanical mixing and diffusion to form hybrid intermediate magmas at depth may also occur."

According to Robinson et al., (1976), the bimodal basalt-rhyolite assemblage of the Salton Sea geothermal field has formed by partial fusion in two stages of mantle peridotite forming successive rhyolitic and basaltic melts in the manner proposed by Yoder (op.cit.). They cite Sr-isotope evidence to rule out a crustal source for the rhyolites and consider crystal fractionation unlikely due to the bimodal character of the association and the failure to intersect cumulates by drilling.

The main objection to this hypothesis is the production and removal of silica oversaturated liquids from the mantle and the problem has been discussed in the literature e.g., Mysen et al., (1974), Ringwood (1974). Experiments by Kushiro et al., (1972) showed that silicic liquids of dacitic composition can be formed by partial melting of hydrous mantle material but the production of rhyolites in the mantle seems less likely. In general, it appears that

two-stage partial melting in the mantle is not favoured as a common process for producing bimodal basaltic-rhyolitic magmas.

#### 8.2.5. Separate Magma Sources.

This hypothesis for the petrogenesis of bimodal associations generally involves partial melting in the mantle to produce the mafic mode and melting of crustal rocks to form the felsic mode. These separate melting episodes are usually related to the same geothermal or magmatic event and some authors e.g., Blake et al., (1965), suggest that the upward movement of basaltic magma with associated high heat flow initiates a melting episode in the crust from where contemporaneous or associated bimodal volcanism takes place. The general "separate magma sources" hypothesis is frequently invoked as evidenced by numerous examples in the literature which commonly also describe possible mechanisms of extrusion:

Pecos greenstone belt, New Mexico, (Robertson, 1981).

Dubois greenstone belt, Colorado, (Condie and Nuter, 1981).

Mid-Proterozoic sequences, southwestern U.S.A., (Condie, 1982).

Karoo volcanics, Lebombo region, (Betton and Cox, 1979; Cleverly et al., 1981).

Some mid-Miocene basaltic-rhyolitic associations of Fiji, (Gill and Stork, 1979).

Medicine Lake, California, (Condie and Hayslip, 1975).

Lassen Peak, California, (MacDonald and Katsura, 1965).

The main objections to the derivation of the felsic mode from the crust are:

- (a) the difficulty in producing granitic melts in oceanic areas (Hamilton, 1965; Yoder, 1973), and
- (b) in some cases, isotope data do not support crustal melting.

#### 8.2.6. Conclusion

More complex hypotheses for the origin of some bimodal associations have been proposed, and these involve multistage partial melting, crystal fractionation and/or magma mixing e.g., Sigurdsson and Sparks, (1981). For the present it appears that the question of the origin of bimodal associations is best answered using multiple working hypotheses as suggested by Chamberlin (1965), because there is evidence for and objections against each of the four main hypotheses. In addition some associations can be interpreted in terms of more complex origins involving two or more of these hypotheses. Clearly, then, each bimodal occurrence must be evaluated using all available field, petrographic and geochemical data so that the more likely answer is selected.

### 8.3. Application to the Koras Lavas.

In this section the hypotheses proposed for the origin of bimodal volcanics are evaluated qualitatively for the Koras lavas. The limited data do not preclude any possibilities and further detailed geochemical work (including isotope studies) is required to test the validity of the interpretations made here. In the author's opinion the two-cycle bimodal basaltic-rhyolitic lavas of the Koras Group were derived from separate sources; the basalts represent partial melts produced in the mantle while the rhyolites (quartz-feldspar porphyries) are probably crustal melts. This view is based on the following interpretations:

1. The Koras quartz-feldspar porphyries contain abundant crustal xenoliths and these are regarded as relict, unmelted phases leftover during the crustal melting episodes. Such interpretations are not uncommon in the literature, but it is well known that they can be ambiguous e.g., Rittman (1962), Keller (1969).
2. The limited geochemical data show that four lava members of the Koras Group are geochemically distinct and probably not related by any simple crystal fractionation process. Crystal fractionation cannot be ruled out, however, because:
  - (a) complex, multistage crystal fractionation may be involved, and
  - (b) the effect of possible contamination of the rhyolites by crustal material has not been examined.
3. There is no specific evidence, such as the presence of rhyolitic globules in basic lava on an outcrop scale or in thin section to suggest that liquid immiscibility may be involved at some stage in the petrogenesis of the Koras Lavas. Thus liquid immiscibility is considered less likely to have occurred.
4. The Koras quartz-feldspar porphyries are reasonably siliceous lavas : rhyodacites to rhyolites, and an origin in the mantle by partial melting of peridotite is considered unlikely. Here again, the interpretation is subject to the results of an examination of the effects of possible crustal contamination. Andesite to dacite melts from the mantle contaminated by siliceous crustal rocks may produce rhyodacitic and rhyolitic magmas.

Although the "separate source" origin for the Koras lavas is speculative, a generalized explanation is proposed and various mechanisms and processes that take place before and during the volcanism are suggested (Fig.8.2).

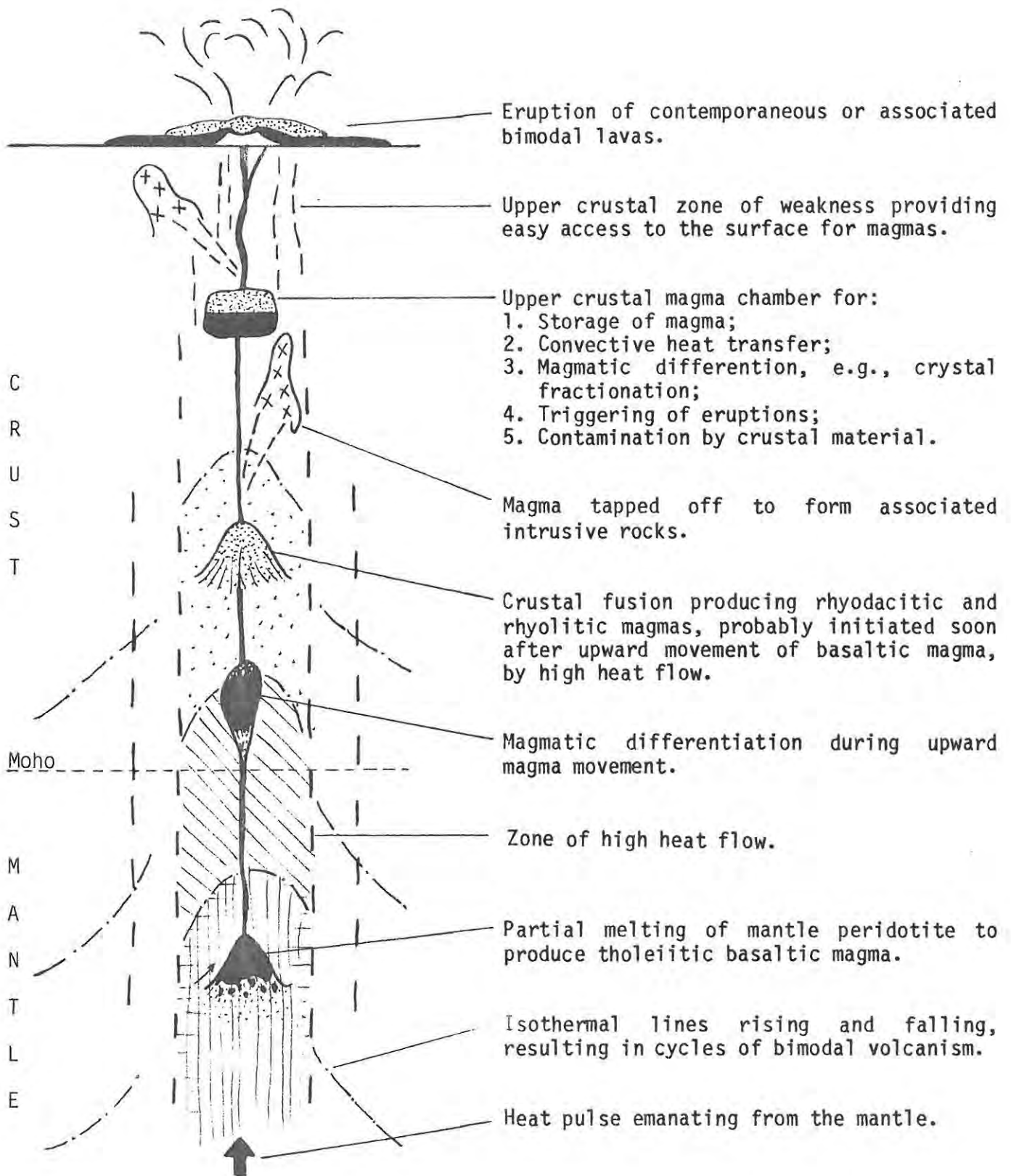


Figure 8.2. Generalized explanation for the petrogenesis of the Koras lavas (see text for explanation).

The diagram centres around a zone of high heat flow e.g., Scheinmann (1968), Hildreth (1981, p.10172), Rice (1981, p.412). Heating within this zone in the mantle results in a progressive rise of the isotherms and eventually the rising heat reaches the earth's crust. Later, the heat flow terminates gradually and the temperatures at depth decrease.

Formation of felsic magmas is caused by the heating of the crust, in the upper part of the zone, to high temperatures so that a selective, and perhaps, locally, a complete fusion of crustal material begins after or during the production and transfer of basaltic magmas from the mantle. In the case of the Boomrivier volcanics the Lambrechtsdrif basaltic andesites were erupted before the Swartkopsleegte rhyodacites and are separated from them by a short hiatus (represented in the Central Domain by the Karos Sedimentary Member). Later the process repeated itself producing the Leeudraai volcanics where the eruptions of the Rouxville basalts and the Swartkop rhyolites were contemporaneous. The absence of evidence for mixing suggests that these magmas were relatively independent of one another and may have moved through separate subsurface access routes, although the Straussburg-Rouxville dyke swarm (section 7.2.3., p.114) may well represent the intrusive system of the Leeudraai volcanics.

#### 8.4. General Depositional Setting.

The general depositional history and the tectonic conditions during the deposition of the Koras Group can be inferred from two main lines of evidence:

1. The stratigraphy, spatial distribution (map 3), lithological composition and petrography of the sedimentary and volcanic rocks.
2. The evaluation of the regional structural setting (section 5.4).

The poorly developed Basal Sedimentary Member marks the interformational unconformity between the Koras Group and the underlying pre-Koras sequences. A reasonable period of uplift and erosion can be inferred during which this major unconformity developed and left residual pockets of heterogeneous, typically locally derived sediments that are here incorporated into the Basal Sedimentary Member. A thick basal sequence in the Northern Domain is reported by Moen (in prep; Christiana Formation) and this suggests that sedimentary conditions were different in this area during early Koras times or possibly that a thick basal sequence was deposited in the Central and Southern Domains, but was eroded before the onset of Lambrechtsdrif basaltic andesite volcanism. The basic lavas of the Lambrechtsdrif Member were erupted over a fairly wide area which included the northern part of the Southern Domain, the southern

part of the Central Domain and possibly part of the Northern Domain as indicated by the present outcrops and they probably covered much of the adjacent areas. If the estimated 20 kilometre dextral, strike-slip movement on the Leeudraai-Kalkwerfputs fault is assumed to be correct then a possible southern limit for the Lambrechtsdrif Member is suggested by its pinching-out against granite-gneiss in the northern part of the Southern Domain (Ezelfontein Noord), because the large sliver-shaped mass west of this major fault would be moved back to the Central Domain and occupy an area presently underlain by Wilgenhoutsdrif Group rocks. However, this suggested southern limit would depend on the amount of Lambrechtsdrif basaltic andesite that was eroded in post-Lambrechtsdrif/pre-Swartkopsleegte Member times.

Following the eruption of these basaltic andesites, the immature conglomerates, lithic greywackes and shales of the Karos Member were formed possibly in a relatively restricted basin covering the southern part of the Central Domain and adjacent areas, but here again the interpretation is restricted by the possible erosion of a presumed Karos Member correlative in the Southern Domain. In addition, the two phases of infolding of the Boomrivier Formation that have taken place, as suggested in section 5.2, have considerably shortened the extent of the Karos Member. Added to this, movement along the Karos fault in the Central Domain probably dissected the Boomrivier Formation and the resultant uplift west of the fault, followed by erosion, removed the westward extension of this formation.

