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A geochemical and petrological
study of the Tertiary minor intrusions of
Rhum, Northwest Scotland.

A thesis submitted for the degree of
Doctor of Philosophy

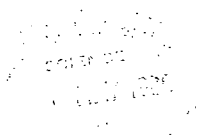
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Graduate Society

February, 1980



Petrogenesis? - God made them.

N.A. Matthew.

Dedicated to my parents, without whom
none of this would have been possible.

ABSTRACT

The Rhum minor intrusion suite is petrographically and compositionally variable, the majority of the basic rocks are aphyric dolerites but olivine phyric (picritic) and plagioclase phyric (big feldspar) dolerites are also present. In addition, several medium to coarse grained gabbro and peridotite plugs occur. Intermediate rocks are not abundant and acid dykes are rare.

The basic and intermediate intrusions occur in a variety of structural environments all over the island, the gabbros and peridotites are generally emplaced as plugs in the northern and southern Torridonian tracts, while the few acid dykes are usually closely associated with the plutonic acid rocks.

Twelve classes of dolerite (Groups 1-12) and five classes of gabbro have been distinguished on geochemical and petrographic grounds. The suite as a whole is characterised by high MgO levels when compared with rocks of analogous differentiation in other Tertiary suites of North-West Britain. Several of the group 1 picrites are believed to have existed as mafic liquids with 15-20 wt% MgO at high crustal levels. In addition the basic members (dolerite groups 2 to 4) and several of the gabbros are characterised by higher Ni and Cr and lower Al_2O_3 than comparable British Tertiary rocks. Discriminant Function analysis of the compositional variation within the basic members of the Rhum

minor intrusion suite has shown that the majority of these rocks are completely transitional between alkali olivine basalt and tholeiite basalt and contrast with the mildly alkaline Skye Main Lava Series and the mildly tholeiitic Ardnamurchan cone sheets. In contrast, the dolerite groups 5 and 6 are very similar to some of the Skye magma types and consequently are believed to be outlying members of the Skye regional dyke swarm. Of the intermediate rocks, the dolerite groups 8 and 9 and the gabbroic differentiates are tholeiitic in affinity and the dolerite groups 10 to 12 are alkalic in affinity.

Detailed field and geochemical investigation has shown there is a progression from tholeiitic basic magmas to high MgO more alkalic composition with time. Despite the known presence of a large upper crustal magma chamber on Rhum, the geochemical variation of the majority of the basic rocks is compatible with processes operating below 15 km within the lower crust, or in the upper mantle at depths up to 80 km. In contrast the big feldspar (group 7) dolerites and the magmas which gave rise to the peridotite plugs are believed to have been tapped from a high level crustal magma chamber. In addition the divergence towards more extreme alkalic and tholeiitic compositions in the intermediate rocks coupled with their general porphyritic nature and their major oxide and trace element variation suggests that they are the product of low pressure fractionation processes.

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CHAPTER ONE

THE GEOLOGY OF RHUM

Introduction

Rhum has received attention from geologists for nearly 170 years, but was first mapped and described in detail by A. Harker (1908, 1908b). Our present understanding of Rhum geology is based on several major contributions including and postdating Bailey's (1945) work in which the major dislocation enclosing the Tertiary intrusive igneous rocks was interpreted as a ring fault. Both Stewart (in Craig, 1965) and Dunham and Emeleus (1967) have reviewed the history of research on Rhum, to which publications the reader is referred for further details. Of the investigations over the past 30 years, the importance of Brown's (1956) and Wadsworth's (1961) demonstration that the layered ultrabasic rocks of Rhum are cumulus in origin and the contributions by Hughes (1960) and Dunham (1965a, 1968) on both the acid rocks and the structure of the complex in general, are outstanding.

I) General outline

Rhum is divided into two major portions by an arcuate fault, the Main Ring Fault, which separates the Torridonian and Triassic sediments of northern and



eastern Rhum from the Lewisian gneisses, the Torridonian grits and shales and the Tertiary intrusive rocks of central and western Rhum (Fig. 1.1). Lewisian gneiss and basal Torridonian grits only occur within the Main Ring Fault indicating uplift of these rocks and their associated intrusives within the confines of this fault (Bailey, 1945). The majority of the Tertiary rocks are intrusive. However a small area of lavas occurs in western Rhum, these lavas are younger than the westerly extension of the Main Ring Fault in this area as they can be seen to overlap the fault on Bloodstone Hill (NM318998) and Bealach a' Bhraig Bhig (NG340.000) (Black, 1952; Emeleus and Forster, 1979).

The intrusive rocks can be divided into two main groups, one consisting essentially of acidic rocks, the other of layered ultrabasic and associated gabbroic rocks. The acid rocks and associated breccias have been subdivided into four types (Hughes, 1960; Dunham, 1968), these being granophyre, felsite, explosion breccia and tuffisite. They occur along with Lewisian and basal Torridonian in two main areas these being the Southern Mountains Complex (Hughes, 1960), in southeastern Rhum and the Northern Margin Complex (Dunham, 1965a, 1965b, 1968) in east-central Rhum. There is also an area composed almost entirely of granophyre in western Rhum (Black, 1952). Much

of central and southern Rhum consists of a sequence of layered peridotites and gabbros.

The Geological sequence on Rhum

The geological succession on Rhum as generally understood at the present day is presented in Table 1.1. It only differs from the sequence outlined by Dunham and Emeleus (1967, Table 1.2b) by the insertion of the Papadil Gabbro pre-dating the layered peridotites and by the insertion of ultrabasic intrusion breccias prior to the intrusion of the later gabbros and peridotites (see p. 10). These ultrabasic breccias generally have poorly exposed contacts, thus Harker (1908) speculated they were intrusive contacts whilst Wadsworth (1961, 1973) considered them to be fault scarp deposits. Mapping by Donaldson (1975) revealed two better exposed breccias with intrusive contacts which led him to reinterpret all the breccia contacts as intrusive. The eastern contact of the Harris Bay breccia (Donaldson, op.cit.) was examined as part of the present study and the breccia matrix is certainly intrusive into the adjacent peridotite. Following Donaldson the ultrabasic breccias on Rhum are considered to be later intrusions into the peridotite as opposed to contemporaneous fault scarp screes.

Pre-Tertiary

Lewisian gneiss outcrops in three main areas, the largest mass lies on the western side of the Southern Mountains Complex (Hughes, 1960), another strip occurs southeast of this on the lower slopes of Sgurr nan Gilleann, the third major outcrop is west of the Long Loch in the Northern Margin Complex (Dunham, 1968). Smaller outcrops are located north of the Long Loch, south of Priomh Lochs, north of Meall Breac, on the summit of Ard Nev and between Ard Nev and Ard Mheall.

The Torridonian sequence has been divided into five major groups (Black and Welsh, 1961). The lowest member, the Basal grits, consisting of grits and shales, occurs entirely within the Main Ring Fault. However, the Bagh na h Uamha shale outcrops on both sides of the Main Ring Fault to the east of Dibidil Glen. The three remaining groups occur entirely outside the Main Ring Fault. The highest of these, the Guirdil Arkose Group, is unconformably overlain by an outlier of Triassic sediments to the north of Glen Shellesder (Fig.1.1).

Tertiary

The earliest known Tertiary rocks on Rhum are basic igneous fragments contributing to the explosion breccia in the Northern Margin Complex. Although locally important (e.g.

northeast of Loch Gammich NM 380989) the vast majority of the explosion breccia in both the Northern Margin and Southern Mountains igneous complexes consists of comminuted Torridonian with rare, but locally abundant Lewisian fragments (Hughes, 1960; Dunham, 1968).

Tuffsites which invariably cut the explosion breccias occur as masses up to 0.5 km long in the Southern Mountains (Hughes op.cit.) and as thin sheets with every angle from vertical to horizontal in the Northern Margin Complex. They are characterised by a matrix of devitrified glass with xenocrystic quartz and plagioclase. A diverse xenolith assemblage of Lewisian, Torridonian, dolerite, felsite granophyre and gabbro have been located in the Southern Mountains tuffsites but only Torridonian and occasional Lewisian fragments have been recorded in the Northern Margin Complex.

The felsites in both areas chill against and intrude the explosion breccias, although Hughes (1960) records a single fragment of felsite in an explosion breccia south of Sgurr nan Gilleann which is cut by later felsite, showing more than one intrusion of felsite magma has occurred (cf. Emeleus and Forster, 1979, p.23). Whilst tuffsite is generally earlier than felsite in the Northern Margin Complex the Southern Mountain tuffsites both contain blocks of felsite and are themselves cut by

later felsites. Thus whilst the explosion breccias are generally of earlier formation the periods of tuffisite and felsite intrusion overlapped.

The age relationships of the granophyre to the other acid intrusions are obscure as the contacts are badly exposed. In the Southern Mountains the critical contact between the Papadil granophyre and the tuffisites and felsites is unfortunately scree covered (Hughes, 1960).

Hughes (op.cit.) commented on the development of an intrusion breccia between felsite and gabbro at the head of Glen Dibidil which he believed was due to rheomorphic melting of the felsite by later gabbro and also commented on the truncation of dykes within the felsite by gabbro in Dibidil Glen. Dunham (1964) presented a more detailed study of rheomorphic melting of felsite by gabbro in the Northern Margin complex. The granophyre-peridotite contact at Harris Bay also shows veining of the more basic rock by acid veins which were attributed to rheomorphic melting by both Bailey (1956) and Wadsworth (1961). Thus the Western Granophyre predates the ultrabasic and basic rocks.

The age relationship between the Papadil granophyre and the gabbros and peridotites is less clear. Hughes (1960) noted that the gabbros from this contact possessed plagioclase clouded with magnetite dust and that magnetite

had also exsolved along the augite cleavages, features he attributed to reheating of the gabbros. Although he noted amphibole veinlets cutting the gabbro he found no evidence of the type of backveining he had encountered in Dibidil and suggested the granophyre postdated the gabbro. However, Dunham and Emeleus (1967) found recrystallisation textures in the granophyre from this contact identical to those from Harris Bay and south of Minishal where back-veining had occurred. Furthermore they pointed out that the gabbro and peridotites cross (and thus probably postdate) the Main Ring Fault and the Lewisian-granophyre boundary (Fig. 1.2).

The contact in question was examined as part of the present study to ascertain which body was the earlier intrusion. Two critical pieces of evidence suggest the gabbro post-dates the granophyre. Firstly, the contact is exposed 100 m north of the granophyre-Torridonian-gabbro triple junction (Fig. 1.2) and the gabbro here chills towards the granophyre. Secondly, basic minor intrusions 50 m north of this locality are back-veined (with veins up to 2 cm thick) in a distinctive angular manner by the enclosing granophyre. This type of veining is a common occurrence at the contacts of the major acid and basic bodies on Rhum and can help produce extensive breccias with increased rheomorphic melting (Emeleus and Forster, 1979, p.9).

Thin sections reveal that both the gabbro and the granophyre show features attributable to reheating, the granophyre in particular exhibits marked fingerprint textures in the relict plagioclase phenocrysts. Fig. 1.2 shows that the peridotite mass northeast of Papadil is in direct contact with Torridonian sandstone and appears to cut out the gabbros which lie both north and east of this contact. A later peridotite body of this size would provide a viable heat source to account for the reheating of both the Papadil granophyre and the gabbro at the contact under discussion. In addition the gabbro at Papadil is atypical when compared with other gabbros marginal to the layered peridotites, as the latter are often deeply weathered and lack the abundant xenoliths found in the Papadil gabbro. The Papadil gabbro is cut by many dykes whereas the adjacent peridotites are relatively dyke free suggesting the latter are younger.

The next event in the Tertiary sequence was the intrusion of elongate tongues of peridotite which cut Lewisian gneiss, Torridonian, explosion breccia and granophyre in the Northern Margin Complex. The easternmost tongue also cuts the Main Ring Fault (Dunham, 1965b). The tongues are petrographically distinct from peridotites of the layered series and are believed by Dunham (op.cit.) to be separated from the layered series by a drift-

covered fault marking the westerly continuation of the fault along which the main ultrabasic mass was emplaced.

The age relationships of the layered peridotites and the associated gabbros to other geological events on Rhum has been assessed by several authors. Bailey (1945) believed the ultrabasic rocks post-dated the development of the Main Ring Fault, this view was supported by Brown (1956), Wadsworth (1961), and Wager and Brown (1968); the age relationships to the adjacent acid rocks have been discussed previously. Both Brown (1956) and Wadsworth (1961) considered the layered series peridotites were emplaced in their present position as an essentially solid mass lubricated by a marginal gabbro. This gabbro is continuous along the margins of the Eastern Layered Series (Brown, 1956). However Wadsworth (1961) commented on its discontinuous nature along the margins of the Western Layered Series. Wadsworth (op.cit.) suggested the lack of faulting in those country rocks which are in direct contact with the peridotites could be explained by firstly, the differential displacement of the lubricating basic magma and secondly, the subsequent annealing of any fractured country rocks by the adjacent hot peridotite.

The layered series peridotites are frequently cut by later gabbros and eucrites. These can occur in every attitude from steeply transgressive dyke-like bodies

(e.g. Fiachinis eucrite dyke, Wadsworth 1961, Fig.2) or as sheets more or less conformable with the peridotite layering (e.g. Askival Plateau gabbro, Brown 1956, Fig.1). The sequence of gabbro intrusion is rarely determinable in the field, however Wadsworth (op.cit. p.55) suggested the gabbro west of the Long Loch fault (NM367958) postdated the Glen Harris eucrite. In addition, both Brown and Wadsworth indicate their lubricating marginal gabbro postdates many of the gabbros associated with the layered series and this marginal gabbro is also cut by a fine-grained olivine gabbro on Cnapan Breaca.

The relative ages of the ultrabasic breccias and the gabbros cannot be stated with any certainty. However Wadsworth (1961, Fig.2) shows the Lag Sleitir breccia apparently cut out by elongate gabbroic bodies on its northwestern and northeastern margins suggesting the gabbros postdate the breccias, similarly the Fiachnis eucrite dyke (Wadsworth op.cit.) may cut the north-western margin of the Ruinsival breccia.

Lavas

The lavas of western Rhum are the youngest major igneous body on Rhum. The age relationships of the lavas on Orval to the underlying granophyre were firmly established by Black (1952) who showed that they rested

unconformably on an eroded granophyre surface. The lavas are underlain by and are interbedded with conglomerates which contain cobbles of Lewisian, Torridonian, tuffisite, explosion breccia, granophyre, dolerite, basalt and gabbro (Dunham and Emeleus, 1967). Subsequent investigation has also revealed cobbles of felsite (Emeleus et al., 1971; Emeleus and Forster, 1979) and allivalite (Emeleus and Forster op.cit.). The presence of the ultrabasic rocks confirms that the emplacement and subsequent erosion with unroofing of the layered peridotites occurred prior to the extrusion of the lavas.

II) Previous research on the minor intrusions of Rhum

Introduction

Two major works form the basis of our understanding of the minor intrusions of Rhum at the present day. The first major contribution was made by Harker (1908) who collated several points of interest in his Small Isles Memoir. A more recent contribution was made by Speight (1972) in a structurally orientated study of dyke distribution patterns in the Small Isles, Skye and Ardnamurchan. In addition to these works the contact relationships of some basic dykes intruded into the western Granophyre were studied by Roobol (1971) and brief reference to other minor intrusions has been made by several authors (Hughes

1960, p.114; Wadsworth, 1961, p.57; Dunham and Emeleus 1967; Emeleus, 1973, p.159).

The two major works differ in scope. Harker incorporated observations on all the minor intrusions including basic sills, rare acid dykes and the gabbro and peridotite plugs. He was concerned with the distribution of the basic dykes over the whole island unlike Speight (1972) who studied only coastal sections within the Torridonian and thus did not deal with dyke relationships within the central complex. A full discussion of the quasi-statistical techniques used in his thesis is given by Speight (1972, Chapter V).

a) Basic Dykes

- i) Distribution of the basic dykes as a function of the host rocks.

Harker (1908) had definite views on the intensity of the dyke swarm as a function of the host rock. He believed the granophyres were relatively dyke free and considered the abundance of dykes exposed along the coast northwest of Harris to be a "noteworthy exception". He also maintained that the Torridonian sandstones and the plutonic basic and ultrabasic rocks were intruded by a similar number of dykes. In addition other authors note the truncation of dykes at major contacts on Rhum.

Hughes (1960) and Dunham and Emeleus (1967) mention the occurrence of basic sheets in the felsite in Dibidil and on Cnapan Breaca respectively which do not cut the adjacent gabbros, similarly Wadsworth (1961) noted the truncation of dykes in the Western Granophyre by the later gabbro and peridotite.

ii) Dyke trends

Rhum is sometimes cited as a good example of a volcanic centre with an associated radial dyke swarm (Richey 1948, p.86). This was first asserted by Harker (1908) and has been reiterated by Richey (1961, pp. 96-97). Stewart (1965) and Dunham and Emeleus (1967). However, this view has been recently contested by Speight (1972). His investigations showed that the Torridonian outside the Main Ring Fault contains a linear dyke swarm (see section iii). Fig. 1.3 (taken from Speight 1972, p.334) shows a radial pattern cannot be discerned using the projection of the average trend of groups of ten dykes. The possibility of a radial dyke swarm cutting the ultrabasic rocks is discussed later (Chapter 2, p. 31). Speight (op.cit.) arbitrarily selected dykes trending NE-SW and referred these to a Rhum sub-swarm (a technique he also applied on Skye and Ardnamurchan) the validity of this sub-swarm is discussed in Chapter 2, p. 29 .

iii) The intensity of the dyke swarm

That dykes are numerous on Rhum is evidenced by the accounts of Harker (1908, p.143) who recorded nearly 700 dykes and Speight (op.cit) located approximately 1000 dykes in coastal sections alone. Fig. 1.4 reproduced from Speight (op.cit. Fig.115) shows the dyke distribution is uneven with axes of high intensity running SE from the coast line at Papadil and the Allt nam Ba and NW from Kilmory. The map illustrating dyke intensity as a function of percentage crustal dilation (Speight op.cit., Fig.114) shows similar dyke intensity distribution patterns, the general maximum crustal dilation along the high intensity axes is between three and four percent although over five percent crustal dilation occurs on the coastline near the mouth of the Allt nam Ba.

Fig. 1.4 shows all the characteristics of a linear swarm, this is highlighted by the low dyke intensities on the northeastern coast of Rhum which Speight (1972, p.334) believed was further evidence against a radial dyke distribution pattern on Rhum.

iv) The dips and thicknesses of the dykes

All the previous work on these topics is incorporated in Speight's (1972) thesis. He noted that in general more dykes dipped SW as opposed to NE, an exception being the

dykes of northwestern Rhum and stated that the dykes varied from 0.2 m to 11.0 m thick with most dykes lying in the range 0.4-0.8 m.

b) Distribution of the sills and inclined sheets

Harker (1908) recognised five different varieties of basic sheet in his classification of the minor intrusions of Rhum. These generally occur only in the Torridonian, however one group, the inclined sheets, was also seen cutting the acid and ultrabasic rocks. A full account of the inclined sheets is presented later (Chapter 2, p. 38). Another group, the dolerite sills cutting the Rhum lavas were reinterpreted as the massive dolerite centres to basaltic lavas by Tomkeiff (1942, p.2).

In northwest Rhum, Harker (op.cit.) recorded the presence of a conspicuous sill running SW from Kilmory which he described as both a "feldspar porphyritic basalt" and a basic augite andesite without olivine. He also noted the presence of a different set of aphyric "basic augite andesites" in the southwestern part of the island.

The fifth type of sheet was only briefly referred to by Harker (op.cit.), these were thin sill-like bodies of limited lateral extent which cut the Torridonian of northern Rhum.

c) Acid Dykes

Harker (op.cit.) noted the rare occurrence of three acid dykes on Rhum, he also mentioned a pitchstone specimen in the older collections of the Geological Survey labelled as coming from Fionchra, which he failed to relocate. A recent detailed survey in the Fionchra region did not locate any pitchstone dykes (Emeleus pers. comm.) thus the survey specimen was probably either incorrectly labelled or not collected in situ.

d) Gabbro and peridotite plugs

Harker (1908) located approximately 15 peridotite plugs ranging up to 700 m in size. He considered them all to be intrusive with near vertical contacts one exception being the intrusion north of Bealach Mhic Neill (NM380998) which he suggested was lacolithic in form. The two ultrabasic dykes he describes occurring west of Papadil are, in fact, small elongate peridotite plugs. Dunham and Emeleus (1967) pointed out that the peridotite knoll west of Loch Sgoarishal show matrix banding and other features recollective of the tongues in the Northern Margin Complex (Dunham, 1965b) and suggested they could be of similar age.

Approximately 45 intrusive gabbroic bodies were located by Harker (1908) varying in dimension from 700 to 75 m. He distinguished 2 compositional varieties, one

gabbroic and the other eucritic, the latter apparently cutting only the layered peridotites. Dunham and Emeleus (1967) noted petrographic similarities between gabbros in the northern Torridonian tract and the early gabbros in the Northern Margin Complex but stated the postulated early age of the former could not be demonstrated in the field.

e) The sequence of intrusion

The chronological sequence of both major and minor intrusions as proposed by Harker (1908) is presented in Table 1.2a. As Harker considered that the gabbros and peridotites predated the felsites, it is clear why he believed there was a greater abundance of dykes in the former. A revised sequence of both major and minor intrusion proposed by Dunham and Emeleus (1967) is also presented in Table 1.2b. The position of both the cone sheets and the late radial dyke swarm in this second sequence is in agreement with the more general account of Stewart (1965).

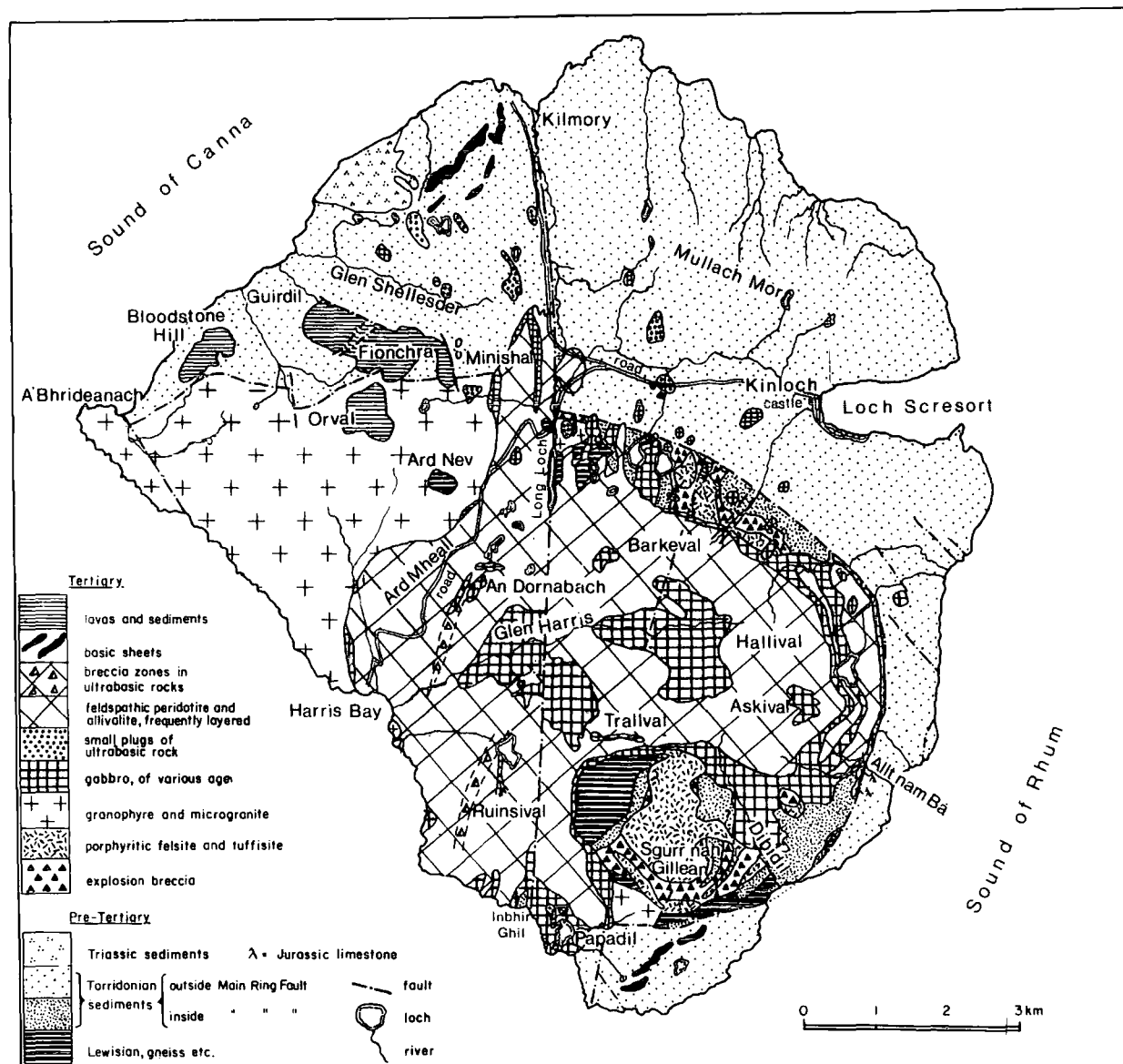
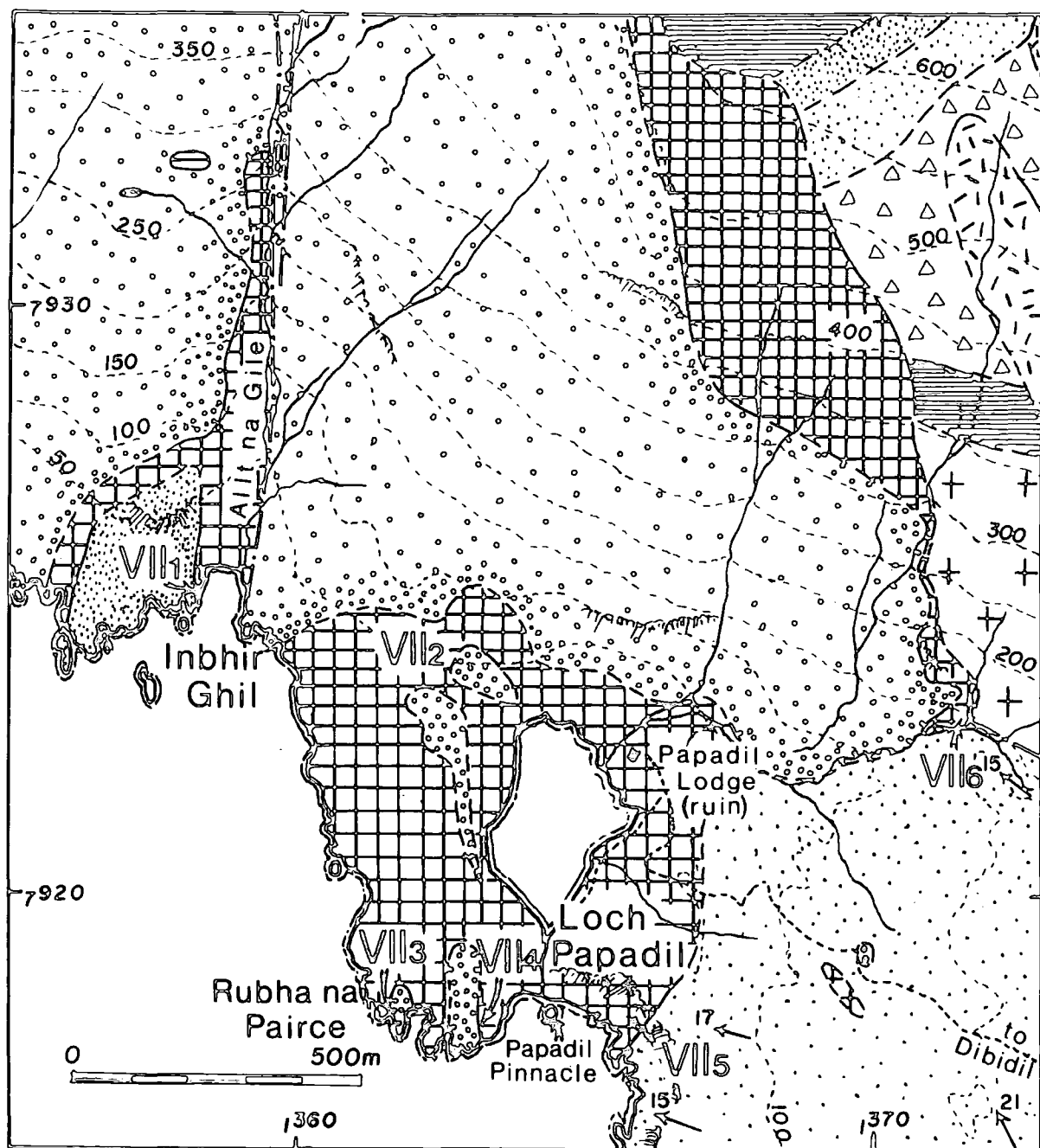


Fig. 1.1 Geological map of Rhum.

Fig. 1.2 Geological map of Papadil, Southern Rhum; taken from Emeleus and Forster (1979, Fig.16). For relationship to general geology see Fig.1.

	Peridotite
	Gabbro
	Granophyre
	Porphyritic felsite
	Explosion breccia
	Torridonian sandstone
	Dip of sediments, in degrees
	Contours in metres
	Footpath



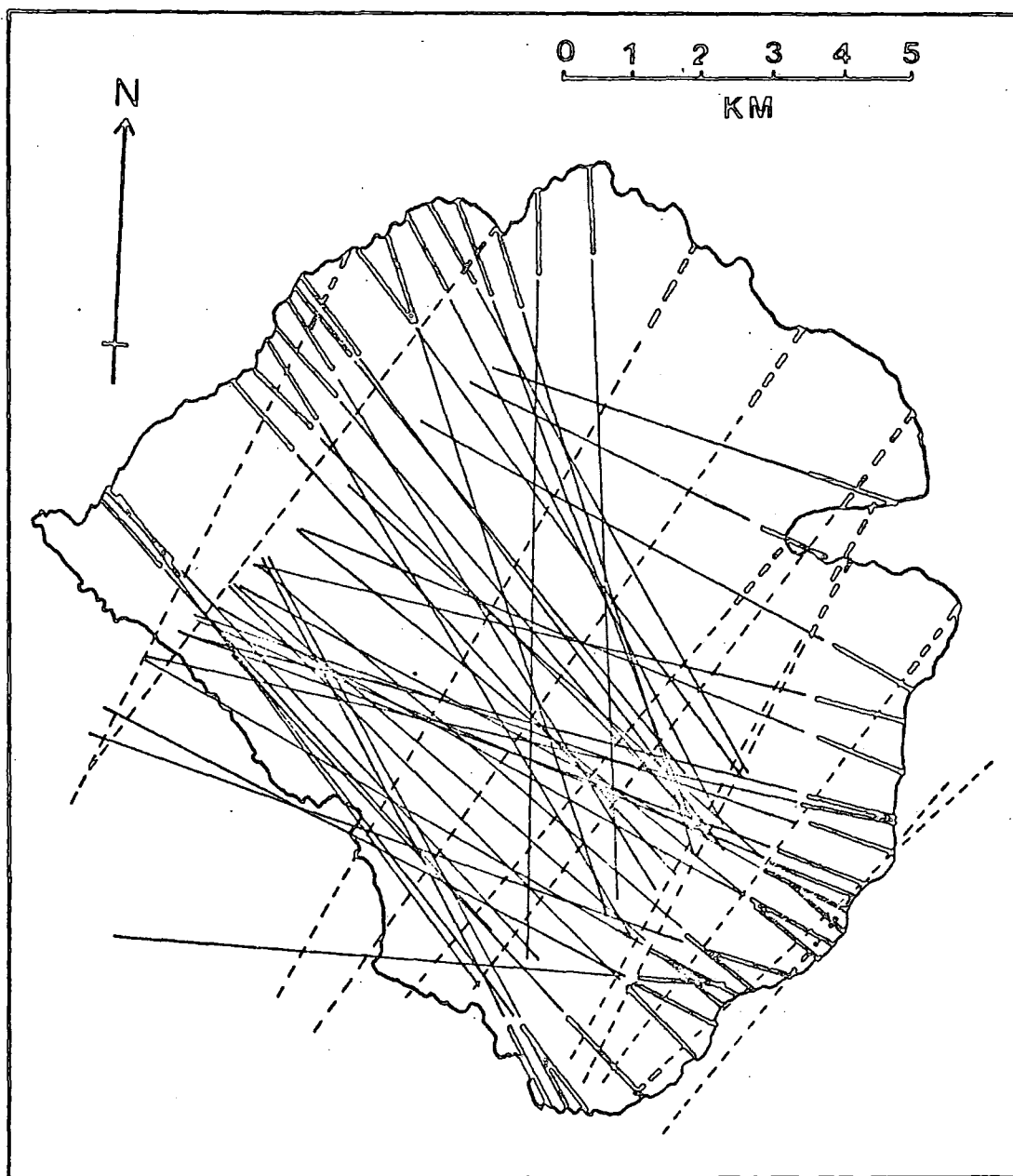


Fig. 1.3. Projection of the average trends of groups of ten dykes (redrawn from Speight 1972, Fig.109)

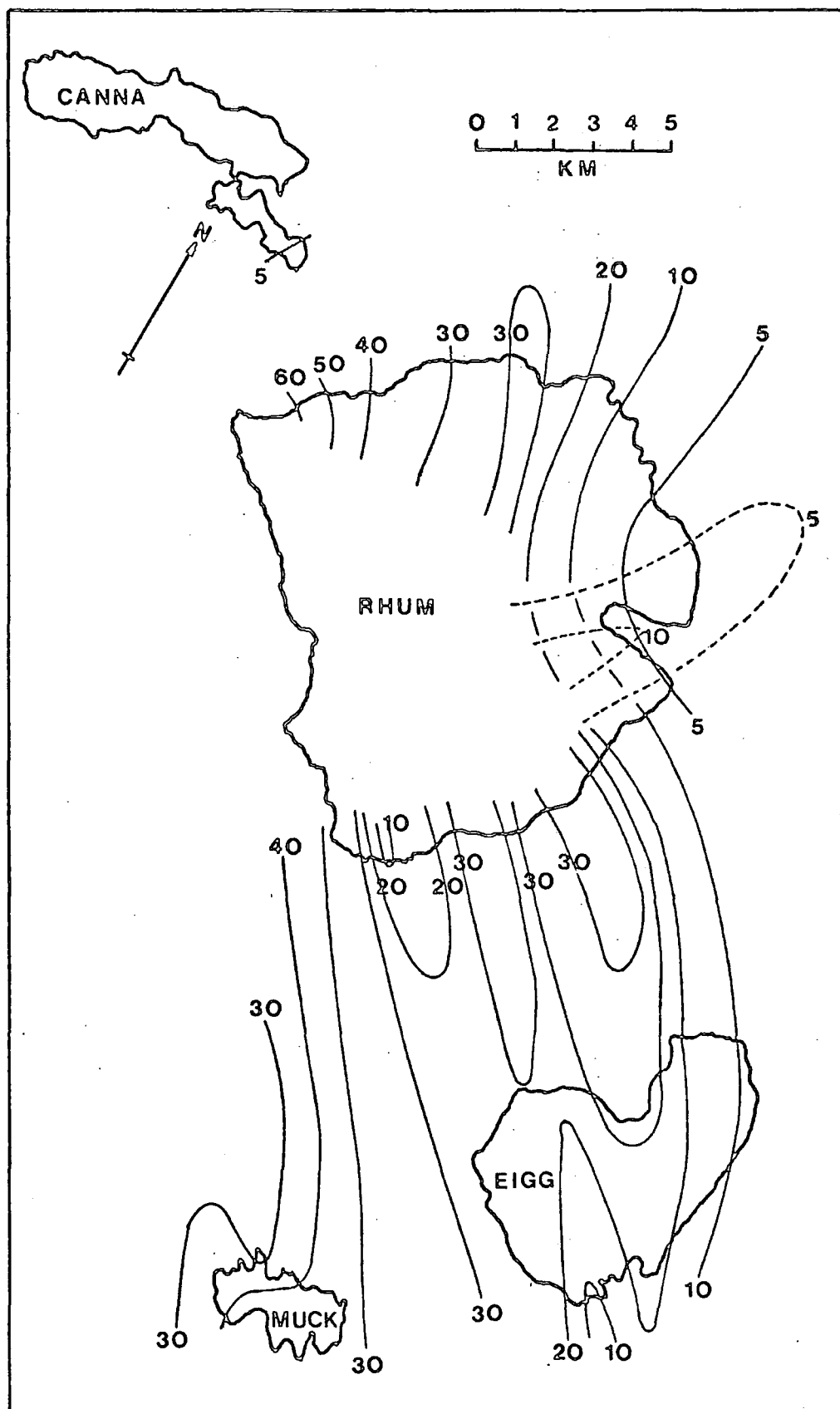


Fig. 1.4. Number of dykes per kilometre in the coastal strata of Rhum, and the Small Isles (redrawn from Speight (1972, Fig.115)).

Lavas

Fine-grained olivine gabbro

Marginal gabbro

Gabbro and peridotites cutting ultrabasic rocks

Ultrabasic intrusion breccias

Layered peridotites

Ultrabasic tongues	} age relations may be reversed
Papadil gabbro	

Main Ring Fault

Granophyre

Felsite

Tuffisite

Explosion breccia

Triassic

Torridonian

Lewisian

Table 1.1. The chronological sequence of major Tertiary events and pre-Tertiary rocks on Rhum.

	Pitchstones	Lavas	
	Ultrabasic dykes		Radial basic and ultrabasic dykes
	Basic Andesite Sheets	Fine-grained olivine gabbro	
	Inclined sheets		
Felsite	Quartz felsite dyke	Ultrabasic tongues	Peridotite plugs
			Cone sheets
Granophyre			
Basic rocks	Gabbro and peridotite plugs	Granophyre	
		Felsite	
Ultrabasic rocks			Tachylitic sheets
	Great group of sills		
Basaltic Lavas		Tuffisites	
	Basaltic material in solfataric dykes	Explosion breccia	
			Early Gabbros
	<u>A</u>		<u>B</u>

Table 1.2. The sequence of major and minor intrusion envisaged by (A) Harker (1908) and (B) Dunham and Emeleus (1967).

CHAPTER TWO

FIELD RELATIONSHIPS

Introduction

Approximately 4 months fieldwork was undertaken to establish a minor intrusion stratigraphy. This was achieved by detailed mapping of cross-cutting relationships in well exposed areas and assessing the behaviour of minor intrusions along well exposed contacts. Four major categories of minor intrusions were recognised in the field, these are in order of decreasing abundance:

- 1) Dolerite dykes, sheets and sills.
- 2) Gabbroic plugs.
- 3) Peridotite plugs.
- 4) Acid dykes and sheets.

The Main Ring Fault forms a major break in the Tertiary geological sequence on Rhum and this is reflected in the distribution and the orientation of the minor intrusions. Poor exposure along the line of the fault makes correlation of the sequences of minor intrusions developed on both sides of the fault impossible. The sequence of minor intrusions on each side of the fault is presented in Table 2.1. The location within the sequence of each of the minor intrusion types is discussed in the text.

1. Dolerite dykes, sheets and sills.

These have been divided in the field into four types, these being: dykes, inclined sheets, thin conformable sheets and thick conformable sheets. The term dyke as used in this thesis is defined as an intrusive discordant tabular body which can vary in attitude from approximately 60° to vertical; the term inclined sheets refers to intrusive discordant tabular dolerite bodies which have dips of 60° or less. The term parallel inclined sheet is restricted to a distinct set of intrusions on Rhum as discussed in the text.

a) Dykes and inclined sheets

i) Field and hand specimen characteristics.

This description included all the dolerites except the picritic and big feldspar dykes which are discussed separately. The dykes and inclined sheets are typically aphyric or microporphyritic and thus lack distinctive field characteristics. The vast majority are between 20 cm to 80 cm thick, however dykes up to 18 m thick have been located. Some dykes vary in thickness along strike and can be seen to progressively expand then thin to a tachylitic termination before continuing en echelon along strike. This range in dyke thickness reflects in the grain size of the dykes, some (in particular the thinner dykes) are extremely fine-grained whereas other thicker dykes

have virtually "gabbroic" centres.

The Torridonian sediments adjacent to the contacts of some dykes (eg. a northern trending dyke in Kinloch Glen NG 372005) may be bleached up to 20 cm from the contact. This thermal metamorphism is attributed to passage of magma through the dyke fracture which may have acted as a feeder to overlying lavas and sills (cf. Preston, 1967). These dykes possess only slight chilled margins and contrast with other tachylitic margined dykes (tachylitic sheets of Dunham and Emeleus, 1967), which possess thick chilled margins.

Despite the gross similarity of the bulk of the dolerite hand specimens it is possible to recognise some differences in the field. In general, the dark grey-black specimens tend to be more mafic than the more common dull grey varieties. Increasing differentiation produces mesocratic specimens often characterised by a green-grey colour and the most differentiated specimens are a pale cream-grey colour on fresh faces. Plagioclase, clinopyroxene and to a lesser extent olivine phenocrysts (in various combinations) can be recognised in some specimens.

Xenoliths have been located in some dykes and inclined sheets but they are extremely sparse. Although Speight (1972) found that xenoliths were more abundant in dykes adjacent to the central complexes, xenoliths in

dykes associated with the central complexes of Arran (Tyrrel, 1928), Ardnamurchan (Richey and Thomas, 1930) and Mull (Bailey et al., 1924) are not abundant thus Rhum is not anomalous in this respect.

Multiple dolerite dykes (those involving two or more phases of dolerite injection into the same fissure) are not abundant on Rhum. A simple multiple dolerite involving two facies, the later central facies possessing a slight chill can be seen on Dibidil shore (NM 385925) a more complicated example is located at Papadil (NM 362918).

ii) Distribution and orientation of the dykes and inclined sheets.

The strike trends of dykes and inclined sheets recorded from 11 different areas on Rhum are presented as rose diagrams on Fig. 2.1. Some duplication of the work of Speight (1972) has been unavoidable and the data itemised by Speight (op.cit. p.535, Appendix 18) has been used to supplement this account when necessary.

The rose diagrams for dykes and inclined sheets cutting the Torridonian between Papadil and Dibidil and at the Allt nam Ba (roses 4 and 7, Fig. 2.1) confirm the linearity and the NW-SE strike of the dykes and inclined sheets in the southern part of the island. However, the rose diagrams for dykes and inclined sheets in the northern part of the island (roses 11, 12 and 13, Fig. 2.1) suggest

a more radial distribution. Rose diagrams plotted using Speight's (op.cit.) original data for the northern and eastern part of the island (Fig. 2.2 and 2.3) substantiate this apparent radial distribution, the change in strike trend from NNW through N to NNE, between Glen Shellesder, Kilmory and Rubna na Roinne in particular, suggest a radial dyke distribution.

The dyke intensity map (Fig. 1.4) is clear evidence of the linearity of the Rhum swarm. To account for the anomalous strike directions in the Rubna na Roinne area Speight suggested they represented a separate sub-swarm distinct from the Rhum linear swarm similar to perpendicular sub-swarms he had encountered on Skye. Reference to rose 10 (Fig. 2.1) shows a bimodal distribution of dyke strike trends in the Allt Slugan a Choilich (based on 51 readings) somewhat similar to the trends encountered around Rubna na Roinne (rose 11 Fig. 2.1 and RE Fig. 2.2 and 2.3), thus supporting Speight's ideas.

Mapping east of the Long Loch fault in the Mullach Mor area has revealed dykes following N-S fractures in the Torridonian which parallel the Long Loch fault. The only unimodal N-S trending dyke sets on Rhum occur in traverses across the Long Loch fault at Papadil and Kilmory (roses 3 and 12, Fig. 2.1 and RD Fig. 2.2). It is likely that the N-S basement fracture which gave rise to

the Long Loch fault has strongly influenced the dyke trends in the Papadil and Kilmory areas.

Examination of the dyke and inclined sheet trends within the Main Ring Fault cutting the sequence Torridonian to tuffisite in Corrie Dubh and the Southern Mountains (roses 5 and 7, Fig. 2.1) show that dykes and inclined sheets of all trends occur, with two trends at NNW and NNE being better represented. Dykes and inclined sheets of all trends have been recorded in the gneisses and Torridonian in lower Dibidil and in the felsite on Beinn nan Stac (rose 6, Fig. 2.1). The strong E-W trend defined in this last rose diagram may be in part attributable to the N-S trend of the traverse in the Dibidil river which is more likely to encounter E-W as opposed to N-S dykes.

These diagrams support the impression gained in the field that the numerous dykes and inclined sheets within the Main Ring Fault strike in all directions and testify to a complicated structural history. Analysis of the cross cutting relationships exhibited by the dykes and inclined sheets on Cnapan Breac and in Stony Corrie (Figs. 2.4, 2.5, 2.6) confirms this complicated history, as no simple age relationships of one trend relative to another can be resolved, although dykes or inclined sheets trending 270° - 310° generally cut dykes or inclined sheets trending 320° - 335° in Stony Corrie.

The northwesterly trend of the dykes cutting the Western Granophyre at Harris (rose 1, Fig. 2.1) is somewhat anomalous and may be due to basement control as postulated for Kilmory and Papadil.

It was suggested in Chapter 1 (p. 13) that the dykes cutting the layered peridotites may have developed a radial distribution. To test this hypothesis the dykes from five different localities were plotted on Fig. 2.7 where the abscissa is the strike trend of the dyke in question and the ordinate is the angular bearing of this dyke outcrop relative to the centre of the ultrabasic mass estimated to be at NM 370960. The diagram is heavily biased from dykes recorded in Harris Bay as the well exposed coastal section revealed relatively abundant dykes when compared with the inland exposures. A perfect radial distribution would result in the dykes plotting along Line A-B in Fig. 2.7. The dykes from the inland exposures (Barkeval etc.) plot fairly close to A-B however the dykes from Harris clearly cover the complete range of possible dyke orientations with the majority lying in the range 40° - 100° . The Harris Bay section is the best exposed area and thus could possibly be viewed as the most representative data set. However, it is possible that the dyke trends in this area are the product of a radial dyke distribution with a superimposed NW-SE trending set attributable to basement

fractures as postulated for the NW-SE trending dykes in the Western Granophyre.

Despite the limitations of the data and the arbitrary selection of a centre for the ultrabasic mass, the dyke orientations presented in Fig. 2.7 suggest that a radial dyke distribution can be discerned in the ultrabasic rocks of Rhum, a radial dyke swarm will develop when the maximum principal stress (P_{max}) is vertical (Robson and Barr, 1964); thus the radial dyke swarm is supporting evidence for the upward emplacement of the ultrabasic rocks as envisaged by Brown (1956) and Wadsworth (1961).

iii) Age relationships

Detailed mapping along well exposed contacts and the interpretation of the rose diagram trends in Fig. 2.1 has allowed evaluation of the dolerite dykes and inclined sheets relative to the major igneous bodies and other minor intrusions on both sides of the Main Ring Fault (Table 2.1). The change in strike direction across the ring fault at the Allt nam Ba and between Papadil and Dibidil (Fig. 2.1) suggests that the Main Rhum Linear Swarm is truncated by the fault. Although many of the dykes in the linear swarm may be contemporaneous with some of the dykes within the Main Ring Fault, the former were originally emplaced at a higher structural level.

There are several episodes of intrusion within the Rhum Linear Swarm as some dykes in well exposed traverses (e.g. at the foot of Glen Shellesder NG 329016) can be seen to cut older dykes. In addition the thick and thin conformable sheets truncate and are cut by dykes of the Rhum Linear Swarm thus allowing some subdivision of the swarm relative to these stratigraphic indicators. The age relationship of the Rhum Linear Swarm to the layered peridotites and gabbros is demonstrated on Minishal (NG 358005) and at the Allt nam Ba (NM 408943) where the dykes can be seen to be veined and thermally metamorphosed in the Torridonian sediments but are not found in the adjoining mafic rocks which are well exposed in and near Allt nam Ba.

The dykes cutting the post-central complex lavas of western Rhum are the youngest identifiable dolerite dykes on Rhum. The sparse dykes cutting the gabbro and peridotite plugs may be of similar age.

The relative age relationships of dykes and inclined sheets within the Main Ring Fault has been achieved by mapping the contacts between the rock types involved in the early "acid" phase of magmatism and between these and the later basic and ultrabasic igneous rocks. Maps from two of the critical areas are presented in Figs. 2.5 and 2.6.

Dunham (1968, p.330) noted occasional dolerite fragments in the explosion breccias of the Northern Margin Complex which would indicate a "pre-acid" dyke phase. However, the bulk of the explosion breccia consists of Torridonian blocks in a comminuted Torridonian matrix and dolerite fragments are extremely rare. Thus the vast majority of the dykes and inclined sheets postdate the explosion breccias. The presence of a liquid-liquid contact between dolerite and felsite in Stony Corrie, Dibidil (Fig. 2.6) is evidence of contemporaneous acid-basic magmatism but such occurrences are rare.

Mapping along the well exposed explosion breccia-felsite-tuffisite contacts on Cnapan Breaca (Fig. 2.5) and between explosion breccia and felsite in Stony Corrie (Fig. 2.6) has shown that none of the dykes or inclined sheets are truncated at these contacts strongly suggesting the bulk of the dykes and inclined sheets in this area postdate the emplacement of the acid rocks. Supporting evidence comes from several contacts on the island listed in Table 2.2.

As previously stated (Chapter 1, p. 6) the contacts between the granophyre and the earlier "acid phase" rocks on Rhum are not exposed. However, in view of the close temporal and spatial association of the acid rocks proposed by Dunham (1968) it is unlikely that any significant

dyke phase developed in the tuffisite-granophyre interval.

The contact between the Western Granophyre south of Harris Mausoleum (Fig. 2.8) shows that the abundant dolerite dykes and inclined sheets in the granophyre are not found in the adjacent peridotite. Truncation of dolerite dykes and inclined sheets perpendicular to the acid-basic and acid-ultrabasic contacts can be clearly seen at the localities listed in Table 2.3. These contacts confirm the impression gained in the field that dykes and inclined sheets are less abundant in the ultrabasic tract.

In conclusion the majority of the dolerite dykes and inclined sheets on Rhum appear to postdate the emplacement of the acid rocks and predate the emplacement of the gabbros and peridotites.

b) Picritic dykes

Olivine phyric dykes are typically black in hand specimen. They are generally 30 cm to 60 cm thick and rarely exceed 1 m. Several (but not all) of the dykes have olivine enriched centres attributed to laminar flow differentiation during emplacement, a process believed to have operated in similar but wider picritic dykes on Skye (Gibb, 1968).

