THE GEOLOGY, PETROLOGY AND GEOCHEMISTRY OF THE KANYE VOLCANICS AND NNYWANE FORMATION: RAMOTSWA AREA, SOUTHEAST BOTSWANA

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by

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ABSTRACT

Two major felsic volcanic sequences of late Archean to early Proterozoic age are distinguished in southeast Botswana: the Kanye Volcanics and the Nnywane Formation. The Kanye Volcanics are red, purple and grey, dense, porphyritic rocks with pink and white feldspar phenocrysts in a felsitic to aphanitic groundmass. Presently, these rocks are regarded as part of the Gaborone Granite Complex. In addition to the volcanic rocks, the complex contains rapakivi and alaskitic granites, leucocratic microgranites, porphyritic granophyres, and variable amounts of mafic and ultramafic rocks.

The Nnywane Formation is an interbeded sequence of felsic flows, porphyries, tuffs and agglomerates. It is part of the Lobatse Volcanic Group which is correlated with the early Proterozoic Ventersdorp Supergroup of South Africa.

Despite the current correlation of the Kanye Volcanics and the Nnywane Formation with different stratigraphic units and the suggestion that these rocks are products of two distinct magmatic events, the evidence is not irrefutable. In addition, previous explanations for the origin of these volcanic rocks are inconsistent with available petrological, geochemical and geochronological data.

This study examines the relationship between the Kanye Volcanics and the Nnywane Formation in the Ramotswa area. The geology of the Ramotswa area is described. Major, minor and rare-earth element analyses of numerous samples from the Kanye Volcanics, porphyritic granophyres, leucocratic microgranites and the Nnywane Formation are discussed. Chemically, the Kanye Volcanics, porhyritic granophyres and Nnywane Formation have alkaline affinities, while the intrusive microgranites have major and trace element characteristics of within-plate type granites. Further, comparison of whole-rock major, trace and rare-earth element abundances shows that the Kanye Volcanics and porphyritic granophyres are virtually identical. In contrast, the microgranites have higher TiO_2, Al_2O_3, total iron, CaO, Sr, Zr and Ba and lower SiO_2, average K_2O, Rb, Y and Nb relative to the Kanye Volcanics and porphyritic granophyres. The Nnywane Formation has anomalously high SiO_2 and K_2O and low Na_2O and CaO and more variable Rb, Sr and Ba values relative to the Kanye Volcanics, but relatively the same range TiO_2, Al_2O_3, MgO, total iron as Fe_2O_3, Y, Nb, Ga and Zr. Rare-earth element abundances of these four units are very similar, but the microgranite has a more pronounced negative Eu anomaly.

Contrary to previous interpretations, these results suggest that the granophyres, Kanye Volcanics and Nnywane Formation (excluding mafic units) crystallized from essentially the same magma. The anomalous SiO_2, K_2O, Na_2O, CaO, Rb, Sr and Ba concentrations of the Nnywane Formation are probably due to subsequent hydrothermal and groundwater alteration.

However, the results of this study are inconclusive regarding the relationship of the leucocratic microgranites to the other units.

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INTRODUCTION

1.1 Location and Access

The study area is located in the southeastern part of Botswana, approximately 9 km south of Gaborone (Fig. 1.1). The area is part of the Gaborone quarter-degree sheet 2425B, and lies entirely within the South-East District. It is bounded by latitudes 24°44 S and 25°53 S to the north and south, respectively. The international border with the Republic of South Africa and longitude 25°54 E mark the eastern boundary, while longitude 25°42 E marks the western boundary of the study area.

The area is accessible through a network of motorable tracks and roads, including the Lobatse-Gaborone and Ramotswa-Thamaga main roads. Ramotswa village is the major settlement and two smaller settlements, Mogonye and Metsemaswane are also located within the study area. Besides these, several small farms and cattle posts are scattered throughout the region.

1.2 Topography and Drainage.

The map area has very undulating topography, with rounded hills separated by flat pavements and narrow stream valleys. The entire area is more than 1000 m above sea level and a few peaks attain elevations in excess of 1300 m. Three of these peaks: Phiriyabokwete, Rasemong and Mabofula are capped by flat-lying erosional remnants of Waterberg Supergroup sediments. Exposure is very good throughout the map area.

Several intermittent streams and rivers drain the area. The Notwane river and its tributaries the Taung and Metsemaswaane are the most important. Most of the streams follow prominent structural lineaments.

1.3 Present Investigation

This study examines field, petrologic and geochemical aspects of the Kanye Volcanics and the felsic volcanic rocks of the Lobatse Volcanic Group (the Nnywane Formation). It is based mainly on work done in the South-East District, between Ramotswa and Kgale (see Fig. 1.1). Field work was carried out in the period May to September 1985. Numerous samples of both volcanic suites and adjacent granitic rocks of the Gaborone Granite Complex were collected for petrographic study and for chemical analysis of major, trace and rare earth elements.

Despite the considerable amount of literature on the origin and possible regional correlations of the Kanye Volcanics and felsic volcanics of the Lobatse Volcanic Group, as well as the spatially associated plutonic rocks of the Gaborone Granite Complex, available data are considered neither sufficient to test the validity of proposed correlations nor to constrain the suggested petrogenetic models. It is hoped that the results of the present study will shed some light on these problematic relationships, both petrogenetic and stratigraphic.

CHAPTER 2

GEOLOGY OF SOUTHEAST BOTSWANA

2.1 Introduction

Five major lithostratigraphic units are recognized in southeast Botswana: the Basement Complex (i.e. Archean metamorphic rocks in Figure 1.1), the Gaborone Granite Complex, and the Ventersdorp, Transvaal and Waterberg supergroups. In addition, three minor intrusions occur in the region: the Modipe Gabbro, the Moshaneng Granite (not shown in Figure 1.1) and Mmathethe Granite (Fig. 1.1). However, these intrusions will not be covered in this review as they do not occur in the immediate study area.

2.2 The Basement Complex

The term Basement Complex is applied to a heterogeneous mixture of undifferentiated, metamorphosed and deformed rocks of pre-Gaborone Granite Complex and pre-Ventersdorp Supergroup age that occur in southeast Botswana, southeast of Mochudi and southwest of Lobatse, respectively. Very little is known about these rocks because of poor exposure.

On the geological map of southeast Botswana (Fig. 1.1), these areas are shown as underlain by undifferentiated quartzo-feldspathic gneisses of various ages. Associated with these are belts, lenses and pods of metasediments, amphibolites and schists. This information comes from isolated exposures of these rocks in the Mochudi area (Jones, 1959, 1961, 1966) and southeast of Lobatse (Crockett, 1971a).

2.3 The Gaborone Granite Complex

The Gaborone Granite Complex underlies an area of more than 5000 km^2 in southeast Botswana (Fig. 1.1). It was emplaced about 2.83 Ga ago (Sibiya, 1988) and is one of the largest intrusions in the Kaapvaal craton. The Complex consists mainly of rapakivi type granites, coarse- to medium-grained alaskites and felsic volcanic rocks. Granites are more abundant compared to the volcanic rocks.

Various textural varieties of granites can be distinguished in the Complex (Poldervaart, 1954; Wright, 1961; Crockett, 1969; Key and Wright, 1982; Sibiya, 1988). These units together with the associated volcanic rocks are disposed in a roughly concentric zonal pattern within the Complex. The apparent compositional and textural zonation of granitic and volcanic rocks in the Gaborone Granite Complex has long been recognized and has been used as a basis for various lithostratigraphic subdivisions (Table 2.1). For example, in a recent review, Key and Wright (1982) subdivided the Complex into four units. Starting from the centre to the periphery of the Complex these are: Thamaga Granite, Kgale Granite, Ntlhantlhe Microgranite and Kanye Volcanics (Fig. 1.1). The Thamaga Granites consist predominantly of rapakivi type granites which are distinguished by their mantled feldspar phenocrysts and megacrysts and mafic enclaves. In contrast, the Kgale Granite which also has rapakivi affinities (Sibiya, 1988) typically consists of plagioclase, potash feldspar and quartz with variable amounts of biotite and hornblende. It does not contain either mantled feldspars or mafic enclaves. The Kgale Granite grades into the surrounding Ntlhantlhe Microgranite (Fig. 1.1) which consists

Table 2.1 Correlation of previous and current subdivisions of the Gaborone Granite Complex

Poldervaart (1954)	Wright (1961)	Crockett (1969)	Key & Wright (1982)
	Lobatse Volcanics[1]	Kanye Volcanic Group	Kanye Volcanics
	Porphyritic Granophyre	Outer Marginal Assemblage	Ntlhantlhe Microgranite
	Marginal Granite	Inner Marginal Assemblage	Kgale Granite[2]
Gaborone Granite	Central Granite	Central Assemblage	Thamaga Granite

1. The Lobatse Volcanics (Wright, 1961) include the porphyritic granophyres (at the base of the Kanye Volcanics), the Kanye Volcanics and the felsic volcanic rocks of the Nnywane Formation.

2. The Kgale Granite (key and Wright, 1982) is equivalent to the coarse-to medium-grained part of the Inner Marginal Assemblage of crockett (1969), whereas the Ntlhantlhe Microgranite includes the porphyritic granophyres (Outer Marginal Assemblage) and the chilled margin of the Inner Marginal Assemblage.

of a fine-grained equigranular granite (closer to the Kgale Granite) and purple, porphyritic granophyres with numerous large (~7mm) feldspar phenocrysts in a very fine-grained granophyric to graphic groundmass. The Kanye Volcanics are typically massive, porphyritic felsites.

Until fairly recently, granites and felsic volcanic rocks were believed to be the only units of major significance in the Gaborone Granite Complex (Poldervaart, 1954; Wright, 1961; Crockett, 1969; Key and Wright, 1982). However, recent work (Sibiya, 1988) has shown that the Gaborone Granite Complex contains, in addition to granites and felsic volcanic rocks, significant amounts of ultramafic and mafic rocks: mainly anorthositic gabbros, leucogabbros and norites. This association of granites and mafic rocks, as Sibiya (1988) has already noted, is similar to that of the well known Proterozoic rapakvi granite-massif anorthosite complexes in the world. Unlike the other complexes however, the Gaborone Granite Complex is Archean (2.83 Ga) and contains enormous amounts of felsic volcanic rocks.

The origin of the Gaborone Granite Complex has been discussed by various workers. Poldervaart (1954) argued that the Gaborone Granite (i.e. Thamaga Granite, excluding the mafic assemblages) was the only intrusive unit in the complex. He regarded the two surrounding assemblages, the Kgale Granite and the Ntlhantlhe Microgranite, as recrystallized and partly remobilized equivalents of the the Kanye Volcanics and some of the siliceous volcanic rocks presently correlated with the Ventersdorp Supergroup (see Figure 1.1). At that time all the siliceous volcanic rocks of Southeast Botswana were correlated with the Dominion Reef System of South Africa (Du Toit, 1939; Truter, 1949).

In contrast, Wright (1961) and Key and Wright (1982) suggested that all the granitic assemblages within the Gaborone Granite Complex as well as the Kanye Volcanics were comagmatic. In the original version of this model, Wright (1961) treated the felsic volcanic rocks of the Lobatse Volcanic Group (i.e. the Nywane Formation) as part of the complex, whereas Key and Wright (1982) correlated the same rocks with the Ventersdorp Supergroup as previously suggested by Boocock (1959), Crockett (1971b) and Tyler (1979a).

Apart from the fact that they are mutually exclusive, these models, that is, the "two event hypothesis" of Poldervaart (1954) and the "one event hypothesis" of Wright (1961) and Key and Wright (1982), have significant problems. Firstly, they cannot be reconciled with available geochronological, petrological and geochemical data (see Harding et al., 1974; Key, 1983; Sibiya, 1988; Tables 2.4 and 5.1 this thesis). Secondly, the discovery of ultramafic and mafic rocks in the Complex (Sibiya, 1988) has added another dimension to the problem of the origin of the Gaborone Granite Complex. Some of these problems as well as new ideas on the origin of the Gaborone Granite Complex are discussed in Sibiya (1988).

2.4 The Ventersdorp Supergroup

At present, rocks correlated with the Ventersdorp Supergroup of South Africa (formerly Ventersdorp System) are known from the following areas in Botswana: Sikwane, between Molepolole and Mochudi, and along the southwest and southeast margin of the Gaborone Granite Complex (Fig. 1.1).

In the Sikwane area, east of Mochudi, the sequence consists of 900 m of mafic to intermediate volcanic rocks at the base overlain by flow-banded rhyolites, tuffaceous grits, shales, agglomerates, conglomerates and acid porphyries (Jones, 1959). These rocks are separated from the Basement Complex by a thrust fault (Jones, 1959). A southeasterly extension of the Sikwane units into South Africa, the Derderpoort Belt, was mapped by Tyler (1979a). He also correlated rocks of this belt with the Ventersdorp Supergroup.

Cullen (1955) described a succession of interbedded shaly tuffs, agglomerates and conglomerates of pre-Transvaal age in the Dipotsana area, on the southwest margin of the Gaborone Granite Complex. He called these rocks the Dipotsana Series and correlated them with the Ventersdorp Supergroup. Subsequent work by the Geological Survey of Botswana (Cullen, 1958; Boocock, 1962) has shown that these rocks are not confined to the Dipotsana area but outcrop sporadically along the southwest margin of the Gaborone Granite Complex between the Kanye Volcanics and the Transvaal Supergroup (Fig. 1.1).

Between Molepolole and Mochudi, the Ventersdorp Supergroup (not shown in Figure 1.1) is represented by a discontinuous belt of interbedded lavas, pyroclastic rocks, shales, sandstones and conglomerates, extending from Maopane, east of Molepolole, to Senamane, in the east (Cullen, 1959; Jones, 1973). Farther east, on Seleme Hill and Tshele Hill, sediments correlated with the Ventersdorp lie unconformably on a pink, weathered and partly eroded granite

(Kgale Granite). The succession, which was mapped by Jones (1961, 1966), consists of thin, discontinuous, pink, laminated, ripple-marked, shaly tuffs overlain by a polymictic boulder conglomerate, containing numerous clasts, including volcanic and granitic fragments. The conglomerate is overlain by the Black Reef Quartzite of the Transvaal Supergroup. Jones (1961, 1966) correlated this unit with the Ventersdorp Supergroup. If correct, this correlation establishes the relative ages of the Gaborone Granite Complex and the Ventersdorp Supergroup.

The most extensive exposures of Ventersdorp rocks occur along the southeast margin of the Gaborone Granite Complex in a continuous belt extending from the Notwane river valley, north of Ramotswa, southwards past Lobatse and into the Republic of South Africa at a point 12 km south of Lobatse. They consist of felsic porphyries, lavas, tuffs, agglomerates and volcanogenic sediments at the base overlain by a predominantly argillaceous assemblage of grey mudstones, shales, pink siltstones, flaggy sandstones and conglomerates. Crockett (1969, 1971b) and Key (1983) have discussed the stratigraphy and possible subdivisions of these rocks (Table 2.2). Crockett did not believe that the Ventersdorp Supergroup in Botswana could be divided into more formal stratigraphic units; he stated:

> "At present a reliable chronostratigraphic classification is unattainable owing to the extreme diachronous relationships displayed between each of three assemblages."

His classification was intended primarily for field mapping. In

Table 2.2 Proposed subdivisions of Ventersdorp units between Lobatse and Gaborone

Key (1983)		Crockett (1971b)	
Group	Formation	Unit	Lithology
Lobatse Volcanic Group		Upper Volcanic Assemblage	Amygdaloidal andesite flows (approx. 20 m thick)
	Mogobane	Mogobane Assemblage	Interbedded grey mudstones, shales, siltstones, sandstones and conglomerates
	Nnywane*	Lower Volcanic Assemblage	Felsic porphyries, lavas, tuffs and agglomerates

* The Nngwane Formation includes units that were in the Lower Volcanic Assemblage and Upper Volcanic Assemblage

contrast, Key (1983) divided the Ventersdorp between Lobatse and Gaborone into more formal stratigraphic units and established the Lobatse Volcanic Group. He gave the Mogobane Assemblage the status of a formation and combined the other two assemblages to form a second formation; the Nnywane Formation.

It is important to note that prior to Key's (1983) stratigraphic revisions, Tyler (1979a) had suggested that both the Lower Volcanic Assemblage and the Mogobane Assemblage were continous with two important stratigraphic units within the Ventersdorp Supergroup in the west-central Transvaal, the Makwassie Quartz Porphyry Formation and the Bothaville Formation, respectively. Hence, it is conceivable that Tyler's work may have provided the necessary impetus to review the stratigraphy of the Ventersdorp in Botswana and bring it more in line with the latest geological developments in South Africa. Surprisingly, both Crockett (1971b) and Key (1983) confined their attention only to outcrops of Ventersdorp along the southeastern margin of the Gaborone Granite Complex and totally ignored exposures of similar age elsewhere.

In a regional context, the Ventersdorp Supergroup reflects one of the most intensive periods of volcanic activity in Southern Africa. It is estimated that the Ventersdorp basin covered an area of more 200,000 km^2, and the combined thickness of the Ventersdorp Supergroup in the Bothaville area exceeds 7 km (Button, 1982; Bowen et al., 1986). Rocks of Ventersdorp age are known from the central and western Transvaal, northwestern Cape Province, the Orange Free State and southeastern Botswana (Boocock, 1962; Button, 1982; Tankard et al.,

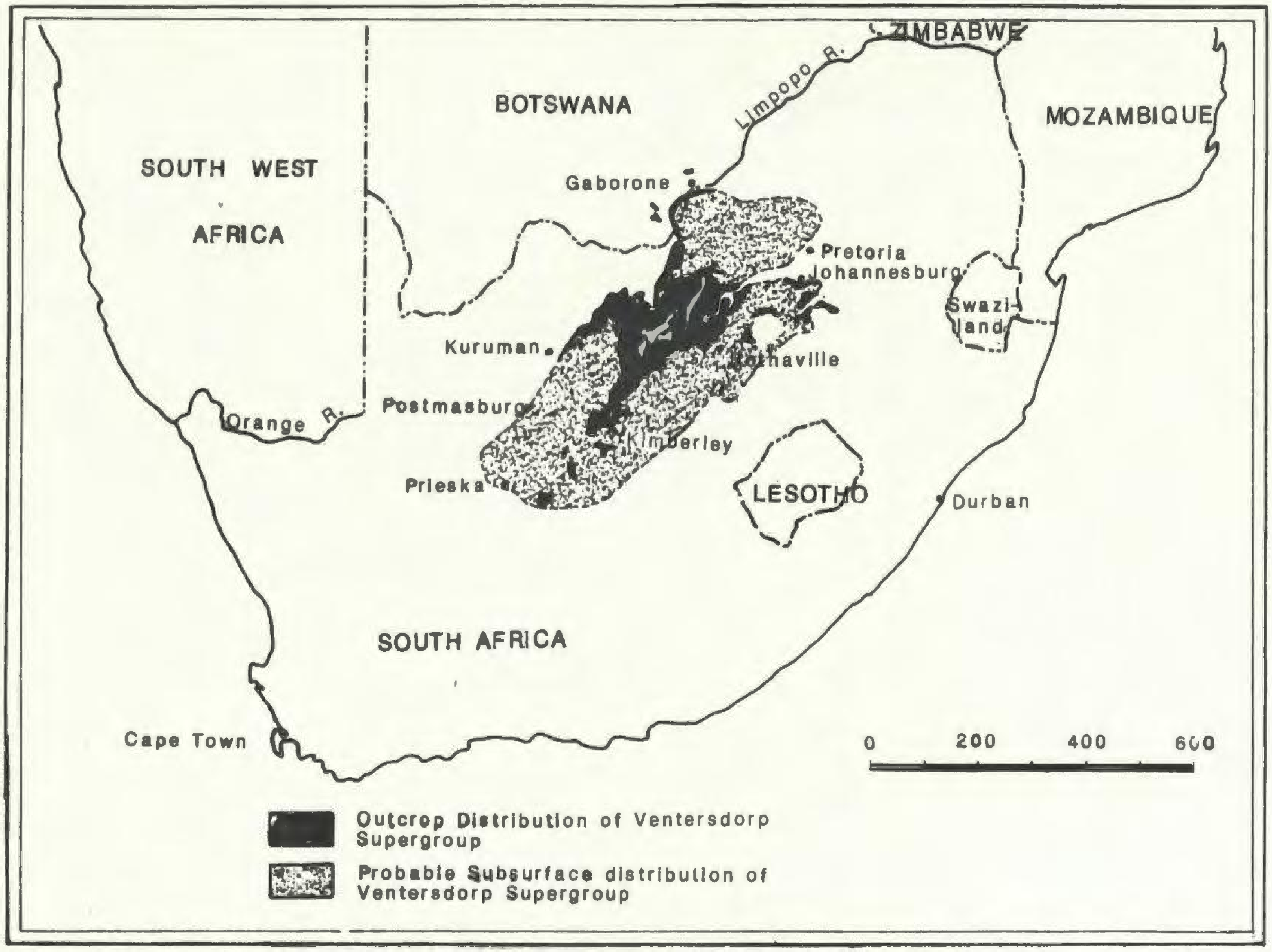


Figure 2.1 Locality map of the Ventersdorp basin showing the distribution of the Ventersdorp Supergroup outcrop (after Button, 1982)

1982). These rocks were deposited in a series of northeast-trending grabens (Winter, 1976; Burke et al., 1985). Figure 2.1 shows the distribution of the Ventersdorp Supergroup in southern Africa. Winter (1976) established the Ventersdorp Supergroup as a formal lithostratigraphic unit and Table 2.3 shows the stratigraphic subdivision of the Ventersdorp Supergroup in South Africa. Brief descriptions of stratigraphic units are also given in Table 2.3. Two major unconformities are recognized in the Ventersdorp: at the bases of the Platberg Group and the Bothaville Formation (Winter, 1976). Contacts between the Klipriviersberg and the underlying upper Witwatersrand sediments are conformable, and the Klipriviersberg Group is largely confined to the Witwatersrand basin (Winter, 1976).

An attempt has been made to fit the Ventersdorp rocks of Botswana into Winter's (1976) classification. Tyler (1979a) has correlated the felsic volcanic rocks of the Ramotswa-Lobatse and Sikwane areas with the Makwassie Quartz Porphyry Formation, and the Mogobane Formation with the Bothaville Formation. He correlated the mafic to intermediate volcanic rocks of the Sikwane area with the Klipriviersberg Group.

However, there are large disparities in thickness and diversity of rock types between the Ventersdorp in South Africa and proposed correlatives in Botswana. For instance, three mafic volcanic sequences occur in the Ventersdorp in South Africa: the Klipriersberg Group, the Rietgat and Allanridge Formations. In contrast, correlatives of the Klipriviersberg Group only are recognized in Botswana. Three distinct belts of Ventersdorp rocks were mapped by

Table 2.3 Stratigraphic subdivisions of the Ventersdorp Supergroup in South Africa - after Winter (1976) (Table 1 of Bowen et al., 1986).

Group	Formation	Lithology
	Allanridge	Dark green amygdaloidal lavas
	Bothaville	Quartzites, conglomerates, subordinate dark shales
Platberg	Rietgat	Green-grey porphyritic lavas, minor limestone quartzites and conglomerates
	Makwassie	Quartz and feldspar porphyries, green-grey amygdaloidal lavas, minor sedimentary horizons
	Kameeldoorns	Conglomerates, quartzites, calcareous shales, impure calcareous rocks
Klipriviersberg	Edenville	Fine-grained grey-green lavas, occasionally amygodaloidal
	Loraine	Lavas and agglomerates
	Jeannette	Fine-grained amygdaloidal lavas
	Orkney	Feldspar-phyric amygdaloidal lavas
	Alberton	Fine-grained dark green lavas
	Westonaria	

Tyler (1979a) in the west-central Transvaal, close to the border with Botswana: the Seokangwana, Tshwene-Tshwene and the Dederpoort belts (Fig. 2.2). At its base, the Tshwene-Tshwene consists of a thick succession of mafic to intermediate lavas which are correlated with the Klipriviersberg Group. However, this belt does not extend into Botswana.

2.5 Previous work on the Gaborone Granite Complex and the Ventersdorp Supergroup

Molyneux (1907) made brief descriptions of granitic and volcanic rocks of the Gaborone Granite Complex west of Mochudi. Later Wagner (1929) described a flesh-coloured granite at Moshaneng which intruded and metamorphosed dolomites of the Transvaal Supergroup. He thought that this granite was part of the complex. It has since been shown that the Moshaneng granite is a separate and younger intrusion than the Gaborone Granite Complex.

Poldervaart (1954) discussed the petrogenesis of the Gaborone Granite Complex. He suggested that the rapakivi granite was the only intrusive unit in the complex, while the succeeding zones of coarse- to fine-grained granites and porphyritic granophyres were variously recrystallized and remobilized equivalents of the Dominion reef felsites. Subsequently, Wright (1961) suggested that the entire complex, including flow lavas and tuffs of the Lobatse Volcanic Group were comagmatic. DuToit (1939) placed all extrusive rocks of southeast Botswana into the Ventersdorp System, which was divided into the Zoetlief and Pniel Series. Later the Zoetlief Series was correlated with the Dominion Series of the Witwatersrand System

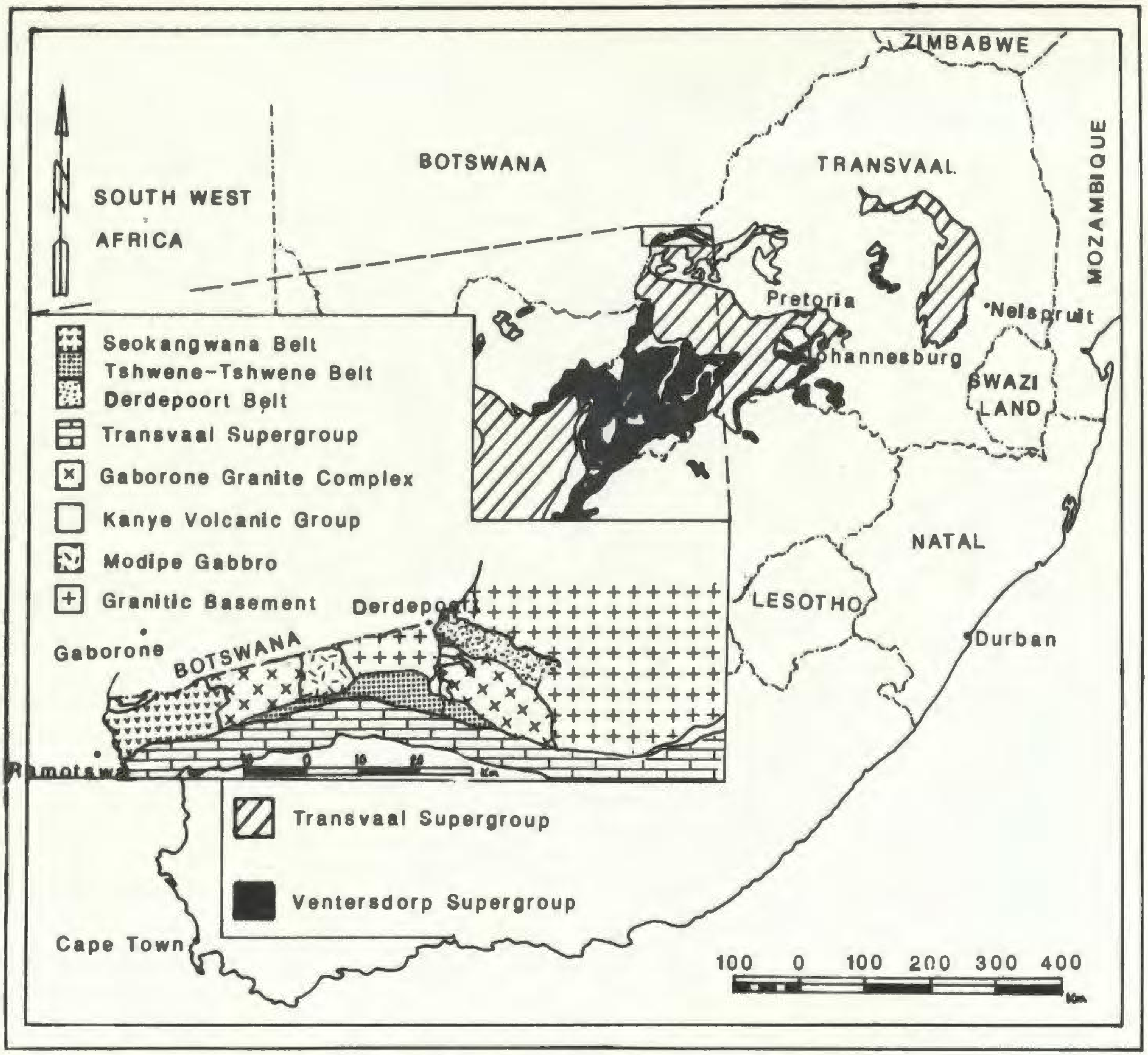


Figure 2.2 Distribution of the Ventersdorp Supergroup in the west-central Transvaal (after Tyler, 1979a)

(DuToit, 1946, quoted in Boocock, 1962). Truter (1949) upgraded the status of the Dominion from a Series to a System while maintaining the correlation of all the siliceous lavas, tuffs, agglomerate and sediments of pre-Transvaal age in southeast Botswana with the Dominion Reef System. At this time, the only rocks correlated with the Ventersdorp were a sequence of shales, conglomerates, tuffs, and a mafic lava unit (Upper Volcanic Assemblage, see Table 2.2) southeast of Lobatse. The shales around Mogobane Village were correlated with the Witwatersrand system (Poldervaart and Green, 1952).

Subsequently, McConnell (1955) argued that the entire succession of conglomerates, sandstones, shales, and mafic rocks above the siliceous lavas and tuffs of the Lobatse and Ramotswa areas should also be correlated with the Ventersdorp System, as they were continuous with Ventersdorp rocks in South Africa. He called the former the Mogobane Series and the underlying siliceous volcanic rocks the Lobatse Volcanic Series. Following this revision, therefore, all the rocks previously in the Witwatersrand System and some of those in the Dominion Reef System became part of the Ventersdorp System.

As mapping of southeast Botswana progressed, more rocks of Ventersdorp age were discovered west and north of the main exposures (Cullen, 1959; Jones, 1959, 1961, 1966). As a result of these subsequent mapping exercises, Boocock (1959) suggested that the name Lobatse Volcanic Series should be abandoned as it included rocks of two different ages: an older, pre-Gaborone Granite (i.e. pre-Thamaga Granite) suite of red and grey porphyritic felsites which was intruded by a coarse- to medium-grained granite of the Gaborone Granite

Complex, and a younger suite which was correlated with the Ventersdorp System. The older suite of volcanic rocks was given the name Kanye Volcanics by the Geological Survey of Botswana (then Bechuanaland), and correlated with the Dominion Reef System of South Africa. Crockett (1971b) agreed with Boocock (1959) and McConnell (1955) that the interbedded volcanic and sedimentary succession above the Kanye Volcanics in southeast Botswana should be correlated with the Ventersdorp Supergroup.

Tyler (1979a) has correlated acid volcanic rocks of the Seokangwana and Dederpoort belts (Fig. 2.2) with the Makwassie Quartz Porphyry Formation (Table 2.3). The mafic to intermediate lavas of the Dederpoort belt are correlated with the Klipriviersberg Group; sediments of the Seokangwana belt, which are believed to be the equivalent of the Mogobane Assemblage, are correlated with the Bothaville Formation (Tyler, 1979a, see Table 2.3).

2.6 The Transvaal Supergroup

Detailed descriptions of the Transvaal Supergroup in Botswana are given by Crockett (1969, 1972; Key, 1983). Figure 1.1 shows some of the Transvaal Supergroup outcrops in southeastern Botswana; more Transvaal outcrops occur west of the area covered by Figure 1.1. Exposures in the Southeast District represent the western margin of the Bushveld basin of South Africa. This basin is one of two basins in southern Africa in which Transvaal rocks were deposited, the other one being the northern Cape basin. Extensions of this basin have also been recognised in Botswana, around the Molopo area (Crockett, 1969;

1972).

Crockett (1969, 1972) reviewed the stratigraphy of the Transvaal in Botswana. Following South African stratigraphic terminology, he divided these rocks into three series:

3. Pretoria Series
2. Dolomite Series
1. Black Reef Series

The Black Reef Series consists predominantly of grey, highly indurated quartzites, called the Black Reef Quartzite. Locally, this unit contains lenses or intercalations of dark-grey, sandy mudstones. Crossbedding and ripple marks are very common in this unit, with ripple marks commonly indicating a NE-SW direction of transport, that is, perpendicular to basin margins (Key, 1983). The Black Reef quartzite is regarded as a beach deposit.

In the Ramotswa area (Fig. 1.1), the Black Reef Quartzite is immediately underlain by a reddish-brown, well sorted pebble conglomerate containing clasts of vein quartz and volcanic rocks. Lenses of a similar conglomerate also occur in the Black Reef Quartzite. This conglomerate rests unconformably on sediments of the Mogobane Formation. Although the Mogobane Formation also contains conglomerate interlayers, they are less well sorted and less continuous than the conglomerate immediately beneath the Black Reef Quartzite.

Crockett (1971b) placed the conglomerate beneath the Black Reef Quartzite in the Ramotswa and Lobatse areas in the Mogobane

Assemblage, while Wright (1958), Clark and Machacha (1977) and Key (1983) have correlated it with the Transvaal Supergroup. In the present study, this unit was mapped as part of the Transvaal Supergroup because lenses of a similar conglomerate also occur within the Black Reef Quartzite. Further, this unit differs from conglomeratic interlayers in the underlying Mogobane Formation as already stated. It is nevertheless interesting to note that while Key (1983) correlated this unit with the Transvaal Supergroup in the Ramotswa and Lobatse areas, he correlated a similar unit in the Mochudi area with the Ventersdorp Supergroup.

The Dolomite Series consists of massive light-blue dolomite, grading upwards into interbedded chert and dolomite and, at the top, into massive chert. These chert beds are very often ferrugenous and manganiferous. Stromatolitic and oolitic structures are very common. The cherts are overlain by red and yellow, ferrugenous shales, occasionally containing thin tillite interlayers (Crockett, 1969). Contacts between the Dolomite and Black Reef Series are gradational (Key, 1983).

Overlying the Dolomite Series is the Pretoria Series, a predominantly argillaceous sequence containing several volcanic horizons. In South Africa, this Series has been divided into four stages: Timeball Hill, Daspoort, Magaliesburg and Smelterskop. All stages are represented in southeast Botswana (Crockett, 1969). Several important quartzite marker horizons occur in the Pretoria series. The boundary between the Pretoria Series and the underlying Dolomite Series is defined by a very important chert pebble conglomerate, the Bevet's Conglomerate.

Key (1983) revised the stratigraphic subdivisions of the Transvaal Supergroup sediments along the western margin of the Bushveld Basin in southeast Botswana. He divided these sediments into fourteen formations (Table 2.4).

2.7 The Waterberg Supergroup

Crockett and Jones (1975) have discussed the geology, stratigraphy, and distribution of the Waterberg Supergroup in southern and eastern Botswana. The Waterberg Supergroup is underlain by the Transvaal Supergroup and is overlain by the Karoo Supergroup. It has been divided into three sectors (Crockett and Jones, 1975). The northernmost exposures around Palapye belong to the Palapye Sector. South of this sector, extensive outcrops of Waterberg sediments in the area bounded by Buffelsdrift, Olifants Drift, Mochudi and Molepolole are assigned to the Notwane Sector. The Kanye Subsector includes all isolated outcrops of Waterberg between Kanye and Gaborone, while those in the Southeast District, around Otse, were assigned to the Otse Subsector. West of Kanye, the Waterberg disappears under the young Kalahari sand cover.

The Waterberg Supergroup consists mainly of reddish-brown, ferrugenous sandstones, shales, siltstones, and conglomerates. Crockett (1969) and Crockett and Jones (1975) have pointed out that the rarity of good marker horizons as well as the presence of widespread diachronous relationships makes it difficult to subdivide these rocks into well defined lithostratigraphic units. They

Table 2.4 Subdivision of the Transvaal Supergroup in Botswana and South Africa

Crockett (1969)	Key (1983)	South African Committee for Stratigraphy (SACS), 1980	
		Formation	Group
Pretoria Series	Woodlands Formation	Rayton Formation	Pretoria Group
	Sengoma Quartzile Form	Magaliesburg Quartzite Formation	
	Sengoma Argillite Formation	Silverton Shale Formation	
	Ditlhojana Quartzite Formation	Daspoort Quartzite Formation	
	Ditlhojana Volcanic Formation	Strubenkop Shale Formation	
	Ditlhojana Shale Formation	Hekpoort Andesite Formation	
	Tsokwane Quartzite Formation	Timeball Hill Formation	
	Lephala Formation	Rooihoogte Formation	
Dolomite Series	Ramotswa Shale		Chuniespoort Group
	Mogopane Formation	Penge Formation	
	Maholota Formation	Malmani Sub Group	
	Ramotswa Dolomite		
Black Reef Series	Black Reef Quartzite Formation	Black Reef Quartzite Formation	

have suggested that these sediments were mostly laid down under shallow water conditions. Key (1983) divided the Waterberg Supergroup into four formations:

Top	Mannyelanong Fm. (W4)
	Maladiepe Fm. (W3)
	Moeding Fm. (W2)
Base	Ditsotswane Fm. (W1)

The designations in brackets are those of Crockett (1969).

2.8 Geochronology: Gaborone Granite Complex and the Ventersdorp Supergroup

Although attempts have been made to date the Gaborone Granite Complex and the Lobatse Volcanic Group, the results are extremely ambiguous and open to numerous interpretations (see Table 2.5).

McElhinny (1966) obtained a Rb-Sr whole-rock age of 2340 ± 44 Ma on three samples of the Thamaga Granite. Harding et al. (1974) reported several Rb-Sr and K-Ar ages from the Gaborone Granite Complex. Samples from the Kanye Volcanics gave an errorchron age of 1831 Ma, compared to 2249 ± 44 Ma and 2592 ± 75 Ma from the Kgale Granite and Thamaga Granite, respectively. Apparent ages for the Kanye Volcanics calculated using a $^{87}Sr/^{86}Sr$ initial ratio Ri = 0.705 range from 2251 Ma to 3227 Ma. In addition, three K-Ar ages of hornblendes from the Thamaga Granite were reported: 2185 ± 100, 2225 ± 100 and 2305 ± 115 Ma (Harding et al., 1974).

This data is extremely discordant, and is difficult to reconcile with both the observed field relationships and present petrogenetic models (Poldervaart, 1954; Wright, 1961). Key and Wright (1982) have

Table 2.5 Isotopic ages from the Gaborone Granite Complex and Lobatse Volcanic Group (LVG)

unit	Method	Age	Reference
Central Assemblage	Rb-Sr isochron (3 whole-rock points)	2340 ± 44 Ma	McElhinny (1966)
Kanye Volcanics	Rb-Sr isochron (8 whole-rock points)	1831 Ma	Harding et al. (1974)
Inner Marginal Assemblage	Rb-Sr isochron (8 whole-rock points)	2249 ± 44 Ma	"
Central Assemblage	Rb-Sr isochron (8 whole-rock points)	2592 ± 75 Ma	"
Central Assemblage	K-Ar (hornblende): BP 15	2185 ± 100 Ma	"
	BP 16	2305 ± 115 Ma	"
	BP 20	2225 ± 100 Ma	"
Central Assemblage	U-Pb (zircon)	2.85 ± Ga	Sibiya (1987, pers. comm)
Quartz-feldspar porphyry (LVG)	Rb-Sr model age (whole-rock):		Crockett (1971b)
	sample No. BP 51	2200 ± 100 Ma	
	sample No. BP 55	2230 ± 100 Ma	"
	sample No. BP 69	2215 ± 100 Ma	"
	sample No. BP 47	2695 ± 125 Ma	"
Quartz-porphyry (LVG)	Pb-Pb isochron	2640 ± 100 Ma	Van Niekerk & Burger (1968)

recently suggested an emplacement age of 2400 Ma for the Gaborone Granite Complex. However, in view of their opinion regarding the origin of this complex, this age is very difficult to justify because it is based on the data of Harding et al. (1974) but excluding the data points for the Kanye Volcanics.

Sibiya (1988) has recently obtained a U-Pb zircon age of 2.83 Ga from the Thamaga Granite. This age places certain constraints on the younger age limit of the Kanye Volcanics and the Nnywane Formation.

One Pb-Pb isochron and four apparent Rb-Sr ages of the Lobatse Volcanic Group are available. All the samples used for these studies were obtained from a quartz porphyry sill (the Plantation Porphyry) which is part of the Nnywane Formation. Van Niekerk and Burger (1968) obtained a Pb-Pb isochron age of 2638 ± 105 Ma from this unit. Four samples of the Plantation Porphyry were dated at the Institute of Geological Sciences in London using the Rb-Sr method. They gave the following apparent ages: 2230 ± 100, 2200 ± 100, 2215 ± 100 and 2695 ± 125 Ma (Crockett, 1971). Crockett (1971) rejected the oldest age and used a mean of the first three dates as the age of the Ventersdorp. Similarly, Harding et al. (1974) preferred a three-point isochron age of 2083 Ma based on the data of Crockett (1971b); the fourth point was not considered because the sample apparently contained enclaves of black shale.

The significance of the Rb-Sr data is particularly doubtful because the Transvaal Supergroup which overlies the Ventersdorp has yielded a Rb-Sr age of 2224 Ma. Therefore, the 2083 Ma age quoted by Harding et al. (1974) may in fact be a metamorphic age as Cornell

(1978) has suggested. While it is tempting to accept the Pb-Pb isochron age, it can only be a minimum age if the Plantation Porphyry is indeed a sill as suggested by Crockett (1971b). However, this age does fall within the 2500 to 2700 Ma range reported by Van Niekerk and Burger (1978) for the Ventersdorp Supergroup.

CHAPTER 3

GEOLOGY OF THE STUDY AREA

3.1 Introduction

Figure 3.1 is the geological map of the study area. The study area is underlain by various rock types ranging in age from late Archean (> 2.83 Ga) massive felsites (Kanye Volcanics), to the 1.7 Ga old sediments of the Waterberg Supergroup. Except for the Ntlhantlhe Microgranite, formational names and lithostratigraphic subdivisons of Key and Wright (1982) and Key (1983) have been retained. Nevertheless, some of their formational boundaries and stratigraphic correlations may have to be revised as pointed out in this thesis and in Sibiya (1988). But it is premature to make revisions at this stage because a lot of investigations in the Gaborone Granite Complex and in the Ventersdorp Supergroup are still in progress.

The northwest half of the study area is underlain mainly by the peripheral assemblages of the Gaborone Granite Complex: a reddish-brown to pink microgranite, porphyritic granophyres and porphyritic felsites (Kanye Volcanics) (Fig. 3.1).

In the south the Kanye Volcanics pass imperceptibly into the Lobatse Volcanic Group which in turn is overlain by rocks of the Transvaal Supergroup in the area around Ramotswa village. Flat-lying erosional remnants of the Waterberg Supergroup outcrop on Phiriyabokwete, Mabofula and Rasemong hills (Fig. 3.1). The Waterberg Supergroup is the youngest supracrustal sequence in the study area.

All rocks of pre-Transvaal age have been intruded by numerous diabase dikes and sills. However, except for the thick mafic dike in the central part of Figure 3.1, most of the dikes are very thin. These dikes generally appear as very prominent lineaments on aerial photographs. Not all the the lineaments in aerial photographs of the study area coincide with dike intrusions, however. For example, despite the presence of prominent photogeologic lineaments in both the Transvaal and Waterberg Supergroups, no mafic dikes or sills have been observed in these units in the study area. Some of the lineaments are probably fractures and not dikes. The dikes and structural lineaments are dominated by northeast-trending sets (Fig. 3.1).

3.2 Microgranites

A fine-grained, reddish-brown to pink granite (microgranite) occurs in the northeast and northwest parts of Figure 3.1. This granite is part of a variable zone of microgranites that grade into and surround the medium- to coarse-grained Kgale-type granites to the north of the study area.

Typically, the microgranite is equigranular, but porphyritic patches are not uncommon towards the top of this unit. It consists predominantly (over 95%) of quartz and feldspar with minor amounts of interstitial biotite. Quartz grains include light-blue, milky and colourless varieties. Feldspar is present as subhedral to anhedral, pink grains. The microgranite intrudes both the porphyritic granophyres and the Kanye Volcanics (Fig. 3.2), although the contact with the volcanic rocks was not observed in the study area. The contact between the microgranite and the underlying Kgale Granite is

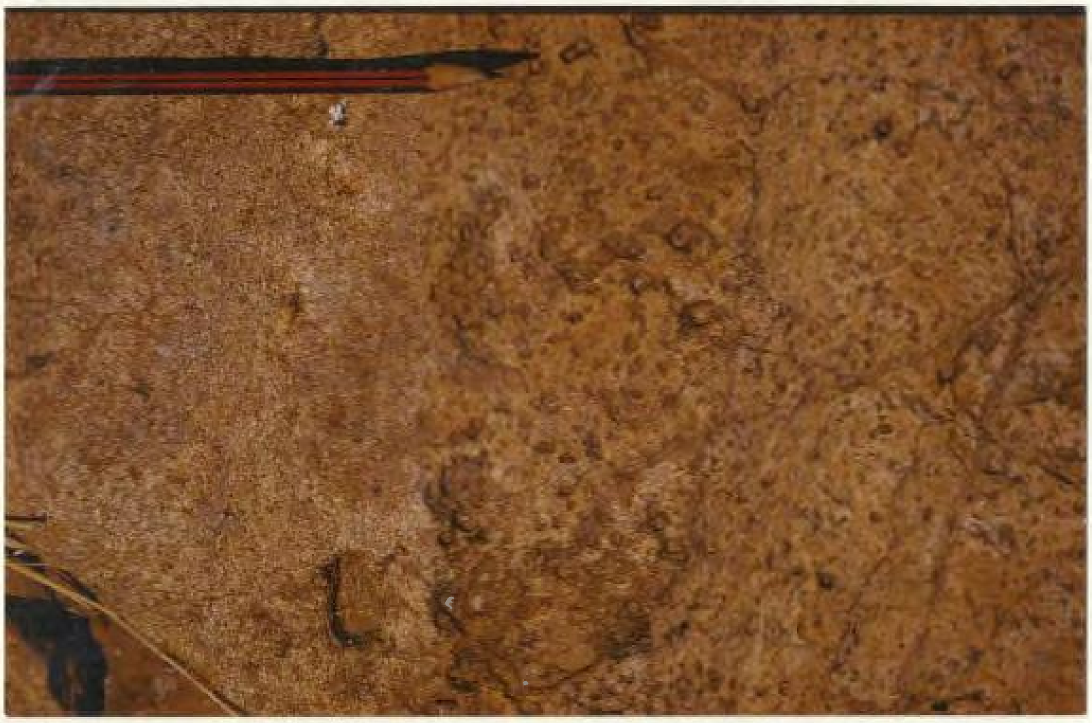


Figure 3.2 Contact between the porphyritic granophyres (right) and the microgranite (left) south of Kgale.

gradational. Mineralogically, the microgranite is very similar to the Kgale Granite and appears to be a chilled margin of these medium- to coarse-grained granites (Kgale Granite). The development of the microgranites above the Kgale Granite could have been caused by rapid cooling as a result of the intrusion of the granitic magma into relatively cold country rocks, that is, the porphyritic granophyres and the Kanye Volcanics.

3.3 Porphyritic granophyres

When present, these rocks occur between the Kanye Volcanics and the reddish-brown microgranites described above. They are characterised by numerous, large, white and pink feldspar phenocrysts in a purple fine-grained groundmass of quartz and feldspar. Compared to the overlying porphyritic felsites (Kanye Volcanics), the granophyres have significantly more and larger feldspar phenocrysts (up to 7 mm) and a distinctly coarser groundmass. Towards the contact with the Kanye Volcanics, however, the porphyritic granophyres show a gradual decrease in the amount of feldspar phenocrysts, from approximately 20% to 10%, and in the grain size of the matrix.

Feldspar phenocrysts in the porphyritic granophyres occur singly and in clusters. Some of the phenocrysts are fractured. But none of the broken feldspar fragments were displaced during this process so that the original grain shapes are still discernible. Furthermore, these fractures, as noted by Wright (1961, page 37 and 38), do not seem to extend into the groundmass, although they probably did originally but have since healed. Inclusions of mafic and opaque minerals are very common in the feldspar phenocrysts.