The extrusion of the Swartkopsleegte rhyodacites followed Karos Member deposition and may have occurred after the first phase of infolding started. This is suggested by the minor disconformities between the bedding of the Karos Member sandstones and the rhyodacites, and by geological contacts where rhyodacite directly overlies Lambrechtsdrif basaltic andesite (e.g., see map 1 : A15-JJ/KK). The extrusive event may have been less widespread than the Lambrechtsdrif volcanism, because present-day Swartkopsleegte outcrops occur in the Southern Domain and the southern part of the Central Domain, but according to G Moen (pers. comm.), Swartkopsleegte correlatives are absent from the Northern Domain.

Deposition of the Ezelfontein Member followed and like the Karos Member in the Central Domain, the Ezelfontein outcrops are restricted to the Southern Domain, a feature that suggests a relatively restricted extent for this sedimentary unit. Major fault movement on the Karos and Leeudraai-Kalkwerfputs faults together with weak first phase infolding makes

it difficult to determine the original extent of the Ezelfontein Member. In addition, the upper part of this unit is complicated by the early, intermittent eruptions of the Rouxville basalts which have produced the interbedded and intertonguing relationships that are seen at Ezelfontein Suid (map 2B). Rouxville basalts were erupted over a very wide area as represented by outcrops throughout the Central and Southern Domains as well as correlatives in the Northern Domain. Swartkop Member rhyolite extrusions and ignimbrite flows were relatively contemporaneous with the Rouxville basalt extrusions in the Central Domain. The succession on the northern flank of the Kalkpunt basin (Central Domain) suggests that the Kenilworth quartz-porphyrines (rhyolites) were probably extruded before the Rouxville basalt and Swartkop rhyolite extrusions in this area.

The Kalkpunt red beds mark the final depositional event in the evolution of the Koras Group and a significant part of its basin has been preserved, probably by infolding associated with the major dextral, strike-slip faulting. It is clear, however, that the above interpretation of the evolution of the Koras Group rests to a certain extent on the structural evaluation presented in chapter 5. It assumes that early infolding of the Boomrivier Formation was related to some pre-F<sub>4</sub> regional stresses of the Namaqua Event and that the major dextral strike-slip faulting was responsible for late-Koras tectonic instabilities, assumptions that are difficult to prove conclusively.

However, the immature character of the sedimentary rocks supports the generally accepted view that there was continued tectonic instability throughout Koras times. This is also suggested by another aspect of the composition of the sedimentary members i.e., the conglomerates and sandstones of the Karos, Ezelfontein and Kalkpunt units contain fragments derived from their respective underlying members in the Koras succession which indicates continual uplift and erosion of lower Koras rocks so that they acted in part as source areas for overlying sedimentary members.

Grobler et al. (1977) proposed that the major faults of the area were active before, during and after Koras times and despite the present post-Koras expression of the Karos and Leudraai-Kalkwerfputs faults these faults may well have had a longer history and may even have been initiated as normal faults in a regional rift zone and then with a gradual change in the orientation of the stress field, were converted to major strike-slip faults. Exactly how the faults were initiated is almost impossible to determine and Hobbs et al. (1976, p.386) point out:

"The role and importance of wrench faults in the early history of orogens is almost completely unknown. One difficulty here is that it may be difficult to recognize whether or not a given mapped discontinuity originated as a wrench fault or, for example, as a thrust fault".

In the western part of the Central Domain there is some evidence to support wrench fault movement by Leeudraai Formation times. If the 15 kilometre strike-slip movement of the Brakbos fault, as proposed by Stowe (1981), is correct and seems quite likely to the present author, then this movement must have taken place in pre-Kalkpunt Formation times because the Brakbos fault does not appear to affect the Kalkpunt Formation. In addition the Rouxville basalt outcrop at Rouxville farm overlies the step-uplifted block between the Dagbreek and Brakbos faults but Dagbreek faulting with upthrow to the west continued probably after the Brakbos fault movement ceased. This is shown at Rouxville where the basalt outcrop is cut off by the Dagbreek fault. In fact, the early cessation of Brakbos faulting in this area probably accounts for the preservation of the Rouxville basalt outcrop in this block. In any event, there is evidence in this area for major strike-slip faulting with step-like dip-slip faulting (downthrow to the east) in pre-Rouxville Member times, an interpretation that suggests the possible regional development of the Koras Group in basins controlled by major strike-slip faulting.

In conclusion it is suggested that the tectonic setting of the Koras Group must remain to some extent speculative. Exactly where or what the regional structure was that controlled Koras deposition is very difficult to reconstruct but it is suggested here that the major controls of Koras deposition were:

1. late regional stresses of the Namaqua Event during early Koras times and
2. major strike-slip and subordinate dip-slip faulting during middle and late Koras times.

#### 8.5. The Koras Group and Plate Tectonic Theory.

To infer the tectonic and depositional setting of the Koras Group in terms of present day (Cenozoic) plate tectonic theory various geological and geochemical parameters are required:

1. The extent, stratigraphy, lithological composition and character of the sedimentary, volcanic and associated intrusive rocks of the group.
2. The recognition of rifts or geosutures and the position and direction of movement of possible plates with respect to subduction zones.

3. Geochemistry of the volcanics and associated intrusive rocks.
4. The position, extent and type of basement.

For many Precambrian sequences, structural deformation (and metamorphism) commonly eliminates much geological evidence so that unequivocal recognition of parameter 2 (above) and the general extent of a group or sequence is virtually impossible. In addition the stratigraphy, composition and character of a sequence can vary quite considerably and are frequently not diagnostic even for particular plate tectonic settings, although some general inferences can be made. Thus to determine plate tectonic-type environments for Precambrian associations, heavy reliance must be made on the available geochemical data for the igneous rocks.

In the case of the Koras Group, the regional structural setting suggests that the outcrops seen today represent the infolded and faulted remnants of a somewhat more widespread sequence. On the question of basement rocks there seems little doubt that a considerable thickness of crustal material (including Proterozoic supracrustal sequences) existed during Koras times. Indeed, if Moen's (1980) "continental collision" model is assumed to be correct, then the Koras Group can be interpreted as a post-collision sequence that formed on an ancient geosuture. This zone of crustal weakness with high heat flow (Moen, 1980), developed into a regional lineament consisting of major strike-slip faults during Koras times and certainly after the Koras Group was deposited. Modern analogues are, therefore, the San Andreas fault system in California and the Alpine fault system of New Zealand.

Recent work has shown that the chemical compositions of modern volcanic rocks are related to their tectonic environments. Statistically valid graphs are drawn on which some or all of the chemical data of modern volcanic rocks are plotted, e.g. the  $TiO_2-K_2O-P_2O_5$  diagram (Pearce et al., 1975). Boundaries marking off areas of specific tectonic environments can be drawn in on these graphs so that the chemical compositions of ancient volcanics can be used to determine their tectonic environments. Thus the principle behind these methods is the comparison of the chemical compositions of volcanic rocks whose tectonic environments are unknown with the chemical compositions of present day volcanic rocks whose tectonic environments are known. (Considerable controversy exists over the application of such methods because, to a large extent they assume that modern plate tectonic theory can be applied to the Precambrian, an assumption that is not generally accepted).

In general, unusual rocks e.g., fractionated rocks, which do not appear to follow the general trends are screened out by laying down certain conditions. Therefore, when using these methods the chemical composition of the rock whose tectonic environment you wish to determine must satisfy those conditions. In this respect, the limited data from this study has been restricted so that only a preliminary determination can be carried out, the results of which are presented in Table 8.2.

The ambiguity of the results is obvious and no reasonable conclusion can be reached mainly because of the paucity of data. Further tests of the applicability of this method must await a more detailed geochemical study of the Koras Group and further research into the geochemical characterization of ancient tectonic environments.

TABLE 8.2 Results of a Preliminary Geochemical Evaluation of the Tectonic Environment of the Koras Group using the Basaltic Lavas.

Author(s)	Discriminant Diagram	Member (no. of samples used in parentheses)	Suggested Tectonic Environment
Pearce et al., (1975)	TiO <sub>2</sub> -K <sub>2</sub> O-P <sub>2</sub> O <sub>5</sub> ternary	Rouxville (4) Lambrechtsdrif (6)	Non-oceanic (continental) Non-oceanic (continental)
Pearce et al., (1977)	MgO-FeO(T)-Al <sub>2</sub> O <sub>3</sub> ternary	Rouxville (3) Lambrechtsdrif (9)	Continental Continental/Orogenic
Pearce and Cann, (1973)	Ti/100-Zr-Y.3 ternary	Rouxville (5) Lambrechtsdrif (8)	Not classified Volcanic Arc (calc-alkaline)
	Ti vs. Zr	Rouxville (3) Lambrechtsdrif (8)	Ocean Ridge (tholeiitic) Volcanic Arc (calc-alkaline)
	Ti/100-Zr-Sr/2 ternary	Rouxville (4) Lambrechtsdrif (8)	Volcanic Arc (calc-alkaline) Volcanic Arc (calc-alkaline)
Pearce and Norry (1979)	Zr/Y vs. Zr	Rouxville (4) Lambrechtsdrif (8)	Within-plate Setting Within-plate Setting

## 9. SUMMARY AND CONCLUSIONS

The Central and Southern Domains of the Koras Group are situated on the Doornberg Lineament, a northeast-trending zone of major strike-slip and subordinate dip-slip faulting that separates the Namaqua metamorphic belt in the west from the Kaapvaal craton in the east. Evaluation of the regional structural setting of the Koras outcrops suggests that these two domains are the infolded and faulted relicts of a once more widespread late-syntectonic cover sequence that formed during the late stages of the Namaqua Event in middle or late-Proterozoic times.

Detailed mapping has resulted in the proposal of a new geological succession which consists of three formations, the lower two each consisting of four members. The lowermost Boomrivier Formation consists of a poorly developed basal sedimentary member which is overlain by basaltic andesites (Lambrechtsdrif Member) and these, in turn, are overlain by fine-grained, quartz-feldspar porphyries (Swartkopsleegte Member). The Lambrechtsdrif and Swartkopsleegte Members are separated by the Karos Sedimentary Member which is present only in the Central Domain, a feature that suggests a relatively restricted extent for the basin of the Karos Member with its immature conglomerates, lithic greywackes and shales. In the Southern Domain, the second (Leeudraai) formation comprises the Ezelfontein Sedimentary Member which is generally overlain by basalts of the Rouxville Member. In the Central Domain, Rouxville basalts underlie the Swartkop Member porphyries at Karos Nedersetting but generally overlie the Swartkop and Kenilworth porphyries in the area north of the Kalkpunt basin. This is taken to indicate contemporaneous basalt and rhyolite volcanism in Leeudraai Formation times and is supported by the exposures at the type area on Leeudraai farm where basalts both underlie and overlie the Swartkop Member porphyries.

The uppermost Kalkpunt Formation occupies a roughly elliptical basin in the Central Domain and consists of basal, immature, polymictic orthoconglomerates overlain by red arkosic sandstones. As a whole, the character of the sedimentary rocks of the Koras Group suggests that tectonically unstable conditions prevailed and that the pre-existing members of the group as well as the adjacent underlying pre-Koras sequences acted as the sediment source areas. This is particularly well-shown by the Kalkpunt conglomerates which are made up of pebbles from all the underlying members of the Koras Group and pebbles from the adjacent, pre-Koras sequences.

Geochemically, the volcanics of the Koras Group are poorly understood and a limited geochemical study using 30 new analyses (all major elements and 14 trace elements) suggests that the Koras lavas can be classified as an "average-K" to high-K, tholeiitic, subalkaline association consisting of bimodal basaltic-rhyolitic lavas. Although the Lambrechtsdrif basaltic andesites are transitional tholeiitic/calc-alkaline rocks, their low  $Al_2O_3$  - contents supports the general classification as tholeiitic. On the basis of detailed mapping and the new stratigraphy proposed here a more detailed petrological and geochemical investigation can be carried out to examine the following features:

1. The effects of flow-differentiation on chemical analyses from the Rouxville Member.
2. The effects of possible crustal contamination in the quartz-feldspar porphyries.
3. Correlation of the Central and Southern Domain volcanics with those of the Northern Domain.
4. Inter-member relationships and the origin of the basaltic and rhyolitic magmas.
5. Relationships between the lavas and the associated intrusive rocks.