Picritic dykes have been found at several localities (see Fig. 2.9). They do not represent a single discrete

magmatic event as several different petrographic types are represented (Chapter 4, p.94). The petrographic variation makes assessment of their field relationships difficult. Some (Type 2 picrites p.96) contribute to the Rhum Linear Swarm and a dyke petrographically similar to these cuts Lewisian inside the Main Ring Fault. Another petrographically similar dyke cuts the peridotite plug east of Loch Sgoarishal (NG 351023) suggesting a fairly young age for these dykes.

The picritic dykes in the Allt Slugan a Choilich (Type 1, p. 94) cut inclined sheets and other dolerite dykes, a petrographically similar dyke from Rubna nam Meirlach is cut by a younger dolerite dyke. The picritic dykes truncated and thermally metamorphosed by the peridotite body on eastern Minishal (NG 358005) have variolitic groundmass plagioclase somewhat similar to some of the dykes in the Allt Slugan a Choilich, thus it is possible the latter predate the emplacement of the layered series.

In conclusion the picritic dykes postdate the inclined sheets and some appear to pre-date the emplacement of the peridotites. They are generally fresh suggesting that they post-date the dolerite dykes and inclined sheets which are often altered but are occasionally cut by later dolerite dykes.

c) Big feldspar dykes

The majority of these dykes occur as 0.5 m to 1.5 m grey-black weathering dykes with abundant (up to 50%) 0.5 cm to 2 cm diameter tabular euhedral plagioclase phenocrysts. The dykes are resistant to erosion and generally form slight topographic highs in areas of outcrop. They show no appreciable flow differentiation as phenocrysts are abundant across the full width of the dyke.

Big feldspar dykes are found on both sides of the Main Ring Fault (see Fig. 2.11) and the dyke on Bealach Mhic Neill (NM 378994) appears to cut the fault. However, another big feldspar dyke on An Mam (NM 382993) located approximately 50 m south of the Main Ring Fault is cut by a minor fault sub-parallel to the Main Ring Fault and is also sheared and crushed suggesting a pre-ring fault age. On balance the extensive occurrence of big feldspar dykes on both sides of the Main Ring Fault suggests they postdate that event and the shearing in the dyke on An Mam may be due to later minor movement along the Main Ring Fault.

That these dykes post-date the acid rocks but pre-date the layered peridotites and associated gabbros is clearly seen at the felsite-gabbro contact on Meall Breac (Emeleus and Forster, 1979, p.18) on the granophyre-peridotite contacts at Papadil and Ard Nev (Emeleus and Forster op cit.,

p.39). A 20 cm thick big feldspar dyke cuts a thick conformable sheet east of Papadil (NM 376914) and a 1 m thick dyke cuts a thin conformable sheet north of Glen Shellesder (NG 349006).

d) Parallel inclined sheets

These sheets are generally composed of a grey weathering aphyric or mildly porphyritic dolerite. Many of the parallel inclined sheets are very resistant to erosion and they form a distinctive minor cap rock to waterfalls in the Allt Slugan a Choilich stream section SW of Kinloch Castle. When examined in detail, some sheets can be seen to thin and progressively wedge out suggesting that individual sheets are not laterally continuous.

The parallel inclined sheets are abundant in the Allt Slugan a Choilich stream section and can also be seen cutting Torridonian sediments north of Corrie Dubh and on Bealach Mhic Neill. They are not seen in the deep gully immediately south of the ring fault on the Allt Slugan a Choilich and thus pre-date the ring fault. They are cut by picritic and dolerite dykes and by the gabbro plug east of the Allt Slugan a Choilich (NM 315985). Their relationship to the Main Rhum Linear Swarm and the conformable sheets is not known.

Dunham (1962, p.211) noted that two sets of parallel

inclined sheets were present in the Allt Sluggan a Choilich, one dipping towards the southwest, the other westwards. In a later published account (Dunham and Emeleus, 1967, p.401) the authors identified two sets of parallel inclined sheets in the Allt Sluggan a Choilich, one set dipping towards Glen Harris, the other dipping in a southwesterly (as opposed to westerly in the earlier account) direction. The dip directions of all the dolerite sheets exposed in the Allt Sluggan a Choilich have been plotted on Fig. 2.10 and only a single dominant SSW trend is represented. It seems possible that in his original account Dunham (1962) incorrectly considered the thin conformable sheets with a regional west to north-west dip exposed in the lower reaches of the stream were structurally analogous to the southwesterly dipping parallel inclined sheets situated nearer the central complex.

Inclined sheets or cone sheets?

The set of dolerite sheets on the northeastern margin of the complex were originally referred to as inclined sheets by Harker (1908) but later workers Hughes (1955), Dunham (1962), Dunham and Emeleus (1967) have used the term cone sheet to describe both these and the other inclined dolerite sheets on the island.

The term cone sheet was first used by the authors of the Mull Memoir (Bailey et al., 1924, p.6), these authors plainly state that the term is a synonym of "inclined sheet" as described on Skye by Harker (1908). A more precise definition of the term cone sheet is offered by the authors of the Ardnamurchan Memoir (Richey and Thomas, 1930, p.56) who state:

"cone sheets consist of relatively thin sheets, which viewed as members of a suite, occupy conical fissures that have a common apex and common vertical axis".

Harker (1908, p.163) considered the dolerite sheets dipping north in Dibidil and dipping WNW in the ultra-basic rocks of Askival to belong to the same set of inclined dolerite sheets on the northeastern margin of the complex. It is clear from his original account he considered these scattered inclined sheets were analogous to the intense inclined dolerite sheets he had encountered on Skye (Harker op cit., p.163).

Later workers using the term cone sheet expanded Harker's (1908) ideas. Hughes (1955, p.132) described three ages of cone sheet; an earlier set dipping 25° N was cut by a later set dipping 40° NNE with another set dipping in a south-westerly direction. He noted that the age relationships could be reversed and there was no

systematic variation in dip. Dunham (1962, p.212) correlated the parallel inclined sheets outside the Main Ring Fault with inclined sheets cutting rocks inside the fault and considered them to be part of a cone-sheet system.

It is clear from these accounts that the distribution of inclined sheets within the Main Ring Fault is erratic. In addition mapping within the fault shows a multiplicity of inclined dolerite sheets and dykes striking and dipping in all directions (see Fig. 2.1, 2.4). The set of parallel inclined sheets on the NE margin of the complex formed at a different structural level to sheets within the central complex as the former are truncated by the Main Ring Fault. In view of the complex and erratic distribution of the inclined dolerite sheets within the Main Ring Fault it seems unlikely that they are analogous to the more regular arrays of concentrically arranged cone sheets in other Tertiary centres. The parallel inclined sheets outside the Main Ring Fault could be part of an incomplete cone-sheet system; however, their role in the structural history of the complex is not clear.

e) Thin conformable sheets

Sheets of dolerite generally conformable with the Torridonian bedding are fairly abundant in the arkosic

Torridonian outside the Main Ring Fault in northern and southern Rhum but are absent from the shale-rich horizons of eastern Rhum. They vary from black to grey in hand specimen and some specimens contain plagioclase and occasionally olivine macrophenocrysts. They can range from 2 cm to 1 m in thickness but are generally less than 0.5 m thick. They generally possess the regional Torridonian dip of $20-30^{\circ}\text{NW}$ but can be transgressive along false bedding planes. They produce only minimal contact alteration in the enclosing sediments.

Although cross-cutting relationships have not been located it is likely in view of their varied petrography that they were emplaced in more than one event. Field evidence supporting this can be seen east of Kinloch (NM 410998) where two sheets converge with no intervening Torridonian screen. They both possess chilled margins on the adjacent dolerite faces and with the Torridonian suggesting that the earlier sheet had completely cooled before the later sheet was intruded.

Sheets both cut and are cut by dolerite dykes and have been seen to be cut by picritic and big feldspar dykes. Direct evidence concerning the relative ages of the thick and thin conformable sheets is available at Kilmory where a vertical dyke cutting a thin sheet is truncated by an overlying thick sheet. Thermally metamorphosed thin

conformable sheets occur in the contact aureoles of peridotite and gabbro plugs in Glen Shellesder (NG 351103) and north of Bealach Mhic Neill (NM 380995). In addition the gabbro-Torridonian contact west of Papadil Pinnacle (NM 365926) shows truncation of the thin conformable sheets by later gabbros.

Although the age relationships of the thin conformable sheets relative to the Main Ring Fault and the inclined sheets are not exposed, the former appear to be of an early age and may predate the formation of the ring fault.

f) Thick conformable sheets

Two petrographically different sets of 3 m thick conformable sheets have been located on Rhum, one set outcrops SW of Kilmory, the other NNE of Papadil (Fig. 2.11). The former consist of a pale grey plagioclase-clinopyroxene aphyric dolerite. The sheets are more resistant to weathering than the enclosing arkoses and produce a distinctive topography in areas of outcrop. The sheets are occasionally transgressive and although the majority are of constant thickness a 0.5 m thick sheet located at Kilmory is petrographically identical to the thicker-sheets.

The Papadil sheets are similar in topographic expression to those near Kilmory but differ as they are aphyric. They usually possess a 30-40 cm thick vesicular

band approximately 1 m below the upper contact, in addition a discontinuous 10 cm thick vesicular band occasionally develops approximately 75 cm below the main vesiculated band.

The Papadil sheets cut dolerite dykes but are themselves cut by later dolerite dykes, a big feldspar dyke and a peridotite plug (NM 379917) but dykes cutting the Kilmory sheets have not been located suggesting they may be younger than the Papadil type. The relative age of the Kilmory and the thin conformable sheets have been discussed previously (p.42). In conclusion the thick conformable sheets are all probably of a similar general age, postdating the thin conformable sheets and much of the Rhum Linear Swarm and predating the gabbro and peridotite plugs.

The thick conformable sheets intrude Torridonian sediments of different stratigraphic height (the Papadil sheets lie approximately 3000 m stratigraphically below the Kilmory sheets). However, this difference in stratigraphic height is probably fortuitous. The Torridonian sediments developed their regional northwest dip prior to the development of the Tertiary complex. The location of the sheets NW and SSE of the central complex is probably related to upwelling of magmas along the NW-SE striking axes identified by Speight (1972, Fig. 1.4). The

ability of the Torridonian to cleave along major bedding planes allowing sill emplacement in these areas is probably more important than its location within the stratigraphic sequence.

2. Gabbro Plugs

Abundant gabbro plugs have been located (Fig. 2.11); they range in size from 20 m to 150 m diameter and occur as circular to elongate masses. They are variable in hand specimen, the majority are medium grained but coarse grained varieties with pegmatitic patches are found in the Northern Margin Complex (Dunham and Emeleus, 1967, p. 395). Differentiated gabbros have been located in the northern Torridonian tract, they are leucocratic in hand specimen but as with the less differentiated gabbros the mafics have been altered.

The gabbros can induce considerable bleaching in the enclosing sediments up to 30 m from the contacts. The sediments adjacent to the contacts often show fritted textures indicative of partial melting and the gabbros are unchilled. It seems likely that the gabbros infill a fracture which previously acted as a conduit to overlying lavas.

The relative ages of the early and late gabbros in the Northern Margin Complex were discussed by Dunham and

Emeleus (1967, p.405). The former are characteristically coarse grained and can contribute to the explosion breccias whereas the latter are medium grained and cut Lewisian gneiss, Torridonian explosion breccia, granophyre, the Main Ring Fault and the peridotite tongues.

Dunham and Emeleus (op.cit) tentatively correlated some of the altered gabbros outside the Main Ring Fault with the early gabbros of the Northern Margin Complex on a petrographic basis. However, the altered early gabbros within the Main Ring Fault contain both hypersthene and augite and the plagioclase is characteristically zoned and consequently contrast with the altered gabbros outside this fault as the latter lack hypersthene and often contain pseudomorphed olivine. The early gabbros have a distinctive composition (Chapter 7, p.241) and three gabbros immediately NE of the Northern Margin Complex are compositionally similar to the early gabbros suggesting that they are coeval. However, the compositional and petrographic dissimilarity of the remaining gabbros outside the Main Ring Fault suggests they are of different age.

The gabbros outside the Main Ring Fault cut the thick and thin conformable sheets and are generally dyke free in areas of known high dyke intensity (e.g. the Sgoarishal area), thus several of these gabbros are likely to be young in age and are probably much younger than the compositionally distinctive early gabbros within the Main Ring Fault.

The geographic distribution of the gabbro plugs on Rhum is shown in Fig. 2.11. There are two main gabbro plug concentrations in northwestern Rhum and along the northeastern margin of the complex. A few gabbros outcrop between Papadil and Dibidil and in the Torridonian of Mullach Mor whilst others cut the layered peridotites.

Many of the gabbro plugs around Loch Sgoarishal and east of Papadil are elongate along a NW-SE trend coincident with the axes of dilation identified by Speight (1972, Fig. 1.4) and their location is probably attributable to regional stress patterns. The structural control on the emplacement of the plugs along the northeastern margin of the central complex is not clear. However, their location may reflect the interaction of the NE-SW trending Rhum sub-swarm axis (p. 29) with the regional stress field or possibly the Main Ring Fault.

3. Peridotite Plugs

The gabbro and peridotite plugs are often in very close association (e.g. the two plugs in Glen Shellesder NG 351103). They tend to be resistant to erosion and form topographic highs in areas of outcrop, an exception being the large plug on the north side of Kinloch Glen (NG 375005). The plugs consist of a medium grained, rusty brown weathering feldspathic peridotite in hand specimen and

individual plugs tend to be homogenous. However, felspathic peridotite xenoliths have been found in the peridotite plug east of Loch Sgoarishal (NG 351023) and dunite xenoliths are abundant in a plug north of Minishal (Emeleus and Forster, 1979, p.35).

The peridotites can induce considerable bleaching of the enclosing Torridonian sediments up to 30 m from the contact although the bleaching is often much less pervasive. At well exposed contacts, e.g. the western margin of the plug west of Loch Sgoarishal (NG 342020) the Torridonian sandstones have suffered severe partial melting with acicular quartz crystals (paramorphs after tridymite) embedded in a matrix of acid glass and friable quartz grains. The peridotite at this contact and at other exposed plug margins is unchilled. Dunham and Emeleus (1967, p.413) suggested these plugs occupied conduits which had previously fed overlying lavas.

The similarity of the banding in some of the peridotite plugs to matrix banding in the tongues east of the Long Loch (Dunham, 1965b) led Dunham and Emeleus (1967) to suggest they could be of similar age. This late age is supported by the cross cutting of the thick conformable sheets and the general lack of dykes in areas of known high dyke intensity.

The distribution of the peridotite plugs on Rhum is

shown in Fig. 2.11, the apparent lack within the layered series probably reflects the difficulty of locating plugs intruded into an almost identical country rock as detailed mapping by McClurg (pers. comm.) has located previously unmapped plugs in the Barkeval peridotites. The elongation and distribution of some of the plugs is probably attributable to the controls suggested for the gabbro plug distribution (p.47).

4. Acid dykes

Four acid dykes have been located on Rhum, two have been discussed previously by Harker (1908, p.140,177), the others are previously undescribed. Two occur as leucocratic spherulites cutting granophyre and Torridonian. Another, a pitchstone, occurs in a flow-banded deeply weathered dyke cutting granophyre whilst another, a felsite, occurs as a black flinty rock cutting sediments in Dibidil. They are generally thick varying between 1.5 m to 2 m however the felsite dyke is less than 50 cm thick. Their age relationships are obscure, one of the spherulite specimens is located outside the Main Ring Fault and the felsite is cut by a dolerite dyke. In view of their rarity, the close association of two specimens with the Western Granophyre and the absence of contradictory evidence it would seem reasonable to suggest they slightly postdate the plutonic acid rocks of Rhum.

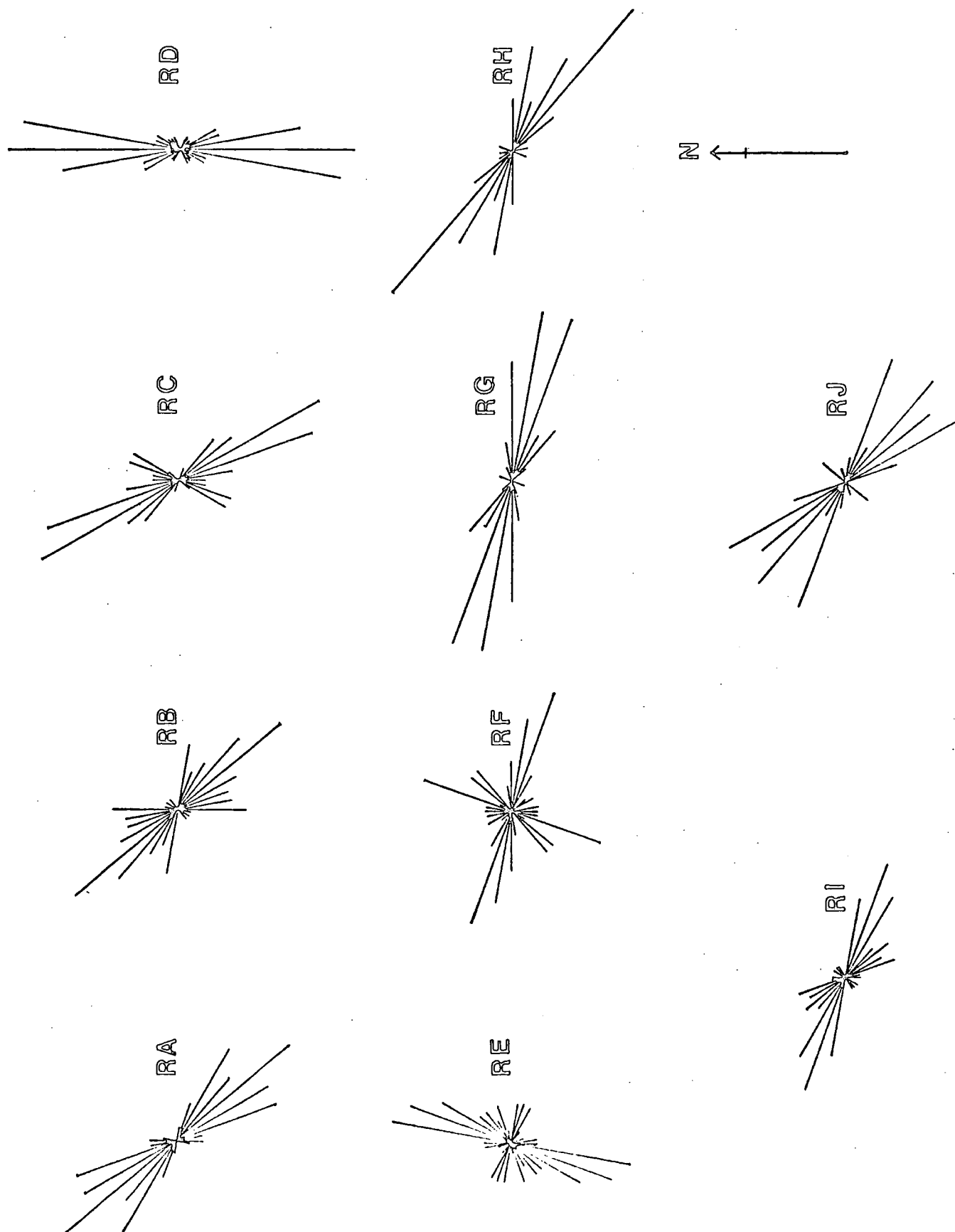


Fig.2.2 Dyke strike orientations in the coastal Torridonian of Rhum, see Fig 2.3 for the location of the traverses. (Drawn from data in Speight 1972 Appendix 18).

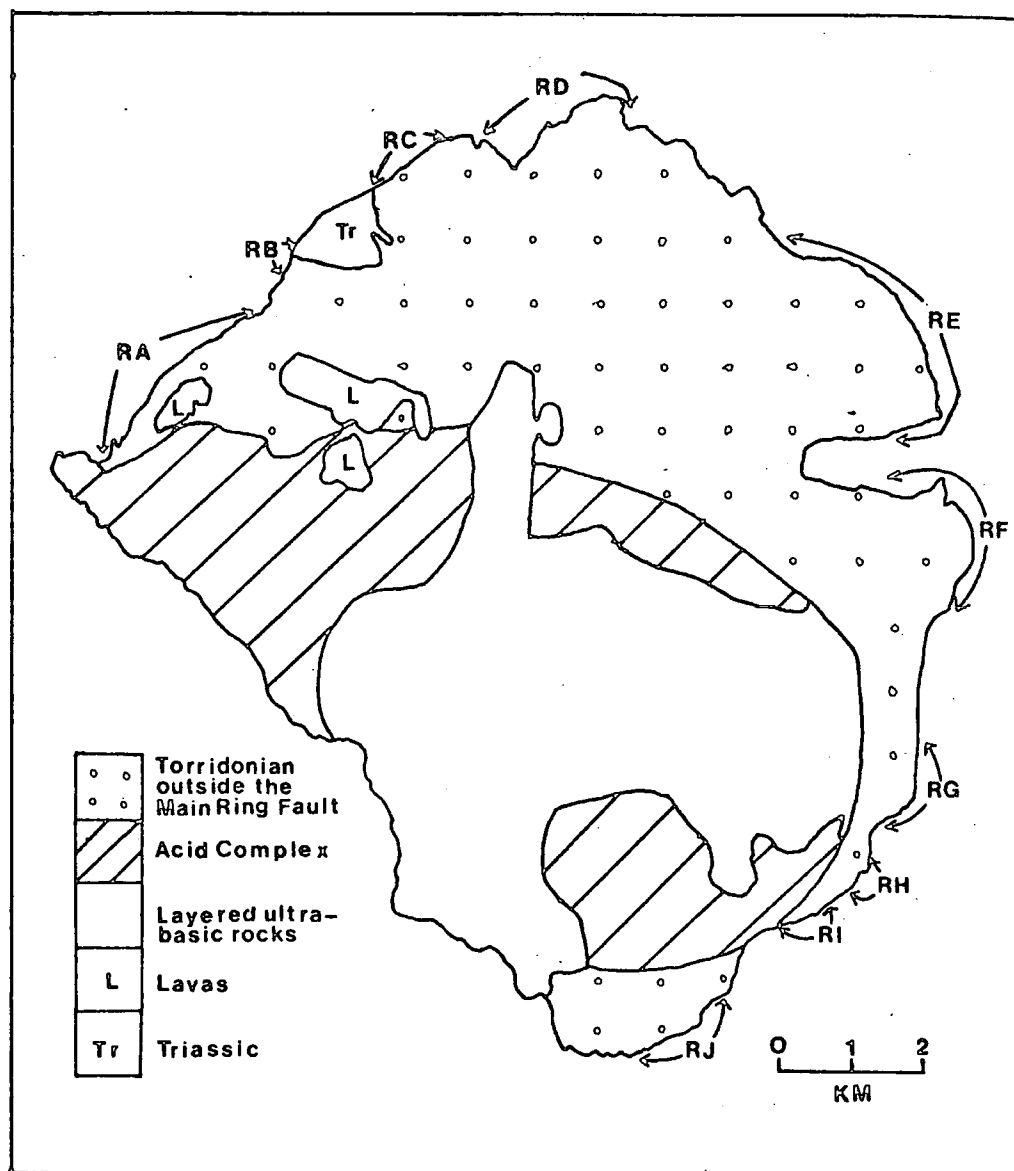
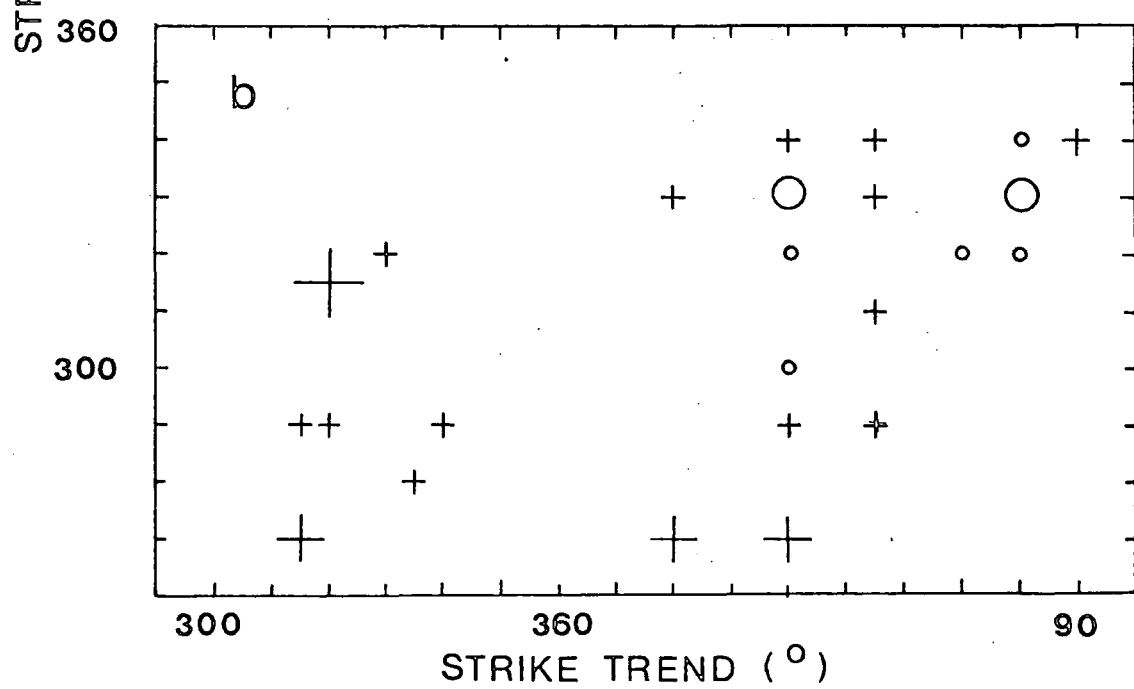
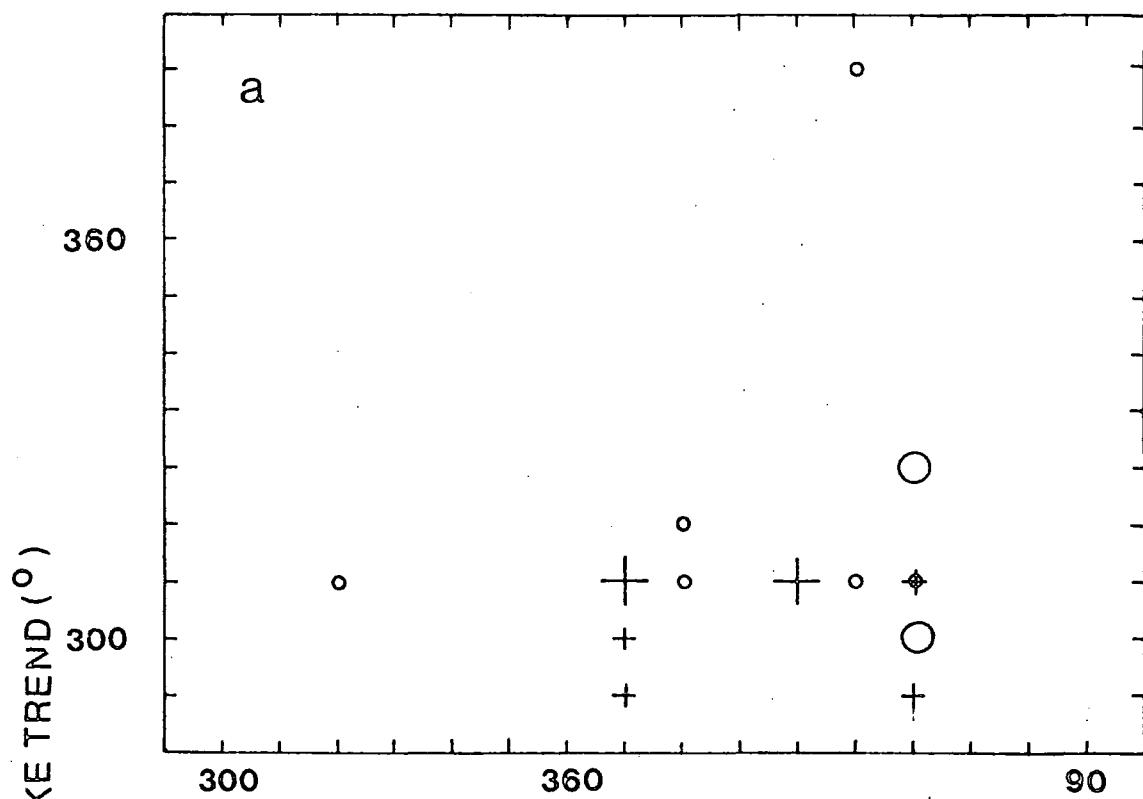


Fig. 2 3 Location of traverses represented in Fig. 2.2. (Taken from Speight, 1972, Fig. 107).

Fig. 2.4 Structural analysis of dyke cross-cutting relationships on (a) Chapán Breaca (b) Stony Corrie.

Explanation:

The ordinate and abscissa refer to dyke strike trends. A circle indicates that a dyke of the ordinate orientation cuts a dyke of the abscissa orientation, a cross indicates the reverse relationship. The small symbols refer to one observation, the larger symbols indicate two observations, except the largest cross which is the product of three observations.



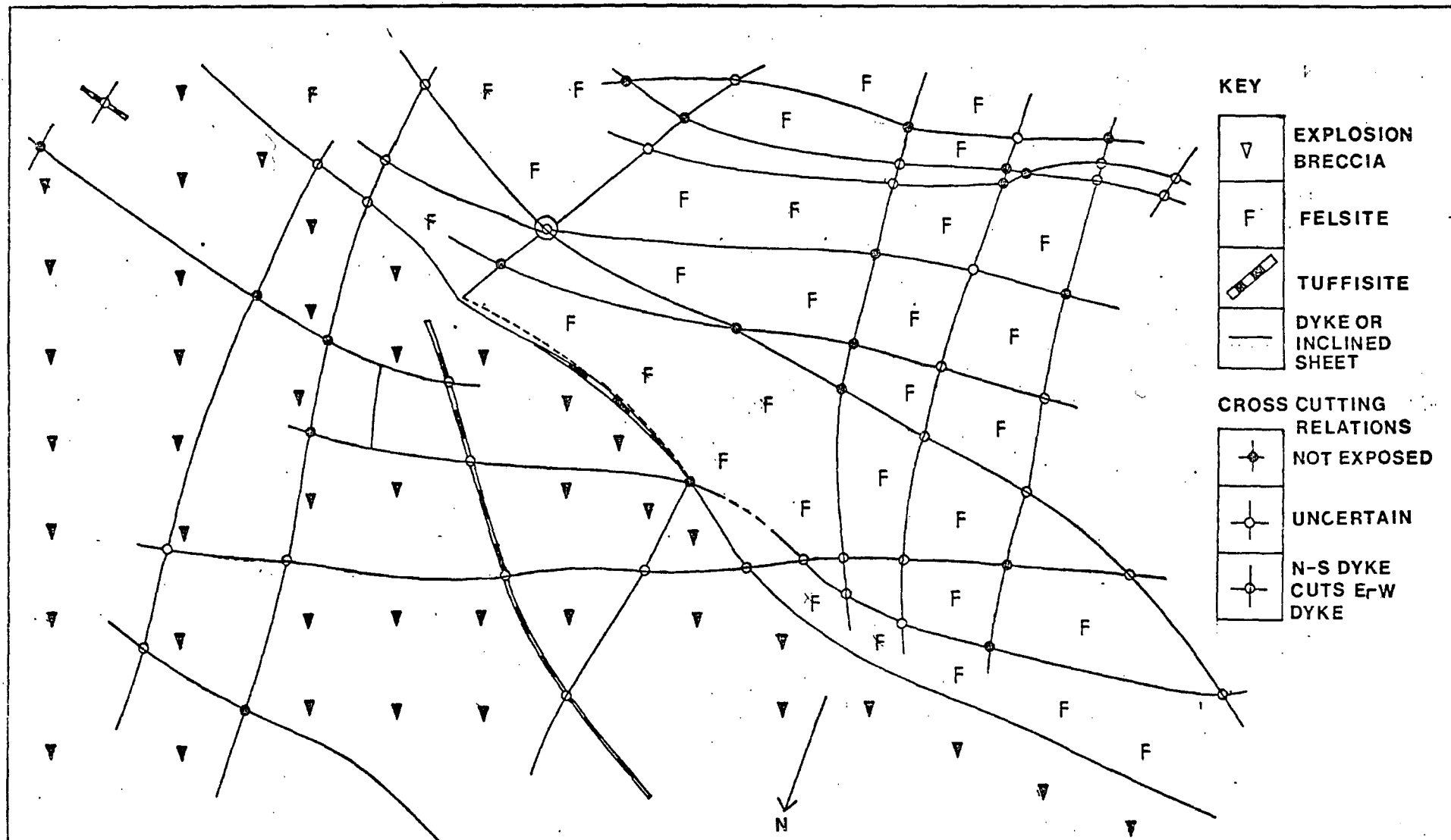


Fig 2.5 Sketch of dyke and country rock relationships on Cnapan Breaca (NM392968)

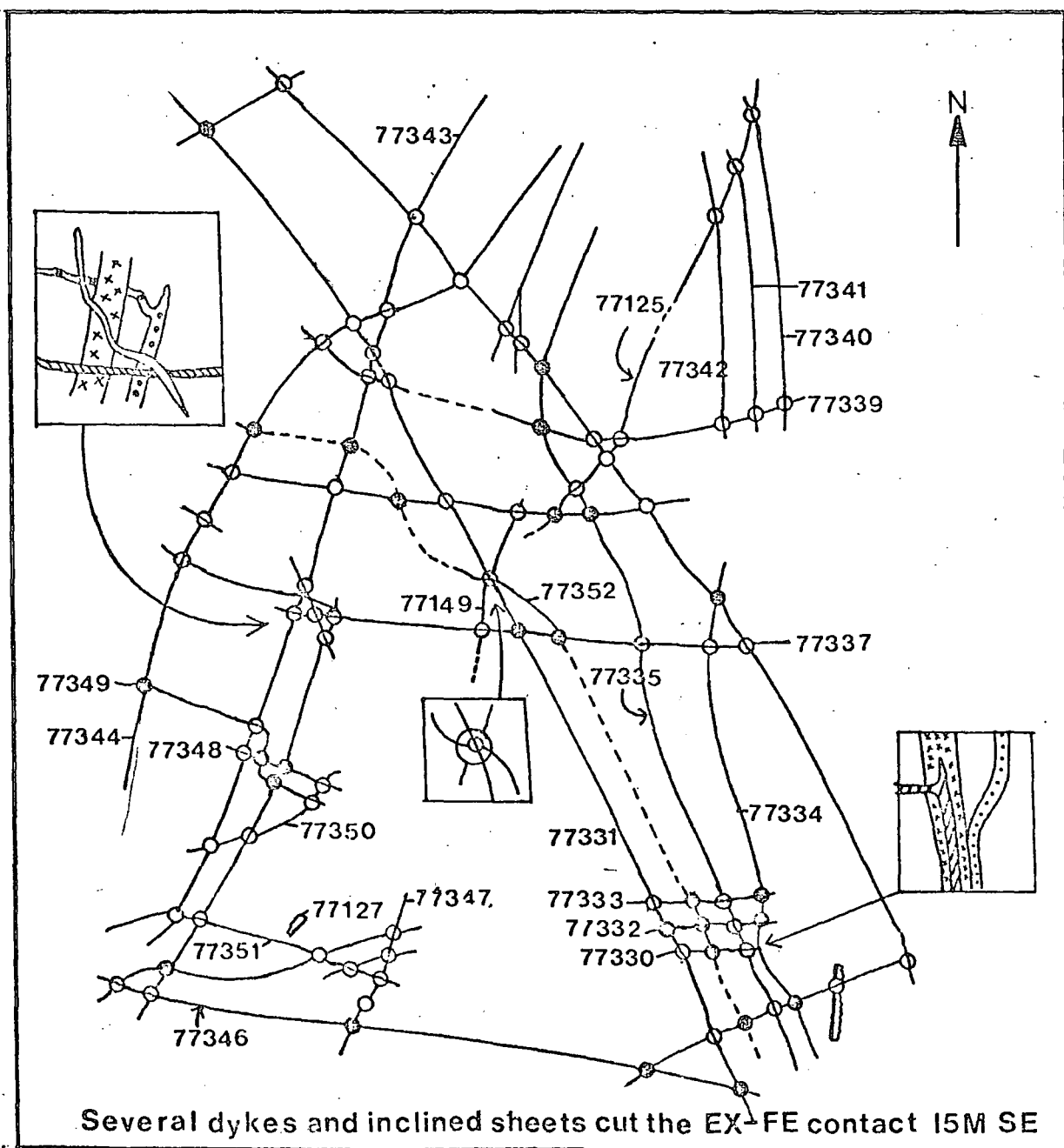


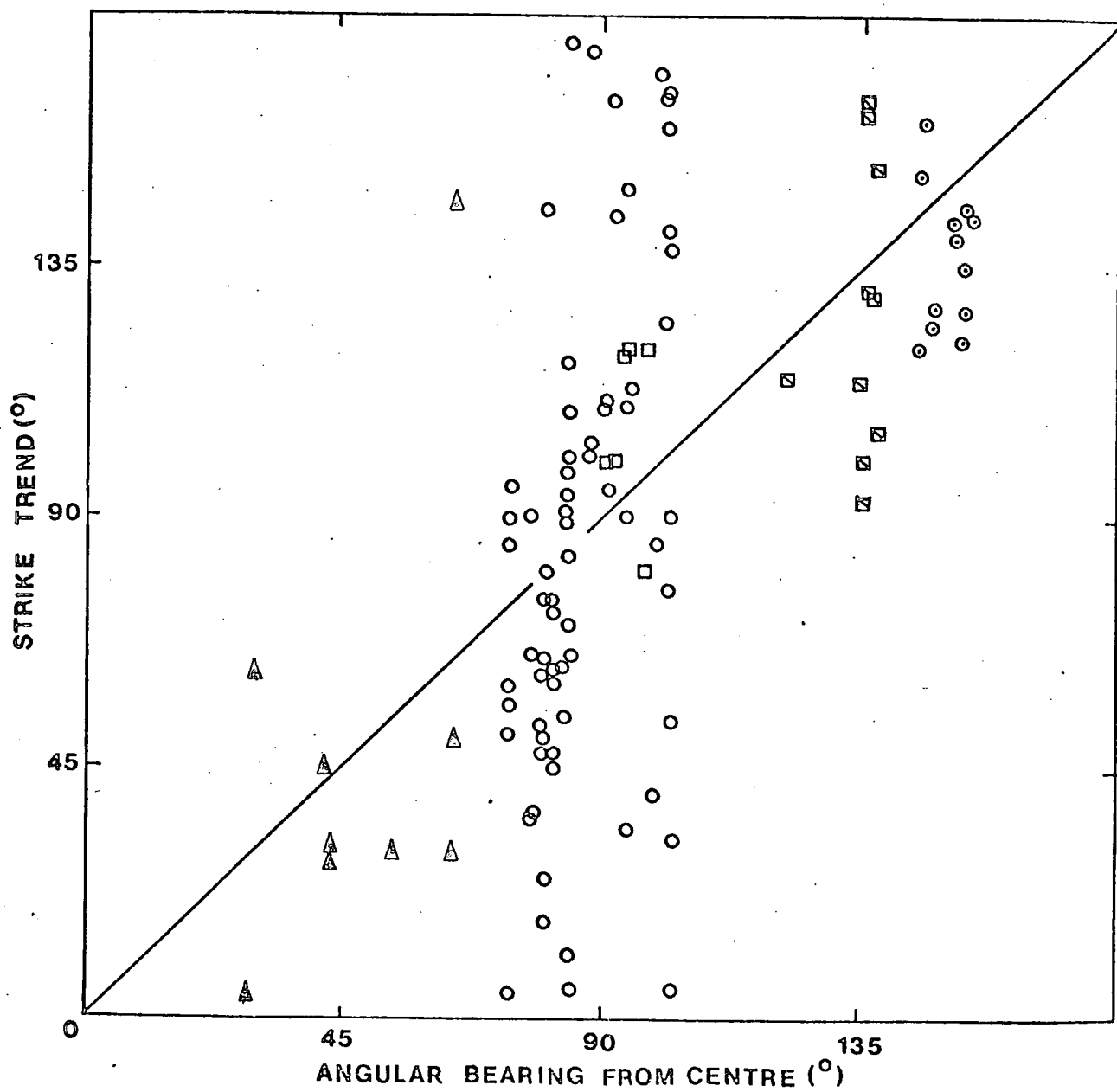
Fig 2.6 Sketch of dyke and inclined sheet cutting felsite in Stony Corrie, Dibidi (NM384936) Key on Fig 2.5

NB: Ornament on insets refers to dykes of different age.

Fig 2.7 Structural analysis of dykes cutting the layered peridotites, relative to the centre of the ultra-basic mass, estimated to be at NM370960. The angular bearing of dykes from localities west of the Long Loch Fault have been corrected for the 1.5 Km northward movement of the layered peridotites west of this fault.

Key to locality symbols.

- △ Barkeval
- Harris bay
- Corrie nan Grund
- ☒ An Dornabac
- ⊙ Trollval



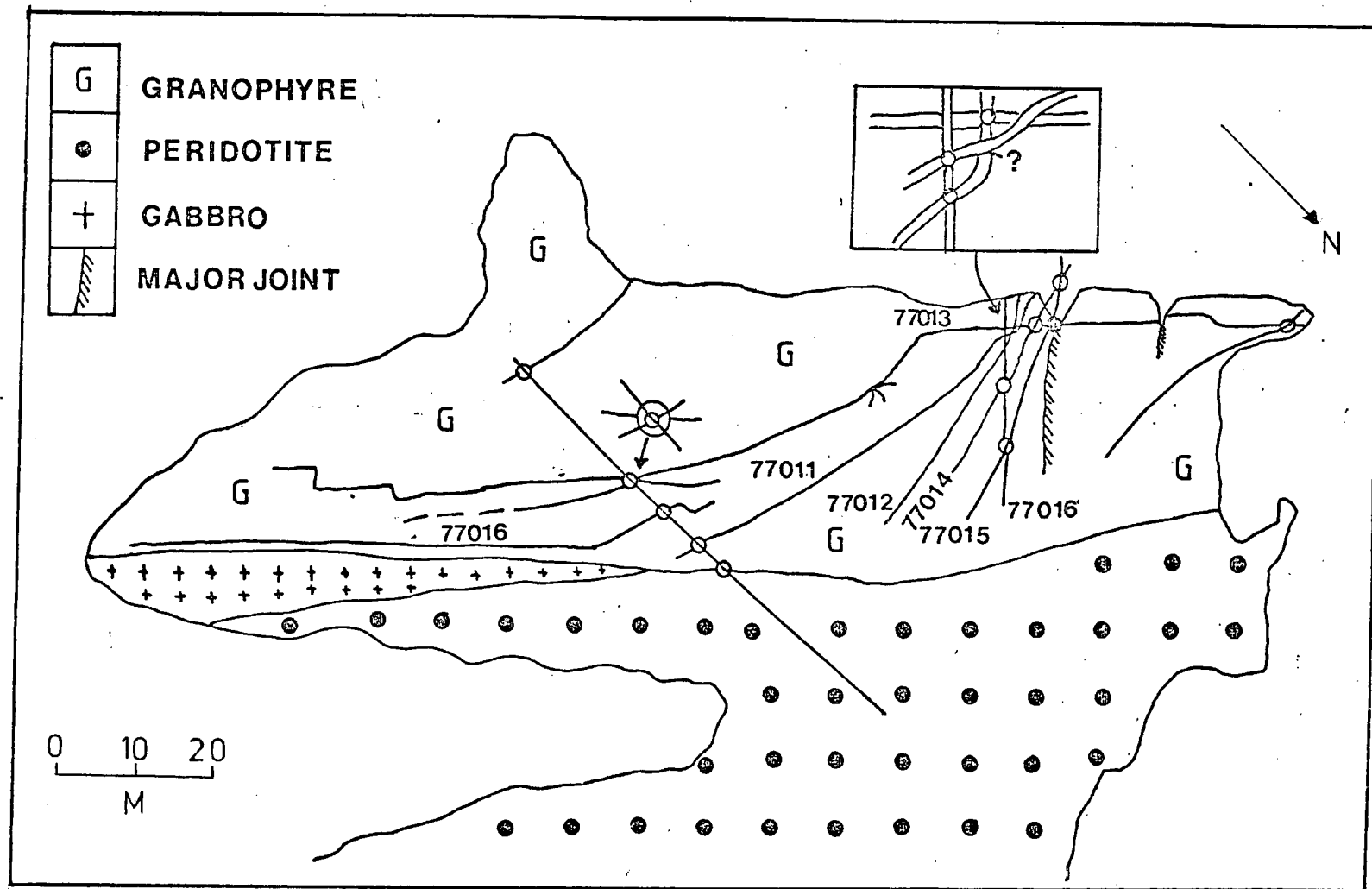


Fig 2.8 Sketch map illustrating some dyke cross-cutting relationships adjacent to the Granophyre-Peridotite contact at Harris Bay (NM336995)
For key to dyke intersect relationships see Fig 2.5

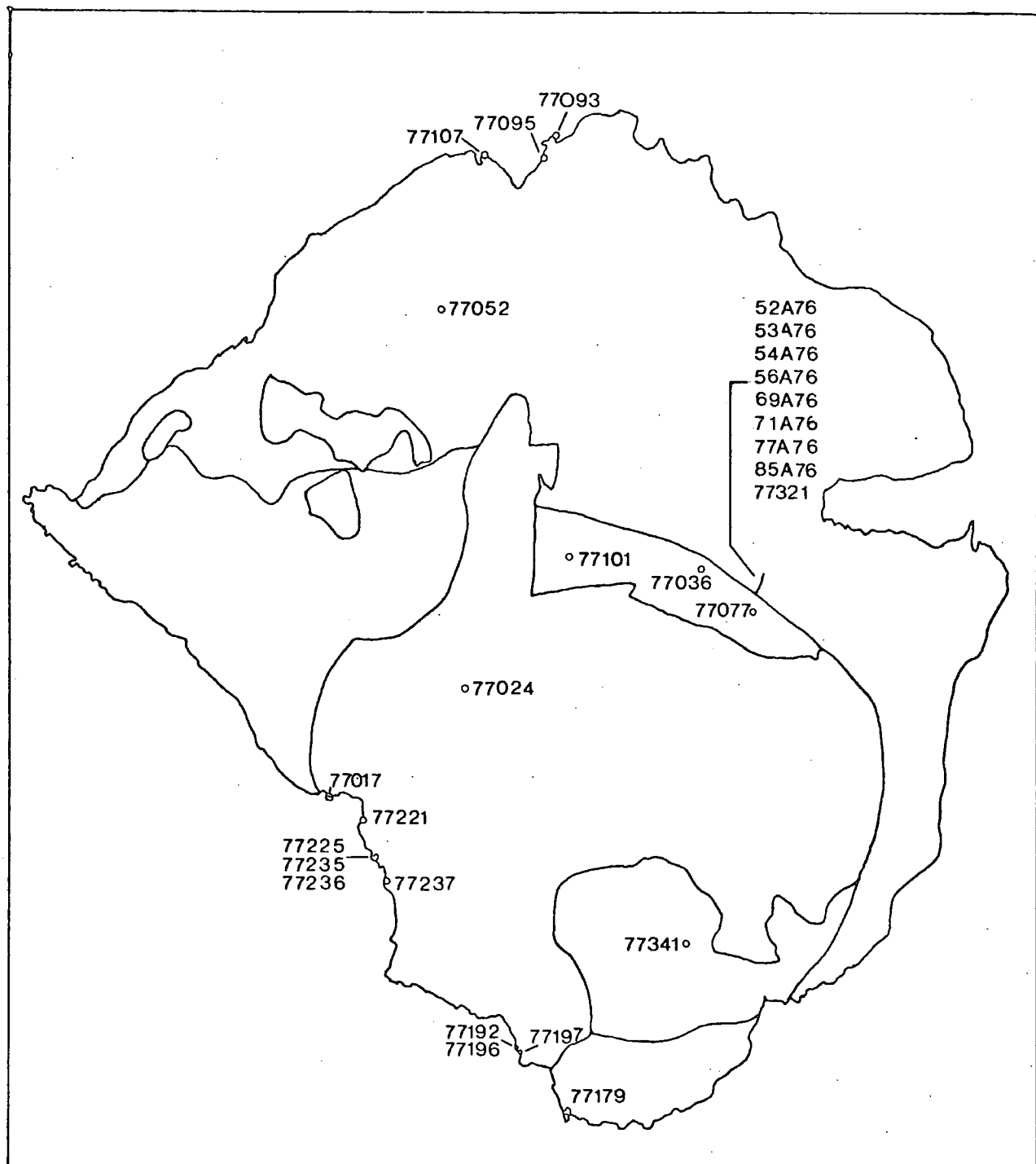
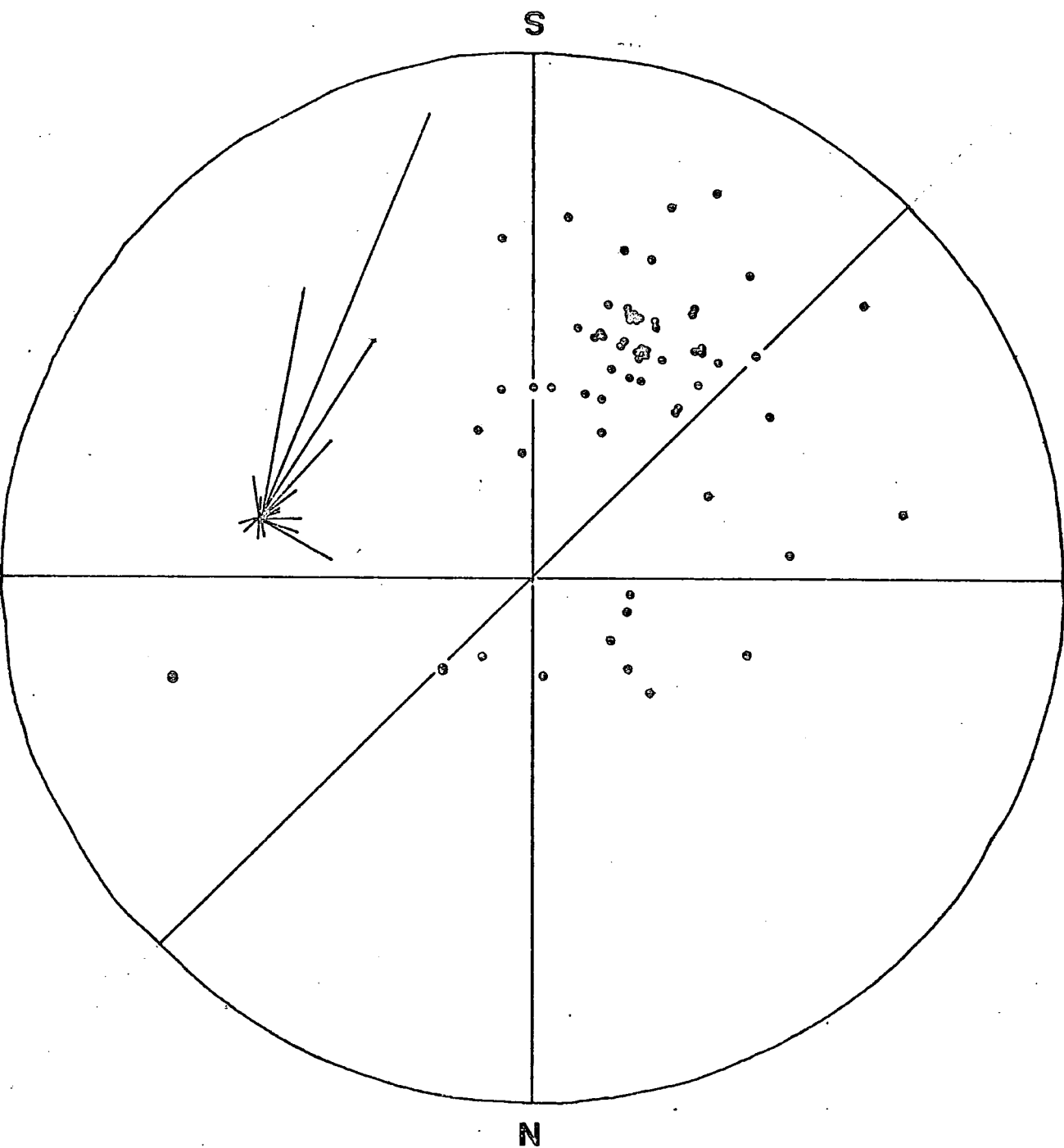


Fig.2.9 Map showing location of the picrite specimens.