Most of the feldspar phenocrysts in the granophyres have a thin, greyish rim around them. These mantles, it appears, are more resistant to weathering compared to the enclosed phenocrysts. As a result, the breakdown of feldspars during weathering leaves small, distinctive pits on the outcrop. Quartz occurs as very fine grains in the groundmass of the granophyres and, because of the fine-grained texture of the groundmass, it is not usually visible in the outcrop. Closer to the contact with the Kanye Volcanics, reddish and light-coloured, occasionally spatially-connected patches are very common in the groundmass. These patches probably reflect incipient alteration along fluid pathways. In addition to feldspar phenocrysts, the granophyres contain small amounts of greenish amphibole.

The upper contact of the porphyritic granophyres is always against the Kanye Volcanics. This contact is gradational, but it can be mapped with a great deal of precision because the Kanye Volcanics and the porphyritic granophyres can be distinguished easily. Texturally, the granophyres appear to have crystallized more slowly and at slightly deeper crustal levels than the Kanye Volcanics. The contact between the granophyres and the microgranites was described on page 30. It has been established that the microgranite is younger than and intrudes the granophyres (see Figure 3.2).

3.4 The Kanye Volcanics

Typically, the Kanye Volcanics comprise red, grey, and purple porphyritic felsites with 1% to 4% white and pink feldspar phenocrysts in a fine-grained to aphanitic groundmass. The amount of feldspar phenocrysts in the Kanye Volcanics does not vary considerably. Feldspar phenocrysts occur as euhedral to subhedral grains and include tabular and equant varieties. As in the porphyritic granophyres, feldspar phenocrysts in the Kanye Volcanics occur singly and in clusters, giving the rock a glomeroporphyritic texture in places. Dispersed throughout the groundmass are black to green phenocrysts and specks of mafic and opaque minerals. The total amount of these minerals in the Kanye Volcanics is very low but fairly constant.

The Kanye Volcanics outcrop in a series of low rounded hills. In general, these rocks are well exposed throughout much of the study area, the only exceptions are areas in the vicinity of the Metsemaswaane River and west of the Notwane Dam (Fig. 3.1) where outcrop is rather patchy.

Exposures of Kanye Volcanics are generally covered by a thin mantle of loose rock fragments. These fragments were derived in situ by weathering of the Kanye Volcanics. They are more angular compared to those derived from and covering outcrops of the Nnywane Formation. This difference is extremely useful when mapping adjacent outcrops of Kanye Volcanics and Nnywane Formation. Weathered outcrops of Kanye Volcanics are reddish-brown to buff coloured.

Jointing is very common in the Kanye Volcanics. Joint fractures occur in closely-spaced sets which intersect mostly at high angles. Individual joints vary from thin, indistinct hairline fractures to large, mappable sets of fractures. They are generally straight, but in a few places joint fractures are curved into small open folds. Although the significance of these fold-like structures is not known, they could have been formed during deformation.

In places, the Kanye Volcanics are cut by thin closely-spaced, reddish-brown streaks. These structures are relatively rare and are only about a few centimetres in length. Individual streaks vary from very well defined, veinlike structures to irregular patches with diffuse boundaries. Where these streaks cut feldspar phenocrysts, the affected phenocryst often shows a distinct red staining or discoloration within the fracture. In a few instances, however, the entire phenocryst and part of the surrounding groundmass were also stained. These features were also noted by Wright (1961, page 31), and he believes the streakyness in the Kanye Volcanics indicates probable movement within the magma.

Superficially, some of the structures described above resemble eutaxitic texture, but some of their characteristics do not accord with this interpretation. For instance, they are typically thin, about one millimeter across, and occasionally terminate in a much larger, irregular patch with diffuse boundaries. They sometimes show crosscuting relationships. They also occur in very massive units which do not show any evidence of bedding or brecciation. All these features suggest that the observed structures are very thin veinlets or fratures along which fluids moved through the rock. The red staining seen in most of these structures is probably due to hematite or other iron oxides.

Bedding and flow structures are rare in the Kanye Volcanics.

However, closer to the contact with the overlying Lobatse Volcanic Group, a very distinct ribbing consisting of closely spaced, parallel structures resembling flowbanding was observed in places (Fig. 3.3). They occur in sets, with individual sets being only a few meters apart. Each set consists of several, closely-spaced ridges. The same structures were observed by the writer in the Ntlhantlhe area 15 km southeast of the study area (Figure 1.1). In the Ntlhantlhe area, as in the study area, they occur very close to the contact with the overlying Lobatse Volcanic Group. Between the flowbanded zones the outcrop is blocky in places. The blocky appearance is due to the presence of small, round, knobby structures about 3 cm to 4 cm across in a flowbanded matrix (Fig. 3.4). The fragments are very similar to the rhyolitic host and are not visible in fresh samples; their blocky texture is enhanced by weathering. These blocky units possibly represent autobrecciated tops of lava flows in the Kanye Volcanics. If the ribbing and associated structures represent flowbanding and flow breccias, respectively, it indicates that in the study area and elsewhere the Kanye Volcanics were probably locally extrusive.

(i) Discussion of field relationships

Field relations between the Kanye Volcanics, porphyritic granophyres and the microgranite have been described. These are fairly straightforward except for the contact between the Kanye Volcanics and the microgranites which is not exposed in the study area. Nevertheless, the nature of this contact can be correctly inferred from available field and geochemical evidence. For example,

Figure 3.3 Flowbanding in the Kanye Volcanics (15 cm ruler for scale shown in the photograph: top centre).

Figure 3.4 Autobrecciated rhyolite flow (?): Kanye Volcanics (note round breccia fragments in the centre of the photograph).

it has been established that the microgranite is younger than the porphyritic granophyres which are the same age as the Kanye Volcanics. It follows, therefore, that the microgranite intrudes the Kanye Volcanics as well. The presence of an abrupt contact between the Kanye Vocanics and the microgranite is also supported by major and trace element analyses (see chapter 5).

Besides the study area, the writer has spent considerable amounts of time elsewhere in the Gaborone Granite Complex examining the Kanye Volcanics, the granophyres and the microgranite. In some of these places the porphyritic granophyres are completely missing and have presumably been crosscut by the granites. Such places are ideal for examining the Kanye Volcanics-microgranite contact. For example, in Mochudi (see Figure 1.1), the contact between the Kanye Volcanics and a medium-granined granite is well exposed. The granite clearly intrudes the Kanye Volcanics. These intrusive granites, as Jones (1961) pointed out, are continuous with and of the same age as the microgranites in the Ramotswa area (Fig. 3.1).

The results of field work show that the granophyres are older than the microgranite. It will also be shown in Chapter 5 that these rocks have different major and trace element chemistry. In view of these facts, it is incorrect to lump these units together in a single formation as Key and Wright (1982) did in their proposed subdivisions of the Gaborone Granite Complex. Without sufficient justification, Key and Wright (1982) placed the microgranite and the porphyritic granophyres in the so-called Ntlhantlhe Microgranite (see Table 2.1). Since the microgranite (see section 3.2) is a chilled margin of the underlying coarse- to medium-grained granites (Kgale Granite), it would have been more appropriate to leave it as part of this unit.

This study has also shown that the microgranite and the porphyritic granophyres are not partly recrystallised and locally remobilised equivalents of the Dominion Reef felsites (Kanye Volcanics) as previously suggested by Poldervaart (1954), Crockett (1969), and Tyler (979b). Such an interpretation ignores very important and contradictory field evidence. For instance, it fails to account for the present distribution of the porphyritic granophyres. And, if the granophyres formed by contact metamorphism of the overlying felsites (Kanye Volcanics) as suggested by these workers, why is this unit not present all around the microgranites? Instead, it is discontinuous and has evidently been crosscut by the microgranites. Further, xenoliths of the Kanye Volcanics and granophyres are found in the microgranite close to the intrusive contacts indicating that both units are older than the granite. Finally, major and trace element analyses (see Chapter 5) show that the microgranite could not have formed by simple metamorphic reconstitution of the Kanye Volcanics.

3.5 The Lobatse Volcanic Group

Rocks belonging to the Lobatse Volcanic Group occur in the south and southeastern part of the study area between the Kanye Volcanics and the Transvaal Supergroup (Fig. 3.1). These rocks extend into South African territory east of the Notwane River (Fig. 3.1). A lithologically similar sequence of rocks in the west-central Transvaal

(South Africa), the Seokangwana belt (Figure 2.2), which is interpreted as extension of the Lobatse Volcanic Group, was described by Tyler (1979b).

The lower part of the Lobatse Volcanic Group, the Nnywane Formation (Key, 1983), consists of a thick succession of interbedded felsic flows, tuffs and minor amounts of agglomerates and volcanogenic sediments. The Nnywane Formation is unconformably overlain by the Mogobane Formation, a predominantly argillaceous assemblage of dark-grey mudstones, shales, pink siltstones. Subsidiary amounts of conglomerates and sandstones occur at the base and top of the Mogobane Formation.

(i) The Nnywane Formation

Figure 3.1 shows the distribution of the Nnywane Formation. Rhyolite flows occur throughtout the Nnywane Formation; they are not restricted to any particular stratigraphic level. In terms of areal distribution, however, rhyolites are more common in the eastern two thirds of the study area than in the west. Most of the rhyolite bodies are too small to map at the scale of Figure 3.1.

Rhyolites outcrop as small irregular and lenticular bodies flanked by bodies of the more laterally persistent crystal tuffs and lapilli tuffs. They range in colour from cream-green to dark-grey. The majority of these bodies are feldspar-phyric, the remainder being aphyric. Feldspar phenocrysts occur as euhedral to subhedral grains. In porphyritic flows, the amount of feldspar phenocrysts varies considerably and may be as high as 15%.

Rhyolites are more resistant to weathering than tuffs, both units weather reddish-brown. Loose, weathered and jointed blocks of rhyolite tend to be smooth and round, but in most cases the constituent minerals are well preserved, whereas in tuffs primary minerals are not often preserved or, if they are, they are not generally visible in outcrop. Quartz veining is ubiquitous in rhyolites. The majority of veins are irregular and vary in width along their length (Fig. 3.5). Quartz also occurs as round to oval-shaped aggregates or nodules of various sizes (Fig. 3.6) and as thin rims or mantles around both feldspar phenocrysts and other primary minerals (Fig. 3.6). The siliceous nodules are probably amygdules. Outcrops of tuffs and rhyolites are highly jointed.

Flowbanding is very common, particularly towards the southern margin of the Nnywane Formation. The orientation of the flowbanding is extremely variable; it is generally steep and contorted (Fig. 3.7). Crockett (1971a) attributed the contortion to folding, but while there is evidence of folding in the Lobatse Volcanic Group, the contortion seems to be a primary flow feature. Autobrecciated flows occur locally in the Nnywane Formation (Fig. 3.8).

Contacts between tuffs and rhyolites are rarely exposed. This is due, in part, to an ever-present mantle of loose weathered rock fragments on the outcrop. Lack of well exposed contacts between the tuffs and rhyolite bodies makes it difficult to estimate thicknesses of individual flows and and pyroclastic units. The only locality where contacts were observed is in a road cut 800 m south of Boatle (Fig. 3.2), along the Gaborone-Lobatse road. The exposure shows an

Figure 3.5 Quartz veining in rhyolite: Nnywane Formation.

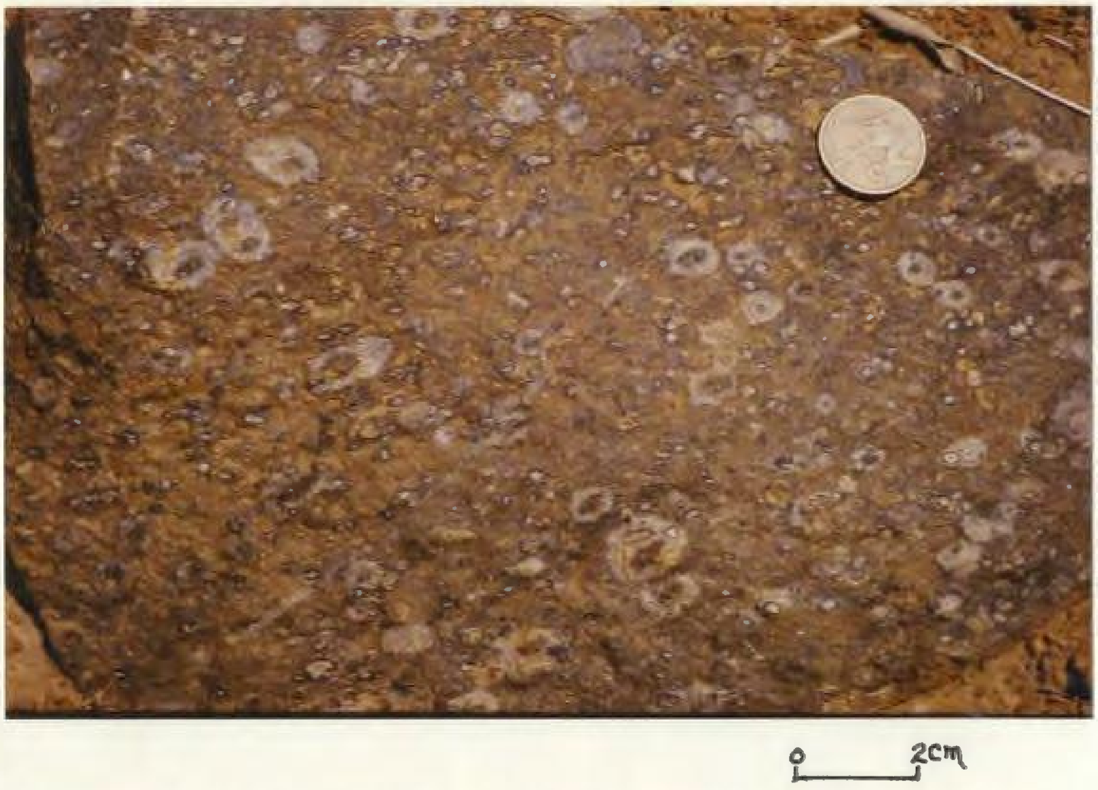


Figure 3.6 Rhyolite showing ovoidal to spherical secondary quartz aggregates (white). Some of these are probably amygdules. Secondary quartz also mantles other minerals such as feldspars and biotite.

Figure 3.7 Contorted flowbanding in rhyolite flow: Nnywane Formation (15 cm ruler for scale).

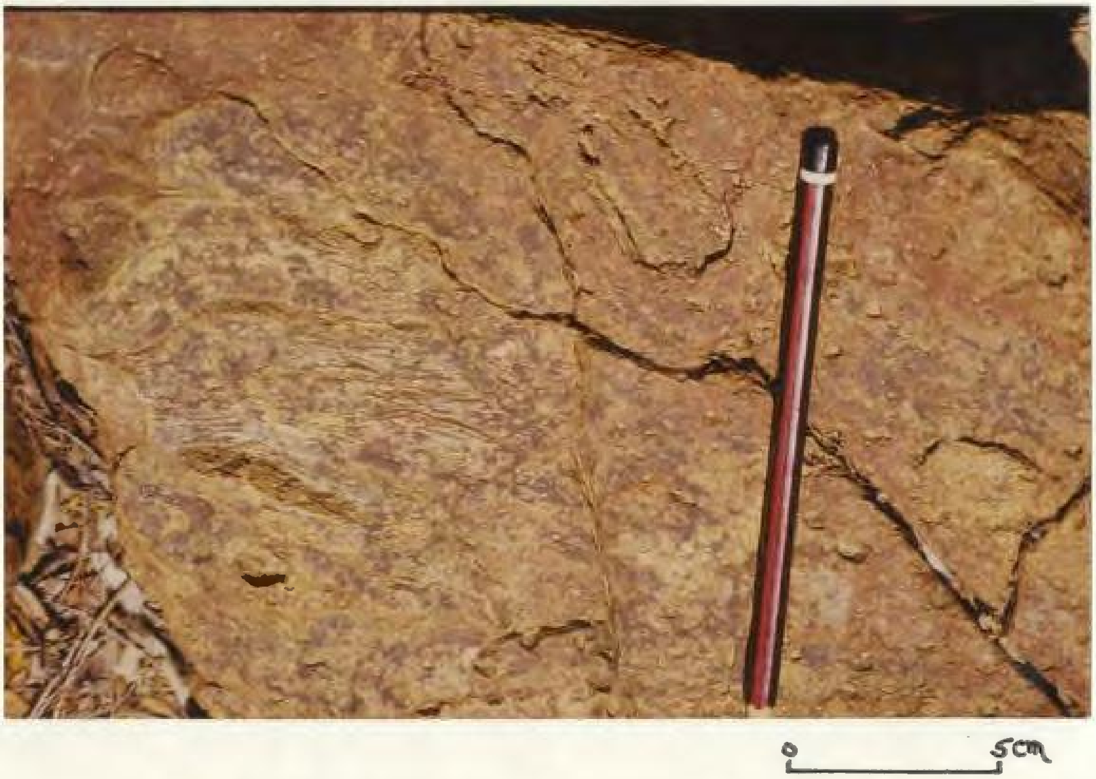


Figure 3.8 Autobrecciated rhyolite flow: Nnywane Formation (note flowbanded rhyolite fragment on the left side of the pencil).

interbedded sequence of grey tuffs and porphyritic rhyolite ranging in thickness from 5 m to 15 m. The attitude of the succession at this locality is S80°E/20°SW. However, this attitude has to be used with caution because bedding attitudes vary throughout this area, making thickness estimates very uncertain.

Pyroclastic deposits, mainly tuffs and minor amounts of agglomerates are an important part of the Nnywane Formation. Tuffs occur as laterally persistent bodies of variable thickness. They include: (1) very fine-grained, green, compact, silicified units, (2) grey, more degraded (weathered) tuffs with a distinct black, mottled appearance resulting from the presence of numerous tabular and round aggregates of biotite (Fig. 3.9), (3) light-grey, very fine-grained units consisting primarily of quartz and white flakes of sericite. Colour variations in tuffaceous units probably reflect the effects of secondary processes such as weathering, metamorphism and metasomatism rather than primary compositional differences.

In addition to fine-grained tuffs, slightly coarser grained bodies of lapilli tuff occur sporadically in the sequence. They consist of 1 mm to 20 mm light grey, angular rhyolite clasts in a fine-grained light grey, tuffaceous matrix. The matrix is highly sericitized. Lapilli tuffs may be more common in the Nnywane Formation than is presently realized, but because the clasts and matrix in these rocks are similar in colour, it is difficult to distinguish them from other rock types in the study area.

A classification of fine-grained pyroclastic units in the Nnywane Formation on the basis of such parameters as the relative proportion

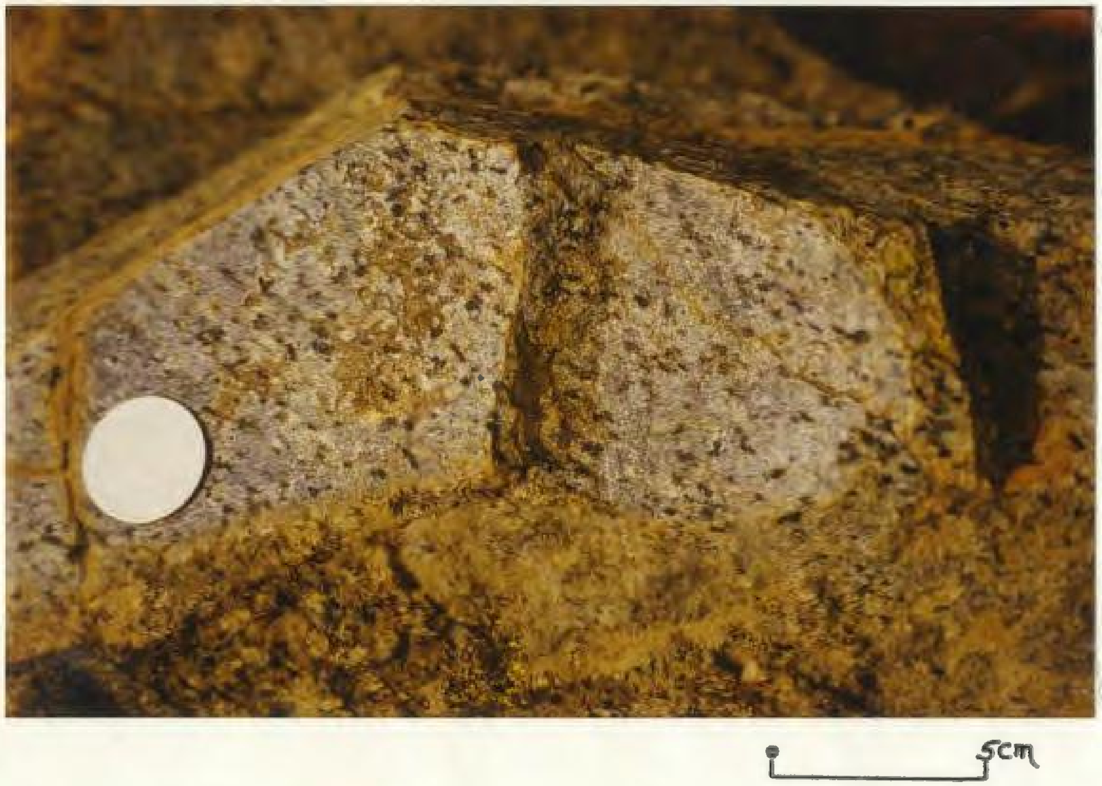


Figure 3.9 Grey, fine-grained tuff, distintively mottled with black tabular and round aggregates of secondary biotite (Nnywane Formation).

of lithic and vitric fragments and xenocrysts, and the degree of welding is rendered impossible by weathering and alteration of primary minerals. No flow or cooling units can be identified for the same reasons. The effects of these processes are so penetrative that almost all primary structures have been obliterated. But a very weak layering is occasionally present in some of the grey fine-grained tuffs (Fig. 3.10). Therefore, the term tuff is used rather loosely, because essential characteristics of these deposits are not discernible. There is, however, no doubt as to the unique identity of these rocks compared to the interbedded rhyolites.

Agglomerates occur sporadically and typically form small rounded mounds or hills with an average area of 2500 m^2. They consist of grey rhyolitic clasts up to 20 cm across in a fine-grained, tuffaceous matrix. Some of the agglomeratic bodies show clear evidence of reworking such as current bedding. One of these reworked agglomerates occurs immediately south of Mafukutswane Hill (Fig. 3.1). The presence of reworked, coarse pyroclastic deposits and volcanogenic sediments probably indicates synvolcanic sedimentation during the deposition of the Nnywane Formation.

Some of the coarse-grained pyroclastic deposits in the Ramotswa area were indentified by previous workers as volcanic centres (Crockett, 1971b; Key, 1983), but the field evidence is not really conclusive because some of these deposits have definitely been reworked. That notwithstanding, the presence of volcanic rocks in the Nnywane Formation indicates that southeast Botswana and the neighbouring territory of South Africa were sites of impressive volcanic

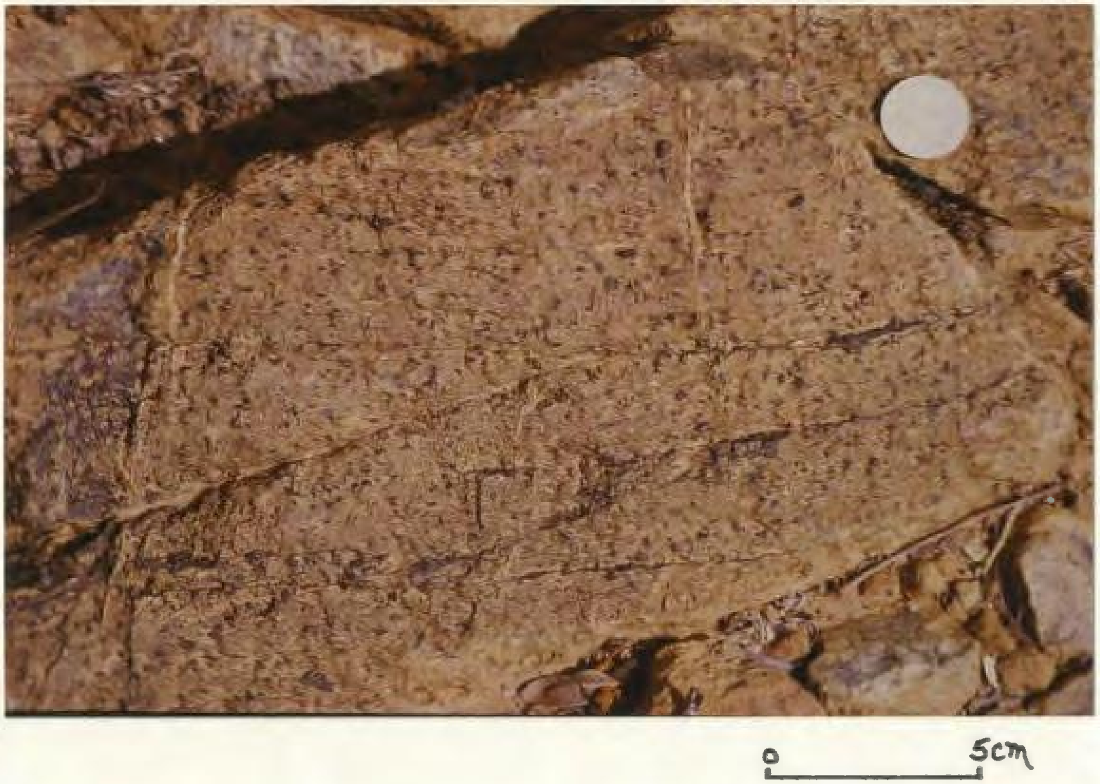


Figure 3.10 Weak layering (right to left) in grey tuffs: Nnywane Formation.

activity in the late Archean to early Proterozoic times.

The basal contact of the Nnywane Formation is always with the Kanye Volcanics. However, despite large areas of exposures of both units, a distinct and unequivocal boundary has never been observed in southeast Botswana (e.g., Crockett, 1971b; Key, 1983; Gould, 1972). In the present study, the contact between the Kanye Volcanics and the Nnywane Formation was placed at the base of a grey, laterally persistent, sparsely porphyritic unit with numerous mafic xenoliths. The stratigraphic position of this unit, when present, is fairly consistent; it always occurs between the last outcrop of typical Kanye Volcanics and the first exposures of greenish-grey tuffs. It therefore constitutes an appropriate and useful marker-horizon separating the massive porphyritic felsites (Kanye Volcanics) from the overlying, predominantly extrusive volcanic rocks. A similar grey unit overlies the Kanye Volcanics in Ntlhantlhe, 15km southeast of the study area. In the study area, this unit can be followed from Mogagabe in the east to the western end of Rankepa Hill (Fig. 3.1). It was not observed between Rankepa Hill and Mafukutswane Hill. But it appears again around Mafukutswe Hill and may be followed to the western end of the map area. Apart from the sudden appearance of mafic xenoliths, the transition from the Kanye Volcanics is very subtle, and involves a gradual change from a fine-grained aphanitic to a distinctly granular groundmass with randomly distributed feldspar phenocrysts. The groundmass consists of very thin, randomly distributed feldspar laths and dispersed acicular grains of mafic minerals. Mafic xenoliths range in size from several millimeters to about 6 cm. Most of the xenoliths are subround, possibly due to partial resorption by the magma. Observed variations across the strike of this unit include changes in both the grain size of the matrix and the proportion of mafic xenoliths. In the eastern part of the study area, this unit seems to be interbedded with a green tuffaceous unit. Hence, the transition at the top appears to be gradational.

The origin of this unit is uncertain. However, Crockett (1971b) believes these rocks represent parts of Kanye Volcanics remobilised during the eruption and emplacement of the Nnywane Formation. But this interpretation fails to account for a number of critical features. First of all, it cannot explain the presence of mafic xenoliths, since there are no mafic rocks in the Kanye Volcanics. Secondly, this hypothesis does not take into account the apparent interbedding of this unit with the overlying tuffs. On these grounds it seems more appropriate to include it in the Nnywane Formation.

(ii) Mogobane Formation

The Mogobane Formation is an assemblage of interbedded grey mudstones, shales, pink siltstones and minor conglomerates and sandstones. Conglomerates and sandstones are more common towards the top and bottom. It is overlain unconformably by the Transvaal Supergroup, the base of which is defined by a thin reddish-brown pebble conglomerate or a grey quartzite (the Black Reef Quartzite), where the basal conglomerate is not present. The contact between the Nnywane Formation and the Mogobane Formation varies along strike (see next page).

The Mogobane Formation is confined to a topographically low area in the southeastern part of the study area. This area contrasts quite sharply with the hilly country to the west and east, underlain by the Nnywane Formation and Black Reef Quartzite, respectively. A prominent ridge of Black Reef Quartzite marks the eastern margin of the Mogobane Formation (Fig. 3.1).

The base of the Mogobane Formation has only been observed in a few places, and differs from one locality to another. On the eastern side of the railway (Fig. 3.1), it is marked by a poorly sorted, polymictic, pebble orthoconglomerate. All the clasts in the conglomerate appear to be of volcanic origin, and the matrix is an immature, green sandstone. The conglomerate passes upwards into a green sandstone which in turn passes upwards into a dark-grey, laminated shale. At least three cyles of this fining upwards sequence: conglomerate-sandstone-shale have been observed at this locality.

On the western side of the railway, the base of the Mogobane Formation is marked by a moderately well sorted, pebble conglomerate with a light-grey sandstone matrix. This conglomerate rests directly on a weathered, light-grey, flow-banded rhyolite, and is overlain by a thin quartzitic sandstone which passes gradually upwards into grey mudstones.

Southeast of the Ramotswa Station, the base of the Mogobane Formation is again exposed, but unlike at other localities described above, it is transitional and consists of grey, tuffaceous shales which grade downwards into weathered tuffs of the Nnywane Formation.

The tuffaceous shales are overlain by grey laminated shales. The latter are very fissile and are interbedded with red siltstones. Interbedded shales and siltstone units of the Mogobane Formation vary in thickness from 0.5 cm to 50 cm. Locally, these beds contain grey, shale fragments, suggesting strong local syndepositional reworking.

The siltstones contain clay minerals as well as coarser-grained flakes of white mica, possibly muscovite. At the top of the Mogobane Formation the sediments change character and coarser units, consisting of interbedded pink, flaggy sandstones and conglomerates become more important. A 300 m thick section of these rocks is exposed along the Ramotswa road, east of the railway line, just below the Black Reef Quartzite (Fig. 3.1). Starting at the bottom of the basal conglomerate of the Transvaal Supergroup, the succession consists of a poorly sorted, polymictic conglomerate with a pink, micaceous sandstone matrix.

No strike and dip measurements were obtained from the Kanye Volcanics, the porphyritic granophyres or the microgranite. These rocks are typically massive and lack bedding structures. It is nevertheless evident from the disposition of these units, particularly on Phiriyabokwete Hill and Rasemong Hill, that they have variable attitudes. Therefore, thickness estimates based on approximate dips of lithological contacts and outcrop widths within the study area are likely to be in error. However, according to Crockett (1969) and Key (1983), there are a number of places in the Gaborone Granite Complex where thicknesses of these units may be obtained. These workers suggest that the Kanye Volcanics are 1 to 2 km thick. The granophyres are comparatively thinner, although their thickness varies considerably.

Well exposed contacts are rare in the Nnywane Formation. In addition, the Nnywane Formation is deformed (see section 3.6). Therefore, strike and dip measurements from this unit are somewhat unreliable as far as computing thicknesses is concerned. But, on average, the Nnywane Formation is comparable to the Kanye Volcanics in thickness.

Even though a lot of attitude measurements were obtained from the Mogobane Formation compared to the Nnywane Formation, they are extremely variable due to folding. It has however been suggested by Crockett (1971b) that this unit is approximately 300 m thick. But this can only be a minimum thickness because there are places where the Mogobane Formation is more than 300 meters thick.

3.6 Structure

Faults and lineaments are the most important structural features in the Kanye Volcanics, the granophyres and the microgranite (Fig. 3.1). The lineaments comprise a very prominent, ENE to NE-trending set which is cut by oblique and more widely spaced lineaments (Fig. 3.1). Accurate mapping of these structures can be accomplished only with the aid of aerial photographs, as the majority of them are indistinct in the field. Comparatively fewer lineaments occur in the Lobatse Volcanic Group, the Transvaal and Waterberg Supergroups.

Aldiss (1986) has examined the distribution and relative ages of photogeologic lineaments in southeast Botswana. He believes that most of the lineaments are deeply-weathered mafic dikes and he has suggested that they are mainly pre-Transvaal in age. However, work in the study area has shown that only a few of these structures actually coincide with zones of mafic dike intrusions.

Faults occur with the same frequency in all the lithological units in the study area. A division or classification of these faults into age groupings is not possible.

Compared to the other lithostratigraphic units, the Lobatse Volcanic Group in particular, and the Transvaal Supergroup in general show a diversity of structures. In addition to lineaments and faults, these rocks are folded. Small folds were observed in the Nnywane Fomation between Bojanjwe Hill and the Lobatse-Gaborone road. The best exposures are, however, in the Mogobane Formation, 1.25 km southeast of Ramotswa station, in the Taung river valley (Fig. 3.11) and farther south, about 2 km southeast of the station, just below the contact with the overlying Black Reef Quartzite. They are mainly small, open, upright folds, with axes plunging about ten degrees to the southeast. Similar folds also occur in the Black Reef Quartzite, but have not been observed in the Waterberg Supergroup.

A very weak foliation is developed in the Nnywane Formation. In addition, stretched amygdules have been observed in this unit (Fig. 3.12). But, unlike the foliation which is definitely due to secondary deformation, stretched amygdules are probably not. The stretching of vesicles could have happened during viscous flow or after the formation of the amygdules.

Figure 3.11 Fold in the Mogobane Formation, near Ramotswa Station (hammer for scale).

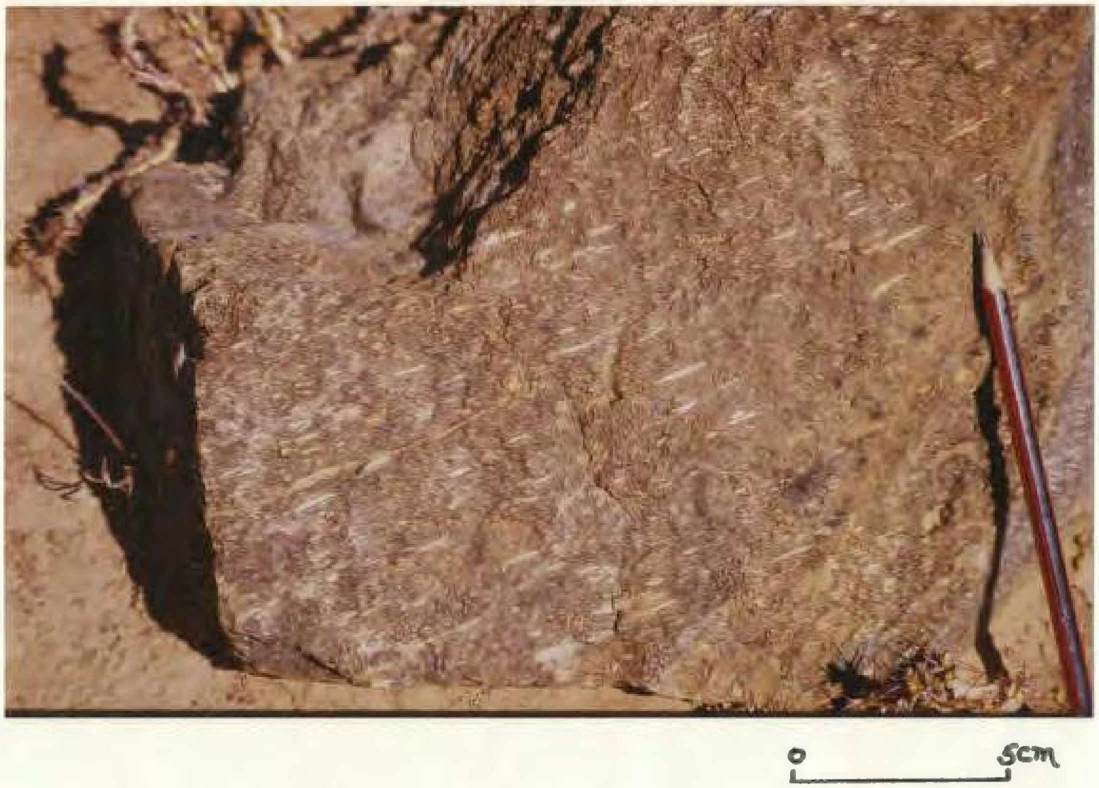


Figure 3.12 Stretched amygdules in rhyolite flow: Nnywane Formation.

The presence of previously unrecognised folds provides the first unequivocal evidence that these rocks, including the Kanye Volcanics and associated lithologies, are deformed. It is perhaps difficult to see these structures in the other units due to lack of bedding markers. The metamorphism, which will be discussed in the next chapter, was probably associated with this deformational event.

CHAPTER 4

PETROGRAPHY

4.1 Introduction

Thin sections of samples from the microgranite, porphyritic granophyres, Kanye Volcanics and the Nnywane Formation were examined under a petrographic microscope. Petrographic descriptions of these rocks are given below. Mineralogically, these rocks consist of fairly similar suites of minerals. The assemblages are dominated by quartz and feldspar, and minor amounts of biotite and amphibole. Accessory minerals include sphene, zircon and Fe-Ti oxides. Important alteration minerals are biotite, calcite, chlorite, epidote and a second generation of sphene. Some of these minerals were examined with a scanning electron microscope for compositional variations (e.g. zoning and alteration) and were also analysed with an electron microprobe, but these results are not included in this thesis.

4.2 Microgranites

Field descriptions of the microgranites are given in Chapter 3. Grain-size variations across this unit were attributed to changing rates of crystallization and cooling during magma ascent and emplacement at shallow crustal levels. Quartz and feldspar are the main constituents of the microgranites. Quartz ranges in size from 2 mm at the base to less than 1 mm at the top of this unit. Feldspars occur as subhedral to anhedral grains up to 2 mm in size. However, in sporadic patches of porphyritic granite close to the contact with the Kanye Volcanics and porphyritic granophyres, large feldspar phenocrysts up to 10 mm were observed. The microgranites typically have a xenomorphic granular texture. Rare patches of micrographic quartz-feldspar intergrowths were also observed in a few thin sections (Fig. 4.1).

The amount of quartz in the granite is relatively constant (31% to 35%). Quartz invariably shows undulose extinction. In micrographic intergrowths, quartz grains have the same crystallographic orientation while feldspars do not.

Feldspar minerals include albite and potash-rich alkali feldspars which is completely exsolved to microperthites. The microperthites are variably altered and appear cloudy. Their internal microstructures are extremely variable. In relatively fresh microperthites, exsolved albite and potash feldspar (orthoclase?) occur as very fine rods, beads and strings with very sharp outlines (Fig. 4.2), while in the more altered samples, the original alkali feldspars are frequently replaced by patches of albite and potash feldspar.

Albite invariably shows chequer-board texture. Unlike microperthite, chequer-board albite does not occur in all samples from the microgranite. It is rare to absent in fresh microgranite but abundant in altered samples. In slightly altered granite, chequer-board albite occurs as discrete bands in exsolved feldspars (Fig. 4.3). With increasing alteration, entire grains of microperthite are replaced by patches of chequer-board albite and potash feldspar (orthoclase?) and the original grain boundaries are not discernible (Figure 4.4). Even though the presence of primary albite in the microgranites can not be ruled out, all the petrographic

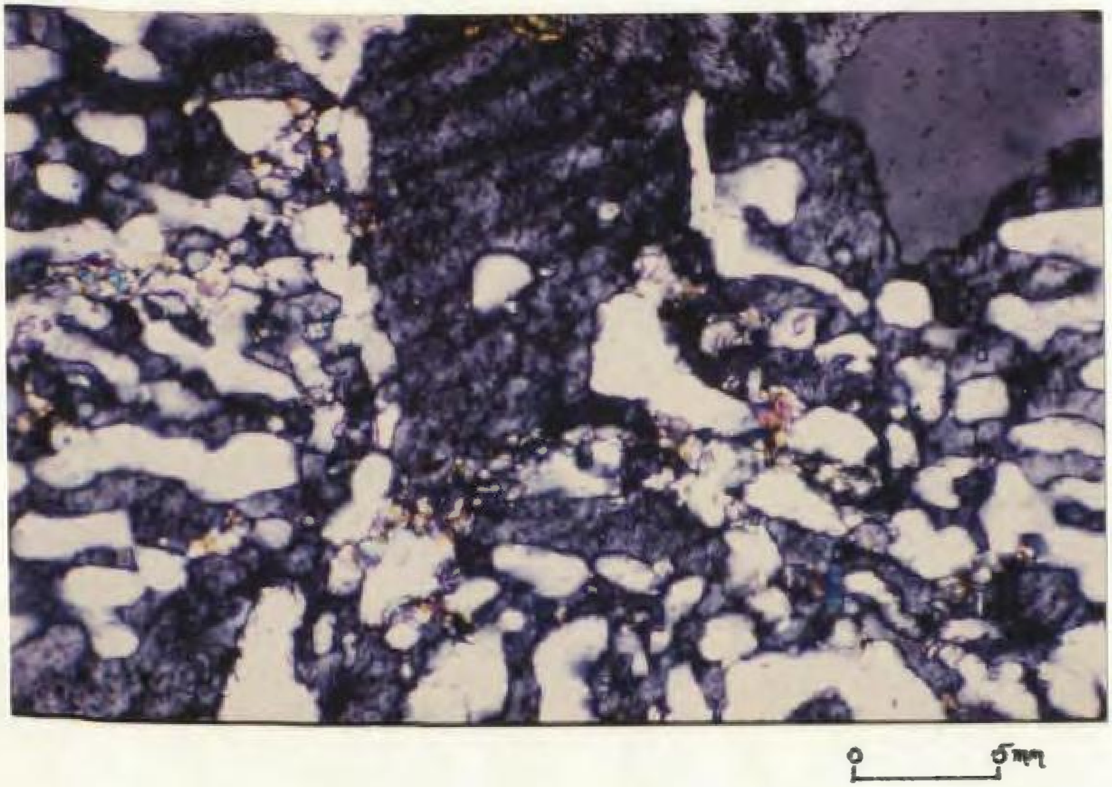


Figure 4.1 Quartz-feldspar intergrowths in the microgranite (5/47) (quartz is white).

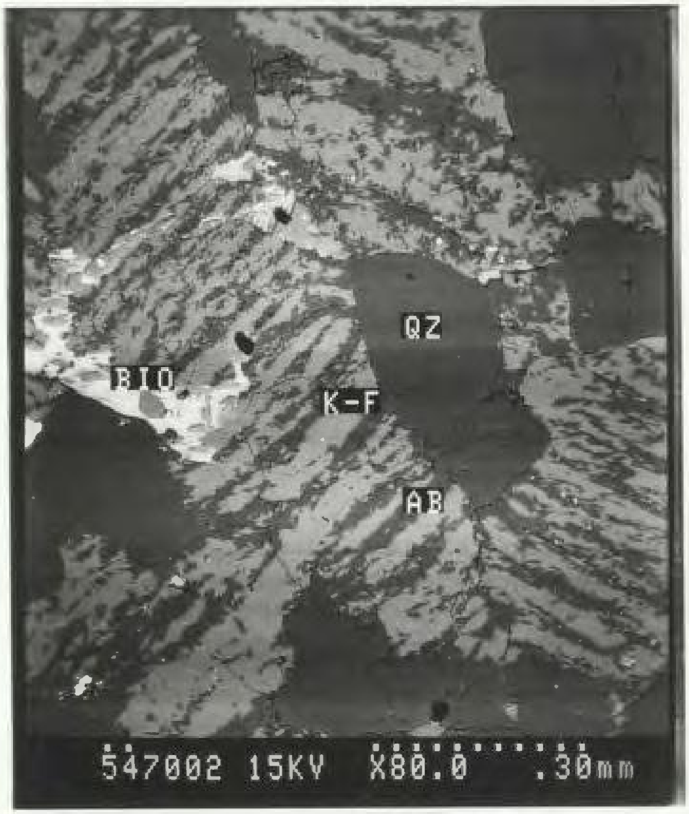


Figure 4.2 Exsolved alkali feldspars in the microgranite (5/47). K-feldspar and albite appear as white and grey lamellae, respectively. Note also grey, irregular quartz grains (Qz).

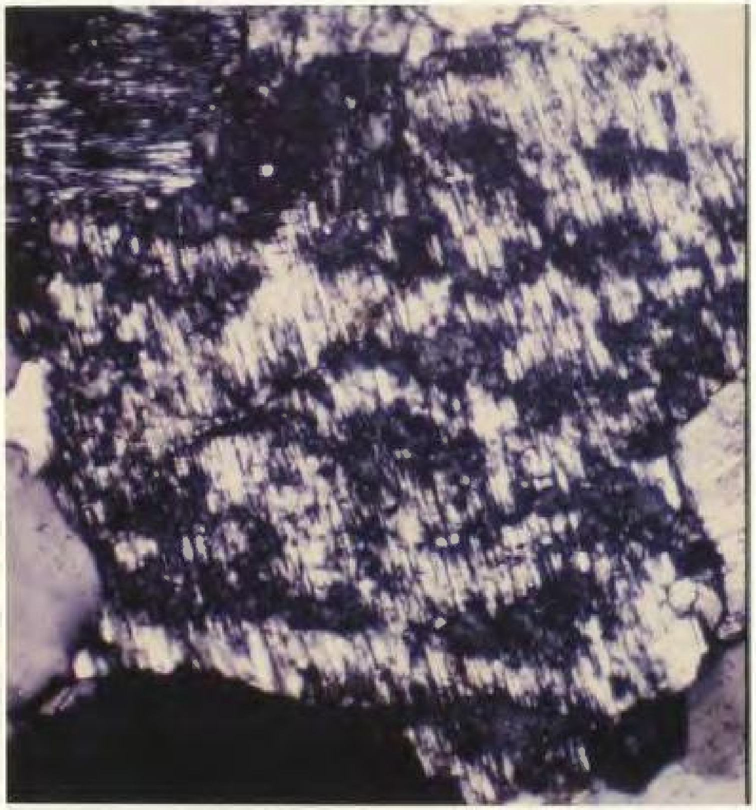


Figure 4.3 Alkali feldspar showing patchy albite exsolution (light areas) (5/48).

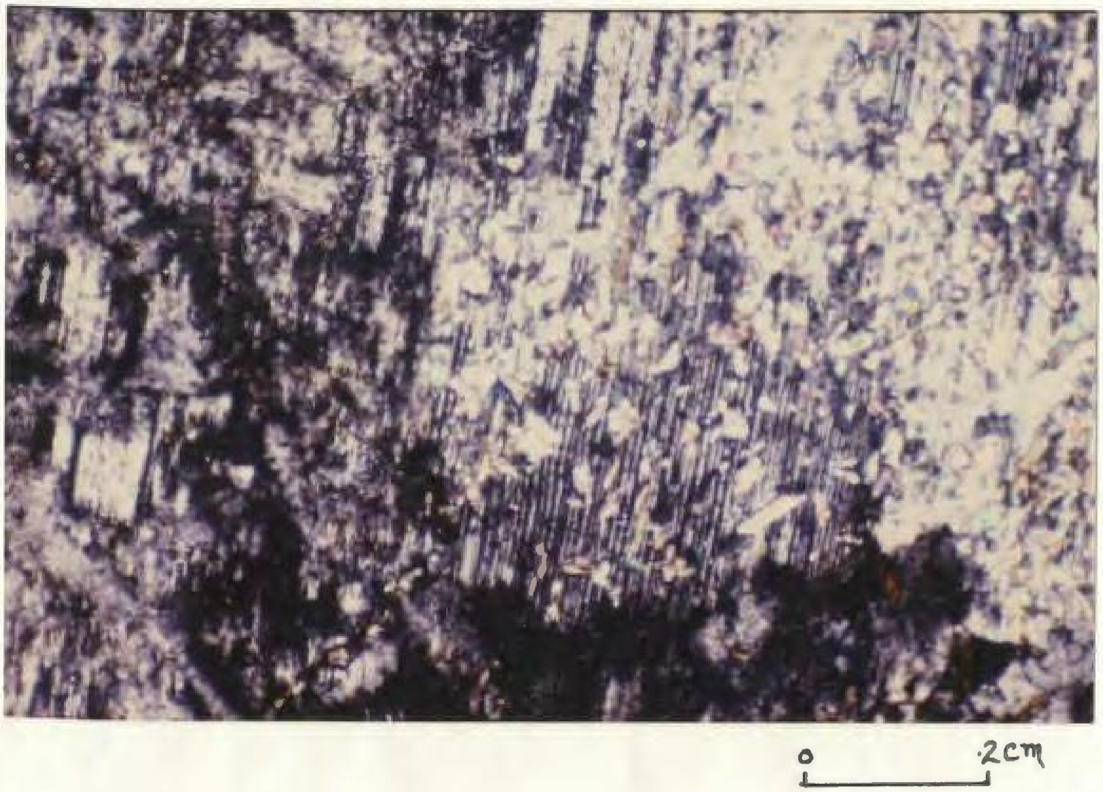


Figure 4.4 Exsolved feldspar showing albite patches (see albite twinning) in K-feldspar host (Note that there are no regular exsolution lamellae as in Figure 4.2). Grains with high order colors in the photograph are sericite. Sample 5/48.

evidence suggests that chequer-board albite formed by exsolution andalteration of primary and originally homogeneous potash-rich alkali feldspars.