Geochemical comparison with the previous work of Grobler et al. (1977), indicates that similarities exist but differences can only be resolved by a more detailed study. However, using the results of Morrison's (1980) review of the shoshonite association, the data from the present study suggests that the Koras lavas do not represent a shoshonitic association. The Koras Group is petrologically similar to the Sinclair Sequence of southern S.W.A./Namibia which is at present considered to be its coeval equivalent, but the dominantly calc-alkaline igneous rocks of the Sinclair Sequence distinguishes them from the dominantly tholeiitic Koras lavas. Major element similarities exist between the Koras lavas and the tholeiitic, bimodal, basaltic-rhyolitic lavas of the Wilgenhoutsdrif Group, but they are distinguished using trace elements. Comparison of the Koras lavas with those of the Witwatersrand triad sequences (Klerksdorp area) shows that the Swartkopsleegte Member exhibits a major and trace element similarity to the Makwassie Formation (Ventersdorp Supergroup) and that the Lambrechtsdrif Member is similar to the Alberton Formation of the Klipriviersberg Group (Ventersdorp Sgp.), as well as some of the basic lavas of the Dominion Group. This geochemical similarity might be used to correlate the Boomrivier Formation with the above cratonic sequences, but this is constrained by the presently accepted ages of these sequences as well as ages for the immediately underlying pre-Koras sequences. The alternative, suggested

explanation is that similar magma generating processes, probably involving similar source rocks, have operated through time.

A review of the literature on bimodal basaltic-rhyolitic associations reveals that four main hypotheses have been invoked for their origin:

1. Liquid immiscibility.
2. Crystal fractionation.
3. Two-stage partial melting of the same parent material.
4. Separate magma sources.

Other more complex, multistage, petrogenetic models involving two or more of the above processes (and magma mixing in some cases), have also been proposed for bimodal associations. Using the field, petrographic and limited geochemical data for the Koras lavas, a generalized explanation is proposed, in which two cycles of mantle-derived basalts and crustal-derived rhyolites are produced in a zone of high heat flow and erupted at the margin of an orogenic region.

The general extent and setting of the Koras depository is speculative but the evidence from the volcanic and sedimentary rocks suggests a somewhat more widespread occurrence in a setting that was possibly controlled by:

- (a) folding of the underlying basement-forming sequences during the late Namaqua tectogenesis.
- (b) major strike-slip and subordinate dip-slip faulting.

Economic Aspects. Apart from very minor occurrences of malachite, no other general signs of possible mineralization were noted within the Central and Southern Domains of the Koras Group and the group exhibits very little potential as an exploration target. However, the geophysical picture has not been examined and this may provide some possibilities. (The economic geology of the adjacent pre-Koras sequences is discussed by Moen, 1980, p.238). As far as industrial rock potential is concerned, Karos Member sandstone has been excavated from pits at Karos and near Lambrechtsdrif and used for gravelling roads, and Lambrechtsdrif basaltic andesite has been excavated from a locality near beacon 84 (map 1: A7-EE) and crushed, presumably also for road construction.

APPENDICES

ACKNOWLEDGEMENTS

REFERENCES

APPENDICES

APPENDIX 1 : Localities and Brief Descriptions of the Analyzed Samples.

Boomrivier Formation:

Lambrechtsdrif Member (Central Domain), Basaltic Andesites

CS-1 (Map 2A : J-15. Also as KS-5 on map 1 : A8-FF)

Hand specimen: dark grey, aphanitic.

Hyalopilitic texture made up of acicular plagioclase and augite with interstitial dark brown glass and some quartz.

CS-2 (Map 2A : O-20)

Hand specimen: grey, generally aphanitic, with small dark mafic minerals (up to 1mm in diameter), and sparse thin (less than 1mm width) white veins. Intersertal texture made up of highly saussuritized plagioclase, subophitic augite, zoned chloritized pigeonite and opaque euhedra. The interstitial brown glass contains skeletal opaque minerals.

CS-3 (Map 2A : P-21)

Hand specimen: light greenish-grey, aphanitic with sparse thin (less than 1mm) white veins.

Hyalopilitic texture. Plagioclase laths are set in a devitrified light brown glass with quartz and epidote.

CS-4 (Map 2A : R-22)

Hand specimen: greenish-grey, aphanitic.

Hyalopilitic texture. Plagioclase laths and granular augite are set in a slightly epidotized brown glass with quartz.

CS-5 (Map 2A : R-20)

Hand specimen: greenish-grey, aphanitic.

Hyalopilitic texture. Plagioclase laths and granular augite are set in a partially devitrified groundmass with quartz. For a more detailed description see Sanderson (1979), appendix 2, KA-724.

Lambrechtsdrif Member (Southern Domain), Basaltic Andesites

CS-6 (Map 2B : U-33)

Hand specimen: greenish-grey, aphanitic, sparse thin white veins (1/2 mm - 1mm wide) present.

Hyalopilitic texture. Plagioclase laths and augite are set in a partially devitrified dark brown glass with quartz and minor epidote.

CS-7 (Map 2B : T-32)

Hand specimen: light greenish-grey, aphanitic.

Hyalopilitic (quench) texture. Acicular, hollow, plagioclase laths are set in a brown glass with minor epidote and quartz.

CS-8 (Map 2B: R-28)

Hand specimen: grey, subporphyritic; dark mafic minerals (less than 1mm in diameter) set in an aphanitic groundmass. Occasional veins (1/2mm in width).

Hyalopilitic texture. Plagioclase laths, acicular and subophitic granular augite together with some chloritized phenocrysts (pigeonite?) are set in a dark brown partially devitrified groundmass with minor quartz.

CS-9 (Map 2B : R-28)

Hand specimen: grey, aphanitic. Thin (1/2mm) white veins are rare.

Hyalopilitic texture. Plagioclase laths and acicular augite are set in a partially devitrified dark brown glass.

CS-10 (Map 2B : S-29)

Hand specimen: dark grey, aphanitic.

Porphyritic texture. Sparse phenocrysts of faintly pleochroic orthopyroxene are set in an intergranular groundmass. The groundmass consists of plagioclase laths, granular augite, abundant opaque grains and minor patches of glassy mesostasis.

Swartkopsleegte Member, Rhyodacites

In hand specimen these porphyritic volcanic rock samples are all similar and consist of abundant whitish feldspar and glassy quartz with minor mafic minerals set in a reddish-brown to brownish-grey aphanitic groundmass. In thin section the following general features were noted:

Quartz: corroded, rounded, strained crystals with fractures and spherulitic rims.

Feldspars: corroded, rounded, fractured, altered, rarely subhedral.

Mafic minerals: usually completely altered to epidote, chlorite and/or opaques and associated with opaque phases and apatite. Glomeroporphyritic aggregates (resorbed rock fragments ?) are commonly present.

Groundmass: devitrified glassy to microcrystalline.

Central Domain:

CS-11 (Map 2A : O-18)  
CS-12 (Map 2A : N-19)  
CS-13 (Map 2A : O-19)  
CS-14 (Map 2A : P-21)

Southern Domain:

CS-15 (Map 2B : R-29)  
CS-16 (Map 2B : T-31)  
CS-17 (Map 2B : S-32)  
CS-18 (Map 2B : S-33)

Leeudraai Formation:

Rouxville Member (Southern Domain), Basalts to Basaltic Andesites.

CS-19 (Map 2B : S-32)

Hand specimen: dark grey, aphanitic, with sparse white amygdales (1mm to 2 cm in diameter).

Intergranular texture made up of plagioclase laths and subophitic augite with interstitial quartz, chlorite, opaques and glassy mesostasis.

CS-20 (Map 2B : S-32)

Hand specimen: dark purplish-brown, aphanitic with white amygdales (1mm to 1/2cm in diameter).

Hyalopilitic texture. Saussuritized plagioclase laths and subophitic prismatic augite (with brown Ti-biotite alteration) are set in a dark brown almost opaque glass with skeletal opaques and some chlorite. Amygdales consist of calcite, chlorite and an unidentified (zeolite ?) mineral.

CS-21 (Map 2B : S-32)

Hand specimen: dark grey, aphanitic, no amygdales.

Hyalopilitic to intersertal texture consisting of zoned plagioclase (labradorite), chloritized subophitic augite and interstitial chlorite, quartz and a dark brown glassy mesostasis with skeletal opaques.

CS-22 (Map 2B : S-32)

Hand specimen: dark brownish-grey, aphanitic, with white to greenish amygdales. Hyalopilitic texture made up mainly of saussuritized plagioclase set in an almost opaque (probably devitrified) glass with minor epidote and Ti-biotite. Amygdales are made up mainly of quartz and calcite with minor chlorite and an unidentified (zeolite ?) mineral.

Rouxville Member (Central Domain), Basalts to Basaltic Andesites.

CS-23 (Map 2A : R-20)

Hand specimen: grey-brown, aphanitic, with occasional amygdales. Intergranular texture made up of plagioclase laths, opaque euhedra with Ti-biotite alteration, ophitic augite (plus some pigeonite ?) and interstitial quartz. Some of the augites have chloritized cores.

CS-24 (Map 2A : R-20)

Hand specimen: glomeroporphyritic; pale green plagioclase phenocrysts are set in a non-amygdaloidal aphanitic brownish-grey groundmass. In thin section, slightly saussuritized plagioclase (labradorite) phenocrysts are set in an intergranular groundmass which consists of plagioclase laths, augite and opaques with interstitial quartz, calcite and K-feldspar. Altered mafic phenocrysts (augite ?) are associated with the glomeroporphyritic plagioclase and are completely altered to chlorite and opaque phases.

CS-25 (Map 2A : R-20)

Hand specimen: dark purplish-brown, aphanitic, with white amygdales. Hyalopilitic texture. Seriate plagioclase laths (up to 2mm in length) are set in an opaque glassy groundmass with minor quartz and augite. Amygdales consist of quartz and calcite.

CS-26 (Map 2A : R-20)

Hand specimen: dark purplish-brown, aphanitic, with white amygdales. Hyalopilitic texture. Seriate plagioclase laths (up to 4mm, but generally less than 1mm) are set in an opaque glassy groundmass. The amygdales are composed mainly of quartz with minor calcite.

Swartkop Member, Rhyolites.

(All samples are from Karos Nedersetting, Central Domain).

CS-27 (Ignimbrite) (Map 2A : P-19)

Hand specimen: porphyritic, crystals of quartz and feldspar are set in an aphanitic brick-red to orange-red groundmass. In thin section, broken and corroded crystals of quartz, feldspar, altered mafic minerals and opaques are set in a brown to bright orange-red glassy groundmass. The groundmass consists of welded glass particles that are partially devitrified and exhibit flow texture.

CS-28 (Map 2A: P-19)

CS-29 (Map 2A: Q-19)

CS-30 (Map 2A: S-20)

These samples are all similar in hand specimen and thin section and exhibit the features described in section 4.3.3E, p.52.

#### APPENDIX 2 : Sample Preparation for Analysis.

The samples were initially crushed by a hand-operated rock splitter and all visible weathered material was removed. The samples were then reduced in a jawcrusher to thumbnail-size chips. (At this stage, amygdales were extracted from the sparsely amygdaloidal rock, CS-19). The amygdaloidal samples, CS-20, 22, 25, 26, were crushed to matchhead-size chips in a rollermill and chips of the amygdale-free matrix were extracted for analysis. (CS-25A and CS-26A are analyses of samples whose amygdales were not removed). A Herzog swingmill was used to crush all the samples to  $\pm$  120 mesh size, using a manganese-steel container. This powder was further ground to less than 300 mesh size by hand with an agate mortar and pestle. Pressed pellets were made using approximately 4 g of the finely-crushed powder. Fusion discs were prepared by the method of Norrish and Hutton (1969).

H<sub>2</sub>O was determined gravimetrically by heating the samples at 110°C for 6 hours. Similarly, L.O.I. (loss on ignition) was determined by heating the samples overnight in a furnace at 950°C. The samples were contained in silica crucibles for these ignition processes.

#### APPENDIX 3: X-Ray Fluorescence analysis

The major element analyses (except Na) were obtained using duplicate fusion discs and all iron was determined as Fe<sub>2</sub>O<sub>3</sub>. Na and the trace elements were determined on pressed powder pellets. The analyses were carried out using a Phillips 1410 X-ray spectrometer and the data were processed using standard computer programs of the Department of Geology, Rhodes University. Lower limits of determination and average absolute errors for the trace element runs are given in Table A, and the details of analytical conditions for the major and trace element runs are presented in Table B.