Fig 2.10 Stereographic representation of the inclinations and dip directions of the inclined dolerite sheets exposed in the Allt Slugan a Choilich. The inset is a rose diagram of the dip directions of the sheets represented in the main figure.



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a) Within the Main Ring Fault	b) Outside the Main Ring Fault	Some probably of equivalent age
Dykes (including picritic varieties), inclined sheets and late gabbro plugs possibly some peridotite plugs	Dykes cutting lavas Lavas and sediments Dykes cutting the gabbro and peridotite plugs including picritic varieties	
Emplacement of the layered ultrabasic rocks etc.	Gabbro and peridotite plugs	
Ultrabasic tongues and some plugs, gabbroic plugs.	Big Feldspar Dykes Thick Conformable sheets (two ages) Picritic Dykes	
Big Feldspar Dykes	Main Ring Fault-----Main Ring Fault	Relative ages not known
Intrusion of the majority of the dykes and inclined sheets.	Dykes of the Main Rhum linear swarm (majority of dykes intruded here)	
Granophyre	Thin conformable sheets	
Dyke with liquid/liquid contact within the felsite.	Inclined Sheets	
Tuffisite, explosion breccia	Some dykes probably pre-date the inclined and thin conformable sheets	
Early Gabbro		

Table 2.1. The sequence of Tertiary minor intrusion.
on Rhum

TABLE 2.2
LOCATION AND NUMBER OF DYKES OR INCLINED
SHEETS CUTTING THE SEQUENCE
BASAL TORRIDONIAN TO TUFFISITE.

<u>Locality</u>	<u>Approx. Grid Reference</u>	<u>Contacts exposed between</u>	<u>Approx. number of dykes or inclined sheet cutting contact</u>
Corrie Dubh	NM393978	Tb-Ex-Tu	2
Corrie Dubh	NM393977	Ex-Fe	1
Cnapan Breaca	NM391974	Tb-Ex-Tu	4
Dibidil Shore	NM394927	Tb-Ex	3
Dibidil River	NM394930	Le-Tu	5
Beinn nan Stac	NM398938	Ex-Fe	1

Le = Lewisian

Tb = basal Torridonian

Ex = Explosion breccia

Fe = Felsite

Tu = Tuffisite

TABLE 2.3

LOCATION OF CONTACTS BETWEEN EARLIER
ROCKS AND GABBRO OR PERIDOTITE

<u>Locality</u>	<u>Approx Grid Reference</u>	<u>Contact between</u>
Cnapan Breaca	NM394977	Fe-Ga
Meal Breac	NM385980	Fe-Ga
Bealach-an- Fuhrain	NM378949	Fe-Ga
Harris Bay	NM340950	Gr-Ga+Pe
Ard Nev	NM348978	Gr-Pe
Monadh Dubh	NM356997	Gr-Ga
Sandy Corrie	NM365945	Le-Ga

Le = Lewisian

Fe = Felsite

Gr = Granophyre

Ga = Gabbro

Pe = Peridotite

CHAPTER THREE

CLASSIFICATION

Introduction

The classification of the basic and intermediate Rhum minor intrusions is presented in the first part of this chapter. The second part of the chapter is an appraisal of the transitional nature of the Rhum dolerites and gabbros between typical alkaline and tholeiite magma types. The unusual geochemistry of the Rhum minor intrusions presented several difficulties with respect to generally accepted classifications (eg. the Skye lavas nomenclature; Thompson et al., 1972) invalidating the use of strictly defined terms (eg. Hawaiite) to describe the Rhum minor intrusions as discussed in the text.

I. The classification of the minor intrusions of Rhum

Classifying a suite of igneous rocks serves two main purposes. Firstly it subdivides the suite into manageable classes or groups which can be geochemically and petrographically categorised. This categorisation allows for intergroup comparison which may subsequently lead to petrogenetic interpretation. Secondly labelling of the groups with an approved nomenclature aids comparison with similar rock types from other areas.

Four categories of minor intrusion were recognised in the field. The histogram (Fig. 3.1) shows there is a broad range of compositions from ultrabasic to intermediate. This diagram allows appraisal of the range in silica composition in the suite and confirms the separation of some of the types recognised in the field. However, subsequent laboratory investigation of the geochemistry and petrography has revealed distinct sub-groups within the broad field categories, hence a more detailed classification is required.

The problems of classifying a suite of igneous rocks have been discussed by the authors of several petrologic texts (eg. Carmichael et al., 1973 p.29; Hatch et al., 1975 p.185) the principal difficulty being the location of arbitrary boundaries between successively more differentiated rock types within the suite. Although rigid use of these arbitrary boundaries allows for strict comparison with other authors the transitional nature and unusual chemistry encountered in the Rhum suite (discussed later) did not allow application of a standard nomenclature. Thus an alternative approach was adopted which involved the grouping together of petrographically and/or geochemically similar specimens. A brief description of the geochemical and petrographic characteristics of the types of minor intrusion encountered

on Rhum is presented in the subsequent sections.

1) Dolerites

The dolerite specimens were resolved into 12 groups using geochemical and petrographic criteria. The former chiefly involved the major oxide (principally SiO_2 , MgO , CaO , Na_2O and K_2O) and trace element abundances and the normative mineralogies (chiefly the Differentiation Index (Thornton and Tuttle, 1960) the abundance of normative hypersthene, nepheline and quartz and finally the proportion of anorthite in the normative plagioclase). The main petrographic criteria used were the presence or absence of characteristic phenocryst phases and the degree of differentiation of the groundmass. Groups 1 to 7 are basic in composition and include the picritic and big feldspar dolerites, groups 8 to 12 are intermediate in character.

A brief outline of the characteristic geochemical and petrographic features of these groups is presented below.

Group 1 D.I 6-19

These picritic dolerites all contain olivine and chrome spinel phenocrysts. The main geochemical characteristics are high MgO (10.0 - 31.0 wt %) and low SiO_2 (41.0 - 46.0 wt %) and Al_2O_3 (8.0-15.0 ct %). They are petrographically alkalic in affinity as they contain

groundmass olivine but do not generally possess normative nepheline.

Group 2 D.I. 13-20

The majority of this group are aphyric and are characterised by unusually high MgO (10.0-15.0 wt %) Ni (140-425 ppm) and Cr (375-900 ppm) abundances for aphyric rocks. SiO_2 (44.0-47.0 wt %) total alkalis (1.3-2.5 wt %) TiO_2 (1.0-2.0 wt %) and Ba (20-180 ppm) are low. The group is hypersthene normative but also displays alkalic traits, they can be viewed as high-MgO transitional basalts.

Group 3 D.I. 18-25

This group is geochemically transitional between groups 2 and 4 in that the ranges of the major oxides (especially MgO, Na_2O and K_2O) and trace elements (especially Ni and Cr) generally lie between the group 2 and group 4 values. All the specimens are hypersthene normative but the presence of groundmass olivine in some specimens reveals alkalic traits. Taken as a whole the group is transitionally tholeiite in character.

Group 4 D.I. 20-30

This is the largest of the dolerite groups and is petrographically and geochemically diverse. Rocks in the group typically possess SiO_2 in the range 46.0-48.0 wt % and contain less MgO but more Na_2O , K_2O , TiO_2 and P_2O_5

than the group 2 dolerite. Ni values in the range 58-170 ppm are lower than in group 2 but Cr can reach the 600 ppm level. Some high total iron, and CaO variants are found in this group characterised by Fe_2O_3 and CaO values above 13.5 wt % and 12.5 wt % respectively. Members of the group can be hypersthene or nepheline normative thus the group is completely transitional in character.

Group 5 D.I. 15-19

This small group of exceptionally fresh dolerites is geochemically distinct from the other dolerite groups. Members of this group are characterised by higher Al_2O_3 and lower total alkalis TiO_2 , Zr, Y and Sr than other Rhum dolerites and closely resemble the low alkali, high CaO olivine tholeiite magmas of Skye (Esson et al., 1975; Matty et al., 1977).

Group 6 D.I. 26-31

Members of this group are only found cutting the lavas of Western Rhum. They possess slightly higher Al_2O_3 (14.0-16.0 wt %) and much lower MgO contents (5.5-8.0 wt %) than the dolerites in other groups. They are predominantly hypersthene normative and can be viewed as low MgO transitional tholeiites.

Group 7 D.I. 18-24

This group is characterised by abundant large (1-4mm) tabular plagioclase phenocrysts and consequently possesses high Al_2O_3 and CaO contents ranging from 15.5-19.0 wt % and 12.5-15.0 wt % respectively.

Group 8 D.I. 20-40

Specimens in this group have SiO_2 contents ranging from 49.0 to 53.0 wt %; the Na_2O , K_2O , TiO_2 , P_2O_5 , Ba, Sr, Nb, Zr and Y values are generally higher than those encountered in the group 4 dolerites but compositional overlap between the 2 groups is considerable. Some members of the group have Fe_2O_3 contents greater than 13.0 wt %. The term tholeiitic basaltic andesite adequately describes the degree of differentiation.

Group 9 D.I. 36-47

Specimens in this small group are characterised by silica contents greater than 54.4 wt %. Their fractionated nature is also revealed by the MgO, CaO, Ni and Cr contents which are lower than those in group 8. The group's tholeiitic nature is revealed by the presence of normative quartz and the low total alkalis. They show only moderate iron enrichment (0.60-0.71) attributable to their normal Fe_2O_3 (8.5-11.0 wt %) but high MgO

(4.5-7.0 wt %) contents when compared with other tholeiitic rocks of similar SiO_2 content.

Group 10 D.I. 30-36

Although the silica content is similar to the group 4 dolerites (46 -47 wt %) the Na_2O , K_2O , Ba, Zr and Sr contents are appreciably higher. This group is alkaline and their differentiation indices and normative anorthite contents fall within the ranges of the Skye hawaiites (Thompson et al., 1972). Their MgO contents are much higher than those encountered on Skye (7.0-11.0 wt % as opposed to 2.5-5.5 wt %) thus they can be termed high MgO hawaiites.

Group 11 D.I. 41-52

The SiO_2 content is similar to that found in the group 9 rocks however comparisons between the groups show the group 11 specimens have higher Fe_2O_3 , Na_2O , K_2O , P_2O_5 , Ba and Sr contents and lower Ni and Cr values.

Group 11 is not quartz normative and has fairly high total alkali abundances giving them a distinctly alkaline character. They are more differentiated than the group 10 dolerites as the SiO_2 Ba and Zr contents are appreciably higher. Their differentiation indices and normative anorthite contents are similar to those found

in the Skye mugearites (Thompson et al., 1972) but the MgO content in the Rhum specimens is higher (5.0-6.0 wt % as opposed to 2.5-4.5 wt %).

Group 12 D.I. 65-66

This group comprises only 2 specimens but they are sufficiently petrographically and geochemically distinct to merit a separate group. The group 12 rocks are characterised by high Al_2O_3 , Na_2O , K_2O , P_2O_5 , Ba, Zr, Nb, Y, Sr and Rb contents, the K_2O , Na_2O , Ba and Nb levels in particular being much higher than in the remainder of the suite. Their high differentiation index and low normative anorthite content is analogous to the values exhibited by the Skye benmor^eaxites (Thompson et al., op.cit) however the MgO content is once again much higher in the Rhum specimens.

2) Gabbros

Two main geochemical classes of gabbro plugs have been distinguished, a high MgO class and a low MgO class. The latter class has been further subdivided into three types, a large group of transitional gabbros, a few quartz gabbros and one differentiate of ferrodiorite composition.

High MgO Gabbros D.I. 16-25

This group is characterised by high MgO, CaO, Ni

and Cr levels and low Na_2O , K_2O and TiO_2 . Although similar to the high MgO dolerite groups 2-4, none of the gabbro falls exactly within the ranges of any of the dolerite groups. The group as a whole is transitionally tholeiitic with some nepheline normative members.

Low MgO Gabbros

a) Transitional gabbros

The gabbros are characterised by high CaO (9.4-13.3 wt %) and Sr (204-592 ppm) values and fairly high total alkali and TiO_2 contents. They can be either mildly nepheline or mildly hypersthene normative and thus are completely transitional.

b) Quartz gabbros D.I. 28-29

These all possess normative quartz and two contain modal interstitial quartz testifying to their more differentiated nature. They contain more SiO_2 , Na_2O , K_2O , Ba, Zr, Y, Nb and Rb than the previous low MgO gabbro type and less MgO, CaO, Ni, Cr and Sr. They are tholeiitic in character.

c) Ferrodiorite D.I. 58

The ferrodiorite contains moderately abundant interstitial quartz. It possesses high SiO_2 , Na_2O , K_2O , Nb, Zr and Y. MgO and Sr, Ni and Cr are present in extremely low quantities. It shows moderate iron

enrichment (0.82) which along with the modal quartz testifies to its tholeiitic nature.

The acid dykes and peridotite plugs are petrographically and geochemically distinct from the dolerites and gabbros. The peridotites exhibit limited geochemical variation and geochemical subdivision is unwarranted. The geochemical variation within the acid rocks is discussed in Chapter 7 (p.249).

II. Appraisal of the transitional nature of the Rhum Suite

It is generally recognised that there are three dominant basalt magma types these being tholeiitic basalt, alkali olivine basalt and the calc-alkali basalt type (Wilkinson 1967, Irvine and Baragar, 1971; Floyd and Winchester, 1975). The first two magma types are particularly well documented and embrace basalt magmas from different tectonic settings, the latter (referred to as High Alumina basalt by Wilkinson, 1967) is found in association with calc-alkali differentiates.

The petrological study of basaltic suites over the past fifty years has clearly established the differences between typical tholeiitic and alkali olivine basalts (see reviews by Wilkinson, 1967; Middlemost, 1975) however the recognition of basalt magmas with properties intermediate between typical alkali and tholeiitic basalts (eg. Green, 1970; Bass,

1972; Gass et al., 1973) has obscured the clear cut distinction between these basalt types.

When plotted onto the standard diagrams (Figs. 3.2 to 3.4) the Rhum dolerites clearly straddle the alkali basalt - tholeiite basalt discriminant line indicating a transitional nature. Whilst transitional basalts are clearly present the abundance of what may be termed "true alkaline" and "true tholeiitic" basalts is difficult to establish. Reference to the trace element data further confuses the issue; Winchester and Floyd (1975) consider that the Nb/Y ratio is a good indicator of the alkaline or tholeiitic nature of a basaltic rock. These authors (op.cit,p.335) suggest that alkaline basalts and alkaline differentiates possess Nb/Y ratios greater than 0.67 which would exclude even the extreme alkali affinity differentiates in the Rhum suite Table 3.1.

It is petrogenetically important to assess whether a bimodal or unimodal basalt population is represented in the Rhum suite as magma mixing in a bimodal population could account for the transitional types. Previous discussion of the Tilley-Muir diagram (Fig. 3.4) by Cox (1972) shows it is unsuitable for this type of interpretation.

In order to overcome the difficulties of projection

and to make use of all the analytical data available, it was decided to investigate the geochemical distinction between alkaline and tholeiitic basalts using Discriminant Function Analysis.

Discriminant Function Analysis is a multivariate statistical technique which linearly combines discriminating variables (in this case the analysed major oxide and trace element abundances) to make the classes undergoing analysis (in this case the basaltic magma types) as statistically distinct as possible. The variables are first combined into linear discriminant functions (Ap.3.3), the validity of the functions can also be tested with classification functions (see Appendix 3.2). These reclassify the cases of known class type into the classes as defined by the discriminant functions, a high success rate in reclassification indicates that there is a statistical difference between the classes under discussion. The classification functions can also operate on cases of unknown class; statistics are available which show the probability of an unknown case belonging to any of the analysed classes and also its proximity to that class centroid or mean (Appendix 3.2). These features are extremely useful as they give a good indication of the validity of the supposed class of an unknown case.

a) Data acquisition

A literature search was undertaken to acquire analyses of alkaline, tholeiitic and calc-alkali basalts. The data sources for the basalts used in the discriminant analyses and the mean values for each basalt class are listed in Appendix 3.1. The alkali and tholeiitic classes include representative analyses from both continental and oceanic environments, the latter included ocean floor basalts. The term basalt in this investigation was defined as analyses with SiO_2 values ranging 45-52 wt % (cf. Floyd and Winchester, 1975). An alternative scheme adopted by Pearce (1976, p.17) defining basalts as analyses with $\text{CaO} + \text{MgO}$ ranging 12-20 (wt %) was deemed inappropriate as this would have precluded many of the Rhum dolerites under investigation. Any basaltic suites referred to as transitional between typical alkali and tholeiitic basalts were referred to a separate class and their transitional nature was tested as part of the investigation. All the cases contained the major oxides. Many included some trace element data however several had no trace element analyses. This lack of trace element data has been encountered by other workers on compilations of basaltic analyses (eg. Floyd and Winchester, 1975), sufficient numbers of each variable were included in the compilation to give a representative

data set for each basalt class.

b) Results

The results presented in Table 3.2 and Fig. 3.5 show that the three main basalt classes under investigation are statistically distinct in terms of both major or major plus trace elements. The discriminant functions which separate these basalt classes are presented in Appendix 3.3. This investigation confirms that there are real and distinct chemical differences between the alkali, tholeiite and calc-alkali classes and the classifications proposed by the authors listed in Appendix 3.1 were valid. The vast majority of the Rhum minor intrusion suite classify (as expected) as either tholeiite or alkali basalts.

A function was then derived to discriminate between only the alkali and tholeiitic basalt class. The function is listed in Appendix 3.3 and the classification results are presented in Table 3.3 the high success rate on reclassification once again confirms that the classes are statistically separate.

The derivation of the value known as the discriminant score is described in Appendix 3.2. It is obtained by multiplying the standardised variable for each case by the values for each variable listed in the discriminant function, the score can have either a positive or

negative value or can be zero.

The frequency of the discriminant scores based on world-wide occurrences for both the alkali and tholeiite basalt classes, is presented in Fig. 3.6 along with the discriminant scores of some documented basalts believed to be transitional between alkali and tholeiite basalts. The Rhum dolerites, gabbros and lavas are each shown separately. A positive discriminant score indicates a basalt of tholeiitic affinity and a negative score a basalt of alkalic affinity. A discriminant score close to zero indicates that the rock is transitional between the alkali and tholeiite magma types. The alkali and tholeiite basalt classes show a clear bimodal distribution with a distinct paucity of cases with discriminant scores -0.35 to $+0.35$. Conversely the basalts believed to be transitional by the authors in Appendix 3.1 have a unimodal distribution as do the Rhum dolerites. The modal discriminant score of both these populations lie in the range -0.35 to $+0.35$ thus the existence of truly transitional basalt magmas on Rhum and elsewhere is confirmed. The Rhum gabbros and the Rhum lavas also span the range from thoroughly alkaline through transitional types to thoroughly tholeiitic basalts.

Additional data on basaltic compositions from the Mull, Ardnamurchan and Blackstones Bank Tertiary centres and the basalts of the Small Isles is presented in

Fig. 3.7. The basalts from the Small Isles once again show a broad range of compositions with a distinct peak in the transitional region. The abundant basalt data from Skye have been separated into the three different magma types defined by Matty^e_Λ et al., 1977. The Skye Main Lava Series show a bimodal distribution with peaks at -1.55 and +0.75 probably reflecting the distribution of the nepheline normative and hypersthene normative basalt types within the Skye Main Lava Series (Thompson et al., 1972). There is a distinct lack of basalts with zero to -0.35 discriminant scores in the Skye Main Lava Series. The Fairy Bridge magma type (Matty^e_Λ et al., 1977) appears to be thoroughly transitional and the low Alkali Tholeiite magma type spans the range transitional to thoroughly tholeiitic as expected. The data from the Tertiary centres of Ardnamurchan, Mull and the Blackstones span the range transitional alkali to tholeiite, the Mull lavas tend to be more alkaline and the Ardnamurchan cone sheets and the Blackstone Bank gabbros are generally more tholeiitic.

In conclusion the validity of the alkaline, tholeiitic and calc-alkaline basalt classes on a world wide scale has been confirmed. However, the existence of basaltic compositions thoroughly transitional between the alkali and tholeiitic magma types has been convincingly

demonstrated on Rhum, in the Hebrides and elsewhere in the world.

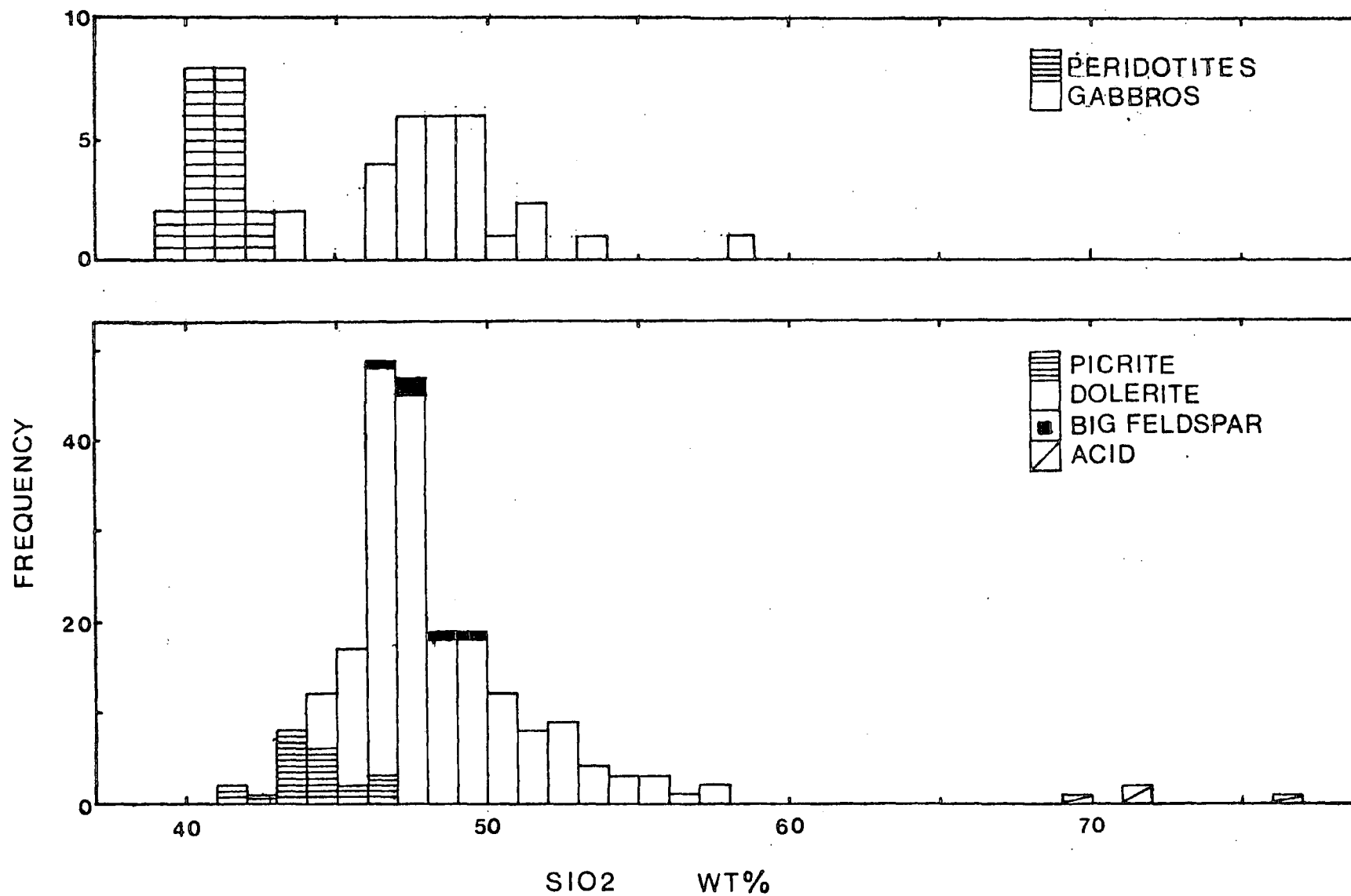


Fig 3.1 SiO₂ frequency in the Rhum minor intrusion suite

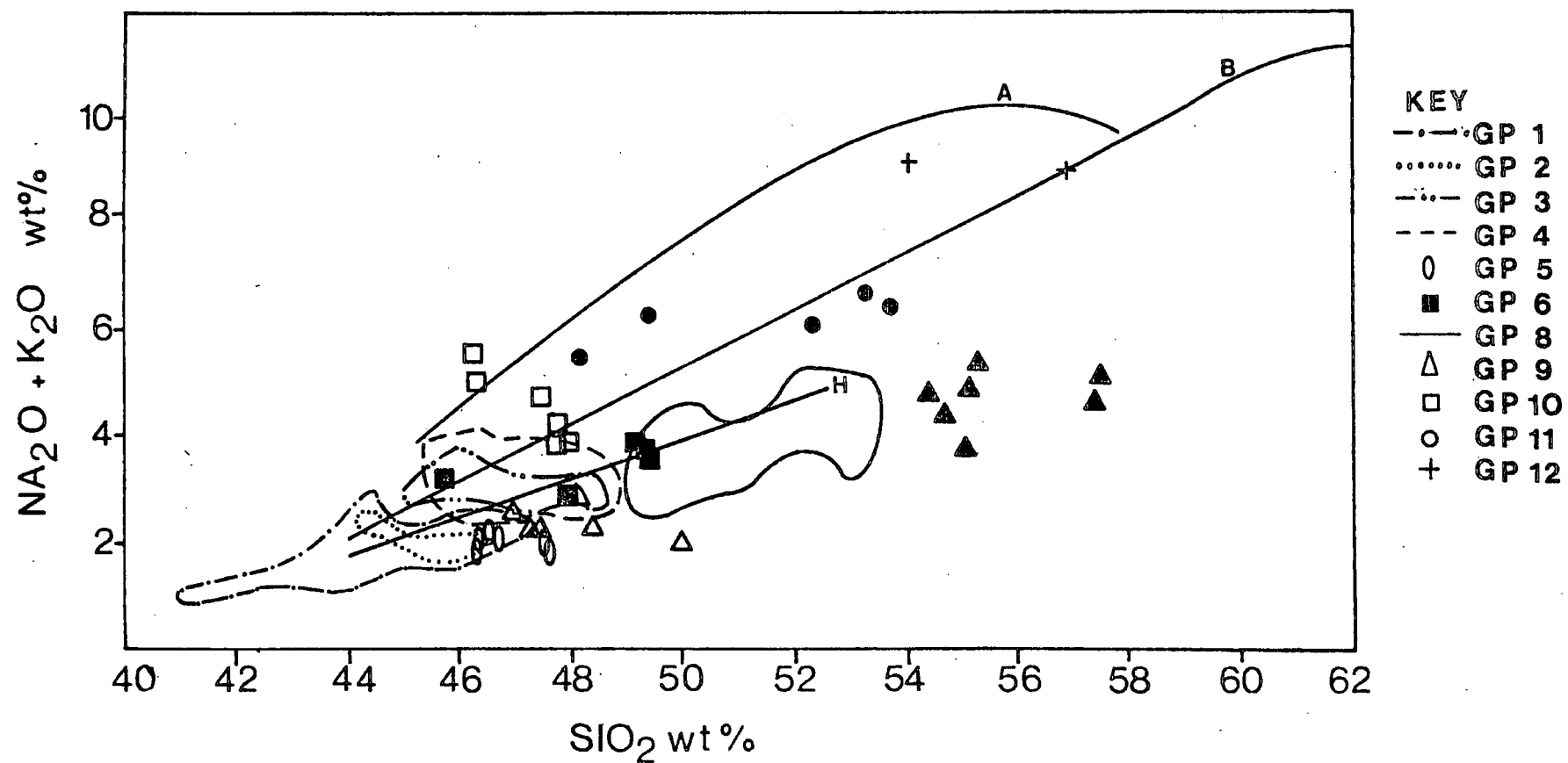


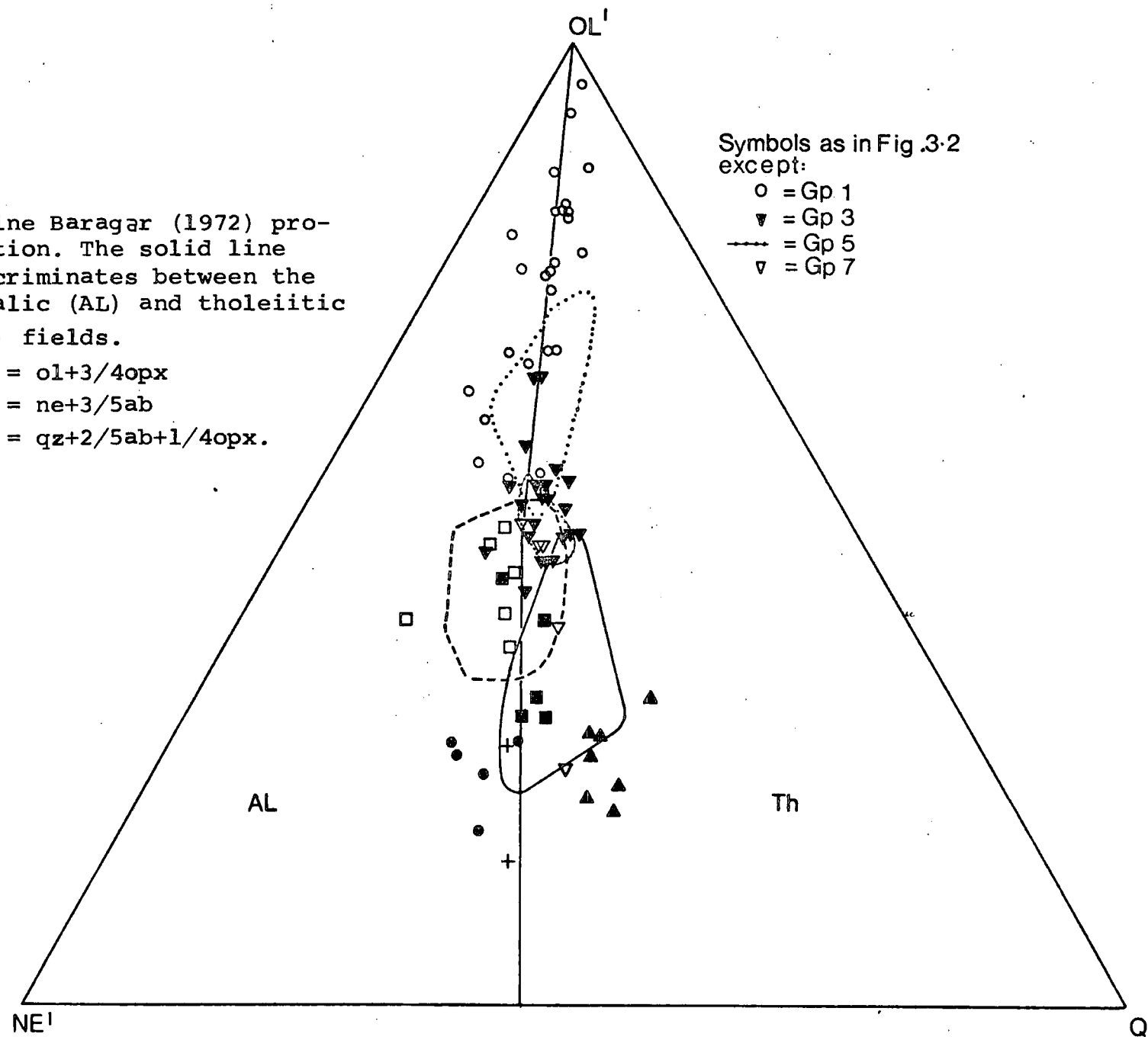
Fig.3.2 SiO₂ v. Na₂O + K₂O variation in the Rhum dolerites, lines A and B refer to the trend of the Skye Main Lava Series, line H is the discriminant line between Hawaiian alkali and tholeiite basalts (all taken from Thompson et al., 1972, Fig.6).

Fig.3.3 Irvine Baragar (1972) projection. The solid line discriminates between the alkalic (AL) and tholeiitic (TH) fields.

$OL' = ol+3/4opx$

$NE' = ne+3/5ab$

$Q' = qz+2/5ab+1/4opx.$



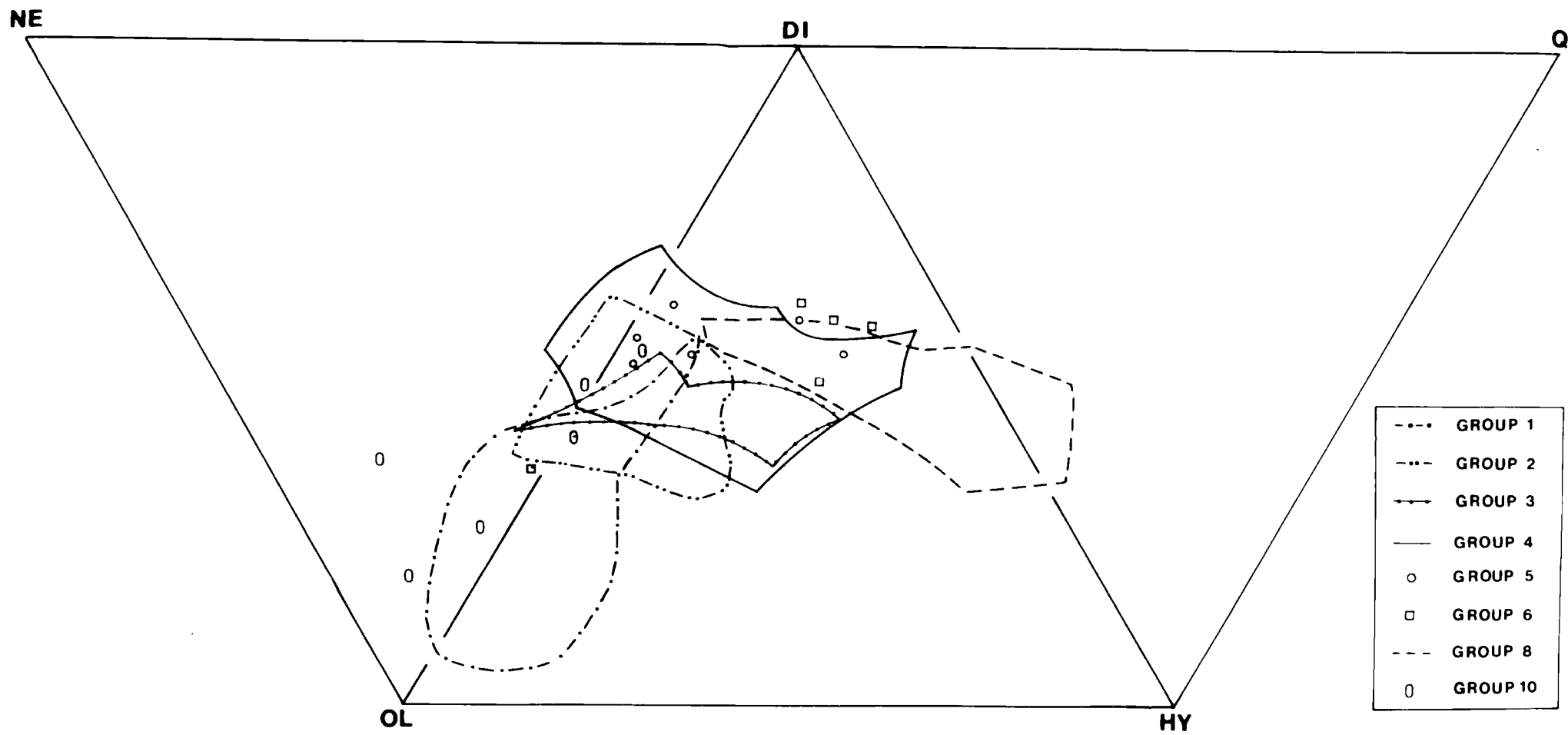


FIG 3.4 Tilley-Muir diagram of the Rhum dolerites

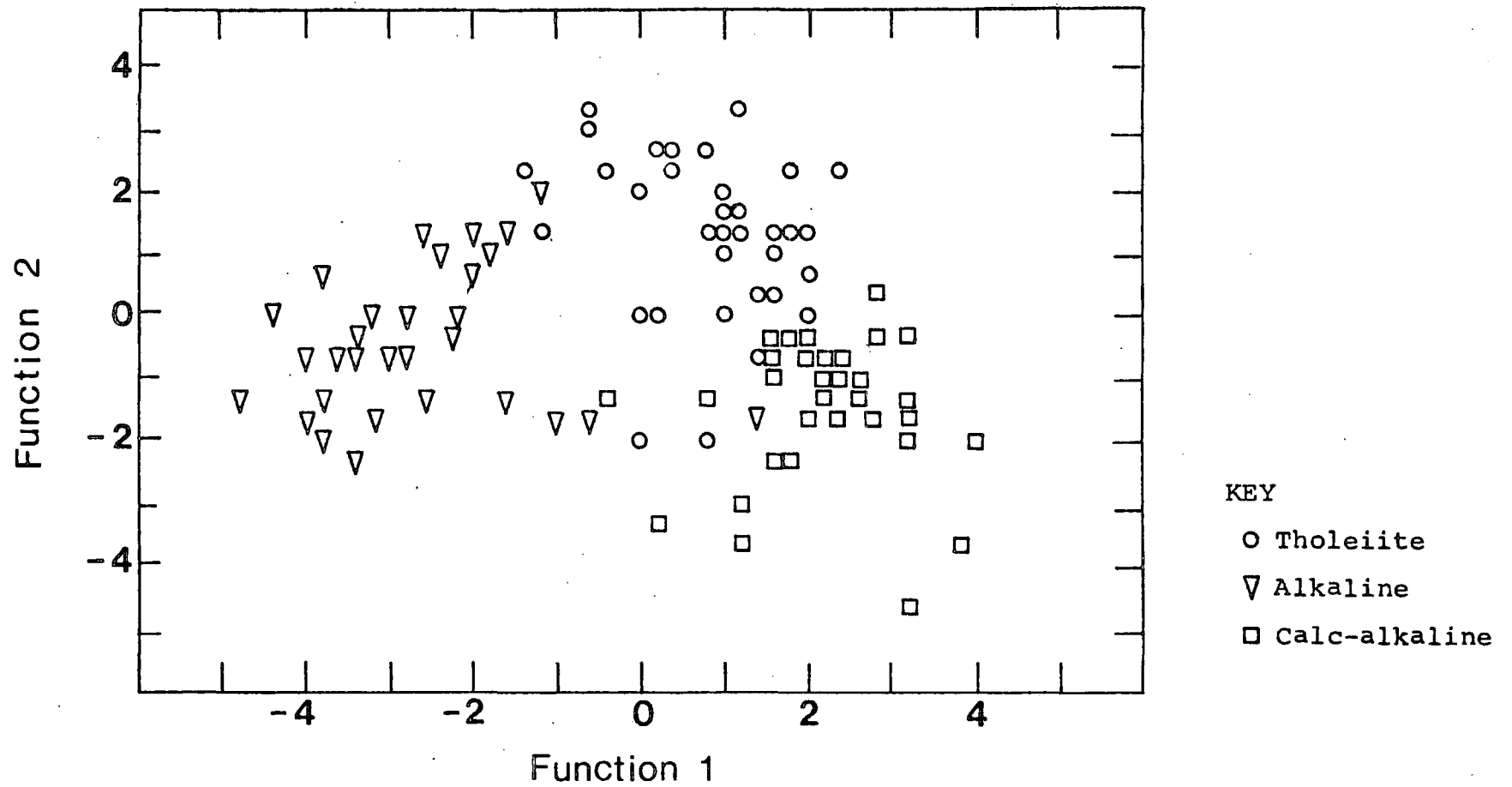


Fig. 3.5 Distribution of tholeiite, alkaline and calc-alkaline basalts, with respect to the 2 discriminant functions as discussed in text.

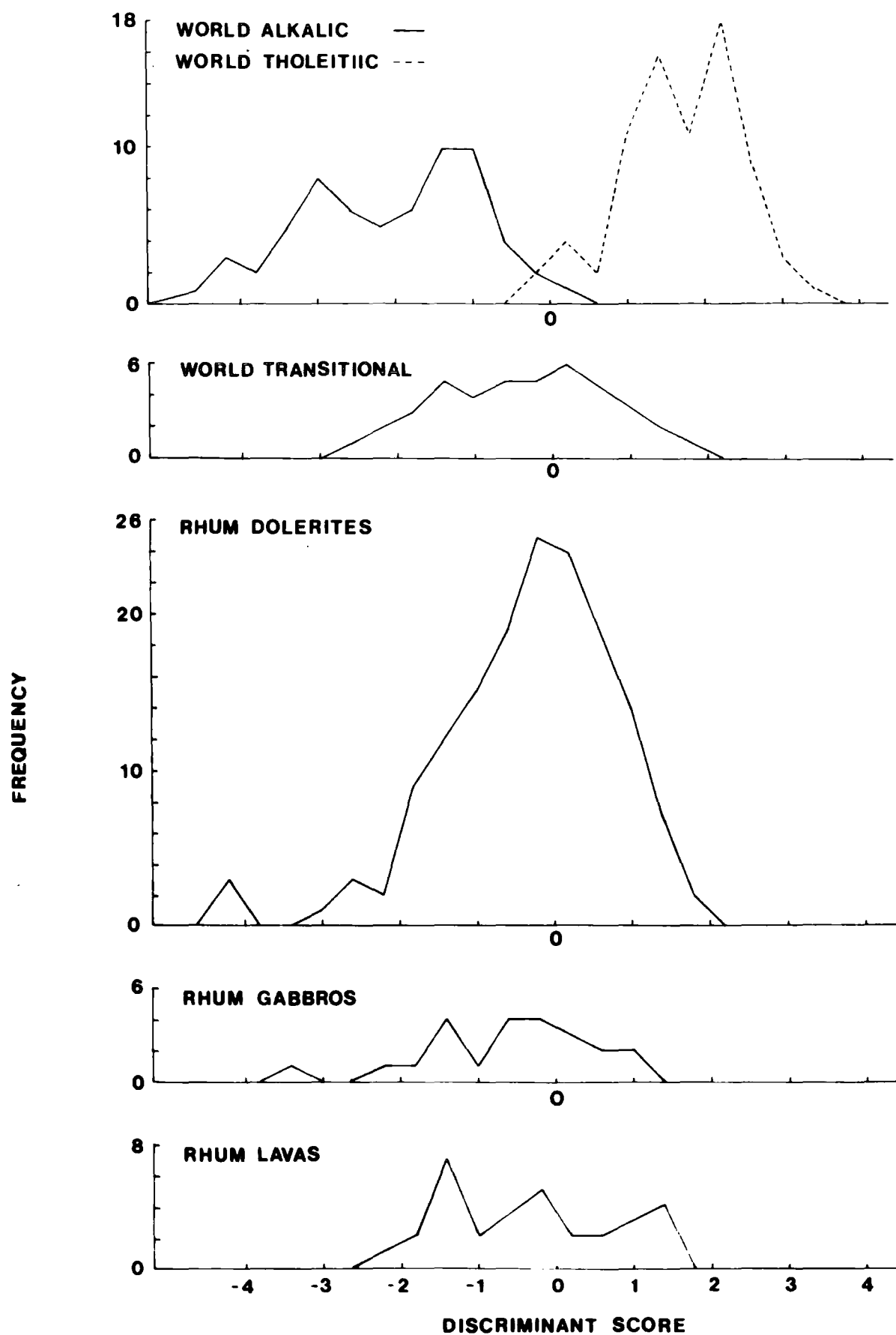
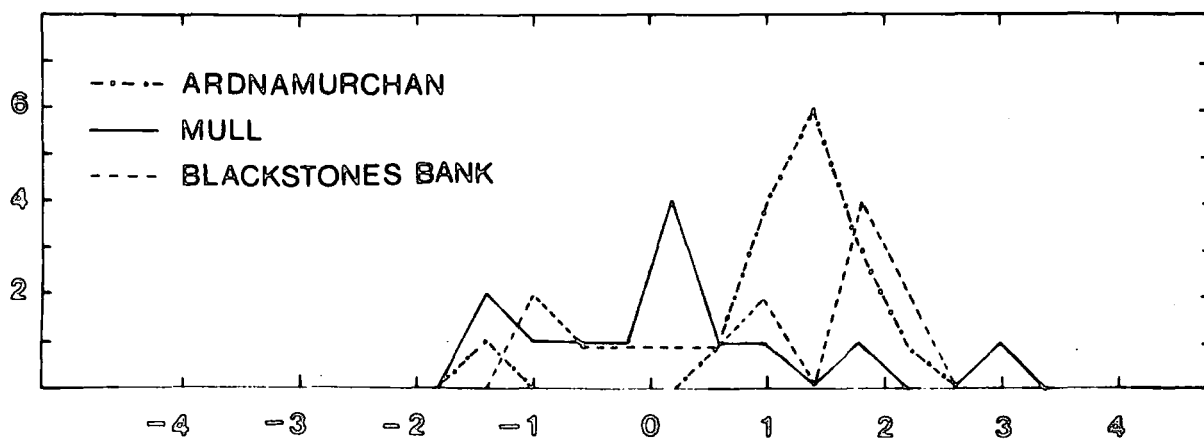
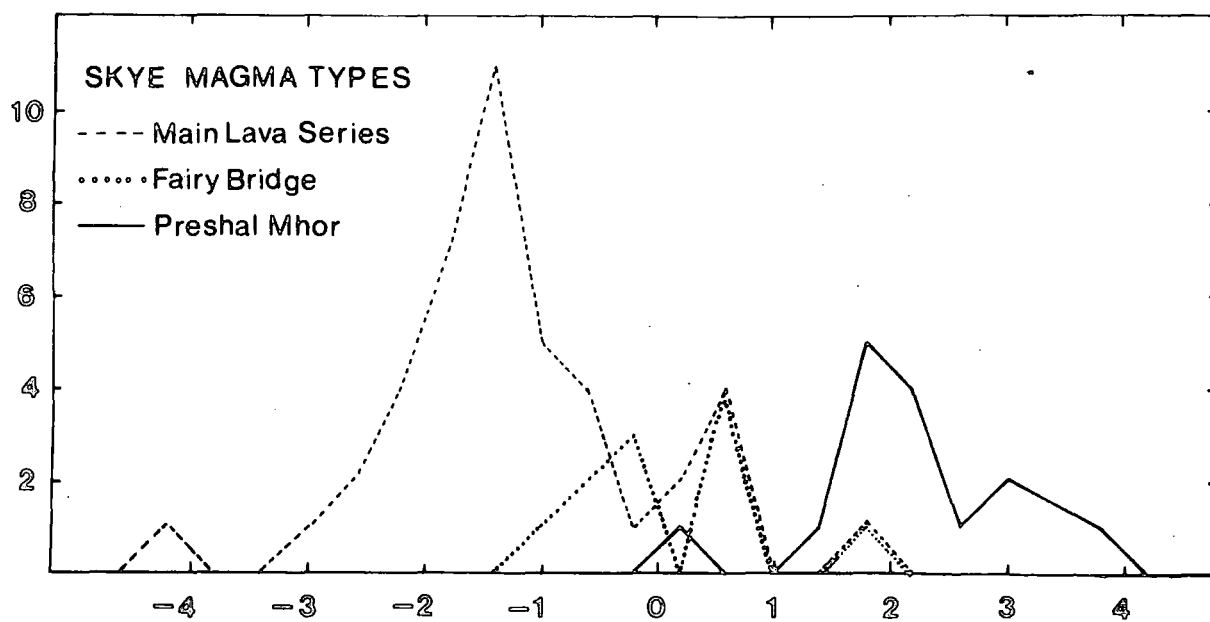
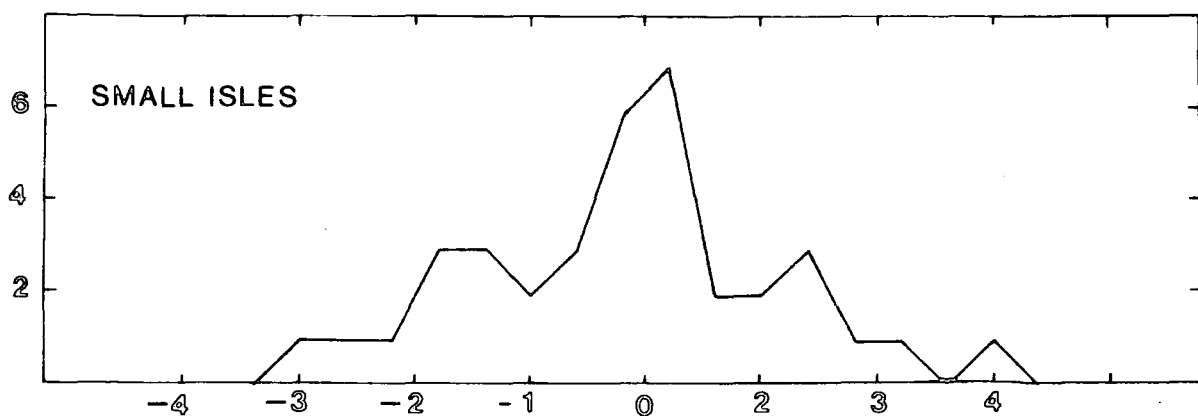


FIG 3.6 Frequency distribution of the discriminant scores of worldwide alkali,tholeiite and transitional basalts and Rhum magmas.