Biotite and amphibole occur interstitially, and make less than 2% of the mode. Both minerals are partly replaced by chlorite. In altered granite, biotite also occurs in fractures and along grain boundaries. Common accessory minerals are sphene, Fe-Ti oxides and zircon.

4.3 Porphyritic granophyres

Porphyritic granophyres consist mainly of large, white to pink feldspar phenocrysts in a purple, fine-grained granophyric to microgranitic groundmass. They can be easily distinguished from adjacent outcrops of Kanye Volcanics by their relatively coarser-grained groundmass, larger and more abundant feldspar phenocrysts.

Feldspar grains vary from subuhedral to anhedral, and commonly contain inclusions of both opaque and mafic minerals. Euhedral phenocrysts typically have rhomboidal cross-sections. The amount of feldspar phenocrysts varies from 10% to 20% and decreases gradually towards the top of this unit. Near the narrow transitional boundary separating this unit from the Kanye Volcanics, there is a sudden drop in the amount of phenocrysts in the granophyres to levels comparable to those in the volcanic rocks.

All the feldspar phenocrysts in the lower and interior parts of the porphyritic granophyres are surrounded by radiating intergrowths

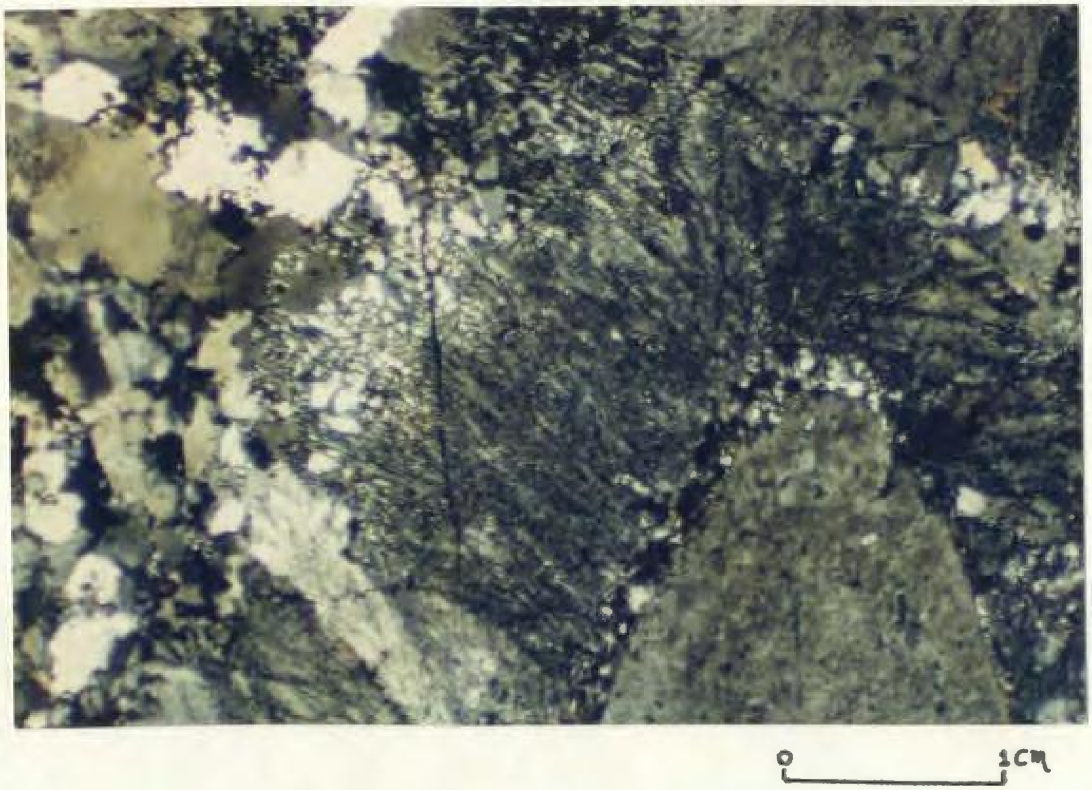


Figure 4.5 Photomicrograph of porphyritic granophyres showing an alkali feldspar phenocryst. The phenocryst is surrounded by a radiating (granophyric) intergrowth of quartz and feldspar. Away from the phenocryst, the groundmass is microgranitic.

of quartz and feldspar (Fig. 4.5). These mantles (granophyric intergrowths) strongly resemble spherulitic intergrowths, and may have formed by devitrification of the groundmass. On rotation under crossed nicols, white to grey and black radiating sheaths of long skeletal quartz and feldspar rods sweep across the microscope's field of view as different sectors of the radiating granophyric intergrowths go in and out of extinction. Away from the mantled phenocrysts, the groundmass is microgranitic (Fig. 4.5). Very few feldspars close to the contact with the Kanye Volcanics have mantles of granophyric quartz-feldspar intergrowths around them, and none were observed in the immediately adjacent units of the volcanic rocks.

Compositionally, feldspar phenocrysts in the granophyres are extremely heterogeneous due to the presence of fine exsolution microstructures. Some of the feldspar phenocrysts contain irregular patches of chequer-board albite. These patches, as in the microgranites, were probably formed by exsolution of originally homogeneous alkali feldspars. Microprobe analyses of optically homogeneous alkali feldspar phenocrysts in the granophyres are extremely variable, suggesting that even these feldspars are finely exsolved despite their apparent homogeneity. Some of the optically homogeneous feldspars were examined with a scanning electron microscope. Their back-scattered electron images show that they consist of a complex mosaic of sodium- and potassium-rich patches. It is evident from these back-scattered electron images of exsolved feldspars in the granophyres, however, that the albitic phase is more abundant and that these feldspar phenocrysts were originally anorthoclases. This observation agrees well with the results of wet chemical analyses of feldspar separates from the granophyres and Kanye Volcanics carried out by Wright (1961). His analyses show that these feldspars range in composition from $<Or_{10}$ to Or_{46}.

Approximately 1% of the porphyritic granophyres is made up of mafic minerals, mainly amphibole and lesser amounts of biotite. Chlorite is a common alteration product of both minerals. Amphibole occurs as green, subhedral to anhedral grains up to 0.6 mm in size, and shows green to dark bluish-green pleochroism. It is commonly associated with opaque minerals, some of which are present as inclusions. Besides chlorite, amphibole is also occasionally altered to a yellowish, fibrous mineral, possibly biotite.

Biotite is relatively rare in the basal and interior parts of the porphyritic granophyres compared to the top of this unit. It occurs as interstitial granular aggregates or decussate mats. It also occurs within fractures and along grain boundaries. Accessory minerals include sphene, zircon, epidote and Fe-Ti oxides. Oxide minerals range in size from very fine-grained black specks to fairly large grains up to 0.9 mm. Opaque grains are frequently surrounded by a variable reaction rim of fine-grained sphene. Besides the reaction rims around oxide minerals, sphene also occurs as fine-grained, euhedral to anhedral grains. The latter may possibly be of primary origin.

4.4 The Kanye Volcanics and Nnywane Formation

There are striking textural, mineralogical and chemical similarities between the Kanye Volcanics and fresh units of the Nnywane Formation. Both units are typically porphyritic, and contain phenocrysts of both albite and anorthoclase. In plane light all feldspar phenocrysts are slightly turbid, and have euhedral to subhedral outlines. Some are partly recrystallised along the margins. Replacement by granoblastic quartz is also not uncommon.

Albite phenocrysts show both chequer-board and normal polysynthetic twinning. But chequer-board albite occurs only in the Nnywane Formation. The presence of chequer-board albite in the more altered and possibly metasomatised Nnywane Formation suggests that it might have formed as a result of metasomatism and alteration of primary alkali feldspar phenocrysts.

Anorthoclase occurs as 3 mm, grey, euhedral to subhedral and slightly turbid phenocysts. Both twinned and untwinned grains were observed. Twinned grains show either Carlsbad and/or cross-hatched twinning (Fig. 4.6). Some of the anorthoclase phenocrysts show fine exsolution.

Although most of the feldspar phenocrysts in the Kanye Volcanics and a few in the Nnywane Formation appear homogeneous under a petrographic microscope, they are in fact submicroscopically heterogeneous as shown by the variability of microprobe analyses of these feldspars. Furthermore, unmixed phases do not seem to lie along specific crystallographic planes as in normal perthites, but are rather randomly distributed. Figure 4.7 shows a back scattered electron image of an alkali feldspar phenocryst in a sample from the Kanye Volcanics. This picture shows a potassium-rich core surrounded

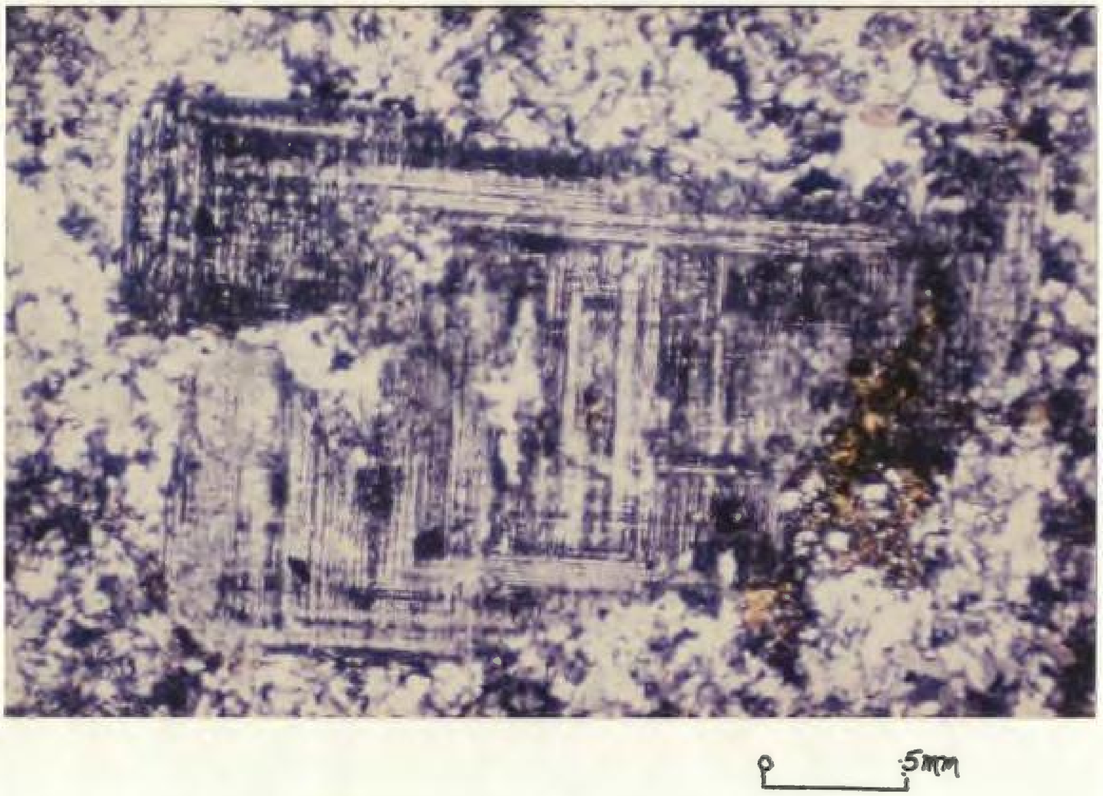


Figure 4.6 Anorthoclase phenocryst in the Kanye Volcanics showing cross-hatched twinning (RC-95).

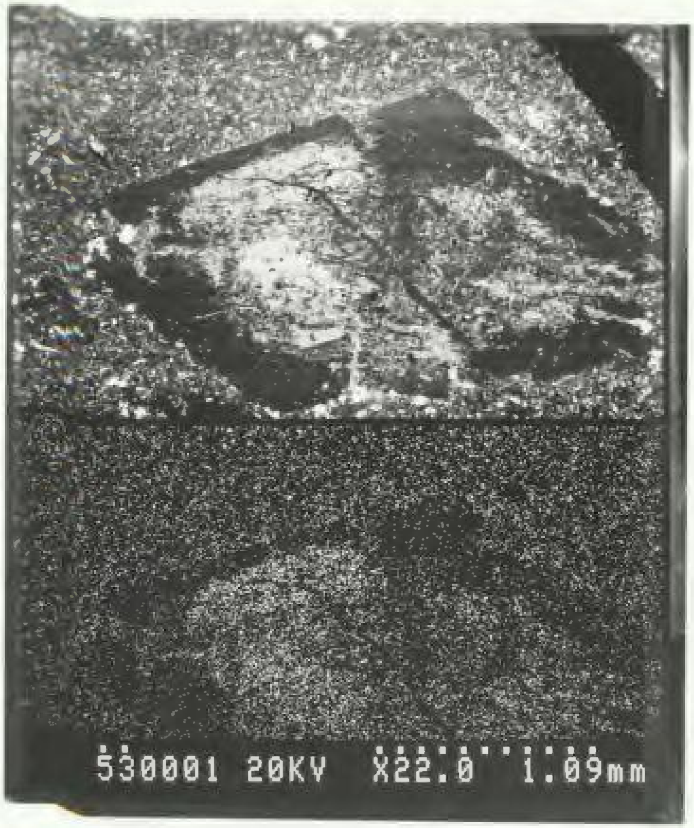


Figure 4.7 Back-scattered electron image of alkali feldspar phenocryst in the Kanye Volcanics showing complex exsolution. The phenocryst has a K-rich core (white area) and Na-rich (dark zone) margins (RC-53B).

by a sodium-rich zone. The centre of the phenocryst also contains irregular Na-rich patches. Under a petrographic microscope, this grain appears fairly homogeneous except for a small patch towards the right end of the grain which shows albite twinning. This patch does not lie entirely within the dark area of the phenocryst (i.e., the Na-rich zone), however. It is possible, therefore, that the observed twinning is a relict microstructure developed before exsolution.

Considering the complexity of exsolution microstructures in these feldspar phenocysts, both observed and deduced from the results of microprobe and SEM (scanning electron microscope) analyses, it is almost impossible to obtain reliable analyses by optical and microbeam techniques. Even the results of Wright (1961) should be used with caution.

The amount of mafic minerals in the Kanye Volcanics is very insignificant compared to quartz and feldspar. It is approximately 1% and is fairly constant, although the relative proportions of the two main minerals, amphibole and biotite, vary from one sample to another. Biotite generally occurs as aggregates of very fine-grained, 0.4mm grains. Small amounts of biotite occur in thin fractures and along the margins of feldspar phenocrysts. It is typically green and platy.

Amphibole occurs as green, stubby to prismatic grains of variable length. Some grains show very strong pleochroism from green to dark green colours that are usually associated with alkalic amphibole varieties. Amphibole grains are frequently associated with aggregates of biotite. Sphene, calcite and iron oxides may also be present in these clusters. Some of the biotite aggregates, especially those associated with amphibole, calcite and sphene, have very sharp and well defined outlines suggesting that the whole assemblage is secondary and pseudomorphic after possibly a mafic precursor such as clinopyroxene or another amphibole. Some of the amphibole and biotite have textural features that suggest a secondary origin.

Qualitative microprobe analyses of biotites and amphiboles from the Kanye Volcanics have shown that the biotites are mainly annites. Amphiboles include actinolite and hornblende. The latter was found only in sample RC-146, although it may be present in other samples that were not analysed. Because sample RC-146 did not contain actinolite, the relationship between these two amphiboles is not known at present. Actinolite may be replacing hornblende.

Biotite in the Nnywane Formation shows more diverse textural features than in the Kanye Volcanics. Furthermore, the amount of biotite in these rocks is extremely variable. It is more abundant in more altered rocks as well as in pyroclastic units. Amphibole is comparatively rare in the Nnywane Formation and was only observed in fresh rhyolite samples.

All the biotite in the Nnywane Formation is secondary; it replaces everything, including the groundmass and feldspar phenocrysts as well as glass in glassy samples. In samples which had a high proportion of glass, biotite is initially restricted to perlitic fractures, leaving phenocrysts relatively free (Fig. 4.8). As alteration progressed, however, the entire groundmass and some of the feldspar phenocrysts were replaced by biotite (Fig. 4.9). In other samples, especially those with a microgranitic matrix, biotite selectively replaced phenocrysts leaving the groundmass relatively unaffected. This is well illustrated in Figure 4.10 and 4.11. Figure 4.10 shows two feldspar phenocrysts partly replaced by fine-grained, green biotite along fractures and grain boundaries, while in Figure 4.11 the entire mafic phenocryst has been replaced by aggregates of fine-grained biotite, quartz and calcite. Selective replacement of feldspar and mafic phenocysts by biotite (e.g. Fig. 4.10 and 4.11) gives altered outcrops a distinct black mottled appearance (see Fig. 3.10). In the field, some of the biotite pseudomorphs may be mistaken for mafic phenocrysts. And it is possible that the mafic segregations described by Key (1983, p.37) were in fact deccusate mats of secondary biotite instead of mafic phenocrysts. Chemically, biotites from the Nnywane Formation are very similar to those from the Kanye Volcanics. They are very iron-rich (annites).

Since the formation of secondary biotite in the Nnywane Formation requires FeO, MgO and K_2O, it is important to identify the source of these components. This will establish whether the formation of secondary biotite in the Nnywane Formation was an isochemical process or not. Accordingly, modal analyses of both altered and slightly altered samples from the Nnywane Formation were compared. It was observed that the least altered samples contained small amounts of amphibole and opaque minerals, while the highly altered samples do not. Despite the absence of amphibole and opaques in the highly altered samples (i.e. those samples with a lot of secondary biotite),

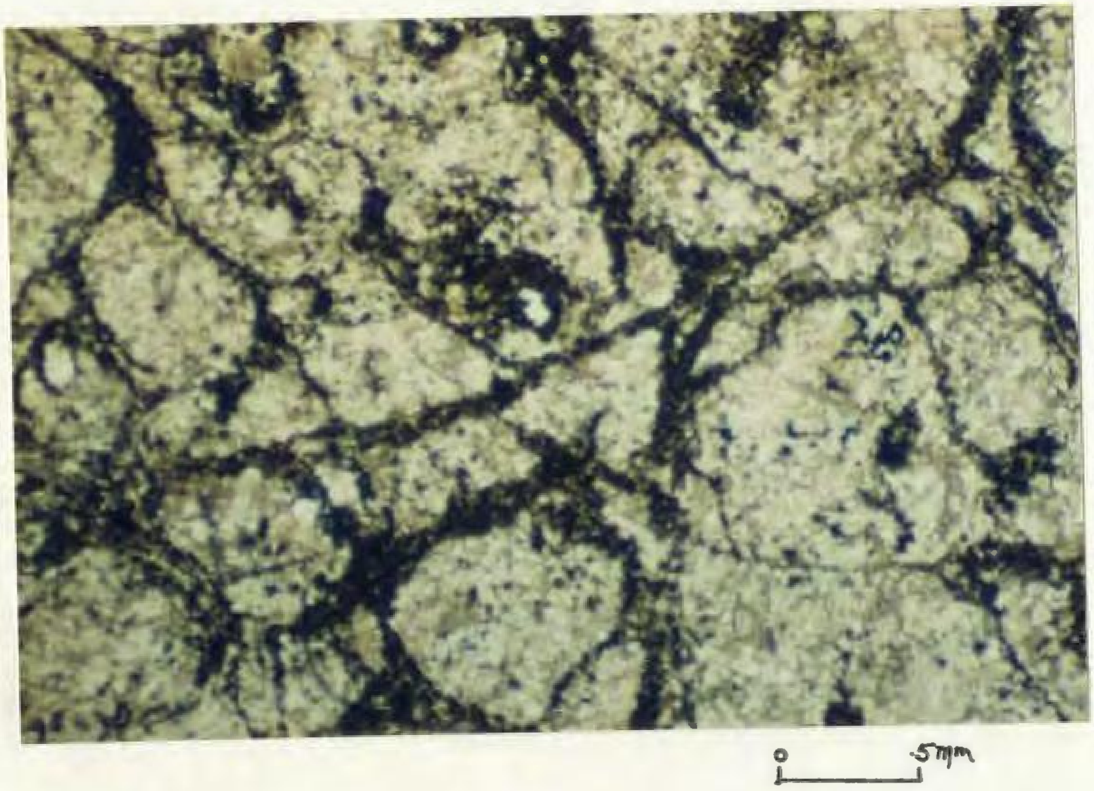


Figure 4.8 Secondary biotite (dark) filling perlitic cracks in rhyolite: Nnywane Formation (RC-73).

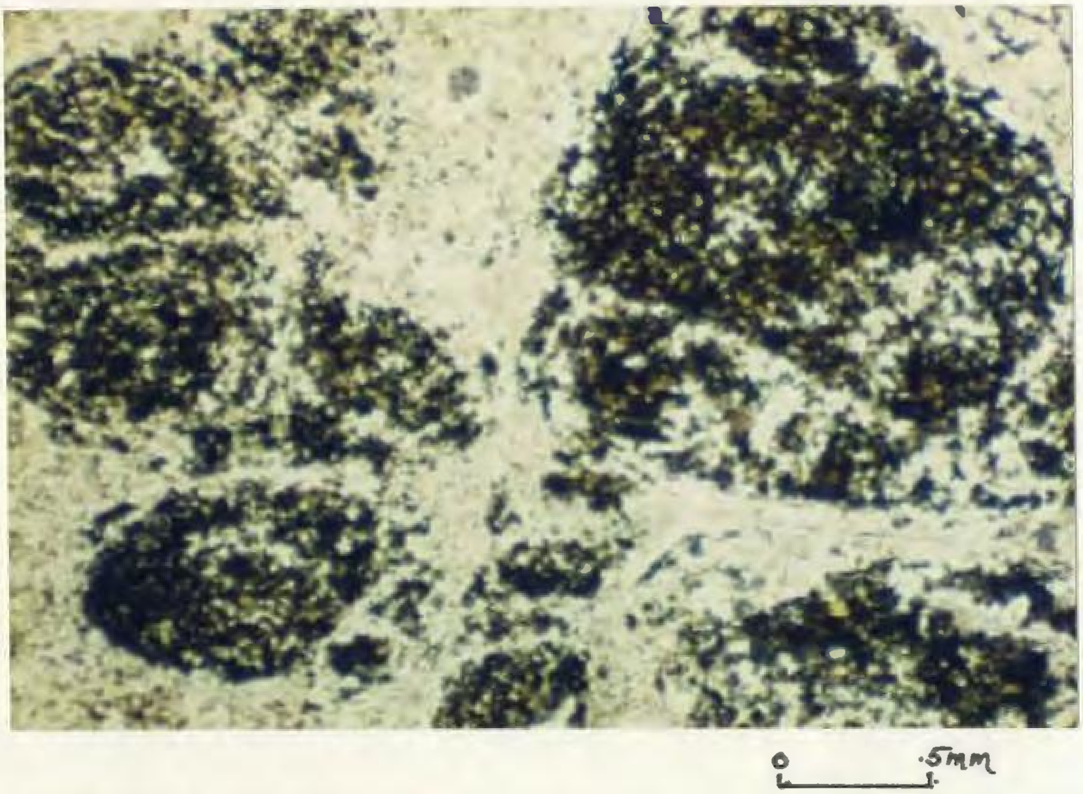


Figure 4.9 Biotite (dark) replacing glassy matrix: Nnywane Formation (5/61).

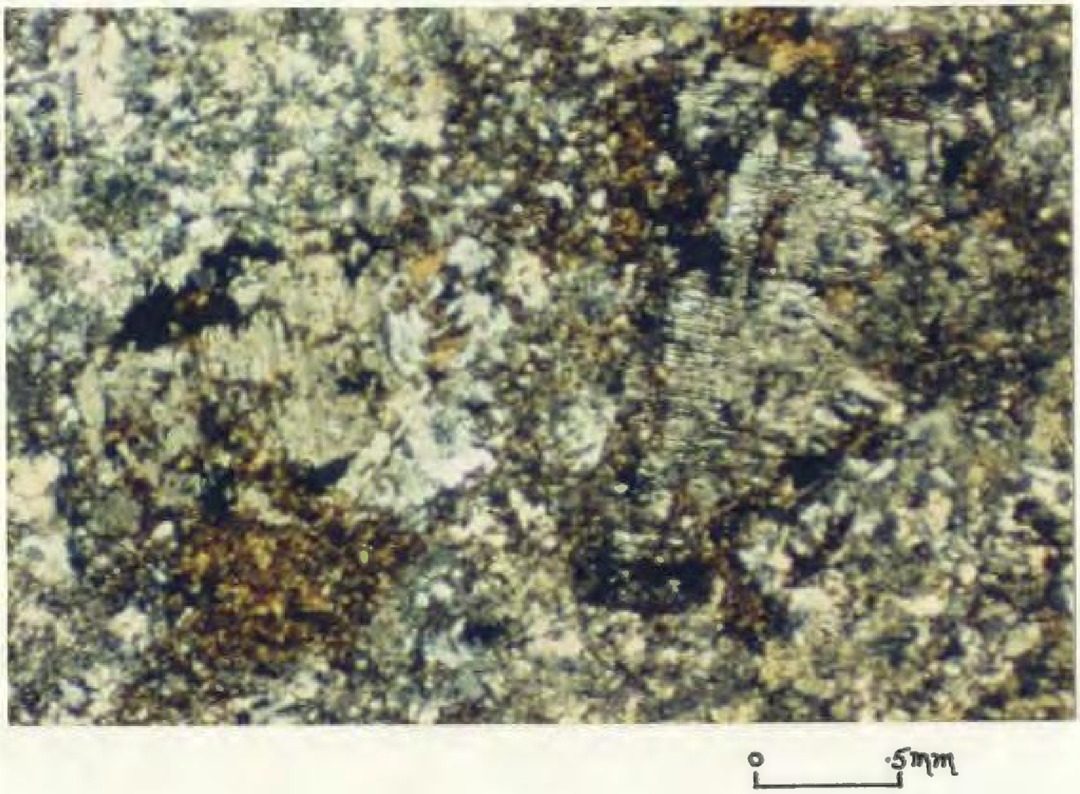


Figure 4.10 Biotite replacing feldspar phenocrysts: Nnywane Formation (5/44).

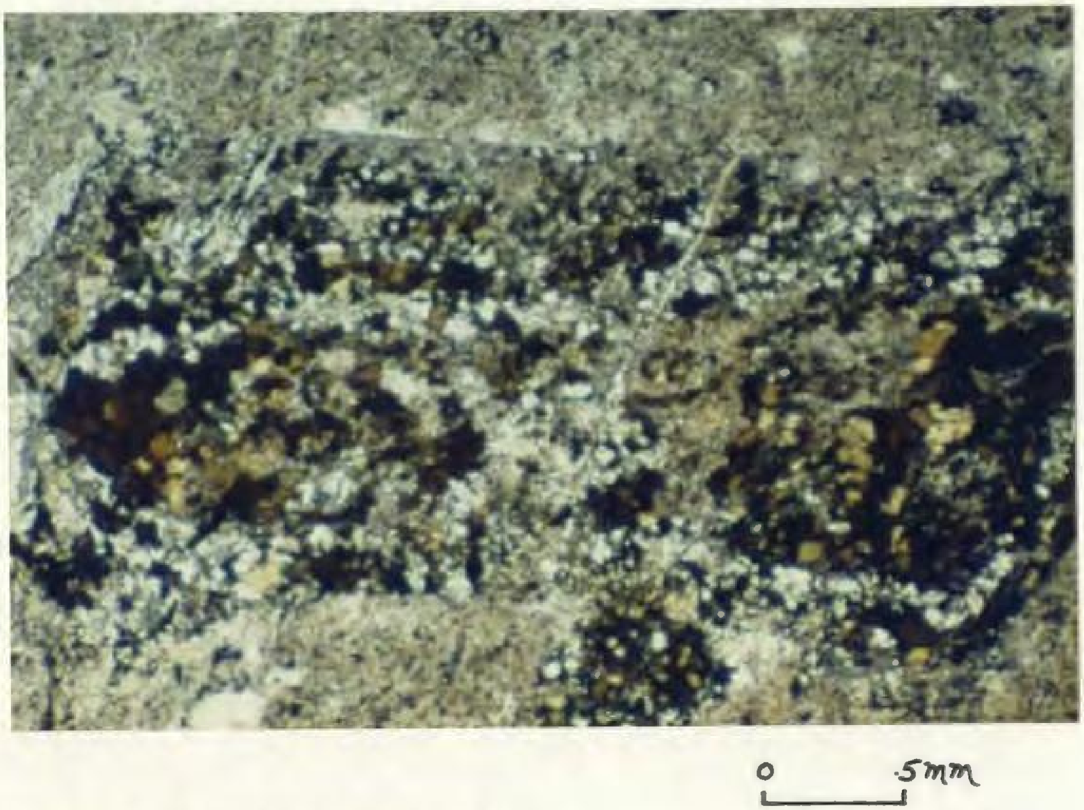


Figure 4.11 Amphibole (?) phenocryst replaced by biotite calcite and quartz (5/92A).

however, there is no difference between the two groups of samples with respect to their FeO (total iron as FeO) and MgO contents (see Chapter 5). Further, the amount of these oxides in the Nnywane Formation does not vary considerably and is comparable to that of the Kanye Volcanics. All the required FeO and MgO, therefore, could have come from the breakdown of amphibole and Fe-Ti oxides in altered samples.

The source of K_2O is not as straightforward, however. First of all, the amount of K_2O in the Nnywane Formation varies considerably (see Chapter 5), but can be roughly correlated with the amount of secondary biotite. In samples with low amounts of secondary biotite, all the required K_2O could have come from the breakdown of potassium-bearing phases such as amphibole and potash feldspars. But the the breakdown of K-bearing phases alone in the Nnywane Formation is insufficient to account for samples with very high amounts of secondary biotite and anomalously high K_2O. It is suggested that some of the K_2O in highly altered samples is of metasomatic origin.

Accessory minerals in the Kanye Vocanics and Nnywane Formation include zircon, sphene, epidote, chlorite, calcite and Fe-Ti oxides. Zircon occurs as very small, irregular grains. More zircons were observed in the Kanye Volcanics than in the Nnywane Formation, even though these rocks have the same amounts of Zr (Table 5.1, page 80). Zircon is also commonly included in other minerals. Zircon grains do not have visible overgrowth rims. Two generations of sphene can be distinguished in the Kanye Volcanics. The first variety consists of pale brown, euhedral to subhedral grains and is often associated with biotite and amphibole. In all respects this variety of sphene seems to be primary. The second variety of sphene typically occurs as rims around opaque minerals. It consists of aggregates of tiny, irregular grains. These grains formed as a result of the breakdown of titanomagnetite (Fig. 4.12). The majority of opaque grains are surrounded by a reaction rim of fine-grained sphene.

Epidote occurs as fine needles and granular aggregates in feldspars (Fig. 4.13). It also occurs as thin veins in the Kanye Volcanics. Chlorite is a common alteration product of biotite and amphibole. Calcite generally occurs as irregular patches in feldspar phenocrysts and in the groundmass.

No phenocrystic quartz was observed in any volcanic samples from the study area. In the Kanye Volcanics quartz is mainly a groundmass phase. However, in the Nnywane Formation quartz occurs as veins (Fig. 3.5), amygdules (Fig. 4.14a); it also frequently mantles feldspar phenocrysts and aggregates of mafic minerals (Fig. 3.6, page 41). Amygdules such as the one shown in Figure 4.14a occasionally have a calcite core. Internally, the amygdules(?) have a fine-grained granoblastic texture (Fig. 4.14b); the coarsest grains tend to be near or at the core of the amygdules.

4.5 Metamorphism

The results of the petrographic analyses show that all the four units examined in this chapter are metamorphosed in lower greenschist facies. In addition to feldspar and quartz, the Kanye Volcanics and porphyritic granophyres contain chlorite + actinolite + hornblende +

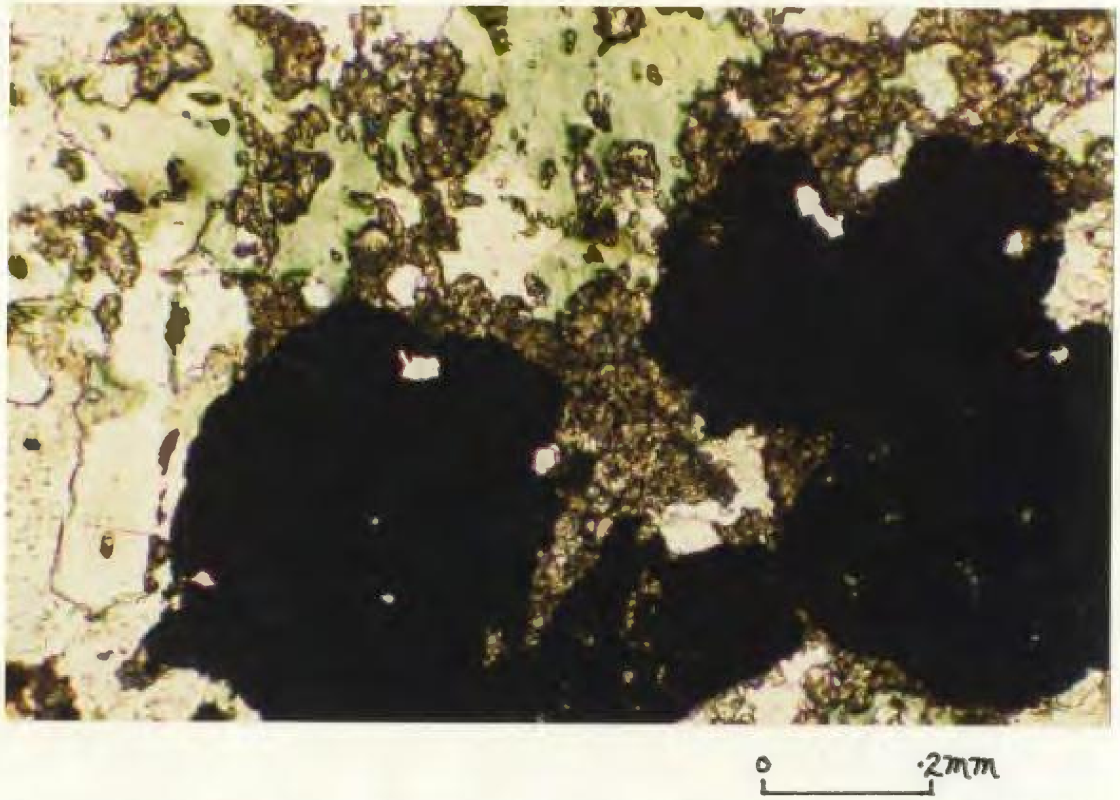


Figure 4.12 Secondary sphene (fine-grained, brown mineral with high relief) surrounding and possibly replacing titanomagnetite (black). The green mineral with low relif is chlorite.

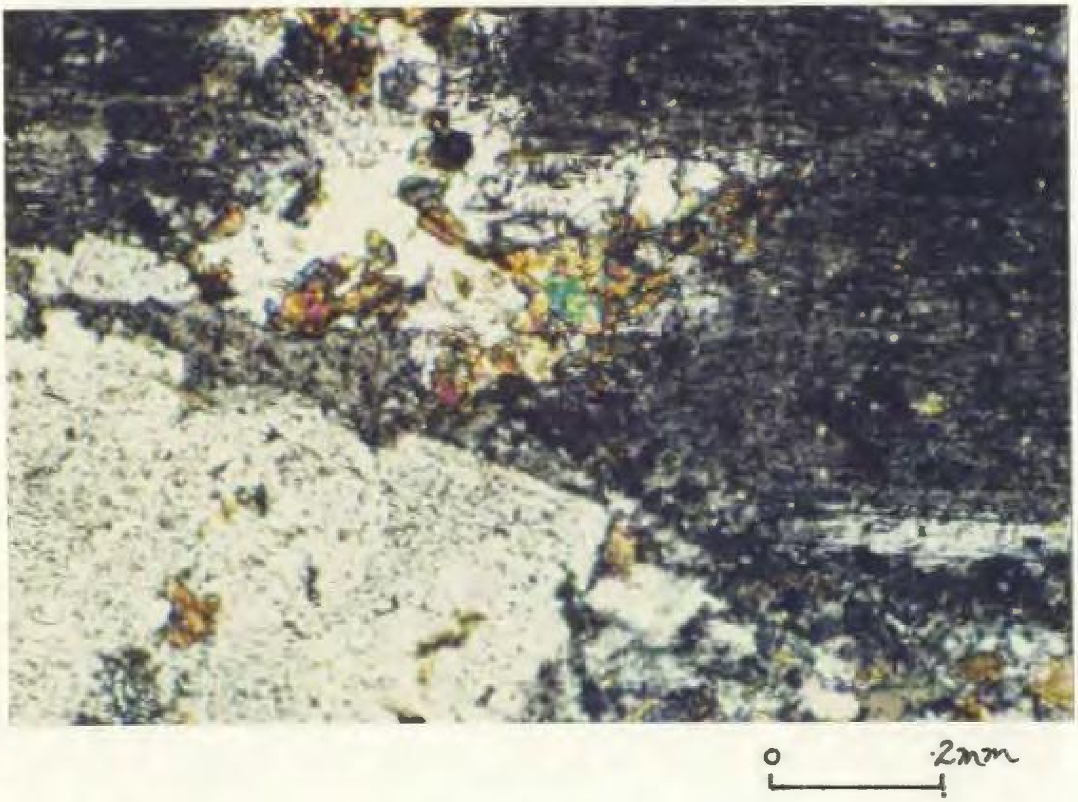


Figure 4.13 Epidote grains (high order colours) in feldspar phenocrysts (RC-95).

epidote + albite + sphene. In the micrograṅites, biotite has been altered to chlorite.

The Nnywane Formation is extremely altered (see section 4.4). Biotite is an important secondary mineral; chlorite occurs sparingly and epidote is very rare. Highly altered samples of the Nnywane Formation do not contain amphibole. It is not possible to say whether biotite formation in the Nnywane Formation coincides with peak metamorphic conditions. It probably postdates it, and some of the metamorphic minerals may have been destroyed during the alteration.

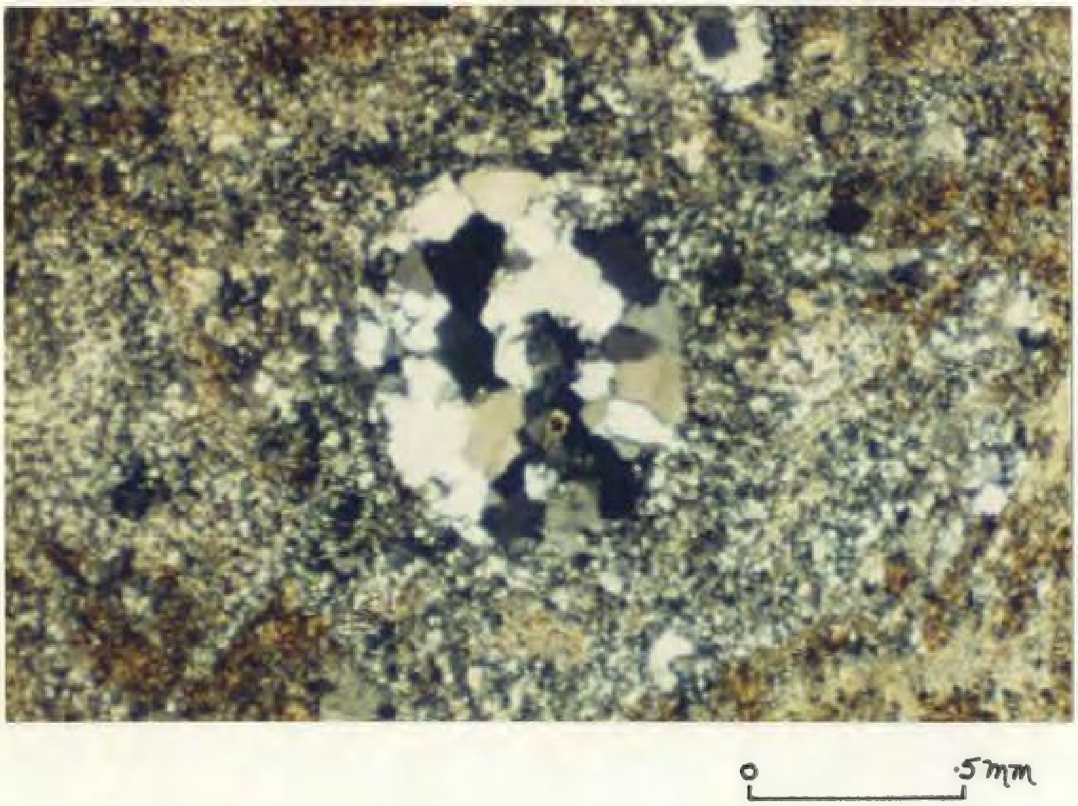


Figure 4.14a Amygdule in rhyolite flow: Nnywane Formation (5/62).

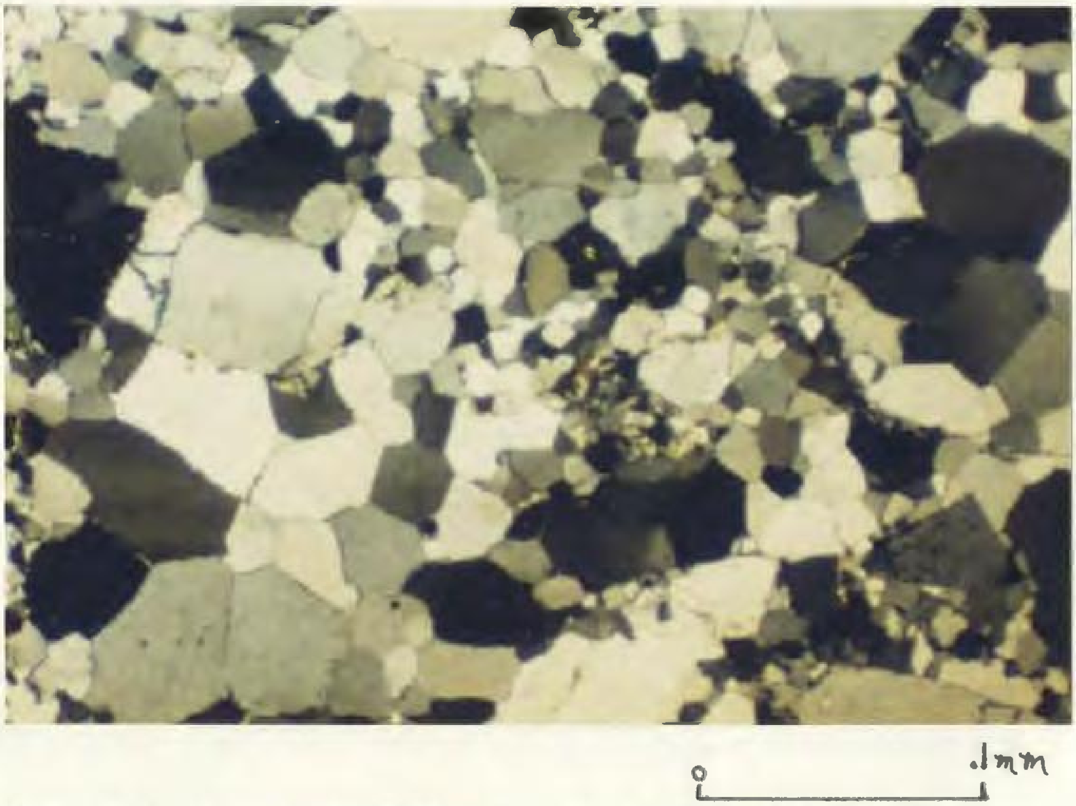


Figure 4.14b Amygdule at high magnification showing granoblastic texture (5/65).

CHAPTER 5

WHOLE-ROCK GEOCHEMISTRY

5.1 Introduction

Whole-rock major and minor element analyses of eighty nine samples from the microgranite, porphyritic granophyres, Kanye Volcanics and Nnywane Formation are presented in Table 5.1. Each sample was analysed for SiO_2, TiO_2, Al_2O_3, total iron (as Fe_2O_3), MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, LOI (loss on ignition), Rb, Sr, Y, Zr, Nb, Ga and Ba. In addition, some of the samples in Table 5.1 were analysed for rare-earth elements (Table 5.2). Included in Table 5.1 are normative mineral compositions of each sample. The means, ranges and standard deviations of major and trace element analyses for each unit are given in Table 5.3.

All the analyses were carried out at Memorial University of Newfoundland. Major element oxides were determined by atomic absorption spectrophotometry (AAS), rare-earth elements analyses by thin film techniques (Fryer, 1977), traces by XRF analyses of pressed pellets. Brief descriptions of analytical procedures and methods are given in appendix A.

Except for a few samples, only total iron (as Fe_2O_3) contents were determined. The total iron content of each sample was normalised to $FeO = 0.9Fe_2O_3$ for CIPW norm calculations in order to minimize the effects of oxidation. Normalization of Fe analyses is necessary because oxidation increases the Fe_2O_3/FeO ratio which in turn results in higher amounts of quartz in the norm and lower amounts of diopside, hypersthene and olivine (Le Maitre, 1976, Cox et al., 1979, p.412).

Table 5.1 Major and trace element analyses and CIPW norms

SAMP.	5/15	5/47	5/48	5/49	5/50	5/86	RC-36	RC-200	GBKE	NTS
GROUP	1	1	1	1	1	1	1	1	1	1
SiO_2	78.10	75.90	75.90	77.90	77.30	77.10	76.60	76.70	78.40	76.50
TiO_2	0.16	0.12	0.12	0.08	0.16	0.12	0.14	0.16	0.12	0.24
Al_2O_3	11.30	11.30	11.40	11.00	11.10	10.50	11.10	11.00	11.20	11.20
Fe_2O_3	0.92	1.66	0.81	1.55	0.71	0.83	1.96	1.53	1.15	1.25
FeO	0.50	-	0.59	-	0.75	1.02	-	-	0.39	0.70
MnO	0.01	0.02	0.01	-	0.01	0.03	0.01	0.01	0.01	0.02
MgO	0.13	0.20	0.35	0.08	0.18	0.52	0.16	0.23	0.16	0.14
CaO	0.26	0.16	0.40	0.14	0.26	0.22	0.10	0.42	0.20	0.54
Na_2O	2.86	3.09	2.61	3.27	3.07	2.75	2.88	3.08	2.85	3.00
K_2O	5.73	5.04	5.40	5.08	5.22	5.00	5.71	5.33	5.47	5.49
P_2O_5	-	-	0.02	-	-	0.03	0.01	-	0.03	0.01
LOI	0.50	0.80	1.05	0.47	0.57	0.78	0.44	0.53	0.78	0.52
TOTAL	100.47	98.29	98.66	99.57	99.33	98.90	99.11	98.99	100.76	99.61
Rb	413	515	430	484	450	283	486	443	420	361
Sr	37	4	12	14	9	10	5	9	25	36
Y	124	127	111	90	164	184	151	160	104	117
Nb	58	116	63	77	79	49	90	81	48	40
Ga	18	29	20	-	24	21	23	-	22	18
Zr	254	421	237	360	370	396	343	345	291	250
Ba	107	7	73	428	17	91	31	90	233	323
Rb/Sr	11	129	36	35	50	28	97	49	17	10
K/Rb	115	81	104	87	96	147	98	100	108	126
K/Ba	445	5976	614	99	2549	456	1529	492	195	141

CIPW Norms

Q	37.99	37.01	37.87	38.16	37.80	39.61	36.41	36.62	39.37	35.94
C	-	0.47	0.58	-	-	0.24	0.02	-	0.30	-
Or	33.87	29.79	31.92	30.03	30.85	29.55	33.75	31.50	32.33	32.45
Ab	24.20	26.14	22.08	27.67	25.97	23.27	24.37	26.06	24.11	25.38
An	1.07	0.79	1.85	0.34	1.09	0.90	0.43	0.45	0.80	0.88
Ac	-	-	-	-	-	-	-	-	-	-
Di	0.19	-	-	0.32	0.17	-	-	1.40	-	1.51
Hy	2.06	2.66	2.75	2.07	2.28	3.92	2.93	1.76	2.44	2.04
Mt	0.21	0.24	0.21	0.22	0.22	0.29	0.28	0.22	0.23	0.29
Il	0.30	0.23	0.23	0.15	0.30	0.23	0.27	0.30	0.23	0.46
Ap	-	-	0.05	-	-	0.07	0.02	-	0.07	0.02

Note: Group 1 = Microgranite, 2 = Kanye Volcanics, 2a = Porphyritic granophyres, 3 = Tuffs (Nnywane Formation) and 4 = Rhyolites (Nnywane Formation).