Corrections were made for position factors, dead-time, background, instrumental drift and spectral line interferences. Mass absorption coefficients, used in the trace element data reduction, were derived from the major element data using Heinrich's (1966) values. Working curves were calculated using the following International and In-house rock standards:

Major Elements: AGV, GSP-1, NIM-N, BCR, JG-1, G-2.  
Na: AGV, GSP-1, NIM-N, BCR, JG-1, G-2, M-38, NIM-P, NIM-G.  
Rb, Sr, Nb, Zr, Y: KRF-13, CAR-08, S-9, S-12, S-15, PRO-1.  
Co, Cr, V: KRF-13, PRO-1, PCC, S-9, S-12, S-15.  
Zn, Cu, Ni: PCC, S-9, S-10, S-12, S-15, CAR-08, KRF-13.  
La, Ce, Nd: GSP, G-2, AGV-1, BCR, NIM-G.

TABLE A: Average Lower Limits of Determination (L.L.D.) and Errors of Determination for Trace Element Analyses by X-ray Fluorescence Spectrometry.

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<u>ELEMENT</u>	<u>L.L.D.</u>	<u>ABSOLUTE ERROR</u>
Sr	1.80	0.96
Rb	1.87	0.81
Y	2.05	0.71
Zr	1.62	0.93
Nb	2.23	0.68
Zn	2.25	1.14
Cu	2.56	1.11
Ni	3.17	1.36
Co	2.62	0.87
Cr	2.67	1.19
V	3.37	1.54
La	9.14	2.46
Ce	12.51	3.36
Nd	7.43	1.95

TABLE B : X-ray Fluorescence Analytical Conditions

Element	Emission Line	Tube	kV	mA	Crystal	Time (secs)	Counter	Collimator	Specimen
Si	K $\alpha$	Cr	55	40	PET	40	flow	coarse	fusion disc
Ti	K $\alpha$	Cr	55	40	LiF(200)	10	flow	fine	fusion disc
Al	K $\alpha$	Cr	55	40	PET	40	flow	coarse	fusion disc
Fe	K $\alpha$	Cr	55	40	LiF(200)	20	flow	fine	fusion disc
Mn	K $\alpha$	Cr	55	40	LiF(200)	20	flow	coarse	fusion disc
Mg	K $\alpha$	Cr	55	40	TLAP	200	flow	fine	fusion disc
Ca	K $\alpha$	Cr	55	40	LiF(200)	10	flow	fine	fusion disc
Na	K $\alpha$	Cr	55	40	TLAP	100	flow	fine	powder pellet
K	K $\alpha$	Cr	55	40	LiF(200)	10	flow	fine	fusion disc
P	K $\alpha$	Cr	55	40	Ge	20	flow	coarse	fusion disc
Sr	K $\alpha$	W	55	40	LiF(220)	200	scint.	fine	powder pellet
Rb	K $\alpha$	W	55	40	LiF(220)	200	scint.	fine	powder pellet
Zr	K $\alpha$	W	55	40	LiF(220)	200	scint.	fine	powder pellet
Y	K $\alpha$	W	55	40	LiF(220)	200	scint.	fine	powder pellet
Nb	K $\alpha$	W	55	40	LiF(220)	200	scint.	fine	powder pellet
Co	K $\alpha$	W	55	40	LiF(220)	200	flow	fine	powder pellet
Cr	K $\alpha$	W	55	40	LiF(220)	200	flow	fine	powder pellet
V	K $\alpha$	W	55	40	LiF(220)	200	flow	fine	powder pellet
Zn	K $\alpha$	Mo	55	40	LiF(220)	200	flow + scint.	fine	powder pellet
Cu	K $\alpha$	Mo	55	40	LiF(220)	200	flow + scint.	fine	powder pellet
Ni	K $\alpha$	Mo	55	40	LiF(220)	200	flow + scint.	fine	powder pellet
La	L $\alpha$	W	55	40	LiF(220)	200	flow	fine	powder pellet
Ce	L $\beta$	W	55	40	LiF(220)	200	flow	fine	powder pellet
Nd	L $\alpha$	W	55	40	LiF(220)	200	flow	fine	powder pellet

APPENDIX 4 : Major Element Analyses (H<sub>2</sub>O<sup>-</sup> and L.O.I. included) and Trace Element Analyses.

TABLE C: Lambrechtsdrif Member, (Boomrivier Formation), Basaltic Andesites.

	Central Domain					Southern Domain			Average		S.D.	CS-10
	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	CS-9	(1-9)		
SiO <sub>2</sub>	54,25	53,60	52,88	54,24	55,25	54,46	54,57	54,55	54,27	54,23	0,63	51,64
TiO <sub>2</sub>	1,06	1,08	1,13	1,10	1,06	1,06	1,02	1,20	1,04	1,08	0,05	2,71
Al <sub>2</sub> O <sub>3</sub>	14,95	14,38	14,52	14,47	14,54	14,38	14,25	14,84	14,87	14,59	0,23	13,01
Fe <sub>2</sub> O <sub>3</sub>	10,40	10,63	11,44	10,55	10,34	10,29	9,88	10,73	10,26	10,50	0,41	14,36
MnO	0,14	0,10	0,10	0,10	0,15	0,15	0,15	0,14	0,14	0,13	0,02	0,19
MgO	5,80	5,22	5,20	5,52	5,34	5,13	5,23	5,30	5,63	5,37	0,21	4,78
CaO	8,28	9,38	9,44	8,92	6,55	9,92	8,81	8,98	8,88	8,80	0,91	8,30
Na <sub>2</sub> O	1,96	2,42	2,01	1,92	3,18	1,50	2,66	2,14	2,01	2,20	0,46	1,87
K <sub>2</sub> O	2,00	1,37	1,00	1,70	1,13	0,76	0,88	1,18	0,71	1,19	0,41	1,68
P <sub>2</sub> O <sub>5</sub>	0,13	0,13	0,13	0,14	0,13	0,13	0,14	0,15	0,14	0,14	0,01	0,81
L.O.I.	1,76	1,56	2,16	1,15	1,84	2,28	2,49	1,25	2,01	1,83	0,43	0,57
H <sub>2</sub> O <sup>-</sup>	0,11	0,06	0,07	0,11	0,12	0,10	0,13	0,11	0,08	0,10	0,02	0,07
TOTAL	100,84	99,93	100,08	99,92	99,73	100,16	100,21	100,57	100,04	100,16	-	99,99
Rb	63,3	93,3	45,8	57,6	49,1	43,4	44,7	45,5	36,4	53,2	16,0	46,1
Sr	223	215	316	245	312	296	454	237	213	279	73	333
Zr	139	144	154	149	136	139	146	147	140	144	6	313
Y	32,1	32,1	35,3	32,6	30,2	31,7	32,2	34,5	32,3	32,6	1,4	66,2
Nb	11,9	11,2	10,8	9,8	10,3	8,6	10,4	12,4	10,2	10,6	1,1	31,4
Cr	167	160	63	83	117	119	152	116	165	127	35	163
V	239	221	254	241	238	239	219	251	232	237	11	354
Co	50	49	51	52	50	51	46	52	50	50	2	53
Ni	62	70	66	67	60	59	59	67	64	64	4	88
Cu	90	79	85	78	80	85	79	98	86	84	6	45
Zn	79	85	93	85	92	78	82	84	83	85	5	112
La	20	19	19	17	20	13	15	13	20	17	3	51
Ce	49	47	53	49	52	44	46	50	44	45	11	112
Nd	27	24	25	23	25	23	24	24	22	24	2	63

	Central Domain					Southern Domain		CS-18	Average (11-18)	S.D.
	CS-11	CS-12	CS-13	CS-14	CS-15	CS-16	CS-17			
SiO <sub>2</sub>	63,39	68,83	65,36	65,73	67,62	66,01	67,45	65,75	66,27	1,56
TiO <sub>2</sub>	1,21	1,06	1,14	1,16	1,00	1,05	1,02	1,13	1,10	0,07
Al <sub>2</sub> O <sub>3</sub>	13,65	11,87	13,24	12,80	12,52	12,68	12,53	13,02	12,79	0,50
Fe <sub>2</sub> O <sub>3</sub>	7,45	6,67	6,98	7,49	6,42	6,76	6,77	7,52	7,01	0,40
MnO	0,07	0,05	0,12	0,06	0,08	0,11	0,14	0,11	0,09	0,03
MgO	1,50	1,02	1,46	1,02	1,04	0,99	0,69	1,36	1,13	0,26
CaO	2,35	1,83	2,42	2,17	2,74	3,61	3,07	2,67	2,61	0,52
Na <sub>2</sub> O	3,17	2,90	2,67	2,47	1,79	2,18	2,14	1,76	2,39	0,48
K <sub>2</sub> O	4,57	4,37	4,98	4,87	4,74	4,30	4,67	4,64	4,64	0,22
P <sub>2</sub> O <sub>5</sub>	0,48	0,40	0,56	0,44	0,40	0,41	0,43	0,43	0,44	0,05
L.O.I.	1,16	0,81	0,96	1,09	1,23	1,41	0,99	1,71	1,17	0,27
H <sub>2</sub> O <sup>-</sup>	0,06	0,03	0,05	0,07	0,12	0,09	0,06	0,10	0,07	0,03
TOTAL	99,06	99,84	99,94	99,37	99,70	99,60	99,96	100,20	99,71	-
Rb	142,3	155,6	187,8	243,0	180,1	190,6	184,6	210,5	186,8	29,0
Sr	331	188	220	344	172	248	243	253	250	57
Zr	401	365	404	394	375	390	377	389	387	13
Y	72,7	67,4	72,9	71,1	70,0	71,3	69,3	67,8	70,3	1,9
Nb	29,8	27,7	28,0	28,4	30,1	29,7	28,7	27,8	28,8	0,9
Cr	15	15	9	20	15	17	19	18	15	3
V	96	86	102	99	76	84	87	115	93	12
Co	20	18	21	18	19	17	20	21	19	2
Ni	21	24	18	25	20	18	17	17	20	3
Cu	9	9	11	7	17	16	13	13	12	3
Zn	136	76	106	89	86	90	97	102	98	17
La	83	72	85	82	75	78	77	75	78	4
Ce	175	149	172	158	156	159	157	159	161	8
Nd	89	74	85	76	74	82	79	81	80	5

APPENDIX 4 (Contd). TABLE E : Rouxville Member, (Leeudraai Formation), Basalts to Basaltic Andesites.

	Southern Domain						Central Domain				Average	S.D.
	CS-19	CS-20	CS-21	CS-22	CS-23	CS-24	CS-25	CS-26	CS-25A	CS-26A	(19-26)	
SiO <sub>2</sub>	47,77	49,07	51,84	49,66	50,18	52,84	53,46	51,52	55,82	59,15	50,79	1,83
TiO <sub>2</sub>	1,65	1,93	1,73	1,78	2,29	2,17	2,54	2,66	2,12	1,95	2,09	0,36
Al <sub>2</sub> O <sub>3</sub>	15,68	14,45	14,47	14,75	14,60	14,73	13,54	12,69	12,14	12,32	14,36	0,83
Fe <sub>2</sub> O <sub>3</sub>	13,43	14,54	12,23	13,90	13,33	11,59	13,21	16,91	11,13	10,57	13,64	1,50
MnO	0,18	0,19	0,15	0,18	0,13	0,18	0,08	0,04	0,06	0,03	0,14	0,05
MgO	6,91	6,24	5,87	5,28	5,50	3,11	2,68	1,39	2,08	1,37	4,62	1,84
CaO	9,07	7,50	8,72	7,09	7,43	7,47	5,62	6,18	7,33	5,73	7,39	1,08
Na <sub>2</sub> O	1,69	2,46	2,14	2,65	2,16	2,30	4,45	5,07	3,77	4,73	2,87	1,14
K <sub>2</sub> O	0,97	0,82	0,65	1,55	1,98	2,87	1,00	0,06	0,91	0,24	1,24	0,82
P <sub>2</sub> O <sub>5</sub>	0,34	0,39	0,38	0,39	0,72	0,78	0,83	0,90	0,70	0,64	0,59	0,22
L.O.I.	2,15	2,58	1,52	2,55	1,60	1,68	1,99	1,15	3,24	2,04	1,90	0,47
H <sub>2</sub> O <sup>-</sup>	0,08	0,15	0,17	0,11	0,11	0,10	0,12	0,24	0,07	0,09	0,14	0,05
TOTAL	99,92	100,32	99,87	99,89	100,03	99,82	98,52	99,81	99,37	98,86	99,77	-
Rb	27,4	29,6	19,8	42,2	56,8	81,5	15,7	0,1	15,3	8,0	34,1	24,0
Sr	304	427	303	335	387	434	212	78	183	97	310	111
Zr	160	178	202	173	322	397	449	484	380	351	296	126
Y	39,5	44,4	42,2	43,5	58,0	63,7	70,3	77,5	59,8	55,2	54,9	13,6
Nb	12,2	12,8	13,9	13,9	25,4	28,0	34,8	36,0	31,0	28,0	22,1	9,5
Cr	290	342	269	330	188	74	95	118	79	83	212	101
V	2,3	325	264	292	266	227	267	314	220	176	281	30
Co	60	62	55	59	49	37	46	45	37	31	52	8
Ni	113	113	102	120	90	56	59	68	53	49	90	24
Cu	41	25	42	29	32	27	49	14	39	17	32	11
Zn	111	120	107	110	136	120	116	64	90	57	111	20
La	24	28	28	27	48	67	80	92	57	65	49	25
Ce	59	62	78	69	119	150	161	195	133	131	112	49
Nd	29	31	42	35	62	77	85	104	67	79	58	27

APPENDIX 4 (contd.). TABLE F: Swartkop Member, (Leeudraai Formation), Rhyolites.