Fig. 3.7 Frequency of the discriminant scores in some Hebridean basalts. For data sources see appendix 3.1.



Group	Mean	Maximum	Minimum
1	0.2404	0.5000	0.0909
2	0.2356	0.3125	0.1429
3	0.2231	0.2632	0.1429
4	0.1886	0.3043	0.1071
5	0.1389	0.1667	0.1200
6	0.1653	0.1795	0.1481
7	0.2000	0.2727	0.1429
8	0.2294	0.6154	0.1000
9	0.2535	0.3043	0.1818
10	0.2990	0.3929	0.1905
11	0.3012	0.3667	0.2222
12	0.5305	0.5610	0.5000

Table 3.1 The range of Nb/Y ratios of the Rhum dolerite groups.

TABLE 3.2

CLASSIFICATION STATISTICS FOR THE THOLEIITE ALKALINE AND
CALCALKALINE MAGMA TYPESMajor and trace elements

<u>Actual Class</u>	<u>No. of cases</u>	<u>Predicted Class Membership</u>		
		1	2	3
Class 1 Tholeiite	78	74 94.9%	1 1.3%	3 3.8%
Class 2 Alkali	62	3 4.8%	58 93.5%	1 1.6%
Class 3 Calc-alkali	51	1 2.0%	0 0.0%	50 98.8%
Rhum dolerites	156	84 53.8%	68 43.6%	4 2.6%
Rhum gabbros	24	12 50%	12 50%	0 0.0%

Major elements

<u>Actual Class</u>	<u>No. of cases</u>	<u>Predicted Class Membership</u>		
		1	2	3
Class 1 Tholeiite	78	73 93.6%	2 2.6%	3 3.8%
Class 2 Alkali	62	3 4.8%	57 91.9%	2 3.2%
Class 3 Calc-alkali	51	6 11.8%	4 7.8%	41 80.4%
Rhum dolerites	156	84 53.8%	72 46.2%	0 0.0%
Rhum gabbros	24	10 41.7%	14 58.3%	0 0.0%

TABLE 3.3
CLASSIFICATION STATISTICS FOR THE THOLEIITE
AND ALKALINE MAGMA TYPES

Major and trace elements

<u>Actual Class</u>	<u>No of cases</u>	<u>Predicted Class Membership</u>	
		1	2
Class 1 Tholeiite	78	76 97.4%	2 2.6%
Class 2 Alkali	62	3 4.8%	59 95.2%
Rhum dolerites	156	85 54.5%	71 45.5%
Rhum gabbros	24	10 41.7%	14 58.3%

Major elements

<u>Actual Class</u>	<u>No of cases</u>	<u>Predicted Class Membership</u>	
		1	2
Class 1	78	75 96.2%	3 3.8%
Class 2	62	3 4.8%	59 95.2%
Rhum dolerites	156	85 54.5%	71 45.5%
Rhum gabbros	24	10 41.7%	14 58.3%

CHAPTER FOUR

PETROGRAPHY

Introduction

This chapter describes the variable petrography of the Rhum dolerites and includes a more detailed description of the petrographical features used in the classification. The gabbro and peridotite plugs and the acid dykes are also described and a small section is devoted to the xenoliths in the dolerite dykes. The mineralogy and mineral chemistry is described in Chapter 6.

Particular attention was paid to petrographic features which offer insight into petrogenetic processes; this includes the presence of different phenocryst assemblages, the relationships of the groundmass minerals and the development of unusual textures.

Several of the dolerites are amygdaloidal; chlorite and calcite are by far the most abundant vesicles but epidote, quartz, amphibole and zeolites can also contribute. One of the thick conformable sheets (77243) has a unique occurrence of amygdaloidal hydrogarnet.

Group One

Olivine and to a lesser extent spinel are ubiquitous phenocryst phases; the group is petrographically variable

as the phenocryst abundance varies from specimen to specimen. Three main petrographic types are represented in the group, two are characterised by the presence of pale brown groundmass clinopyroxene; the other by additional chestnut brown, strongly pleochroic amphibole. The picritic rocks are often fresh; the general lack of alteration facilitates comparisons of individual specimens and enables recognition of subtle differences between the different petrographic types.

Type 1

These specimens possess variable quantities of phenocrystic olivine (Fo84-Fo88) and chrome-spinel, the former can be fresh (53A76, Plate 4.1) or altered (69A76). The spinel occurs as phenocrysts either enclosed by olivine or independently. They are usually opaque but red-brown translucent varieties are also present. The titanium-rich aluminous groundmass clinopyroxenes are deep brown in colour and are strongly pleochroic, they are generally interstitial to the elongate, mildly zoned (An55-An78) plagioclase laths and the abundant altered groundmass olivine. The plagioclase crystals are generally equidimensional but sparse larger laths may be microphenocrysts. Most sections contain minor quantities of a green pleochroic amphibole which partially rims some of the clinopyroxenes, as well as occurring as an independent groundmass phase.

One section (56A76) exhibits a sharp but unchilled contact between a normal picrite and a more leucocratic facies. The latter contains abundant lilac-brown elongate clinopyroxene laths, altered feldspar and abundant amygdaloidal calcite. There is also abundant emerald green, strongly pleochroic amphibole which both mantles some of the clinopyroxenes and also occurs independently. Opaque oxides are abundant in this leucocratic facies, the majority are granular but some occur as very elongate fibrous crystals which are possibly ilmenite. In addition quartz and minor green and brown amphibole contribute to the vesicle infill and both phenocrystic and groundmass olivine are absent. This atypical facies is probably due to crystallisation from a volatile-rich differentiated liquid.

Three members of this type were collected from the olivine rich portions of picrite dykes. One fresh specimen (52A76) contains abundant olivine phenocrysts upto 6mm in diameter. The brown groundmass pyroxenes and the mildly zoned plagioclase often interfinger in variolitic growth structures; (Plate 4.2), as with other specimens of this type green amphibole is also present. 77179 is similar but there is less phenocrystic olivine, and the variolitic texture is poorly developed.

Type 2

Although they are similar in many respects to Type 1, individual specimens generally have a much greater range in olivine phenocryst size (0.3-2.5 mm), finer grained groundmass minerals and less groundmass olivine. The olivine phenocrysts (Fo84-Fo88) are usually granular anhedral or subhedral crystals but skeletal hopper shapes (terminology from Donaldson 1976) are also found in some specimens (eg. 77052, 77095). A weak variolitic groundmass texture is found in some specimens (eg. 77052, 77101). The latter has suffered mild thermal metamorphism and a peculiar dendritic texture formed by exsolution of opaque minerals has developed in the olivine phenocrysts. Plagioclase microphenocrysts have also been observed in some specimens.

Type 3

These specimens have variable quantities of phenocrystic olivine and spinel, the latter is always opaque. They possess olivine (which is usually fresh), very pale brown coloured clinopyroxenes, plagioclase and spinel as groundmass minerals. In addition they all contain a chestnut brown, strongly pleochroic amphibole (kaersutite) in variable abundance. This amphibole partially and wholly rims clinopyroxene and can also be seen replacing the latter. In the freshest section (77236) it occurs as sub-ophitic plates enclosing all

the other minerals. The remaining specimens exhibit recrystallisation textures of the groundmass minerals which vary in degree from specimen to specimen. In addition the clinopyroxene and to a lesser extent the olivine phenocrysts can show considerable exsolution of opaque oxides. Although it can be seen replacing clinopyroxene the amphibole appears to be a late stage primary magmatic mineral as it can develop ophitic relationships to other minerals and it has been recrystallised along with the other major phases in some of the specimens.

One final specimen (77024) deserves special mention as it is petrographically unusual. It contains abundant phenocrystic olivine (Fo76) and chrome spinel, the former varying in morphology from elongate chain olivines (Plate 4.3) through hopper olivines to granular varieties (terminology from Donaldson, 1976). The groundmass is extremely fine-grained and consists of granular aggregates of blackened olivine (Fo75), clinopyroxene and plagioclase (An40-An66), with subordinate opaques. The petrological significance of this dyke is discussed in Chapter 6 (p.173).

Group Two

Several of the members of this group have no phenocrysts, others contain very sparse phenocrysts of altered olivine and titanomagnetite or plagioclase (An60-An82), others contain all three of the phenocryst phases

(Table 4.1). The typical group two specimens are aphyric and possess neutral coloured subophitic aluminous clinopyroxenes, zoned elongate plagioclase (An₄₃-An₇₄), abundant altered groundmass olivine and titanomagnetite opaque oxides. Several specimens (eg. 77039, 93A76) exhibit variolitic groundmass textures (Plate 4.4), composed of fans of radiating plagioclase (terminology following Lofgren 1974, p.249) with interstitial clinopyroxene, olivine and opaque oxide. Several of the plagioclase crystals in these variolites are hollow cored, (eg. 77240). Most of the variolites contain sparse granular olivine phenocrysts (eg. 77039) but hopper olivines have also been located (77019).

One coarse-grained specimen (39A76) is atypical as it possesses a pale brown (as opposed to neutral coloured) ophitic clinopyroxene and fibrous opaques in rounded areas which may be amygdale infills. Although phenocrystic plagioclase is sparse it is found in certain specimens. 65A76 and 70A76 contain plagioclase microphenocrysts in glomerophyric aggregates and as single crystals. These phenocrysts appear to be in equilibrium with the groundmass. Both 77214 and 77245 carry phenocrystic plagioclase in addition to subordinate altered olivine; once again the plagioclase appears to be in equilibrium with the groundmass but there are suggestions of reaction rims

around several of the plagioclase crystals in the former. In addition 77214 contains rare, lighter coloured clinopyroxene plates in optical continuity with the enclosing subophitic groundmass pyroxenes which may be microphenocrysts.

Group Three

The group three specimens are petrographically variable but 4 main types can be distinguished by their phenocryst content (Table 4.1).

(i) Aphyric. The aphyric varieties typically possess a neutral coloured interstitial feathery edged Ca-augite, elongate mildly zoned plagioclase (An50-An67), many of which have hollow cores. Both granular and skeletal needle-like titanomagnetite crystals are present, the granular groundmass olivine is invariably altered. An extremely fine-grained chilled facies can be seen in 77080 showing these dykes do not have variolitic chills. Only one true variolite is present in group 3 (77346) which closely resembles the variolites in group two but lacks the sparse olivine phenocrysts.

(ii) Plagioclase-olivine phyric. Phenocrystic olivine is subordinate in quantity to phenocrystic plagioclase in the plagioclase-olivine phyric specimens. The former is always altered and some contain included chrome-spinels.

reaction rims have developed around the plagioclase phenocrysts in one of the specimens (77251). The calcic augites are neutral in colour and vary from granular to subophitic, the sub-parallel plagioclase needles in 77191 give it a distinctive flow aligned groundmass texture.

(iii) Plagioclase-clinopyroxene-olivine phyrlic. Aluminous clinopyroxene phenocrysts occur in aggregates with either plagioclase (An₈₂) or with both plagioclase and olivine whereas the latter two can occur as independent phenocrysts. Texturally these aggregates resemble xenolithic accumulations although reaction rims with the groundmass are not always present. One specimen (77082) contains a single plate of phenocrystic clinopyroxene in addition to abundant phenocrysts of plagioclase and altered olivine. Although it is difficult to be certain, it seems that the aggregates of clinopyroxene in these rocks are xenolithic (perhaps cognate in origin) and the pyroxene is not a true phenocryst phase.

(iv) Plagioclase phyrlic. The fourth main type resembles the aphyric rocks but are characterised by the presence of sparse phenocrystic plagioclase.

Group Four

Three main petrographic types can be recognised in Group Four. These are aphyric, plagioclase phyrlic and

plagioclase-olivine phyrlic. Although clinopyroxene, plagioclase and opaque oxides are ubiquitous groundmass phases in group four, olivine can be absent.

(i) Aphyric. The aphyric specimens have a variable petrography, clinopyroxene varies from a neutral coloured non-pleochroic variety to a deep brown titaniferous augite. Compositional zoning is marked in some specimens (eg. 77035, 77012, 95A76) by a diffuse pale brown rim to otherwise neutral coloured pyroxene. The clinopyroxene which is a calcic augite in composition, has a variable habit, the majority is interstitial but ophitic and granular pyroxenes have also been found (eg. 77176 and 95A76 respectively) there is no consistent relationship between clinopyroxene colour and habit. Plagioclase (An40-An43)* generally occurs as small rather elongate laths but pools of interstitial plagioclase are also present; some specimens (eg. 41A76, 77086) contain some moderately skeletal plagioclase crystals. Olivine is always granular in habit and is pseudomorphed by chlorite, talc etc when present. The opaque oxides (titanomagnetites) can be found as elongate rods (eg. 41A76) but the majority are anhedral grains.

(ii) Plagioclase phyrlic. Plagioclase phenocrysts occur as single crystals and in glomeroporphyritic aggregates;

*Based on very limited analytical data.



they show mild zoning. Finger print textured reaction rims have developed around plagioclase phenocrysts in several specimens. The groundmass relationships are variable, several specimens have a differentiated aspect similar to the group eight specimens (see p.107) whereas others are typically basaltic. There is no consistent relationship between the clinopyroxene colour (which is generally neutral but can be pale brown) and habit (which is typically either interstitial or granular but can be subophitic) in these plagioclase phyric specimens.

(iii) Plagioclase-olivine phyric. Phenocrystic plagioclase can also occur with subordinate altered olivine, the latter may carry included opaque phenocrysts, the opaque phenocrysts can also occur as independent crystals. Deep brown interstitial groundmass clinopyroxene is found in 77073 and the groundmass in 77015 (which carries rare phenocrystic olivine) is mildly differentiated; however, these specimens are atypical. The majority of the plagioclase-olivine phyric specimens possess neutral or very pale brown calcic augite; (which is generally interstitial), mildly zoned plagioclase laths and moderately abundant granular titanomagnetite.

(iv) Plagioclase-opaque oxide phyric. Some specimens possess plagioclase and opaque phenocrysts without associated olivine. The latter can occur either as

inclusions in the plagioclase or as independent phenocrysts and are rare (sometimes only two per thin section). The lack of phenocrystic titanomagnetite suggests that the group four magmas had a low oxygen fugacity which inhibited the formation of phenocrystic titanomagnetite.

(v) Plagioclase-clinopyroxene phyric. Phenocrystic clinopyroxene (generally a calcic augite) always occurs in association with plagioclase. Although it can occur in glomerophyric aggregates (47A76 cf. group three) the majority occurs as single crystals and appears to be a true phenocryst phase, two specimens (77032, 77351) carry neutral coloured pyroxene whereas 77348 carries a pale brown slightly pleochroic variety. In all three specimens the groundmass pyroxene is similar in colour to the phenocrystic pyroxene.

The high iron variants noted in Chapter 3 could not be distinguished from the remainder of group four, they are generally either aphyric or mildly plagioclase phyric.

Group Five

These specimens all contain calcic plagioclase and magnesian olivine microphenocrysts either as single crystals or in aggregates up to 4mm long. The plagioclase is unzoned and occurs as tabular laths which appear to be

in equilibrium with the groundmass. The olivine is generally fresh and usually occurs as spherical grains although elongate tabular olivine phenocrysts can be seen in 77323. The groundmass is distinctive as the neutral to very pale brown coloured clinopyroxenes are ophitic with individual crystals up to 3mm long, this ophitic texture is preserved in the finegrained chilled specimens (eg. 77056), although it is only weakly developed in one of the coarser specimens (77323). The groundmass plagioclase occurs mainly as needles embedded in the pyroxenes but some is interstitial. The groundmass olivine is generally fresh and is granular in habit, the opaque minerals occur as ragged anhedral interstitial grains.

Group Six

Three petrographic types are developed in group six. Specimens SR182, SR159 and SR282 are similar, they possess sparse, poorly formed, strongly zoned plagioclase microphenocrysts in a matrix of grey coloured subophitic augite, elongate mildly zoned plagioclase laths, sparse altered olivine, interstitial opaques and devitrified interstitial glass. One aphyric specimen (SR211) is distinctive as it contains a deep lilac, moderately pleochroic interstitial clinopyroxene along with fresh granular olivine, elongate plagioclase and granular

opaques. The final specimen (SR141) is atypical as it is the only post-lava dyke to have suffered serious alteration. It carries altered olivine phenocrysts in a groundmass of acicular plagioclase (often with hollow cores), interstitial pale brown slightly pleochroic clinopyroxene and small granular opaques.

Group Seven

All these specimens contain variable amounts of large (up to 6mm diameter) well formed sub-equant plagioclase phenocrysts; one specimen contains a single olivine phenocryst. The plagioclase phenocrysts are slightly zoned (An83-An88) and show no signs of reaction with the groundmass, they occur as either single crystals or as 2-4 crystal aggregates. The groundmass typically consists of a neutral coloured ophitic calcic augite enclosing acicular plagioclase (An38-An41) and some of the granular opaques. Some of the specimens were collected from areas adjacent to later basic intrusions and show mild recrystallisation of the groundmass minerals. Two specimens are atypical, 77014 contains fewer plagioclase phenocrysts and the clinopyroxene is interstitial rather than ophitic. The groundmass in 12A76 is coarser than usual for the group; the sub-ophitic aluminous calcic augite being pale brown in colour as opposed to neutral. The only analysed pyroxenes in group seven are from

12A76 as this was the only specimen with a sufficiently coarse groundmass.

Group Eight

Four main petrographic types are encountered in group eight (see table 4.1). Despite the variation in phenocryst content many of the specimens have petrographically similar groundmass textures. The groundmass generally contains abundant plagioclase (An₂₆-An₆₈) as laths and in interstitial pools this imparts a leucocratic appearance, granular neutral or straw coloured non-pleochroic augite is subordinate in abundance to plagioclase as are the opaque titanomagnetites. Specimens with groundmass textures as described above are referred to as differentiated (as opposed to basaltic) in this account.

Several of the group eight specimens are characterised by the presence of brown devitrified glass, some specimens are virtually hyalocrystalline (eg. 77078) with plagioclase microlites whereas in others the glass is interstitial to plagioclase and intersertal clinopyroxene. A peculiar angular mesh of extremely fine acicular opaques is developed in the interstitial glass and in some of the hyalocrystalline specimens (Plate 4.5). Several of the glassy specimens contain variolitic plagioclase either as fans as described in group two or as extremely well developed bow-tie structures (Plate 4.6). The

variolitic plagioclase often nucleates at both ends of the elongate plagioclase microlites (Plate 4.7). Plagioclase is the principal phenocryst phase in these glassy specimens and occurs as extremely well formed sparse crystals.

The aphyric and plagioclase phyric specimens are similar as both types have a differentiated groundmass, rare plagioclase microphenocrysts are encountered in the former but are more abundant in the latter. These microphenocrysts have poor crystal forms and often appear to be in disequilibrium with the groundmass, some of the aphyric specimens have basaltic textures and can carry sparse altered groundmass olivine.

Plagioclase-clinopyroxene phyric and plagioclase-clinopyroxene-olivine phyric specimens are generally similar as they both possess a differentiated groundmass texture. The olivine is always altered to a green pseudomorph and is virtually absent in some specimens. The plagioclase (An₄₄-An₈₀) occurs as altered poorly formed crystals and the calcic augite is always a neutral coloured granular variety, the phenocrysts can occur as single crystals or in aggregates. The majority of these rocks have a low phenocryst abundance but some specimens possess up to 50% phenocrysts (eg. 77040).

Some of the plagioclase-clinopyroxene phyric

specimens have a peculiar feathery lobate edged neutral coloured clinopyroxene (Plate 4.8) which can be in association with skeletal plagioclase and elongate rod like opaque oxides. Elongate rod opaques also occur in otherwise typical groundmass textures (eg. 75A76).

Group Nine

The phenocryst phases in these rocks are plagioclase clinopyroxene and altered olivine with subordinate titanomagnetite microphenocrysts. The plagioclase is generally more abundant than either olivine and clinopyroxene and the latter is subordinate to olivine in the plagioclase-olivine-clinopyroxene-opaque phyric rocks. Both the clinopyroxene and plagioclase often develop reaction rims with the adjacent groundmass and in some specimens (eg. 29A76) seem to have been partially resorbed. The latter feature is also evident in the corroded margins of the titanomagnetite micro-phenocrysts (29A76, 76A76, 77209). The groundmass in these phyric rocks is generally leucocratic and very fine grained and the mafic minerals are generally altered. 55A76 is unusual as it carries altered, olive green mildly pleochroic amphibole phenocrysts in addition to the plagioclase (An45-An54) and clinopyroxene phenocrysts. The fresh groundmass in 55A76 contains abundant plagioclase

($\sim$ An47) and subordinate green amphibole, neutral granular augite, granular opaques and interstitial quartz. One of the aphyric specimens is hyalocrystalline with a faint acicular variolitic texture, the other has developed a stronger variolitic texture but differs from the basaltic variolites as in its more sodic plagioclase composition.

Group Ten

The majority of these specimens are plagioclase-olivine-chrome-spinel phyric, the phenocrystic magnesian olivine varies from fresh to altered and the tabular plagioclase laths (An63-An70) are generally in slight disequilibrium with the groundmass. Some contain included opaque phenocrysts which can also occur as independent phenocrysts (eg. 77137). The groundmass clinopyroxene is generally a deep brown pleochroic aluminous titanaugite and occurs interstitially to plagioclase, K-feldspar, olivine and opaque oxides. In addition two specimens (77137, 77184) contain a tan coloured mildly pleochroic primary amphibole, the groundmass of these two specimens is very similar to one of the aphyric specimens (32A76).

Group Eleven

These specimens contain only sparse amounts of the phenocryst phases (oligoclase feldspar and calcic augite)

which are usually less than 1mm diameter. As with groups nine and ten the plagioclase and clinopyroxene phenocrysts often show signs of disequilibrium with the adjacent groundmass but this is obscured by the generally altered nature of the specimens. Phenocrystic olivine where present is always altered and some specimens (77279, 77347) carry ilmenite or titanomagnetite microphenocrysts. The groundmass is always leucocratic with abundant plagioclase, the mafic minerals are generally altered and the opaque minerals are usually granular. The group as a whole is petrographically homogeneous.

Group Twelve

Both the specimens are very similar, they are leucocratic with abundant K-feldspar and some plagioclase feldspar laths, the parallelism of these imparts a trachytic texture. The clinopyroxene and brown hornblende are altered although very rare blue-green pleochroic amphiboles are fresh. The opaque minerals (probably titanomagnetite) are small and granular; apatite needles are fairly abundant as inclusions in the feldspar crystals. Amygdales infilled with calcite and chlorite testify to the presence of volatiles in the original magma.

Gabbros

High MgO gabbros

The dominant phase assemblage in most of the gabbros is olivine-clinopyroxene-plagioclase-opaque oxide, however some carry additional hypersthene. The olivine in the former is always altered although one specimen has occasional fresher crystals which exhibit pervasive opaque exsolution along cleavages. The clinopyroxenes are generally sub-ophitic although some specimens exhibit interstitial (77031) and granular (77252) textures, they range from colourless to a very pale brown. The plagioclase varies from tabular plates to rather elongate laths and can show extensive alteration. Some specimens (eg. 77256, 77288) have primary green pleochroic amphibole, which generally mantles earlier pyroxene; the opaque minerals are usually interstitial. Sphene and apatite are minor phases in some specimens (eg. 77031, 77256) and secondary epidote is common.

The hypersthene gabbros generally carry olivine which can be fresh (77104) or altered (77033) but the olivine is absent in 77292. The pale pink pleochroic hypersthene is generally subordinate to clinopyroxene but is abundant in 77290. The hypersthene is occasionally jacketed by the later Ca-rich clinopyroxene in 77033

Low MgO gabbros

The most distinctive petrographic features in these specimens is the abundance of sphene, epidote and apatite (eg. 77098, 77267), the presence of analcite and other zeolites (eg. 77067, 77270) and the presence of brown and green amphiboles which can show spectacular zonation from their colourless clinopyroxene cores through brown amphibole to green amphibole (eg. 77270, Plate 4.9). The gabbros show varying degrees of alteration of the colourless or brown tinted clinopyroxene which can be locally pervasive. The pyroxene and opaque oxides are generally interstitial to the strongly zoned somewhat altered plagioclase. The opaque oxides can develop a distinctive skeletal habit (Plate 4.10).

The quartz gabbros are petrographically variable, but all possess colourless clinopyroxene, granular or interstitial opaques and interstitial quartz. 77102 is characterised by the presence of pink pleochroic hypersthene and strongly zoned plagioclase. In contrast 77103 possesses a green pleochroic amphibole which mantles the earlier pyroxene, this specimen also has interstitial sphene and epidote. The amphibole in 77274 is brown pleochroic and can be seen both rimming and replacing the clinopyroxene along cleavages. Both 77103

and 77274 have turbid orthoclase feldspar which is intergrown with the quartz in the former.

The ferrodiorite (77264) is similar to 77274 but is much more leucocratic, the clinopyroxene is distinctly granular with occasional fresh areas. The plagioclase is zoned to alkali feldspar and interstitial quartz is moderately abundant.

Peridotites

The peridotite plugs are usually composed of a homogeneous, feldspathic peridotite consisting of abundant olivine with subordinate chrome-spinel, plagioclase and clinopyroxene. Primary chestnut brown pleochroic amphibole and brown pleochroic biotite are minor phases in some specimens (eg. 77086, 77183) and a green pleochroic amphibole may also be present (eg. 77259). The olivine is typically fresh occurring as rounded to tabular grains (1-4mm diameter) in a matrix of slightly zoned plagioclase and a colourless to pale brown clinopyroxene. The latter is virtually absent from some specimens (eg. 77051, 77290).

The olivine grain morphology is variable, a few specimens possess almost spherical olivine crystals (eg. 77357) whilst others contain lobate skeletal crystals up to 7mm diameter (eg. 77089). Although the peridotite

plugs do not possess chilled margins, specimens from the marginal facies can be finer grained than those from the centre of the plug (see Plate 4.11).

The chrome-spinels vary in size from specimen to specimen ranging 0.02 to 0.5mm diameter, they occur as inclusions in the olivines and as independent phases. The clinopyroxene and plagioclase always occur interstitially, the clinopyroxene generally postdating the latter. The inferred order of crystallisation thus being:

Chrome spinel-olivine-plagioclase-clinopyroxene ⁺
mica and hornblende

Although the plugs are generally petrographically homogeneous xenoliths of dunite (77285) are abundant in the feldspathic peridotite plug north of Minishal (77284) (see p.115) and a skeletal olivine textured xenolith (77054) has been located in 77055.

Acid dykes

These specimens are petrographically variable and are best described separately. The felsitic glass (77159) contains feldspar, opaque oxides and quartz phenocrysts in decreasing order of abundance. The former have developed fingerprint textures probably attributable to reheating by the adjacent gabbros, which would also account for the blackening of the glass Specimen 77180

is a quartz sanidine spherulite which was described by Harker (1908, p.140) although sanidine was not included in the original account. The quartz phenocrysts can be deeply embayed although subhedral crystals are also found. The groundmass is texturally variable with quartz-feldspar spherulites developed amidst aggregates of 0.05-0.1mm diameter quartz and feldspar crystals.

The pitchstone (77239) was also described by Harker (op cit. p.177) it carries rare quartz opaque and orthoclase phenocrysts in an altered brown glass matrix. The latter contains abundant slightly flow aligned feldspar crystallites. The final acid dyke (77241) carries moderately abundant plagioclase phenocrysts which are usually altered to epidote and clay minerals, the groundmass glass is devitrified to quartz-feldspar aggregates (cf 77180) with occasional indications of spherulitic structure.

Xenoliths

Although xenoliths are not abundant in the dolerite minor intrusions several different types have been encountered. Small bodies of feldspathic Lewisian gneiss have been located in the inclined sheets in the Allt Slugan a Choilich. These have suffered varying amounts of partial melting and strong reaction rims can develop around the fingerprint-textured feldspars. Localised production of

acid magma is indicated by the presence of devitrified acid glass in one of the specimens (30A76). The dolerite immediately adjacent to these xenoliths is always chilled to a tachylite facies. One specimen in the same stream section contains a pure calcic plagioclase xenolith (78A76b) which has developed slight reaction rims to the adjacent unchilled dolerite.

Other dolerites contain gabbroic xenoliths, the majority of these appear to be cognate as they are texturally similar despite their coarser size, an exception being the one-pyroxene gabbro nodule in the differentiated groundmass of 77112. The petrography of the xenoliths in the peridotite plugs has been discussed previously (p 114).

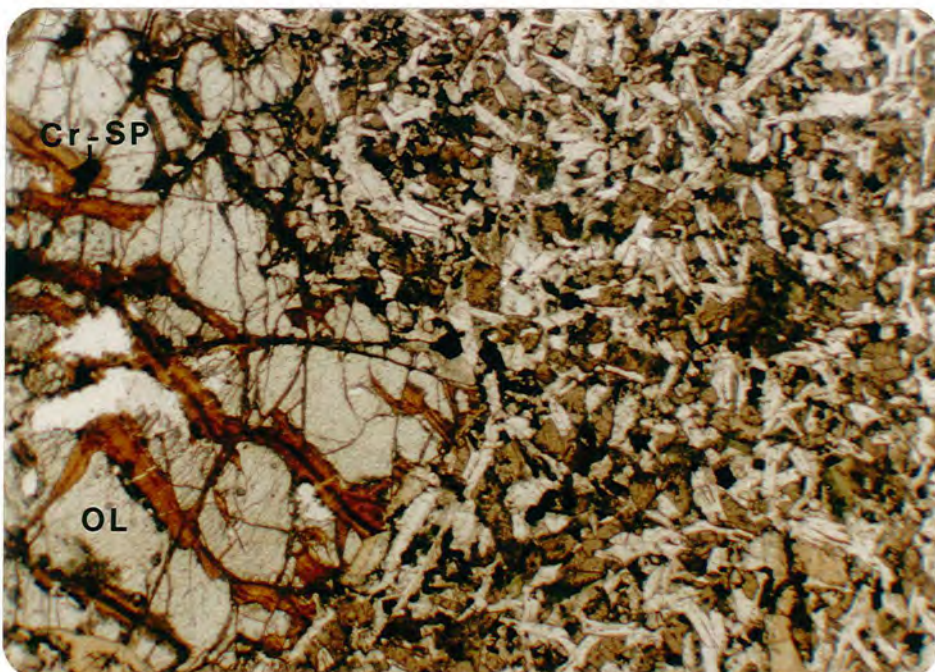


Plate 4.1. 53A76, Olivine phyric group 1 picrite. Note large granular olivine with included Cr-spinel and deep brown groundmass clinopyroxene. X20.P.P.

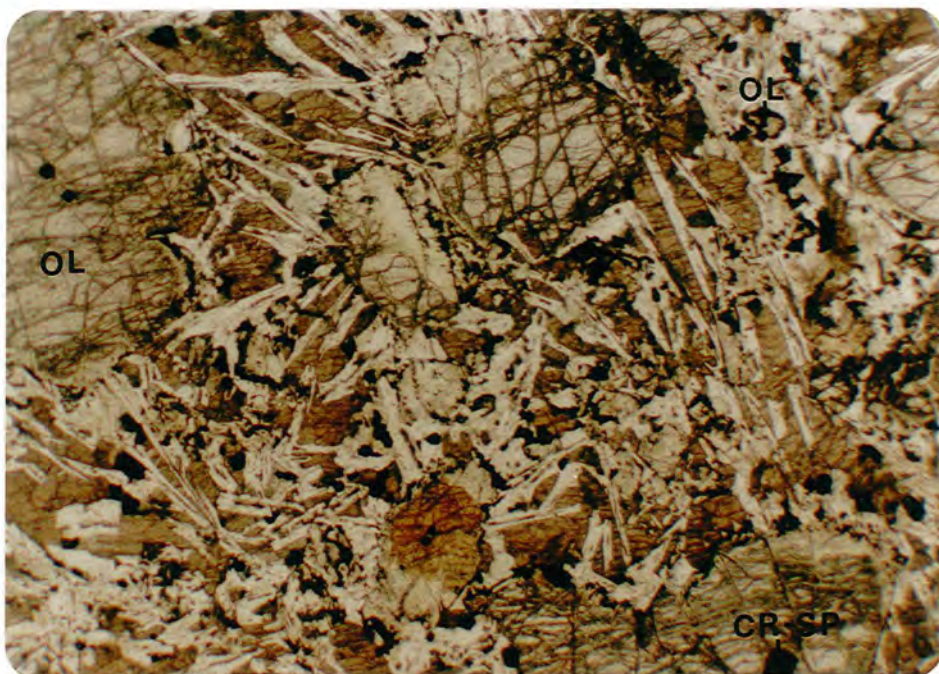


Plate 4.2. 52A76, Group 1. Olivine and Cr-spinel phenocrysts in a groundmass of variolitic textured plagioclase and clinopyroxene, note altered groundmass olivine. X20. P.P.

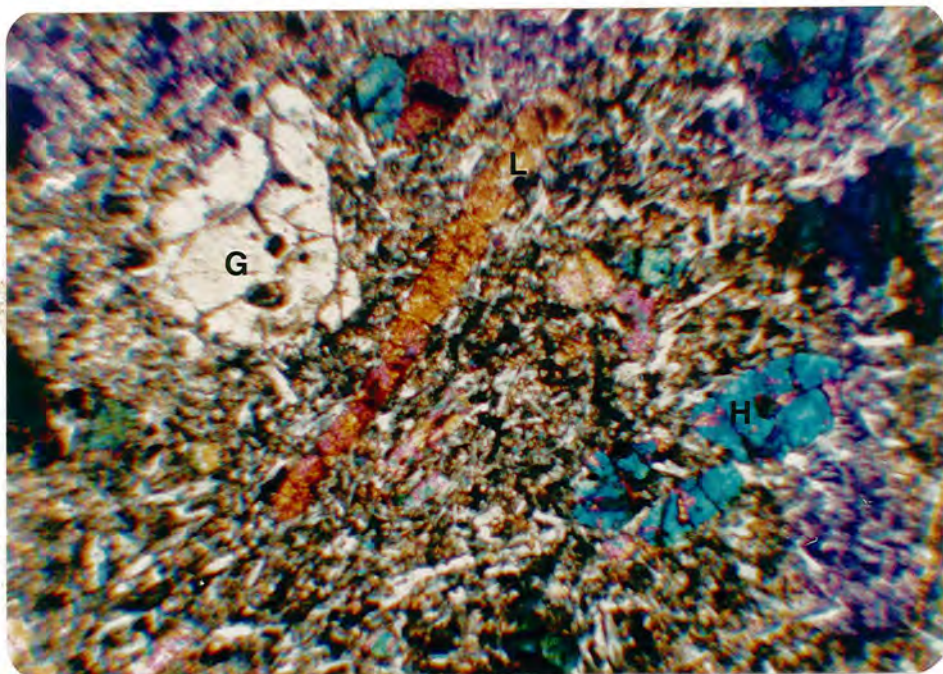


Plate 4.3. 77024, Group 1. Olivine phenocrysts in a fine grained groundmass of olivine, clinopyroxene plagioclase and Cr-spinel. G, H and L refer to granular, hopper and lattice textured olivine crystals respectively. X50. X.P.

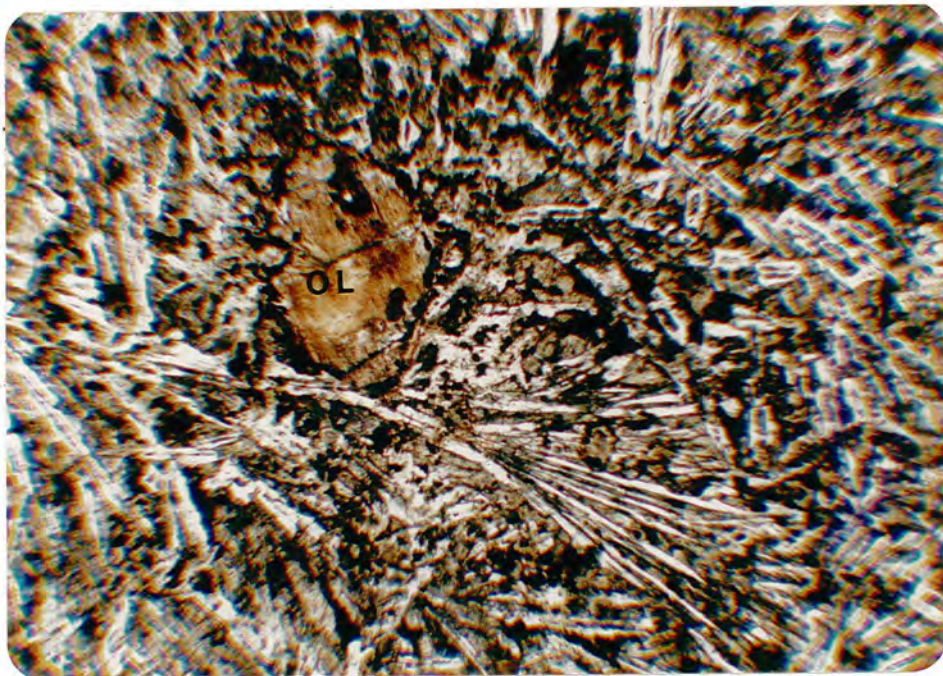


Plate 4.4. 77039, Group 2. Rare altered olivine microphenocrysts with included Cr-spinel in a groundmass of variolitic plagioclase (note hollow cores) with clinopyroxene and opaque oxides. X45. P.P.

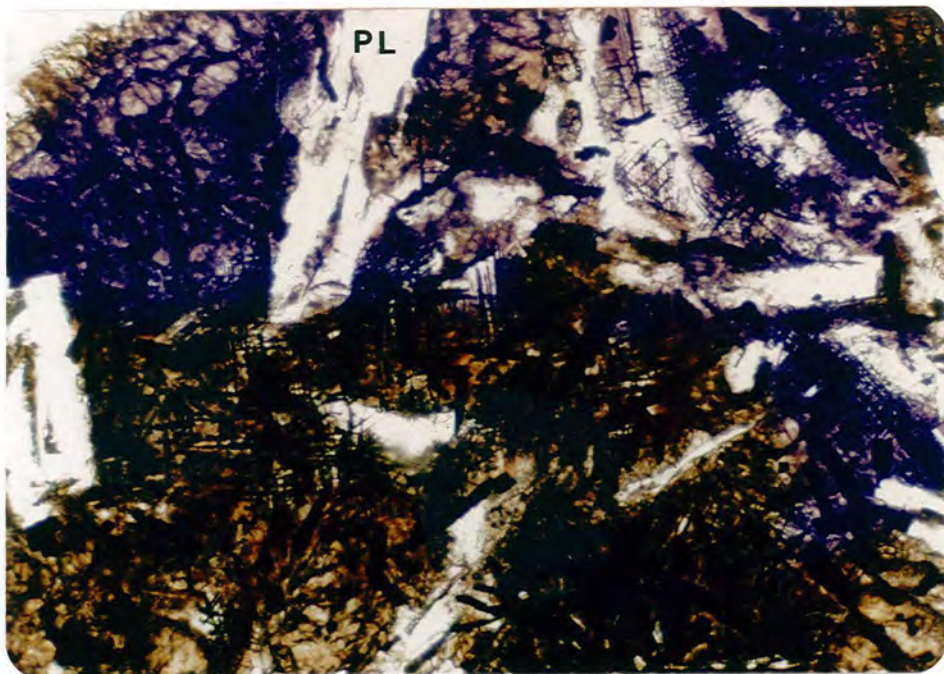


Plate 4.5. 23A76, Group 8. Large opaque rods (ilmenite?) and fine angular meshes of opaque in deep brown clinopyroxene and occasionally in plagioclase. X50. P.P.

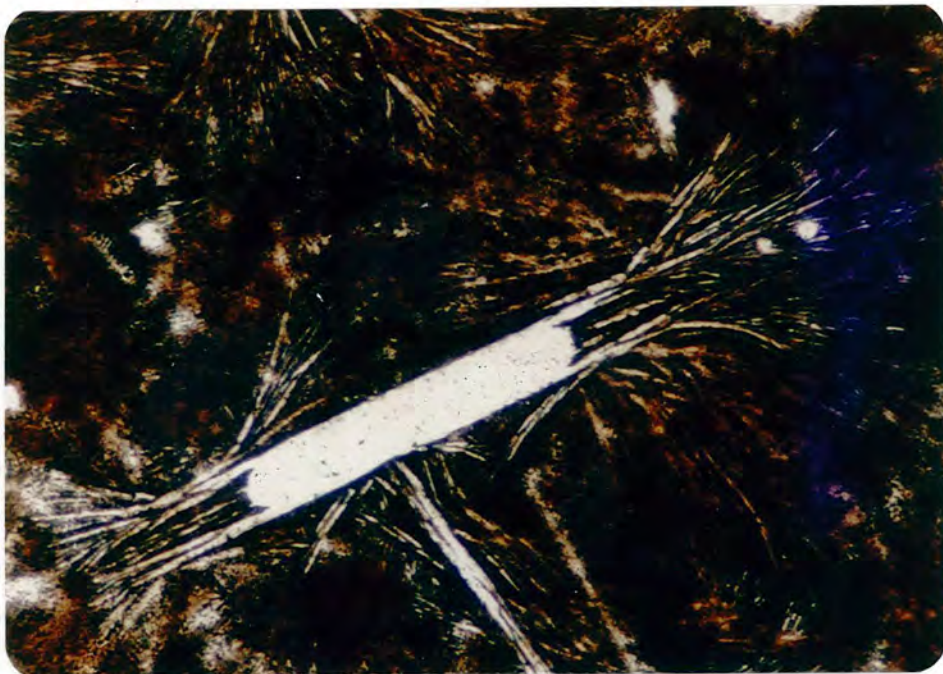


Plate 4.6. 20A76, Group 8. Bow-tie variolitic plagioclase in altered brown glass matrix. X100. P.P.

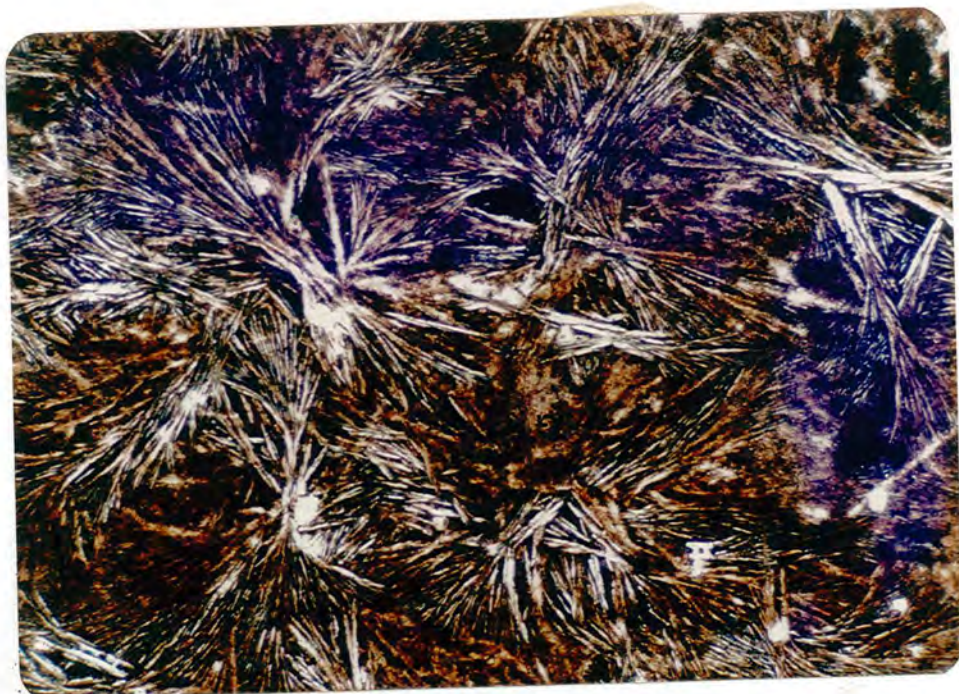


Plate 4.7. 20A76, Group 8. Elongate plagioclase microlite in dark brown glass, note how groundmass plagioclase variolites have nucleated on the ends of the plagioclase microphenocryst. X150. P.P.

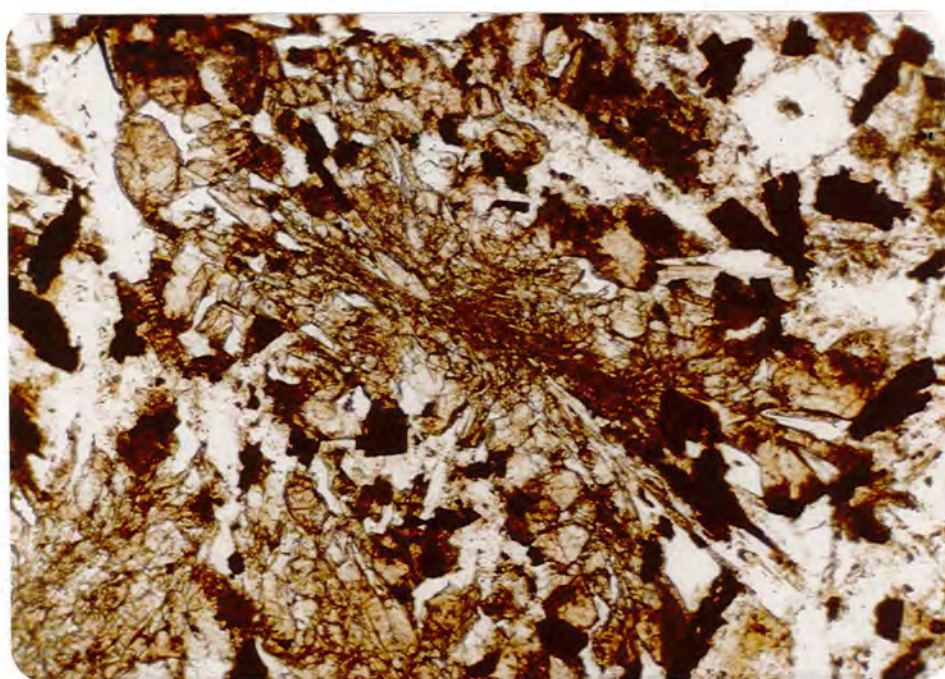


Plate 4.8. 46A76, Group 2. Lobate edged groundmass clinopyroxene in a plagioclase-opaque oxide matrix. Note euhedral plagioclase micro-phenocryst in top right hand corner. This clinopyroxene texture is more typical of the group 8 rocks but was more easily photographed in this group 2 specimen. X50. P.P.

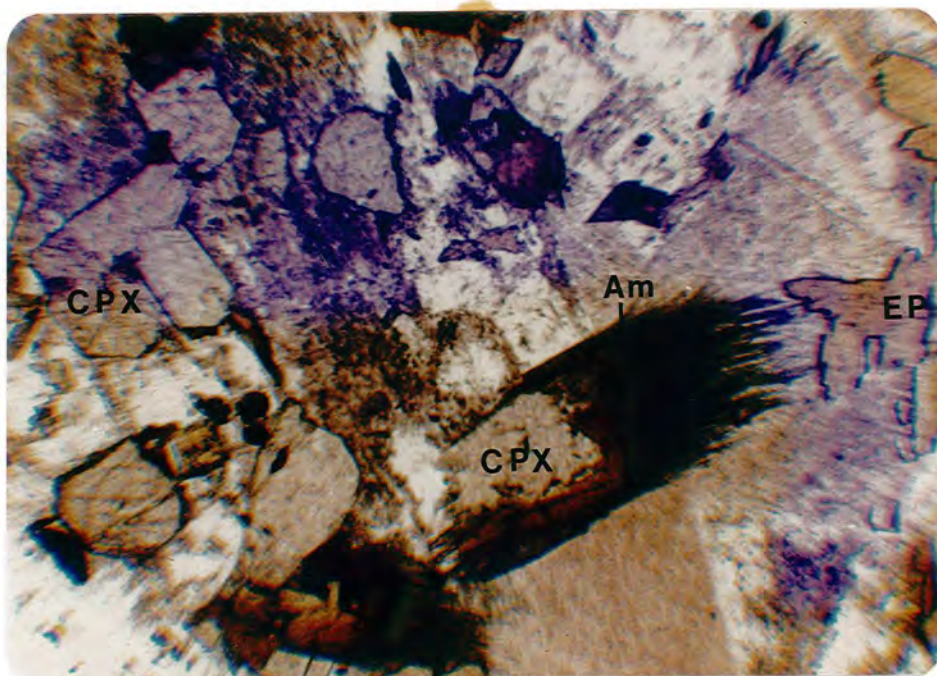


Plate 4.9a. 77250, Gabbro. Granular clinopyroxene some with brown and green amphibole overgrowths in a matrix of light brown altered feldspar with accessory epidote and opaque oxides. X50. P.P.

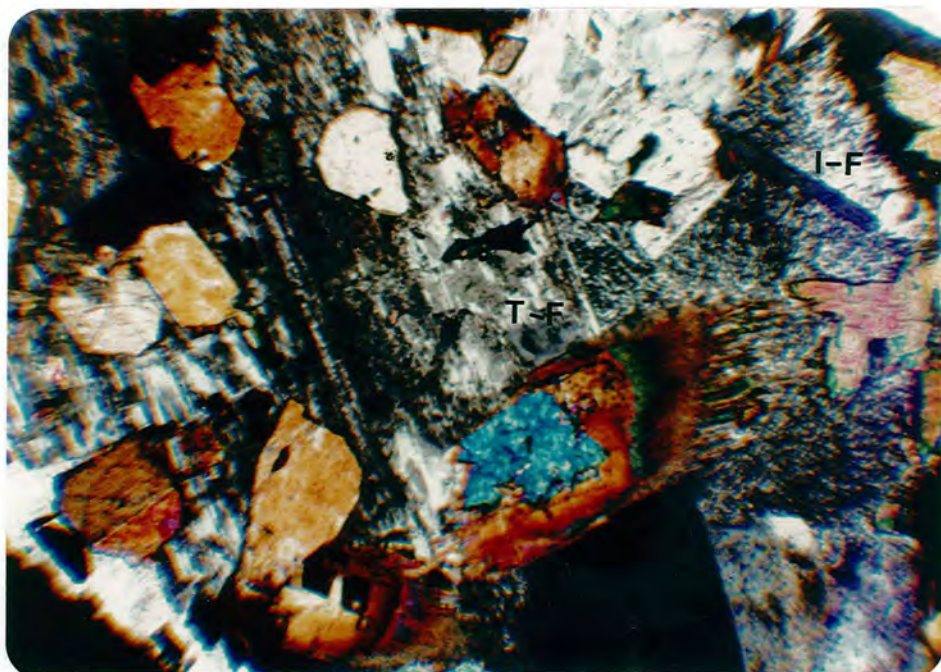


Plate 4.9b. As above. Note the systematic optical variation in the amphibole jacketing the clinopyroxenes. Note also the two generations of (i) large tabular feldspar (T-F) and (ii) interstitial feldspar (I-F) brought out by crossed polars. X50. X.P.