SAMP.	RC-18A	RC-18C	RC-19B	RC-21	RC-30	RC-31	RC-33	RC-43A	RC-43B	RC-46
GROUP	2	2	2	2	2A	2A	2A	2A	2	2
SiO_2	73.00	72.00	71.80	71.60	71.40	70.90	70.90	71.80	72.40	70.90
TiO_2	0.30	0.40	0.43	0.38	0.52	0.49	0.47	0.38	0.44	0.56
Al_2O_3	11.80	11.90	12.00	12.00	12.20	12.00	12.00	12.20	11.90	12.10
Fe_2O_3	3.72	4.54	4.65	4.54	4.83	4.96	5.07	4.29	4.56	4.58
FeO	-	-	-	-	-	-	-	-	-	-
MnO	0.05	0.05	0.03	0.09	0.06	0.10	0.06	0.06	0.08	0.09
MgO	0.30	0.40	0.21	0.37	0.31	0.28	0.52	0.31	0.33	0.26
CaO	0.72	0.82	0.58	0.80	0.94	1.16	0.96	0.72	0.98	0.88
Na_2O	3.32	3.76	3.51	3.82	3.75	4.00	3.82	3.78	4.07	3.77
K_2O	5.46	4.88	5.51	5.24	5.16	5.16	4.98	5.21	4.78	5.26
P_2O_5	0.06	0.06	0.09	0.08	0.08	0.08	0.08	0.06	0.09	0.10
LOI	0.44	0.53	0.45	0.33	0.04	0.10	0.24	0.35	0.19	0.38
TOTAL	99.17	99.34	99.26	99.25	99.29	99.23	99.10	99.16	99.82	98.88
Rb	272	225	250	243	233	234	268	268	235	237
Sr	22	30	25	33	51	45	43	42	37	37
Y	100	125	110	109	103	116	102	85	103	92
Nb	37	33	32	36	34	36	35	36	35	36
Ga	24	22	23	23	22	24	23	25	22	22
Zr	720	747	754	771	745	746	727	728	754	762
Ba	453	573	684	606	641	651	635	629	571	634
Rb/Sr	12	8	10	7	5	5	6	6	6	6
K/Rb	167	180	183	179	184	183	154	161	169	184
K/Ba	100	71	67	72	67	66	65	69	70	69

CIPW Norms

	RC-18A	RC-18C	RC-19B	RC-21	RC-30	RC-31	RC-33	RC-43A	RC-43B	RC-46
Q	29.20	27.16	26.65	25.31	25.46	23.54	24.80	26.01	26.34	24.94
C	-	-	-	-	-	-	-	-	-	-
Or	32.27	28.84	32.57	30.97	30.50	30.50	29.43	30.79	28.25	31.09
Ab	28.09	31.81	29.70	32.32	31.73	33.00	32.32	31.98	34.44	31.90
An	1.17	1.18	0.72	0.12	1.22	-	0.89	0.94	0.09	0.56
Ac	-	-	-	-	-	0.74	-	-	-	-
Di	1.75	2.17	1.38	2.90	2.56	4.59	2.91	1.96	3.66	2.76
Hy	4.66	5.68	5.68	5.32	5.48	4.84	6.24	5.26	4.75	4.87
Mt	0.54	0.66	0.68	0.66	0.70	0.35	0.73	0.62	0.66	0.66
Il	0.57	0.76	0.82	0.72	0.99	0.93	0.89	0.72	0.84	1.06
Ap	0.14	0.14	0.21	0.19	0.19	0.19	0.19	0.14	0.21	0.24

SAMP.	RC-49	RC-50	RC-51	RC-52	RC-53B	RC-55	RC-75	RC-88	RC-92	RC-95
GROUP	2	2	2	2	2	2	2	2	2	2
SiO_2	70.60	71.90	71.90	73.00	71.80	72.40	72.70	72.40	72.40	72.80
TiO_2	0.56	0.52	0.56	0.52	0.38	0.52	0.56	0.52	0.52	0.47
Al_2O_3	12.10	12.10	11.80	12.10	12.10	11.90	11.80	11.60	12.00	12.10
Fe_2O_3	4.45	4.43	4.48	4.59	4.50	4.44	3.85	4.33	4.54	4.68
FeO	-	-	-	-	-	-	-	-	-	-
MnO	0.06	0.07	0.08	0.09	0.08	0.07	0.07	0.09	0.07	0.09
MgO	0.24	0.30	0.32	0.25	0.35	0.33	0.34	0.35	0.33	0.29
CaO	0.80	0.82	0.66	1.06	0.98	0.90	1.24	1.28	0.80	0.76
Na_2O	3.72	3.71	4.10	3.36	3.73	4.18	3.35	3.30	3.70	3.22
K_2O	5.14	5.04	4.57	4.57	5.12	3.73	4.64	5.30	5.05	5.48
P_2O_5	0.10	0.11	0.07	0.08	0.07	0.07	0.14	0.07	0.07	0.06
LOI	0.43	0.43	0.13	0.32	0.21	0.59	0.54	1.27	0.54	0.27
TOTAL	98.20	99.43	98.67	99.94	99.32	99.13	99.23	100.51	100.02	100.22
Rb	209	208	218	214	242	115	141	227	212	243
Sr	30	41	31	47	32	39	85	34	31	40
Y	98	98	100	102	92	101	107	102	98	101
Nb	35	34	35	36	35	34	36	35	35	37
Ga	20	23	26	21	23	24	27	21	22	20
Zr	757	756	755	773	758	755	794	758	756	780
Ba	611	626	590	800	617	437	783	681	624	698
Rb/Sr	7	5	7	5	8	3	2	7	7	6
K/Rb	204	201	174	177	176	269	273	194	198	187
K/Ba	70	67	64	47	69	71	49	65	67	65

CIPW Norms

Q	25.49	27.03	26.90	30.99	26.12	29.36	30.97	28.41	27.46	28.37
C	-	-	-	-	-	-	-	-	-	-
Or	30.38	29.79	27.01	27.01	30.26	22.05	27.42	31.33	29.85	32.39
Ab	31.47	31.39	34.69	28.43	31.56	35.37	28.34	27.92	31.31	27.24
An	1.14	1.48	0.30	4.44	1.15	2.70	3.46	1.19	1.22	2.38
Ac	-	-	-	-	-	-	-	-	-	-
Di	1.91	1.63	2.20	0.26	2.84	1.15	1.55	4.10	2.00	0.88
Hy	5.03	5.39	5.16	6.24	5.23	5.74	4.65	4.13	5.43	6.96
Mt	0.64	0.64	0.65	0.67	0.65	0.64	0.56	0.63	0.66	0.75
Il	1.06	0.99	1.06	0.99	0.72	0.99	1.06	0.99	0.99	0.89
Ap	0.24	0.26	0.17	0.19	0.17	0.17	0.33	0.17	0.17	0.14

SAMP.	RC-96	RC-101	RC-103	RC-105	RC-107	RC-109	RC-112	RC-116	RC-117	RC-118
GROUP	2	2	2	2A	2	2	2	2	2	2
SiO_2	72.80	73.10	72.80	71.70	73.00	71.10	73.00	71.30	72.70	72.00
TiO_2	0.40	0.48	0.43	0.45	0.38	0.52	0.38	0.45	0.45	0.48
Al_2O_3	12.10	12.10	12.10	12.30	12.20	12.00	12.20	12.00	11.90	12.20
Fe_2O_3	4.80	4.46	4.63	4.90	4.30	4.71	4.57	4.73	4.56	4.47
FeO	-	-	-	-	-	-	-	-	-	-
MnO	0.10	0.05	0.08	0.07	0.06	0.09	0.07	0.07	0.07	0.14
MgO	0.29	0.48	0.82	0.28	0.58	0.32	0.36	0.34	0.23	0.29
CaO	0.72	0.26	1.10	0.74	0.90	0.96	0.62	0.82	1.08	0.58
Na_2O	3.82	3.63	3.26	3.75	3.67	4.02	3.45	3.87	3.90	3.56
K_2O	4.72	4.42	4.32	5.13	4.79	4.96	4.97	5.19	4.63	5.23
P_2O_5	0.05	0.11	0.07	0.09	0.05	0.11	0.06	0.10	0.06	0.09
LOI	0.56	0.90	1.13	0.40	0.75	0.39	0.41	0.16	0.15	0.54
TOTAL	100.36	99.99	100.74	99.81	100.68	99.18	100.09	99.03	99.73	99.58
Rb	174	129	183	221	183	240	182	180	214	207
Sr	30	28	26	33	27	43	30	30	40	34
Y	102	95	99	122	101	117	95	97	104	103
Nb	36	37	34	38	34	36	38	35	34	36
Ga	24	22	21	23	22	23	23	22	21	22
Zr	770	776	755	759	770	752	779	751	745	772
Ba	641	586	538	719	624	657	643	606	611	666
Rb/Sr	6	5	7	7	7	6	6	6	5	6
K/Rb	225	284	196	193	217	172	227	239	180	210
K/Ba	61	63	67	59	64	63	64	71	63	65

CIPW Norms

Q	28.11	31.57	31.21	25.98	28.47	24.67	29.52	24.93	27.96	27.33
C	-	1.14	0.23	-	-	-	0.16	-	-	-
Or	27.90	26.12	25.53	30.32	28.31	29.32	29.38	30.68	27.37	30.91
Ab	32.32	30.71	27.58	31.73	31.05	34.01	29.19	32.74	33.00	30.12
An	1.93	0.57	5.00	1.58	2.67	0.05	2.68	0.05	1.29	1.87
Ac	-	-	-	-	-	-	-	-	-	-
Di	1.15	-	-	1.32	1.27	3.49	-	2.94	3.23	0.37
Hy	6.39	6.75	7.99	6.26	6.32	4.90	6.81	5.33	4.67	6.27
Mt	0.70	0.65	0.67	0.71	0.62	0.68	0.66	0.68	0.66	0.65
Il	0.76	0.91	0.82	0.85	0.72	0.99	0.72	0.85	0.85	0.91
Ap	0.12	0.26	0.17	0.21	0.12	0.26	0.14	0.24	0.14	0.21

SAMP.	RC-119	RC-123	RC-124	RC-125	RC-126	RC-133	RC-134	RC-145	RC-146	RC-150
GROUP	2	2	2	2	2	2	2	2	2	2
SiO_2	72.60	72.00	72.80	71.20	72.90	73.20	72.00	71.90	71.80	71.30
TiO_2	0.36	0.48	0.45	0.38	0.44	0.44	0.38	0.48	0.52	0.48
Al_2O_3	11.90	12.00	12.10	12.00	11.90	11.60	12.10	11.90	11.70	12.00
Fe_2O_3	4.50	4.50	4.74	4.69	4.21	4.55	4.59	4.74	4.32	5.10
FeO	-	-	-	-	-	-	-	-	-	-
MnO	0.10	0.08	0.11	0.05	0.05	0.06	0.09	0.05	0.11	0.03
MgO	0.60	0.26	1.03	0.52	0.61	0.42	1.12	0.33	0.57	0.85
CaO	0.54	0.86	0.48	0.96	0.86	0.60	0.66	0.86	1.23	0.36
Na_2O	3.40	3.58	2.95	3.67	3.21	3.33	2.56	3.40	3.23	3.23
K_2O	5.10	5.05	4.63	4.95	5.19	4.82	5.44	4.65	5.12	5.04
P_2O_5	0.09	0.10	0.06	0.12	0.09	0.07	0.07	0.11	0.08	0.08
LOI	0.69	0.43	0.40	0.85	0.65	0.43	0.60	0.64	0.93	0.65
TOTAL	99.88	99.34	99.75	99.39	100.11	99.52	99.61	99.06	99.61	99.12
Rb	213	192	195	193	219	222	230	162	325	188
Sr	35	40	23	32	19	32	24	43	31	27
Y	105	103	111	126	104	95	110	99	101	104
Nb	36	37	36	39	35	35	37	37	38	36
Ga	23	24	24	22	22	21	20	19	23	24
Zr	776	770	770	769	761	758	777	782	781	776
Ba	691	654	618	638	602	665	790	700	676	656
Rb/Sr	6	5	8	6	12	7	10	4	10	7
K/Rb	199	218	197	213	197	180	196	238	131	223
K/Ba	61	64	62	64	72	60	57	55	63	64

CIPW Norms

Q	28.82	27.71	32.74	26.16	29.66	30.96	30.67	29.61	28.39	28.48
C	0.02	-	1.51	-	-	-	0.97	-	-	0.77
Or	30.14	29.85	27.37	29.26	30.68	28.49	32.15	27.48	30.26	29.79
Ab	28.77	30.29	24.96	31.05	27.16	28.17	21.66	28.77	27.33	27.33
An	2.09	1.76	1.99	1.65	2.74	2.47	2.82	3.48	2.31	1.26
Ac	-	-	-	-	-	-	-	-	-	-
Di	-	1.62	-	2.02	0.81	0.38	-	0.06	2.82	-
Hy	7.39	5.47	8.68	6.30	6.38	6.63	8.77	6.74	5.38	8.54
Mt	0.65	0.65	0.69	0.68	0.61	0.66	0.67	0.69	0.63	0.74
Il	0.68	0.91	0.85	0.72	0.84	0.84	0.72	0.91	0.99	0.91
Ap	0.21	0.24	0.14	0.28	0.21	0.02	0.17	0.26	0.19	0.19

SAMP	5/16	5/34	RC-73	RC-82C	RC-83	RC-138	RC-142	RC-143	5/32A	5/39
GROUP	2A	2	3	3	3	3	3	3	3	3
SiO_2	71.80	73.00	74.00	72.70	72.90	72.70	73.20	76.40	73.20	70.90
TiO_2	0.48	0.48	0.40	0.40	0.48	0.43	0.48	0.40	0.44	0.44
Al_2O_3	12.00	11.70	12.30	11.80	11.70	11.90	11.80	11.00	12.10	13.50
Fe_2O_3	2.76	4.31	4.44	3.82	4.20	4.96	4.78	4.89	4.02	4.86
FeO	2.01	-	-	-	-	-	-	-	-	-
MnO	0.09	0.08	0.07	0.07	0.05	0.14	0.06	0.07	0.06	0.09
MgO	0.52	0.56	0.71	0.48	0.45	0.82	0.45	0.56	0.70	0.83
CaO	0.56	1.30	0.30	0.46	0.64	1.76	0.18	0.26	0.18	0.44
Na_2O	3.25	2.22	1.44	0.37	2.72	2.55	2.62	0.08	3.57	3.77
K_2O	5.49	5.15	5.43	8.19	5.18	2.64	4.26	4.30	3.60	4.17
P_2O_5	0.11	0.07	0.09	0.08	0.07	0.04	0.10	0.16	0.07	0.10
LOI	0.63	0.63	1.06	0.60	0.56	0.78	0.81	1.56	0.75	0.71
TOTAL	99.70	99.50	100.24	98.97	98.95	98.72	98.74	99.68	98.69	99.81
Rb	265	216	295	268	209	169	166	223	138	206
Sr	40	39	28	34	45	50	24	6	22	49
Y	105	99	96	95	99	107	96	104	101	95
Nb	37	35	38	35	34	34	35	34	33	33
Ga	21	23	23	12	21	17	17	22	20	14
Zr	770	754	821	769	766	763	747	745	738	709
Ba	756	670	767	998	766	721	524	757	449	526
Rb/Sr	7	6	11	8	5	3	7	37	6	4
K/Rb	172	198	153	254	206	130	213	160	217	168
K/Ba	60	64	59	68	56	30	68	47	67	63

CIPW Norms

Q	27.33	34.49	40.80	35.52	33.04	39.91	38.13	55.65	35.13	28.25
C	-	0.28	3.72	1.68	0.62	1.74	2.79	6.12	2.17	2.23
Or	32.45	30.44	32.09	48.41	30.62	15.60	25.18	25.42	21.28	24.65
Ab	27.50	18.78	12.18	3.13	23.01	21.58	22.17	0.68	30.21	31.90
An	1.94	5.99	0.90	1.76	2.72	8.47	0.24	0.24	0.44	1.53
Ac	-	-	-	-	-	-	-	-	-	-
Di	0.10	-	-	-	-	-	-	-	-	-
Hy	7.62	6.81	7.47	6.03	6.32	8.57	7.15	7.73	6.78	8.34
Mt	0.72	0.63	0.64	0.55	0.61	0.72	0.69	0.71	0.58	0.71
Il	0.91	0.91	0.76	0.76	0.91	0.82	0.91	0.76	0.84	0.84
Ap	0.26	0.17	0.21	0.19	0.17	0.09	0.24	0.38	0.17	0.24

SAMP.	5/40	5/43	5/44	5/55	5/56B	5/59A	5/60A	5/60B	5/61	5/62
GROUP	3	3	3	3	3	3	3	3	3	3
SiO_2	71.80	74.10	73.80	74.80	84.30	72.70	78.40	75.10	75.50	71.40
TiO_2	0.44	0.44	0.44	0.36	0.20	0.40	0.36	0.44	0.36	0.56
Al_2O_3	12.00	11.60	12.00	12.30	9.44	12.10	10.20	11.30	10.90	12.50
Fe_2O_3	5.90	4.61	4.79	3.45	0.28	1.34	2.95	3.80	4.78	6.03
FeO	-	-	-	-	-	3.10	-	-	-	-
MnO	0.09	0.09	0.06	0.05	-	0.09	0.04	0.06	0.06	0.10
MgO	0.68	0.60	0.53	0.48	0.03	0.42	0.38	0.53	0.58	0.94
CaO	0.16	0.22	0.28	0.18	0.02	1.28	0.20	0.18	0.26	0.50
Na_2O	0.22	2.05	2.70	1.79	0.18	1.42	0.07	0.16	2.85	0.27
K_2O	7.25	5.38	4.05	5.60	2.67	5.34	4.17	6.47	3.30	6.13
P_2O_5	0.06	0.05	0.07	-	0.01	0.08	0.29	0.05	0.08	0.08
LOI	0.93	0.57	0.76	1.21	1.41	1.67	1.36	1.36	0.67	1.19
TOTAL	99.53	99.71	99.48	100.22	98.54	99.94	98.42	99.45	99.34	99.70
Rb	308	187	160	231	108	275	219	275	131	255
Sr	24	29	36	39	6	49	39	20	20	27
Y	98	92	108	96	65	94	137	96	95	102
Nb	37	32	35	37	29	35	32	34	31	39
Ga	18	20	18	29	19	22	22	24	18	-
Zr	737	762	761	783	670	747	642	721	689	803
Ba	767	906	523	705	120	836	795	691	493	680
Rb/Sr	13	5	4	6	18	6	6	14	7	9
K/Rb	195	239	210	201	205	161	158	195	209	200
K/Ba	79	49	64	66	185	53	44	78	56	75

CIPW Norms

Q	38.06	37.66	38.62	39.88	72.94	38.02	60.21	46.22	42.26	40.60
C	3.64	2.12	2.83	2.97	6.24	1.85	5.90	3.83	2.36	4.70
Or	42.85	31.80	23.94	33.10	15.78	31.56	24.65	38.24	19.50	36.23
Ab	1.86	17.34	22.84	15.14	1.52	12.01	0.59	1.35	24.11	2.28
An	0.40	0.76	0.93	0.89	0.03	5.83	-	0.57	0.77	1.96
Ac	-	-	-	-	-	-	-	-	-	-
Di	-	-	-	-	-	-	-	-	-	-
Hy	9.42	7.41	7.43	5.53	0.15	7.28	4.56	6.04	7.67	10.06
Mt	0.86	0.67	0.69	0.50	0.04	0.69	0.43	0.55	0.69	0.87
Il	0.84	0.84	0.84	0.68	0.38	0.76	0.68	0.84	0.68	1.06
Ap	0.14	0.12	0.17	-	0.02	0.19	0.68	0.12	0.19	0.19

SAMP.	5/63N	5/64	5/92B	5/93	5/95	RC-72	RC-82B	RC-120	RC-129	RC-131
GROUP	3	3	3	3	3	4	4	4	4	4
SiO_2	76.00	71.30	69.80	74.40	75.90	72.10	76.90	76.40	72.00	74.90
TiO_2	0.40	0.44	0.44	0.40	0.48	0.42	0.38	0.35	0.35	0.40
Al_2O_3	11.00	11.00	12.00	11.30	12.10	13.10	11.40	12.10	12.00	10.90
Fe_2O_3	4.22	6.18	5.82	4.64	3.22	3.90	4.52	4.40	5.34	5.74
FeO	-	-	-	-	-	-	-	-	-	-
MnO	0.04	0.10	0.12	0.12	0.07	0.04	0.03	0.04	0.07	0.07
MgO	0.42	1.24	1.19	0.85	0.29	0.44	0.65	0.33	0.49	0.33
CaO	0.04	0.54	1.00	1.26	0.34	0.08	0.04	0.10	0.12	0.06
Na_2O	0.09	1.79	2.08	2.13	0.70	0.14	0.08	0.07	1.77	0.10
K_2O	3.84	5.04	4.85	4.39	5.59	8.74	4.02	3.91	5.37	3.70
P_2O_5	0.08	0.08	0.08	0.07	0.05	0.08	0.07	0.08	0.09	0.08
LOI	2.06	0.96	0.99	0.96	1.43	1.03	1.81	2.10	0.86	1.89
TOTAL	98.19	98.67	98.37	100.52	100.17	100.07	99.90	99.88	98.46	98.17
Rb	206	169	255	208	234	357	243	267	212	245
Sr	9	33	46	31	34	26	30	13	18	15
Y	93	124	94	88	113	87	92	97	93	69
Nb	36	35	37	33	35	33	35	36	36	36
Ga	21	20	28	20	22	23	25	29	21	25
Zr	731	800	814	762	755	766	699	754	760	801
Ba	475	732	685	704	741	1123	613	492	713	405
Rb/Sr	23	5	6	7	7	14	8	21	12	16
K/Rb	155	248	158	175	198	203	137	122	210	125
K/Ba	67	57	59	52	63	65	54	66	63	76

CIPW Norms

Q	57.86	35.10	31.95	38.67	47.65	35.01	57.56	57.97	37.21	56.33
C	6.81	1.81	1.70	0.92	4.40	3.46	7.01	7.76	3.27	6.81
Or	22.70	29.79	28.67	25.95	33.04	51.66	23.76	23.11	31.74	21.87
Ab	0.76	15.14	17.60	18.02	5.92	1.18	0.68	0.59	14.98	0.85
An	-	2.16	4.44	5.79	1.36	-	-	-	0.01	-
Ac	-	-	-	-	-	-	-	-	-	-
Di	-	-	-	-	-	-	-	-	-	-
Hy	6.39	11.24	10.64	8.19	4.59	5.96	7.38	6.48	8.26	8.35
Mt	0.61	0.90	0.84	0.67	0.47	0.57	0.65	0.64	0.77	0.83
Il	0.76	0.84	0.84	0.76	0.91	0.80	0.72	0.66	0.66	0.76
Ap	0.19	0.19	0.19	0.17	0.12	0.19	0.17	0.19	0.21	0.19

SAMP.	5/6	5/28	5/31	5/57	5/58	5/63S	5/91	5/92A	5/94
GROUP	4	4	4	4	4	4	4	4	4
SiO_2	73.60	77.60	75.80	73.30	75.80	75.70	77.00	74.70	70.30
TiO_2	0.48	0.40	0.44	0.44	0.36	0.40	0.40	0.40	0.44
Al_2O_3	12.40	11.50	11.70	11.90	11.80	11.40	11.30	11.60	11.80
Fe_2O_3	4.61	2.65	3.78	4.25	4.06	4.24	3.64	0.52	1.06
FeO	-	-	-	-	-	-	-	2.88	4.66
MnO	0.05	0.02	0.05	0.04	0.05	0.04	0.04	0.05	0.08
MgO	0.45	0.43	0.57	0.39	0.58	0.31	0.23	0.44	0.76
CaO	0.04	0.02	0.20	0.04	0.12	0.04	0.06	0.12	0.14
Na_2O	0.10	0.09	0.94	0.07	0.14	0.10	0.07	0.17	0.26
K_2O	6.18	3.84	5.47	5.02	5.82	5.80	5.12	7.68	6.60
P_2O_5	0.06	0.03	0.07	0.10	0.06	0.06	0.06	0.06	0.09
LOI	1.58	1.92	1.05	1.65	1.30	1.67	1.53	1.46	2.03
TOTAL	99.55	98.50	100.07	97.20	100.09	99.76	99.45	100.08	98.22
Rb	293	268	222	253	280	243	197	328	282
Sr	25	13	20	22	13	19	17	21	26
Y	93	79	95	97	92	106	85	88	93
Nb	36	34	34	35	33	32	31	34	37
Ga	27	27	27	25	25	18	24	24	23
Zr	760	689	744	762	732	740	735	741	762
Ba	712	380	767	666	730	910	709	775	744
Rb/Sr	12	21	11	12	22	13	12	16	11
K/Rb	175	119	205	165	173	198	216	194	194
K/Ba	72	84	59	63	66	53	60	82	74

CIPW Norms

Q	46.15	60.37	46.18	50.87	49.39	50.10	54.63	41.45	38.62
C	5.62	7.23	4.04	6.52	5.20	5.03	5.68	2.93	4.19
Or	36.53	22.70	32.33	29.67	34.40	34.28	30.26	45.39	39.01
Ab	0.85	0.76	7.95	0.59	1.18	0.85	0.59	1.44	2.20
An	-	-	0.53	-	0.20	-	-	0.20	0.11
Ac	-	-	-	-	-	-	-	-	-
Di	-	-	-	-	-	-	-	-	-
Hy	6.88	4.16	6.11	6.30	6.64	6.13	5.09	5.76	10.07
Mt	0.67	0.38	0.55	0.62	0.59	0.61	0.53	0.54	0.90
Il	0.91	0.76	0.84	0.84	0.68	0.76	0.76	0.76	0.84
Ap	0.14	0.07	0.17	0.24	0.14	0.14	0.14	0.14	0.21

Table 5.2 Rare-earth element analyses

Sample #	5/15	5/47	5/48	5/50	5/86	GBKE	NTS	RC-21	RC-30	RC-33
Group #	1	1	1	1	1	1	1	2	2a	2a
La	143.7	153.8	153.2	117.5	169.8	129.0	201.6	102.2	113.9	122.9
Ce	217.7	398.3	292.0	205 8	285.2	249.5	317.7	221.7	225.9	250.4
Pr	28.9	28.5	27.6	23.7	35.7	24.3	34.0	24.1	23.1	28.3
Nd	88.7	88.1	92.7	81.5	117.8	74.6	113.2	84.8	84.6	94.4
Sm	19.6	19.8	20.2	19.3	25.0	14.8	20.6	17.0	17.0	18.4
Eu	-	-	0.2	-	-	-	-	0.8	1.4	0.8
Gd	15.2	15.4	17.2	20.2	25.7	13.9	16.8	14.8	15.2	17.4
Dy	39.0	29.5	18.6	23.7	28.1	13.5	14.2	17.1	15.2	17.2
Er	14.1	19.7	12.4	16.7	17.5	10.3	9.1	11.6	9.7	11.1
Yb	13.3	9.5	10.8	15.2	14.3	9.1	8.3	10.3	9.3	10.3

Sample #	RC-43B	RC-96	RC-105	RC-107	RC-117	RC-119	RC-126	RC-133	RC-146	5/16
Group #	2	2	2a	2	2	2	2	2	2	2
La	105.0	110.0	134.7	112.4	132.0	94.6	107.5	115.9	105.6	123.1
Ce	212.4	229.3	242.7	219.3	252.0	191.4	213.4	227.9	219.8	245.0
Pr	24.4	23.5	27.5	23.6	26.8	21.7	21.5	24.1	24.1	24.7
Nd	84.2	83.8	101.8	83.8	97.8	75.8	77.7	86.4	84.4	89.8
Sm	16.5	17.5	20.6	17.5	19.9	14.3	16.2	18.1	17.8	19.4
Eu	1.1	1.4	2.0	1.0	0.6	1.4	1.0	1.0	1.8	1.7
Gd	17.0	16.0	18.7	16.5	17.7	15.0	14.9	15.3	17.1	16.2
Dy	15.4	16.7	18.9	15.3	17.2	15.0	31.3	29.4	33.2	-
Er	10.8	10.0	12.6	10.5	10.7	9.6	9.6	9.6	10.7	10.2
Yb	9.5	9.0	10.5	8.6	9.3	8.8	9.3	8.3	10.2	10.0

Sample #	5/40	5/43	5/44	5/55	5/59A	5/60B	5/63N	5/93	5/95	5/6
Group #	3	3	3	3	3	3	3	3	3	4
La	130.6	118.7	105.9	144.1	120.6	110.8	115.9	75.8	164.9	131.5
Ce	252.5	232.9	210.3	278.8	239.0	223.4	201.9	151.4	323.0	241.8
Pr	27.5	25.0	23.5	29.1	24.1	23.4	24.5	15.9	32.3	27.4
Nd	93.6	84.8	81.3	104.2	89.4	81.3	82.1	58.3	120.5	94.5
Sm	19.7	16.8	16.8	22.1	17.3	17.6	18.1	13.1	25.8	18.3
Eu	1.1	0.4	0.9	1.6	1.2	1.6	1.1	1.2	1.5	0.7
Gd	15.7	13.6	14.0	16.7	16.3	16.0	16.3	13.3	21.5	13.3
Dy	-	20.3	12.4	15.6	16.4	16.8	12.9	14.3	17.3	19.4
Er	6.3	7.9	6.7	9.6	11.0	9.7	6.2	9.5	10.4	6.5
Yb	7.0	7.5	6.8	8.1	7.0	8.4	6.0	8.0	8.8	7.2

Sample	5/31	5/58	5/63S	5/91	5/92A	5/94
Group	4	4	4	4	4	4
La	78.6	99.0	136.1	101.7	104.3	139.2
Ce	156.1	205.7	216.9	211.2	214.6	268.0
Pr	16.9	22.9	28.8	21.3	21.6	27.8
Nd	58.4	77.2	107.4	77.5	77.9	99.5
Sm	12.6	16.4	22.0	14.7	15.1	21.2
Eu	1.4	1.6	1.8	1.7	1.0	1.4
Gd	11.4	15.6	18.8	13.9	14.0	16.2
Dy	25.7	16.6	13.4	nd	13.0	12.7
Er	8.7	9.2	7.9	7.9	7.0	7.5
Yb	8.5	8.0	6.3	7.2	6.6	6.7

Table 5.3 The ranges and averages of major and trace element abundances

	Inner Marginal Assemblage		Kanye Volcanics and Feldspar Porphyry		Nnywane Formation	
	Range	Mean	Range	Mean	Range	Mean
SiO_2	75.90 - 78.40	77.04 ± 0.88	70.60 - 73.00	72.10 ± 0.72	69.80 - 84.30	74.40 ± 2.70
TiO_2	0.08 - 0.24	0.14 ± 0.04	0.30 - 0.56	0.46 ± 0.06	0.35 - 0.56	0.41 ± 0.06
Al_2O_3	10.50 - 11.40	11.11 ± 0.25	11.60 - 12.30	12.00 ± 0.16	9.44 - 13.50	11.70 ± 0.70
Fe_2O_3	1.47 - 2.03	1.68 ± 0.22	3.72 - 5.10	4.56 ± 0.27	0.28 - 6.23	4.51 ± 0.89
MnO	0.00 - 0.03	0.01 ± 0.01	0.03 - 0.14	0.07 ± 0.02	0.00 - 0.14	0.06 ± 0.03
MgO	0.08 - 0.52	0.22 ± 0.13	0.21 - 1.12	0.42 ± 0.21	0.03 - 1.24	0.56 ± 0.24
CaO	0.10 - 0.54	0.27 ± 0.14	0.26 - 1.30	0.83 ± 0.24	0.02 - 1.76	0.32 ± 0.40
Na_2O	2.61 - 3.27	2.95 ± 0.19	2.22 - 4.18	3.55 ± 0.39	0.07 - 3.77	1.07 ± 1.17
K_2O	5.00 - 5.73	5.35 ± 0.26	3.73 - 5.51	4.98 ± 0.36	2.64 - 8.74	5.11 ± 1.42
P_2O_5	0.00 - 0.03	0.01 ± 0.01	0.01 - 0.14	0.08 ± 0.02	0.00 - 0.29	0.08 ± 0.04
LOI	0.44 - 1.05	0.64 ± 0.20	0.04 - 1.27	0.49 ± 0.27	0.56 - 2.10	1.25 ± 0.50
Rb	283 - 515	429 ± 67	115 - 325	215 ± 39	108 - 357	232 ± 56
Sr	4 - 37	16 ± 12	19 - 85	34 ± 7	6 - 50	27 ± 12
Y	90 - 184	133 ± 30	85 - 126	103 ± 8	65 - 137	96 ± 13
Nb	40 - 116	70 + 23	32 - 39	36 + 1	29 - 39	34 + 2
Ga	18 - 29	22 ± 4	19 - 27	23 ± 2	12 - 29	22 ± 5
Zr	237 - 421	326 ± 65	720 - 794	761 ± 15	642 - 821	748 ± 38
Ba	7 - 428	140 ± 142	437 - 800	642 ± 72	120 - 1123	678 ± 184

A frequency distribution plot of SiO_2 contents is shown in Figure 5.1. Note that in the histogram, SiO_2 analyses of the porphyritic granophyres and the Kanye Volcanics are combined. The reasons for this are discussed later. Figure 5.1 shows that the Kanye Volcanics (including the granophyres) and the microgranite are characterised by distinct and fairly restricted SiO_2 compositions. The microgranite has higher SiO_2 values (75.9% to 78.4%) relative to the Kanye Volcanics and granophyres which range from 70.6% to 73.1%. In contrast, SiO_2 analyses of the Nnywane Formation show considerable variation, ranging from 69.8% to 84.3%.

Plots of major and trace elements against SiO_2 are shown in Figure 5.2 and 5.3, respectively. Major and trace element analyses in Table 5.1 are divided into three main groups: (1) the microgranite, (2) the Kanye Volcanics and the porphyritic granophyres and (3) the Nnywane Formation, which is further subdivided into rhyolites and tuffs. As plots of major and trace element analyses and Table 5.3 show, there are significant compositional differences among these groups. These differences and compositional variations are the subject of the succeeding discussions.

5.2 Micrograntes

Ten samples from the microgranite were analysed in this study. Of these, three are from outside the study area (Fig. 3.1): 5/86, GBKE and NTS (see Table 5.1). Sample 5/86 is from Tshele Hill, west of Mochudi (Fig. 1.1), while GBKE and NTS are from the University of Botswana collection.

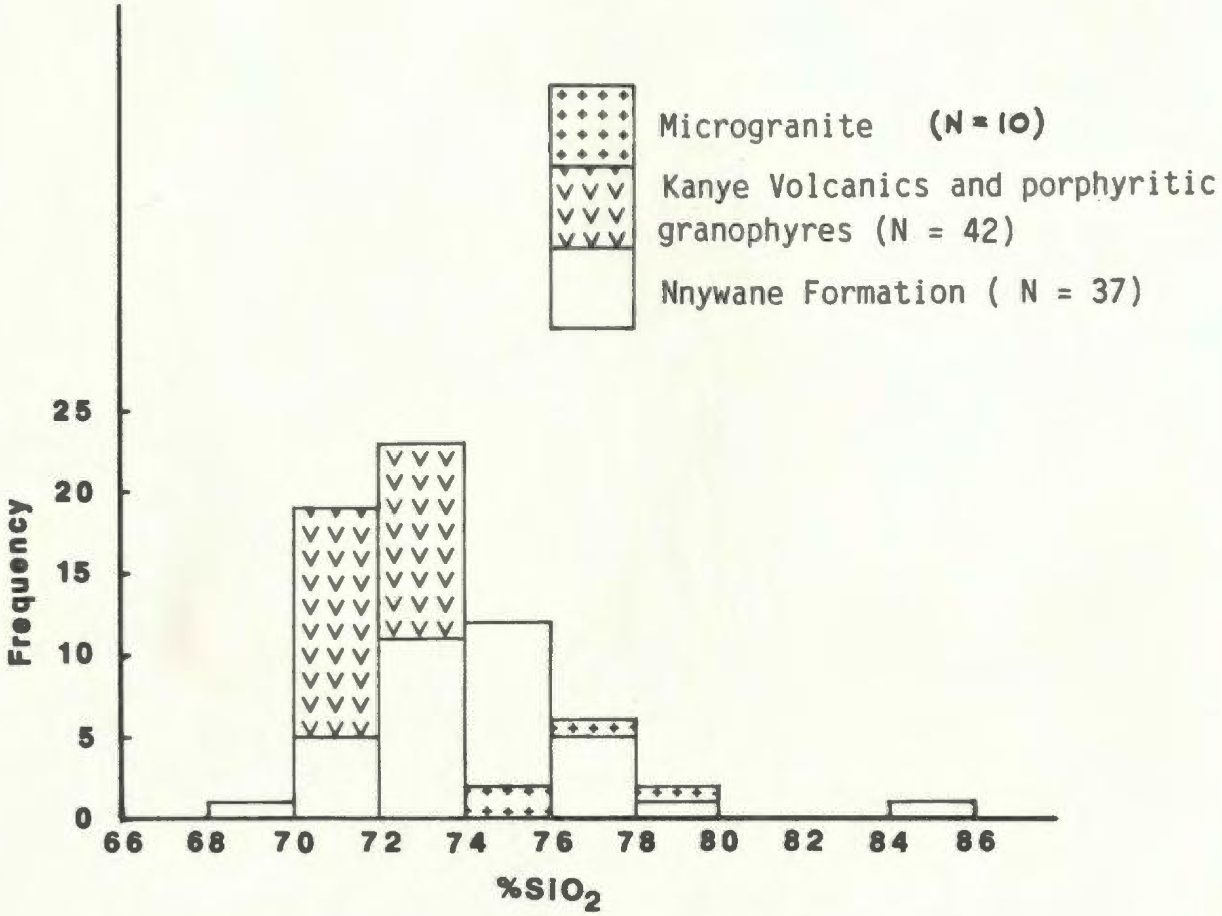
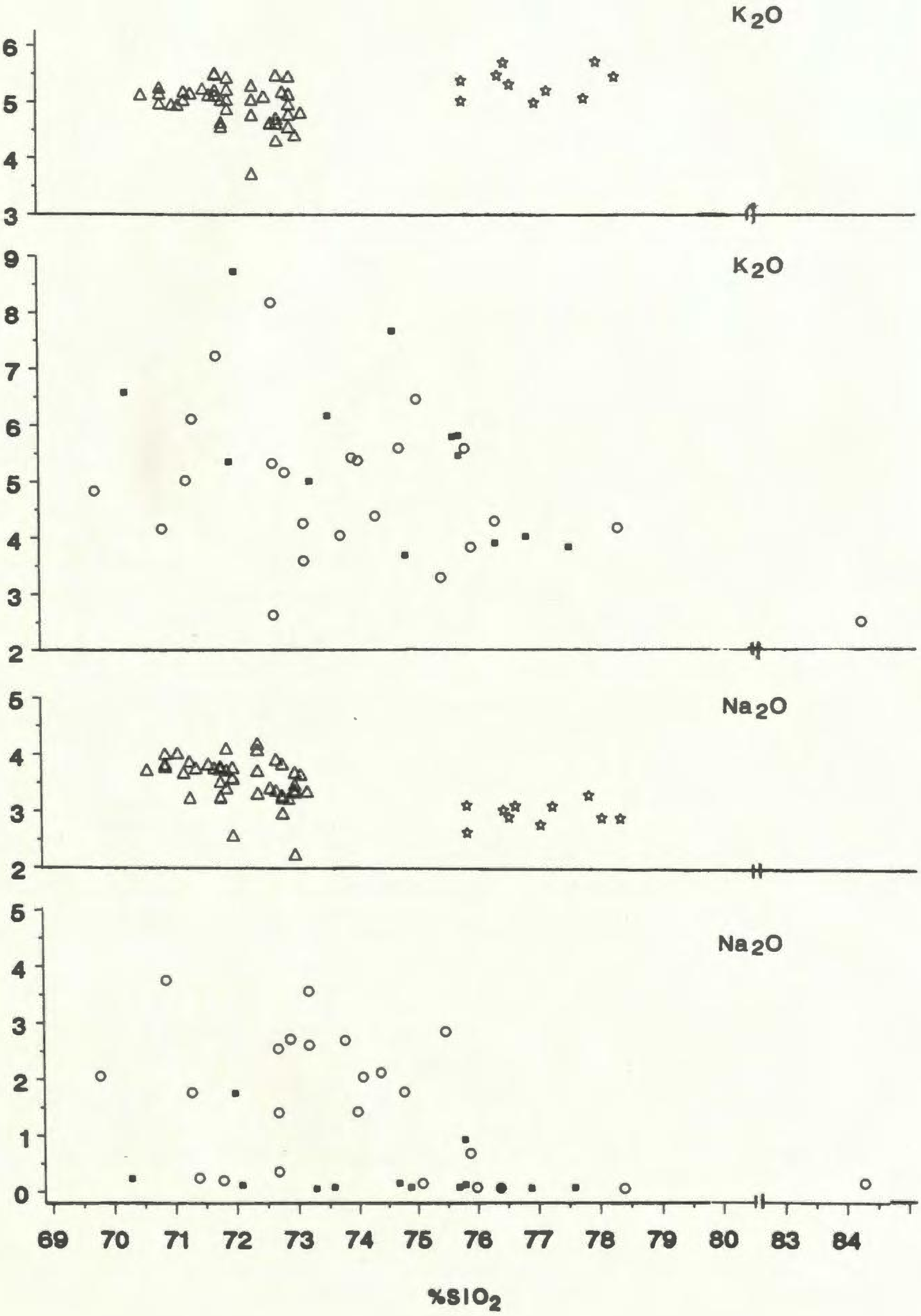
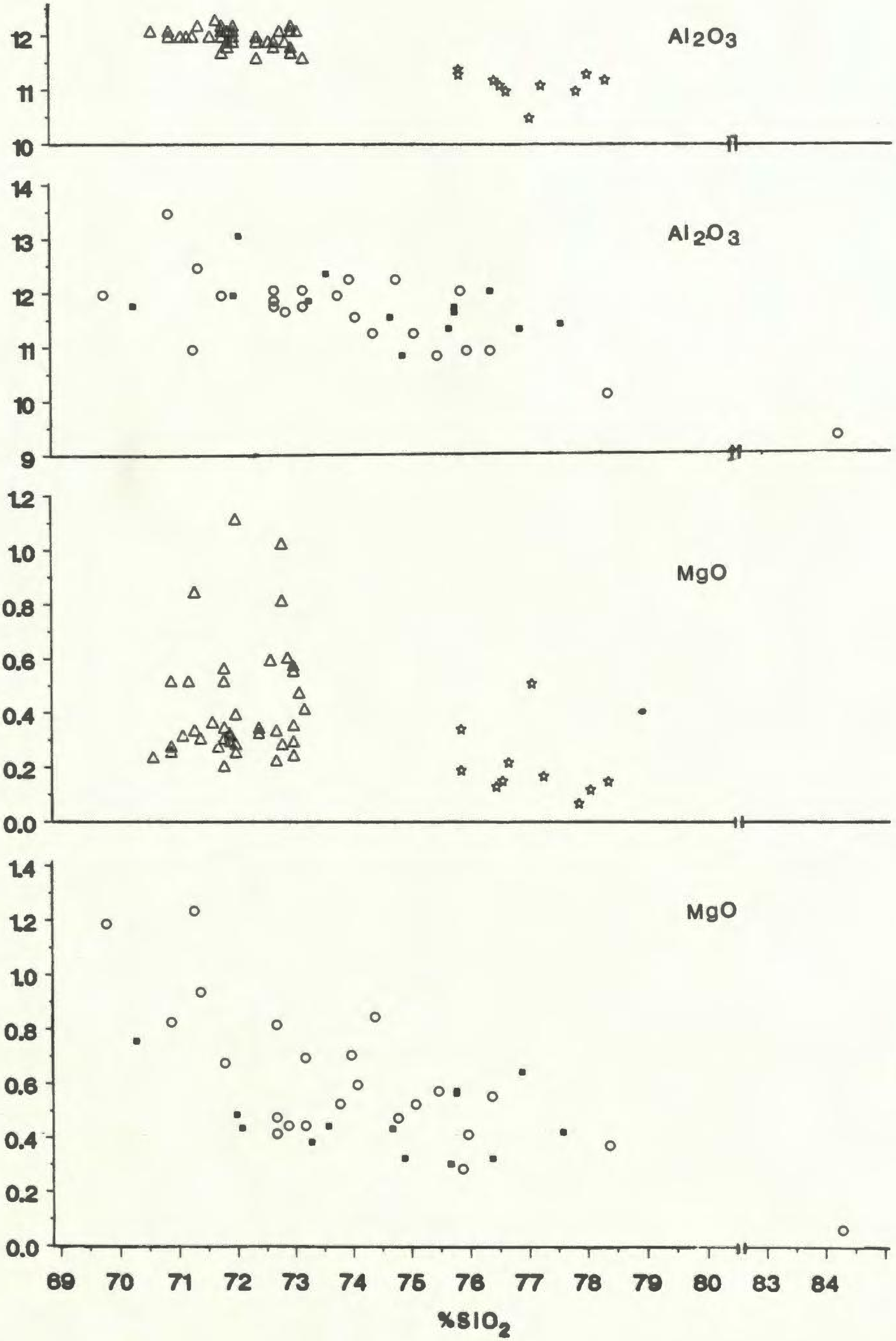
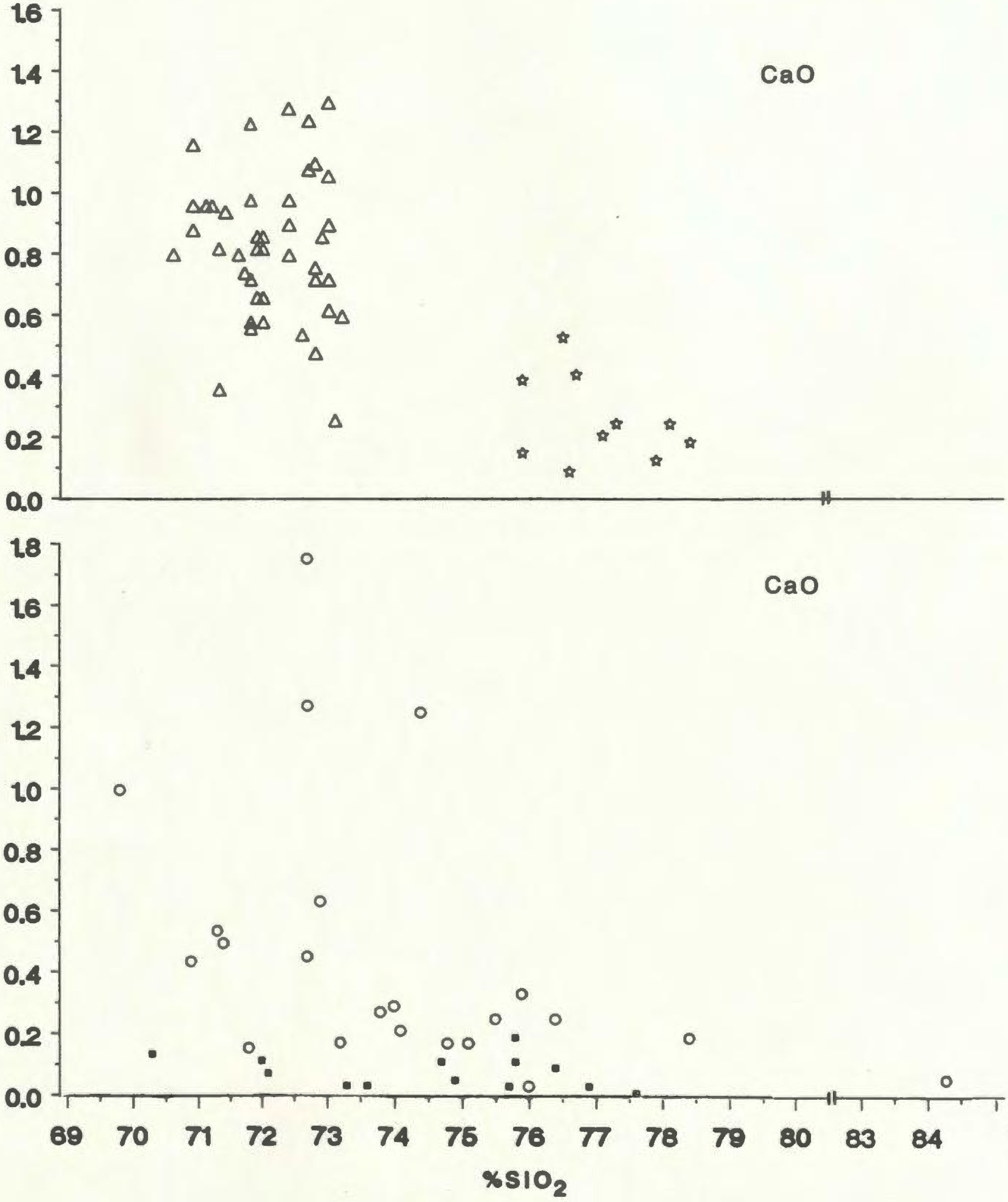


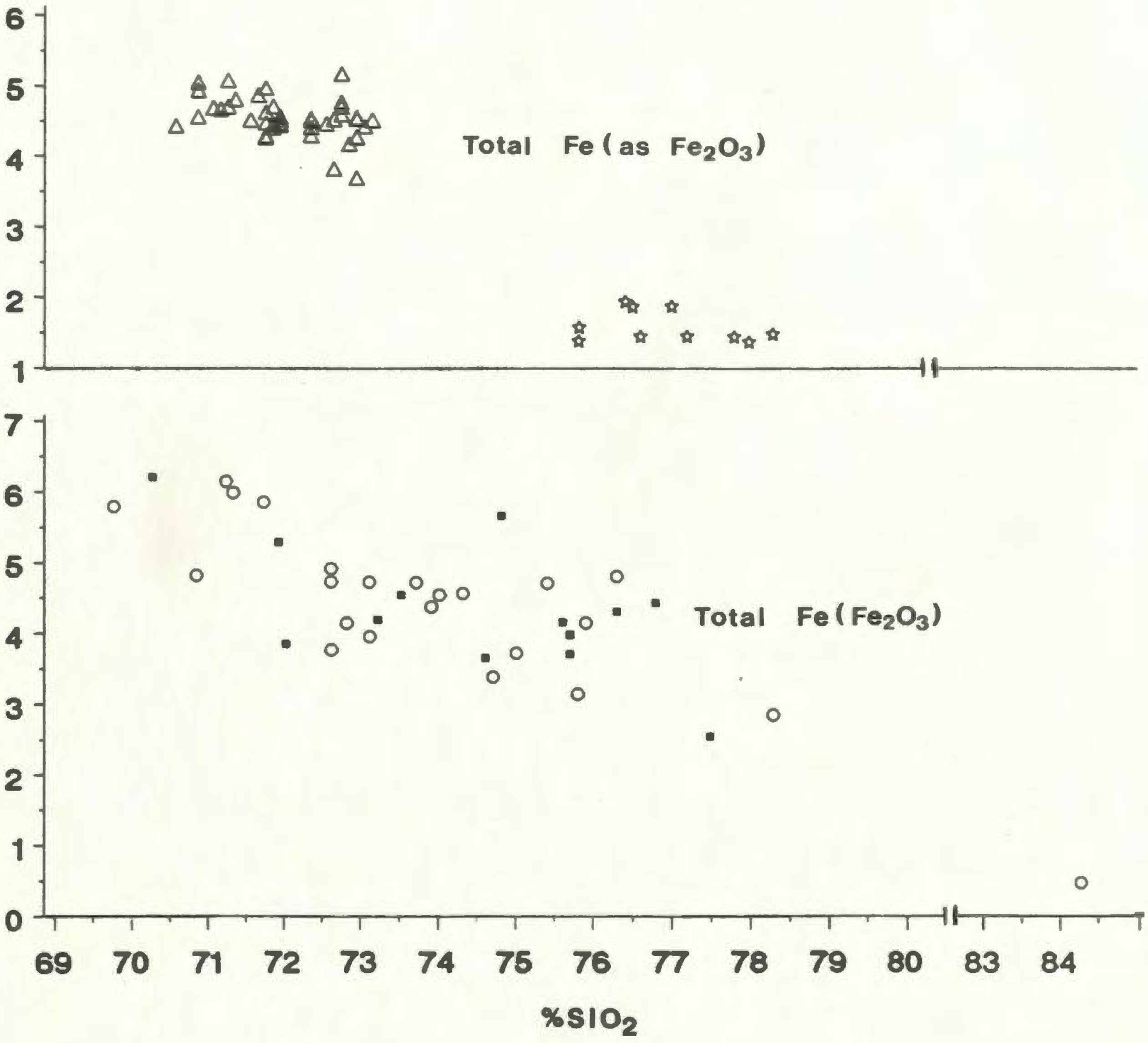
Figure 5.1 Frequency distribution plot of SIO_2 analyses

Figure 5.2 Major elements versus SiO_2 plots for the microgranite (☆), Kanye Volcanics and porphyritic granophyres (Δ), Nnywane Formation: tuffs (•) and rhyolites (∘).