All samples are from Karos Nedersetting (Central Domain)

	CS-27	CS-28	CS-29	CS-30	Average (27-30)	S.D.
SiO <sub>2</sub>	69,76	70,13	69,96	71,12	70,24	0,52
TiO <sub>2</sub>	0,72	0,69	0,67	0,64	0,68	0,03
Al <sub>2</sub> O <sub>3</sub>	12,50	12,70	12,42	12,68	12,58	0,12
Fe <sub>2</sub> O <sub>3</sub>	4,44	4,27	4,33	3,99	4,26	0,17
MnO	0,02	0,02	0,02	0,07	0,03	0,02
MgO	0,66	0,69	0,62	0,65	0,65	0,03
CaO	1,46	2,05	1,93	1,50	1,74	0,26
Na <sub>2</sub> O	2,86	2,56	2,41	2,83	2,67	0,19
K <sub>2</sub> O	5,62	5,35	5,43	5,39	5,45	0,10
P <sub>2</sub> O <sub>5</sub>	0,17	0,17	0,16	0,20	0,17	0,02
L.O.I.	0,60	1,06	0,99	0,88	0,88	0,18
H <sub>2</sub> O <sup>-</sup>	0,04	0,07	0,06	0,06	0,06	0,01
TOTAL	98,85	99,76	99,00	100,01	99,41	-
Rb	227,9	220,3	223,2	221,4	223,2	2,9
Sr	201	159	185	186	183	15
Zr	444	405	409	436	424	17
Y	74,4	73,4	73,5	75,7	74,3	0,9
Nb	40,7	38,6	38,6	40,3	39,6	1,0
Cr	13	9	12	4	10	4
V	33	36	38	36	36	2
Co	16	21	23	23	21	3
Ni	11	11	11	11	11	0
Cu	10	8	9	6	8	2
Zn	66	61	65	69	65	3
La	99	104	102	107	103	3
Ce	213	190	194	203	200	9
Nd	89	82	81	85	84	3

APPENDIX 5: Major Elements Analyses ( $H_2O$ -free, normalized to 100%) and CIPW Weight Percent Norms ( $Fe_2O_3 = TiO_2 + 1.5$ ). TABLE G: Lambrechtsdrif Member, (Boomrivier Formation), Basaltic Andesites.

	Central Domain					Southern Domain			Average		S.D.	CS-10
	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	CS-9	(1-9)		
SiO <sub>2</sub>	54,80	54,52	54,04	54,98	56,51	55,70	55,92	54,99	55,41	55,21	0,71	51,98
TiO <sub>2</sub>	1,07	1,10	1,16	1,11	1,08	1,09	1,04	1,21	1,07	1,10	0,05	2,72
Al <sub>2</sub> O <sub>3</sub>	15,10	14,63	14,84	14,67	14,98	14,71	14,61	14,96	15,18	14,85	0,20	13,10
Fe <sub>2</sub> O <sub>3</sub>	10,51	10,81	11,69	10,69	10,57	10,52	10,13	10,82	10,47	10,69	0,40	14,45
MnO	0,15	0,10	0,11	0,10	0,16	0,15	0,15	0,14	0,15	0,13	0,02	0,19
MgO	5,87	5,31	5,32	5,59	5,47	5,24	5,36	5,34	5,75	5,47	0,21	4,81
CaO	8,36	9,54	9,64	9,04	6,70	10,14	9,03	9,05	9,07	8,95	0,92	8,35
Na <sub>2</sub> O	1,98	2,46	2,05	1,95	3,25	1,54	2,73	2,15	2,05	2,24	0,47	1,88
K <sub>2</sub> O	2,02	1,39	1,02	1,72	1,16	0,78	0,90	1,19	0,73	1,21	0,41	1,69
P <sub>2</sub> O <sub>5</sub>	0,14	0,14	0,14	0,14	0,13	0,13	0,14	0,15	0,14	0,14	0,01	0,82
CIPW Weight % Norms. ( $Fe_2O_3 = TiO_2 + 1,5$ )												
Ap	0,32	0,32	0,33	0,33	0,31	0,32	0,34	0,36	0,33	0,33	0,01	1,96
Il	2,03	2,09	2,19	2,10	2,05	2,06	1,97	2,28	2,02	2,09	0,09	5,16
Or	12,03	8,30	6,07	10,28	6,91	4,64	5,34	7,07	4,34	7,22	2,44	10,12
Ab	16,90	20,95	17,51	16,58	27,75	13,11	23,24	18,38	17,48	19,10	4,06	16,09
An	26,56	24,98	28,54	26,42	23,03	31,18	25,16	27,86	30,31	27,23	2,63	22,52
Mt	3,78	3,84	3,94	3,86	3,83	3,83	3,77	3,97	3,80	3,85	0,06	6,20
DiEn	3,47	5,05	4,17	4,25	2,27	4,35	4,55	3,84	3,40	3,93	0,76	3,16
DiFs	2,25	3,73	3,46	2,91	1,59	3,14	3,05	2,73	2,23	2,79	0,63	2,46
DiWo	6,00	9,13	7,86	7,48	4,03	7,80	7,95	6,84	5,90	7,00	1,42	5,82
HyEn	11,25	8,29	9,20	9,79	11,45	8,81	8,91	9,57	11,03	9,81	1,10	8,95
HyFs	7,32	6,12	7,63	6,70	8,02	6,35	5,97	6,81	7,26	6,91	0,66	6,98
Q	8,09	7,21	9,12	9,30	8,78	14,42	9,77	10,28	11,92	9,88	2,04	10,62
TOTAL	100,01	100,01	100,01	100,01	100,02	100,01	100,01	100,01	100,01	100,14	-	100,05

APPENDIX 5 (contd.). TABLE H: Swartkopsleegte Member, (Boomrivier Formation), Rhyodacites.

	Central Domain					Southern Domain			Average	S.D.
	CS-11	CS-12	CS-13	CS-14	CS-15	CS-16	CS-17	CS-18	(11-18)	
SiO <sub>2</sub>	64,79	69,53	66,06	66,93	68,76	67,29	68,20	66,82	67,30	1,42
TiO <sub>2</sub>	1,23	1,07	1,15	1,18	1,02	1,07	1,03	1,15	1,11	0,07
Al <sub>2</sub> O <sub>3</sub>	13,95	11,99	13,38	13,04	12,73	12,93	12,67	13,23	12,99	0,54
Fe <sub>2</sub> O <sub>3</sub>	7,62	6,74	7,06	7,52	6,53	6,89	6,85	7,64	7,12	0,42
MnO	0,08	0,05	0,12	0,06	0,08	0,11	0,14	0,12	0,10	0,03
MgO	1,54	1,03	1,48	1,04	1,06	1,01	0,70	1,38	1,16	0,27
CaO	2,40	1,85	2,45	2,21	2,79	3,68	3,10	2,72	2,65	0,53
Na <sub>2</sub> O	3,24	2,93	2,70	2,51	1,82	2,22	2,17	1,79	2,42	0,48
K <sub>2</sub> O	4,67	4,41	5,04	4,96	4,82	4,38	4,72	4,71	4,71	0,22
P <sub>2</sub> O <sub>5</sub>	0,49	0,41	0,57	0,45	0,41	0,42	0,44	0,44	0,45	0,05
<u>CIPW Weight % Norms.</u> (Fe <sub>2</sub> O <sub>3</sub> = TiO <sub>2</sub> + 1,5)										
Ap	1,16	0,97	1,35	1,07	0,97	0,99	1,04	1,05	1,08	0,12
Il	2,32	2,01	2,18	2,23	1,92	2,02	1,94	2,17	2,10	0,14
Or	27,72	26,20	29,90	29,46	28,59	26,00	28,00	27,98	27,98	1,29
Ab	27,58	24,89	22,93	21,35	15,45	18,87	18,42	15,18	20,58	4,13
An	8,74	6,51	8,48	8,07	11,22	12,12	10,97	10,65	9,63	1,85
C	0,37	0,02	0,40	0,60	0,43	-	-	1,32	0,39	0,41
Mt	4,03	3,76	3,89	3,95	3,70	3,79	3,70	3,90	3,84	0,11
DiEn	-	-	-	-	-	0,56	0,23	-	0,10	0,19
DiFs	-	-	-	-	-	0,76	0,48	-	0,16	0,28
DiWo	-	-	-	-	-	1,32	0,68	-	0,25	0,46
HyEn	3,85	2,57	3,71	2,59	2,64	1,97	1,51	3,46	2,79	0,78
HyFs	3,91	3,11	3,43	4,11	3,02	2,67	3,16	4,37	3,47	0,56
Q	20,34	29,98	23,78	26,60	32,10	28,65	29,92	29,94	27,66	3,64
TOTAL	100,03	100,02	100,05	100,03	100,02	100,02	100,02	100,02	100,03	-

APPENDIX 5 (contd.). TABLE I: Rouxville Member, (Leeudraai Formation), Basalts to Basaltic Andesites.

	Southern Domain				Central Domain				Average		S.D.	
	CS-19	CS-20	CS-21	CS-22	CS-23	CS-24	CS-25	CS-26	CS-25A	CS-26A		(19-26)
SiO <sub>2</sub>	48,90	50,28	52,80	51,07	51,04	53,90	54,89	52,89	58,13	61,15	51,97	1,86
TiO <sub>2</sub>	1,69	1,98	1,76	1,83	2,33	2,21	2,61	2,73	2,21	2,02	2,14	0,37
Al <sub>2</sub> O <sub>3</sub>	16,05	14,81	14,74	15,17	14,86	15,03	13,90	13,03	12,64	12,74	14,69	0,84
Fe <sub>2</sub> O <sub>3</sub>	13,75	14,90	12,46	14,30	13,56	11,82	13,56	17,36	11,59	10,93	13,96	1,57
MnO	0,19	0,20	0,16	0,19	0,13	0,18	0,08	0,04	0,06	0,03	0,14	0,05
MgO	7,07	6,40	5,98	5,43	5,60	3,17	2,75	1,42	2,16	1,41	4,73	1,88
CaO	9,29	7,68	8,88	7,29	7,56	7,62	5,77	6,34	7,63	5,93	7,55	1,09
Na <sub>2</sub> O	1,73	2,52	2,18	2,73	2,20	2,34	4,57	5,21	3,92	4,89	2,94	1,17
K <sub>2</sub> O	0,99	0,84	0,66	1,59	2,01	2,93	1,02	0,06	0,94	0,24	1,26	0,83
P <sub>2</sub> O <sub>5</sub>	0,35	0,40	0,38	0,40	0,73	0,79	0,85	0,92	0,73	0,66	0,60	0,23
CIPW Weight % Norms. (Fe <sub>2</sub> O <sub>3</sub> = TiO <sub>2</sub> + 1,5)												
Ap	0,83	0,95	0,92	0,96	1,74	1,89	2,04	2,22	1,73	1,58	1,44	0,54
Il	3,20	3,76	3,33	3,48	4,41	5,19	4,95	5,19	4,18	3,81	4,06	0,70
Or	5,92	5,01	3,94	9,51	12,00	17,43	6,09	0,37	5,61	1,45	7,53	4,96
Ab	14,78	21,56	18,65	23,34	18,76	19,97	39,01	44,62	33,45	41,67	25,09	10,03
An	33,48	26,93	28,73	24,73	24,99	22,04	14,56	12,17	14,22	12,19	23,45	6,64
Mt	4,72	5,16	4,81	4,95	5,64	5,48	6,08	6,27	5,51	5,21	5,39	0,54
DiEn	2,54	2,01	3,16	1,94	1,93	2,34	1,56	1,24	3,64	2,05	2,10	0,54
DiFs	1,78	1,64	2,10	1,81	1,29	2,07	1,95	4,82	4,30	3,51	2,18	1,03
DiWo	4,51	3,77	5,51	3,84	3,37	4,53	3,63	5,68	7,99	5,47	4,36	0,81
HyEn	15,25	14,11	11,87	11,72	12,15	5,63	5,25	2,35	1,78	1,50	9,79	4,41
HyFs	10,71	11,57	7,89	10,95	8,16	4,99	6,18	9,15	2,11	2,56	8,70	2,20
Q	2,30	3,55	9,11	2,79	5,62	9,48	8,64	5,97	15,53	19,04	5,93	2,71
TOTAL	100,02	100,02	100,02	100,02	100,04	100,04	100,04	100,05	100,04	100,04	100,02	-

APPENDIX 5 (contd.). TABLE J : Swartkop Member, (Leeudraai Formation), Rhyolites.