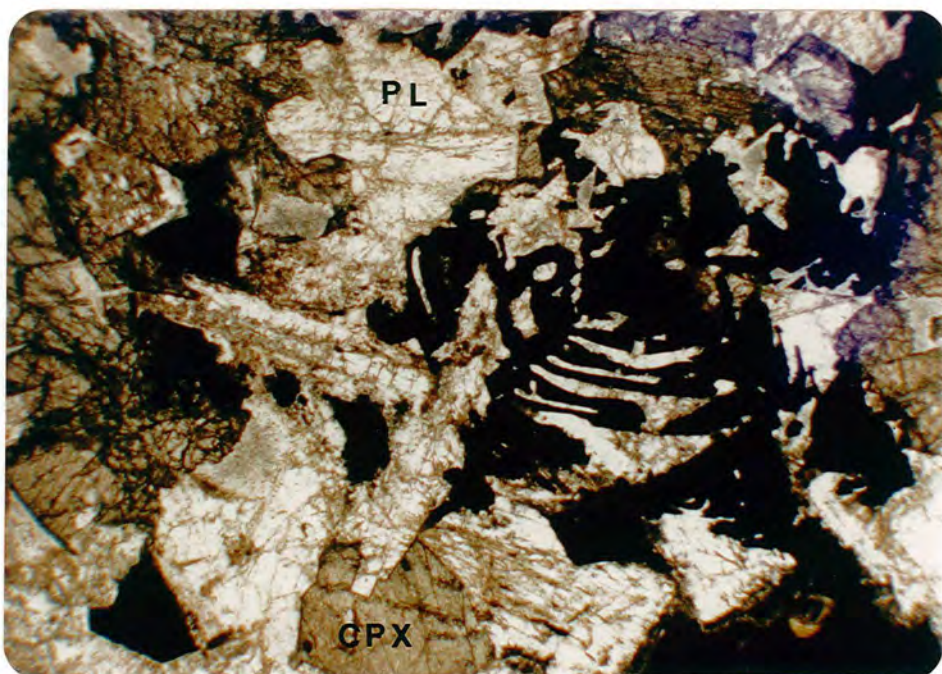


Plate 4.10. 77100, Gabbro. Skeletal textured opaque oxides in a granular clinopyroxene - plagioclase matrix. X15. P.P.

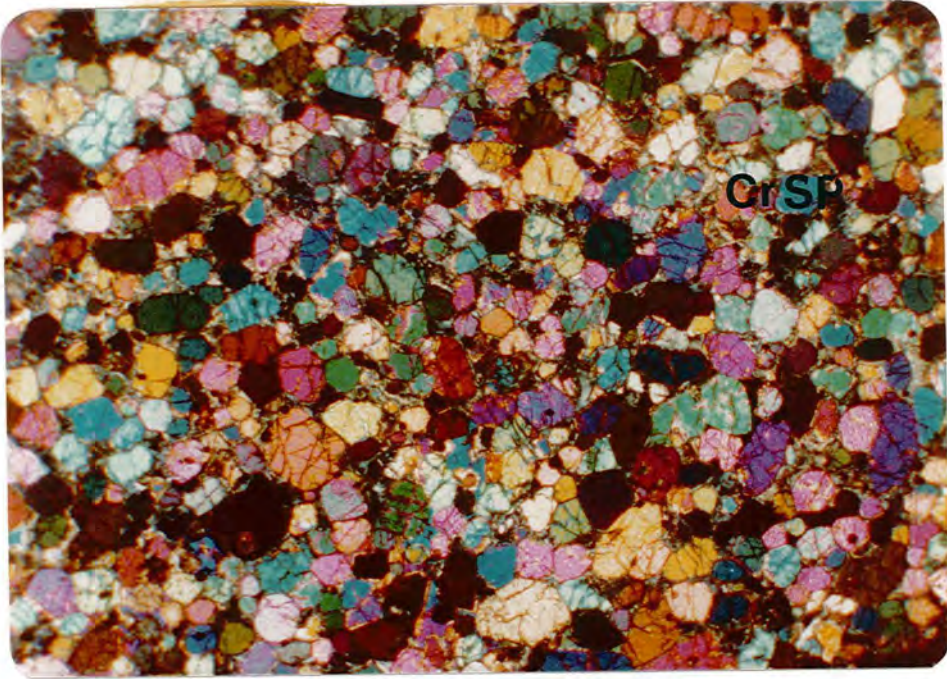


Plate 4.11a. 77357. Peridotite plug chilled margin. Round granular olivine in extremely sparse plagioclase - clinopyroxene matrix. Note the two translucent red-brown Cr-spinels in the top right hand corner. X15. X.P.

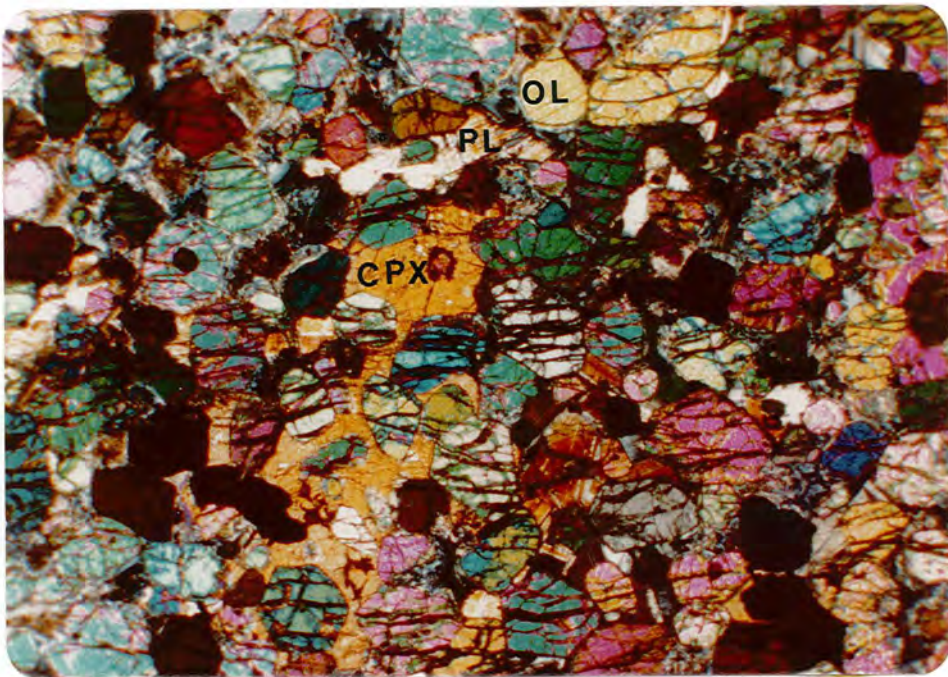


Plate 4.11b. 77358. Peridotite plug core, granular olivine and Cr-spinel (translucent to opaque) in poikilitic clinopyroxene and plagioclase matrix. Contrast grain size and other textural variation with 4.11a. X15. X.P.

Phenocryst Assemblage	GP 1	GP 2	GP 3	GP 4	GP 5	GP 6	GP 7	GP 8	GP 9	GP 10	GP 11	GP 12
A		7	8	31		1		13	3	2	1	2
Ol ⁺ -Op	28	8	1	1		1						
Pl		3	2	12		3	5	8				
Pl-Ol ⁺ -Op		2	3	12	6					4		
Pl-Cpx ⁺ -Op			3	4				16	2		1	
Pl-Op				5								
Pl-Ol-Cpx ⁺ -Op				2				7	3		3	

Table 4.1. Phenocrystic assemblages in the Rhum dolerite groups, the figure refers to the number of specimens with that phenocryst assemblage. NB. many of the specimens have less than 5% total phenocryst abundance, it is only the presence of phases which is recorded here.

A = Aphyric Ol = Olivine Op = Opaque Pl = Plagioclase
Cpx = Clinopyroxene

CHAPTER FIVE

THE MAGMATIC SEQUENCE ON RHUM

Introduction

Analysis of the cross-cutting relationships within and between the dolerite groups allows a more detailed description of the sequence of minor intrusions on Rhum than that presented in Chapter 2 (Table 2.1). The gabbroic plugs and some gabbros associated with the layered peridotites are also considered and a magmatic sequence which also includes the lavas of western Rhum is presented (Fig. 5.2).

a) Dolerites

The proportion of the dolerite groups 1-12 encountered in each of the major dolerite intervals that were defined in Chapter 2 is presented in Fig. 5.1. The relationships illustrated here are discussed along with other relevant observations in the text. As stated in Chapter 3 (p. 82) the collection is considered sufficiently representative of the proportions of the dolerite types on Rhum to allow qualitative discussion of their distribution.

The most comprehensive information on cross-cutting relationships comes from the felsite slabs in Stony Corrie, Dibidil (Fig. 2.6) but conclusions based on this are limited because the dolerite groups 1, 2, 9 and 11

are poorly represented and no group 3 or 10 dykes were found.

(i) Group 1 (28 specimens)

Group 1 magmas are represented in the stratigraphic intervals B-D (Fig. 5.1) but are not found cutting the lavas. They are particularly abundant in the Torridonian outside the Main Ring Fault (which may reflect a sample bias from the picritic dykes in the Allt Slugan a Choilich) but more significantly, are the most abundant dolerite type found cutting the peridotites and gabbros. A cross cutting relationship has been located between two group 1 specimens (77235 and 77236) which indicates that at least two ages of picrites are present within the peridotites. They are known to cut several group 8 dykes and a single group 9 dyke but are themselves cut by the Kilmory thick conformable sheets (group 8) and possibly by a single group 3 dyke SE of Papadil. Although the picrites are abundant in the peridotites the former are also cut by the peridotites on Minishal (Chapter 2, p. 36). To summarise, the picritic dykes appear to have been intruded fairly late in the magmatic sequence on Rhum but do span a considerable time interval.

(ii) Group 2 (20 specimens)

As with group 1, these dykes are represented in the stratigraphic intervals B-D in Fig. 5.1 and thus probably

span a considerable time interval. The cross-cutting relationship between 77212 and 77214 on Dibidil shore (NM 395927) confirms there are at least two group 2 intrusive events. They are cut by group 4b* dykes and cut an early gabbro (77033 NM385986) and a group 8 dyke in Stony Corrie Dibidil. Their age relative to other dolerite groups is not known. The specimens from Dibidil shore are not crushed or sheared suggesting they postdate the Main Ring Fault but one specimen (46A76) appears to be truncated by the Main Ring Fault immediately south of the dam on the Allt Slugan a Choilich (NM393983). On balance they are possibly fairly young in age but not as young as the picrites.

(iii) Group 3 (17 specimens)

Only one group 3 dolerite is found in the peridotite stratigraphic interval (Fig. 5.1) and this specimen comes from the gabbro marginal to peridotite at Papadil, which is believed to be older than the peridotites (Chapter 1, p. 8). Since the group 3 dolerites have not been found cutting the layered peridotite sequence, it seems likely that they pre-date the emplacement of the peridotites. They are known to be cut by group 4 dykes and one intrusion cuts the big feldspar dyke (group 7) on Meal Breac (NM 384981) whilst another probably cuts a picrite dyke (group 1) near Papadil. The majority of the

*Group 4b refers to the high iron group 4 variants (Chapter 3, p.69)

specimens from outside the Main Ring Fault are from the inclined sheets in the Allt Slugan a Choilich which are believed to be fairly early in the minor intrusion sequence on Rhum. As with the preceding groups, they probably span a considerable interval but in view of their lack within the peridotites may be earlier than the group 1 and 2 magmas.

(iv) Group 4 (64 specimens)

This group is the most abundant dolerite group on Rhum and many cross-cutting relationships both between intrusions from this group and with intrusions from other groups have been observed. They are the dominant dolerite type in both the Torridonian outside the Main Ring Fault and in the sequence Lewisian to Granophyre within the Main Ring Fault but are relatively scarce amongst dolerites cutting the peridotites (Fig. 5.1, B-D). They show complex within-group crosscutting relationships in Stony Corrie, Dibidil where at least three separate injections of group 4 magmas have occurred and many other within-group crosscutting relationships have been encountered elsewhere on the island (e.g. Harris Bay, Dibidil Shore).

Members of this group cut a group 2 and a group 3 dyke but the reverse relationship has not been encountered, and a group 4 thin conformable sheet is cut by a peridotite plug (NG 349014). Several group 8 dykes are cut by group 4

dykes, but the latter are cut by the Papadil thick conformable sheets (group 8) and other group 8 dykes. A group 4 thin conformable sheet is cut by a group 7 dyke west of Sgoarishal (NG 348017) and a group 4 dyke on Dibidil shore is cut by a group 9 dyke (NM 395927).

The high total iron (group 4b) dykes are cut by other group 4 dykes in Stony Corrie but cut another group 4 dyke on Minishal. Three group 4b dykes are cut by group 2, 8 and 9 dykes respectively whilst another dyke which must be young in age cuts the peridotite plug west of Loch Beauty (NG 358012). Thus the group 4b dykes span a considerable time interval and are included amongst the youngest known group 4 dykes.

The average analyses of ten group 4 dykes inferred to be young in the sequence and of eight group 4 dykes cut by younger group 4 dykes is presented in Table 5.1. Although the two average analyses are broadly similar with respect to the major oxides, consideration of the trace element data suggests that the younger dykes are slightly more differentiated, as the younger dykes are depleted in Ni and Cr and are enriched in Zr, Y and Rb, relative to the average values of the older dykes.

(v) Group 5 (6 specimens)

It is clear from Fig. 5.1 that group 5 dykes are best represented in the lavas but they are also present in

the granophyres and in the Torridonian outside the Main Ring Fault. Of the 2 specimens not cutting the lavas, the dyke from the granophyre cuts a group 4 and a group 8 dyke and the dyke from the Torridonian cuts a peridotite plug, confirming the very young age implied by their presence in the lavas.

(vi) Group 6 (5 specimens)

These dykes are only found cutting the lavas (Fig. 5.1) and along with group 5 are the youngest known Tertiary rocks on Rhum. As with group 5 no within-group crosscutting relationships have been observed and they may represent a relatively short but discrete chronological interval.

(vii) Group 7 (5 specimens)

The age relationships of the group 7 dykes were discussed in Chapter 2. They are not found in the peridotites (Fig. 5.1) and are known to be truncated at the contacts between peridotite and older rocks (Chapter 2, p. 37). Only limited cross cutting relationships with other dolerite groups are known. They cut a group 4 dyke and a Papadil thick conformable sheet (group 8) and are themselves cut by a group 3 dyke. Their petrographic uniformity suggests that they represent a fairly discrete chronological interval postdating the Main Ring Fault (Chapter 2, p. 37) and thick conformable sheets but pre-dating the emplacement of the layered peridotites.

(viii) Group 8 (45 specimens)

The group 8 specimens have the greatest known time span of any of the dolerite groups on Rhum. A group 8 episode of intrusion produced the dolerites with liquid-liquid contacts with felsite in Stony Corrie (Chapter 2, p. 34) the oldest known dykes on Rhum and they are also encountered cutting the layered peridotites (Fig. 5.1). Several of the thin conformable sheets and the inclined sheets belong to group 8 as do the relatively young Kilmory and Papadil thick conformable sheets. The former have distinctive geochemical and petrographic characteristics and similar dolerites are not encountered within the Main Ring Fault. However, the Papadil thick conformable sheet dolerites may have geochemically similar but petrographically dissimilar analogues within the Main Ring Fault.

The general early age of the group 8 dolerites in Stony Corrie is confirmed by the consistent cross cutting by later group 4 dykes, a relationship also observed elsewhere on Rhum, e.g. between 77316 and 95A76 (group 4) in the Allt Slugan a Choilich (NM 395988) and between 77325 and 77324 (group 4) in the granophyre west of Harris Bay (NM 355955). They are also known to be cut by picritic dykes in the Allt Slugan a Choilich (NM 394987) and in Corrie Dubh (NM 394981). As previously mentioned the

Papadil thick conformable sheets cut group 4 dykes (77174 and 77175) but are themselves cut by a group 7 dyke.

Thus the group 8 magmas were available from very early in the history of the complex and were still available after the emplacement of the layered peridotites, furthermore they are found in all the different structural types of dolerite encountered in the field viz. thick and thin conformable sheets inclined sheets and as dykes.

(ix) Group 9 (8 specimens)

The group 9 dykes appear to be absent from the peridotites (Fig. 5.1) but are found cutting older rocks on both sides of the Main Ring Fault. Their age relationships with other groups are uncertain as few cross-cutting relationships were recorded. One specimen (77209) from Dibidil shore cuts older group 4 dykes but other specimens are cut by group 4 dykes. Another specimen is probably cut by a group 1 dyke in the Allt Slugan a Choilich and the age relations of the dykes in Stony Corrie are unknown. In view of their absence from the peridotites the group 9 dykes may predate the emplacement of the peridotites but their age relationships are obscure.

(x) Group 10 (6 specimens)

In contrast, the group 10 dykes are found cutting the peridotites and associated gabbros. The two specimens are from the Papadil Gabbro and are hornfelsed and thus

are probably pre-peridotite sensu stricto but one specimen definitely cuts fresh marginal gabbro on Monadh Mhiltich (NM 997357). One specimen cuts a dyke which probably belongs to group 4 (from petrography) but their age relationships to other dolerite groups are not known.

(xi) Group 11 (5 specimens)

All but one of these dykes are found cutting the peridotites, the other which cuts the sequence Lewisian to granophyre cuts a group 8 dyke. No group 11 specimens have been located in the Torridonian outside the Main Ring Fault. As the majority of these group 11 dykes are post peridotite the group as a whole is judged to be young in age.

(xii) Group 12 (2 specimens)

Both these intrusions are petrographically fresh; one cuts the eastern Papadil gabbro - Torridonian contact (NM 365917) it is believed to be younger than the peridotites in this area because it is not affected by the thermal metamorphism which affects the other older dolerites (eg. group 3 and group 10). Their age relations relative to other dolerite groups are not known.

b) Gabbros

Three of the gabbros under consideration are known to be early in the history of the complex. Two of these

intrusions are high MgO gabbros (Chapter 3, p. 72) but one is a quartz gabbro. The latter is similar but more differentiated than the group 8 intrusions known to be early from their field relationships in Stony Corrie (Dibidil) (see Table 5.1). The analyses of the high MgO gabbros is also presented in Table 5.1 showing that CaO and MgO rich magmas were also available at an early stage in the evolution of the Rhum central complex.

The precise stage that the younger gabbros were emplaced relative to the dolerite groups cannot be determined from the evidence available at the present time. A late age was inferred from the field relationships discussed in Chapter 2 but there are exceptions (e.g. the altered gabbro plug at NM 378999, which is cut by three later dykes). Thus the late gabbros were probably emplaced over a considerable period of time.

c) Peridotites

Although a relatively young age was inferred for those peridotite plugs which resemble the matrix-banded tongues in the Northern Margin Complex (see Chapter 2, p. 48), the age of petrographically dissimilar plugs (e.g. the deeply weathered peridotite plug on the northside of Kinloch Glen) have not been unequivocally determined. In view of their probable petrogenetic link with the layered peri-

dotites (discussed later, p. 260) the proposed age of these plugs relative to the dolerite magmas of Rhum becomes increasingly important. The evidence presented in Chapter 2, with the qualifications outlined above, all point to a relatively young age for the majority of the peridotite plugs. A chronological sequence of the dolerite groups, the gabbro and peridotite plugs and the acid dykes on Rhum based on the relative age relationships as discussed in this chapter and in Chapter 2, is presented in Fig. 5.2. The acid rocks, peridotites and lavas act as stratigraphic markers and form the basis of the stratigraphy of the magmas which produced the Rhum minor intrusion suite.

The large estimated time gap between the lavas and the layered peridotites is based on the existence of rocks from the Rhum central complex in the conglomerates beneath the Rhum lavas. The estimated time gap between the layered peridotites and the acid rocks is based on the need for multiple dyke injection postdating the acid rocks and predating the peridotites. Although the peridotite tongues are believed to predate the layered peridotites (Dunham, 1965b) they are cut by very few dykes hence the small interval between the two on Fig. 5.3. The age gap between the early folding (Dunham & Emeleus, 1967, p.395) and the emplacement of the acid rocks cannot be estimated and may be considerably less than the interval indicated

here.

Two important points are raised by Fig. 5.2; one is the suggestion that the group 5 and 6 magmas postdate the evolution of the remainder of the Rhum dolerites, the significance of this is discussed later (Chapter 7 , p.225); secondly, the alkaline differentiates (groups 10 to 12) appear to have been intruded later than the majority of the dolerite magmas.

To test whether the basic magmas in the Rhum dolerites become more alkaline with time the dolerite groups 2, 3 and 4 were plotted on Fig. 5.3 using the division into dykes cutting (1) the Torridonian outside the Main Ring Fault, and (2) the sequence Lewisian to granophyre and (3) the layered peridotites. The discriminant score derived in Chapter 3 was used as a measure of alkalinity. The dolerites both sides of the Main Ring Fault in Fig. 5.3 span a similar range although the dykes cutting the peridotites do tend to be more alkaline. The distribution of the individual dolerite groups is shown in Fig. 5.4. Here, within each group, the dykes cutting the Torridonian outside the Main Ring Fault and the sequence Lewisian to granophyre within the Main Ring Fault cover similar ranges but the dykes cutting the peridotites tend to be transitionally alkalic.

Although the alkalic nature of dykes cutting the

peridotites in Figures 5.3 and 5.4 suggests that the younger Rhum dolerites do become more alkaline with time, this assertion must be tempered by the knowledge that:

- (1) Group 8 dolerites of tholeiitic affinity cut the peridotites,
- (2) Gabbros with tholeiitic affinities cut the layered peridotites (specimens 33A76, 77163, 77328, 77383) thus basic tholeiitic magmas were also available sometime after the emplacement of the peridotites,
- (3) The abundant group 4 dolerites show no trend towards alkalinity from known cross-cutting relationships. (This can be shown by plotting the individual discriminant scores (an indicator of alkalinity) of the group 4 dolerites that were used in the compilation of the average analyses of the "young" and "old" dolerites in Table 5.1). Reference to Fig. 5.5 shows that the early and late dolerites span a similar range of transitional alkaline and transitional tholeiitic compositions. The sample sizes are, unfortunately, too small to interpret the relative distribution of the peaks.

In conclusion differentiates of tholeiitic affinity were available throughout the history of the complex whereas alkalic differentiates are only present in the later stages. The specimens from the dolerite dykes

cutting the peridotites are consistently alkalic in affinity thus there appears to be a trend towards alkalinity with time in the Rhum minor intrusions. The significance of the tholeiitic groups 5 and 6 dykes cutting the lavas is discussed in Chapter 7 (p. 225).

The similarity in the span of transitional compositions in groups 2, 3 and 4 (Fig. 5.4) in dykes cutting the Torridonian outside the Main Ring Fault and the sequence Lewisian-granophyre within the fault suggests that magmas of essentially similar chemistry were available both sides of the Main Ring Fault although for much of this time the dykes in the Torridonian at the present erosion level will have been emplaced at structurally higher levels than their counterparts across the Main Ring Fault. The predominance of thoroughly transitional magmas (0 to -0.35 discriminant score) in the group 4 rocks within the Main Ring Fault (Fig. 5.5) may possibly reflect their deeper seated nature (ie. proximity to parental magma truly transitional in composition) than the group 4 magmas emplaced at higher levels outside the Main Ring Fault.

Fig. 5.1 Frequency distribution of the dolerite groups between the major country rock stratigraphic intervals defined in Chapter 2.

- A = Dykes cutting the Rhum Lavas
- B = Dykes cutting the Torridonian outside the Main Ring Fault
- C = Dykes cutting the layered peridotites and marginal gabbros
- D = Dykes cutting the sequence Lewisian to Granophyre within the Main Ring Fault

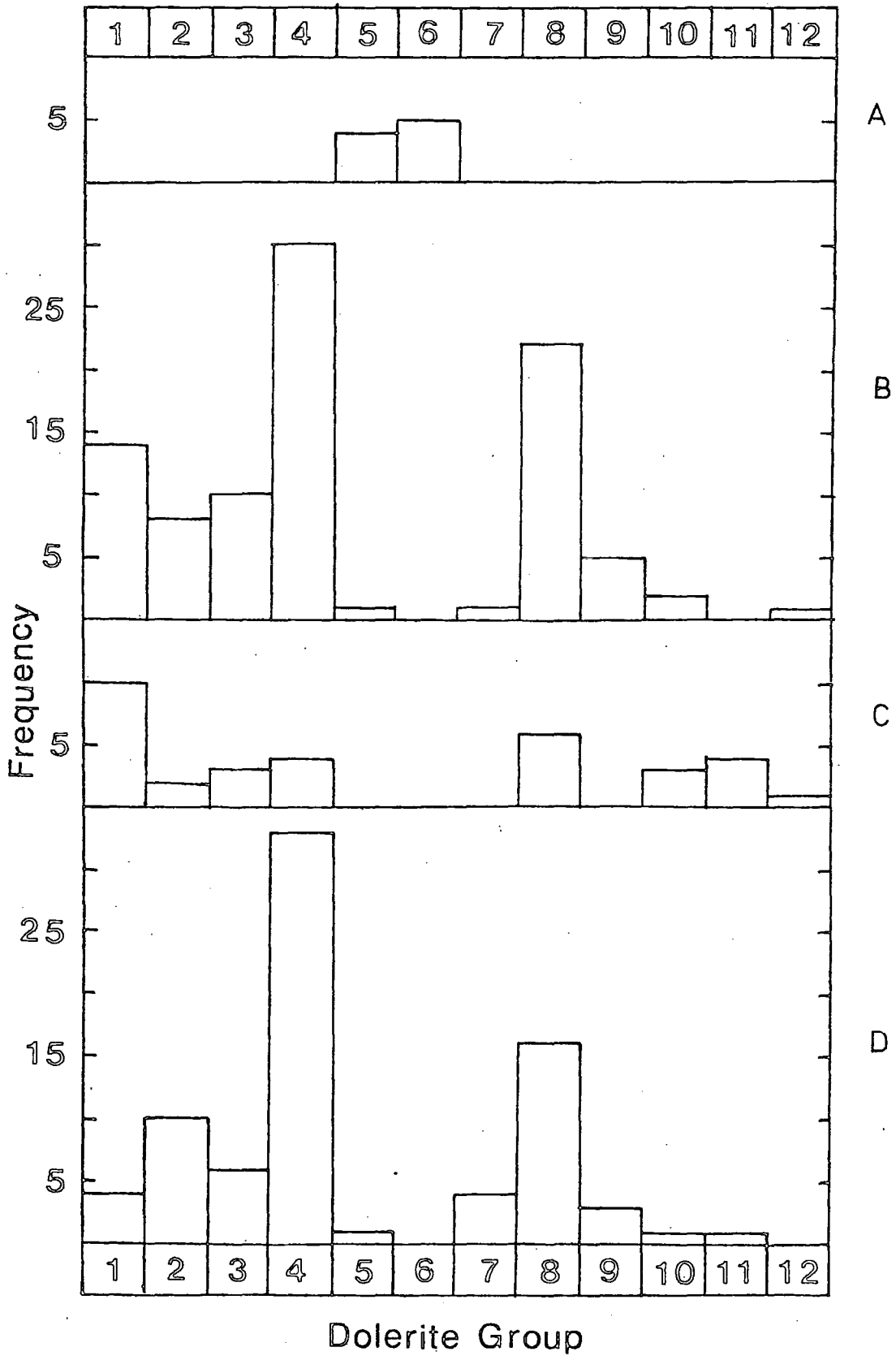


Fig. 5.2 Schematic age relationships of the Rhum minor intrusion suite with respect to the major country rock stratigraphic intervals. Dotted lines indicate areas of uncertainty.

Key to stratigraphic intervals.

- L = The Rhum Lavas
- LU = The layered ultrabasic rocks
- PT = The peridotite tongues
- AC = The plutonic acid rocks
- EF = The early folding

Key to minor intrusion suite

- 1-12 = Rhum dolerite groups
- EG = Early gabbros
- LG = Late gabbros
- A = Acid dykes
- P = Peridotite tongues

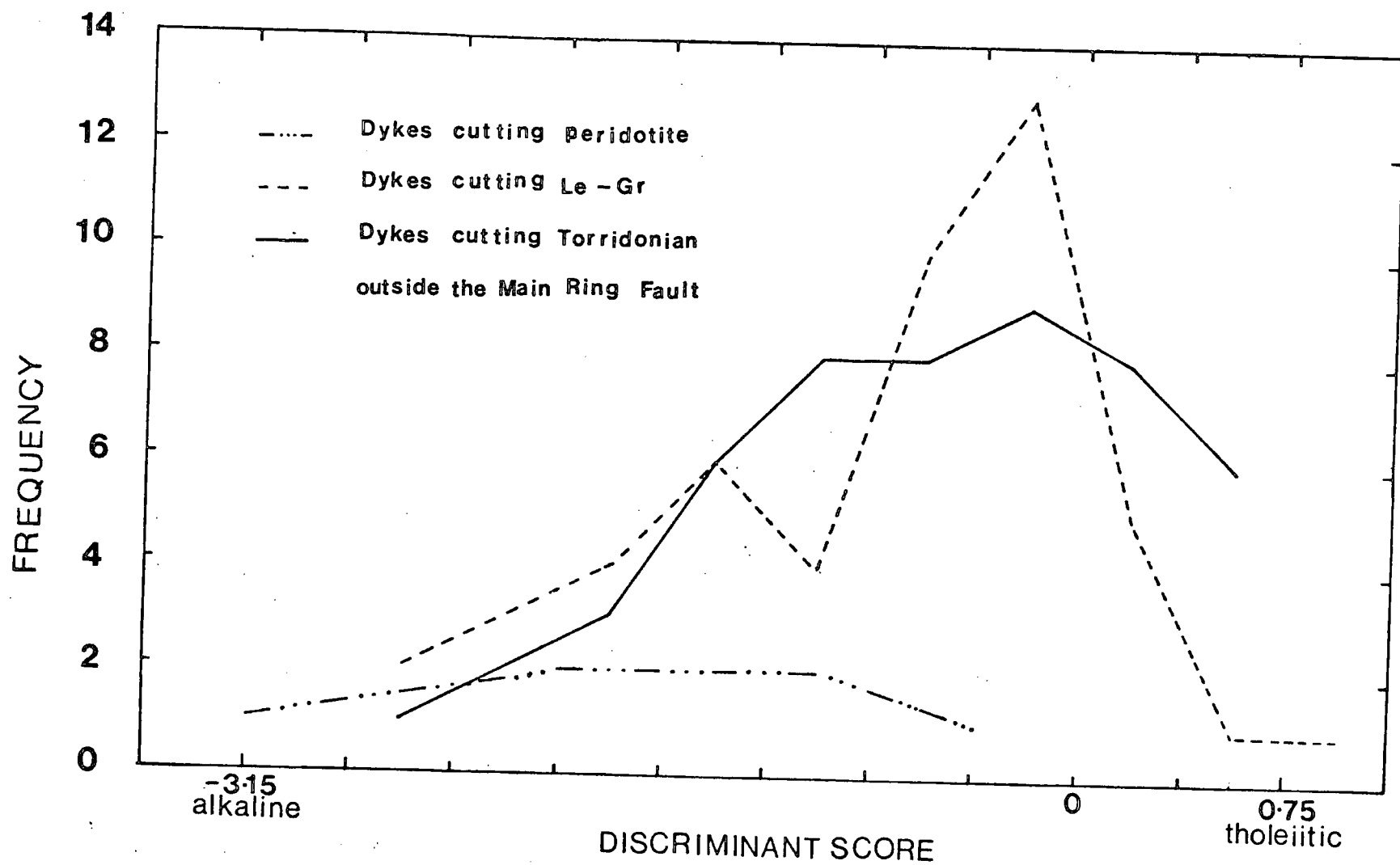


Fig. 5.3 Discriminant score of dykes cutting the three principal country rock stratigraphic intervals. (Le-Gr = dykes cutting the sequence Lewisian gneiss to granophyre).

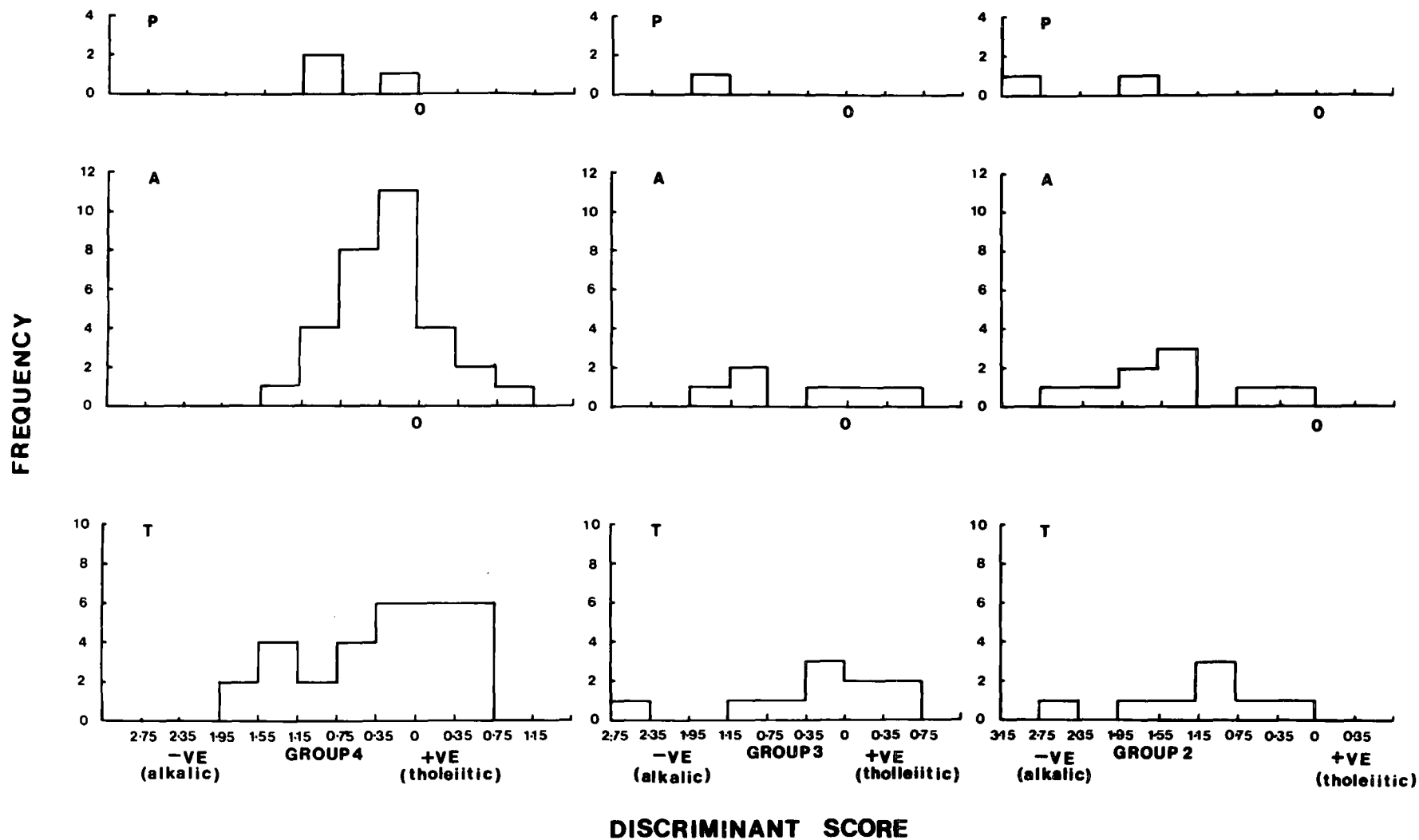


FIG 5.4 Discriminant score of dykes cutting the Torridonian strata outside the Main Ring Fault and the acid and the layered ultrabasic rocks within this fault, (T,A and P respectively).

FREQUENCY

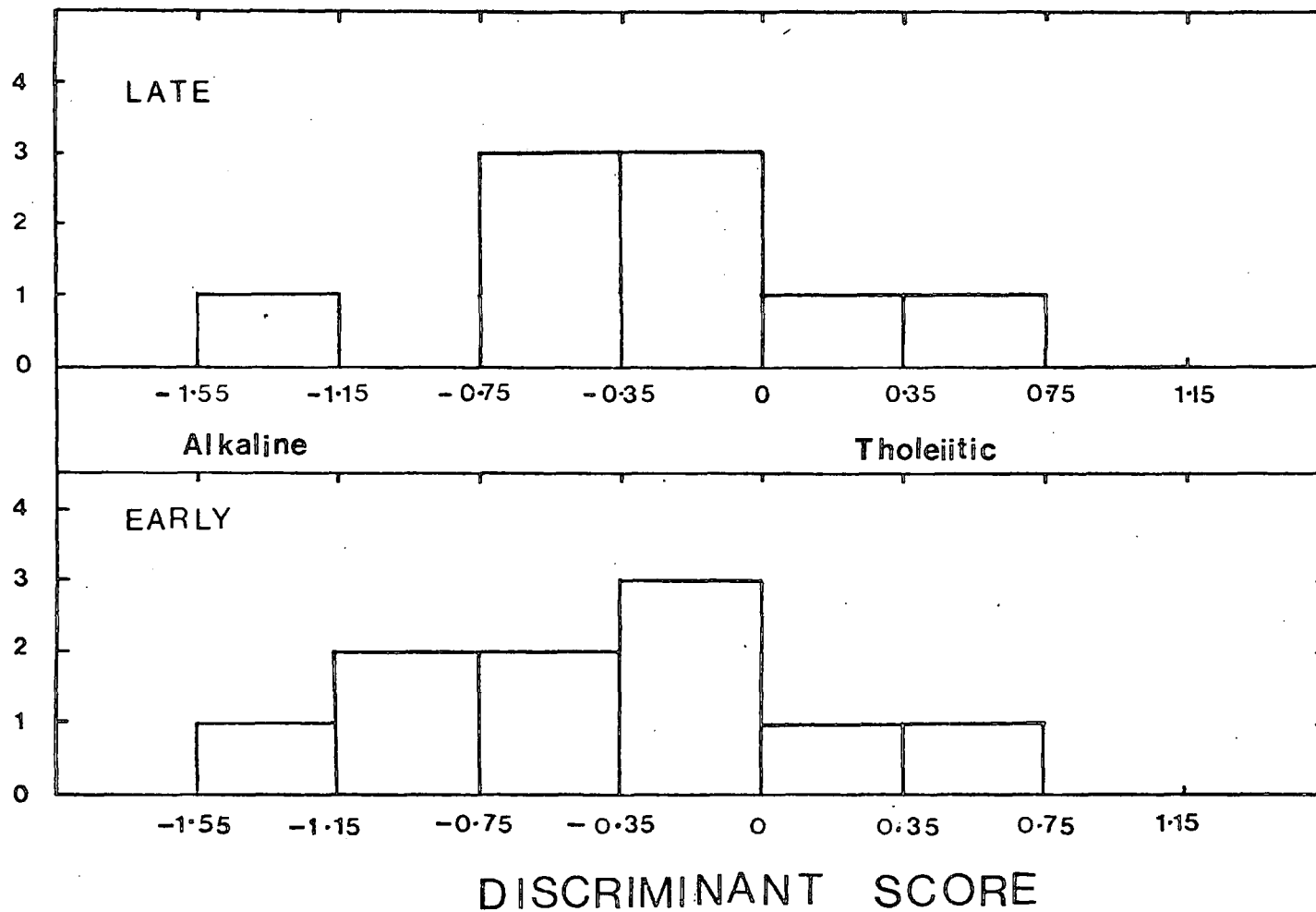


FIG 5.5 Discriminant score of group 4 dykes judged to be early and late in the sequence of intrusion.

	A	B	C	D	E	F
SPEC	-	-	77033	77292	77103	-
SiO ₂	47.23	47.35	49.24	48.98	51.42	49.91
Al ₂ O ₃	14.50	14.10	14.39	15.74	13.84	13.11
Fe ₂ O ₃ *	12.50	13.37	10.02	11.47	13.02	15.08
MgO	8.98	9.20	11.22	9.74	5.72	6.17
CaO	11.83	10.81	12.14	9.99	9.03	8.98
Na ₂ O	2.78	2.43	2.02	2.49	3.38	3.25
K ₂ O	0.21	0.56	0.10	0.16	1.01	0.67
TiO ₂	1.65	1.76	0.62	1.17	2.17	2.26
MnO	0.19	0.19	0.16	0.17	0.21	0.22
wt % P ₂ O ₅	0.18	0.19	0.10	0.09	0.20	0.24
Total	100.05	99.86	100.01	100.00	100.00	99.89
Ni	119	94	95	41	32	29
Cr	337	233	337	158	25	88
Ba	103	145	72	117	272	277
Nb	4	4	2	2	6	4
Zr	109	129	16	33	182	163
Y	20	28	9	10	33	31
Sr	169	290	277	323	190	248
Rb	13	19	2	3	25	31
ppm Zn	106	104	64	76	107	137

Table 5.1 Geochemical comparison of different aged dolerites and gabbros.

A Average of 10 older group 4 dolerites

B Average of 9 younger group 4 dolerites

C, D, E Early gabbros within the Main Ring Fault.

F Average of 4 early group 8 dolerites

*Total iron as Fe₂O₃

CHAPTER SIX

MINERALOGY AND MINERAL CHEMISTRY

Introduction

The mineral chemistry obtained by electron microprobe analysis is presented in this chapter, and the various interpretations which can be put upon this data are discussed. The analytical technique is described in Appendix 6.1 and the complete mineral analyses are presented in Appendix 6.2. Iron was determined as FeO and is presented as such in the pyroxene, plagioclase, olivine and amphibole analyses. The Fe_2O_3 contents of the spinels and ilmenites were calculated by assuming stoichiometry of these phases as described by Carmichael (1967).

The compositional variation in the pyroxenes and spinels is considered to be the product of complex interactions between various petrogenetic processes and consequently requires detailed discussion. The amphibole (kaersutite) analyses from the type 3 picrites are presented in Appendix 6.2 but are not considered further.

PYROXENES

Introduction

The pyroxene lattice can incorporate virtually all the major and minor components of an igneous melt under suitable circumstances. This flexibility, coupled with their common occurrence in igneous rocks offers valuable insight into magmatic processes. Pyroxene chemistry is fundamentally controlled by the host magma chemistry, however, the ultimate composition is affected by several other factors (e.g. the temperature, pressure and rate of crystallisation) and these factors must be taken into account in any interpretation concerning the host magma composition.

a) Dolerites

The individual analyses of pyroxenes in the Rhum dolerite suite have been plotted in the conventional pyroxene quadrilateral (Fig. 6.1), the relevant portions of the tholeiitic Skaergaard trend (Brown, 1957) and the mildly alkaline Shiant Isles pyroxene trend (Gibb, 1973) are included for comparison. The pyroxene from groups 1, 2, 3, 7 and 10 are calcic augites or salites in the classification of Deer et al. (1966), the group 4 pyroxenes are calcic augites and the group 8, 9 and 11 pyroxenes are augites. The group 1, 2 and 4 pyroxenes exhibit a slight decrease in Ca with iron enrichment however this feature is not apparent in the

more limited data for the remaining groups. The pyroxene suite as a whole is characterised by very limited iron enrichment, indeed the principal variation within the pyroxenes in Fig. 6.1 is in the Ca content. This contrasts markedly with the predominance of $\text{Mg}^{2+} - \text{Fe}^{2+}$ variation over Ca^{2+} variation in most pyroxene suites, see for example Gibb (1973, Fig.4). Note, however, that the zoning from core to margins detected in some pyroxene grains involves iron enrichment with little variation in the Ca content.

The variation of Al, Ti, Cr, Na and Mn with iron enrichment is presented in Figs. 6.2 and 6.3. Al and Ti generally increase with iron enrichment, especially in the group 1 pyroxenes. This is also a feature of the Na variation. In contrast, Cr exhibits a negative correlation with iron enrichment. The data for Mn is more ambiguous, the pyroxenes from the basic dolerites (groups 1 to 7) show no correlation of Mn with Fe content and the higher Mn content of some of the pyroxenes from the intermediate rocks exist over a range of Fe contents. This variation in Mn is possibly attributable to the presence or absence of coexisting opaque oxides during pyroxene crystallisation.

The variation of Al against Ti for the groundmass pyroxenes and the phenocryst pyroxenes is shown in Figs. 6.4 and 6.5 respectively. A general increase of Ti with

Al is a feature of both diagrams. Ti generally substitutes in a ratio of approximately 1:5 for the majority of pyroxenes but several of the group 10 pyroxenes in Fig. 6.4 and the group 11 pyroxenes in Fig. 6.5 are Ti enriched for a given Al content when compared with the remainder of the pyroxenes in the suite. The variation of Al and Na with Si content for the groundmass pyroxenes is shown in Figs. 6.6 and 6.7 respectively. Fig. 6.6 shows that Al is present in excess of the amount required to satisfy the silica deficiency in the tetrahedral (z) site thus some of the Al must be located in the octahedral (y) site. In addition Fig. 6.7 shows that Na increases with decreasing Si, which implies there is a positive correlation between Na and Al.

The relative proportions of Al in tetrahedral and octahedral co-ordination in both the groundmass and the phenocryst pyroxenes are presented in Figs. 6.8 and 6.9 respectively. The assignment of Al to Al^{iv} and Al^{vi} was made on the basis of 6 oxygens by allotting sufficient Al to make up the Si deficiency (Al^{iv}) to 2 and allotting the remaining Al to Al^{vi} . Unfortunately this procedure relies on the accurate determination of Si and some of the scatter on Figs. 6.8 and 6.9 is undoubtedly due to some inaccuracy in the Si determinations. However, this

is judged not to have affected the overall relationships in these diagrams. It is clear from Figs. 6.8 and 6.9 that although much of the Al is in tetrahedral co-ordination a considerable amount is in octahedral co-ordination; the significance of this relationship is discussed below.

Discussion

The principal features of the clinopyroxenes in the Rhum dolerite suite are the limited iron enrichment developed in these pyroxenes and, secondly, the high Ca, Al and Ti contents of many of the pyroxenes. The variation in pyroxene chemistry is due to simple or coupled substitution of elements into the pyroxene lattice. These coupled substitutions are necessary to preserve the charge balance if for example Al^{3+} substitutes for Si^{2+} in the tetrahedral site.

Limited substitution of Fe^{2+} for Mg^{2+} in the y site is partly attributable to cooling rate in that the rapidly chilled lava suites of tholeiitic and alkalic basalt associations generally exhibit much more limited $\text{Fe}^{2+} - \text{Mg}^{2+}$ substitution in their pyroxenes, than the pyroxenes in slowly cooled tholeiitic and alkalic intrusions (Carmichael et al., 1973). The high MgO content of many of the Rhum dolerites and the high MgO levels in the intermediate rocks when compared with intermediate rocks from other basaltic suites is probably another contributing factor

(ie. the activity of Mg was high in the Rhum melts). It should be noted however that pyroxene analyses are not available from the few dolerites with Fe_2O_3^* greater than 15.0 wt%, these would probably extend the known range of $\text{Fe}^{2+} - \text{Mg}^{2+}$ substitution in the Rhum pyroxenes.

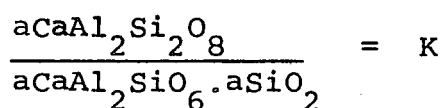
The Al_2O_3 content of the Rhum pyroxenes ranges from 1.5 to 9.0 wt% and is highest in the group 1 pyroxenes (Fig. 6.2). The Al content of pyroxenes is believed to be a function of Si activity and Al activity in the melt, temperature and pressure (Le Bas 1962, Brown 1967, Campbell and Borley 1974, Deer et al. 1979).

The negative correlation of Si and Al and the positive correlation of Al and Ti can be explained by the substitution of Al into the pyroxene lattice via the $\text{Ca Ti Al}_2\text{O}_6$ molecule (Yagi and Onuma, 1967), however this would result in a Ti/Al ratio of 1:2 whereas the Rhum pyroxenes have a Ti/Al ratio of approximately 1: 5, This suggests that there was also extensive substitution of Ca-Tschermaks molecule $\text{Ca Al}_2\text{SiO}_6$. The distribution of Al into Al^{iv} and Al^{vi} sites is known to be in part pressure related, higher pressures favouring entry into the Al^{vi} site (Aoki and Shiba 1973). Although many of the groundmass pyroxenes fall in the field of igneous rocks in Fig. 6.8, many fall into the field of higher pressure pyroxenes, but since these groundmass pyroxenes crystallised at low

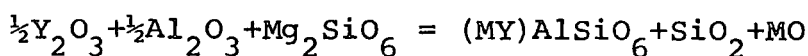
*Total iron as Fe_2O_3

pressures entry of Al as Al^{vi} is not solely a function of pressure. Several of the pyroxene phenocrysts in Fig. 6.9 also fall in the fields of high pressure pyroxenes and thus may possibly be the results of higher pressure crystallisation. These phenocrysts contain less Al than the groundmass pyroxenes and this is consistent with the low Al contents of pyroxenes believed to be high pressure relicts in the Dippin Sill, southern Arran (Gibb and Henderson, 1978).

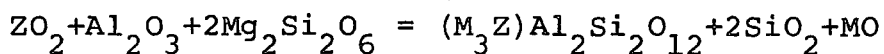
In a low pressure environment, the activity of the various melt components is believed to control pyroxene chemistry. Carmichael et al., 1970 showed that low Si activity in the melt will favour formation of aluminous clinopyroxene rather than plagioclase by the equation:



thus explaining the observations of Le Bas (1962) who found an increase in the Al contents of pyroxenes with increasing SiO_2 undersaturation of the host magmas. This reaction explains the special case in which Al^{3+} is distributed equally between the y and z sites. However, Campbell and Borley (1974) suggest that the general equation takes the form



or



where Y = Al^{3+} , Cr^{3+} or Fe^{3+} , Z = Ti^{4+} , and M = Fe^{2+} , Ca^{2+} or Mg^{2+} .