K$_2$O
6
5
4
3
9
8
7
6
5
4
3
2
K$_2$O
5
4
3
2
Na$_2$O
5
4
3
2
1
0
Na$_2$O
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SiO$_2$


Al2O3
12
11
10
Al2O3
14
13
12
11
10
9
MgO
1.2
1.0
0.8
0.6
0.4
0.2
0.0
MgO
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SiO2


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
CaO
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
CaO
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SiO$_2$



6
5
4
3
2
1
Total Fe (as Fe_2O_3)
7
6
5
4
3
2
1
0
Total Fe (Fe_2O_3)
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO$_2$

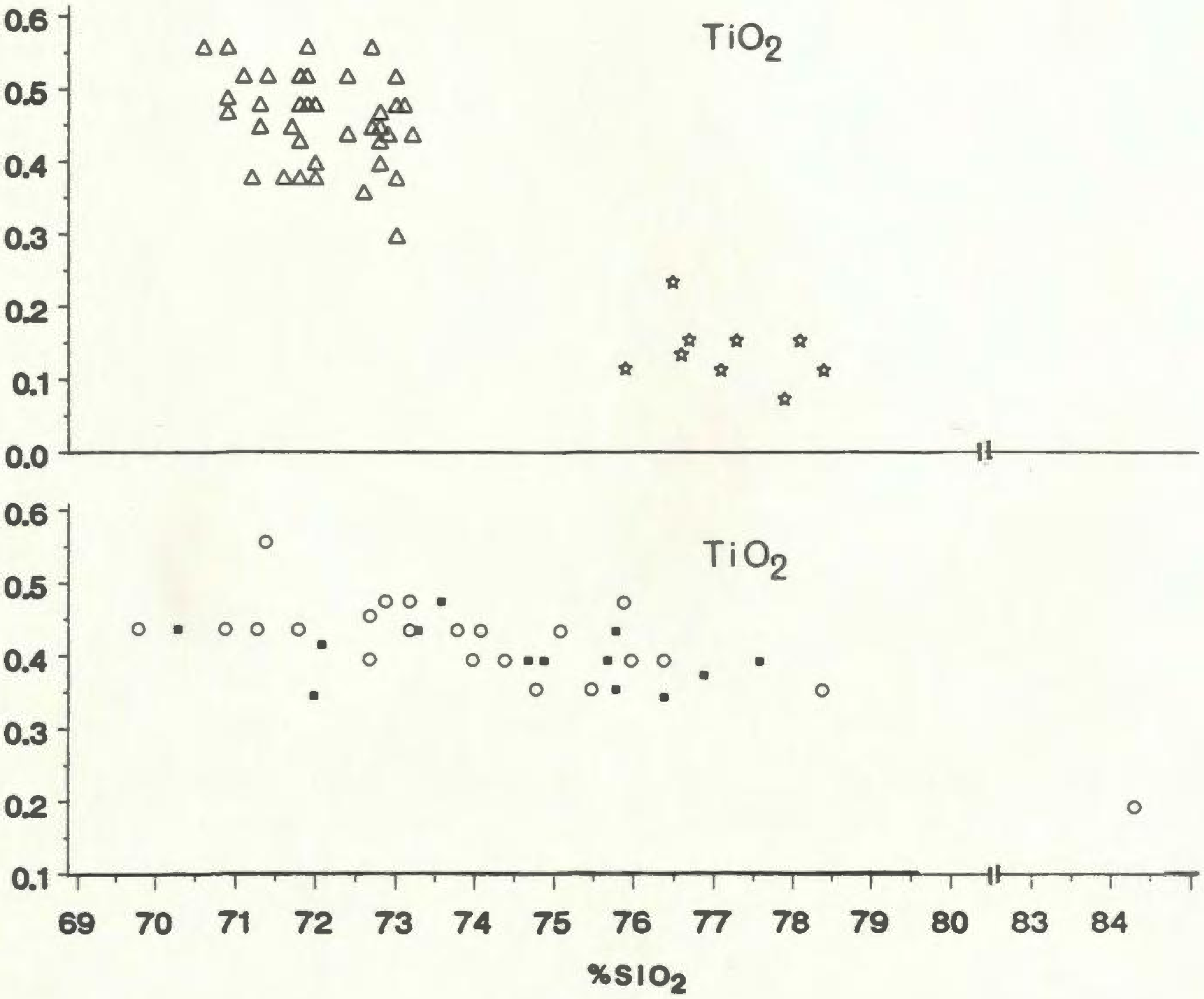
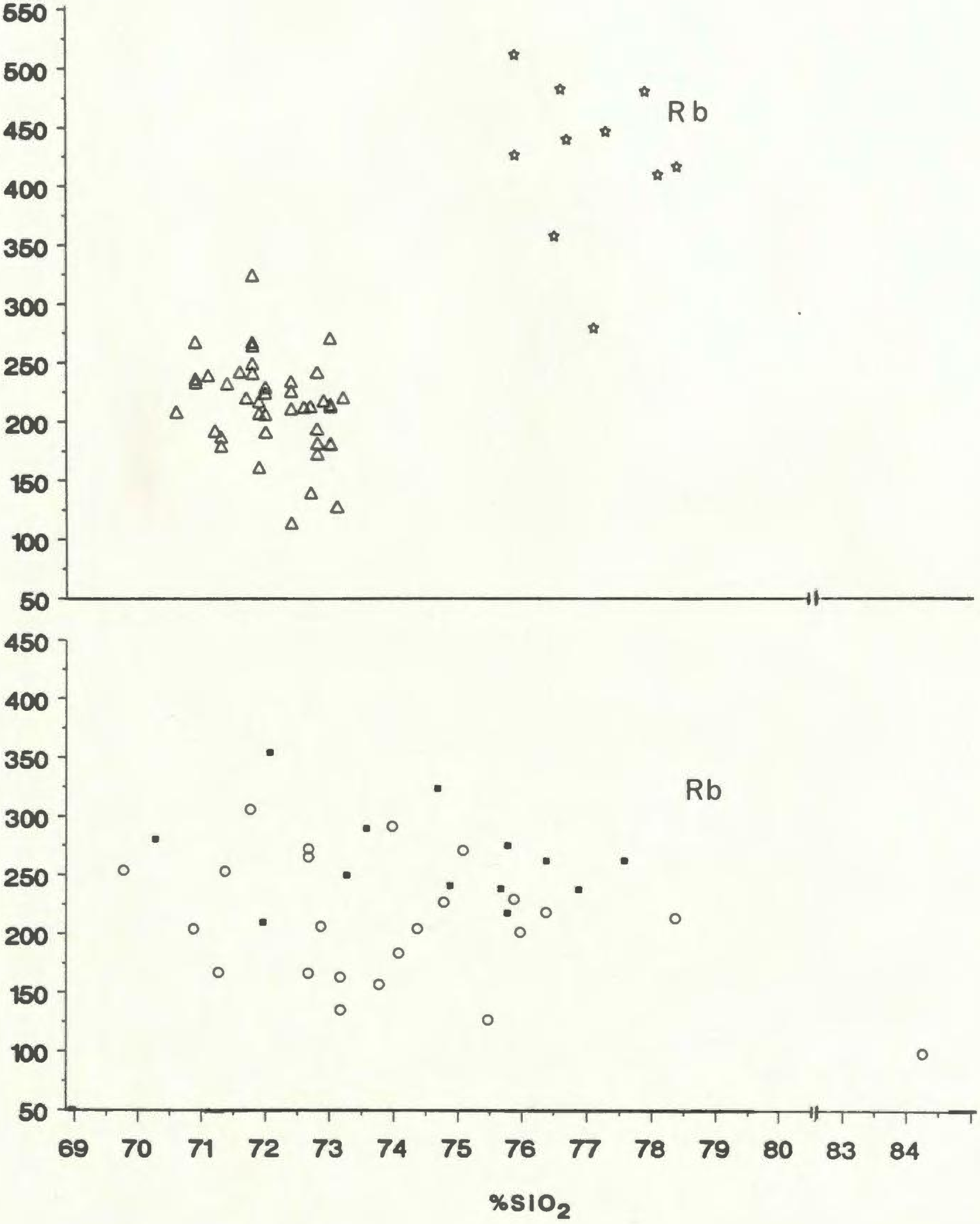
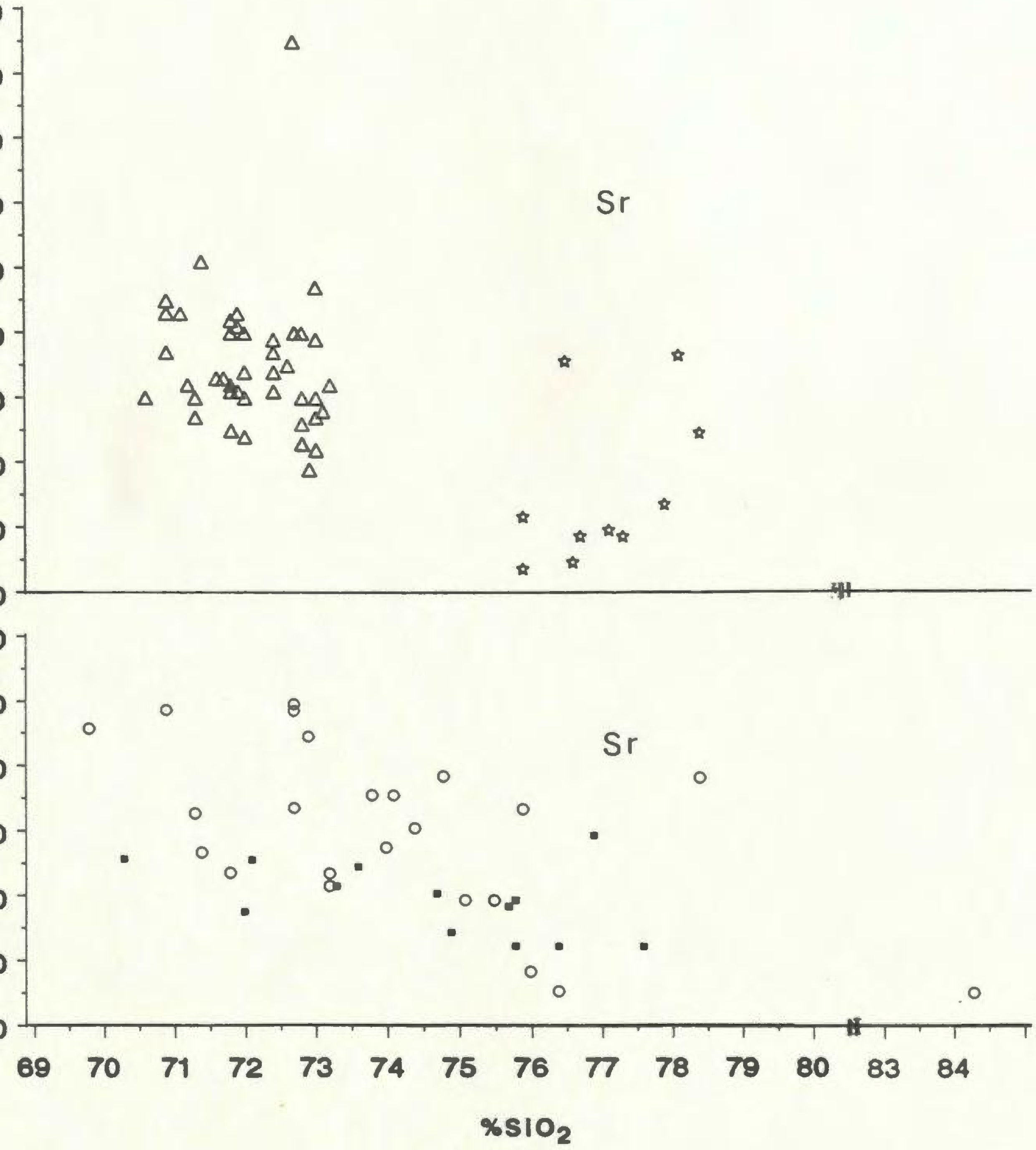
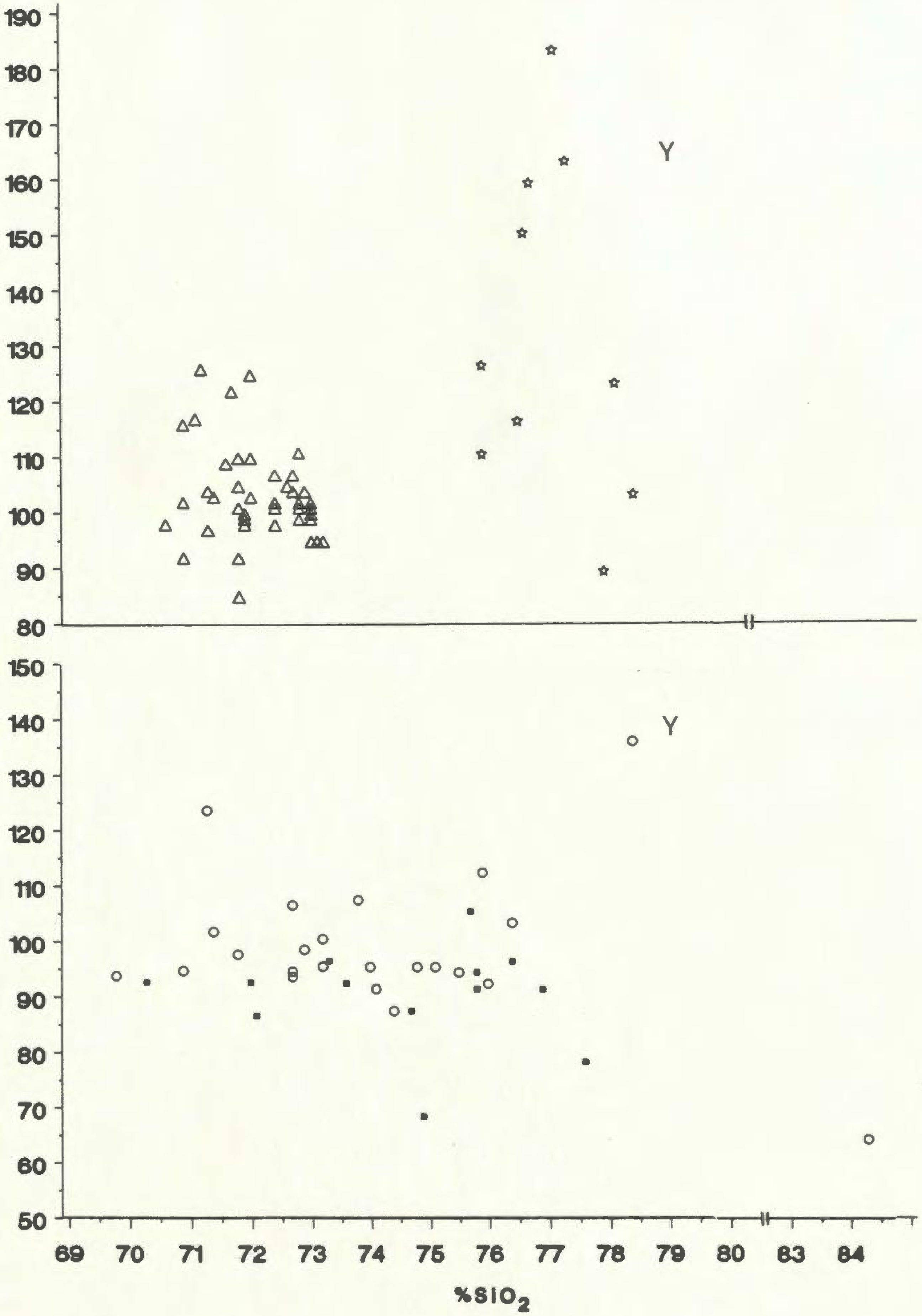
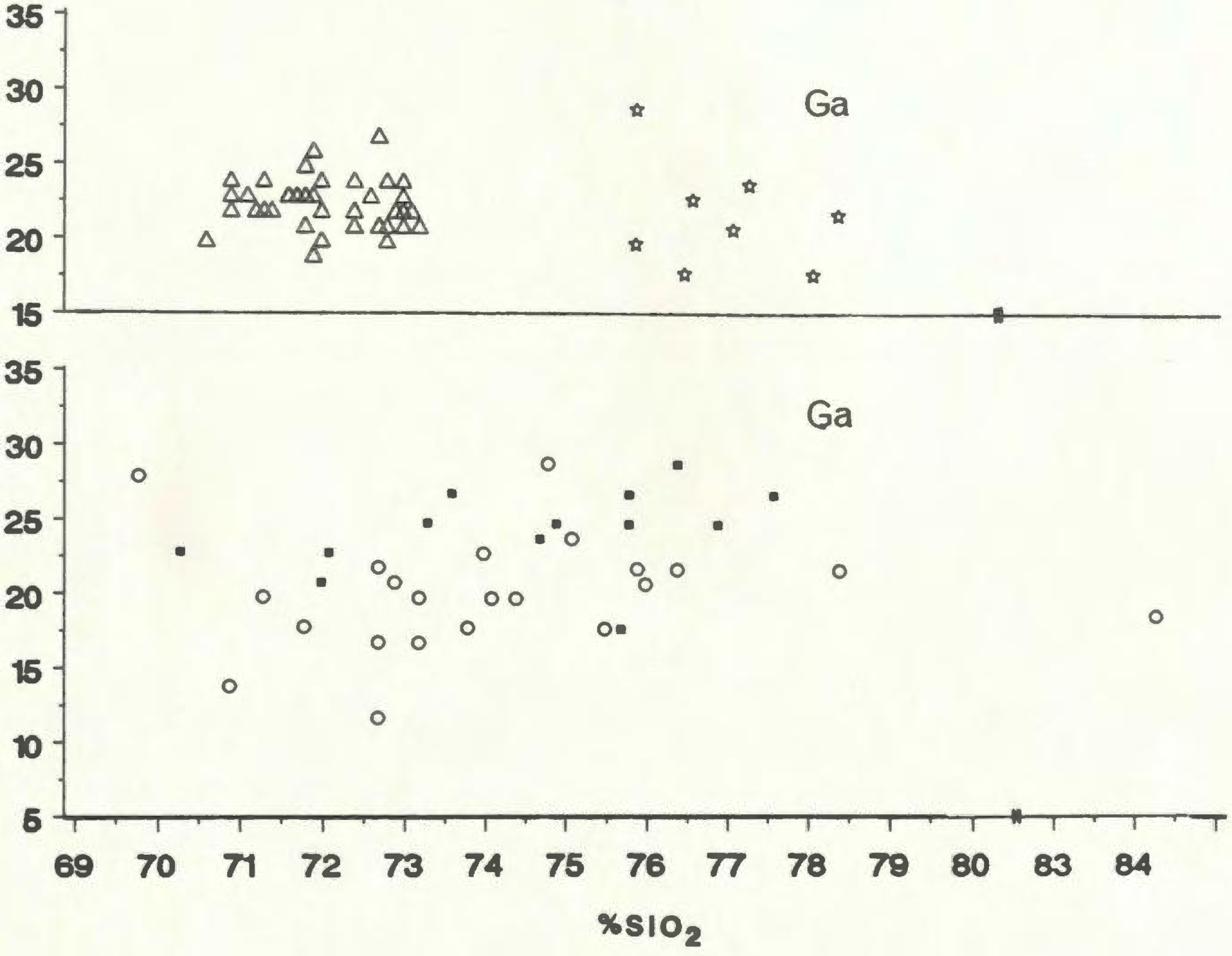

TiO2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
TiO2
0.6
0.5
0.4
0.3
0.2
0.1
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO2

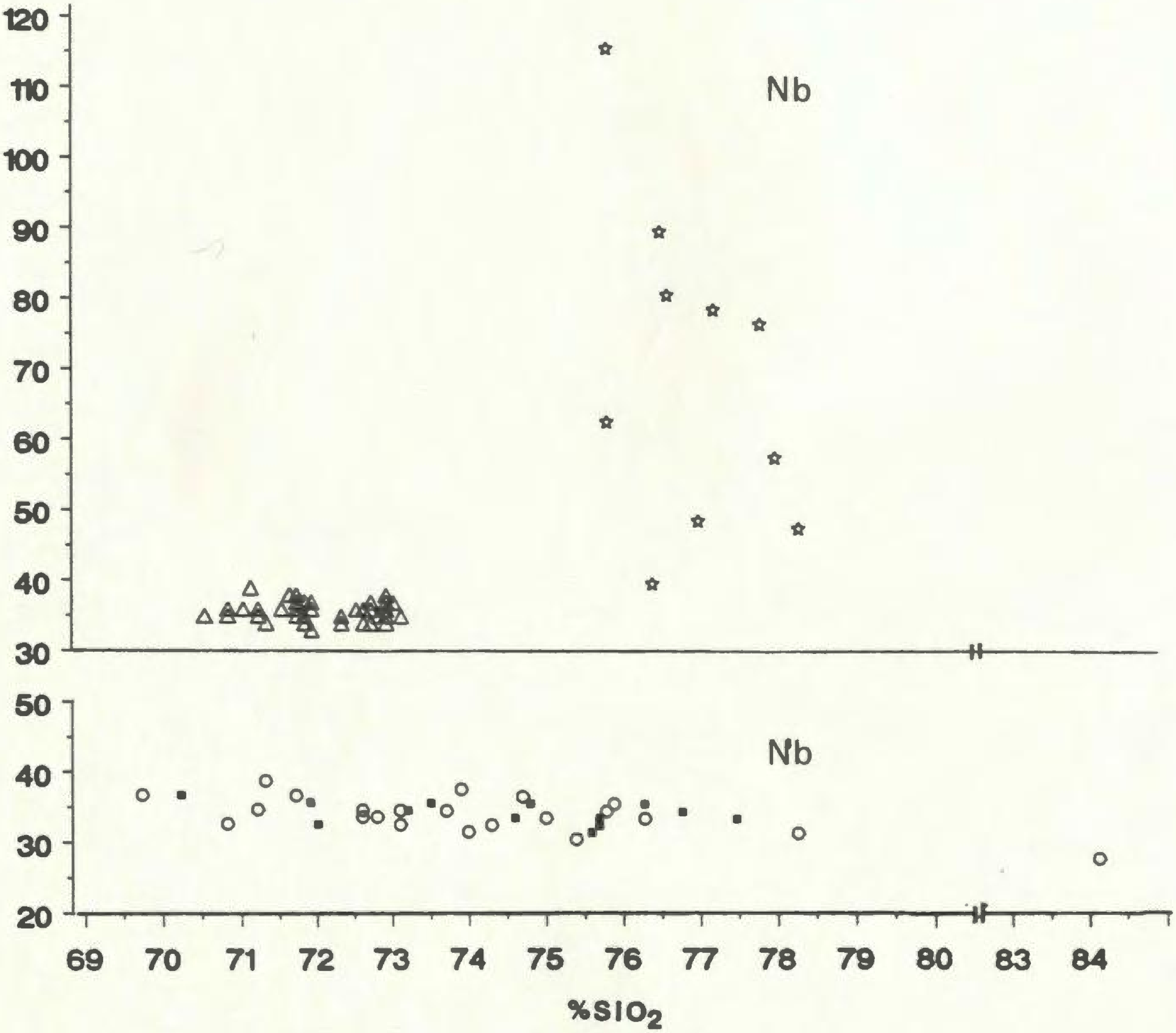
Figure 5.3 Trace elements versus SiO_2. The symbols are as in Figure 5.2.

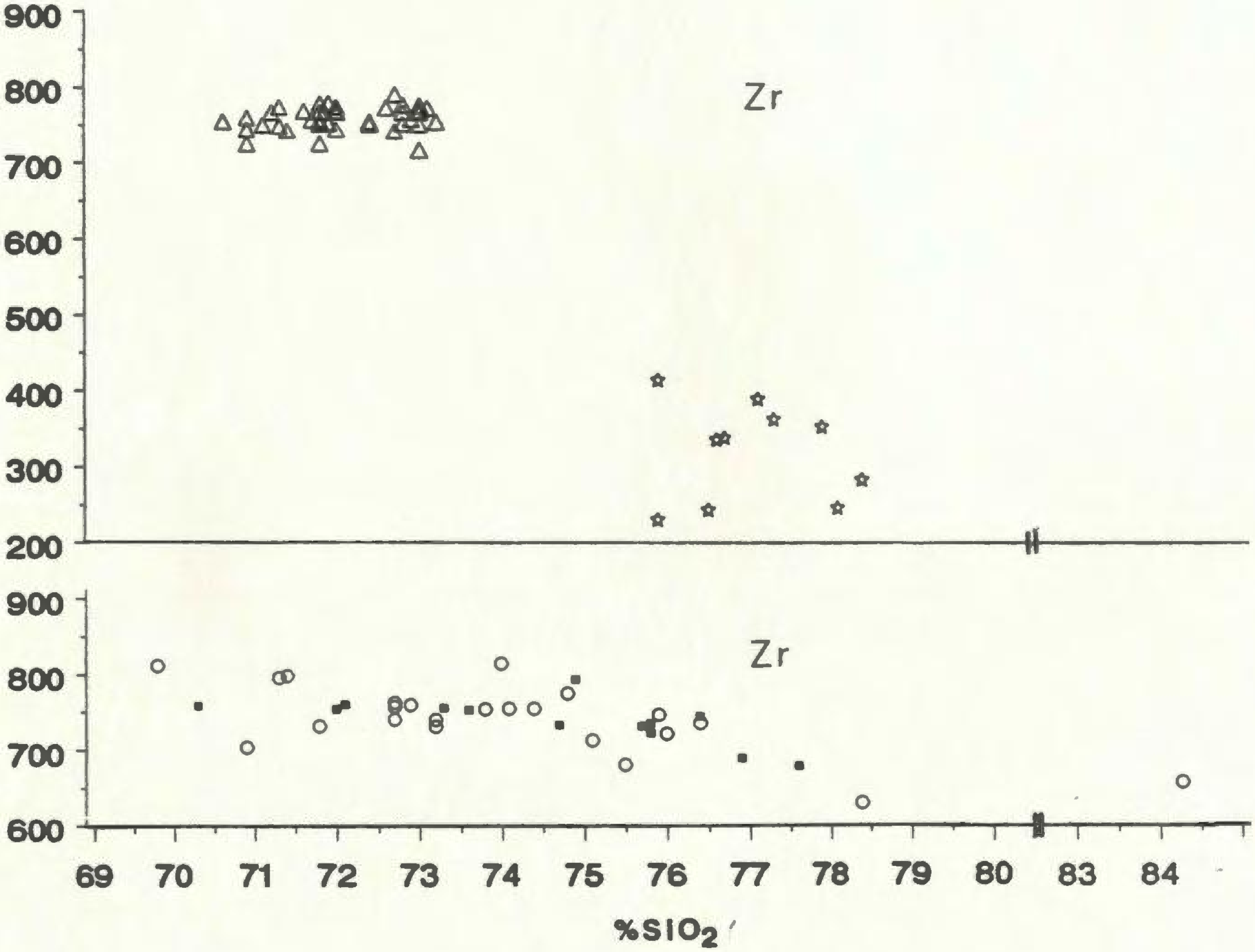

550
500
450
400
350
300
250
200
150
100
50
Rb
450
400
350
300
250
200
150
100
50
Rb
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO2

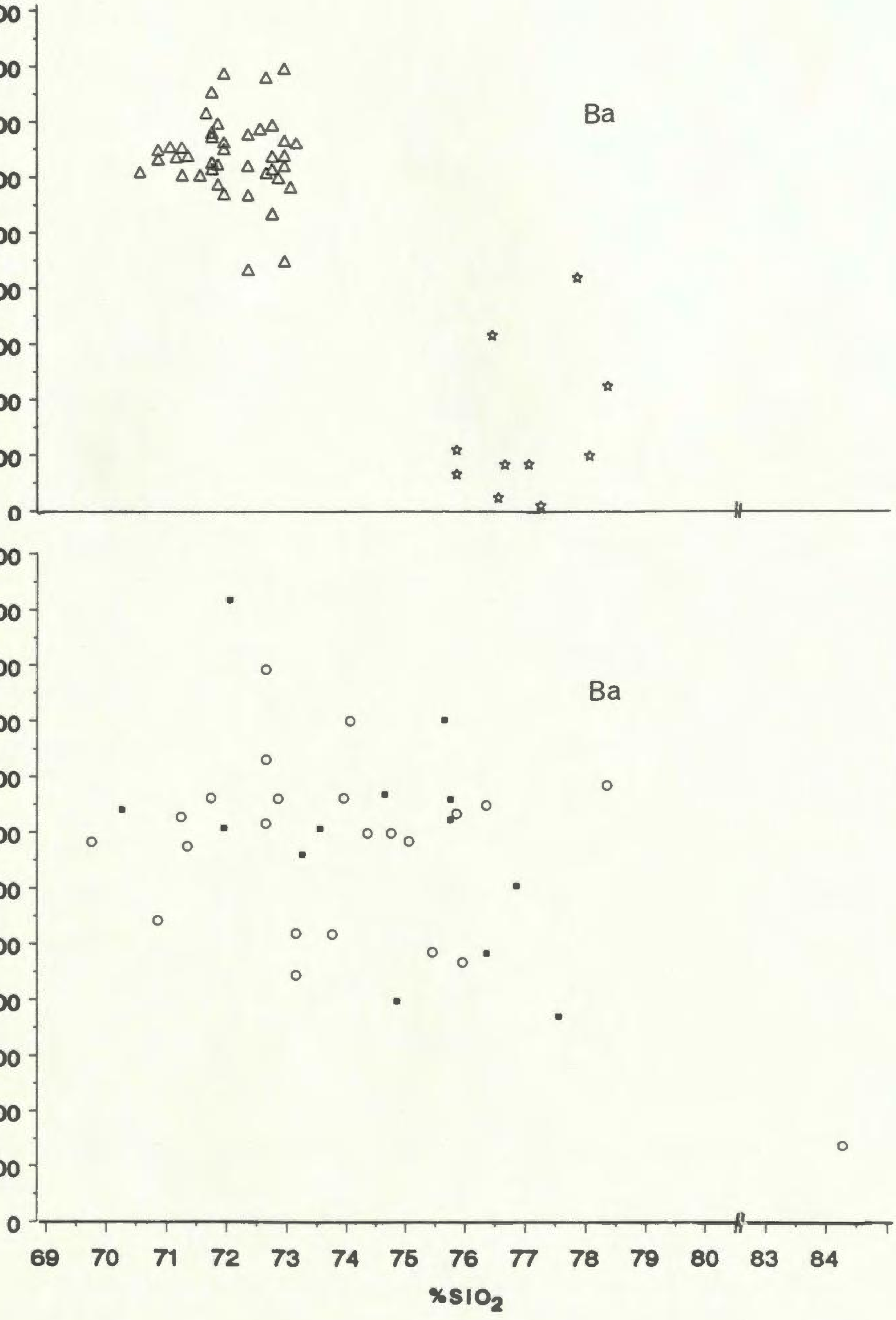

90
80
70
60
50
40
30
20
10
0
Sr
60
50
40
30
20
10
0
Sr
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO$_2$


Y
190
180
170
160
150
140
130
120
110
100
90
80
Y
150
140
130
120
110
100
90
80
70
60
50
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SiO$_2$


35
30
25
20
15
Ga
35
30
25
20
15
10
5
Ga
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO2


Nb
Nb
120
110
100
90
80
70
60
50
40
30
50
40
30
20
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO$_2$


900
800
700
600
500
400
300
200
Zr
900
800
700
600
Zr
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO2


900
800
700
600
500
400
300
200
100
0
Ba
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Ba
69
70
71
72
73
74
75
76
77
78
79
80
83
84
%SIO2

The microgranite has a very small range of TiO_2, Al_2O_3, Na_2O, K_2O and total iron concentrations (see Table 5.3 and Fig. 5.2). MgO and CaO are more variable than the other oxides (see Fig. 5.2). K_2O/Na_2O ratios range from 1 to 2.

In chapter 4 (p. 57) it was reported that the microgranite consists mainly of quartz, microperthite and variable amounts of chequer-board albite which occurs only in altered samples. The origin of chequer-board albite was attributed to exsolution of originally homogeneous alkali feldspars. Besides petrographic evidence, this interpretation is also supported by the distribution of Na_2O in the microgranite samples. There is no correlation between the amount of chequer-board albite and Na_2O in each sample of microgranite. In fact, samples with high amounts of chequer-board albite, such as, 5/48 and 5/50 (Table 5.1) have relatively the same amount of Na_2O as those that have very little or no chequer-board albite.

Chemically, the microgranite varies from metaluminous to peraluminous. A ternary plot of normative Qz, Ab and Or compositions is shown in Figure 5.4. These rocks occupy a well defined field close to the low pressure granite minimum melting point.

Unlike the major elements, trace element abundances of the microgranite show a lot of variation, especially Sr, Y, Nb and Ba (Fig. 5.3). These elements have very high standard deviations (Table 5.3). They do not, however, show any correlation with SiO_2, although this may be difficult to see due to the narrow range of SiO_2 compositions (Fig. 5.2).

Rb/Sr and K/Ba ratios of the microgranite vary considerably,

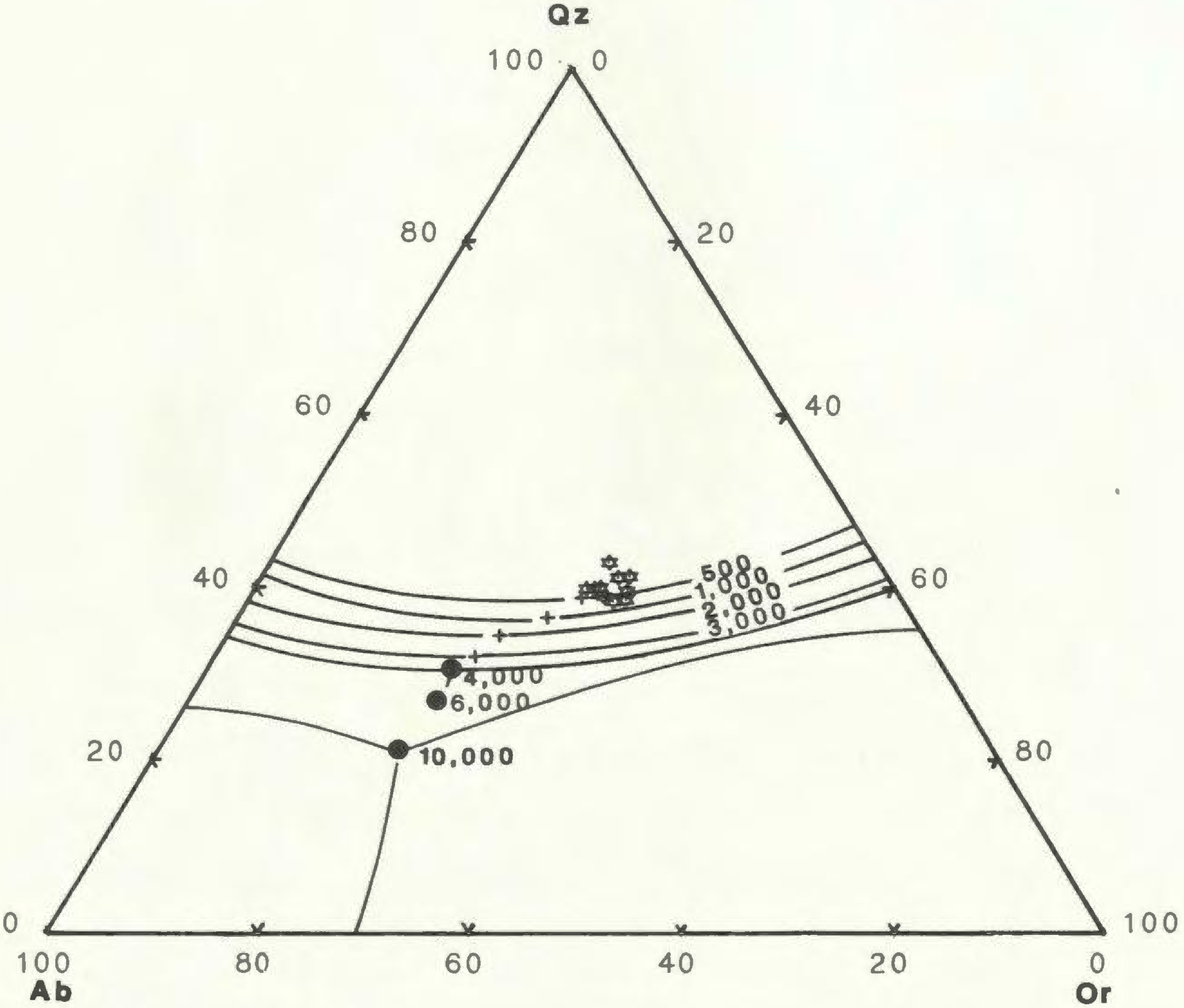


Figure 5.4 Normative Qz-Ab-Or plot for the microgranite. + indicates isobaric minima and ● indicates ternary eutectics (Tuttle and Bowen, 1958; Ehlers, 1972, pp. 189). Pressure is in bars.

from 10 to 129 and 98.5 to 2549, respectively, while K/Rb ratios range from 81 to 147. K/Rb ratios of the microgranite fall below Shaw's (1968) main trend due to high Rb contents of these rocks (Fig. 5.5). Rare-earth element characteristics of the microgranite are discussed in section 5.6.

Pearce et al. (1984) have shown that granites from different tectonic environments have distinct trace element characteristics. They have subdivided granites into the following groups: ocean ridge granites (ORG), volcanic arc granites (VAG), within plate granites (WPG) and collision granites (COLG). In addition to this classification, granites may be classified as I-, S-, M- and A-type on the bases of their source and geochemical characteristics and tectonic setting. I- and S-type granites are those derived from igneous and sedimentary precursors, respectively (Chappell and White, 1974; White and Chappell, 1977), whereas M-type granites include the more restricted plagiogranites. Like the M-type, the A-type classification has no genetic connotations. A-type granites include alkaline and peralkaline granites of anorogenic settings, although subalkaline A-type granites also occur (Loiselle and Wones, 1979; Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987). Geochemically, A-type granites are characterised by high Ga, REE, Zr, Nb, Y and Zn abundances.

The microgranite is subalkaline (Fig. 5.6) and plots in the within plate granite field of Pearce et al. (1984) (Fig. 5.7). It also has geochemical characteristics of A-type granites (Fig. 5.8). However, as Whalen et al. (1987) pointed out, highly fractionated

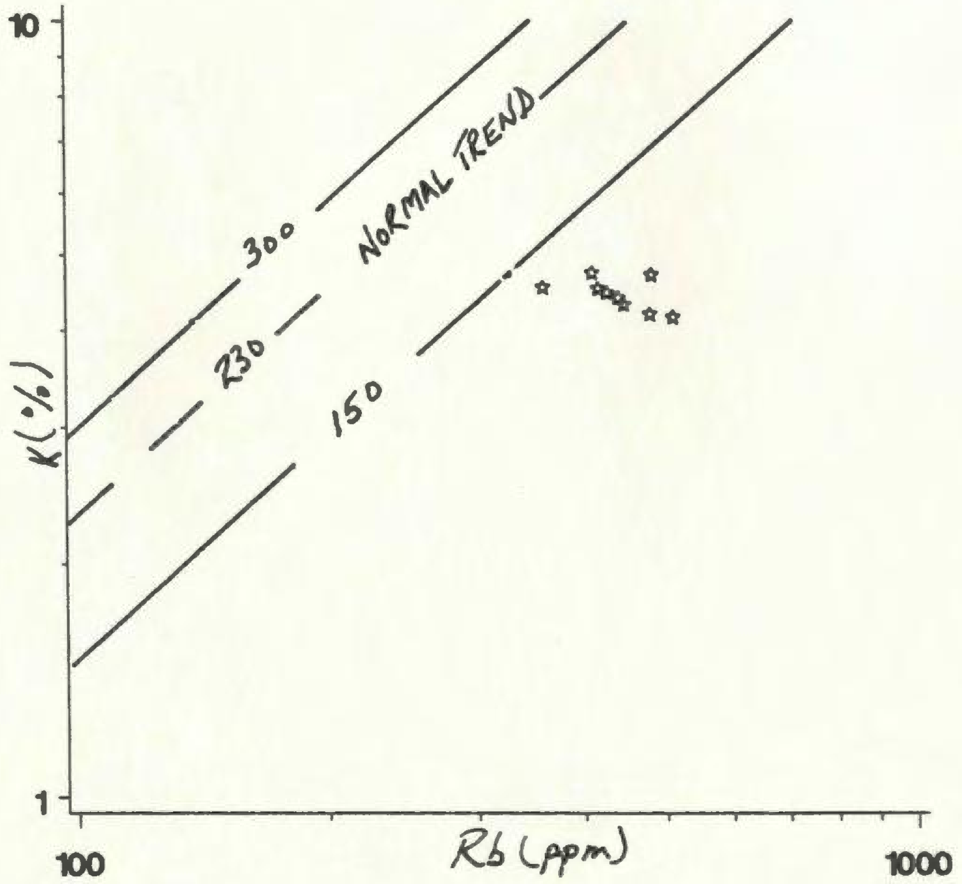


Figure 5.5 K (wt%) versus Rb (ppm) plot for the microgranite. Normal trend is from Shaw (1968).

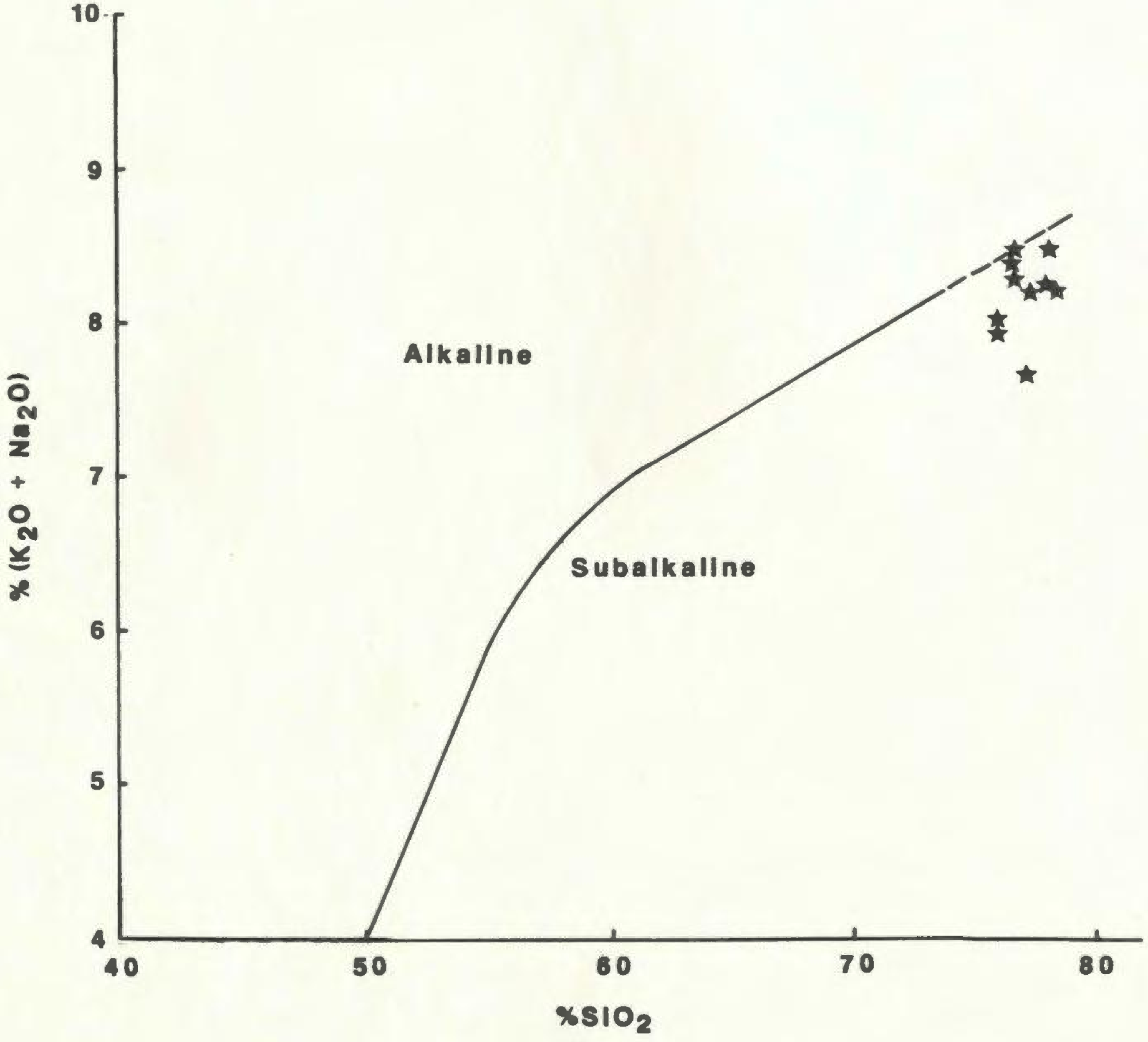


Figure 5.6 (Na_2O + K_2O) versus SiO_2 plot for the microgranite showing the boundary between alkalic and subalkalic rocks (Miyashiro, 1978).