All samples are from Karos Nedersetting (Central Domain)

	CS-27	CS-28	CS-29	CS-30	Average (27-30)	S.D.
SiO <sub>2</sub>	71,04	71,12	71,43	71,79	71,35	0,30
TiO <sub>2</sub>	0,73	0,70	0,68	0,65	0,69	0,03
Al <sub>2</sub> O <sub>3</sub>	12,72	12,87	12,68	12,80	12,77	0,07
Fe <sub>2</sub> O <sub>3</sub>	4,52	4,33	4,42	4,02	4,32	0,19
MnO	0,02	0,02	0,02	0,07	0,03	0,02
MgO	0,67	0,70	0,63	0,65	0,66	0,03
CaO	1,49	2,08	1,97	1,51	1,76	0,27
Na <sub>2</sub> O	2,91	2,60	2,46	2,86	2,71	0,19
K <sub>2</sub> O	5,72	5,42	5,55	5,44	5,53	0,12
P <sub>2</sub> O <sub>5</sub>	0,18	0,17	0,16	0,21	0,18	0,02
<u>CIPW Weight % Norms.</u> (Fe <sub>2</sub> O <sub>3</sub> = TiO <sub>3</sub> + 1,5)						
Ap	0,41	0,40	0,38	0,50	0,42	0,05
Il	1,37	1,31	1,28	1,22	1,30	0,05
Or	33,89	32,10	32,84	32,21	32,76	0,71
Ab	24,69	22,02	20,83	24,20	22,94	1,58
An	4,76	7,48	7,22	6,05	6,37	1,08
Mt	3,28	3,22	3,21	3,13	3,21	0,05
DiEn	0,40	0,50	0,40	0,40	0,33	0,18
DiFs	0,18	0,16	0,19	0,01	0,13	0,07
DiWo	0,63	0,73	0,63	0,05	0,51	0,27
HyEn	1,28	1,25	1,18	1,58	1,32	0,15
HyFs	0,57	0,41	0,57	0,38	0,48	0,09
Q	28,55	30,43	31,27	30,66	30,23	1,02
TOTAL	100,01	100,01	100,01	100,03	100,00	-

APPENDIX 6, TABLE K: CIPW Weight Percent Norms using  $Fe_2O_3/FeO = 0.2$

The  $Fe_2O_3/FeO$  values calculated using Irvine and Baragar's (1971) equation ( $\% Fe_2O_3 = \%TiO_2 + 1.5$ ) are presented in column A of Table L (Appendix 7) and are considerably higher than the value of 0.2 which is used by previous workers in this department. The lower  $Fe_2O_3/FeO$  value does not affect the amounts of normative feldspars in this case, but reduces the amounts of magnetite and quartz in the norm, increases the proportions of normative diopside and hypersthene and reduces the proportion of MgO in the normative diopside and hypersthene.

	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	CS-9	CS-10
Ap	0,33	0,33	0,33	0,33	0,31	0,33	0,33	0,36	0,33	1,97
Il	2,03	2,08	2,20	2,12	2,05	2,07	1,97	2,29	2,03	5,18
Or	12,05	8,33	6,09	10,28	6,91	4,67	5,32	7,09	4,37	10,16
Ab	16,92	20,98	17,51	16,58	27,75	13,11	23,27	18,36	17,51	16,16
An	26,58	24,98	28,57	26,45	23,05	31,20	25,19	27,89	30,33	22,53
Mt	2,33	2,41	2,61	2,39	2,35	2,33	2,25	2,42	2,33	3,23
DiEn	3,20	4,64	3,86	3,90	2,08	3,98	4,17	3,50	3,13	2,64
DiFs	2,61	4,28	3,86	3,36	1,84	3,63	3,59	3,19	2,60	3,17
DiWo	6,00	9,14	7,86	7,47	4,02	7,80	7,99	6,86	5,91	5,85
HyEn	11,54	8,71	9,51	10,17	11,67	9,20	9,30	9,92	11,31	9,48
HyFs	9,43	8,04	9,52	8,76	10,30	8,40	8,02	9,04	9,39	11,38
Q	6,96	6,08	8,09	8,20	7,68	13,28	8,60	9,09	10,76	8,27
TOTAL	100,01	100,01	100,02	100,01	100,01	100,01	100,01	100,01	100,01	100,05

APPENDIX, TABLE K (CONTD.)

	CS-19	CS-20	CS-21	CS-22	CS-23	CS-24	CS-25	CS-26	CS-25A	CS-26A		
Ap	0,83	0,95	0,92	0,95	1,75	1,89	2,04	2,23	1,73	1,59		
Il	3,21	3,77	3,34	3,47	4,41	4,21	4,96	5,20	4,19	3,81		
Or	5,91	5,02	3,96	9,51	12,00	17,49	6,09	0,35	5,61	1,48		
Ab	14,81	21,58	18,70	23,35	18,78	20,05	39,09	44,67	33,51	41,71		
An	33,51	26,98	28,73	24,77	25,05	22,04	14,62	12,23	14,27	12,23		
Mt	3,07	3,33	2,78	3,20	3,03	2,64	3,03	3,90	2,60	2,44		
DiEn	2,36	1,83	2,85	1,77	1,66	1,85	1,28	1,02	2,66	1,42		
DiFs	2,03	1,86	2,55	2,05	1,64	2,76	2,47	5,10	5,59	4,33		
DiWo	4,53	3,76	5,54	3,85	3,37	4,56	3,65	5,67	8,00	5,45		
HyEn	15,44	14,30	12,19	11,92	12,43	6,15	5,65	2,59	2,77	2,14		
HyFs	13,28	14,51	10,92	13,76	12,30	9,18	10,91	12,97	5,83	6,51		
Q	1,04	2,13	7,53	1,41	3,61	7,23	6,27	4,14	13,28	16,92		
TOTAL	100,02	100,02	100,02	100,02	100,04	100,04	100,04	100,07	100,03	100,03		
	CS-11	CS-12	CS-13	CS-14	CS-15	CS-16	CS-17	CS-18	CS-27	CS-28	CS-29	CS-30
Ap	1,16	0,97	1,35	1,07	0,97	0,99	1,04	1,04	0,43	0,40	0,38	0,50
Il	2,23	2,03	2,18	2,23	1,91	2,03	1,93	2,18	1,37	1,31	1,28	1,22
Or	27,77	26,74	29,96	29,49	28,66	26,06	28,07	28,01	33,92	32,15	32,91	32,26
Ab	27,67	24,96	23,01	21,41	15,48	18,87	18,44	15,23	24,71	22,08	20,90	24,28
An	8,76	6,55	8,48	8,07	11,21	12,44	10,98	10,67	4,79	7,48	7,20	6,03
C	0,37	-	0,39	0,60	0,43	-	-	1,32	-	-	-	-
Mt	1,70	1,49	1,58	1,70	1,46	1,54	1,52	1,71	1,00	0,96	0,99	0,88
DiEn	-	-	-	-	-	0,36	0,14	-	0,17	0,21	0,18	0,02
DiFs	-	-	-	-	-	1,03	0,59	-	0,46	0,54	0,51	0,04
DiWo	-	-	-	-	-	1,32	0,68	-	0,60	0,72	0,66	0,06
HyEn	3,86	2,57	3,71	2,59	2,64	2,18	1,60	3,46	1,53	1,55	1,42	1,60
HyFs	7,93	7,00	7,39	7,97	6,87	6,27	6,79	8,16	4,19	3,90	4,09	4,19
Q	18,50	28,23	21,98	24,89	30,37	26,93	28,24	28,25	26,85	28,70	29,52	28,92
TOTAL	100,04	100,03	100,03	100,01	100,02	100,02	100,02	100,02	100,00	100,01	100,03	100,01

APPENDIX 7, TABLE L: Selected Interelement Ratios.

(A =  $\text{Fe}_2\text{O}_3/\text{FeO}$  values using Irvine and Baragar's, 1971, equation:  $\text{Fe}_2\text{O}_3 = \text{TiO}_2 + 1.5$ )

	A	K/Rb	Zr/Nb	Zr/Y	$\text{TiO}_2/\text{P}_2\text{O}_5$	La/Ce	La/Nd	Ce/Nd	Zr/Ce	Y/Nd
CS-1	0,36	262	11,77	4,35	7,98	0,408	0,741	1,815	2,836	1,189
CS-2	0,36	122	13,09	4,50	8,31	0,404	0,792	1,958	3,064	1,338
CS-3	0,33	181	14,00	4,40	8,69	0,358	0,760	2,120	2,906	1,412
CS-4	0,36	245	14,90	4,52	7,86	0,347	0,739	2,130	3,041	1,417
CS-5	0,37	191	13,60	4,53	8,15	0,385	0,800	2,080	2,615	1,208
CS-6	0,37	145	16,15	4,40	8,11	0,295	0,565	1,913	3,159	1,378
CS-7	0,38	163	14,12	4,54	7,31	0,326	0,625	1,917	3,174	1,342
CS-8	0,37	215	11,89	4,26	7,91	0,260	0,542	2,083	2,940	1,438
CS-9	0,37	162	13,75	4,35	7,73	0,454	0,909	2,000	3,182	1,468
CS-10	0,46	303	9,98	4,73	3,32	0,455	0,810	1,778	2,795	1,051
CS-11	0,63	267	13,37	5,49	2,52	0,474	0,933	1,966	2,291	0,817
CS-12	0,69	233	13,04	5,45	2,65	0,483	0,973	2,014	2,450	0,911
CS-13	0,68	220	14,43	5,53	2,04	0,494	1,000	2,024	2,349	0,858
CS-14	0,61	166	14,07	5,55	2,64	0,519	1,079	2,079	2,494	0,936
CS-15	0,71	218	12,46	5,36	2,51	0,481	1,014	2,108	2,404	0,946
CS-16	0,67	187	13,11	5,47	2,56	0,491	0,951	1,939	2,453	0,870
CS-17	0,66	210	13,17	5,45	2,35	0,490	0,975	1,987	2,401	0,877
CS-18	0,60	183	14,00	5,73	2,61	0,472	0,926	1,963	2,447	0,837
CS-19	0,34	294	13,04	4,04	4,88	0,407	0,828	2,034	2,712	1,362
CS-20	0,34	230	13,89	4,02	5,02	0,452	0,903	2,000	2,871	1,432
CS-21	0,40	273	14,57	4,81	4,58	0,359	0,667	1,857	2,590	1,005
CS-22	0,34	305	12,42	3,97	4,57	0,420	0,771	1,971	2,507	1,243
CS-23	0,44	289	12,88	5,55	3,18	0,403	0,774	1,919	2,706	0,935
CS-24	0,52	292	14,18	6,20	2,78	0,447	0,870	2,113	2,647	0,827
CS-25	0,49	529	12,83	6,41	3,06	0,497	0,941	1,894	2,789	0,827
CS-26	0,36	4981	13,44	6,29	2,96	0,472	0,885	1,875	2,482	0,745
CS-25A	0,54	494	12,26	6,33	3,03	0,429	0,851	1,985	2,857	0,893
CS-26A	0,54	249	12,54	6,38	3,05	0,496	0,823	1,658	2,679	0,699
CS-27	1,11	205	10,83	6,00	4,24	0,465	1,112	2,393	2,085	0,836
CS-28	1,17	202	10,38	5,55	4,06	0,547	1,268	2,317	2,132	0,895
CS-29	1,11	202	10,49	5,53	4,19	0,526	1,259	2,395	2,108	0,907
CS-30	1,28	202	10,90	5,74	3,20	0,527	1,259	2,388	2,148	0,891