These reactions show that an increase in $a\text{Al}_2\text{O}_3$ and a decrease in $a\text{SiO}_2$ in the melt will favour formation of aluminous clinopyroxene and that the Al^{3+} content of the pyroxene is also dependent on the behaviour of the octahedrally co-ordinated cations providing the charge balance. The correlation of Na with Al in Fig. 6.7 suggests that some of the Al in the Rhum clinopyroxenes may have been incorporated as jadeite, however some of the Fe probably existed as Fe^{3+} thus the Na may well be present as acmite.

Le Bas (1962) showed there was a positive correlation of the Ti and Al content of pyroxenes and suggested that the Ti content was a function of the presence of Al^{3+} in the z site. This view was supported by Barberi et al. (1971) who suggested that the low activity of SiO_2 in the melt was the dominant control over the Ti content of a pyroxene. This argument was based on the knowledge that entry of Al^{3+} into the z site favours Ti^{4+} entry into the Y site (Verhoogen 1962) and that substitution of Ca-Tschermaks molecule (ie. Al^{3+} into the z site) is favoured

by low $a\text{SiO}_2$. Conversely Gibb (1973) cast Ti in the dominant role and suggested that the Al^{3+} is incorporated into the pyroxene lattice to balance the high Ti^{4+} content of the pyroxene induced by the high $a\text{TiO}_2$ in the melt. These authors have also emphasised the role of co-crystallising phases on pyroxene chemistry. Barberi et al. (1971) suggested that crystallisation of plagioclase prior to pyroxene would deplete the Ca-Tschermaks molecule content of the melt and thus would reduce the Al_2O_3 content of the pyroxenes. Gibb (1973) argues that the onset of titanomagnetite crystallisation in the Shiant Isles sill reduced the activity of Ti in the melt thus giving rise to lower Ti and Al levels in the contemporaneous pyroxenes. It should be stressed at this point that Gibbs' (1973) study of pyroxene compositional variation within a closed system environment is ideally suited to the investigation of the effect of co-crystallising phases on pyroxene composition which is not always possible in studies of pyroxene chemistry in suites (like the Rhum minor intrusions) which are derived from different parent compositions at different stages of differentiation.

Rapid cooling rates are also known to facilitate the incorporation of Al and Ti into the pyroxene lattice. High Al and Ti levels have been reported in studies of lunar pyroxenes (up to 9.4 wt% and 8.5 wt% respectively,

Brown et al. 1973). These compositions were attributed to metastable incorporation of the $\text{CaTiAl}_2\text{O}_6$ molecule during the quench crystallisation of some mare basalts by Brown et al. (op.cit.).

The aluminous group 1 pyroxenes may well be a product of metastable incorporation of Al and Ti as these picrites will have possessed high liquidus temperatures and several have a variolitic groundmass. Variolitic supercooling textures are also a feature of many of the other dolerite groups (see Chapter 4). Thus incorporation of Al and Ti during rapid crystallisation may well have played a part in controlling the groundmass pyroxene chemistry in many of the Rhum dolerites.

The activity of Si and Al are not believed to have played a major role in the genesis of the Rhum dolerite pyroxenes as envisaged by Le Bas (1962) and Barberi et al. (1971) respectively, as early formation of plagioclase did not adversely affect the entry of Al into the clinopyroxene. Aluminous pyroxenes occur in rocks where plagioclase was obviously the earlier phase, e.g. the plagioclase phenocrysts in the group 7 dolerites and the sparse plagioclase microphenocrysts in some of the group 1 dolerites. Chrome-spinel is the dominant opaque phase in groups 1 and 10 thus the activity of Ti is likely to have been higher in these magmas than in those where

titanomagnetite is an important phase. Thus the effect of Ti activity in the magma on pyroxene chemistry as envisaged by Gibb (1973) may well have played a role in determining the compositions of the group 1 and 10 pyroxenes and other pyroxenes in the suite. In conclusion the high activity of Mg and to a lesser extent Ti, in the melt coupled with rapid cooling are believed to be the main controls over the limited iron enrichment and the aluminous nature of the Rhum groundmass pyroxenes. Whilst the pyroxene phenocrysts do plot in the higher pressure field of Aoki and Shiba (1973), their low Al and Ti contents suggest that the entry of Al into the octahedral site is more likely to be a function of the combined activities of Si, Ti and Al rather than pressure.

Pyroxenes as indicators of host magma composition

There have been several attempts to relate the chemical compositions of igneous clinopyroxenes to host magma composition. Le Bas (1962) showed there was an increase in the proportions of Ti and Al in pyroxenes from tholeiitic, alkaline and peralkaline hosts respectively and Coombs (1963) suggested that CIPW norms obtained from clinopyroxene analyses could be used in much the same way as whole rock norms to investigate the parent magma type. More recently, Nisbett and Pearce (1977) utilised Discriminant Function Analysis to investigate clinopyroxene

composition as a function of their host basalts tectonic setting and concluded that pyroxene chemistry could be used as indicators of tectonic environment.

In contrast the Ti and Al contents of clinopyroxenes have been shown to be unreliable indicators of host magma composition. Gibb (1973), for example, states that the aluminous clinopyroxenes from the mildly alkaline Shiant Islands sill fall in the peralkaline field in the SiO_2 - Al_2O_3 diagram of Le Bas (1962) as do many of the Rhum pyroxenes; similarly, Beddoe-Stephens (1977) has shown this diagram to have limited application in calc-alkaline suites. In addition Barberi et al. (1971) have shown that pyroxene with compositions typical of tholeiitic suites can develop from mildly alkaline parents fractionating under low and falling oxygen fugacity. The analysed groundmass pyroxenes in the Rhum dolerites have been plotted on Fig. 6.10, the discriminant scores were calculated using the eigenvectors in Nisbett and Pearce (1977, Table 2) and the discriminant boundaries are redrawn from Nisbett and Pearce (op. cit., Fig.1). The Rhum dolerites are known to be transitional between truly alkaline and truly tholeiitic compositions, the dolerites lie in a "within plate" environment and consequently would be expected to straddle the Within Plate Tholeiite (WPT) and Within Plate Alkaline (WPA) discriminant line. Less than half of the

pyroxenes in Fig. 6.10 lie in the WPA field, most of the remainder plot in the Volcanic Arc Basalt (VAB) and Ocean Floor Basalt (OFB) field and only two lie in the WPT field. This discrepancy is probably due to the low Fe and Mn content of the Rhum pyroxenes, as VAB pyroxenes generally contain less of these constituents than WPT pyroxenes (Nisbett and Pearce, 1977).

Whilst the host magma composition must exert a fundamental control over pyroxene chemistry the other controls discussed earlier in this chapter can cause the pyroxene composition to deviate significantly from the expected composition. Consequently it is suggested that interpretation of host magma composition and tectonic environment on pyroxene composition alone as argued by Nisbett and Pearce (1977) should be approached cautiously.

b) Gabbros and Peridotites

The limited pyroxene data for (i) a high MgO gabbro (77292), (ii) a low MgO gabbro (77067) and (iii) one of the peridotite plugs (77268) is presented in Fig. 6.11. The pyroxenes from the peridotite plug and the low MgO gabbro classify as diopsides and salites respectively in the classification of Deer et al. (1966). Two types of pyroxene are found in the high MgO gabbro, monoclinic augites and enstatitic orthopyroxenes, these high MgO

gabbros are the only rocks in the Rhum minor intrusion suite to possess a 2-pyroxene mineral assemblage. This reflects both their hosts' tholeiitic composition and a slow cooling rate as rapid cooling can produce metastable subcalcic augite in tholeiitic lavas (Kuno 1955 in Deer et al. 1979).

The calcic augites plot in a similar position to some of the group 7 pyroxenes in Fig. 6.1 but are characterised by lower Al_2O_3 and TiO_2 contents (approximately 3.0 and 0.7 wt% as opposed to 1.5 and 5.5 wt% respectively). As with other pyroxenes in the Rhum dolerite suite they are characterised by a low iron content.

The diopsides from the peridotite plug are compositionally dissimilar to other pyroxenes in the Rhum dolerite suite but compare favourably with pyroxenes from the Rhum layered series. Inspection of the pyroxene analyses in Table 6.1 reveals that the pyroxenes from the peridotite plugs are virtually identical to the two average analyses quoted by Dunham and Wadsworth (1978), except that CaO is slightly higher and Cr_2O_3 significantly lower in the latter.

OPAQUE OXIDES

The opaque oxides in the Rhum minor intrusion suite exhibit a wide chemical variation ranging from Cr-spinels

("chromites") to Fe-Ti spinels ("magnetites") and ilmenites. Two broad categories can be recognised: Cr-bearing spinels where Cr is present above trace amounts and Fe-Ti oxides with only minor Cr content. The majority of the analyses are from fresh minerals and give totals between approximately 98.5% and 100.5%, the Cr bearing spinels in the group 2 and 10 rocks are altered and consequently give lower totals. However, they help illustrate important relationships and have been included on Fig. 6.12.

Chrome bearing spinels

Cr-rich spinels are abundant in the group 1 rocks and the peridotite plugs, the majority contain $Al > Cr$ and are Fe-rich and thus classify as picotite (Deer et al., 1966) (some however, do contain $Fe < Mg$) whilst others contain $Al > Cr$ and classify as magnesio-chromite (Deer et al., op.cit.). The remaining Cr-spinels, including those from 77024, contain less Cr + Al than the former and show substantial substitution of Fe^{3+} into the octahedral site.

The variation of the trivalent cations Al^{3+} , Cr^{3+} and Fe^{3+} is presented in Fig. 6.12. The Cr-spinels from the type 1 picrites (Chapter 4, p.94) contain more Cr than the type 2 picrites but less Cr than the spinels from the peridotite plug, the latter contain slightly more Fe^{3+} than the former but the Fe^{3+} contents of all these spinels is consistently low. In contrast, the Cr-

spinel from the group 10 specimen (77184) and the group 1 specimen (77024) contain appreciable Fe^{3+} , there is a consistent decrease in Al^{3+} with increasing Fe^{3+} in all these specimens. The altered spinels in the group 10 rock (32A76) have Fe^{3+} as the dominant trivalent ion, the group 2 spinel phenocrysts (from 77039) are more variable. One contains minor Fe^{3+} and lies in the field of the picrite type 1 and type 2 spinels. The other contains abundant Fe^{3+} and resembles the fresher Fe-Ti groundmass opaque oxides in this and other group 2 specimens.

The chemical variation in Cr-spinels in basaltic liquids can result from primary variation in the composition of liquidus phase and from secondary processes involving either later reaction with the host liquid or subsolidus reaction with adjacent phases or both (Henderson and Suddaby 1971, Henderson 1975, Ridley et al. 1974, Ridley 1977, Dunham and Wadsworth 1978). These secondary processes can make it virtually impossible to elucidate primary variation in spinels unless the phase is included in a co-crystallising or slightly later crystallising phase which effectively prevents reaction between the spinel phase and the melt. However, even when a spinel is included in a silicate phase subsolidus reaction with the enclosing phase may alter the primary spinel composition.

Several of the spinels in the type 1 and type 2 picrites, and all the spinels from the peridotite plug, were totally enclosed by olivine. The limited chemical variation within these spinel types strongly suggests that their compositions are essentially primary, the spinels from the type 1 picrites containing more Cr^{3+} than those in the type 2 picrites. The spinels from 85A76 are similar however, to those from the remaining dolerites, these were not protected by an enclosing silicate phase and thus may have reacted with the melt. The extreme compositional variation exhibited by the spinel phenocrysts in 77039 almost certainly is the result of a two stage process.

Primary variation

The controls over primary compositional variation in Cr-spinels have been discussed by Hill and Roeder (1974) and Ridley (1977). Variations in the activities of the various Cr-spinel components in the melt give rise to the variations in liquidus spinel compositions, the availability and activity of Cr in the melt is of critical importance. Cr^{3+} has a low solubility in basaltic liquids (~ 250 ppm at a $\log_{10} f\text{O}_2$ of -8, Hill and Roeder 1974) and a high octahedral site preference energy. (Burns 1970, In: Hill and Roeder 1974) consequently Cr^{3+} will readily enter a spinel phase and thus promotes

spinel crystallisation. Variations in the initial Cr contents of basaltic melts (which reflects the temperature and pressure conditions in the zone of partial melting and the mineralogy of the source material) will affect the Cr/Al ratio of the liquidus spinels. The activity of Al in the melt must also play a role, however Ridley (1977) has noted that the high Al_2O_3 magmas do not necessarily contain spinels with a high Al/Cr ratio suggesting the activity of Al may not be of critical importance in determining the Cr/Al ratio of the liquidus spinel.

The oxygen fugacity of the melt will determine the Fe^{3+} content of the spinels. Hill and Roeder (1974) show that high oxygen fugacities favour incorporation of Fe^{3+} into spinels mainly at the expense of Cr^{3+} , thus spinels with high $\text{Fe}^{3+}/\text{Cr}^{3+}$ ratios probably crystallised under moderate to high ($\log_{10} f_{\text{O}_2} 10^{-5}$ to $\log_{10} f_{\text{O}_2} 10^{-1}$) oxygen fugacities. This effect is mainly due to the abundance of Fe^{3+} ions in melts with high oxygen fugacities. These ions coalesce to produce much greater quantities of the spinel phase than is produced at lower oxygen fugacities. Consequently this causes the Cr content of the magma to be dispersed amongst a large volume of spinel crystals with a consequent reduction in Cr content of the individual crystals. In addition, Hill and Roeder (op. cit. Fig. 7) have shown that substitution of Fe^{3+} and Ti^{4+} with

a concomittant decrease in Al and Cr occurs with decreasing temperature. The entry of Mg^{2+} and Fe^{2+} into the tetrahedral site is also largely temperature dependent (Hill and Roeder, op.cit., Fig.7) but will also reflect the activities of Mg^{2+} and Fe^{2+} in the melt.

Liquidus spinel compositions are also affected by the co-crystallisation of pyroxene which stabilises Cr^{3+} in its octahedral sites. The reaction relationship between pyroxenes and spinel postulated by Irvine (1967) has been demonstrated experimentally by Hill and Roeder (op. cit.) and accounts for the break in spinel crystallisation between early chromites and later titaniferous magnetites observed in several stratiform intrusions (Irvine 1967).

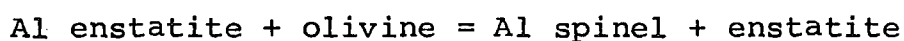
As stated earlier the compositions of the spinels from the type 1 and type 2 picrites and the peridotite plug are considered to be primary. In addition, the spinels from the Western and Eastern layered series were all included in olivines (Dunham and Wadsworth, 1978) and their compositional variation was considered to reflect primary liquidus variation; similarly the Cr-rich end members of the Al and Fe reaction trends (Henderson 1975) and the most aluminous spinel in SR157* (Ridley, 1977) were also protected from reaction with the melt and are primary compositions.

* Specimen SR157 is from the Rhum Lavas.

The spinels have been plotted into Fig. 6.13. The boundaries differentiate the fields of spinels from stratiform and alpine peridotites. The majority of the layered series peridotites lie as expected in the field of stratiform chromites. However, the spinels with higher Mg contents (ie. higher temperature) have Cr/Al ratios more typical of alpine peridotites. On this diagram the Rhum minor intrusion spinels lie in the field of alpine peridotites and the Al-rich Rhum lava spinel with a Cr/Cr+Al ratio of 1:1 lies well into the alpine peridotite field; note once again the similarity of the spinels from the peridotite plug to the layered series peridotites.

The differences between chromites from alpine peridotites and spinels which have crystallised from basaltic liquids in stratiform intrusion have been discussed by Irvine (1967), Pinsent (1974) and Greenbaum (1977). The former have low Fe^{2+} contents and an extremely wide range of Cr/Cr+Al ratios whereas the latter have higher Cr contents, much more restricted Cr/Cr+Al ratios and have a much larger range of Fe^{2+} values. In addition stratiform chromites generally have a greater range in Fe^{3+} content. In his study of the Blue River Alpine body Pinsent (1974) showed that there were distinct compositional differences between the

spinel in the dunites and the spinel in the peridotites. The former are characterised by $\text{Cr}/(\text{Cr}+\text{Al}) > 0.575$ and have $\text{Mg}/(\text{Mg}+\text{Fe}^{2+}) < 0.60$ whereas the latter have higher Al and lower Fe^{2+} contents. Pinsent believed that the Cr-rich spinel in the dunites had crystallised from a basaltic liquid and states categorically that the spinel in the peridotites are too Al and Mg enriched to be derived from a basalt magma under comparable P-T conditions. He attributed the high Al content of the latter principally to the P-T controlled metamorphic reaction



but stated that reaction between the spinel and interstitial liquid (cf. Henderson 1975) may possibly have played a role.

Thus, it appears that spinel crystallised from basaltic liquids at low pressure are characterised by $\text{Cr}/(\text{Cr}+\text{Al})$ ratios > 0.575 and higher Fe^{2+} contents than spinel which have equilibrated at higher pressures and thus emphasises the pressure dependence of the Al/Cr ratio.

Secondary variation

The compositional variation resulting from complex reactions with the host basaltic liquid (an alkali basalt from Muck and an olivine basalt from Rhum) has been described in detail by Ridley (1977). The trend developed

by variations in the Al, Cr and Fe^{3+} contents in a single specimen from the Rhum lavas (SR157) is presented in Fig. 6.12. The principal features of the reaction relationships described by Ridley (1977) are similar for both specimens, these being (i) a substantial increase in the Cr/Al ratio, this was mainly attributed to the peritectic reaction

Aluminous chromite + melt $\rightarrow$ plagioclase + chromite

(ii) a gradual increase in the Fe^{3+} content by the substitution of Al^{3+} for Fe^{3+} . The Fe^{3+} does not replace the Cr^{3+} because the latter has a much higher octahedral site preference energy (see p. 163) and is a stable component of the spinel lattice.

(iii) A gradual increase in the Ti^{4+} content which probably reflects the coupled substitution $\text{Fe}^{2+}\text{-Ti}^{4+}$ for $\text{Al}^{3+}\text{-Cr}^{3+}$.

In contrast compositional variation attributable to subsolidus reactions of spinel in the form

Plagioclase + olivine + chromite $\rightarrow$ Al-enriched
chromite + liquid

has been described by Henderson (1975) and these "Al enrichment trends" in the Rhum layered series chromites are presented in Fig. 6.12. In addition Henderson (1975) recognised an " Fe^{3+} -enrichment trend" (see Fig. 6.12) which he attributed to reaction of cumulus chromite with inter-cumulus liquid over a large temperature range. This

interpretation is consistent with the variation in spinel composition with falling temperature in the data of Hill and Roeder (1974) as discussed earlier (p.165).

Discussion

The spinels from the type 1 and type 2 picrite and the aluminous spinel from the Rhum lavas undoubtedly crystallised from a mafic liquid yet they lie outside the field of stratiform spinels in Fig. 6.13. One possible explanation of this anomalous behaviour is that these spinels crystallised at greater pressures than the spinels in stratiform intrusions. The variation of spinel compositions as a function of pressure has not yet been studied. However, Hill and Roeder (1974) suggest that the solubility of Cr will increase with increasing pressure. This increase in the solubility of Cr will probably result in a lower Cr/Cr+Al ratio in spinels crystallising at higher pressure providing the oxygen fugacity of the melt (which controls the activity of Fe^{3+}) is low. A high pressure origin has also been proposed for aluminous spinel phenocrysts in ocean floor basalts (Ridley et al. 1974). Interpretation of the differences between the spinels from the type 1 and type 2 picrites and the Rhum lavas is speculative but one possibility is that the host magma of the latter contained less Cr than the picritic magmas.

It could be argued that these low Cr/Cr+Al ratios in the spinels from the picrites and the Rhum lavas are a result of reaction with the melt, but Ridley (1977) demonstrated that reactions of this type will increase the Cr/Cr+Al ratio but will also increase the Fe^{3+} , Fe^{2+} and Ti^{4+} contents and the latter are low in these spinels. The subsolidus reactions described by Henderson (1975) do increase the Cr/Cr+Al ratio without altering the Fe^{3+} content but subsolidus reactions are likely to have been minimal in these rapidly cooled bodies.

The primary compositions of spinels in the layered series peridotites have been shown to vary sympathetically with cryptic variation exhibited by the other phases in the layered peridotites (Dunham and Wadsworth 1978). The compositional variation of the layered peridotite spinels in Figs. 6.12 and 6.13 is probably a function of their temperature dependence and related changes in the activities and solubility of Cr, Al and Fe^{3+} in the melt. Note, however, the high Fe^{3+} and Fe^{2+} contents of two of these spinels in Fig. 6.11 and 6.12 suggesting that these spinels were not totally enclosed by olivine in three dimensions.

The similarity of the spinels in the peridotite plugs when compared with the layered series peridotites suggests that they may have a common origin. The dissimilarity of these spinels with those from the picrites

and in the Rhum lava specimen SR157 indicates that these picrites and this Rhum lava are not suitable parent magmas for the Rhum layered intrusion.

The origin of the spinel compositions in 77024, 77039, 77184 and 32A76 are problematic as only limited data is available. The similarity of one of the spinel phenocrysts in 77039 to the spinels from the type 1 picrites was noted previously. This contrasts with the other Fe^{3+} , Ti^{4+} rich spinel in 77039, this variation is probably attributable to the reaction relationships described by Ridley (1977) or may reflect the presence of two generations of spinel phenocryst in this rock. The variation in the spinel chemistry in 32A76 is probably a result of the reaction of a Cr-bearing spinel with the melt. The spinels from 77184 and 77024 subparallel the spinel reaction trend defined by Ridley (1977). The former have more Fe^{3+} than the spinels from the picrites and the peridotite plug which may be a function of higher initial Fe^{3+} with subsequent incorporation of more Fe^{3+} by reaction with the melt.

Iron-titanium oxides

Iron-titanium oxides are ubiquitous minerals in the Rhum minor intrusions other than the group 1 picrites. They occur as discrete grains of exsolved ilmenite and magnetite suggesting that they originally crystallised

as homogeneous titanomagnetites which have re-equilibrated at lower temperatures. Their small size and the presence of very fine exsolution lamellae has led to severe analytical problems. Several of the analyses in Appendix 6.2 contain appreciable SiO_2 (up to ~ 3.0 wt%) which may be due to the incorporation of small quantities of silicate phases adjacent to the iron titanium oxides. In addition several of the analyses do not give totals within an acceptable range (98.5-100.5%) when recalculated on a stoichiometric basis. Both these features are considered to be due to slight movements of the electron beam during analysis which has resulted in poor quality data. Because of these difficulties only limited chemical data on minerals of this composition have been obtained during this study. These confirm in a qualitative manner the composition of the opaque minerals in the Rhum minor intrusions but are not of a sufficiently high standard to merit quantitative treatment.

OLIVINES

Fresh olivine is only found in the group 1 picrites and the peridotite plugs, consequently only limited chemical data are available. The majority of these analyses are of phenocrysts as most of the groundmass olivines in group 1 are either altered or extremely small making them

unsuitable for analysis. The NiO, CaO and MnO contents of the analysed olivines have been plotted against Fo content in Fig. 6.14. The most striking feature of this plot is the bimodal distribution of the Fo content of the olivines, those from 77024 range Fo74-Fo77.5 the remainder range from Fo84 - Fo88.5.

The olivines in the type 1 and type 2 picrites, 85A76 and the peridotite plugs occur as large granular crystals in a matrix of plagioclase, clinopyroxene and opaque oxides, an exception being the single groundmass olivine in a type 2 picrite. The latter contains less magnesium than the olivine phenocrysts in this specimen, this reflects the temperature dependence of the Mg content of olivines. The olivines from the peridotite plug show limited variation in Mg content ($\sim$ Fo85) and all but one of the type 1 and type 2 phenocryst olivines exhibit a limited compositional range (Fo86-Fo88.5). These compositions are typical of high temperature olivine phenocrysts in basaltic melts.

In contrast the olivine phenocrysts in 77024 occur in various morphologies ranging from lattice and chain olivines, through hopper olivines to granular olivines (see Chapter 4, p. 97). Similar textures have been described by Donaldson (1976) who showed that olivine morphology in picritic and basalt magmas varies

systematically with either the degree of supercooling of the melt prior to olivine nucleation or the rate of cooling of the melt or both. High degrees of supercooling and rapid cooling rates favour formation of the lattice and chain olivines and progressively lower degrees of supercooling and lower rates of crystallisation produce branched olivines, hopper olivines and granular olivines respectively (Donaldson 1976, Fig.8). The limited compositional range of the olivine phenocrysts of 77024 in Fig. 6.14 contrasts with the large variation in the morphology of the olivine phenocrysts in this rock. Any petrogenetic interpretation of the chemistry and olivine textures in 77024 must take into account the following features.

- (i) The presence of a fine-grained chilled margin containing abundant elongate olivine crystals.
- (ii) The coexistence of a wide range of olivine morphologies in the central facies of the dyke.
- (iii) The limited compositional range (Fo74.8-Fo76.3) exhibited by all but one of the olivine phenocrysts in this dyke.
- (iv) The high MgO content (~ 15.5 wt%) of the whole rock analysis.

The elongate olivines will have been extremely fragile, however, although some of these crystals are bent the

vast majority have not been snapped or broken. This suggests that these olivines crystallised more or less in situ. It could be argued that the MgO content of this rock is due to enrichment by the addition of cumulus olivine. However, the granular olivines are very similar in composition to more skeletal varieties an exception being a single granular olivine with a higher Fo content (Fo77.5 as opposed to Fo76.3). This similarity in olivine composition suggests all these olivines are produced by isothermal crystallisation of a supercooled MgO rich liquid. The olivine morphology may also reflect rapid cooling rates and this is supported by the presence of elongate chain and lattice olivines in the chilled margin, but the absence of extreme textures, (e.g. swallow-tail olivines, Donaldson 1976, Fig.8) suggests that the enclosing country rock (peridotite) was still at relatively high temperatures (ie. the chilled margin reflects the temperature difference between the MgO-rich liquid ($\sim 1200^{\circ}\text{C}^*$) and consolidated peridotite ($\sim 900^{\circ}\text{C}$)).

To summarise, injection of a supercooled MgO-rich liquid into hot consolidated peridotite resulted in the in situ development of elongate lattice and chain olivines, subsequent rapid, virtually isothermal crystallisation,

*estimate based on the liquidus temperatures quoted by Donaldson (1976).

produced branched, hopper and granular olivines respectively, as the degree of supercooling approached zero.

Having rapidly attained equilibrium, heat losses to the enclosing peridotite resulted in the magma following a "more normal" crystallisation path with the development of a fine-grained groundmass composed of slightly lower temperature phases.

The olivines with Fo contents greater than Fo₈₄ in Fig. 6.14 generally have NiO contents ranging from 0.3 - 0.45 wt%, no systematic depletion in NiO with decreasing Fo content can be discerned in these samples. However, the olivines in 77024 have significantly lower NiO (0.15-0.20 wt%). This decrease in NiO with decreasing Fo content is a typical feature of olivine compositions (Simkin and Smith, 1970). Sato (1977) has shown that the majority of mantle olivines contain 0.35-0.45 wt% NiO, the high NiO contents (0.3-0.4 wt%) of the olivines with Fo contents greater than 84.0 is probably due to a high Ni content in their host magmas. The CaO content of the olivines in Fig. 6.15 varies between 0.15 and 0.65 wt%, the majority of the olivines contain 0.3-0.4 wt% CaO. The CaO content of magmatic olivines is thought to decrease with increasing pressure (Simkin and Smith 1970). A more recent work by Ferguson (1978) related

the CaO content of olivines to the Ca activity in the melt and the dependence of the CaO contents of olivine on the CaO content of the host magma has been shown experimentally by Watson (1979a). Ferguson (1978) also suggested that the lower CaO content of olivines in hypabyssal rocks, when compared with their extrusive counterparts, was reflected in the ability of CaO to diffuse out of the olivine lattice in the slower cooling environment.

The MnO content of the forsteritic olivines varies between 0.15 and 0.25 wt% and increases to approximately 0.60 wt% in the more iron-rich compositions. These are similar to the values reported by Simkin and Smith (1970) who also observed an increase in MnO with increasing iron content.

The olivines in the Rhum layered series vary between Fo78 and Fo88.5. In addition, they contain 0.17 to 0.40 wt% NiO (Dunham and Wadsworth 1978) and thus their compositions compare favourably with the olivines in the Rhum minor intrusions (excluding those in 77024). The layered series olivines contain less CaO (0.02-0.20 wt%, Dunham and Wadsworth 1978) than the olivines in the Rhum minor intrusions, the lower content of the former may reflect the slower cooling rate of their plutonic environment.

FELDSPARS

Chemical data for the feldspar minerals is only available for some of the dolerite groups in the Rhum minor intrusion suite, the limited data for the group 4 plagioclase is embodied in Appendix 6.2 but is not discussed here. The dominant feldspar mineral is plagioclase but K-feldspars are found in the alkaline differentiates.

The variation of the plagioclase data in the picritic group 1 rocks and the basic group 2 and 3 rocks is presented in Fig. 6.15. There is a wide variation in plagioclase composition (An₈₀-An₄₀) in the group 1 and 2 rocks. The sparse data for the group 3 rocks indicate a more differentiated composition (An₇₀-An₄₅). The overlap in compositions between the phenocrysts and groundmass compositions in group 2 is also worthy of note as it emphasises the compositional variability within each of the dolerite groups.

The compositional heterogeneity of the feldspar phenocrysts (An₈₄-An₈₈) is a feature of the group 7 plagioclases in Fig. 6.16, as is the separation of these phenocrysts from the more sodic groundmass (An₄₀). A wide range of compositions are found in the group 8 rocks (Fig. 6.17) the phenocrysts range from surprisingly calcic compositions (these rocks are intermediate);

however the groundmass plagioclases zone to An30.

The group 10 rocks exhibit an extremely wide range of feldspar compositions from calcic phenocrysts in 77090 to coexisting albite and orthoclase in the groundmass of 32A76 (Fig. 6.17). A less extreme range from sodic plagioclase (An36) to orthoclase is encountered in group 11 and the groundmass K-feldspars in the group 12 specimen (77132) exhibit only minor variation.

Key to symbols on Fig. 6.1.

○ Group 1	∅ Group 7
▲ Group 2	⊗ Group 8
⊖ Group 3	□ Group 9
▼ Group 4	■ Group 10
⊥ Group 6	⊕ Group 11

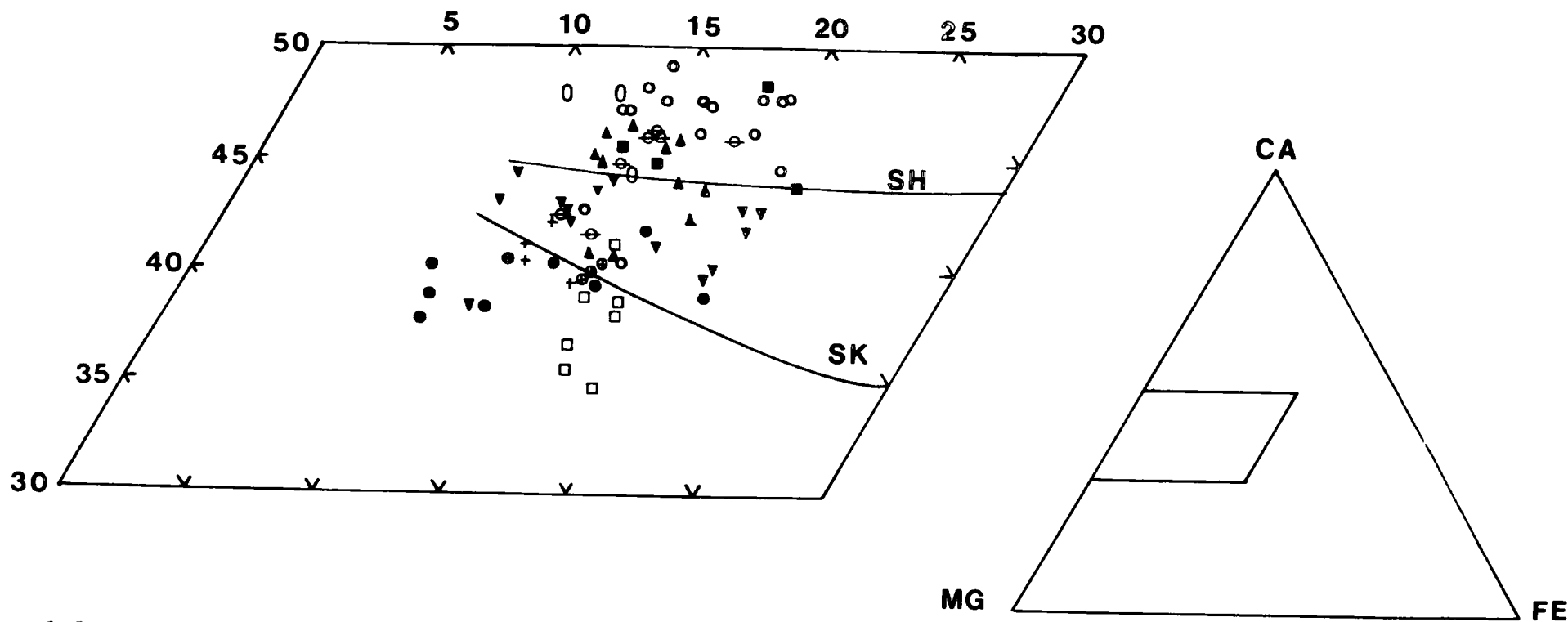


Fig. 6.1 Clinopyroxenes in the Rhum dolerite suite, lines SH and SK are the approximate trends developed by the Shiant Isles sill clinopyroxenes (Gibb 1973) and the Skaergaard intrusion calcic augites (Brown 1957) respectively. See adjacent page for key to symbols.

Fig. 6.2 Al, Ti, Cr in the Rhum dolerite clinopyroxenes plotted against Fe/Fe+Mg (all on the basis of 6 oxygens). Symbols as for Fig. 6.1 except ϕ = Group 11.

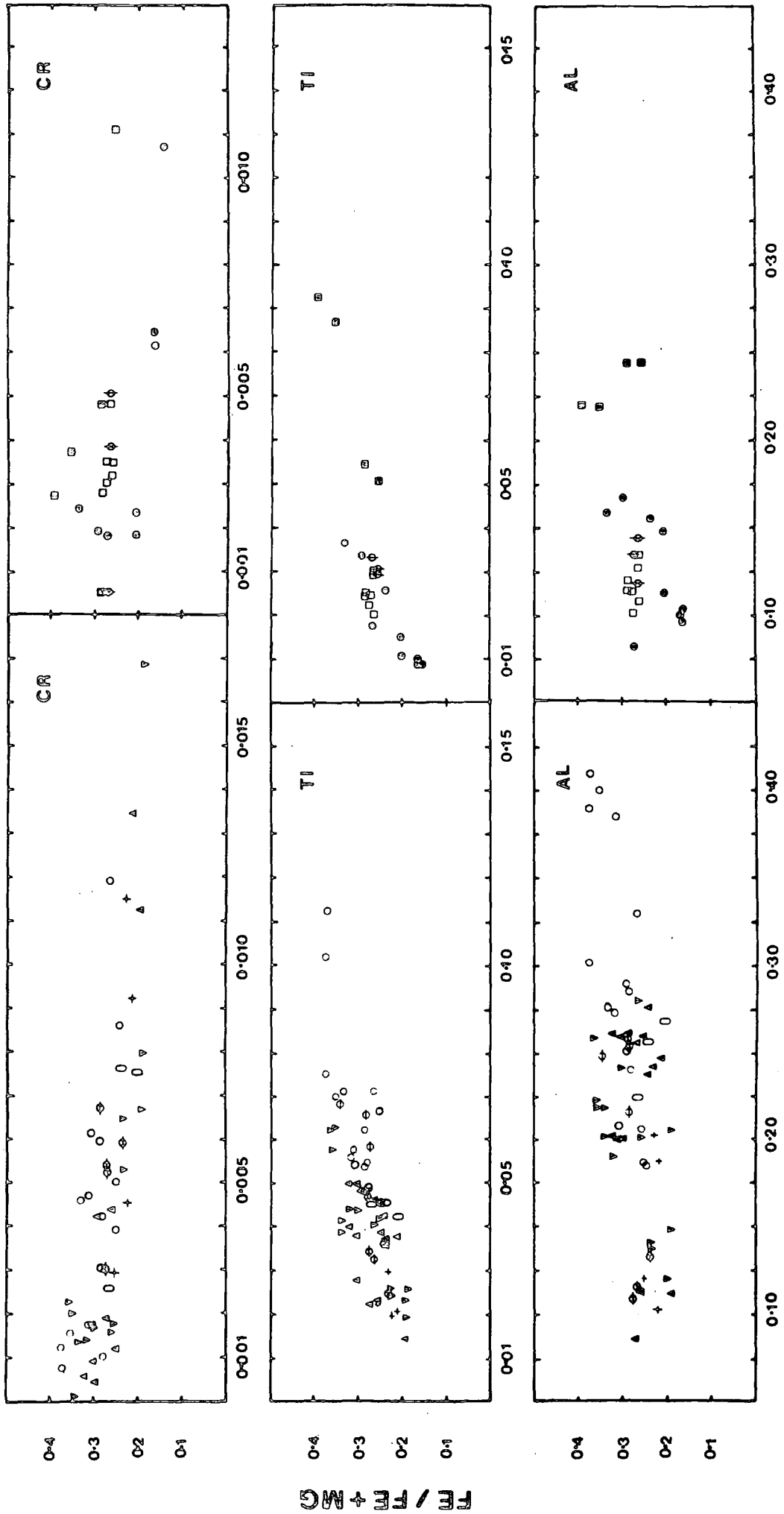


Fig. 6.3 Na and Mn in the Rhum dolerite clinopyroxenes plotted against Fe/Fe+Mg (all on the basis of 6 oxygens). Symbols as for Fig. 6.1 except ϕ = Group 11.

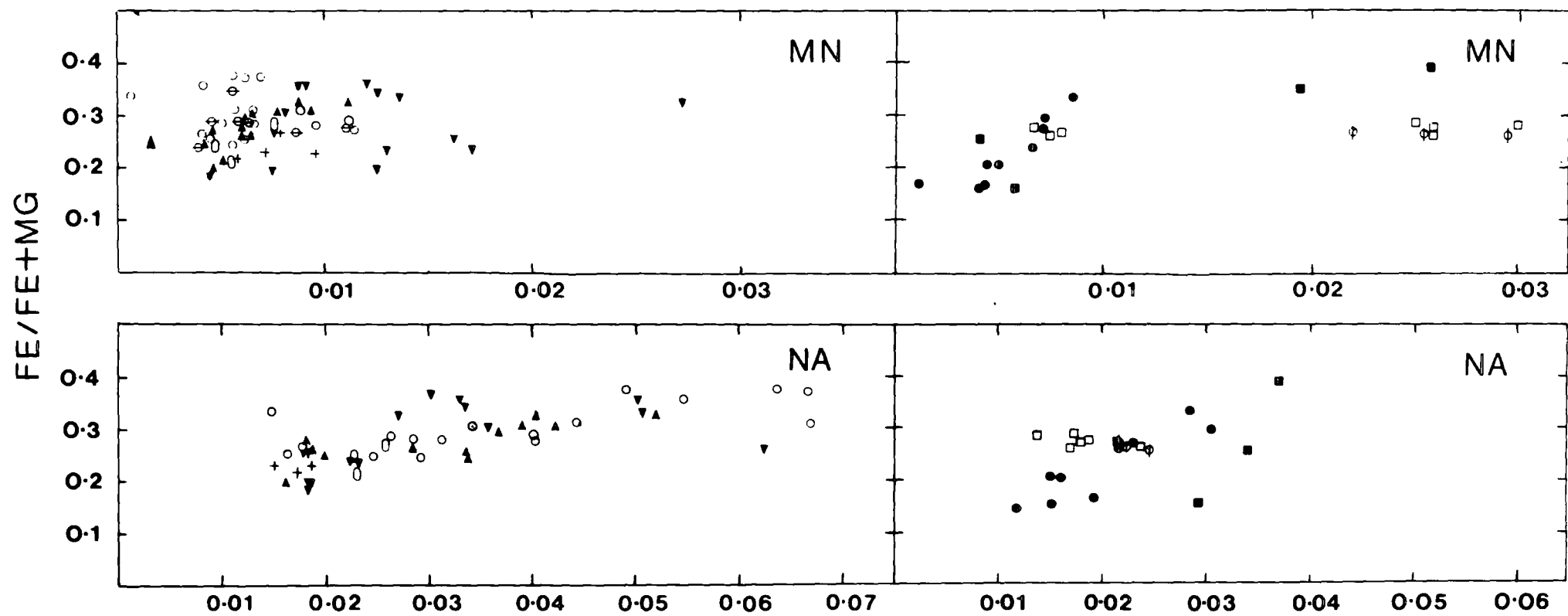


Fig. 6.4 Al v. Ti in the dolerite groundmass pyroxenes,
ratios are the proportion of Ti substituted
relative to Al (all on the basis of 6 oxygens).

Key to symbols in Figs. 6.4 - 6.10

▣ Group 1	● Group 8
∇ Group 2	● Group 9
□ Group 3	■ Group 10
△ Group 4	■ Group 11
0 Group 7	

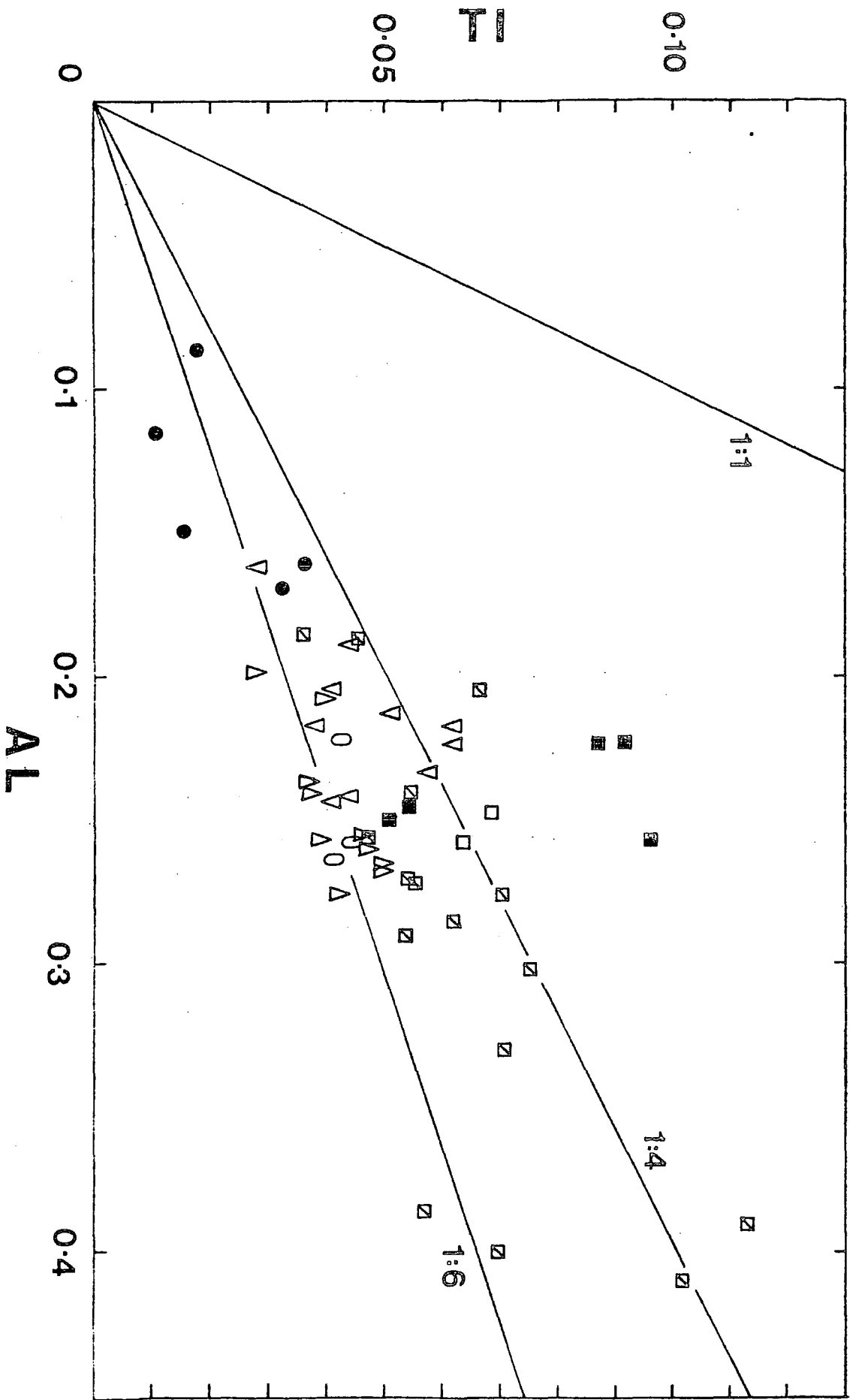
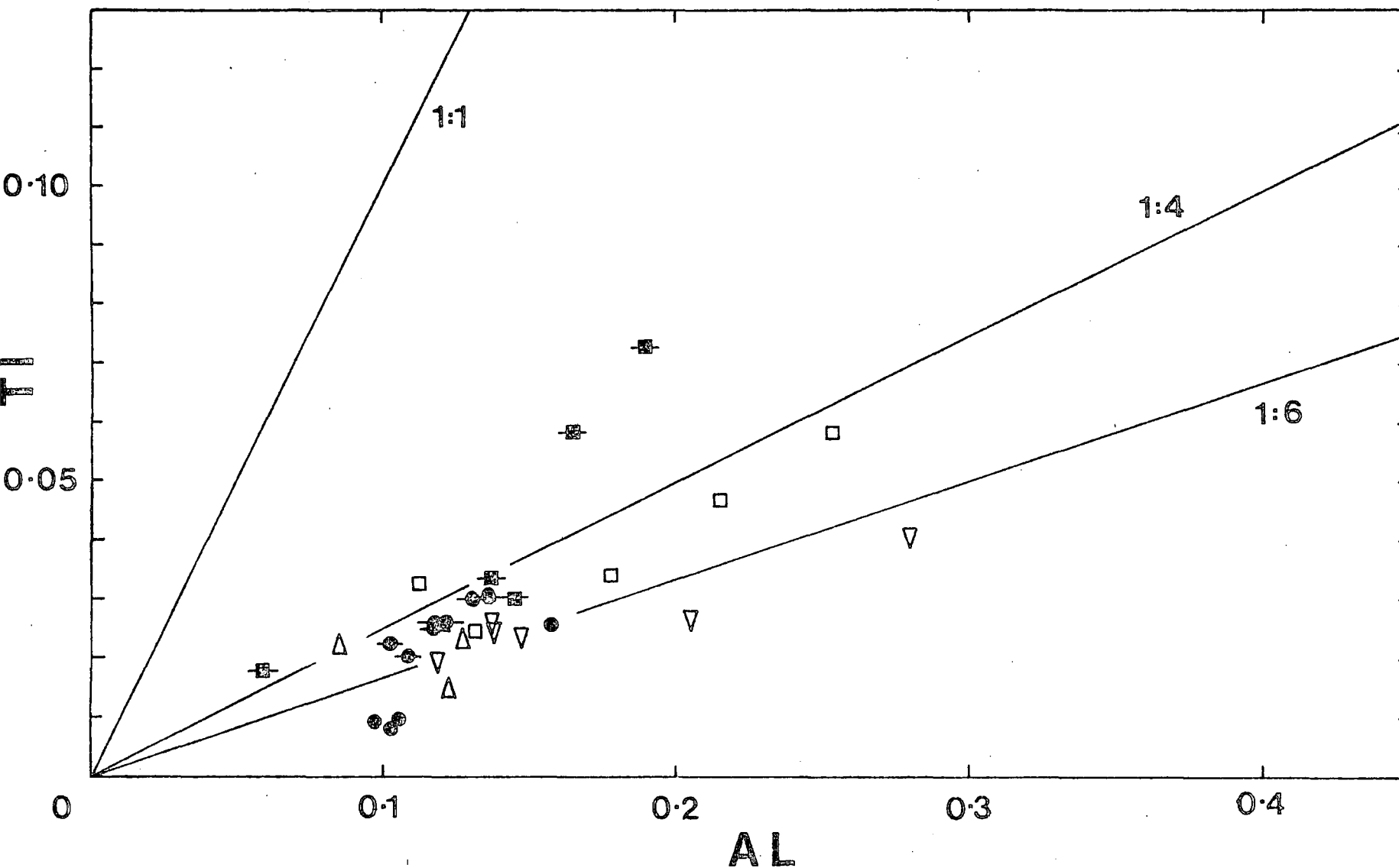


Fig. 6.5 Al v. Ti in the dolerite clinopyroxene phenocrysts,
ratios are the proportion of Ti substituted relative
to Al (all on a basis of 6 oxygens). Key to symbols
on p.186.