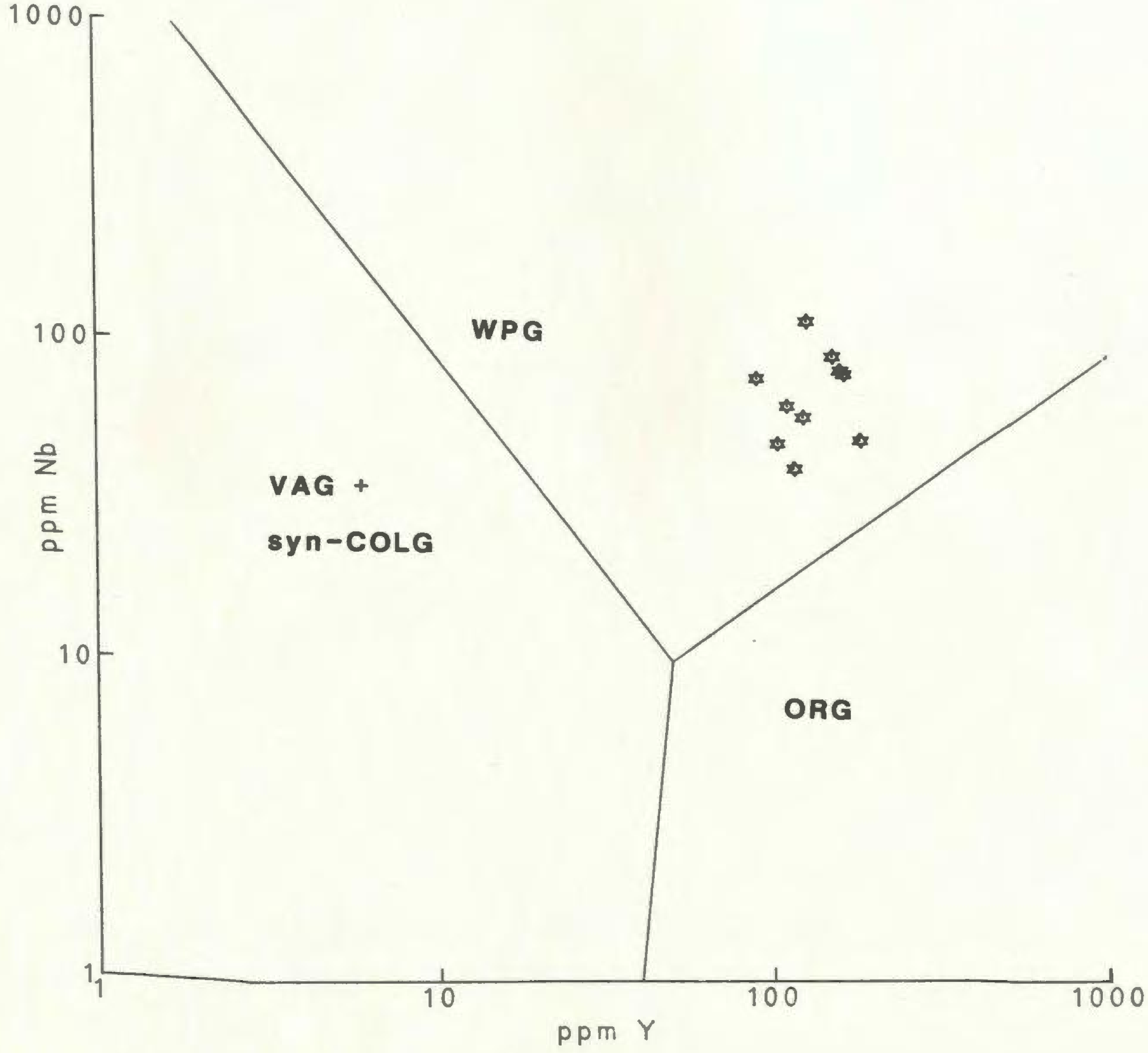


Figure 5.7a Rb versus Y plot for the microgranite Fields for the following granite types are shown: volcanic arc (VAG), syn-collision (syn-COLG), within-plate (WPG) and ocean ridge (ORG) (after Pearce et al., 1984).

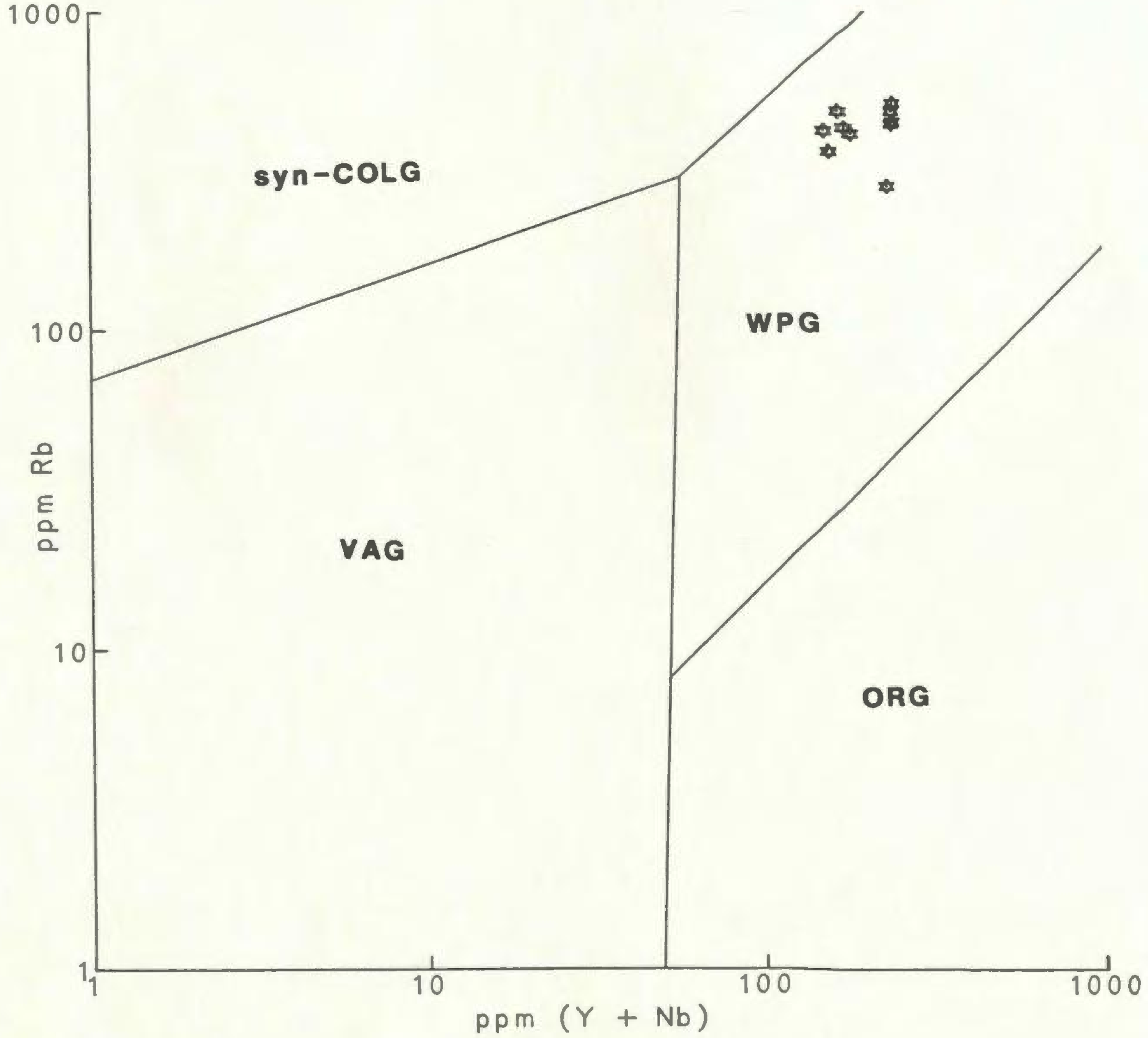


Figure 5.7b Rb versus (Y + Nb) plot for the microgranite (after Pearce et al., 1984, see Figure 5.7a caption for details).

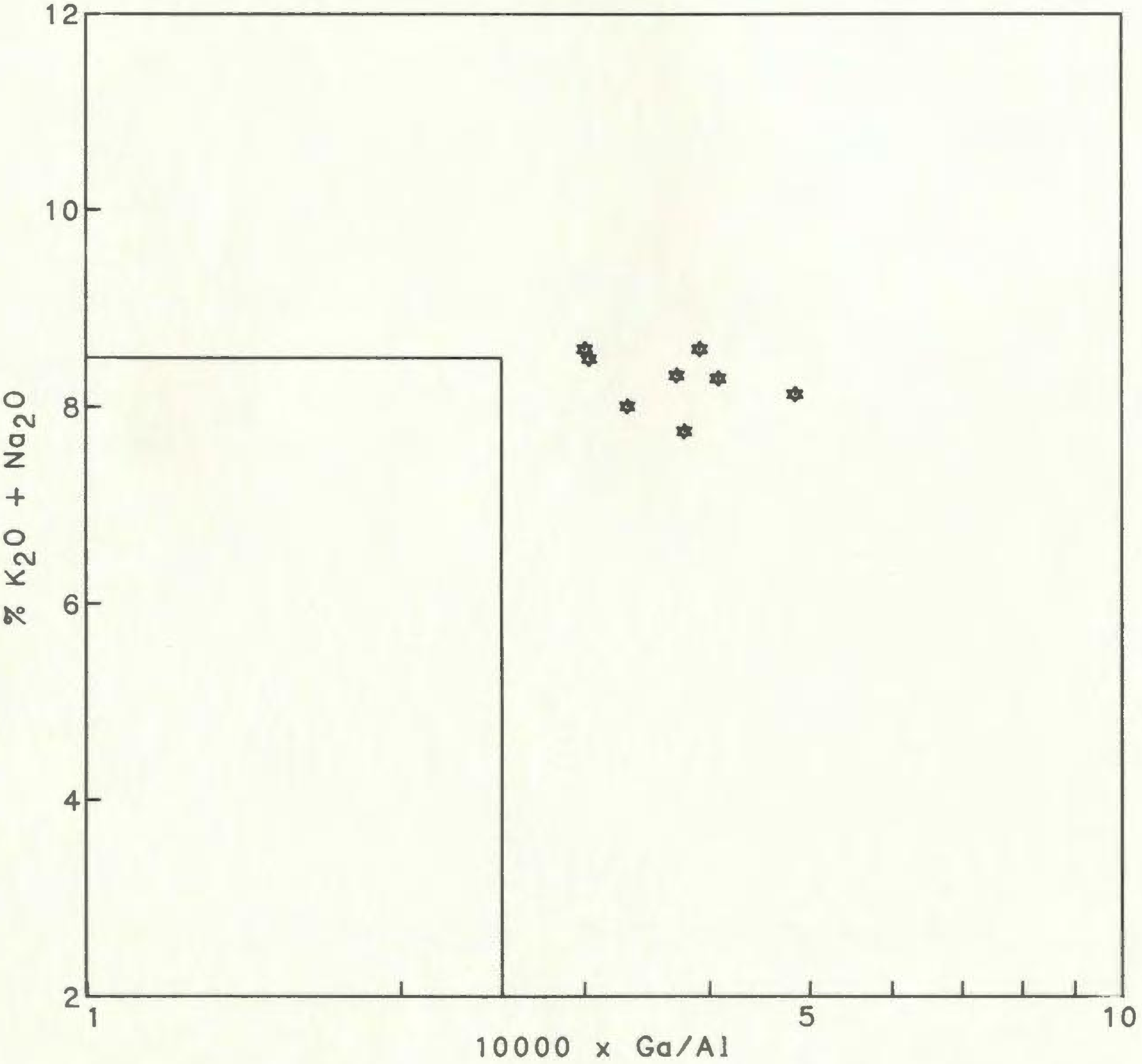


Figure 5.8a Ga/Al versus (K_2O + Na_2O) plot for the microgranite. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

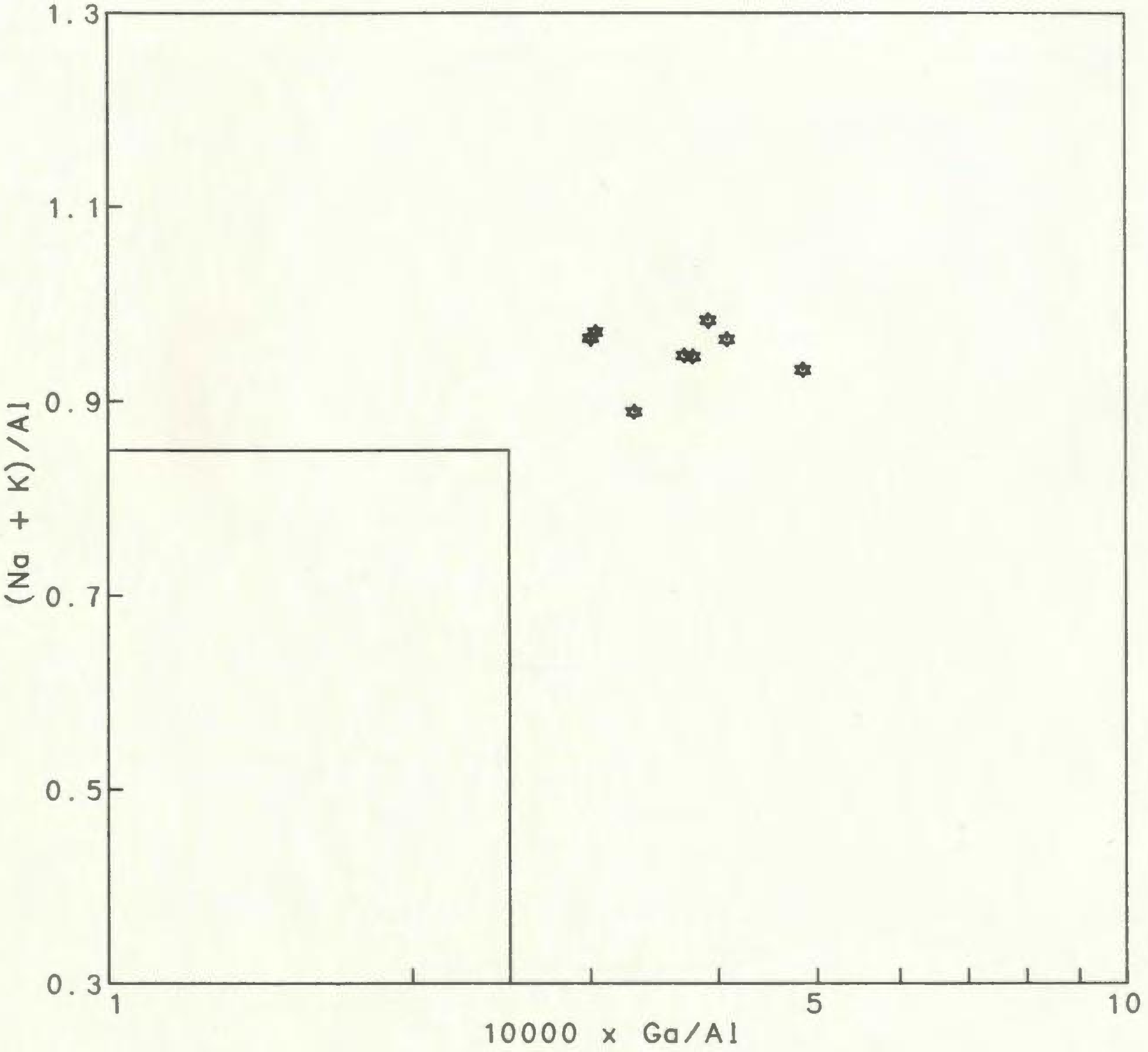


Figure 5.8b Ga/Al versus the agpaitic index {(K + Na)/Al} plot for the microgranite. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

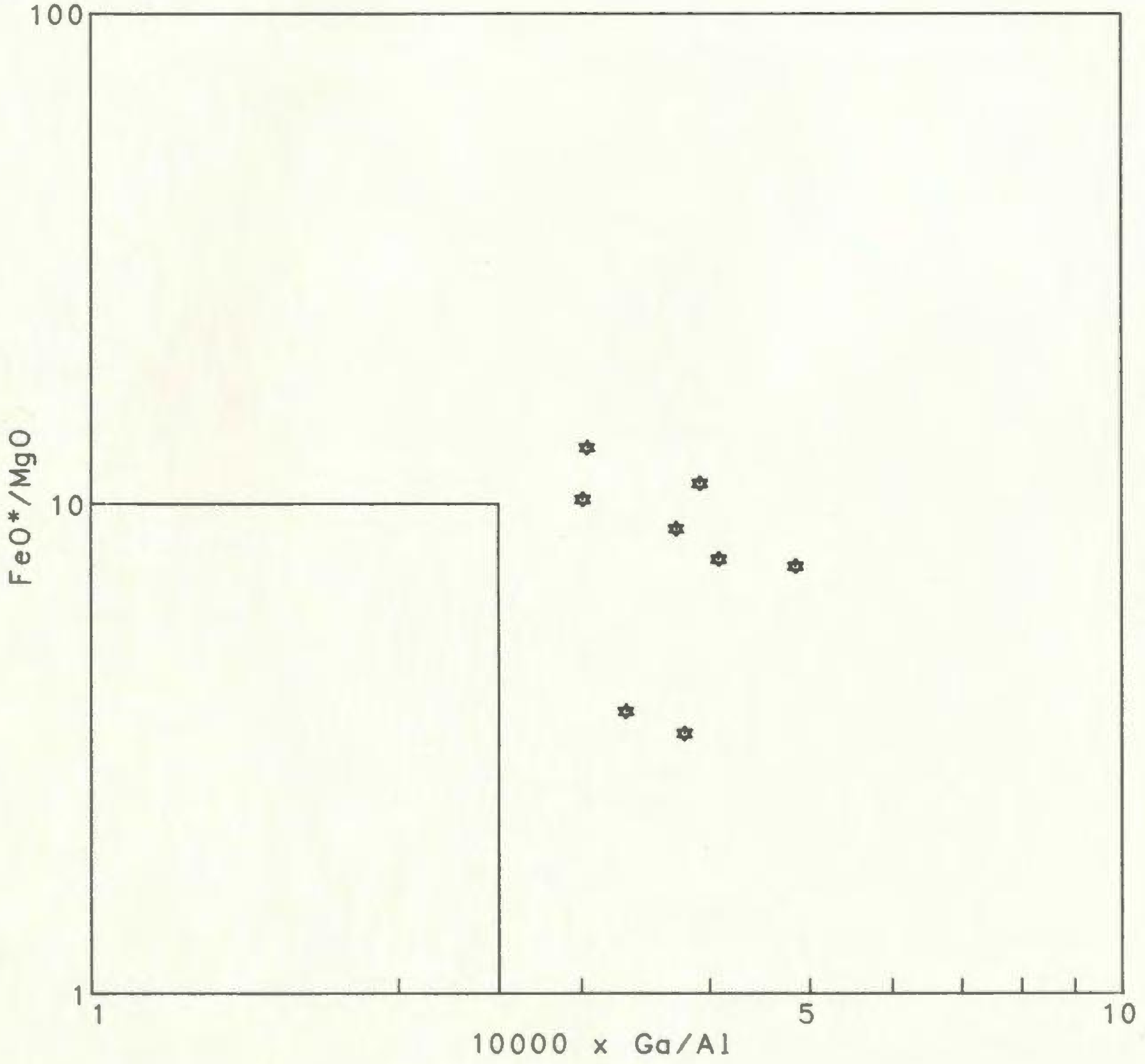


Figure 5.8c Ga/Al versus FeO*/MgO plot for the microgranite. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

FeO* = Total Fe(as FeO)

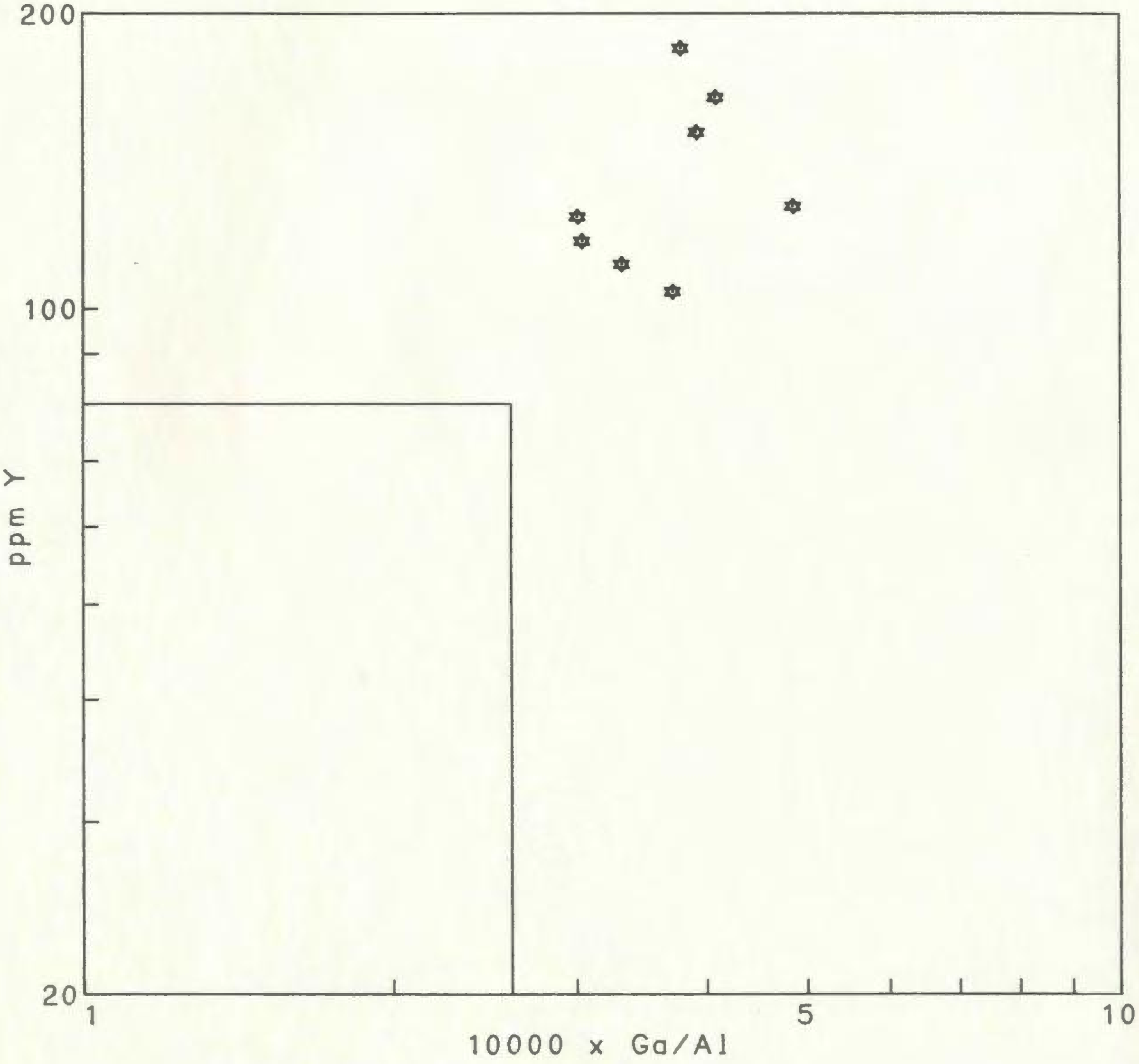


Figure 5.8d Ga/Al versus Y plot for the microgranite. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

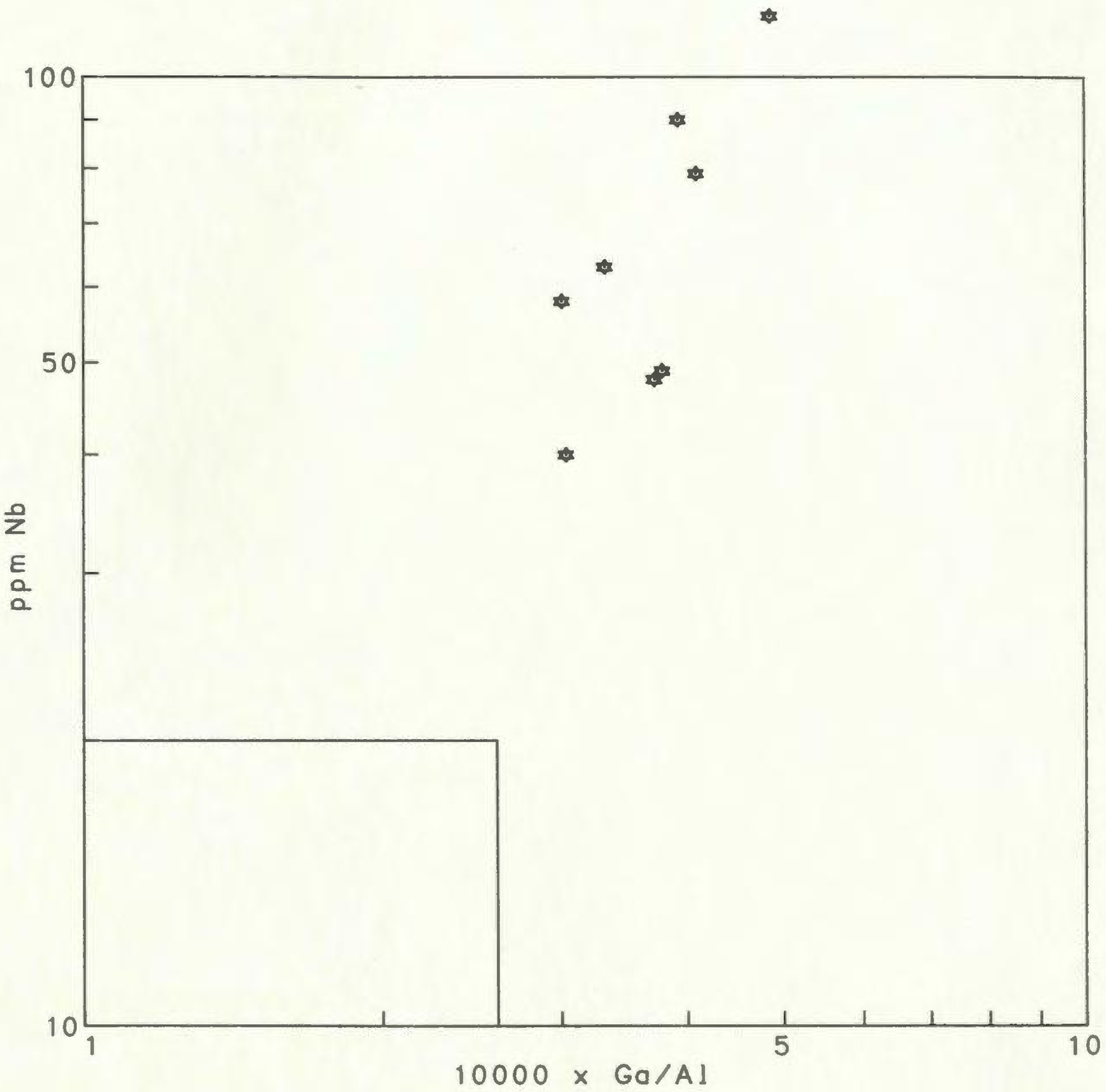


Figure 5.8e Ga/Al versus Nb plot for the microgranite. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

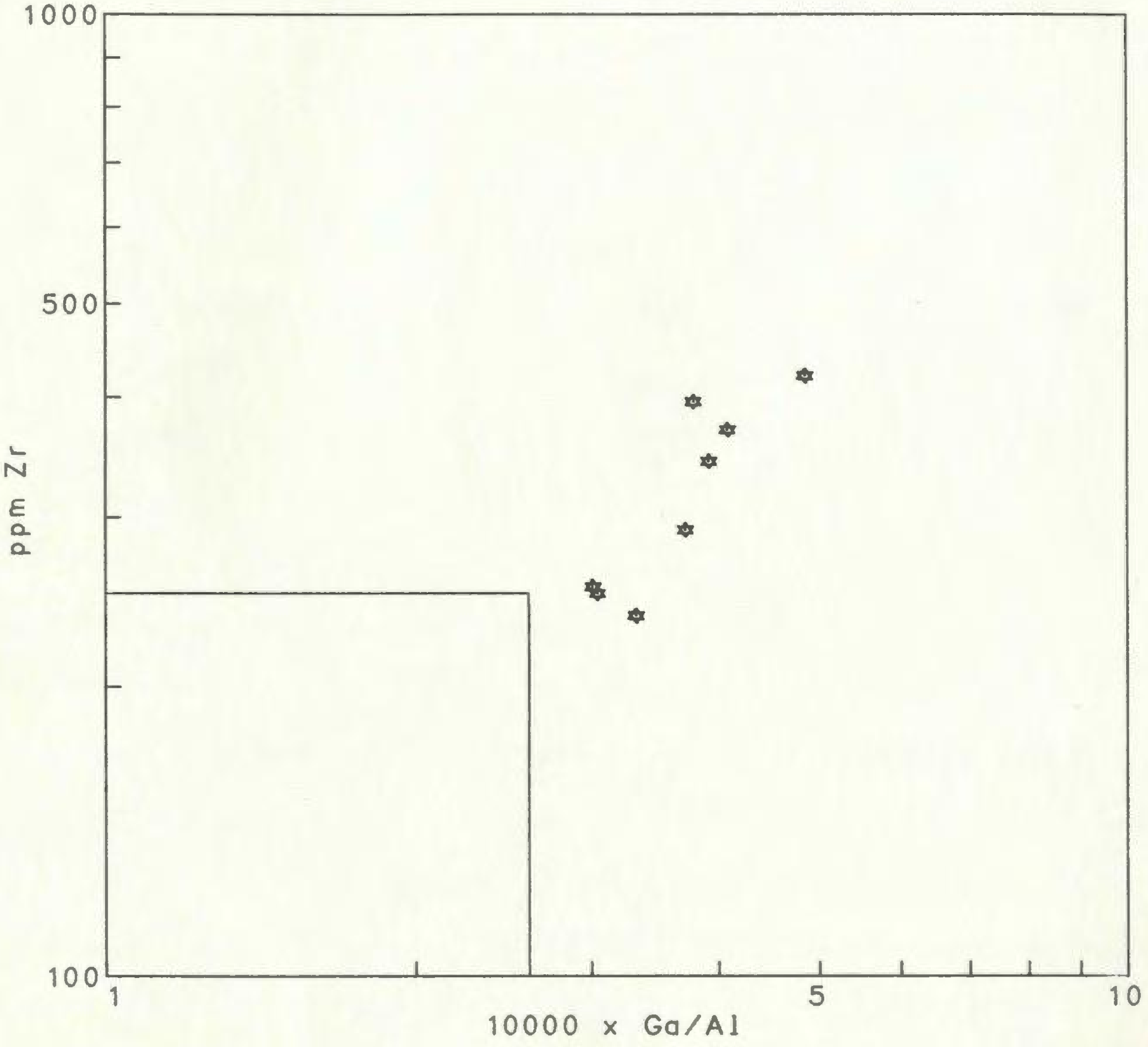


Figure 5.8f Ga/Al verus Zr plot for the microgranite. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

I-type granites have similar characteristics. As the microgranite is a highly evolved granite (Fig. 5.2 and 5.3), its A-type characteristics may also be due to extensive fractionation.

5.3 The Kanye Volcanics and Porphyritic granophyres

The Kanye Volcanics and the porphyritic granophyres, group 2 and 2a, respectively, of Table 5.1, consist of 42 samples of which 6 are from the granophyres. As pointed out in chapter 2, these rocks have a gradational contact. Their field relations and textures suggest an igneous origin. Textural differences between these rocks reflect both gradual changes in the rate of crystallization and cooling. There is, however, no evidence of chemical differentiation as shown by their similar major, minor and REE abundances (Table 5.1). Therefore, in all plots of major, trace and REE analyses the same symbol is used for both the Kanye Volcanics and the porphyritic granophyres.

Al_2O_3 contents of these rocks range from 11.6% to 12.3%. The alkalis, TiO_2 and total iron (as Fe_2O_3) also show significant clustering in Figure 5.2. Average concentrations of these oxides are given in Table 5.3; they have low standard deviations. In contrast, the ranges of MgO and CaO contents are much higher, from 0.21% to 1.12% and 0.26% to 1.30%, respectively. But K_2O/Na_2O ratios are low and fairly uniform; they range from 1.1 to 2.3. Values of K_2O/Na_2O greater than 2 are typical of weathered samples.

Figure 5.9 is a plot of $Na_2O + K_2O$ versus SiO_2 for the Kanye Volcanics and the granophyres. As this diagram shows, all the analyses plot in the rhyolite field of Le Bas et al. (1986).

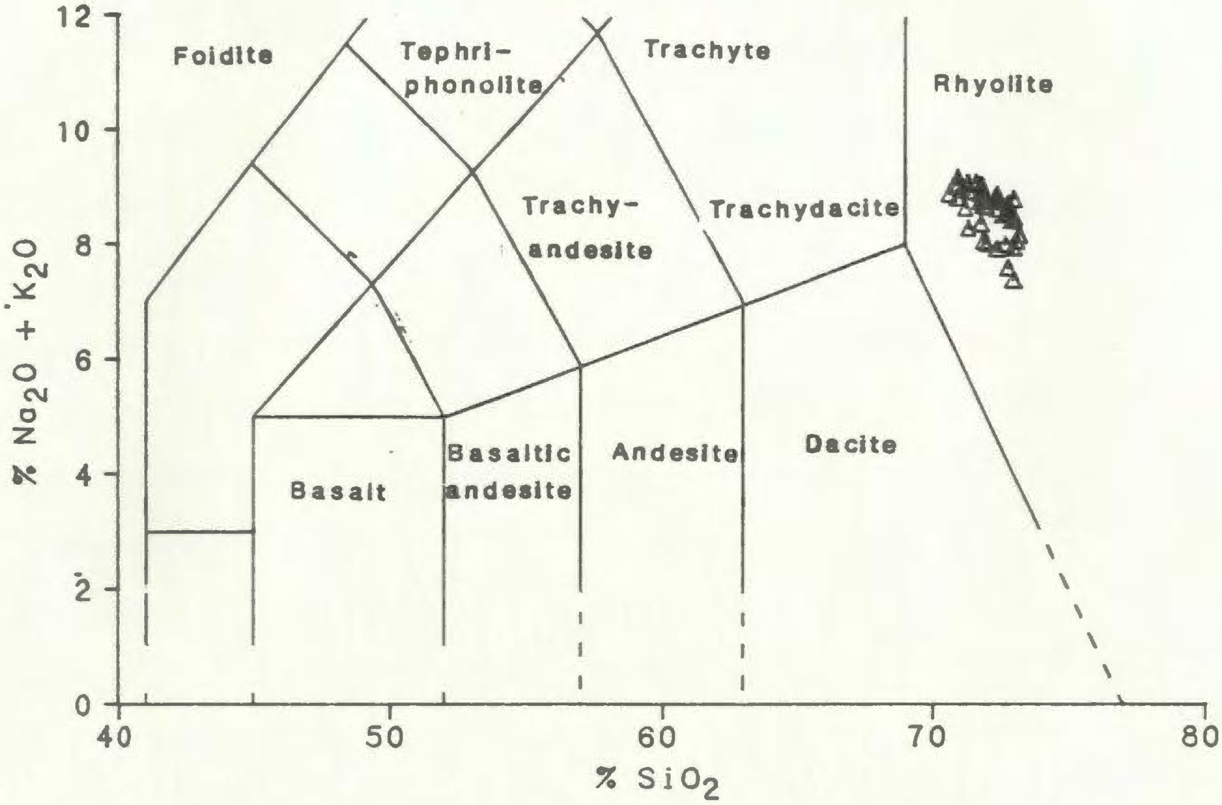


Figure 5.9 Plot of the Kanye Volcanics and porphyritic granophyres in the (Na_2O + K_2O) versus SiO_2 classification diagram for volcanic rocks (Le Bas et al., 1986).

Compositional fields for some common volcanic rocks are also shown in Figure 5.9. The Kanye Volcanics and the granophyres vary from subaluminous to metaluminous. A few samples are peraluminous and contain normative corundum (Table 5.1), but this is probably due to weathering as explained earlier in the case of alkali ratios. In addition, one sample shows acmite in the norm. Normative Qz, Ab and Or compositions of the Kanye Volcanics and porphyritic granophyres are plotted in Figure 5.10. As this diagram shows, the Kanye Volcanics and porphyritic granophyres plot at a higher pressure cotectic than the microgranite (see Figure 5.4).

Mean Nb, Ga and Zr contents for the 42 samples from the Kanye Volcanics and the porphyritic granophyres are as follows: 36 ± 1 ppm, 23 ± 2 ppm and 761 ± 15 ppm, respectively. Statistically, these values are very uniform. This is also evident in Figure 5.3 as well. On the other hand, Rb, Sr, Y and Ba conentrations are variable and do not show any systematic variation with SiO (Fig. 5.3). Rb/Sr, K/Rb and K/Ba ratios range from 2 to 12, 131 to 284 and 47.4 to 100, respectively. All the samples, except one, plot within Shaw's (1968) main trend for crustal igneous rocks (Fig. 5.11).

The Kanye Volcanics and granophyres have alkaline affinities as shown by Figure 5.12. However, a few samples from these rocks plot in the subalkaline field as well. Their major, minor and rare-earth element chemistry is comparable to that of anorogenic or A-type granites and rhyolites which are distinguished from other types of granites and rhyolites (i.e. the M-, I- and S-types) with similar SiO_2 contents by the following characteristics: high $N_2O + K_2O$, Fe/Mg, Zr,

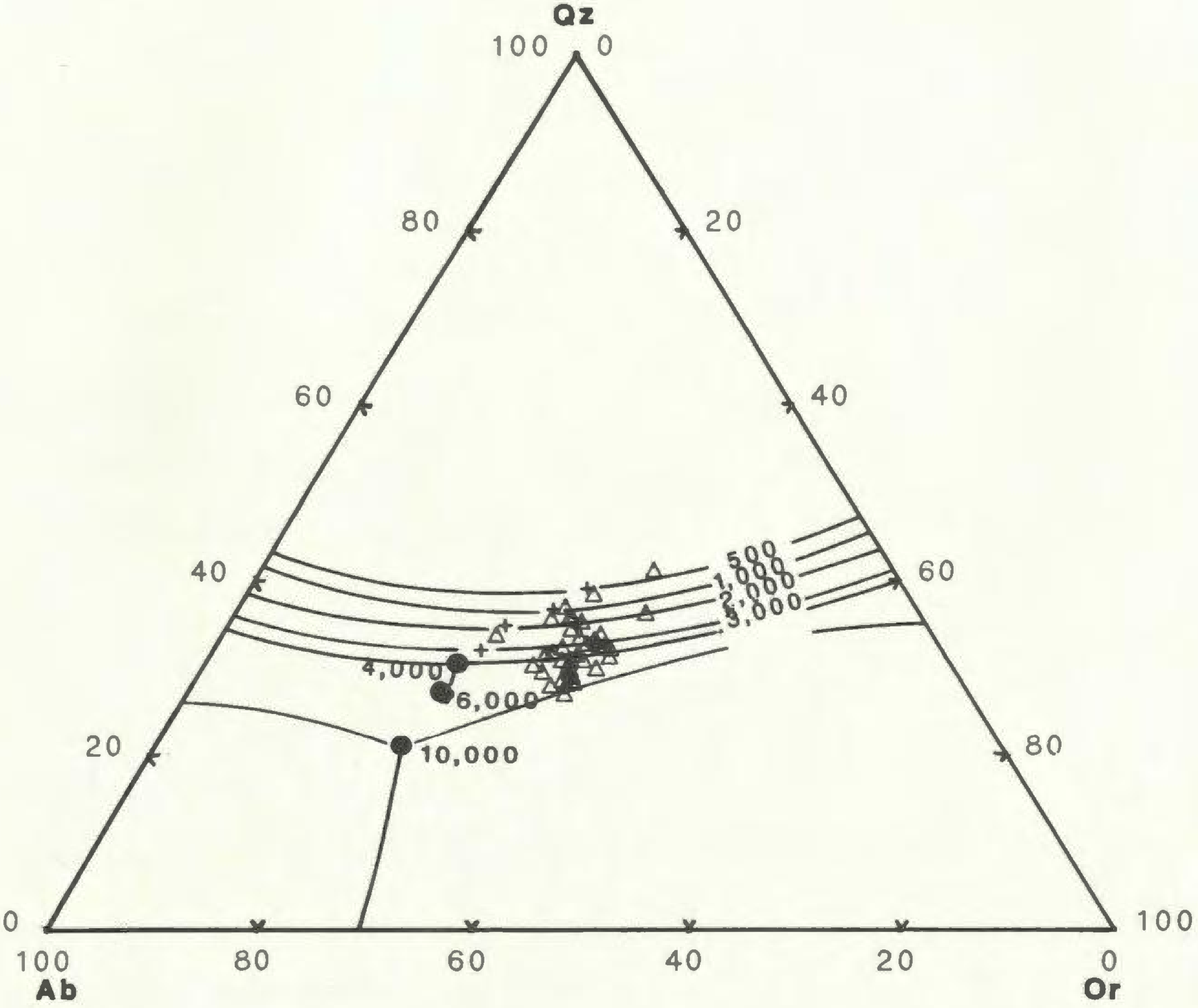


Figure 5.10 Normative Qz-Ab-Or plot for the Kanye Volcanics and the porphyritic granophyres. + indicates isobaric minima and ● indicates ternary eutectics (after Tuttle and Bowen, 1958; Ehlers, 1972, p. 189). Pressure is in bars.

Nb, Y, Ga/Al and REE (except Eu) and low CaO and Sr (Loiselle and Wones, 1979; Collins et al, 1982; Clemens et al, 1986; Whalen et al., 1987). In addition, Whalen et al. (1987) have shown that plots of Ga/Al versus major and trace elements give good discrimination between A-type granites (and rhyolites) and other types of granites except highly fractionated I- and S-types. Figure 5.13 shows plots of Ga/Al versus various major and trace elments for the Kanye Volcanics and granophyres. Also shown in Figure 5.13 is a field (rectangular box in Fig. 5.13) for M-, I- and S-type granites. All the samples from the Kanye Volcanics and porphyritic granophyres plot within the A-type granite field of Whalen et al. (1987).

5.4 The Nnywane Formation

The Nnywane Formation has extremely variable major and trace element contents (see Table 5.3 and Fig. 5.2 and 5.3). With a few exceptions, the variations are typically random. The exceptions among the major oxides are TiO_2, Al_2O_3 and to some extent MgO and total iron. They have comparatively low standard deviations (see Table 5.3). They also show a slight negative correlation with SiO_2. The significance of this correlation will be discussed later.

The remaining oxides, CaO, Na_2O, K_2O and SiO_2 vary considerably (Fig. 5.2). As Table 5.3 and Figure 5.2 show, the ranges, average concentrations and variation of these oxides are clearly anomalous. K_2O/Na_2O ratios of the Nnywane Formation range from 1 to 72. These values are plotted against K_2O in Figure 5.14. Also shown in Figure 5.14 are K_2O/Na_2O ratios for the microgranite, porphyritic

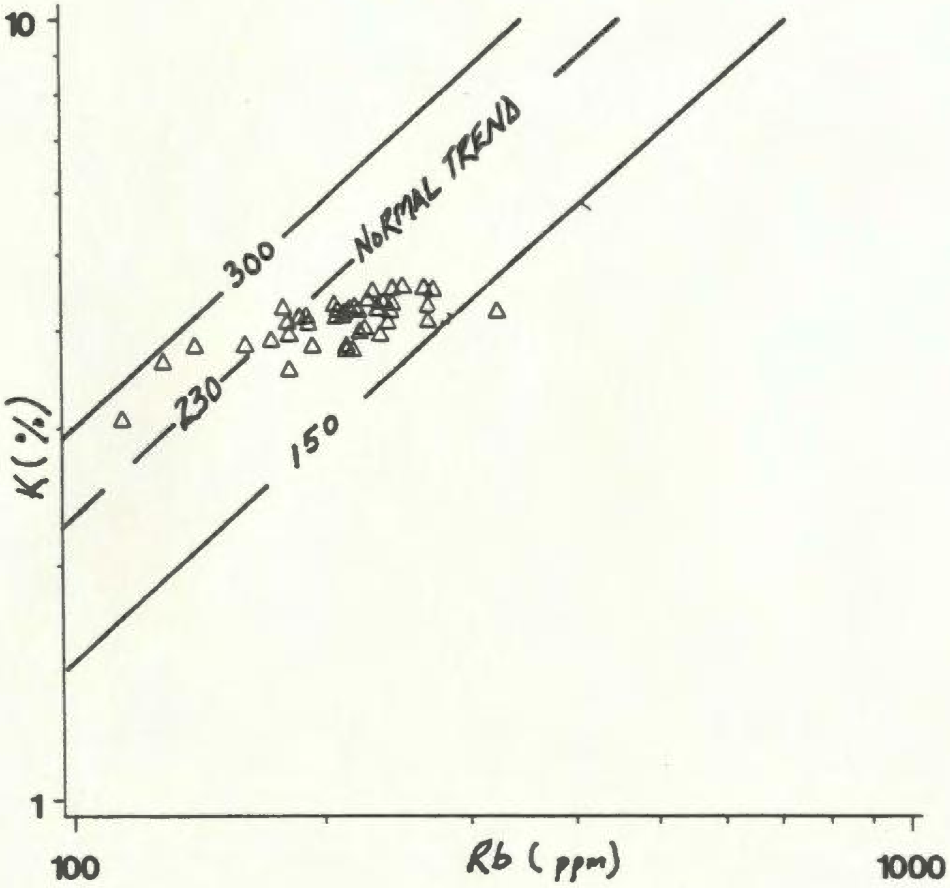


Figure 5.11 K (wt %) versus Rb plot for the Kanye Volcanics and the porphyritic granophyres.