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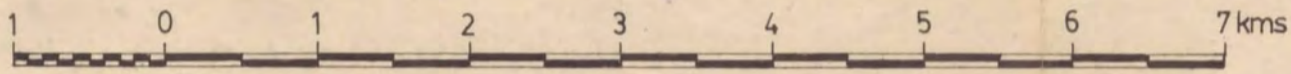
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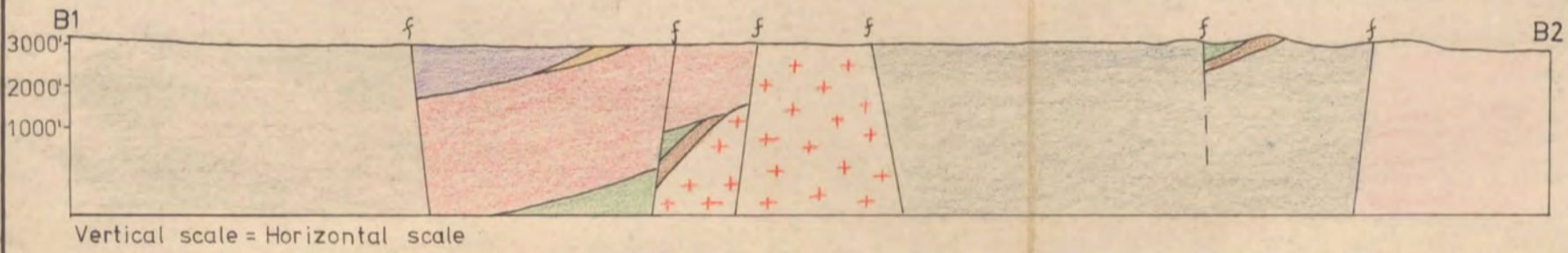
GEOLOGICAL MAP OF  
THE SOUTHERN DOMAIN OF THE KORAS GROUP

MAP 2 B

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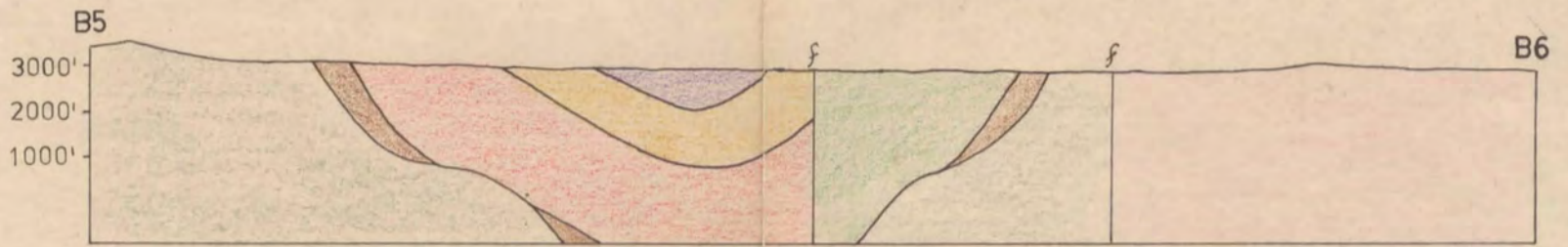
SECTIONS





















GEOLOGICAL KEY

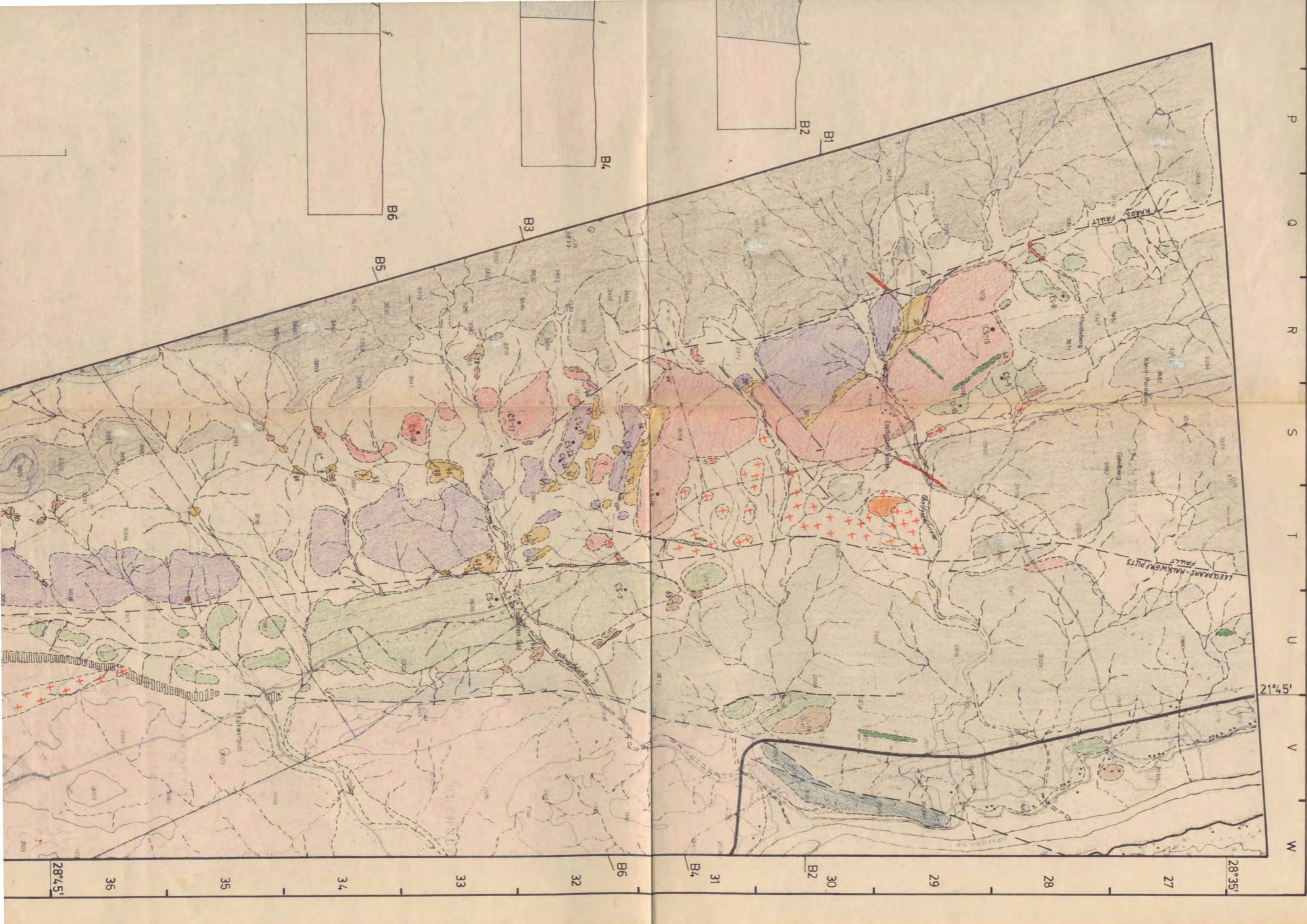
- Surficial Deposits
- Quartz - Feldspar Porphyry Dyke
- Dolerite Dyke
- Syenite

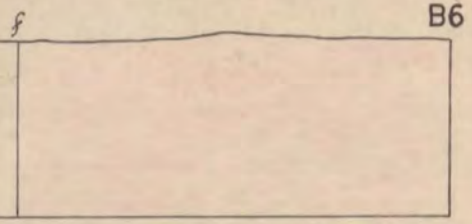
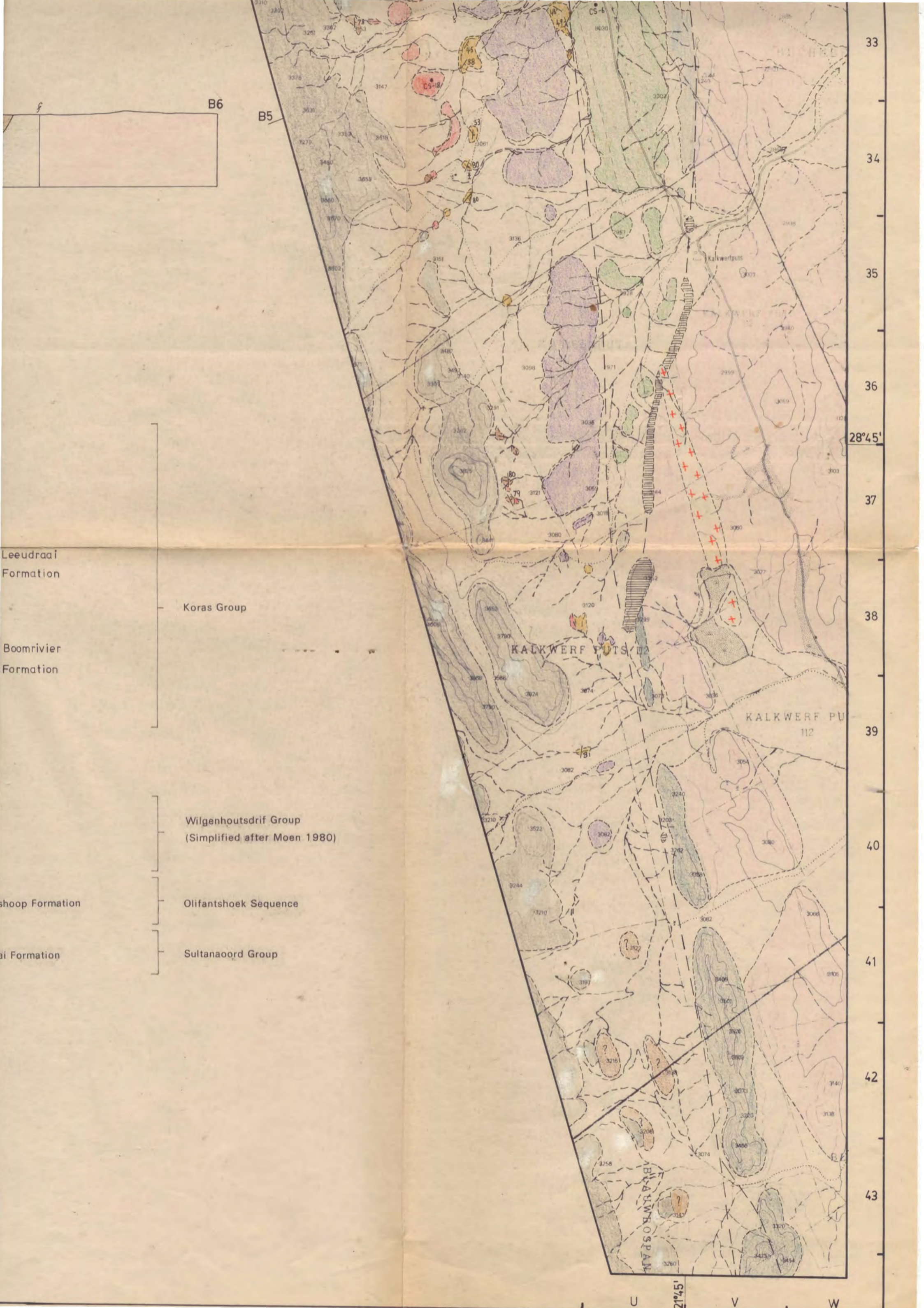