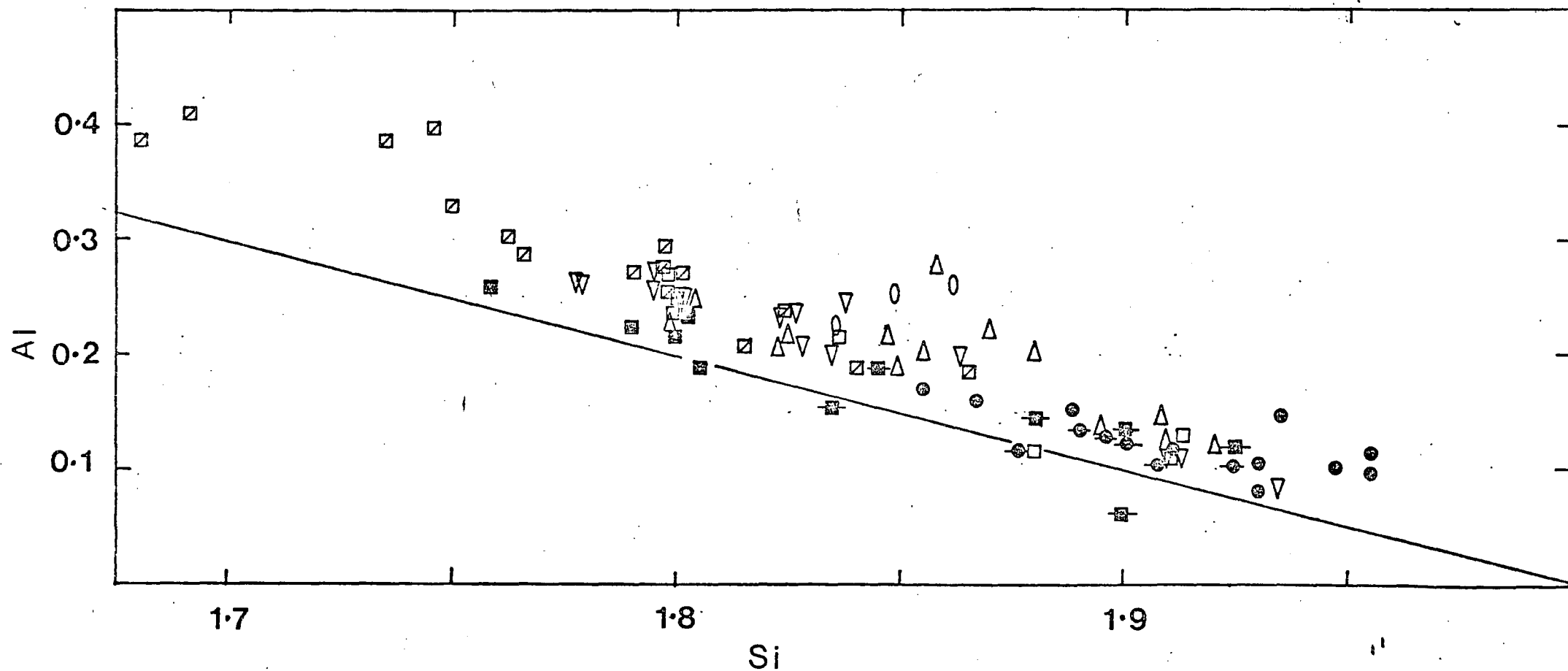


Fig 6.6 Si v Al in the dolerite clinopyroxenes (on a basis of 6 oxygens). The solid line indicates the amount of Al required to fill the Z site. Key to symbols on p 186.

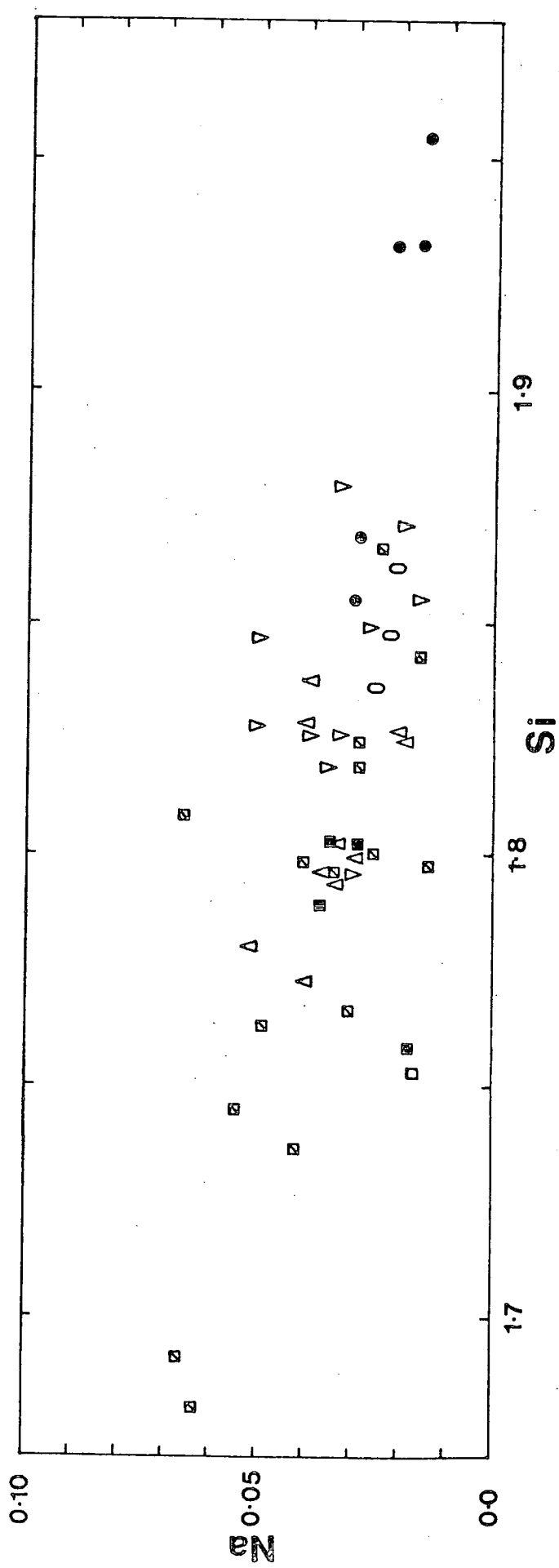


Fig 6.7 Si v Na in the dolerite groundmass pyroxenes. Symbols as in Fig 6.4. (on a basis of six oxygens).

Fig. 6.8 Al^{IV} v. Al^{VI} in the dolerite groundmass pyroxenes.
The fields of pyroxene in igneous rocks and in
basalts with granulites and inclusions are taken
from Aoki and Shiba (1973, Fig. 3). Key to symbols
on p.186.

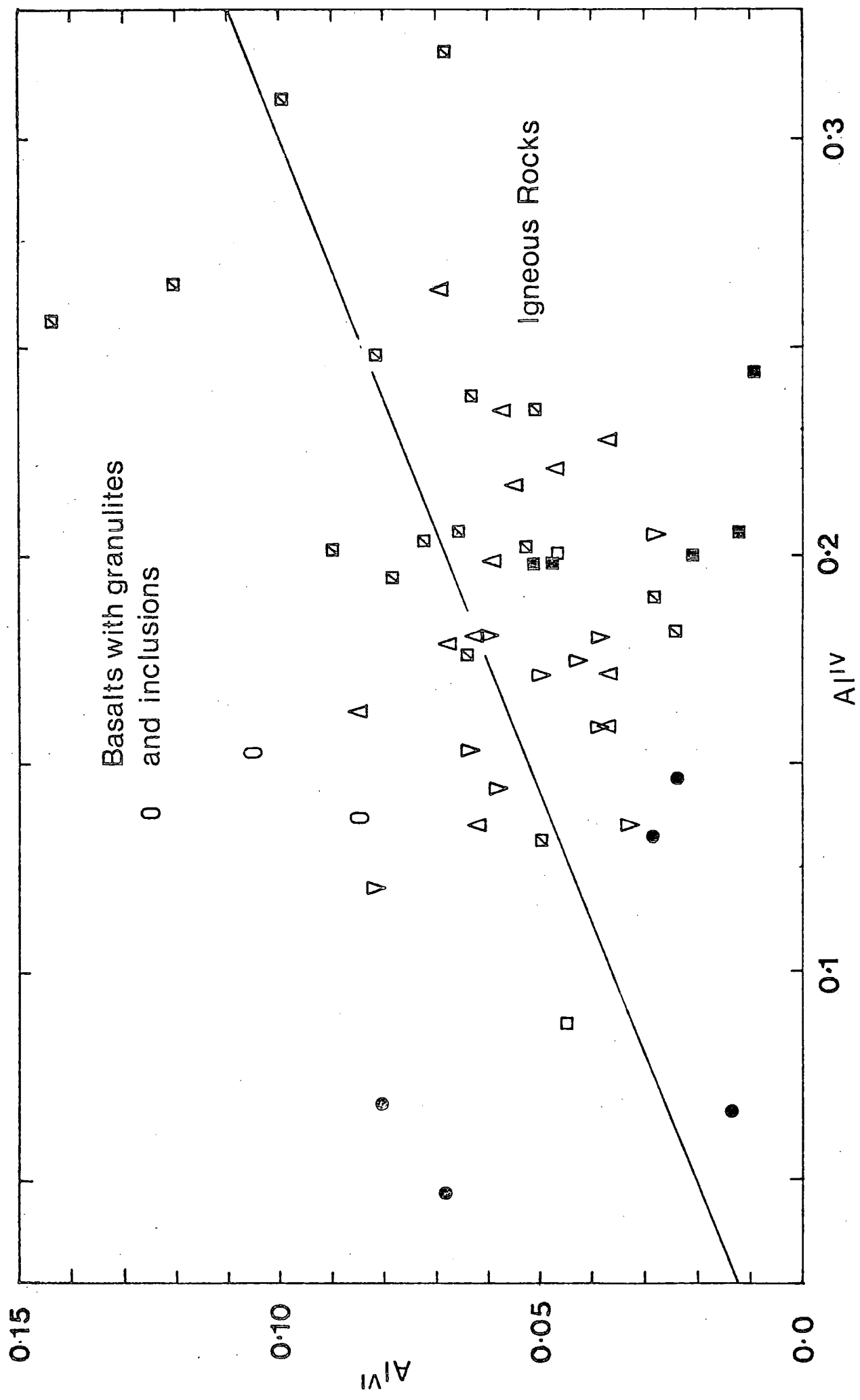


Fig. 6.9 Al^{IV} v. Al^{VI} in the dolerite phenocryst pyroxenes.
The fields of pyroxenes in igneous rocks and in
basalts with granulites and inclusions are taken
from Aoki and Shiba (1973, Fig.3). Key to symbols
on p.186.

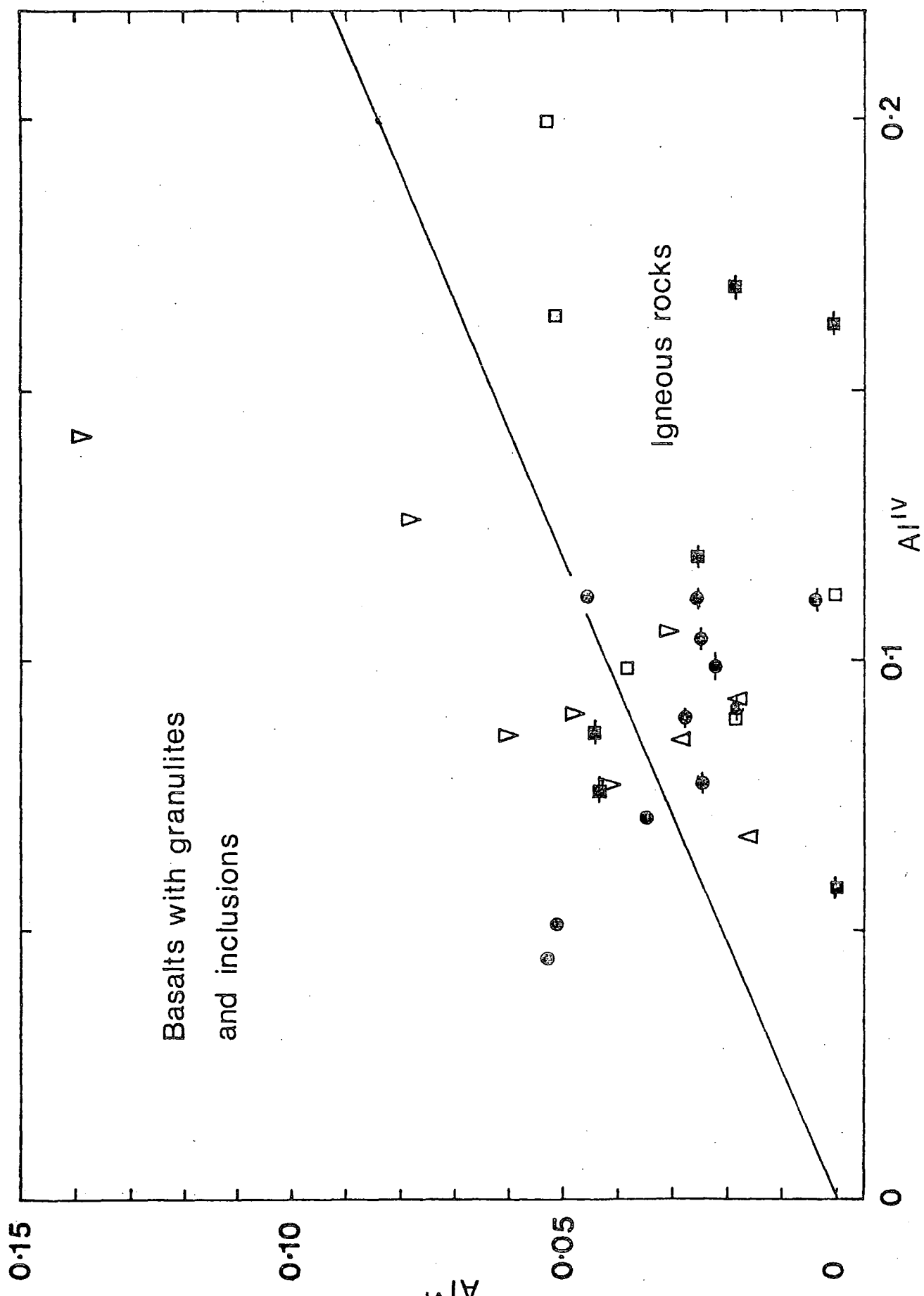
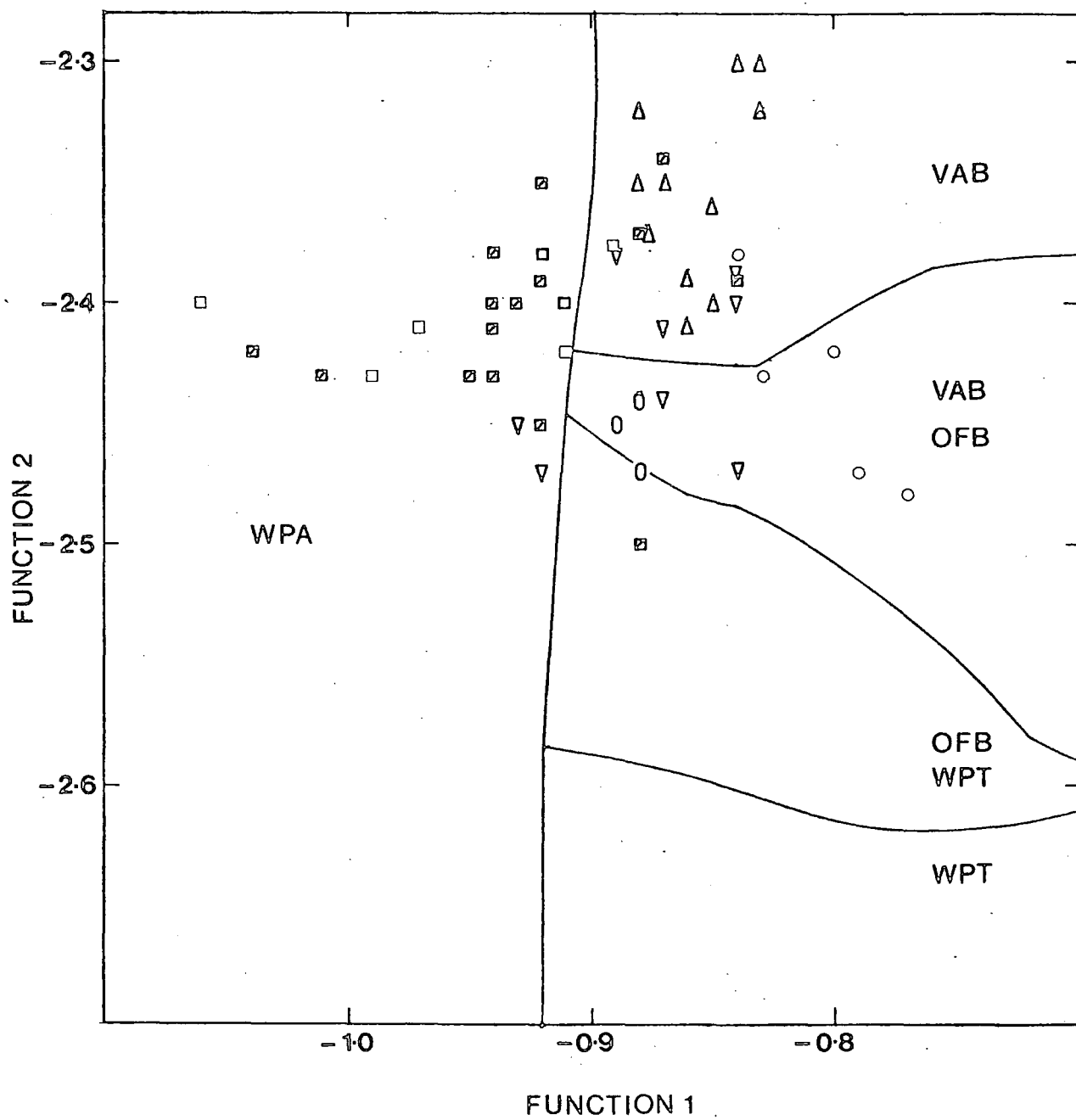


Fig. 6.10 Tectonic discriminant analysis of the Rhum dolerite pyroxenes. The fields for Within Plate Alkaline (WPA), Within Plate Tholeiite (WPT), Volcanic Arc Basalt (VAB) and Ocean Floor Basalt (OFB) are taken from Nisbett and Pearce (1977, Fig.1). The discriminant scores on Functions 1 and 2 were obtained using the functions listed in Nisbett and Pearce (op.cit., Table 2). Key to symbols on p.186.



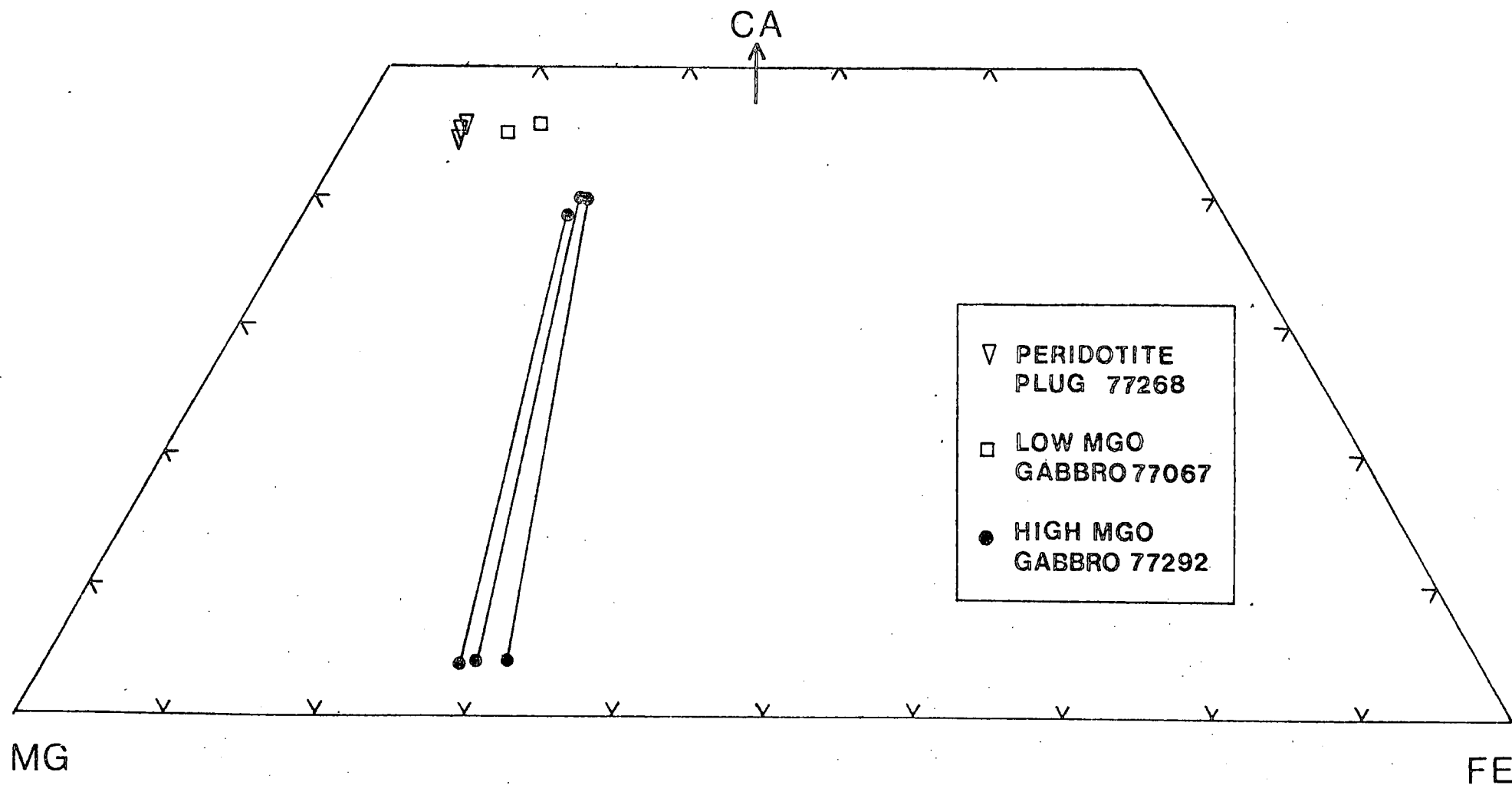


Fig. 6.11 Ca-Mg-Fe variation in pyroxenes from gabbro and peridotite plugs, tie lines join co-existing pyroxenes.

Fig. 6.12 Al-Cr-Fe variation in Rhum Cr-spinels.

Key to symbols

□ Type 1 Picrite (Gp.1)	▣ 77039 (Gp.2)
□ Type 2 Picrite "	+ 77184 (Gp.10)
○ 85A76 (Gp.1) "	* 32A76 (Gp.10)
⊖ 77024 (Gp.1) "	
∇ 77268 (Peridotite plug)	

- Rhum layered peridotite spinels (Dunham and Wadsworth, 1978, Tables IV and V).

U12—U12 Trend of variation exhibited by
layered peridotite spinels of the base
U8—U8 of units 8 and 12 (Henderson, 1975, Fig. 11).

SR157—○—○— Spinel variation in the Rhum Lava specimen
SR157, Ridley 1971, Table 2; circles mark
individual data points and the arrow
indicates the direction of zoning from core
to margin.

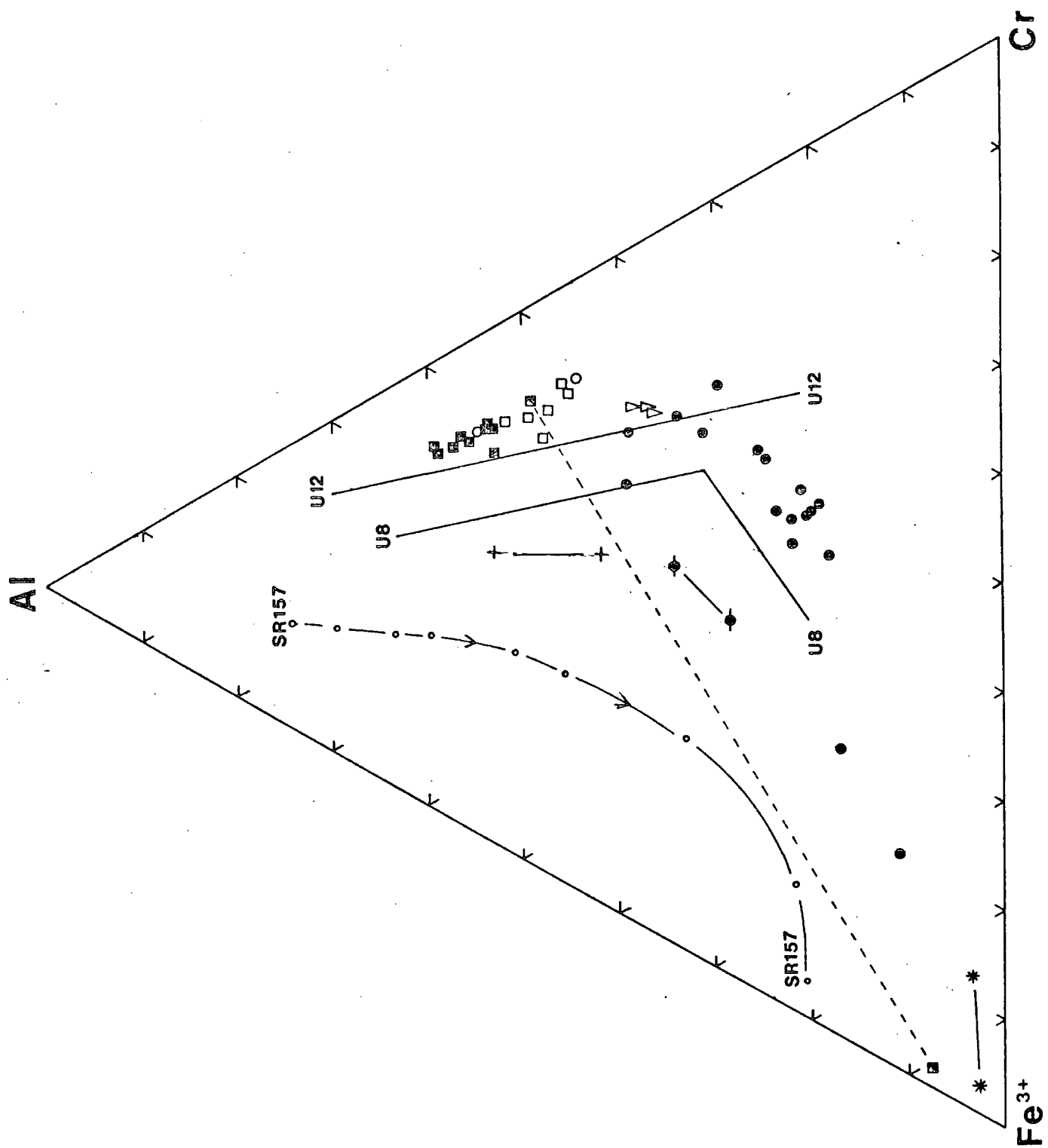


Fig. 6.13 $Mg/Mg+Fe$ v. $Cr/Cr+Al$ variation in Rhum Cr-spinels. The fields of spinels in stratiform intrusions and in alpine peridotites are taken from Greenbaum (1977, Fig.15). Symbols as in Fig. 6.12.

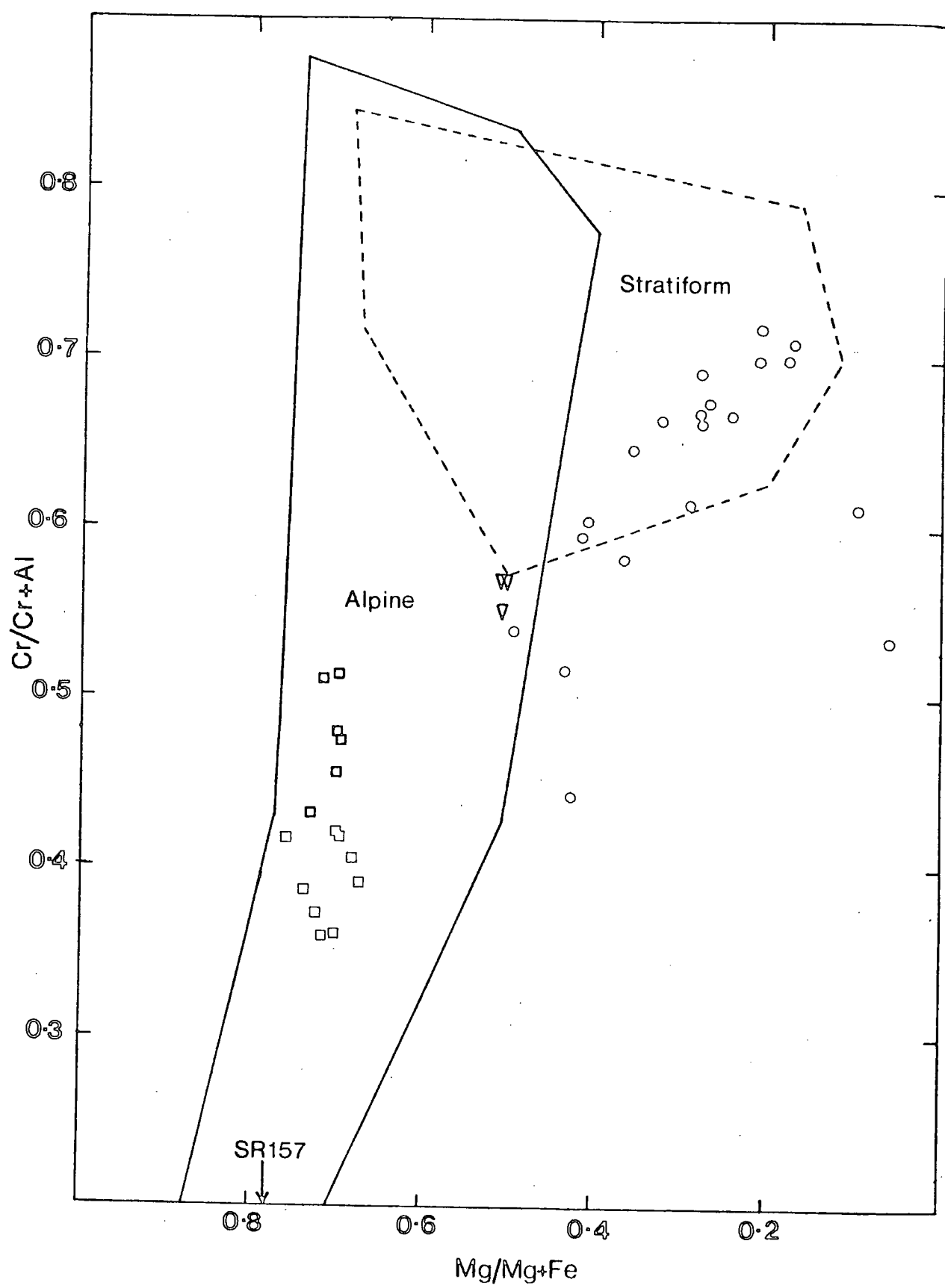
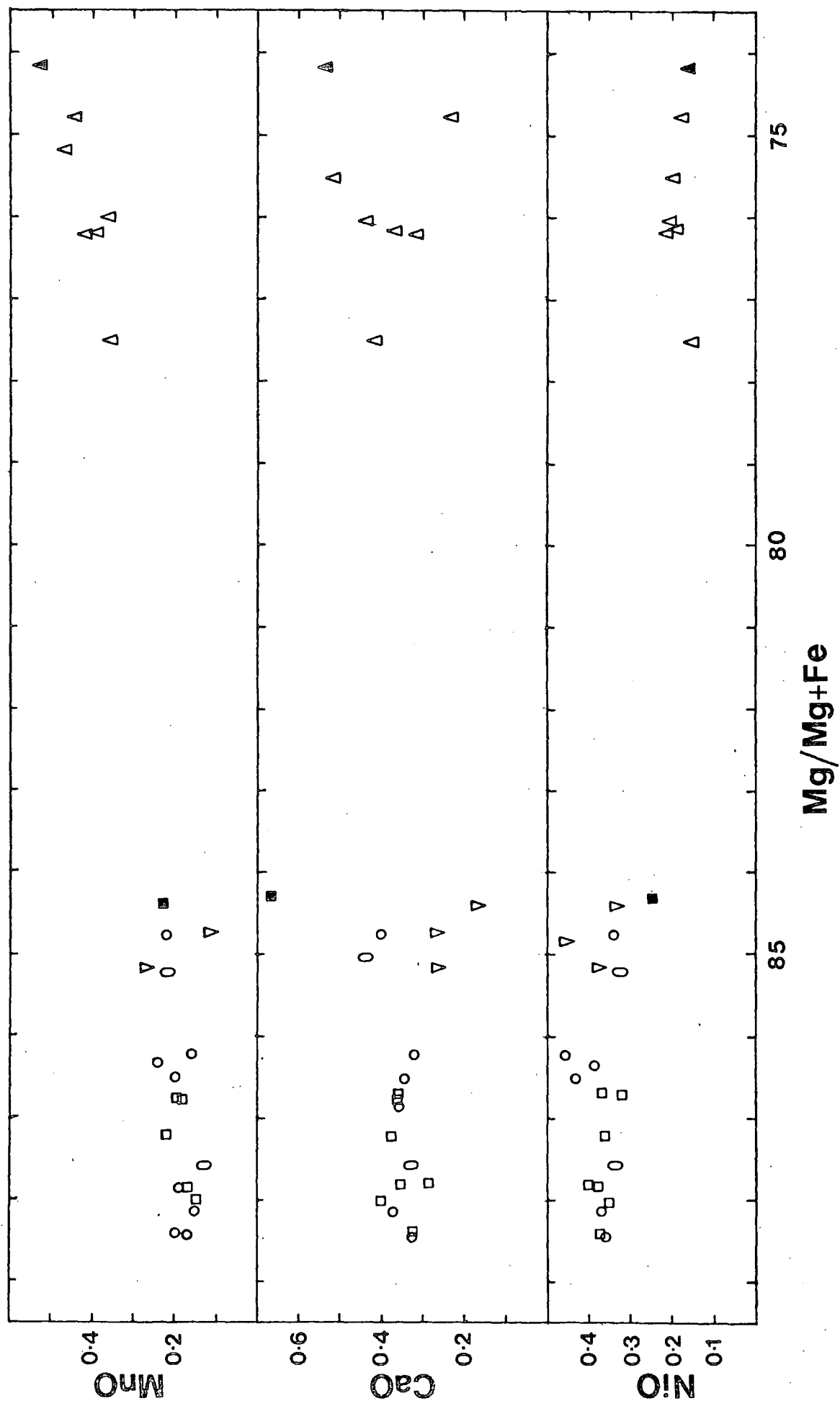


Fig. 6.16 NiO, CaO and MnO variation plotted against Mg/Mg+Fe variation in Rhum minor intrusion olivines. Open symbols are phenocrysts, closed symbols groundmass.

Key to symbols

○ Type 1 picrite (Group 1)	△ 77024 (Group 1)
□ Type 2 picrite (Group 1)	○ 85A76 (Group 1)
▽ 77268 (Peridotite plug)	



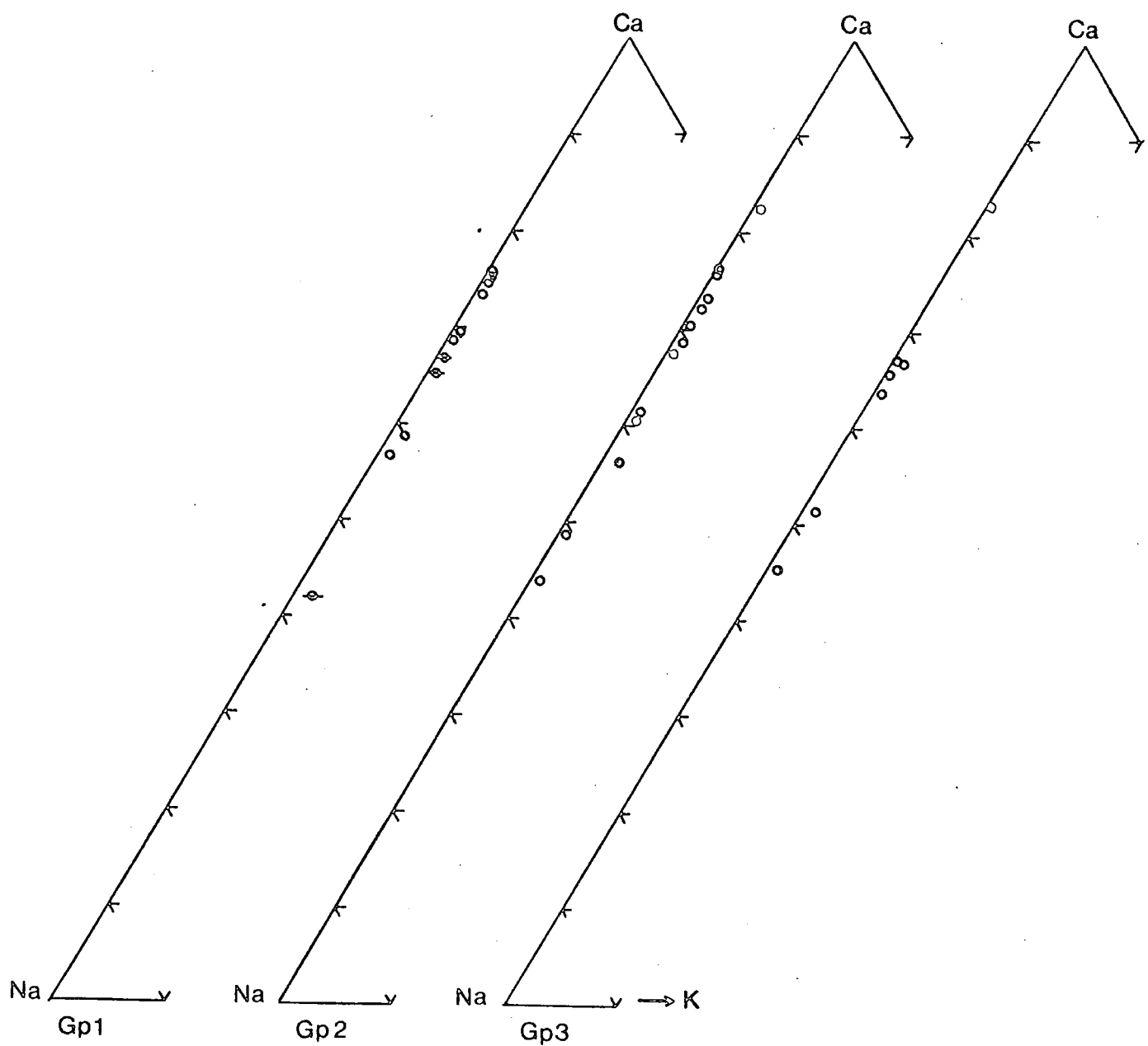


Fig. 6.15 Plagioclase variations in dolerite groups 1-3. Closed symbols phenocrysts, open symbols groundmass.

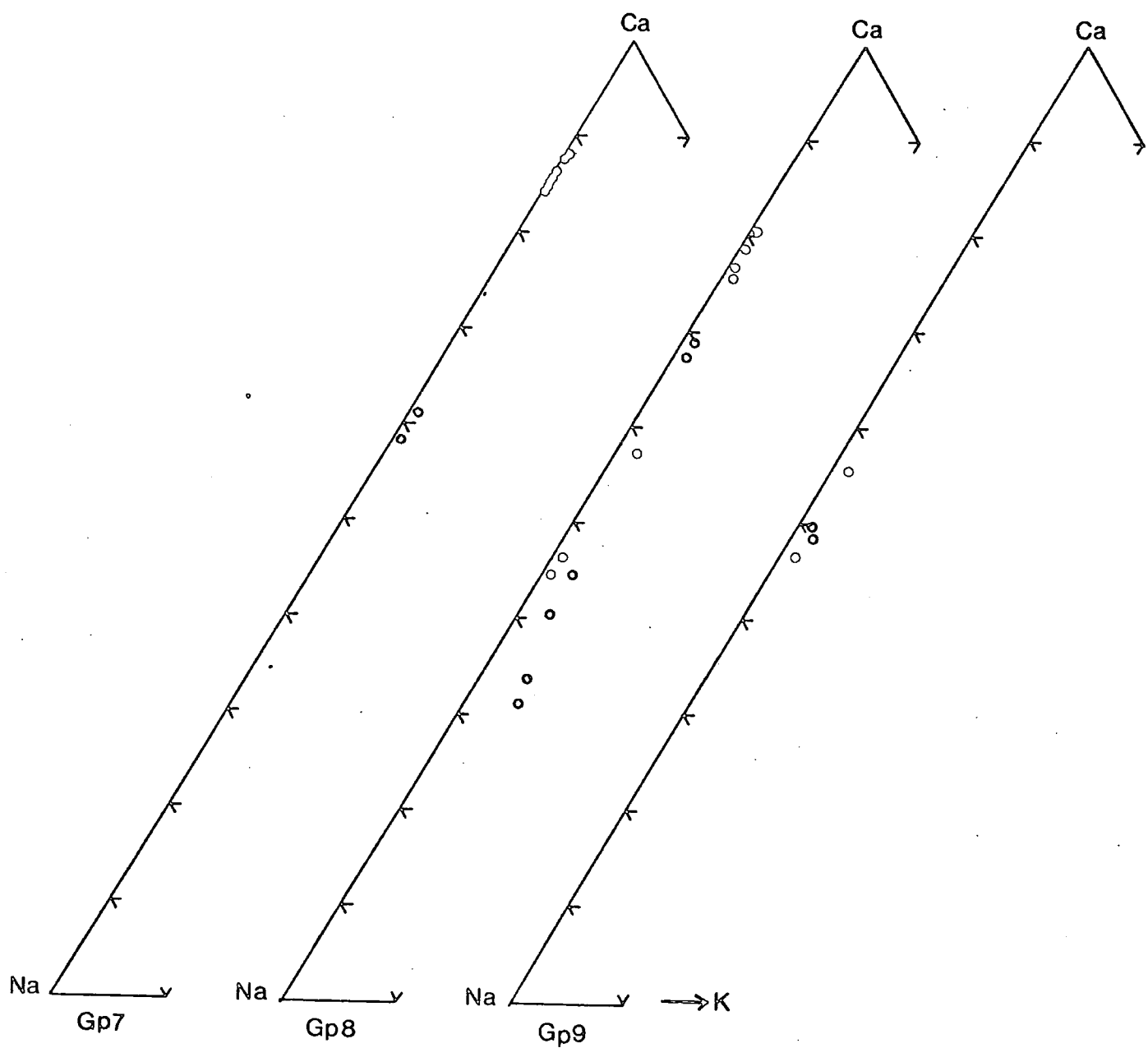
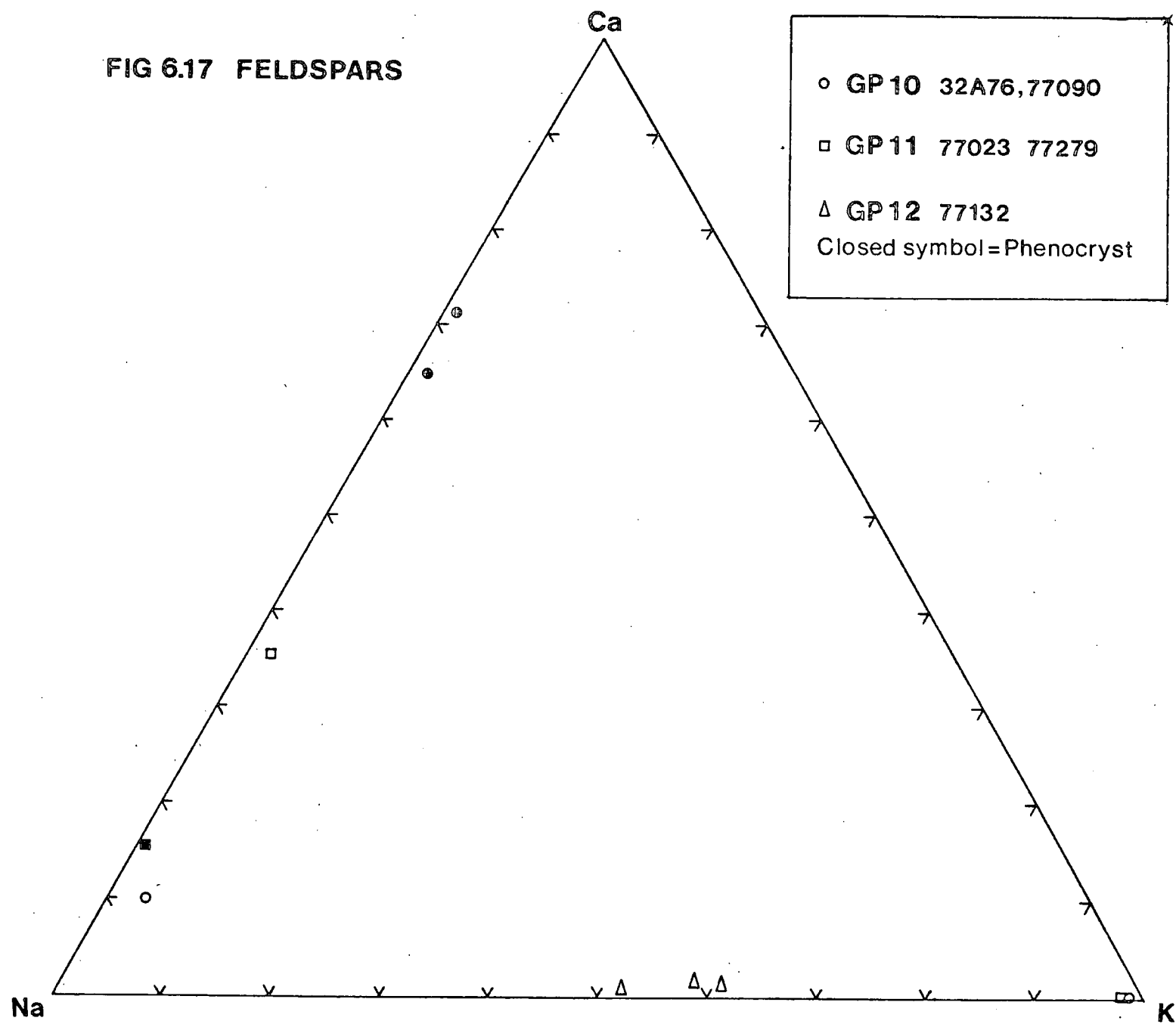


Fig. 6.16 Plagioclase variations in dolerite groups 7-9, closed symbols phenocrysts, open symbols groundmass.

FIG 6.17 FELDSPARS



	1	2	3	4	5
Specimen	7726804	7726805	7726806	9698	DB
SiO ₂	50.36	50.98	51.34	51.46	51.78
TiO ₂	0.56	0.55	0.56	0.50	0.30
Al ₂ O ₃	4.02	3.77	3.71	3.17	3.12
Cr ₂ O ₃	1.40	1.32	1.29	0.61	0.68
FeO	4.40	4.45	4.50	5.48	4.14
MnO	0.28	0.17	0.17	-	-
MgO	16.34	16.09	16.39	15.63	16.63
CaO	21.40	21.38	21.69	23.09	23.00
Na ₂ O	0.27	0.33	0.30	-	-
wt % NiO	0.07	0.09	0.04	-	-
Total	98.89	99.12	99.99	99.94	99.65
Fe	7.22	7.35	7.36	8.71	6.55
Mg	47.78	47.37	47.79	44.27	46.86
Ca	45.00	45.27	44.84	47.02	46.60
Mg No	86.88	86.56	86.65	83.56	87.74

Table 6.1 Pyroxenes in the peridotite plugs and in the layered series peridotites.

Numbers 1 to 3 Pyroxenes from peridotite plug (this study)

Numbers 4 and 5 Average analyses of selected cumulus pyroxenes from the Western Layered Series (Dunham and Wadsworth 1978 Table VI)

Mg No = $\text{Mg}/(\text{Mg} + \text{Fe})$

CHAPTER SEVEN

GEOCHEMICAL VARIATION AND PETROGENESIS

Introduction

This chapter deals with the geochemical variation exhibited by the Rhum minor intrusion suite and considers the various factors which have produced this compositional variation. A brief assessment of the effects of alteration on the geochemistry of the suite is presented in the first section. The subsequent sections consider in detail the geochemistry of the ultrabasic, basic, intermediate and acid rocks respectively and a petrogenetic synthesis is presented in section five.

The analytical procedures used to determine the major oxide and trace element abundances are described in Appendix 7.1 and the analyses of all the minor intrusions are presented in Appendix 7.2. In order to reduce overcrowding on the variation diagrams presented in this chapter, a representative set of the freshest aphyric analyses was selected for each group, these analyses are denoted with an asterisk in Appendix 7.2.

I. An assessment of the affects of alteration

Most geochemical studies of igneous rocks are based on the underlying assumption that the major oxide

and trace element abundances observed in the analysed rock are equivalent to the abundance of these oxides and elements in the original magma; however, petrographic studies reveal that most terrestrial igneous rocks have undergone varying amounts of post-solidification changes (alteration).

In order to discuss magmatic effects, it is necessary to first assess and then minimise the effects of alteration. This problem may be tackled in several ways. The most obvious solution is to use extremely fresh material for analysis. However, this may not always be possible as this extremely fresh material may not be sufficiently representative of the chemical variation exhibited by the igneous rock suite.

Various procedures have been recommended to reduce alteration effects. Irvine and Baragar (1971) recognised that the H_2O , CO_2 and O_2 content of most analyses were unlikely to represent those of the original magma and recommended that analyses should be normalised to 100% volatile free. It has also been recognised that oxidation of a rock during alteration will cause the Fe_2O_3/FeO ratio to deviate significantly from the magmatic ratio (Irvine and Baragar 1971, Thompson, et al., 1972, Brooks 1976, Clarke and O'Hara 1979). The Fe_2O_3/FeO ratio of a rock is of considerable importance

in determining the proportions of Ne or Hy in C.I.P.W. normative calculations. The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio is also critical in the calculations involving the FeO and MgO distribution coefficients between olivine and magma and thus merits attention. The problem is best illustrated by focusing attention on a single analysis and determining the various Fe_2O_3 and FeO values recommended by the various authors. The procedures adopted are as follows:

- (i) $\text{Wt\% Fe}_2\text{O}_3 = \text{wt\% TiO}_2 + 1.5$ (Irvine and Baragar 1971).
- (ii) $\text{Wt\% Fe}_2\text{O}_3 = 1.5$ if $\text{Na}_2\text{O} + \text{K}_2\text{O} < 4.0 \text{ wt\%}$ (Thompson, et al., 1972).
- (iii) $\text{Fe}_2\text{O}_3/\text{FeO} = 0.15$ (Brooks 1976).
- (iv) $\text{Fe}_2\text{O}_3/\text{Fe}_2\text{O}_3 + \text{FeO} = 1.5$ (Clarke and O'Hara 1979).

The results are expressed in Table 7.1. Estimated values for Fe_2O_3 range between 1.45 and 2.88 and the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios vary between 0.150 and 0.344. On the basis of these calculations the consensus of opinion would estimate $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios of 0.15 to 0.18 in basic magmas.

At an early stage in this study, a $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio of 0.25 was adopted on the basis of the discussion of iron oxidation states in Johannesson (1975, p.136) and this value was used in the subsequent normative calculations. The evidence presented above would suggest that a lower $\text{Fe}_2\text{O}_3/\text{FeO}$ value would have been more acceptable. This would have the effect of moving the hypersthene normative

specimens in Fig. 3.2 and Fig. 3.3 towards the critical plane of silica ^{under} saturation and moving the nepheline normative specimens away from this plane giving the suite a slightly more alkaline character. It does not, however, effect the conclusions in Chapter 3 concerning the transitional nature of the suite as the Discriminant Function Analysis procedure operated on total iron in a single oxidation state (Appendix 3.2).