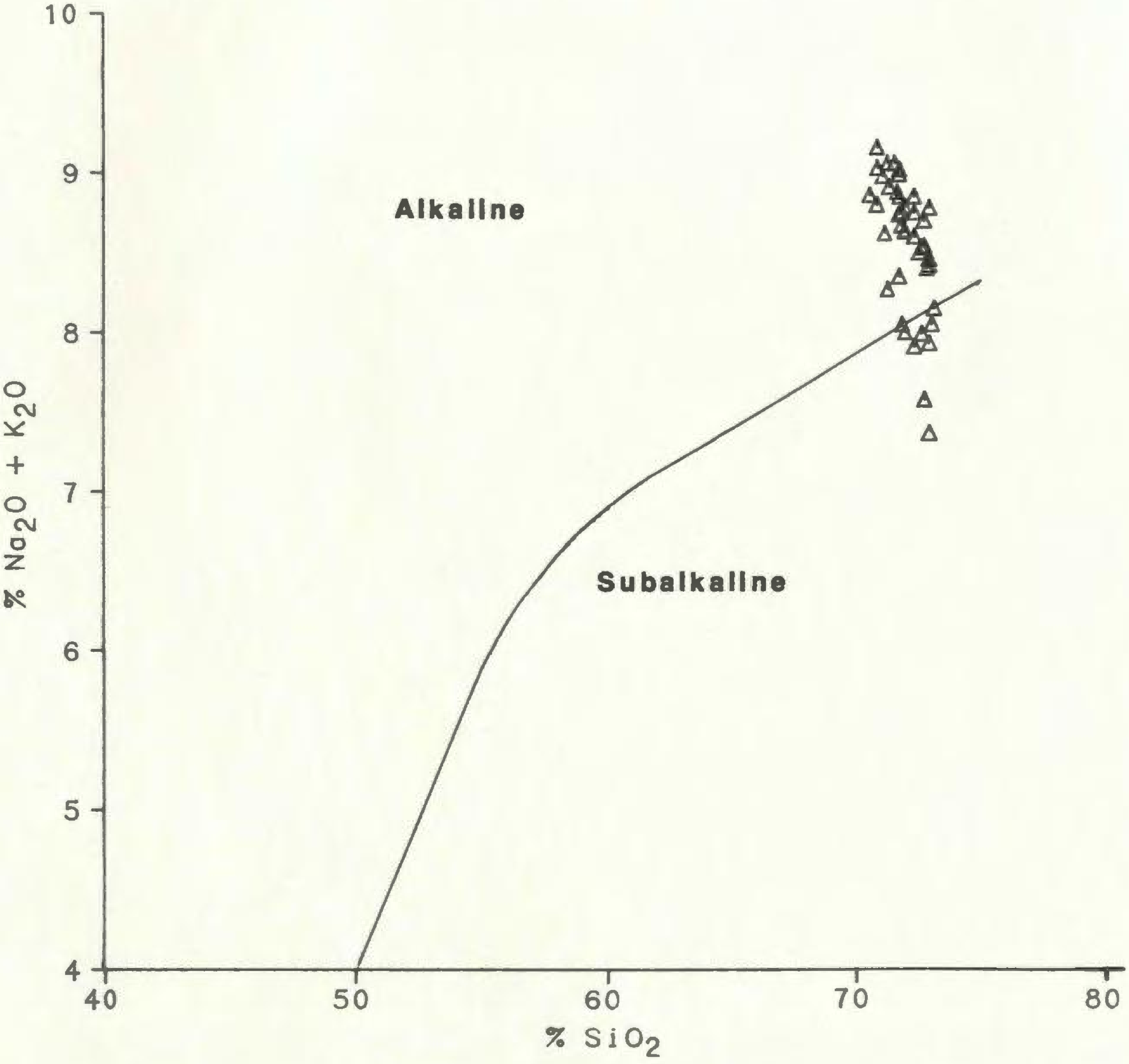


Figure 5.12 (Na_2O + K_2O) versus SiO_2 plot for the Kanye Volcanics and porphyritic granophyres. The diagram shows the boundary between alkalic and subalkalic rocks (Miyashiro, 1978).

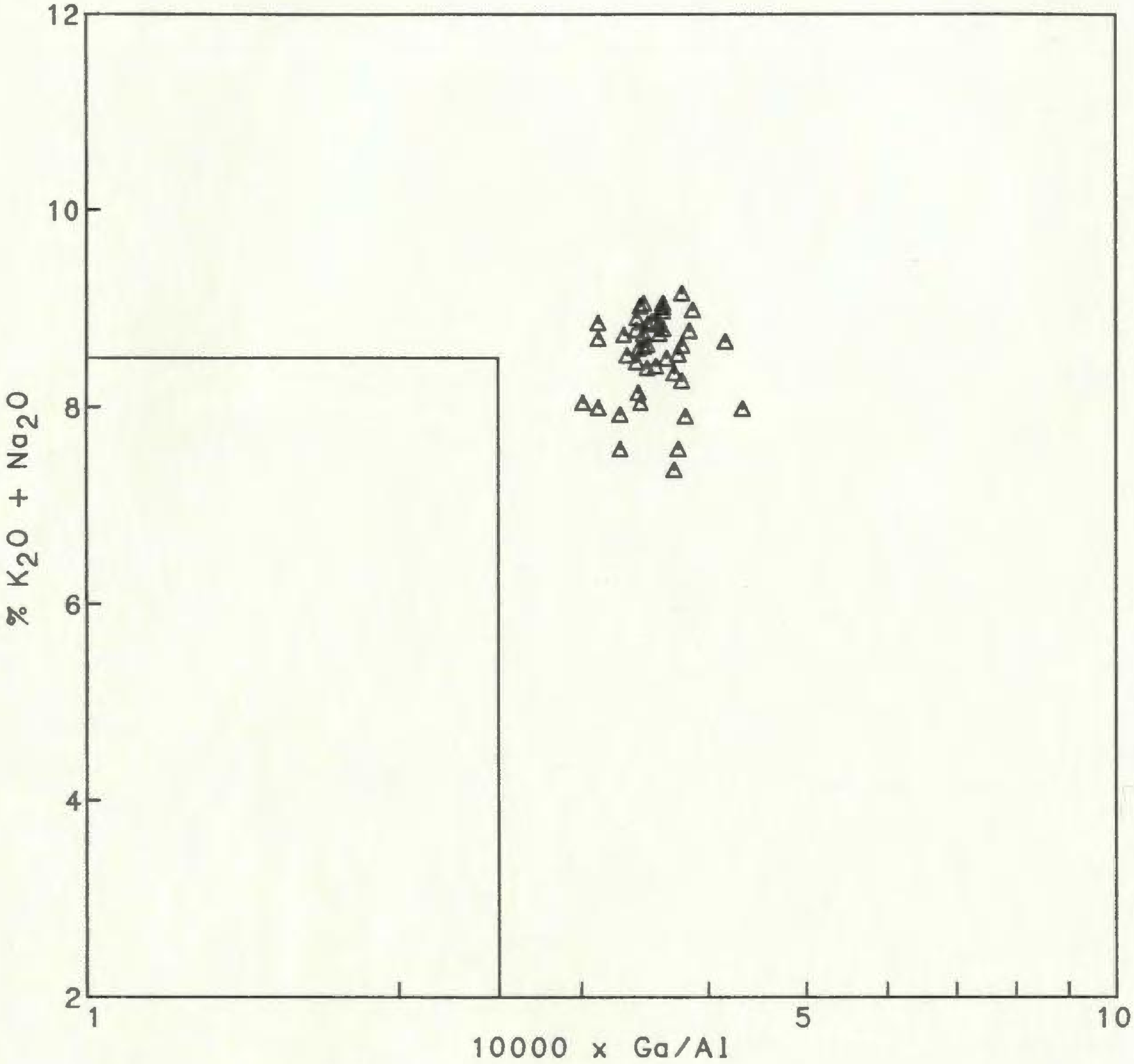


Figure 5.13a Ga/Al versus (K_2O + Na_2O) plot for the Kanye Volcanics and porphyritic granophyres. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

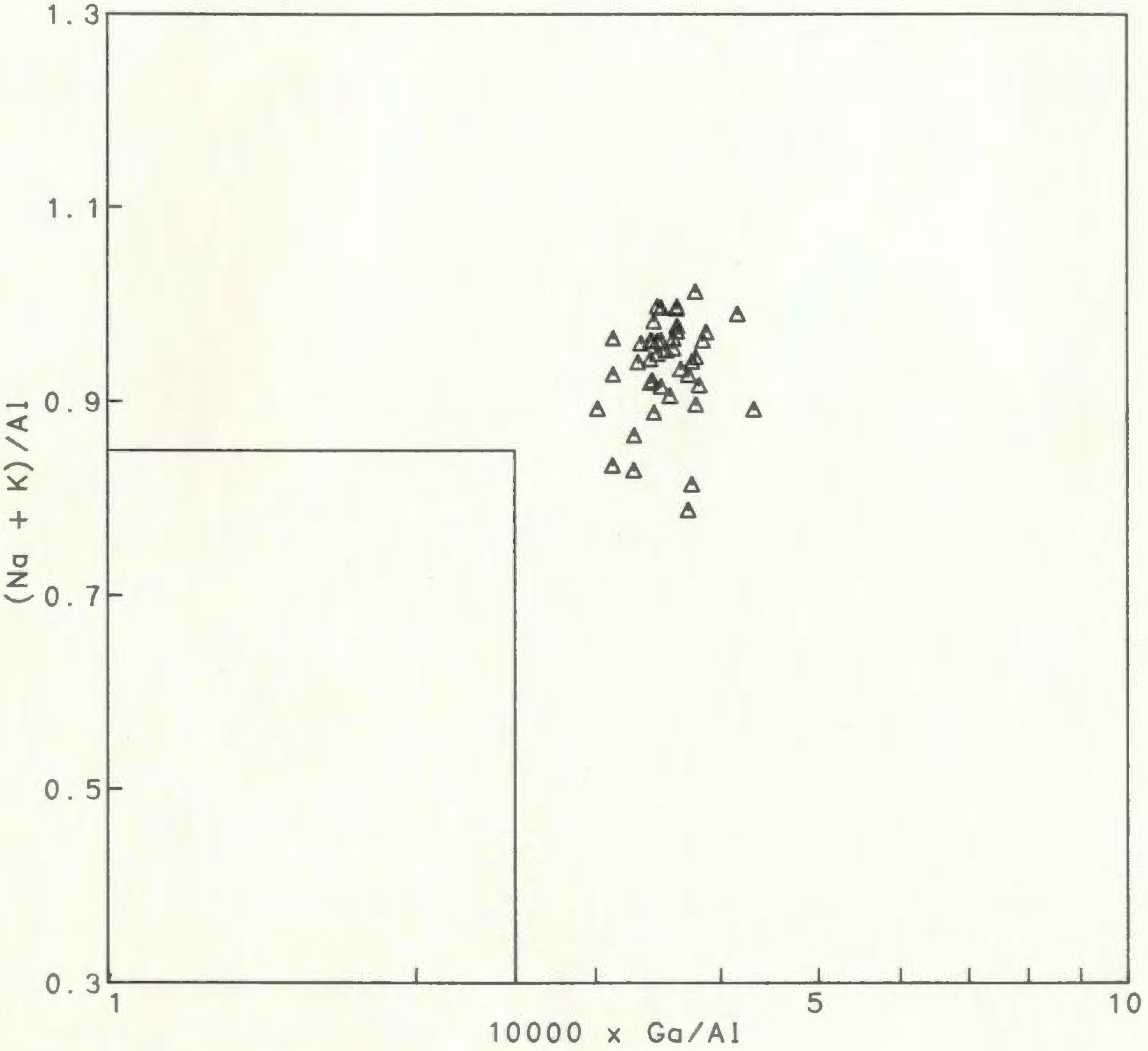


Figure 5.13b Ga/Al versus the agpaitic index {(K + Na)/Al} plot for the Kanye Volcanics and porphyritic granophyres. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

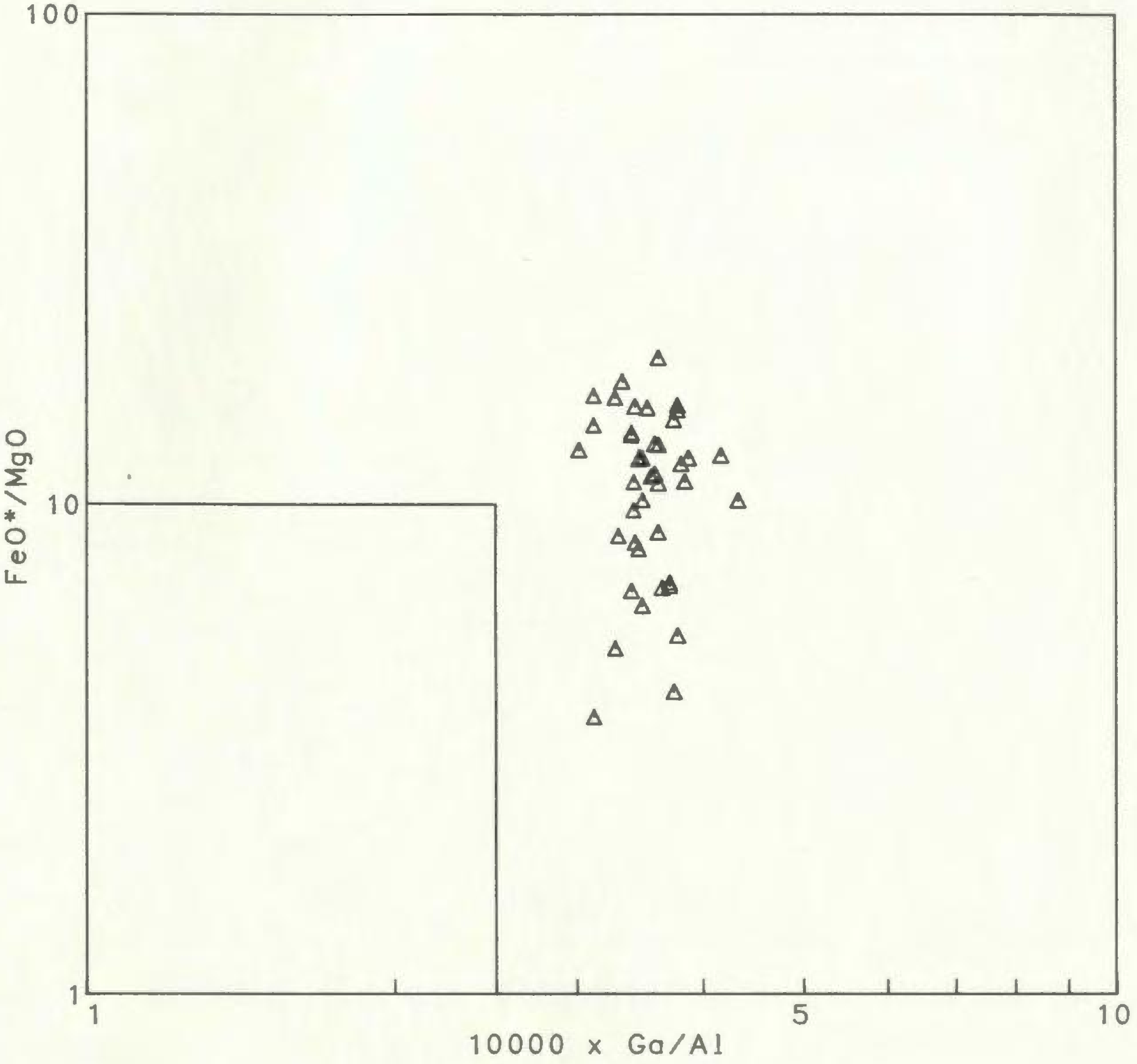


Figure 5.13c Ga/Al versus FeO* /MgO plot for the Kanye Volcanics and porphyritic granophyres. Rectanqular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

FeO* = Total Fe(as FeO)

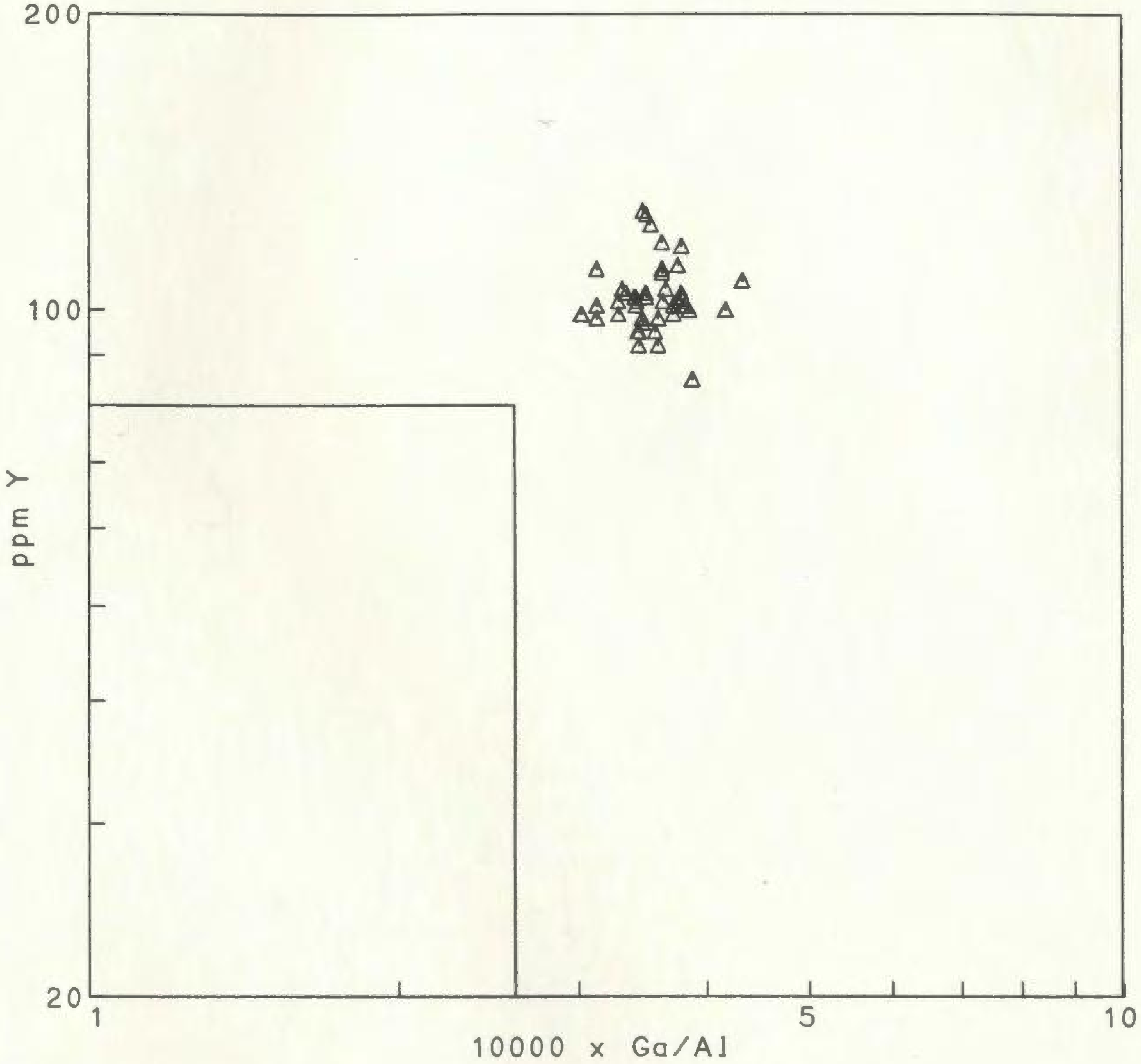


Figure 5.13d Ga/Al versus Y plot for the Kanye Volcanics and porphyritic granophyres. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

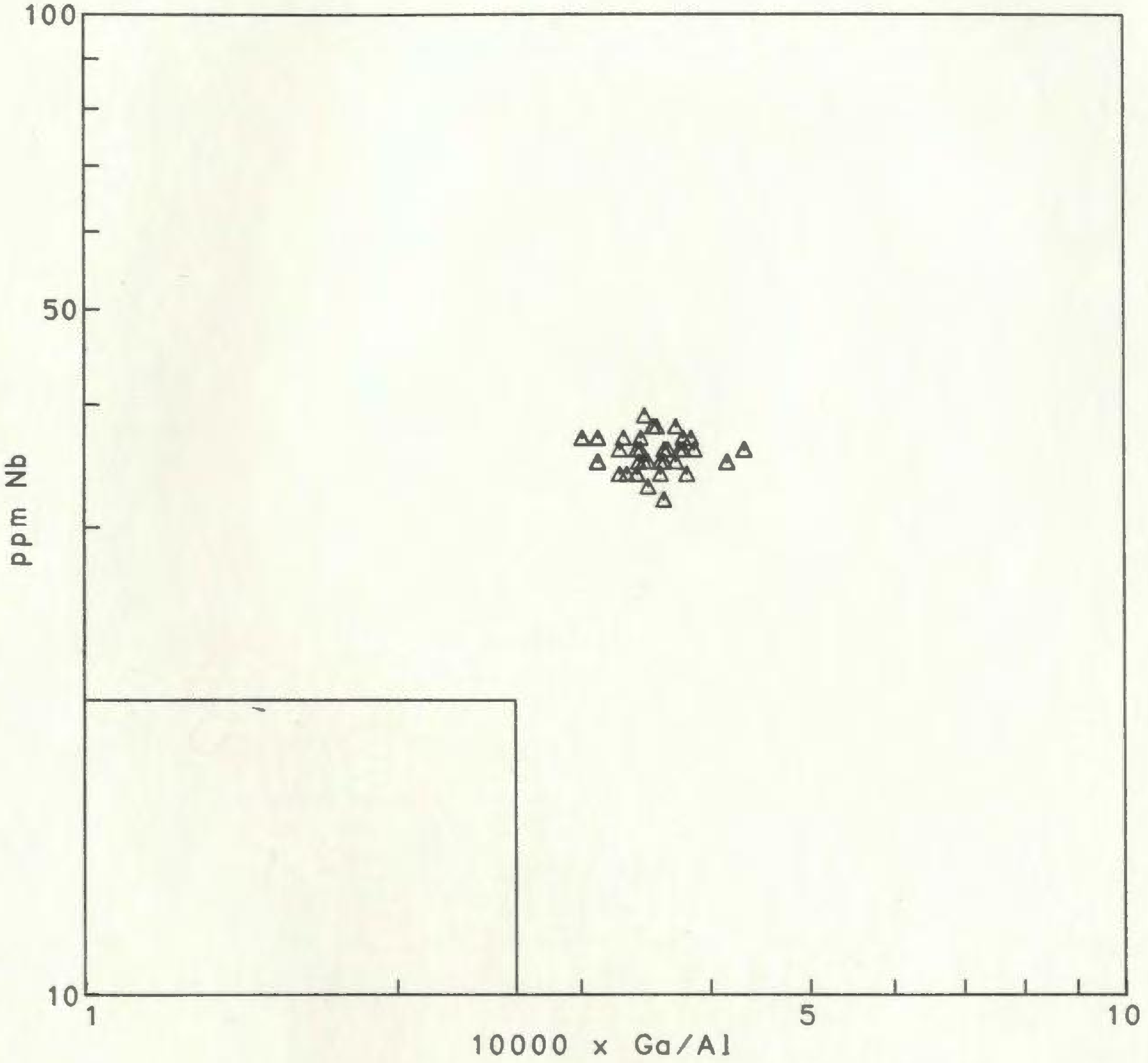


Figure 5.13e Ga/Al versus Nb plot for the Kanye Volcanics and porphyritic granophyres. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

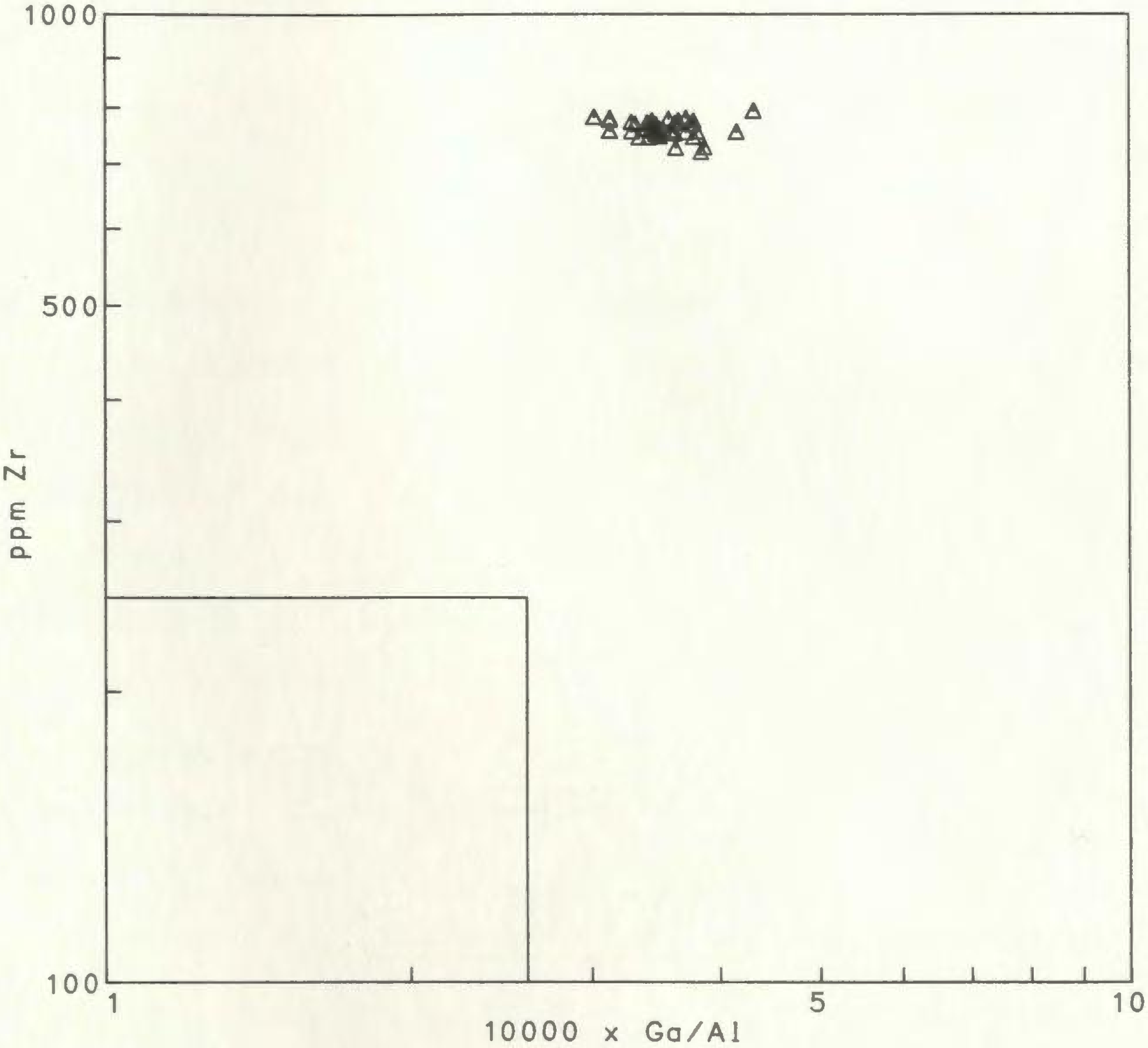


Figure 5.13f Ga/Al verus Zr plot for the Kanye Volcanics and porphyritic granophyres. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

granophyres and Kanye Volcanics. The Nnywane Formation K_2O/Na_2O ratios are considerably scattered in this diagram compared to the other rock types. They are also very anomalous compared to values for granitic rocks compiled by Nockolds (1954) and Wedepohl (1969. Granites and rhyolites generally have $K_2O/Na_2O < 2$.

The Nnywane Formation is to some extent comparable to siliciceous potassic rocks discussed by N. L. Bowen (1928, p. 227)) and later by Stewart (1979, p. 339). Among other things, these rocks are characterised by extremely high K_2O, SiO_2 and low Na_2O and CaO. Because of low Na_2O and CaO contents, the Nnywane Formation has more Al_2O_3 than is required to combine with the alkalis to form feldspars. It is hence peraluminous and contains variable amounts of corundum in the norm. Normative corundum contents range from 0.62% to 7.76%. A ternary plot of normative Qz, Ab and Or is shown in Figure 5.15. These values do not occupy a well defined field but scatter considerably towards the Qz-Or join.

Average trace element abundances of samples from the Nnywane Formation are given in Table 5.3. Among these elements, Zr and Nb are the least variable. They also show a slight negative correlation with SiO_2. The remainder of the elements; Rb, Sr, Y, Ga and Ba are variable (see Table 5.3). Except for Sr, none of these elements shows any correlation with Si_2O, however (Fig. 5.3). Plots of K(wt%) versus Rb and Ba are shown in Figure 5.16. Both trace elements are well correlated with K. The significance of this correlation is discussed in the next section. Figure 5.17 is a plot of Ga/Al ratios versus FeO*/MgO (FeO*= total iron as FeO), Zr, Nb, Y and the agpaitic index

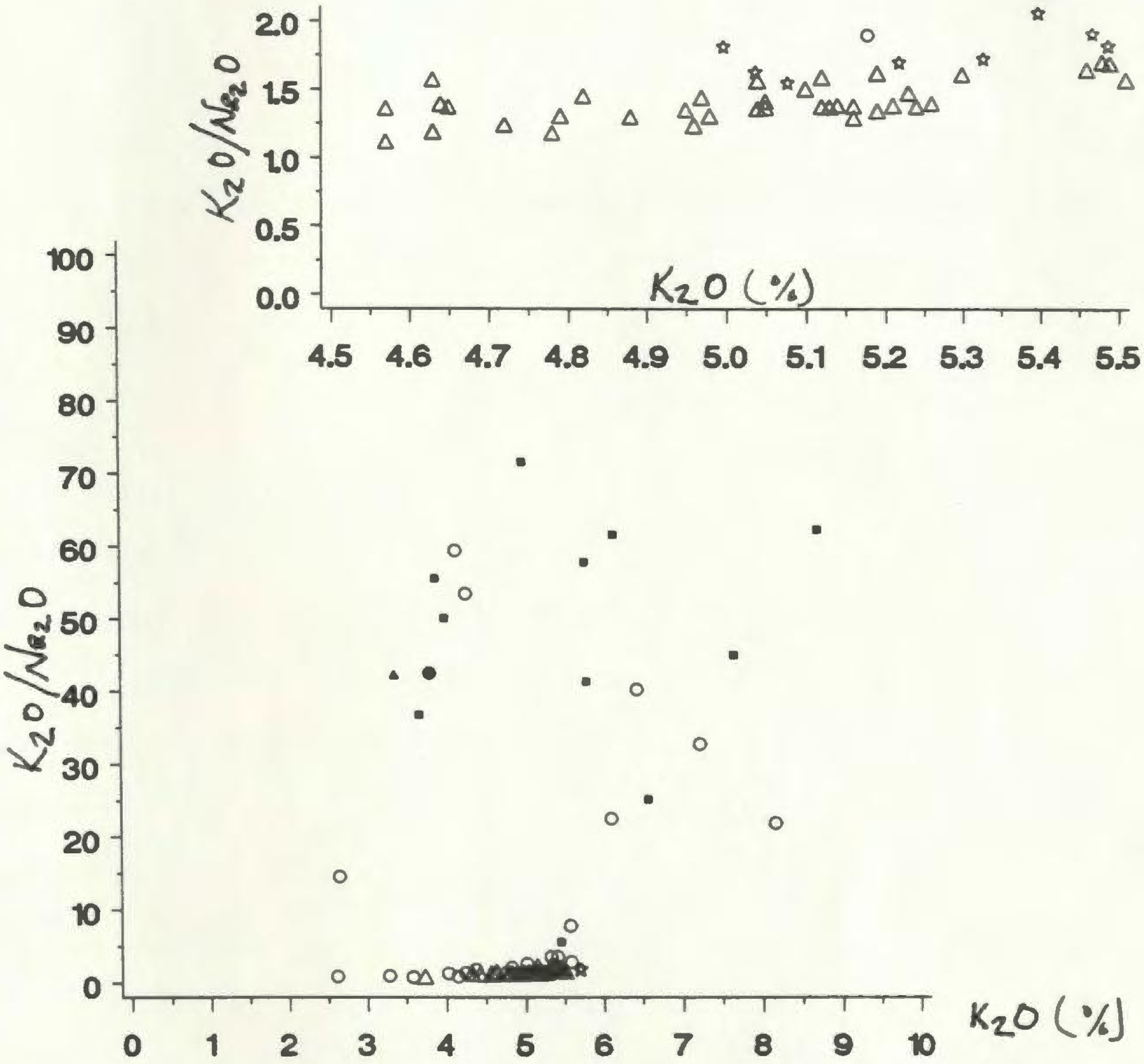


Figure 5.14 K_2O/Na_2O versus K_2O plot for the microgranite (★), Kanye Volcanics and porphyritic granophyres (△) and Nnywane Formation (▪ & ○). Note considerable scatter of samples from the Nnywane Formation.

for the Nnywane Formation. Most of the samples from this unit have A-type affinities like the Kanye Volcanics and the porphyritic granophyres.

Rb/Sr, K/Rb and K/Ba ratios for the Nnywane Formation range from 3 to 37, 119 to 254 and 30.4 to 83.9, respectively (Table 5.1). Sample (5/56B) has an exceptionally high K/Ba ratio of 185. The Nnywane Formation has lower K/Rb ratios relative to the main trend of Shaw (1968). This is consistent with their apparent potassium enrichment.

5.5 Discussion of relative major and trace element abundances (all rock types)

Comparison of major and trace element abundances of the microgranite, granophyres, Kanye Volcanics and Nnywane Formation is very informative. As well as indicating whether or not these units are related and how they are related it is clear that the Kanye Volcanics and granophyres cannot be distinguished on the basis of available geochemical data, but can be distinguished very easily from the microgranite on the bases of these elements.

Compared to the Kanye Volcanics and porphyritic granophyres, the microgranite is more evolved. It has higher SiO_2, mean K_2O, Rb, Nb and Y and lower TiO_2, mean MgO and CaO, Na_2O, total iron (as Fe_2O_3), Zr and Ba. Sr and Y abundances of all three rock types show considerable variation and overlap.

The Nnywane Formation is the most compositionally variable of the four units examined in this chapter. It has anomalously high SiO_2 and K_2O and low Na_2O and CaO and more variable Rb, Sr and Ba relative to

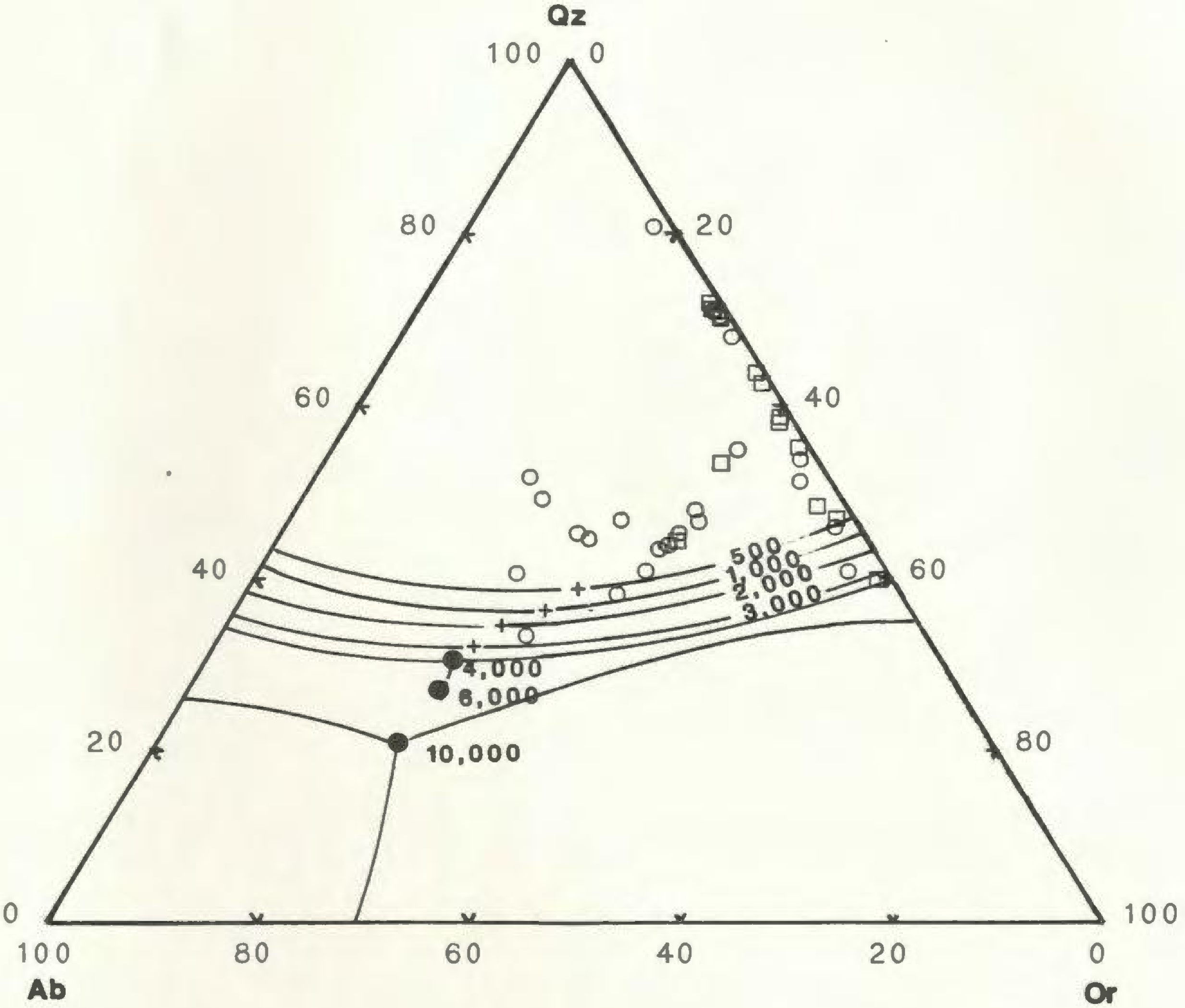
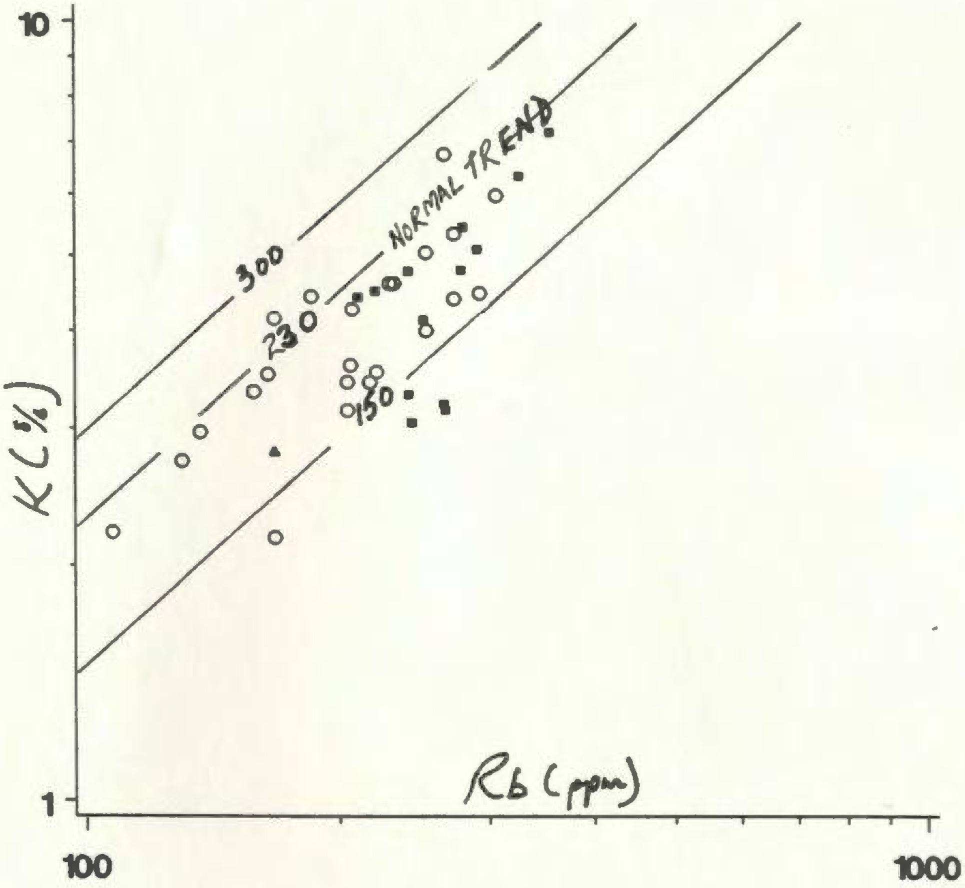
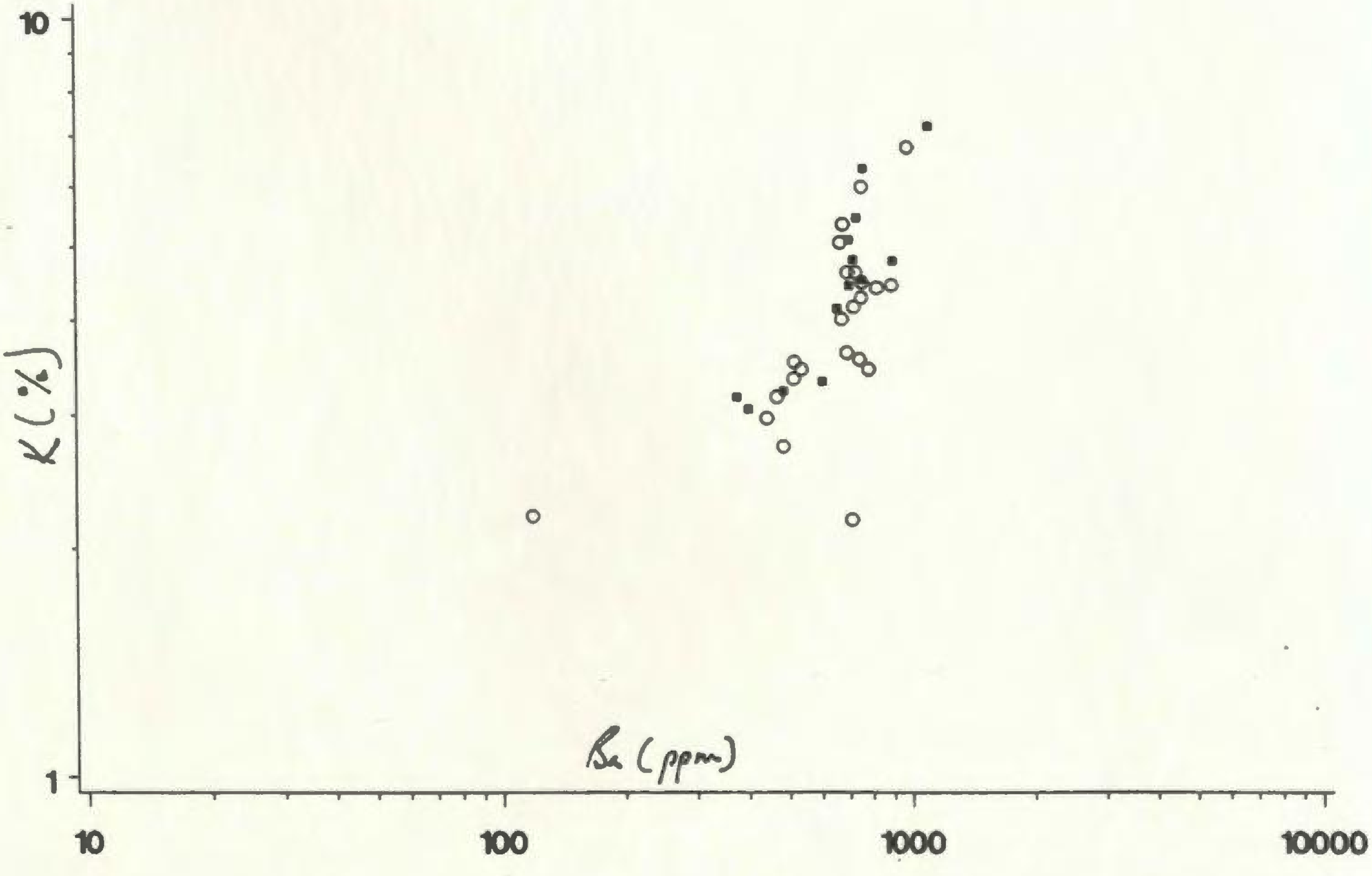


Figure 5.15 Normative Qz-Ab-Or plot for the Nnywane Formation: tuffs (open squares) and rhyolites (open circles). + indicates isobaric minima and ● indicates ternary eutectics (after Tuttle and Bowen, 1958; Ehlers, 1972, p. 189). Pressure is in bars.

Figure 5.16 (a) K (wt%) versus Rb (ppm) and (b) K (wt%) versus Ba (ppm) for the Nnywane Formation (symbols as in Fig.5.15).