GEOLOGICAL KEY

- |   |  |                          |                        |   |
|---|--|--------------------------|------------------------|---|
|    | Surficial Deposits   |                          |                        |   |
|   | Quartz - Feldspar Porphyry Dyke  |                          |                        |   |
|  | Dolerite Dyke  |                          |                        |   |
|  | Syenite  |                          |                        |   |
|  | Amygdaloidal Basalt, Volcanic Breccia  | Rouxville Member         | Leeudraai Formation    | Koras Group                                   |
|  | Conglomerate, Sandstone  | Ezelfontein Member       |                        |   |
|  | Fine-grained Quartz - Feldspar Porphyry (Rhyodacite)                           | Swartkopsleegte Mbr.     | Boomrivier Formation   |   |
|  | Basaltic Andesite, Volcanic Breccia  | Lambrechtsdrif Mbr.      |                        |   |
|  | Conglomerate, Quartzite  | Basal Sedimentary Member |                        |   |
|  | Granite - gneiss   |                          |                        |   |
|  | Quartzite, Greenschist, Phyllite, Chert, Serpentinite, Limestone, Metarhyolite |                          |                        | Wilgenhoutsdrif Group (Simplified after Moen) |
|  | Grootdrink/Kameelpoort Quartzite   |                          |                        |   |
|  | Quartzite, Quartz - sericite Schist  |                          | Groblershoop Formation | Olifantshoek Sequence                         |
|  | Quartzite, Quartz - muscovite Schist, Phyllite, Serpentinite                   |                          | Roodraai Formation     | Sultanaoord Group                             |
|  | Fault  |                          |                        |   |
|  | Fault Breccia, Vein Quartz   |                          |                        |   |
|  | Strike and Dip of Bedding  |                          |                        |   |
|  | Sample position of Analyzed Rock   |                          |                        |   |





B5

B6

33

34

35

36

28°45'

37

38

39

40

41

42

43

Leeudraai Formation

Koras Group

Boomrivier Formation

Wilgenhoutsdrif Group (Simplified after Moen 1980)

shoop Formation

Olifantshoek Sequence

ai Formation

Sultanaoord Group

KALKWERF PUTS 112

KALKWERF PU 112

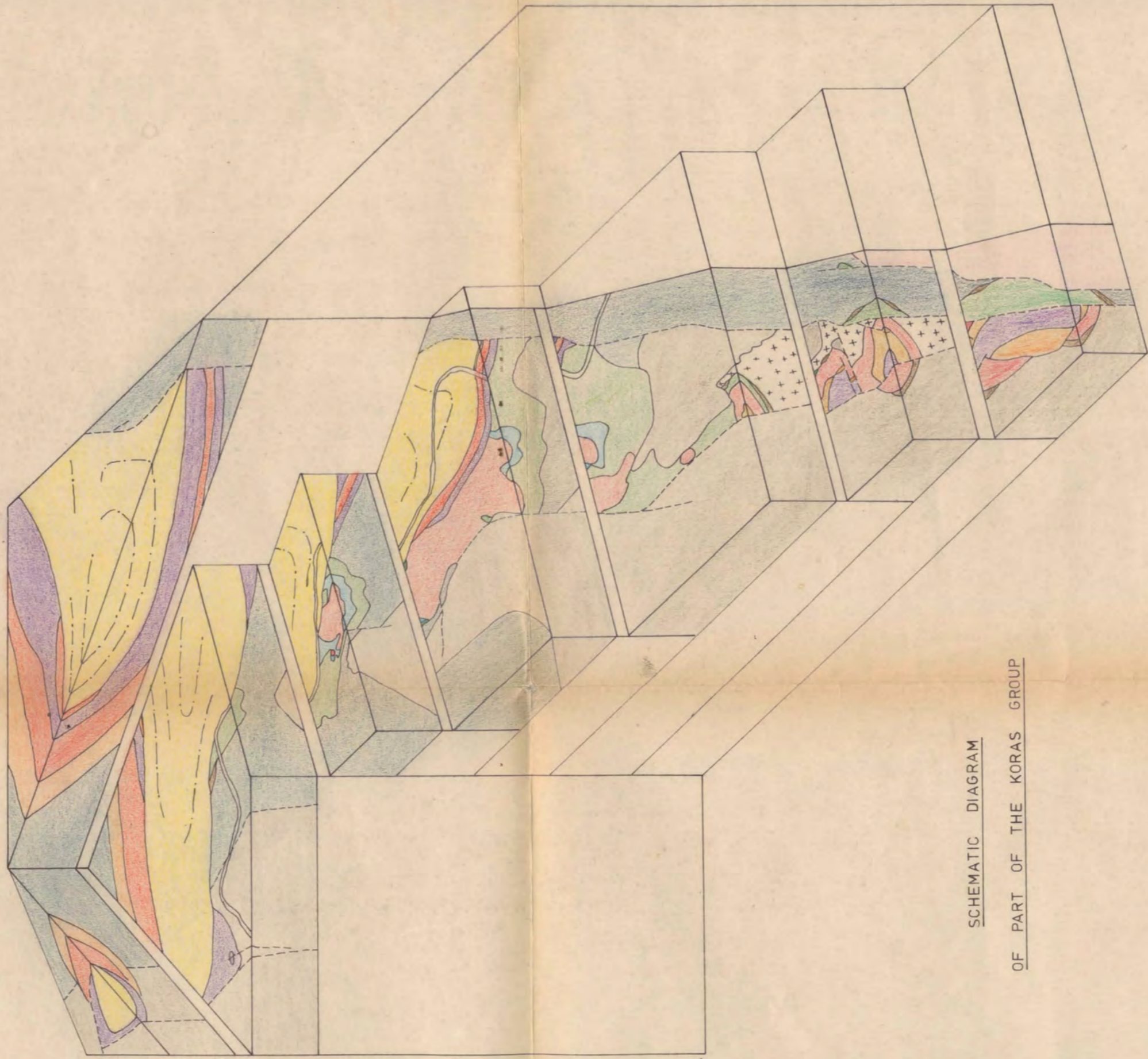
ABRAHAMSPAN

5712'

U

V

W



SCHEMATIC DIAGRAM  
OF PART OF THE KORAS GROUP



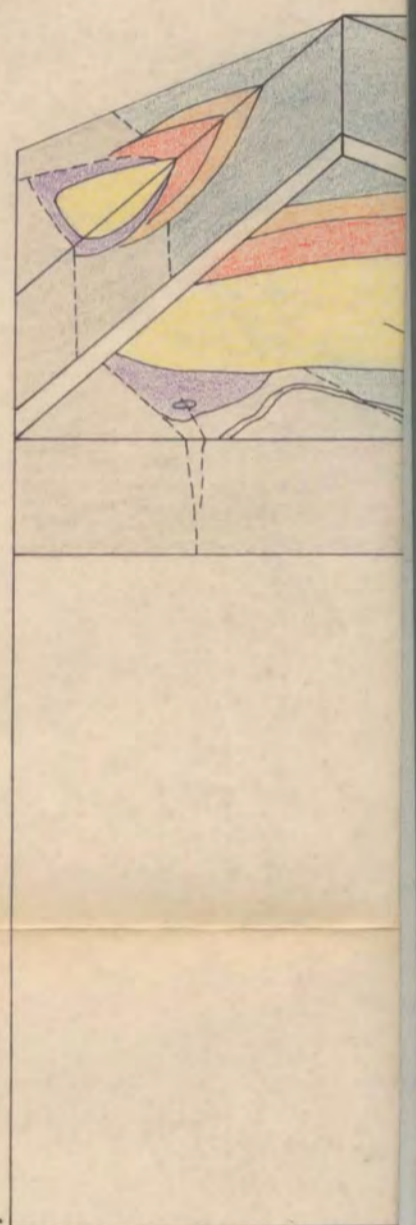
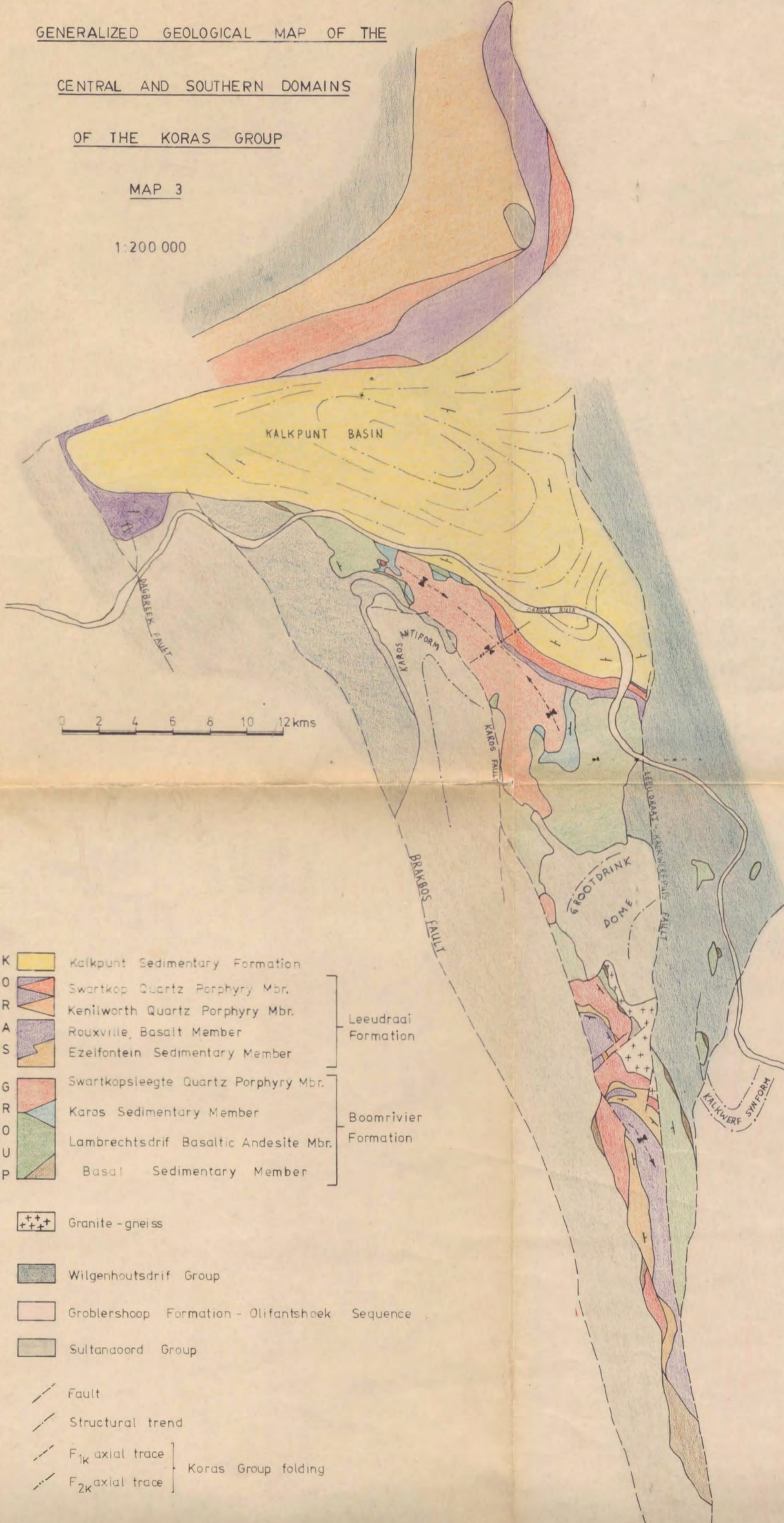
GENERALIZED GEOLOGICAL MAP OF THE

CENTRAL AND SOUTHERN DOMAINS

OF THE KORAS GROUP

MAP 3

1:200 000



SCHMATIC OF PART OF T

- |   |                    |                                       |                      |
|---|--------------------|---------------------------------------|----------------------|
| K | [Yellow box]       | Kalkpunt Sedimentary Formation        |                      |
| O | [Red box]          | Swartkop Quartz Porphyry Mbr.         | Leeudraai Formation  |
| R | [Orange box]       | Kenilworth Quartz Porphyry Mbr.       |                      |
| A | [Purple box]       | Rouxville Basalt Member               |                      |
| S | [Light purple box] | Ezelfontein Sedimentary Member        |                      |
| G | [Red box]          | Swartkopslegte Quartz Porphyry Mbr.   | Boomrivier Formation |
| R | [Green box]        | Karos Sedimentary Member              |                      |
| O | [Light green box]  | Lambrechtsdrif Basaltic Andesite Mbr. |                      |
| U | [Light green box]  | Lambrechtsdrif Basaltic Andesite Mbr. |                      |
| P | [Brown box]        | Basal Sedimentary Member              |                      |
- 
- [+++] Granite - gneiss
  - [Grey box] Wilgenhoutsdrif Group
  - [Light pink box] Groblershoop Formation - Olifantshoek Sequence
  - [Light grey box] Sultanaoord Group
- 
- [Dashed line] Fault
  - [Dotted line] Structural trend
  - [Dashed line with arrow] F<sub>1k</sub> axial trace
  - [Dotted line with arrow] F<sub>2k</sub> axial trace
- } Koras Group folding