10
1
100
1000
K (%)
Rb (ppm)
300
230
150
NORMAL TREND


10
1
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10000
K (%)
Ba (ppm)

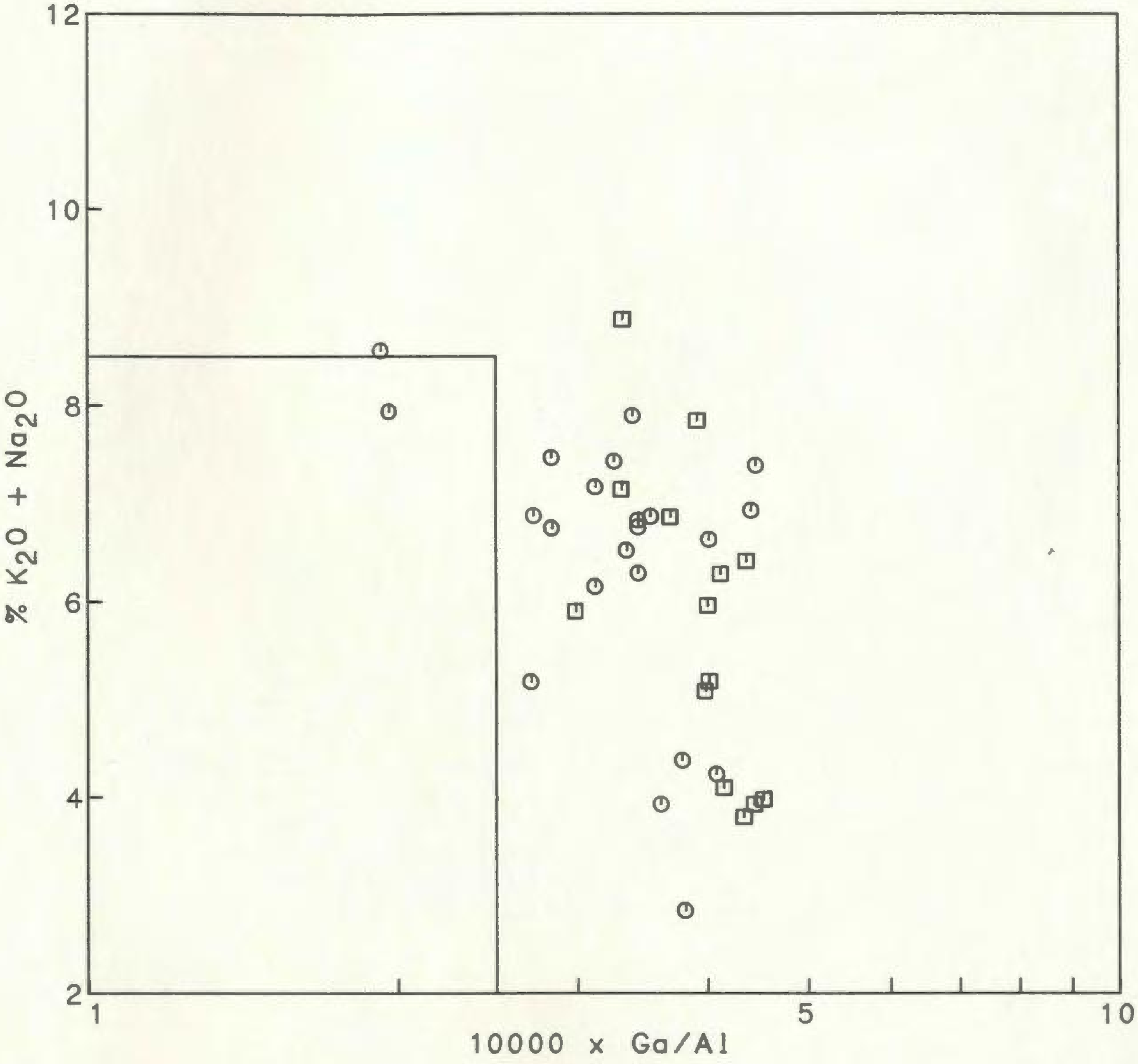

Figure 5.17a Ga/Al versus (K_2O + Na_2O) plot for the Nnywane Formation: tuffs (□) and rhyolites (⊙). Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

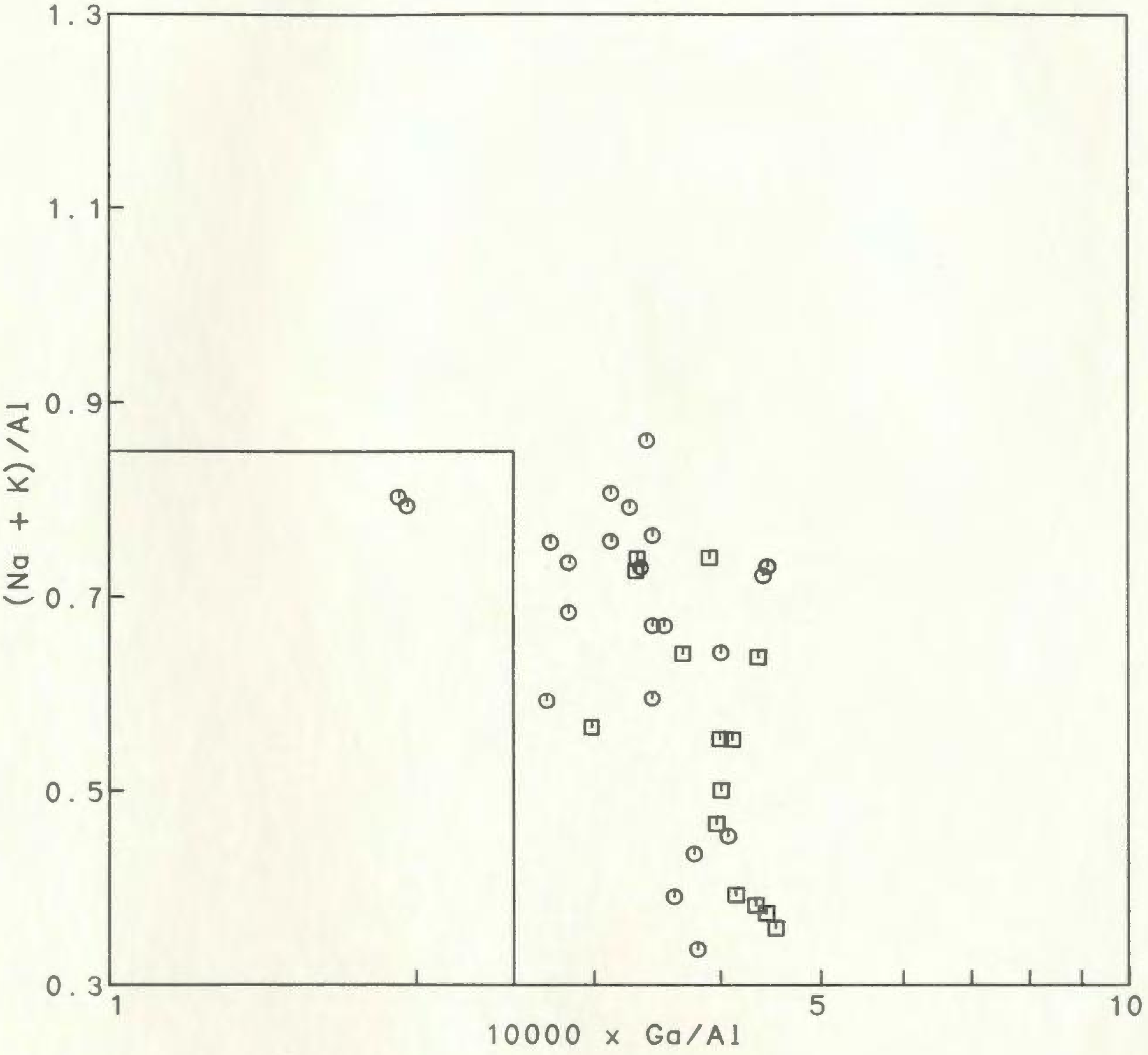

Figure 5.17b Ga/Al versus the agpaitic index [(K + Na)/Al] plot for the Nnywane Formation. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

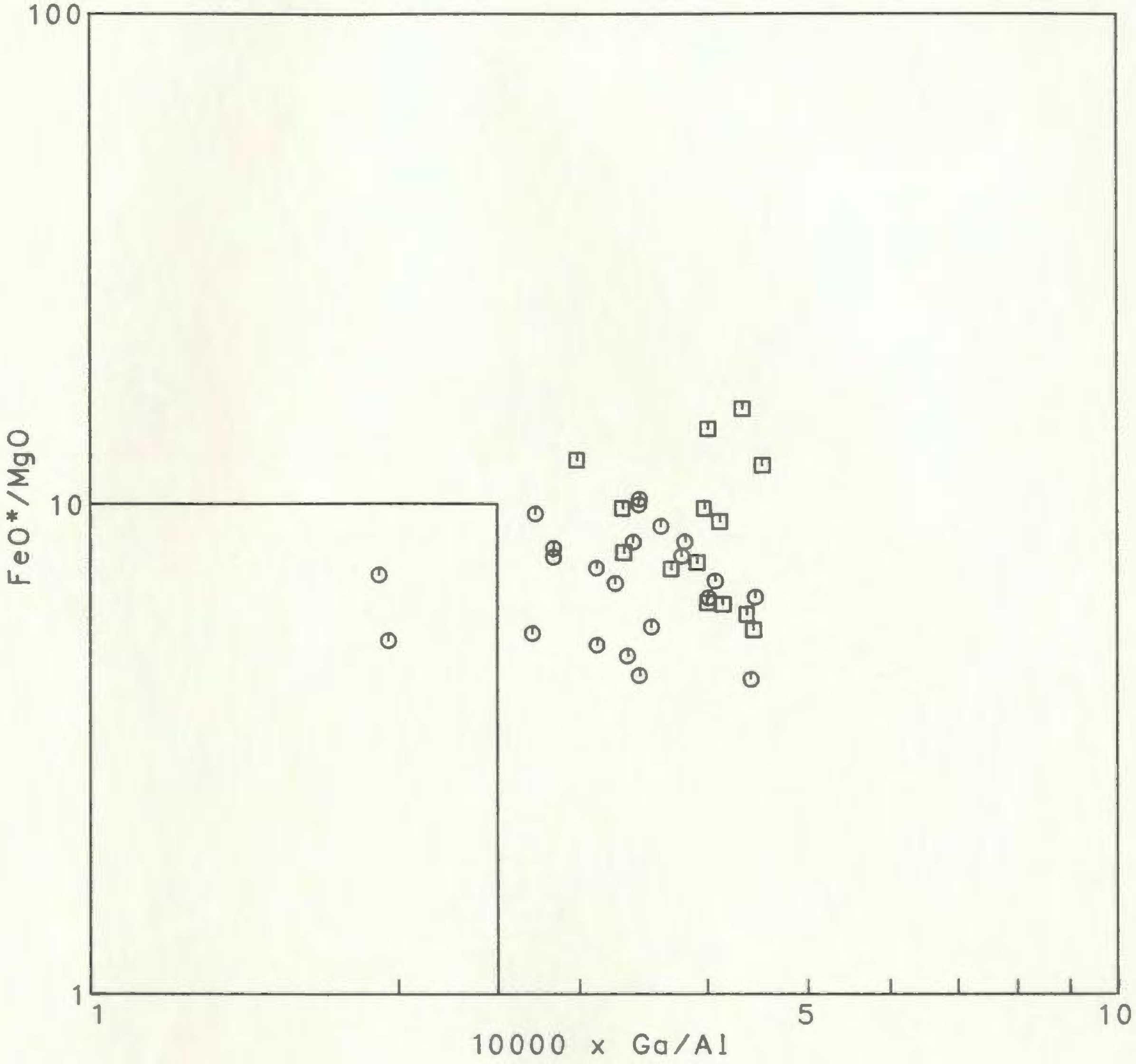

Figure 5.17c Ga/Al versus FeO/MgO plot for the Nnywane Formation. Rectangular box is the field for I-,S- and M-type granites (after Whalen et. al., 1987). FeO* = Total Fe(as FeO)

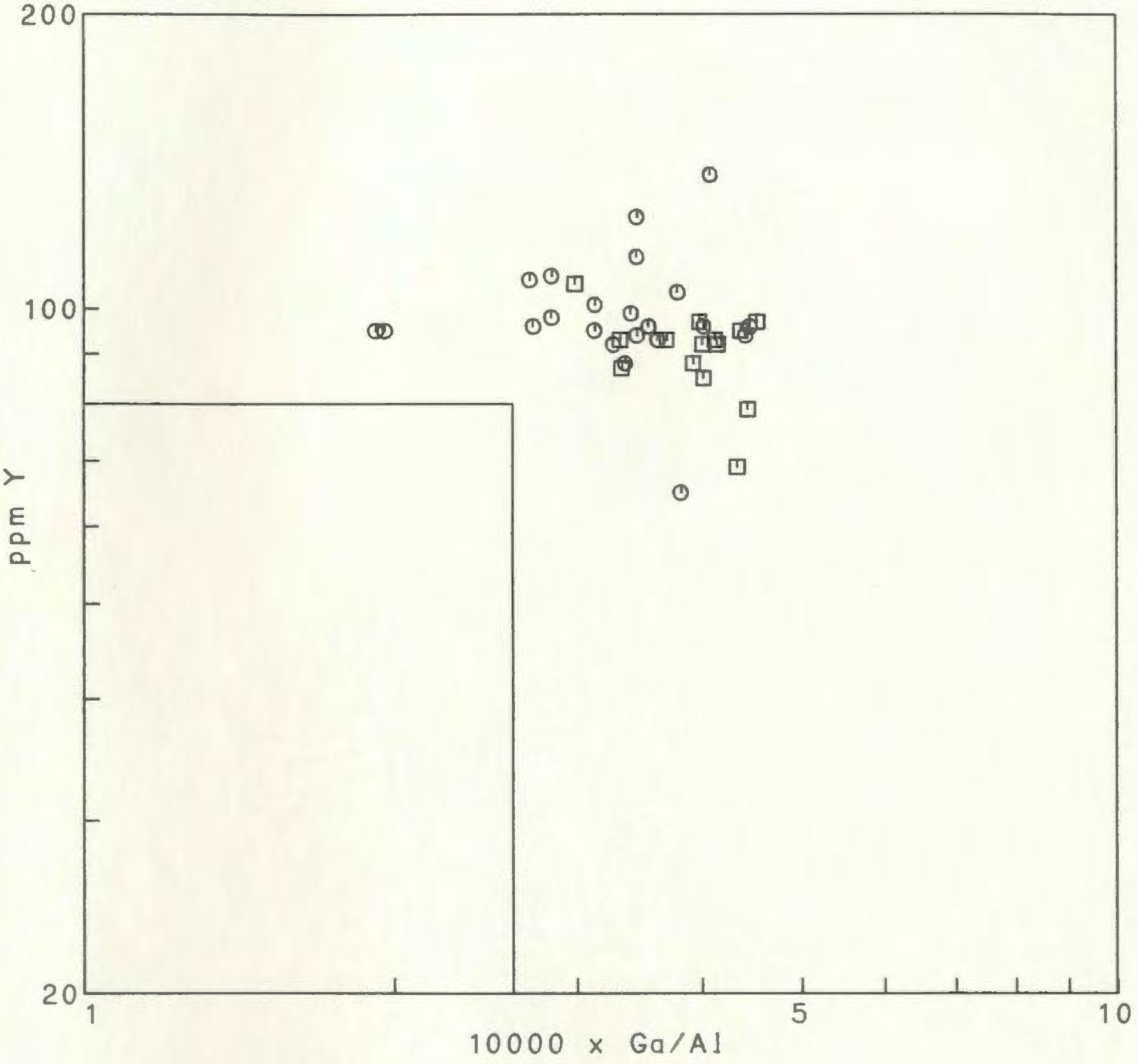

Figure 5.17d Ga/Al versus Y plot for the Nnywane Formation. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

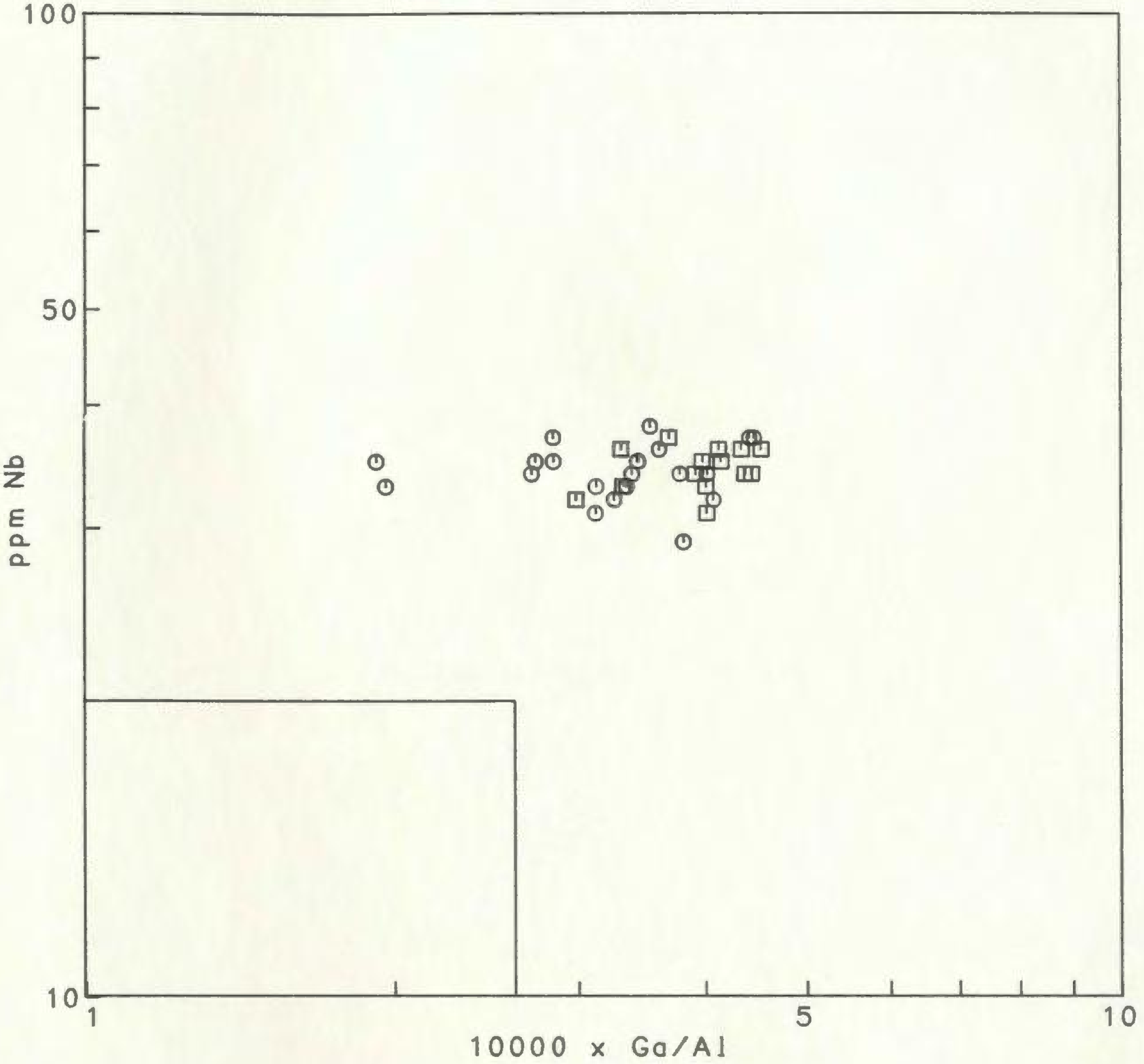

Figure 5.17e Ga/Al versus Nb plot for the Nnywane Formation. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

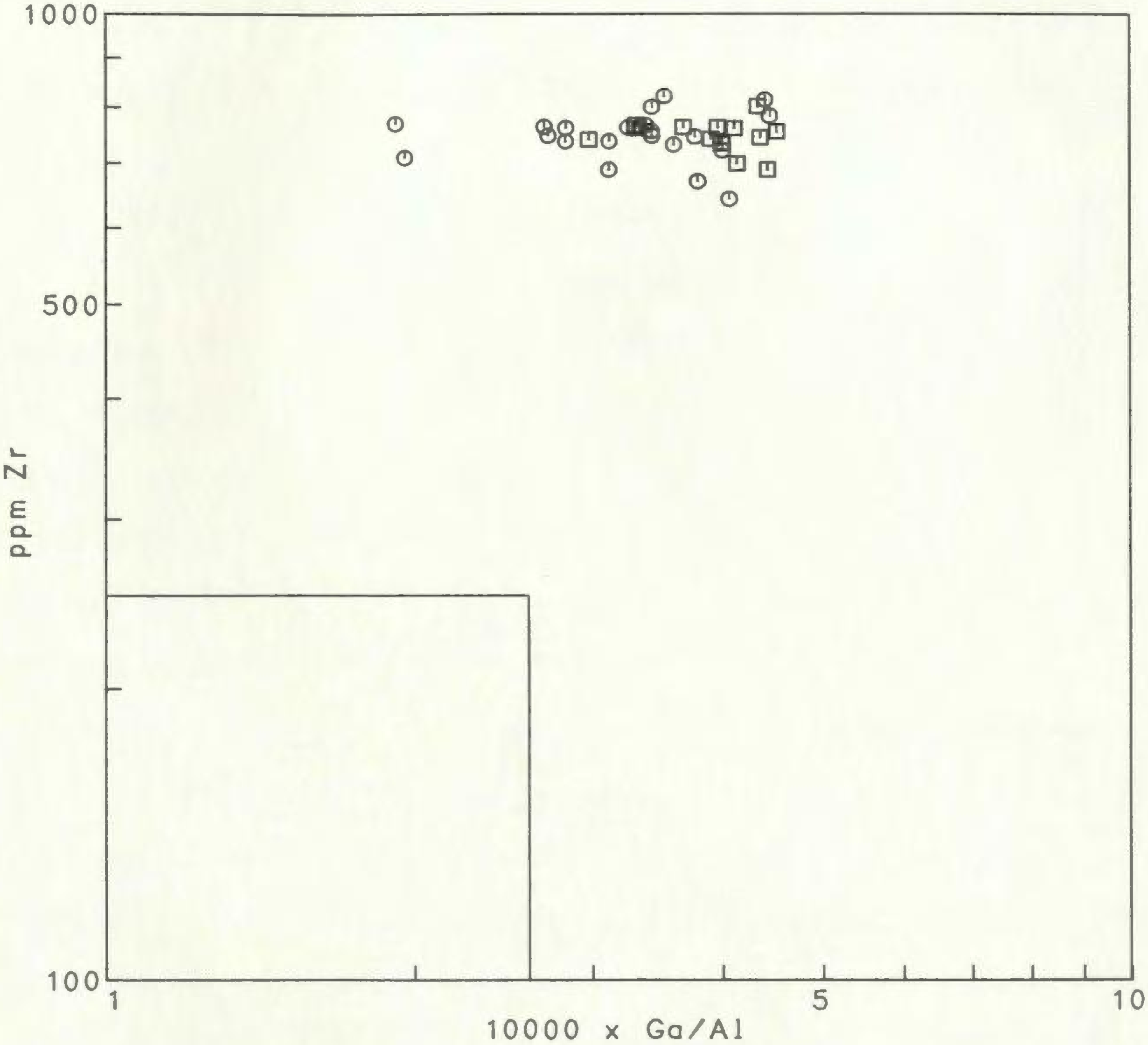

Figure 5.17f Ga/Al verus Zr plot for the Nnywane Formation. Rectangular box is the field for I-, S- and M-type granites (after Whalen et al., 1987).

the Kanye Volcanics and porphyritic granophyres (Table 5.3). Although the Nnywane Formation differs significantly from these units with respect to these elements, it has relatively the same range of TiO_2, Al_2O_3, MgO, total iron, Y, Nb, Ga and Zr concentrations (Fig. 5.2 and 5.3, Table 5.3).

Since Ti, Al, Y, Nb, and Zr are considered relatively immobile during most types of low to medium grade alteration, they are more reliable indicators of primary composition than SiO_2, K_2O, CaO and Na_2O in altered rocks. Therefore, observed compositional similarities between the Kanye Volcanics and the Nnywane Formation with respect to the immobile elements are highly significant. They suggest that these rocks could have crystallized from the same magma with little or no differentiation.

But, it is quite difficult to explain the behaviour of SiO_2, K_2O, Na_2O, CaO, Rb, Sr and Ba in the Nnywane Formation in terms of primary igneous processes. The distribution of these elements reflects the effects of post-emplacement alteration. This interpretation is based on field, petrographic and chemical evidence. Some of this evidence will be discussed in the next section. Chemical alteration of the Nnywane Formation is indicated by the following: (1) extreme compositional variations among samples from the same unit or outcrop, (2) anomalously high and low concentrations of various oxides and trace elements, (3) comparatively high LOI (loss on ignition) values relative to the Kanye Volcanics, (4) anomalously high and low amounts of normative minerals, for example, corundum, quartz and albite (Table 5.1).

If the Kanye Volcanics and Nnywane Formation originally had similar major and trace element abundances as suggested by some of the less mobile constituents, it is possible to obtain quantitative estimates of the amounts of elemental depletions and enrichments in the Nnywane Formation. For instance, the means of the Kanye Volcanics and Nnywane Formation are 72.1% and 74.4% SiO_2 and 4.98% and 5.11% K_2O, respectively. This represents increases of 3.2% and 2.6%, respectively. Similar calculations can be done for the remaining elements. However, it has to be realized that these estimates are based on the premise that the Kanye Volcanics and porphyritic granophyres are not altered.

Selective removal and addition of chemical constituents during alteration invariably camouflages primary geochemical trends on inter-element variation diagrams. This is due in part to the constant sum effect. The constant sum effect arises as a result of reporting analyses as a percentage. Because of this, addition of an element or oxide leads to dilution of all other constituents. This explains the apparent negative correlation of immobile elements with SiO_2 in Figure 5.2 and 5.3. On the other hand, removal of chemical constituents during alteration increases the proportion of immobile constituents relative to the mobile components.

5.6 Rare-earth elements

Chondrite-normalised rare-earth element (REE) patterns for the (1) microgranite, (2) porphyritic granophyres and Kanye Volcanics and (3) Nnywane Formation are presented in Figure 5.18. These rocks have very high rare-earth element abundances relative to chondrites and have relatively similar REE patterns. Their REE patterns are characterised by strong light REE enrichment, moderate to large negative Eu anomalies (indicating variable plagioclase fractionation), and flat heavy REE patterns. Flat heavy REE patterns suggest that the melts from which these rocks crystallized were not in equilbrium with garnet.

Relative REE abundances range from 350 times chondrites for La to 40 times for Yb. A detailed examination of Figure 5.18 and Table 5.2 shows that these rocks differ slightly with respect to their relative Eu anomalies, total REE contents as well as the range of REE concentrations.

Rare-earth element characteristics of the Kanye Volcanics, porphyritic granophyres and Nnywane Formation agree well with major and trace element evidence regarding their suggested genetic relationship. In addition, REE patterns of these rocks are similar to those for A-type granites and rhyolites (Collins et al., 1982; Whalen and Gariepy, 1986; Whalen et al., 1987). The fact that the microgranite has, except for Eu, relatively the same REE pattern as the volcanic rocks inspite of its more evolved major and trace element chemistry and slightly different mineralogy is somewhat difficult to explain.

5.7 Discussion of geochemical variations

While the possibility that the Kanye Volcanics, porphyritic granophyres and microgranite are chemically altered can not be ruled

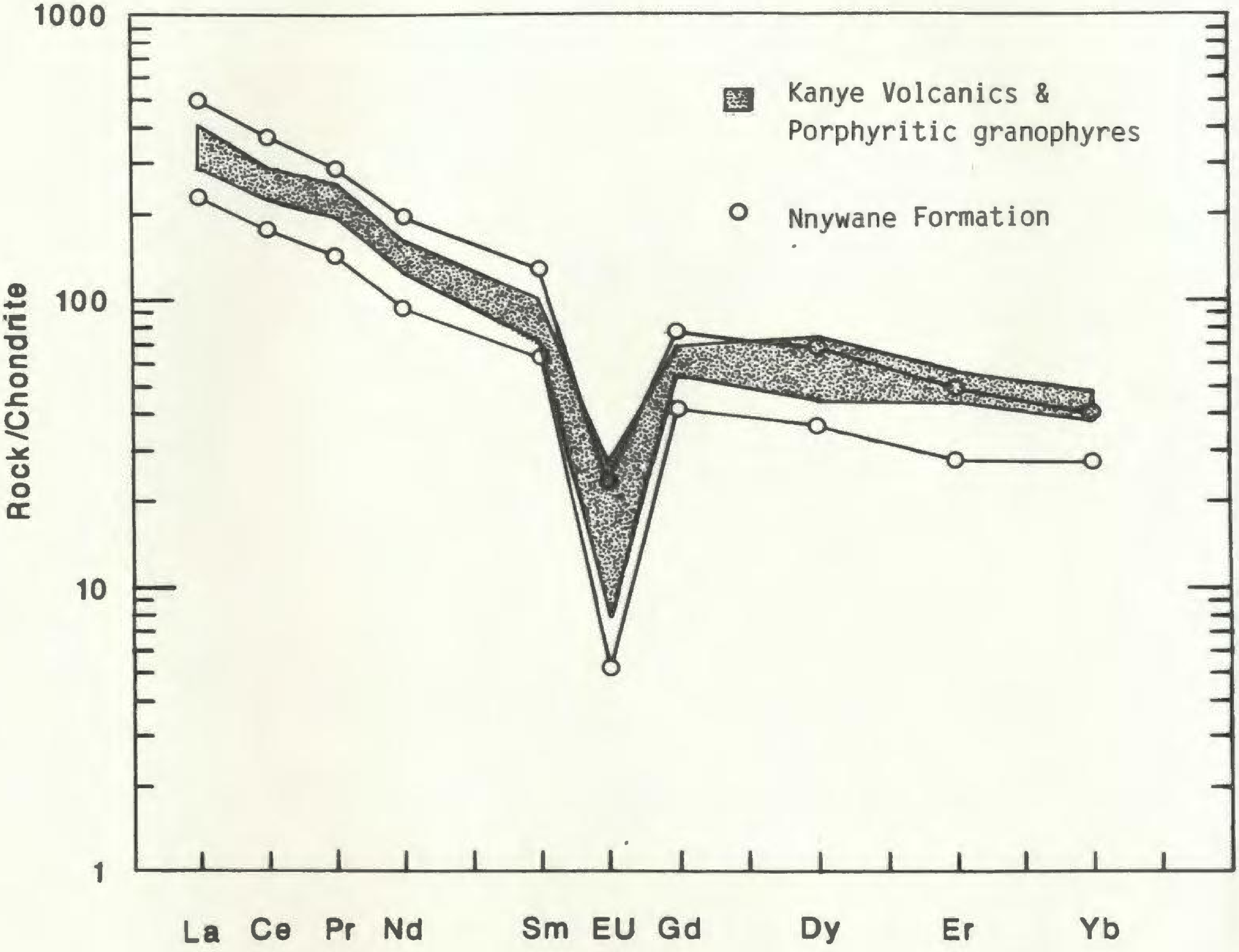

Figure 5.18a Chondrite-normalized REE patterns for the Kanye Volcanics + porphyritic granophyres and the Nnywane Formation.

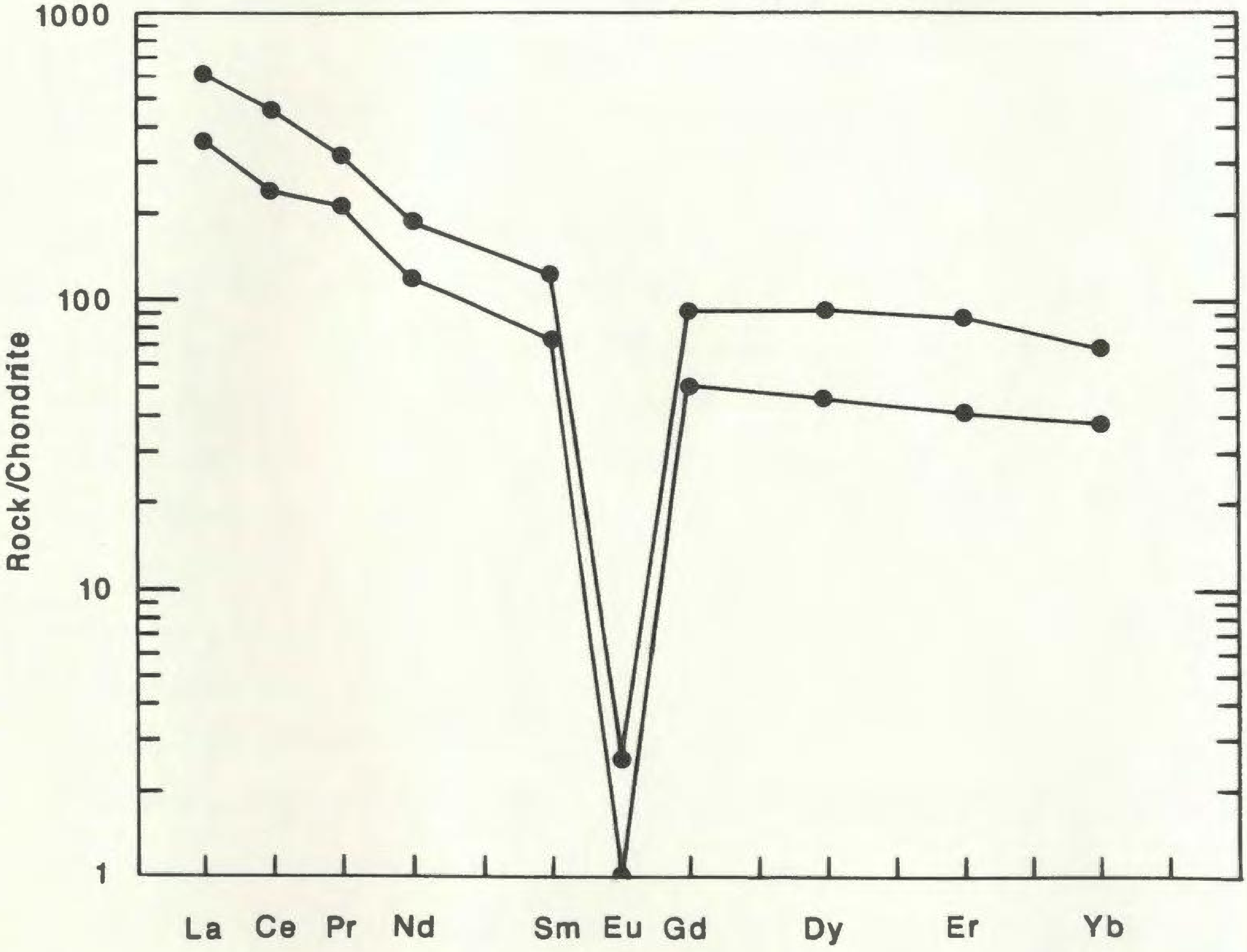

Figure 5.18b Chondrite-normalized REE patterns for the microgranite.

out entirely, there is no overwhelming evidence for a significant change in their major and trace element contents. Major element abundances of these rocks are very uniform except for CaO, MgO, total iron and TiO_2. But the variation of CaO, MgO, total iron and TiO_2 is probably due to changes in the proportion of minor phases such as biotite, amphibole and Fe-Ti oxides.

Similarly, the range of trace element concentrations within these rocks are also fairly normal except for Nb and Y in the microgranite. However, since there are only ten samples of the microgranite have been analysed, it is not clear whether these variations are typical or the analyses are not representative of the whole unit.

The relationship between the microgranite and the Kanye Volcanics is not very clear. Major and trace element abundances of these rocks have been examined, and it has been noted that the microgranite has more evolved chemistry relative to the Kanye Volcanics. Further, their plots of major and trace element analyses do not form smooth trends on Harker diagrams. And there is a significant compositional gap between these units which, in the case of SiO_2, extends from 73.6% to 75.9%. Finally, in haplogranite plots of normative Qz, Ab, and Or compositions (Figure 5.4 and 5.10), the volcanic rocks and granophyres plot at a much higher pressure cotectic than the microgranite. Therefore, as Sibiya (1988) noted, if these rocks are genetically related, it is not by simple and straightforward magmatic differentiation.

Anomalous SiO_2, K_2O, CaO, Na_2O, Rb, Sr and Ba compositional variations in the Nnywane Formation were noted in the previous section. It was suggested that these variations are due to secondary alteration of normal, siliceous volcanic rocks, essentially similar in composition to the Kanye Volcanics. A number of criteria by which the alteration may be recognized were also described.

Compositional variations in the Nnywane Formation may be due to the following processes: (1) weathering, (2) groundwater alteration and (3) hydrothermal alteration. The effects of these processes on major and trace element contents of igneous rocks, particularly acid volcanic rocks have been studied by various workers. As the following discussions show, some of these processes can not sufficiently account for the observed compositional variations in the Nnywane Formation.

1. Chemical weathering involves the breakdown, dissolution and alteration of rocks in the presence of air and water to more stable minerals at low temperatures and pressures. The extent of weathering depends on climate, duration of weathering, the composition and texture of the parent rocks. In highly fractured, porous and permeable rocks weathering profiles may extend to tens and even hundreds of metres. Clays, iron and aluminum oxides and hydroxides are the most common products of weathering.

In general, weathering of granitic parent rocks under subtropical climatic conditions results in high concentrations of SiO_2, TiO_2, Al_2O_3, K_2O, Rb and Ba and low amounts of Na_2O, CaO, Sr and, to some extent, total iron, MgO and MnO (Nesbitt, 1981; Button and Tyler, 1981; Grandstaff et al., 1986; Kimberley and Grandstaff, 1986). The increase in Titanium and Aluminum is a residual effect due to the low solubilities of oxides and hydroxides of these metals.

The amount of elemental enrichment and depletion varies with climate and length of time of weathering. Well developed soil profiles (paleosols) differ considerably from their parent rocks. Grandstaff et al. (1986) showed that soil profiles (weathered granodiorite) beneath the Dominion Reef System and Pongola Supergroup (South Africa) had lost as much as 90% of their original Na_2O and CaO, while K_2O increased by about 80% in the soil profile. SiO_2 and MgO also show a small decrease. While some of these changes and results mirror those observed in the Nnywane Formation, there are important differences. Paleosols are well-developed, mature soils. They are products of advanced weathering. In contrast, the amount of weathering in the Nnywane Formation is very superficial; only the top few centimetres of the outcrop were affected not a thick zone as in paleosols. For this reason, weathering is not considered to have caused the observed chemical variations in the Nnywane Formation.

2. Groundwater alteration is a common cause of compositional variations in volcanic rocks (e.g. Lipman, 1965; Noble, 1967; Lipman et al., 1969; Zielinski et al., 1977; Cerling et al., 1985; Yamamoto et al., 1986). Excellent reviews of the role of groundwater in the alteration of silicic volcanic rocks are given by Stewart (1979) and Fisher and Schmincke (1984, p.312). These studies have shown that groundwater alteration involves hydration of obsidian to perlite, dissolution of the glassy matrix and precipitation of new minerals such as clays and zeolites in the newly formed pore spaces, very extensive ion exchange (hydrolysis) with groundwater, resulting

in the removal of Na and addition of potassium. In addition, oxygen and hydrogen isotopic exchange with groundwater is also very common (Stewart, 1979; Cerling et al., 1985).

In general, hydrated glasses (i.e. altered glasses) contain 2 to 5 wt% H_2O and show an average loss of about 0.5 wt% Na_2O, and an increase of approximately 2 wt% SiO_2 and 0.3% K_2O. However, potassium losses of up to 0.3% have also been reported, especially in highly altered and hydrated glasses (Noble, 1967; Fisher and Schmincke, 1984; Cerling et al., 1985; Yamamoto et al., 1986). Noble (1967) and Fisher and Schmincke (1984) have suggested that the observed K_2O increase in some hydrated glasses is a transient effect and that this oxide is invariably leached during advanced alteration.

Trace elements can also be mobilized during groundwater alteration. Zielinski et al. (1977) examined trace element variations among coexisting obsidian-perlite-felsite samples from the Rocky Mountain area. They observed that perlite had slightly higher Ba and Sr than non-hydrated, unaltered glasses. Yamamoto et al. (1986) also observed that altered glasses had low Rb and Sr and high Nb, Zr and Ba relative to their unaltered equivalents.

The preceeding review illustrates some of the most significant effects of groundwater alteration on volcanic rocks. However, it is apparent that this mechanism has significant limitations. For example, chemical changes due to groundwater alteration are generally very small. In addition, alkali metals and silica are very often leached rather than enriched during advanced alteration. Except for Na_2O, these changes are clearly the opposite of what has occurred in the Nnywane Formation. Even the amounts of Na_2O removed during groundwater alteration are not comparable. Therefore, groundwater alteration cannot adequately explain the changes that have taken place in the Nnywane Formation. If it was a factor at all, it was just a minor contributor.

3. In contrast, hydrothermal fluids are more effective than groundwater as far as leaching, transporting and depositing metals is concerned. Hydrothermal alteration is also generally accompanied by considerable oxygen and hydrogen isotopic exchange with the wall-rock.

Browne (1978) listed a number of factors which determine the extent of hydrothermal alteration; these include: 1) temperature of the fluid 2) pressure 3) fluid composition 4) rock type 5) permeability 6) duration of alteration and 7) pH of the fluid. Alteration occurs when the composition of the fluid or its temperature or both are out of equilibrium with the wall rock.

Despite the importance of hydrothermal alteration in the geologic record, however, there have been very few systematic geochemical studies of hydrothermally altered subaerial acid volcanic rocks. Nevertheless, K and Na metasomatism and silica dissolution or deposition are some of the common effects produced by hydrothermal alteration as will be shown below.

Agron and Bentor (1981) have attributed the high K and low Na compositions of altered, late Precambrian alkali rhyolites of Biq'at Hayareah, south-central Sinai, to hydrothermal alteration. These rhyolites have mean Na_2O and K_2O contents of 0.22% and 7.89%, respectively, compared to a mean of 3.33 wt% Na_2O and 4.98 wt% K_2O in the unaltered specimens. In addition altered rocks showed an average increase of 3 wt% SiO_2 and have lower Fe_2O_3 and significantly higher Rb and Ba contents relative to their fresh equivalents. Rare-earth elements of altered and fresh Biq at Hayareah volcanics were very similar.

In another study, Brooks (1986) showed that potassium metasomatism of Tertiary intermediate volcanic rocks at Picacho Peak, Arizona, was due to hydrothermal alteration. Volcanic rocks at Picacho Peak (Arizona) show systematic chemical variations towards a major detachment fault. The changes are characterised by a gradual increase in K_2O, Zr and Ba and a decrease in Na_2O and MgO towards the fault. Alkali contents of altered rocks vary from 0.5% to 4.4% Na_2O and 3.9% to 13.3% K_2O. Brooks (1986) suggested that the detachment fault was the major conduit for hydrothermal fluids.

It is evident from both Agron and Bentor's (1981) and Brooks' (1986) studies that (1) hydrothermal alteration is capable of leaching and depositing higher amounts of major and trace elements than groundwater (2) the alkalis, CaO and SiO_2 are significantly more soluble in acqueous fluids than the other oxides and trace elements. More importantly, however, compositional variations in the Nnywane Formation are comparable to those produced by hydrothermal alteration of volcanic rocks described by Agron and Bentor (1981) and Brooks 1986). Apart from the geochemical evidence, other features in the Nnywane volcanic rocks suggest hydrothermal alteration. These include extensive quartz veining, the presence of amygdules(?) and secondary quartz rims around primary minerals. The amount and distribution of secondary quartz in the Nnywane Formation can sufficiently account for the observed SiO_2 variations. Other secondary minerals of possible hydrothermal origin include calcite (<1%) and biotite. The latter replaces primary minerals in the Nnywane Formation as well as the groundmass. Biotite is the only secondary K-bearing mineral and varies with the amount of potassium in the sample.

Hydrothermal alteration of the Nnywane Formation is probably related to the intrusion of the Thamaga and Kgale Granites and the microgranite. Although it is not clear why the granophyres and the Kanye Volcanics were not affected by this alteration, they were probably impermeable to aqueous fluids (hot or cold) because of their essentially hollocrystalline texture, dense nature and subvolcanic mode of emplacement. Probably they also did not have have any fractures which may have acted as conduits for hydrothermal fluids. On the other hand, the Nnywane Formation being very glassy and extremely porous was susceptible to alteration, both by hydrothermal fluids and groundwater.

5.8 Petrogenesis

As already noted, the porphyritic granophyres, the Kanye Volcanics and the Nnywane Formation have geochemical characteristics of A-type granites and rhyolites. Brief descriptions of A-type granites are given elsewhere in this chapter.

A-type granites and rhyolites typically occur in anorogenic settings, hence the term (Loiselle and Wones, 1979). They occur within rift zones as well as stable cratons. Common rock associations of A-type granites and rhyolites include (1) granites (including rapakivi and peralkaline granites), syenites, gabbros and anorthosites; and (2) bimodal granite, rhyolite, gabbro and basalt association (Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987).

In southeast Botswana the association includes rapakivi granites, gabbros and anorthositic gabbros (Sibiya, 1988). These rocks are collectively referred to as the Gaborone Granite Complex. However, relationships among the constituent assemblages of this complex still remain to be worked out. The Gaborone Granite Complex was intruded into the Kaapvaal craton about 2.83 Ga ago, but there is no structural evidence for rifting.

The origin of A-type granites has been discussed by a number of workers (e.g. Loiselle and wones, 1979; Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987). In addition to high total alkalis, Fe/Mg, Zr, Nb, Ga, Y and total REE, A-type granites generally have high fluorine and chlorine contents. A-type magmas are very dry, high-temperature melts (Collins et al., 1982; Whalen et al., 1987). These magmas are believed to be derived by high temperature, anhydrous melting of melt-depleted I-type source rocks (granulite) in the lower crust (Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987). Their high concentrations of incompatible trace elements is attributed to fluorine and chlorine complexing (Collins et al., 1982).

CHAPTER 6

SUMMARY

6.1 Summary of research findings

The main objectives of this study were (1) to examine field and stratigraphic relationships among pre-Transvaal Supergroup igneous and sedimentary formations in the Ramotswa area and, (2) to determine the relationship between the Kanye Volcanics and Nnywane Formation. The following is a summary of the findings.

1. The Kanye Volcanics are a suite of red, purple and grey, massive, porphyritic felsites. They are for the most part underlain by porphyritic granophyres and are overlain by the Nnywane Formation. The basal contact with the granophyres is gradational, while the upper contact with the Nnywane Fromation is not well defined.

Both the Kanye Volcanics and the porphyritic granophyres are intruded by a leucocratic microgranite which is regarded as a chilled margin of the Kgale Granite. It has also been established in this study that the porphyritic granophyres, Kanye Volcanics and Nnywane Formation have similar major, trace and REE chemistry and can presently be placed in the same stratigraphic unit. In view of these findings, use of the terms Ntlhantlhe Microgranite and the Lobatse Volcanic Group is not consistent with available data.

Since the age of the volcanic rocks and the granophyres is uncertain, it is not possible to correlate these rocks with any unit of pre-Transvaal age in southern Africa.

2. The stratigraphic position of the Mogobane Formation is problematical. Its contacts with the overlying Transvaal Supergroup and underlying Nnywane Formation are both unconformable. Since the

base of the Transvaal Supergroup is defined as either the Black Reef Quartzite or its basal conglomerate, the Mogobane Formation cannot be placed in this unit. It is also premature to correlate it with the Ventersdorp or any other unit in southern Africa for that matter.

3. The microgranite consists essentially of quartz and alkali feldspar (microperthite) and very small amounts of biotite. Biotite is invariably altered to chlorite. The texture, mineralogy and contact relationships of the microgranite indicate that it is a very high level intrusion.

On the other hand, the granophyres, Kanye Volcanics and Nnywane Formation are all porphyritic, indicating rapid cooling. Phenocrysts include anorthoclase and small amounts of albite, amphibole, biotite and Fe-Ti oxides in a fine-grained groundmass. Of these three units, the Nnywane Formation is considerably altered and contains a lot of secondary biotite and quartz and some calcite. These minerals can be seen replacing amphibole and feldspar phenocrysts. Amphibole and Fe-Ti oxides were not observed in the most altered samples of the Nnywane Formation.

The porphyritic granophyres are undisputably hypabyssal. Although the Kanye Volcanics are flowbanded in places, indicating extrusion, they are predominantly massive and probably dominantly hypabyssal as well. In contrast the Nnywane Formation is mainly extrusive, and is possibly the extrusive equivalent of the Kanye Volcanics. Therefore, any distinction between the Kanye Volcanics and the Nnywane Formation based on the mode of occurrence is very superficial and not always useful.

4. The microgranite is chemically similar to within-plate type granites of Pearce et al. (1984), and it has more evolved major and trace element chemistry compared to the Kanye Volcanics and the porphyritic granophyres. It also has higher total REE contents than the other rocks.

Except for SiO_2, CaO, Na_2O, K_2O, Rb and Ba, the Nnywane Formation has relatively the same range of major and trace element contents as the Kanye Volcanics and the granophyres. They all have major, trace element and rare-earth characteristics of anorogenic or A-type rhyolites. The similarities among these rocks suggest that they were all derived from essentially the same magma with little or no differentiation. Alternatively, the Kanye Volcanics and the Nnywane Formation crystallised from magmas of similar composition.

The variation of Rb and Ba and anomalously high SiO_2, K_2O and low CaO and Na_2O contents of the Nnywane Formation are attributed to hydrothermal and groundwater alteration. However, the amount of compositional variation as well as the degree of elemental enrichment and depletion observed in the Nnywane Formation is more comparable to those of hydrothermally altered silicic and intermediate volcanic rocks than those only involving groundwater interaction.

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APPENDIX A

ANALYTICAL METHODS

A-1 Sample Preparation

Rock samples from the study area were first crushed in a jaw crusher. A small amount of the crushed sample was pulverised to -200 mesh in a tungsten carbide (shatter box) bowl. This powder was used for major, trace and rare-earth element analyses.

A-2 Major Element Analyses

Major element analyses were done by G. Andrews of the Department of Earth Sciences, Memorial University, on a Perkin Elmer model 303 atomic absorption spectrophotometer.

Exactly 0.1 grams of sample were dissolved in 5 ml hydrofluoric acid and 50 ml of concentrated boric acid and heated on a steam bath. The solution was cooled and diluted with 145 ml of distilled water to give 200 ml stock solution. P_2O_5 was determined by colourimetry, while the loss on ignition (LOI) value was obtained by heating 1.5 grams of sample in a Muffle furnace at 1000°C for two hours and weighing it to determine the weight difference due to loss of volatiles.

The precision of major element analyses is monitored by running the standard rock samples (see Table A-2).

A.3 Trace Element Analysis

Trace elements were determined by a Phillips 1450 X-ray fluorescence spectrometer on pressed pellets made of 10 ± 0.5 grams of

Table A-2 Precision of major element analyses

Standard Sample GSP-1

	Published Value	No. of Analyses	Mean (Wt%)	Standard Deviation
SiO_2	67.32	7	68.65	0.60
TiO_2	0.66	7	0.60	0.08
Al_2O_3	15.28	7	14.77	0.22
Fe_2O_3	4.35	8	4.22	0.07
CaO	2.03	8	1.94	0.07
MgO	0.97	7	0.96	0.03
Na_2O	2.81	8	2.74	0.06
K_2O	5.51	6	5.44	0.12
MnO	0.04	8	0.04	0.01

* Abbey (1983)

sample powder mixed with 1.45 ± 0.5 grams of phenol formaldehyde binder. Sample pellets were baked in an oven at 200°C for 15 minutes.

Samples were run in batches of 9 including a standard of kwown trace element composition, usually GSP-1 or G-2. Table A.3 gives typical precision for Rb, Sr, Y, Nb, Ga, Zr and Ba on the XRF.

A.4 Rare-earth Element Analysis

Rare-earth elements were determined by a slightly modified thin film XRF method of Fryer (1977).

About 1 gram of sample (exact weight depends on the Y content) plus a Tm spike was weighed into a teflon beaker and dissolved in 15 ml hydrofluoric acid and a small amount of perchloric acid. The solution was heated on a hot plate to evaporate the HF. Another 15 ml of HF were added and again allowed to evaporate. This procedure was repeated with 15 ml, 15 ml and 20 ml of 2N HNO_3, respectively, to get the sample into solution. The last solution was filtered onto an ion exchange column. A final solution obtained by passing 120 ml of 8 N HNO_3 through the column was collected in a teflon beaker and evaporated to dryness. The residue was dissolved in 1 N HCl (5 ml) and passed through an HCl column.

The final sample was placed on a small paper disc, dried and analysed for REE on a Phillips 1450 X-ray fluorescence spectrometer with a tungsten carbide tube. The spectrometer was calibrated against international rock standards. Estimated errors are less than 10% for all elements except Yb which has an estimated error of less than 20%. The following elements: Tb, Ho and Lu are not reported due to

Table A-3 Precision of X-ray fluorescence analyses

G-2

	Range	Mean ±	Published Value
Rb	167 - 174	170 ± 2	170
Sr	458 - 473	464 ± 4	480
Y	11 - 18	15 ± 2	11
Nb	130 - 1	12 ± 1	13
Ga	20 - 25	23 ± 2	23
Zr	298 - 307	305 ± 3	300
Ba	1841 - 1889	1863 ± 17	1900

Published values from Abbey (1983)

significantly large errors (Fryer, 1977). In addition Tm is not reported because it was used as a spike.