The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio is also important in assessing the molar concentration of FeO (X_{FeO}) for use in calculations involving the distribution coefficient (K_d) of X_{FeO} and X_{MgO} between olivine and magma in the form

$$K_d = \frac{X_{\text{Ol}}^{\text{FeO}}}{X_{\text{Ol}}^{\text{MgO}}} \cdot \frac{X_{\text{liq}}^{\text{MgO}}}{X_{\text{liq}}^{\text{FeO}}}$$

The theoretical composition of the liquidus olivines in equilibrium with 54A76 have been calculated using the estimated X_{FeO} derived in Table 7.1 and a K_d value of 0.30 (Roeder and Emslie 1970) the results are presented in Table 7.1 and reveal olivine compositions ranging Fo90.14-Fo91.33, thus illustrating the dependance of the calculated olivine composition on the assumed $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio.

The main conclusions that can be made from this survey

are, firstly, there is at present no agreement on the precise $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio applicable to basic magmas, and secondly that conclusions based upon assumed or estimated $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios (eg. the transitional nature of the Rhum Suite based on normative parameters) should be independently checked by alternative procedures when possible.

Normalisation of an analysis to 100% volatile free with a fixed $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio actually alters the values quoted in an original rock analysis in an attempt to reduce the effects of alteration when discussing magmatic processes. A complimentary approach is to assess the mobility of a major oxide or trace element during an alteration process, thus giving an indication of its reliability as a petrologic tool.

Several different types of alteration process have been recognised. They can operate simultaneously or independently and each process induces a different geochemical effect. The three main types are:

- (i) Weathering
- (ii) Hydrothermal alteration caused by the circulation of groundwater in convection systems around magma chambers.
- (iii) Zeolitisation attributed to circulation of alkaline solutions in basaltic lava piles.

The effects of weathering on the geochemistry of the rocks

presented in this study were reduced to a minimum during the sample preparation (Appendix 7.1) as considerable efforts were made to use unweathered material. Amygdaloidal zeolites are not common in the Rhum dolerites but interstitial zeolites are locally abundant in several of the low MgO gabbros. This suggests that zeolitisation has not had a profound effect on the chemistry of the dolerites but may be more important in the low MgO gabbros.

The diagnostic petrographic features of hydrothermal alteration have been outlined by Morrison (1978) who recognised three stages:

- 1) Alteration of olivine to serpentine, chlorite and iron oxides.
- 2) Albitisation of plagioclase with patchy development of calcite and epidote and re-equilibration of the titanomagnetite to Fe-Ti oxides and sphene.
- 3) Total re-equilibration of the igneous mineralogy to a quartz-chlorite-albite-amphibole-sphene-epidote assemblage.

Although many of the Rhum minor intrusions have suffered breakdown of olivine to serpentine-chlorite mixtures (see Chapter 4) development of albitised plagioclase, sphene and epidote is not common. None of the specimens

have suffered total re-equilibration of their igneous mineralogy.

The composition of the basalt suffering alteration is important as this affects the location of certain elements within the rock matrix (Humphris et al., 1978). The siliceous interstitial glass in tholeiite basalts is metastable and is susceptible to change during zeolitisation or hydrothermal alteration. Consequently, element mobility in tholeiitic basalts is greater than element mobility in transitional and alkaline basalts (Humphris et al., 1978, Morrison, 1978).

Studies of element mobility in subaerial and submarine basalts has shown that TiO_2 , P_2O_5 , Nb, Zr and Y are immobile in basalts which have suffered moderate hydrothermal alteration and/or zeolitisation and are only slightly mobile in extreme cases (Pearce and Cann 1971, 1973; Hermann et al., 1974; Smith and Smith 1976, Ridley et al., 1974, Floyd and Winchester, 1975; Wood et al., 1976; Morrison, 1978). In addition Al_2O_3 and Cr are also considered to be stable under alteration (Pearce and Flower, 1976; Humphris and Thompson, 1978).

SiO_2 , MgO, CaO, FeO, Fe_2O_3 , K_2O , Sr, Ba and Rb have been shown to be mobile (Smith and Smith 1976, Ridley et al., 1974; Wood et al., 1976; Humphris and Thompson, 1978; Humphris et al., 1978; Morrison, 1978). However, the degree

of mobility is dependent on several factors (eg. basalt composition, type of alteration, degree of alteration). Of the cited studies it is the works of Wood et al. (1976), Morrison (1978) and Humphris et al. (1978) which are most relevant to this study as these authors have assessed element mobility under non-spilitic alteration conditions. The conclusions that can be drawn from these studies are that SiO_2 , MgO and Rb may have been mobile and that K_2O , Sr and Ba probably were mobile during the hydrothermal alteration of the Rhum minor intrusions. However, it should be borne in mind that the transitional nature of many of these Rhum rocks probably makes them less prone to chemical change than tholeiitic basalts. One effect which has not yet been assessed, but may be relevant to any subsequent studies of element mobility, is that hydrothermal effects are most pervasive in the gabbros, suggesting that the grain size of a rock may also determine its susceptibility to hydrothermal alteration. Specimens which exhibit features attributable to mild thermal metamorphism (blackening of the feldspars, clinopyroxenes and olivines by exsolved opaque oxides) have not been used to illustrate geochemical variation wherever possible.

Summary

The effects of postmagmatic alteration on the geo-chemistry of the Rhum minor intrusions has been minimised by:

- (i) Removing all weathered surfaces from specimens prior to analysis and discarding dolerite specimens in which albitisation of the plagioclase has occurred.
- (ii) Using analyses normalised to 100% volatile free with a fixed $\text{Fe}_2\text{O}_3/\text{FeO}$ oxidation ratio where appropriate (a corollary of the analytical technique employed in this department).
- (iii) Cautious interpretation of the variation exhibited by the K_2O , Sr, Rb and Ba data. The large variation exhibited by the SiO_2 and MgO data is judged to reflect large primary variations which have only been slightly effected by secondary processes (ie. the trends developed by the SiO_2 and MgO data are a primary feature in which secondary alteration has produced scatter around the original trend).

II. Basic and Ultrabasic rocks

Introduction

This section describes the geochemical variation exhibited by the dolerite groups 1 to 7 and attention is also focussed on the gabbroic rocks, although only the geochemistry of the high MgO gabbros is considered in detail. The group 7 rocks contain abundant plagioclase phenocrysts and consequently do not approximate liquid compositions and have not been represented on the variation diagrams. The group 1 picrites exhibit various quantities of modal phenocrystic olivine (ranging 1-50%). However, the specimens with abundant phenocrystic olivine have been included on several of the diagrams as they highlight certain geochemical features. The MgO content of rocks believed to have occurred as ultrabasic liquids on Rhum is discussed later. (p. 251)

a) Groups 1 to 4

That magnesian olivine has played a considerable but not exclusive part in the geochemical variation of Groups 1, 2 and 3 is clear from Fig. 7.1 in that high MgO rocks show a systematic decrease in MgO with increasing iron enrichment. The olivine control line for the Kilauean 1959 summit eruption is also represented on Fig. 7.1. The various MgO and Fe_2O_3^* contents of the

*total iron as Fe_2O_3

magmas defining this line are attributed solely to the varying abundance of phenocrystic magnesian olivine (Fo83) in these lavas (Gunn 1971, Murata and Richter 1966) and the data points defining this line all fall very close to it. This would suggest that olivine control is the only feature contributing to the trends of groups 1, 2 and 3 in Fig. 7.1.

However, reference to Fig. 7.2 reveals that there is considerable variation in Fe_2O_3^* for a given MgO content. The Kilauean 1959 olivine control line is also represented in Fig. 7.2 and once again the points defining this control line fall very close to it. The spread of the data points of groups 1 to 3 on Fig. 7.2 suggests that the geochemical variation of MgO and Fe_2O_3^* in these rocks is not attributable to olivine fractionation alone.

Three different types of picritic magmas were defined on petrographical grounds (Chapter 4, p. 94) and this discrimination is substantiated geochemically. For example, the three picritic types are characterised by differing Ni contents for a given MgO value (Fig. 7.3) in addition the Type 1 and Type 2 picrites can be differentiated by comparison of their Ni/Cr ratios, the former generally contain more Ni for a given Cr value (Fig. 7.4). The picrite specimen 77024 does not conform geochemically, with any of the picrites types (note, for

example, the exceedingly high Ni values in Fig. 7.3) and thus must be viewed as an independent magma type. This internal geochemical variation in the group 1 picrites further supports the conclusion that olivine fractionation alone (or with Cr spinel) cannot account for the spread of Fe_2O_3^* values in the group 1 magmas.

The variation of the Al_2O_3 and CaO contents of the dolerite groups 1-4 relative to MgO can be seen in Fig. 7.5 and Fig. 7.6. In general, the group 1 rocks show systematic increases in both Al_2O_3 and CaO with decreasing MgO. A systematic increase in CaO with decreasing MgO is also a feature of the group 2 rocks and despite the scatter of the data points a general increase of Al_2O_3 with decreasing MgO can be discerned in the group 2 rocks plotted on Fig. 7.5. The Al_2O_3 and CaO contents of groups 3 and 4 show little systematic variation with MgO, indeed the group 4 rocks exhibit widely varying Al_2O_3 contents for a given MgO content. However, close examination of the group 4 data reveals that the rocks with lower MgO values generally possess lower CaO contents. The group 3 rocks exhibit greater geochemical homogeneity than group 4 - this is a clear feature in Fig. 7.5 and Fig. 7.6 and also in Fig. 7.2. In the latter variation diagram the group 4 rocks exhibit a systematic increase in Fe_2O_3^* with decreasing MgO.

Having established the relationships between the MgO and the Fe_2O_3^* , Al_2O_3 and CaO contents of groups 1, 2, 3 and 4 it is useful to characterise their Al_2O_3 and CaO variation relative to their iron enrichment ($\text{Fe}_2\text{O}_3^*/\text{Fe}_2\text{O}_3^* + \text{MgO}$) ratios. The CaO contents of the group 1 rocks show systematic linear increases with increasing iron enrichment in Fig. 7.7. However, only a general non-linear increase in Al_2O_3 can be discerned in Fig. 7.8 emphasising once again that there are several different magma types represented in group 1. The group 2, 3 and 4 rocks exhibit a range of CaO and Al_2O_3 values for a given iron enrichment ratio in Fig. 7.7 and Fig. 7.8 respectively. However, viewed as a whole these basic rocks exhibit a fairly constant range of CaO and Al_2O_3 contents over a wide range of iron enrichment values (approximately 0.45 to 0.625); with a slight decrease in the CaO and Al_2O_3 contents when the iron enrichment ratio exceeds 0.625.

The principal geochemical features described above can be summarised thus:

- (i) The group 1 rocks and the group 2 rocks possess internal variation in CaO, Al_2O_3 and Fe_2O_3^* which cannot be explained by olivine fractionation alone. The group 2 rocks occasionally contain plagioclase macro-phenocrysts (Chapter 4, Table 4.1) but these are

not encountered in the group 1 rocks. Thus, whilst plagioclase may be responsible for some of the compositional variation in group 2, the CaO and Al_2O_3 variation in group 1 can be explained only by invoking control by the phases plagioclase and/or aluminous clinopyroxene neither of which are found as phenocryst phases in this group. The variation of Fe_2O_3^* values for a given MgO content in Fig. 7.2 can only be attributed to an iron bearing phase other than olivine , possibly pyroxene.

- (ii) The group 4 rocks show a systematic decrease in MgO with increasing Fe_2O_3^* which cannot be explained by fractionation of forsteritic olivine (Fig. 7.1 and 7.2), thus it is necessary to invoke control by either a less magnesian olivine or control by MgO in pyroxene. It is difficult to explain the sharp change in slope between the MgO rich groups 1 - 3 , and the group 4 rocks in Fig. 7.1 by change in olivine composition alone; thus, pyroxene control over the group 4 trend appears reasonable. However, the petrographic data presented in Table 4.1 shows clinopyroxene is a rare phenocryst phase in the group 4 rocks and orthopyroxene is absent.

- (iii) The group 3 and 4 rocks possess an essentially constant range of CaO and Al_2O_3 values over a wide

range of iron enrichment ratios (Figs. 7.7 and 7.8). This relationship precludes orthopyroxene control as this would increase the CaO values with increasing iron enrichment. Extensive plagioclase fractionation would cause Al_2O_3 and CaO depletion whilst holding the iron enrichment ratio constant, thus plagioclase control can explain some of the variation of CaO and Al_2O_3 perpendicular to the trend but cannot explain the trend itself. The CaO and Al_2O_3 depletion in the group 4 rocks with iron enrichment ratios greater than 0.625 is possibly attributable to plagioclase fractionation.

The plot of CaO against the $\text{CaO}/\text{Al}_2\text{O}_3$ (Fig. 7.9) shows that the $\text{CaO}/\text{Al}_2\text{O}_3$ ratio in the group 2, 3 and 4 rocks decreases systematically with decreasing CaO. This trend results from depletion of both CaO and Al_2O_3 with CaO being more rapidly depleted than Al_2O_3 . This relationship also precludes extensive calcic plagioclase control over the Al_2O_3 and CaO levels in these rocks, as plagioclase contains more Al_2O_3 than CaO. The group 1 picrites also show a systematic relationship between CaO and Al_2O_3 . In this latter trend CaO depletion relative to Al_2O_3 is less marked. A range of plagioclase compositions have been plotted in Fig. 7.9 and indicate that plagioclase can account for the scatter across the trend but cannot account

for the trend itself.

Fig. 7.10 plots CaO against Al_2O_3 for groups 2 to 4, despite the scatter a general increase in Al_2O_3 with decreasing CaO can be discerned. The points X1 and X2 on Fig. 7.10 are the calculated residual liquid compositions following 25% subtraction of a calcic pyroxene (CaO = 20%, Al_2O_3 = 2%) and an aluminous calcic pyroxene (CaO = 20%, Al_2O_3 = 10%) respectively from the high lime liquid X. The slight Al_2O_3 enrichment with decreasing CaO can thus be best explained by aluminous clinopyroxene control. The point X3 is the calculated residual liquid composition after subtraction of 20% plagioclase (An76) from the high lime liquid and illustrates that calcic plagioclase alone cannot control the observed trend. It is possible that the trend developed in Fig. 7.10 is the result of the joint influence of both plagioclase and a diopsidic pyroxene. The general increase in Na_2O , Sr and Ba with decreasing CaO in the group 2-4 rocks implies that plagioclase has not played a significant role in their genesis, consequently it is suggested that the trend in Fig. 7.10 is largely the result of aluminous clinopyroxene control. The group 4 rocks with approximately 9-10 wt% CaO and 13.5 wt% Al_2O_3 , are Al_2O_3 depleted when compared with other rocks with similar CaO contents. This suggests that plagioclase has played a role in the genesis of the former.

The compositions of diopside and the compositional range of the sparse clinopyroxene phenocrysts occurring in groups 3 and 4 along with the projected trend for groups 2 to 4 have been plotted in the inset of

Fig. 7.9. The depletion in CaO suggests that the controlling phase was a Ca-rich clinopyroxene as CaO-poor clinopyroxenes (with CaO approximately 13-14 wt% CaO) would not produce marked CaO depletion. However, the Ca-rich clinopyroxene phenocrysts plotted in Fig. 7.9 and 7.10 contain insufficient Al_2O_3 to produce the observed trends. A suitable clinopyroxene would contain 18-20 wt% CaO and 8-10 wt% Al_2O_3 . Pyroxenes with this sort of composition have been recorded in plutonic nodules occurring in alkali basalts (e.g. Binns et al., 1970). The increase in Fe_2O_3^* with limited MgO depletion exhibited by the group 4 rocks (Fig. 7.2) indicates that this controlling pyroxene probably had a high MgO/FeO ratio.

Some of the trace element data for groups 1 to 4 is presented in Fig. 7.11 and the major oxides K_2O and TiO_2 are plotted against Zr in Fig. 7.12. The group 1 rocks are characterised by low abundances of Zr, Nb and Ba but Sr can reach the 300ppm level; K_2O and TiO_2 are generally low. The groups 2 to 4 rocks exhibit systematic increases in Nb and Y with increasing Zr, Ba is generally low but increases to the 500ppm level in some of the group 4 rocks.

Sr and TiO_2 shows a somewhat scattered but general increase with increasing Zr, K_2O is generally low in all the basic rocks. The K_2O content of the nepheline-normative members of group 4 are anomalous in that K_2O is generally lower than in the hypersthene normative specimens, this is also a feature of the Skye Main Lava series basalts (Thompson et al. 1972) and a possible explanation is discussed later.

b) Groups 5 and 6

Introduction

It was suggested in Chapter 5 (p.135) that the Rhum dolerite groups 5 and 6 (and by inference the Rhum lavas) postdate the mantle partial melting event which gave rise to the Rhum Central Complex and its associated minor intrusion suite. This suggestion is based on five main lines of evidence which are:

(i) The similarity of groups 5 and 6 to the Preshal Mhor and the Main Lava Series magma types of Skye respectively (Mattey et al. 1977, Thompson et al. 1972) and their dissimilarity to the magma types in the Rhum Minor Intrusion Suite.

(ii) The dissimilarity of the Rhum lavas and the Rhum minor intrusion suite.

(iii) The extensive time interval represented by the conglomerates underlying and interbedded with the Rhum Lava succession.

(iv) The relative ages of Rhum and Skye deduced from both geological and geophysical evidence (p. 235).

(v) The disposition of the group 5 and 6 dykes relative to the Skye dyke swarm.

Before comparing groups 5 and 6 with the basic magmas of Skye it is necessary to discuss the term "magma type" in its Hebridean context. Three magma types have been recognised on Skye and have been referred to as the Skye Main Lava Series magma types, the Fairy Bridge magma type and the Preshal Mhor magma type (Mattey et al. 1977). These authors noted that there was considerable geochemical variation within each type but showed that each possessed a distinctive (and therefore diagnostic) geochemical fingerprint. Whilst recognising the overall geochemical similarity of the Preshal Mhor magma type to low alkali-high calcium olivine tholeiite magmas in the Mull dyke swarm, these authors were deterred from grouping the Mull and Skye dykes of similar overall chemistry into a single overall magma type because they considered it possible that the Mull dykes were not chemically identical to those on Skye. In a more recent review, Thompson (1978) has further

emphasised this point and states that:

"It may be most satisfactory at present to treat each geographically-distinct igneous suite as a separate local magma type and postpone the Province-wide correlation of these until adequate data are available". It is evident that, despite their similarities, each of the Tertiary centres in Northwest Scotland and Northern Ireland, is in many respects unique, therefore it is reasonable to suggest (as Matthey et al. 1977 and Thompson 1978 have done) that each centre may possess magma types unique to that centre; however, there is a current trend in the research on these Tertiary Central Complexes to equate any refractory basalt composition with the Preshal Mhor magma type of Skye (eg. Skelhorn et al. 1979, Gamble 1979). It will be shown later that refractory basalt magmas do occur on Rhum but cannot be equated with the Preshal Mhor magma types as defined by Matthey et al. 1977. It is suggested that research workers follow the philosophy outlined by Thompson (1978) and treat each centre as an individual entity rather than invoking the Skye magma succession as the "norm" (as done by Gamble 1979) and assess in detail the relationships of the magmas within each complex before making sweeping comparisons with other centres.

The chemical analyses of all the group 5 dolerites are presented in Table 7.2 along with an average analysis and the range of the major oxides and trace elements of the Preshal Mhor magma type and the refractory magmas found on Rhum. The diagnostic features of the Preshal Mhor magma type (Mattey et al. 1977) are:

- (i) $\text{CaO} > 11.00 \text{ wt\%}$.
- (ii) Low Na_2O , K_2O , TiO_2 , P_2O_5 , Nb, Zr and Y abundances.
- (iii) Distinctive Ti/Y and Zr/Y ratios.

Visual inspection of the analyses reveals that the major oxides and trace element abundances of group 5 dykes all lie with the range of values present in the Preshal Mhor magma type and the values quoted in the group 5 specimens closely resemble the average quoted values of 15 representative Preshal Mhor magma type analyses. An exception to this is the K_2O abundance in the group 5 dolerites which is consistently lower than the average Preshal Mhor magma type value. The diagnostic Ti/Y and Y/Zr ratios of the group 5 specimens also lie within the ranges quoted for the Preshal Mhor magma type. It has been suggested by Sun et al. (1979) that Zr and TiO_2 approximate middle REE

in behaviour and Y approximates heavy REE in behaviour. These characteristic ratios are thus a function of source composition and more importantly the depth and degree of partial melting thus explaining the importance which Matthey et al. (1977) place on these parameters. Inspection of the gabbro analyses presented in Table 7.2 reveals that refractory basalt magmas do occur on Rhum and are characterised by CaO , Na_2O , K_2O , TiO_2 , P_2O_5 , Zr and Y abundances similar to the Preshal Mhor magma type. However, all but one of these gabbros possess Ti/Zr ratios outside the diagnostic values for the Preshal Mhor magma type and all but one have Y/Zr ratios distinctly lower than those found in the Skye magmas. Thus, the group 5 dykes are extremely similar, if not identical to the Preshal Mhor magma type of Skye but are dissimilar to the Rhum refractory basalt types. When compared with other dolerites in the Rhum suite, group 5 are characterised by higher Al_2O_3 and by much lower MgO and Ni values than other olivine phyric dolerites.

The group 6 dolerites are chemically heterogeneous, although three of the specimens are very similar (and may be sampled from the same dyke, see p. 297). An average of these has been presented along with other group 6 dolerites and some Skye Main Lava series analyses in Table 7.3. One of the specimens (SR211) is slightly

nepheline normative, the remainder are hypersthene normative.

The group 6 dolerites are only found cutting the Rhum Lavas. They are geochemically distinct from the other Rhum dolerites in that all the group 6 dykes have low MgO, Ni and Cr and higher Na_2O . In addition, SR211 is characterised by much higher Al_2O_3 than usually found in Rhum basic magmas (cf. group 5); SR141 and the average analysis of SR159, SR182 and SR282 (analysis 7, Table 7.3) have distinctly higher K_2O , Ba and Rb than other members of the Rhum dolerite suite. They compare more favourably with some of the low MgO gabbros (eg. 77261) but the latter have suffered fairly extensive hydrothermal alteration whereas all but one of group 6 (SR141) are exceedingly fresh.

It is not possible to correlate group 6 with basic magmas from Skye with the same degree of certainty as group 5 because only limited trace element data for the Skye Main Lava Series have been published. However, inspection of the analysed Skye Main Lava Series (Thompson et al. 1972) supplemented with analyses supplied by I. Williamson (unpublished data) has revealed analyses of the Skye Main Lava Series basalts comparable to the Rhum group 6 dolerites. The similarity of SR211 and SK291 (Table 7.3) is quite striking and SK932 and SK280 are also

quite similar. Analysis 7 (Table 7.3) compares favourably with 751218 and SK956. The similarity of SR141 to 751201B is less convincing in that Fe_2O_3 in SR141 is slightly higher, TiO_2 is considerably higher and K_2O is appreciably lower, however the overall impression is that group 6 compare favourably with the Skye Main Lava Series and are dissimilar to the remainder of the Rhum Minor intrusion suite.

The relationships between the Rhum Lavas and the Rhum minor intrusion suite are discussed more fully in Chapter 8. The main conclusion that can be drawn from a comparison of the Rhum lavas and the Rhum minor intrusions is they are geochemically dissimilar, as the high MgO, CaO, Ni and Cr fingerprint of the basic minor intrusions cannot be discerned in the basic lavas.

The conglomerates underlying and interbedded with the Rhum Lava succession contain abundant examples of all the rock types represented in the Rhum Central Complex (Chapter 1, p. 11). The common occurrence of allivalite clasts confirms that the central complex was unroofed prior to the eruption of the lavas. Petrographic examination of some of the dolerite cobbles has shown (as expected) that specimens of the Rhum dolerite suite also occur in these conglomerates. Specimen SR140/3 is petrographically identical to some of the petrographically

distinctive big feldspar dolerites (eg. 77047, 77258) and the mildly plagioclase-clinopyroxene phyrlic specimen 79012 is petrographically similar to some of the group 8 specimens. These relationships indicate that the cover over the central complex and its associated minor intrusions was removed by erosion during the Tertiary, postdating the emplacement of the layered ultrabasic rocks and predating the eruption of the lavas.

It is suggested here that the period of time represented by the layered ultrabasic emplacement-lava eruption interval was long enough to allow extinction of the Rhum partial melting event. The actual duration of this time interval can only be assessed unequivocally by radiometric dating, however a more qualitative approach can be made by analogy with the erosion rates encountered in more recent volcanoes which have been radiometrically dated.

Erosion rates are dependent on two main factors, firstly lithology and secondly climatic conditions. It is difficult to estimate the thickness of the strata originally overlying the Rhum central complex but the presence of inverted tridymite in some of the partially melted Torridonian sediments puts an upper limit in the region of 3.0 Km (depths calculated using the stability field of tridymite figured in Deer et al. 1966 p.348, with an upper temperature limit of 1200°C and a rock density of 2.73).

A depth of 2 km was suggested by Dunham (1970, fig. 1, p. 26). This is based on the assumption that the roof of the magma chamber coincides with the Torridonian-Lewisian unconformity. Emeleus (in press) has pointed out that the Lewisian cobbles in the conglomerates do not show the effects of partial melting characteristic of the Rhum Lewisian at the present erosion level. This suggests that a considerable thickness of Lewisian gneisses overlay the central complex and 2 km may be viewed as a minimum value.

The rocks overlying the central complex thus comprised; Lewisian gneiss and Torridonian arkose sediments, in addition the possibility that a lava pile was also present must be taken into account if Brown's (1956) open system fractionation model for the Rhum Magma chamber is valid.

Evaluation of the Tertiary palaeoclimate is intrinsically subjective, however the presence of laterite weathering deposits in the lava successions of Skye (Anderson and Dunham 1966) and Antrim (Emeleus and Preston 1969, p.21) in conjunction with the presence of active water erosion indicated by the river systems envisaged in the Tertiary by Geike (1896) and Emeleus (1973) suggests an environment in which erosion rates will have been high. This conclusion is corroborated by

the presence of felsite boulders up to 2 m diameter in the Rhum conglomerates (Emeleus pers. comm.).

The erosion rates on the Indian Ocean volcanic island of Reunion have been assessed by McDougal (1971) who found them to be rapid, in the order of 680-850 cm/1000 years. In addition he showed that the plutonic rocks (syenites) in the core of the extinct volcano (Piton des Neiges) had been uncovered within the last 0.2 my and probably within the last 0.07 my indicating how quickly a central complex can be unroofed under favourable circumstances.

It is difficult to evaluate whether the erosion rates over the last 0.07 my on Reunion can be applied to the Rhum Tertiary situation. Lateritic boles are present in the lava sequence of Reunion (McDougal, 1971) and in Tertiary lavas of Great Britain, thus there are similarities but Reunion has sub-tropical oceanic island climate whereas Rhum will probably have been more continental. The rainfall on Reunion is likely to have been higher than the Tertiary rainfall on Rhum and as the palaeoclimate suggested for the British Tertiary (Anderson and Dunham, 1966) is analogous to that found in the Northern Mediterranean at the present day. In view of these differences it is probable that any calculations based on the erosion rates of Reunion will give a minimum estimate of the time

interval between the emplacement of the ultrabasic complex and the eruption of the lavas on Western Rhum.

The calculations pertaining to a depth of cover of either 1.5 km, 2.0 km and 2.5 km and with erosion rates of 680 or 850 cm/1000 years are presented in Table 7.4. The minimum value (0.176 my) calculated from a depth of cover of 1.5 km and an erosion rate of 850 cm/1000 year is a considerable period of time and would probably be sufficient for a partial melting event to become extinct, the actual ultrabasic emplacement-lava eruption interval is probably greater than the quoted minimum estimate.

Gravity surveys have revealed considerable positive Bouguer anomalies over Rhum and Skye which are attributed to bodies of dense basic rocks approximately 10 km to 20 km diameter respectively which extend to depths of approximately 15 km (McQuilllin and Tuson 1963, Bott and Tuson 1973). Magnetic surveys have revealed that the basic rocks underlying Rhum are characterised by a reversed magnetic anomaly whereas the basic mass underlying Skye is reversely magnetised at depth beneath the Cuillins but is normally magnetised under the Redhills (Bullerwell, 1972). The relationships indicate that the Skye centre spans a magnetic reversal whereas Rhum does not, thus the centres are of different (although

possibly overlapping) age.

It is of course a prerequisite to the hypothesis advocating a Skye source for the group 5 and 6 dolerites that the Skye Tertiary igneous centre (or at least the generation of the Skye Main Lava Series and Preshal Mhor magma types) postdate the Rhum centre. The relative ages of these Skye magma types have been assessed by Matthey et al. (1977) who considered the Preshal Mhor magma type to be generally younger than the Skye Main Lava series magma type.

The evidence concerning the relative ages of the Tertiary centres of Rhum and Skye is sparse and equivocal. A radiometric (K/Ar) age for the Western Granophyre is 58 my (Emeleus pers. comm.), this compares with K-Ar dates 59 my to ~ 55 my and Rb-Sr dates of 52^{+3} and 51^{+4} for the Skye Lavas and the Redhills granophyres respectively (Brown and Musset 1976). These authors consider the young ages (< 55 my) for the Skye lavas are due to resetting by hydrothermal alteration associated with the Redhills granophyres and considered the dates of $59.2^{+0.7}$ and $59.3^{+1.0}$ my from lavas outside the O^{18} depleted hydrothermal aureole (Taylor and Forrester 1971) to be more realistic. This would suggest the Skye Lavas are coeval with the Western Granophyre.

Conflicting evidence comes from the interbasaltic

conglomerates located towards the base of the Skye lava series in southwest Skye. These conglomerates contain granophyre pebbles which cannot be derived from the Skye Redhills granophyres as field evidence has shown that these postdate the lavas. Some of the granophyre pebbles are petrographically similar to the granophyres in the Rhum granophyres (I.T. Williamson pers. comm.). In view of the presence of granophyre pebbles in the inter-basaltic conglomerates of Canna which are petrographically identical to the Western Granophyre of Rhum (Emeleus 1973) and the sub-marine connection between the lava piles of Skye and Canna along the Canna Ridge (Binns et al. 1973) it seems reasonable to suggest that the granophyre pebbles in the Skye interbasaltic conglomerates are derived from Rhum.

To summarise, the relative ages of the Rhum and Skye centres assessed by radiometric methods would suggest that Rhum and Skye are coeval whereas the bulk of the geological evidence favours Rhum as the older centre. Evaluation of radiometric ages is extremely difficult as indicated by the degree of error on published analyses; in addition, the resetting of ages by hydrothermal activity must also be taken into account. In view of these known difficulties of radiometrically dating the British Tertiary centres it is perhaps not surprising that these dates conflict with the

geologic evidence. The bulk of the evidence available at this time suggests that the Rhum and Skye centres are of different age and that Rhum is the older of the two.

The geometry of the Skye dyke swarm was determined by Speight (1972) and the distribution of the Skye magma types within the swarm was investigated by Matthey et al. (1977). These authors showed that the Skye dyke swarm at the present erosion level consists predominantly of the Preshal Mhor magma type with subordinate Skye Main Lava Series and Fairy Bridge type dykes. Furthermore, Matthey et al. (1977) found that there was spatial geochemical variation across the swarm with the bulk of the Preshal Mhor type dykes being located within 6 km of the central axis of the swarm.

The orientation of the dykes cutting the Rhum lavas relative to the trend of the Skye dyke swarm is presented in Fig. 7.13 where it can be seen that the Rhum dykes generally strike NW-SE and span the strike direction of the Skye dyke swarm. However, only very limited conclusions may be drawn from this observation as the Rhum sample population is very small. The Rhum dykes lie approximately 25 km from the centre of the Skye dyke swarm on Sleat and represent a dilation of approximately 0.66%, thus if they are members of the Skye dyke swarm they can only be considered as outliers. Matthey et al. (1977) located dykes

of Preshal Mhor and Skye Main Lava series magma type up to 18 km and 16 km respectively from the central axis of the Skye swarm. Their sampling range extended to only 18 km from the central axis of the swarm thus the possibility of the Rhum dykes being outliers of the Skye swarm cannot be rejected on the basis of their observations alone

Summary

The evidence discussed previously shows that the group 5 and group 6 dolerites are very similar to the Preshal Mhor and the Main Lava Series magma types of Skye. A period of time greater than 0.176 my elapsed following the emplacement of the layered peridotites and prior to the eruption of the lavas of western Rhum, this time interval is judged sufficient to allow extinction of the Rhum partial melting event. Although the relative ages of the Rhum and Skye Centres have not been unequivocally determined the bulk of the evidence available at this time suggests that Rhum is the older centre. Although the Rhum dykes cutting the lavas are displaced 25 km from the centre of the Skye swarm they represent less than 1% dilation and could be outliers of the Skye swarm. Their general NW-SE strike direction is compatible with the regional dyke swarms of both Rhum

and Skye (Speight, 1972) and cannot be cited as evidence in favour of a Skye or Rhum origin.

In conclusion, although there are many uncertainties pertaining to the hypothesis that Rhum group 5 and group 6 dykes are outliers of the Skye regional dyke swarm it is suggested the group 5 and group 6 dykes are genetically related to the Skye partial melting event and not the Rhum partial melting event.

c) Group 7

The outstanding petrographic feature of group 7 is the presence of abundant (up to approximately 50%) subequant plagioclase phenocrysts. The compositions of the plagioclase phenocrysts in the three specimens investigated by microprobe analysis are very similar and only mild zoning (An88-An84) was detected. If these dolerites were the result of in situ crystallisation of an aluminous magma, one would expect the phenocrysts to exhibit substantial zoning; furthermore, the subequant faces suggest that these crystals grew in a low nucleation density environment in which the effect of adjacent crystals on the growing faces was minimal. The large plagioclase phenocrysts contrast markedly with the extremely fine-grained groundmass, thus it is suggested that these dykes are produced by intrusion of a magma carrying

abundant cumulus plagioclase.

The composition of the interstitial^{ti} liquid in 77258 was calculated by subtraction of a composition equivalent to the observed modal percentage of plagioclase and the result is presented in Table 7.5. This interstitial liquid is SiO_2 enriched and Al_2O_3 depleted suggesting that some of plagioclase (possibly overgrowths on original cores) is not cumulus. It is difficult to be sure what proportion of the plagioclase in these rocks is non cumulus, however the lack of detected zoning suggest it is not considerable.

One possible source for these cumulus plagioclase crystals is the high level magma chamber associated with the Rhum central complex. However, there is a distinct lack of other phenocryst phases in the group 7 dolerites thus it is unlikely that they are produced by flushing out of the magma chamber floor as one would expect additional phases to be involved. An alternative explanation is that they represent a magma fraction of plagioclase flotation cumulates as this adequately explains the lack of other cumulus phases.

d) Gabbros

The high MgO gabbros contain approximately 10-12 wt% MgO and are consequently MgO depleted when compared with the dolerite groups 1 and 2 (Fig. 7.1, 7.2). They

are characterised by slightly higher Al_2O_3 but similar CaO contents relative to the group 2 to 4 dolerites in Fig. 7.5 and Fig. 7.6 respectively. They also possess lower iron enrichment ratios than the majority of the group 2-4 dolerites in Fig. 7.7. They generally contain higher CaO for a given $\text{CaO}/\text{Al}_2\text{O}_3$ ratio than the group 2-4 dolerites in Fig. 7.9 but follow the trend produced by the dolerites in this diagram. Similarly they exhibit a slight increase in Al_2O_3 with decreasing CaO in Fig. 7.10, an exception being the aluminous gabbro specimen 77104.

An important geochemical feature of these high MgO gabbros is the exceedingly low abundance of the incompatible trace elements Zr, Nb, Y and Ba and the incompatible major oxides TiO_2 and K_2O . This is a clear feature of Figs. 7.11 and 7.12 respectively.

The low abundance of the incompatible elements suggests that these magmas were produced by a high degree of partial melting. In addition their low Ni content (41 to 215ppm) suggests that they have also undergone significant olivine fractionation. The sympathetic relationship of CaO and Al_2O_3 in Figs. 7.9-7.10 may be attributable to either differing degrees of partial melting of mantle material containing aluminous calcic clinopyroxene and/or fractionation of an aluminous clino-

pyroxene. This is discussed in more detail in section five (p.262).

The low MgO gabbros are characterised by MgO contents of less than 9.0 wt%, their differentiated character when compared with the high MgO gabbros and the dolerite groups 2 to 4 is clearly visible in several of the variation diagrams (eg. Fig. 7.1, 7.2, 7.5 and 7.7). However, their high CaO contents distinguish them from the intermediate rocks (Figs. 7.6 and 7.7), as do their Zr, Y and TiO_2 contents (Fig. 7.11 and 7.12). The Ba and Sr data in Fig. 7.11 must be viewed cautiously as these gabbros have suffered significant hydrothermal alteration (p. 215). Their CaO and $\text{CaO}/\text{Al}_2\text{O}_3$ values are juxtaposed with the group 2-4 dolerites in Fig. 7.9.

E) Peridotites

An average analysis and the range of compositions encountered in the peridotite plugs is presented in Table 7.6. The compositional variation in Fig. 7.14 largely reflects the abundance of modal magnesian olivine. The scatter around the trends in Fig. 7.14 are attributable to variations in the proportion of plagioclase and clinopyroxene in the groundmass of these peridotites, as plagioclase is a ubiquitous interstitial phase whereas clinopyroxene may or may not be absent (Chapter 4, p.113).

A possible source for the magmas which gave rise to the peridotite plugs is discussed later. (p. 260).

II. Intermediate rocks

Introduction

The differentiates exhibit considerable geochemical variation. Two main series were recognised in Chapter 3 a series of differentiates with alkalic affinities (groups 10 to 12) and a series with tholeiitic affinities (groups 8 and 9), the gabbroic differentiates are also tholeiitic in affinity. These intermediate rocks generally display sympathetic variation of their major oxides with increasing SiO_2 content. Although these features have not been displayed diagrammatically in this account this relationship should be borne in mind in assessing other geochemical features described here.

It is clear from Fig. 7.2 that several of the intermediate rocks continue the Fe_2O_3^* enrichment, MgO depletion trend characteristic of the group 4 rocks. These rocks have been plotted onto Fig. 7.1 where it can be seen they continue the trend developed by the group 4 rocks. The remaining differentiates in Fig. 7.2 follow an $\text{Fe}_2\text{O}_3^* + \text{MgO}$ depletion trend and consequently must have ^{been} controlled by either a different phase or phases than those responsible for the iron enrichment trend or by similar phase(s) of different composition.

Intermediate rocks of the $\text{Fe}_2\text{O}_3^* + \text{MgO}$ depletion trend.

The variation of MgO against $\text{Fe}_2\text{O}_3^*/\text{Fe}_2\text{O}_3 + \text{MgO}$ is presented in Fig. 7.1 where it can be seen that although the intermediate rocks possess generally similar iron enrichment ratios to the basic groups 2 to 4, the differentiates of tholeiitic affinity generally possess lower MgO for a given iron enrichment ratio than the basic rocks and the same is true for the more advanced alkali differentiates (groups 11 and 12); however, group 10 fall in the same field as the MgO rich group 4 rocks. Some of the relationships in Fig. 7.2 have already been described but the fact that the group 10 rocks are MgO rich and lie within the group 4 field is worthy of note, as is the scatter of both the alkaline and tholeiitic differentiates along the $\text{Fe}_2\text{O}_3^* + \text{MgO}$ depletion trend. These relationships suggest that the intermediate rocks of this trend are controlled by a pyroxene phase poorer in MgO than that producing the Fe_2O_3^* enrichment trend. Some of the Fe_2O_3^* depletion may be due to titanomagnetite control as there is a slight decrease in TiO_2 with decreasing Fe_2O_3^* in the intermediate rocks (Fig. 7.15).

The plots of MgO against Al_2O_3 (Fig. 7.5) and CaO (Fig. 7.6) show that the intermediate rocks generally possess similar levels of Al_2O_3 to the basic rock groups 2 to 4 and show few signs of Al_2O_3 depletion with

decreasing MgO. The aluminous nature of group 12 in Fig. 7.5 is worthy of note. In contrast, CaO in both the alkalic and tholeiitic differentiates shows marked depletion with decreasing MgO in Fig. 7.6. This sympathetic relation of MgO and CaO precludes orthopyroxene control but suggests that a Ca-rich clinopyroxene could control this trend. The lower CaO levels in the differentiates are highlighted in the plot of CaO against iron enrichment ratio (Fig. 7.7).

The relationship of CaO to Al_2O_3 in the intermediate rocks is presented in plots of CaO against Al_2O_3 (Fig. 7.16) and the ratio $\text{CaO}/\text{Al}_2\text{O}_3$ (Fig. 7.17). The relationships of the various groups (which reflect different degrees of differentiation) on Fig. 7.16 are complicated, as there is much greater variation in the levels of CaO and Al_2O_3 in the differentiates than was encountered in the basic groups 2 to 4 (Fig. 7.10).

There is a marked decrease in CaO with a slight decrease in Al_2O_3 with increasing differentiation in groups 10 and 11. However, group 12 shows extreme CaO depletion coupled with Al_2O_3 enrichment. Despite the variation in Al_2O_3 abundance a general trend of a CaO depletion for roughly constant Al_2O_3 can be discerned in the tholeiitic differentiates. Fig. 7.17 shows that there is a decrease in the $\text{CaO}/\text{Al}_2\text{O}_3$ ratio of the

differentiates with decreasing CaO suggesting that clinopyroxene has played a major part in the decrease of CaO with differentiation in the intermediate rocks.

The CaO depletion and Al_2O_3 enrichment in group 12 can be accounted for by invoking Ca-rich clinopyroxene as the only controlling phase. However the Al_2O_3 depletion with increasing differentiation in groups 10 and 11 and the constancy of Al_2O_3 with CaO depletion in the tholeiitic differentiates is best explained by invoking limited plagioclase control, as one would expect an increase in Al_2O_3 (cf. group 2 to 4) if clinopyroxene were the only controlling phase.

These hypotheses can be assessed by referring to the trace element data presented in Figs. 7.11, 7.12. Zr is used as a fractionation index in these plots.

A general feature of these plots is a systematic linear increase of both Nb and Y in the intermediate rocks with increasing Zr. There is considerable scatter of the Sr and Ba data which is probably due in part to alteration effects. Despite the scatter, Sr generally shows a slight initial increase with increasing Zr relative to the basic rocks, then maintains a roughly constant abundance with increasing Zr. Exceptions to this are the group 10 rocks with high Sr (~ 400 ppm) at the Zr 130 ppm level and the slight increase of Sr

in the group 12 rocks. Ba exhibits similar relationships to the Sr data in that Ba increases and then maintains roughly constant values with increasing Zr, however the high Ba rocks (~ 500 ppm) at the 125 ppm Zr level are less well marked and the group 12 rocks are distinctly separate from the other differentiates. No distinction between the alkaline and tholeiitic differentiates can be made using the Nb and Y data, however the tholeiitic differentiates generally possess lower Sr and Ba for a given Zr value.

The lines M1 and M2 on Fig.7.11 refer to the trends developed in the group 1 and group 2 lavas of Mull, (Beckinsale et al. 1978). Note that the general increase in the Y and Ba with decreasing Zr is the reverse of the relationship for the Rhum minor intrusions in the case of Y, and Ba is not nearly so depleted in the advanced differentiates of Rhum when compared with Mull.

The extent of plagioclase control over the geochemistry of the alkaline rocks can be assessed from the Sr and Ba data. The group 10 rocks generally have high initial Sr and Ba abundances but the group 11 rocks are Zr enriched (ie. more differentiated) and can be depleted in Ba and Sr relative to group 10. The group 12 rocks are greatly enriched in Ba relative to groups 10 and 11 and Sr relative to group 11. The Ba and Sr depletion

with differentiation in groups 10 and 11 can be explained by plagioclase control, the high levels of Sr and Ba in group 12 coupled with the high K_2O (Fig. 7.12) and Al_2O_3 abundances precludes extensive plagioclase control during the evolution of these rocks. The fact that Sr is less abundant in the group 12 rocks than in the group 10 rocks suggests that the former are not directly genetically related to group 10. The sharp increase and then roughly constant values of Ba and Sr with increasing differentiation in the tholeiitic intermediate rocks suggests plagioclase control was important in producing the geochemical variation in the more differentiated specimens.

III. Acid Rocks

The analyses of the four acid minor intrusions are presented in Table 7.7 along with an average analysis of the plutonic acid rocks of Rhum and a differentiated acid dyke from Eigg. Specimens are somewhat similar to the acid plutonic rocks, however one of the specimens (77180) is extremely differentiated and is more similar to one of the felsite dykes of Eigg (Anal.E6, Table 7.7). The acid rocks of Rhum and the Small Isles (Ridley, 1973) have^{been} plotted in Fig. 7.18. The Rhum plutonic rocks lie in a tightly constrained field, the Rhum acid hypabyssal rocks are less tightly constrained but do not exhibit the wide variation of the Small Isles acid volcanics.

The origin of the acid magmas of Rhum were discussed by Dunham and Emeleus (1967) and Dunham (1968) who concluded that they were the result of partial melting of Lewisian gneiss. In a review of the Tertiary acid igneous centres, Meighan (1979) noted that if zircon acted as a refractory phase during partial melting of Lewisian gneiss the resulting acid magmas would contain less Zr than the gneiss. Support for this view comes from the experimental work of Watson (1979b) who has demonstrated the low solubility of Zr in peraluminous melts (~ 100 ppm). The acid plutonic and acid minor intrusions of Rhum have higher Zr levels than the Lewisian gneisses of Rhum and northwest Scotland (Meighan 1979, Table 6). These relationships support the contention of Meighan (1979) that the Rhum acid magmas may have been produced by fractional crystallisation of a basic tholeiitic magma.

The paucity of intermediate rocks in the Rhum minor intrusion suite (see Fig. 3.1) would argue against the production of the Rhum acid magmas by fractional crystallisation of a tholeiitic parent. Furthermore, one might expect more than one major episode of acid magmatism if the acid magmas are due to fractional crystallisation of a basaltic parent. The high Zr contents of the Rhum magmas are compatible with an origin by partial melting of Lewisian gneiss, if refractory zircon crystals are

removed along with the acid magma when the magma separates from its source.

In conclusion the close temporal association and general similarity of three of the minor acid intrusions with the plutonic acid rocks of Rhum suggests they have a common origin. The fourth acid dyke more favourably compares with one of the Small Isles felsite dykes (Ridley 1973). It is located on the southernmost tip of Rhum (less than 8 km from Eigg) and possibly is genetically related to the Eigg acid association.

IV. Petrogenesis

a) Ultrabasic magmas and ultrabasic liquids in the Rhum minor intrusion suite.

The term ultrabasic is applied to igneous rocks with less than 45 wt% SiO_2 (Williams et al. 1955, Wyllie 1967). The existence of ultrabasic magmas on Rhum cannot be in doubt since several of the group 2 dolerites, the vast majority of the group 1 picrites and all of the feldspathic peridotites in the peridotite plugs contain less than 45.0 wt% SiO_2 . Whether these compositions ever existed as liquids at high crustal levels is much more open to debate. The possible presence of ultrabasic liquids in the upper crust is an extremely controversial subject. The main arguments both in

favour and against the existence of ultrabasic liquids have recently been reviewed by Clarke and O'Hara (1979) who categorised the two antithetic views.

(i) Bowen (1928) considered that all high magnesian lavas were olivine phyric and that no basaltic liquids with normative olivine greater than 10% can exist in nature. With this interpretation, based on liquid line of descent arguments, low MgO basalts are primary and related high MgO compositions are enriched in early formed olivine.

(ii) However the discovery and interpretation of spinifex textured komatiites as quenched high MgO liquids (eg. Cox 1978) has led to the converse view in which the high MgO liquids are primary and the related low MgO basalts are derived by a process of olivine fractionation. These diametrically opposed views lead to the problem of how can cumulus-olivine enriched compositions be distinguished from a liquid composition. It is generally assumed that aphyric basalts closely approximate liquid compositions as evidenced by the use of aphyric rocks in illustrating liquid lines of descent (eg. Yoder and Tilley 1962; Thompson et al. 1972). This procedure has already been adopted in this study and on this basis the majority of the fine grained essentially non-porphyritic rocks of group 2 are liquids and several

are ultrabasic liquids containing up to 15 wt% MgO (eg. 44A76, 93A76, 77121, 77122). Additionally although the picritic rock 77024 contains abundant olivine phenocrysts, the textural variation and limited compositional variation of the olivine phenocrysts are consistent with the interpretation that this specimen reflects the isothermal crystallisation of a supercooled ultrabasic liquid with 15.5 wt% MgO (Chapter 6, p. 173).

The type 1 picrites have MgO contents ranging from 14.8 to 30.9 wt%. One of the specimens (77321) is the chilled margin of a picrite dyke and contains 9.04 modal % olivine microphenocrysts. The observed composition of 77321 and the calculated olivine-free liquid represented by this specimen are presented in Table 7.8 (Anal. 1 and 2). This procedure estimates the ultrabasic liquids in the type 1 picrites can contain up to approximately 19.5 wt% MgO, thus implying that the group 1 rocks with MgO greater than 19.5 wt% are cumulus olivine enriched and rocks with less than 19.5 wt% have suffered olivine fractionation. The varying abundance of MgO in these type 1 picrites can be explained by a flow differentiation process (cf. Gibb 1968) which can produce magmas containing abundant olivine (MgO enriched compositions) with concomittant MgO depleted magmas in other parts of the same dyke. In this process it is considered that an MgO-rich magma with approximately 10% olivine microphenocrysts was intruded into a fissure. Rapid chilling at the margins

produced a chilled high MgO rock equivalent to the liquid composition + 10% olivine microphenocrysts (77321). The magma within the fissure started to crystallise large quantities of olivine and subsequent flow movement of the magma through the fissure caused the olivine to differentiate into cumulus olivine enriched portions and olivine depleted portions. The MgO content of a specimen from a flow differentiated dyke is consequently dependent on two factors:

- (i) The amount of cumulus olivine in the specimen
- (ii) The degree of olivine fractionation which the interstitial liquid has undergone.

This latter point explains the low MgO content of the virtually aphyric specimen 54A76 (1.5 modal % olivine phenocrysts) with 14.89 wt% MgO. This specimen has suffered olivine removal and is a fractionate of the original magma. The olivine that crystallised from the original magma fraction contributed to the cumulus-enriched portion of the dyke. Specimens like 71A76 with 11.6 modal % olivine phenocrysts and 19.6 wt% MgO represented fractionated interstitial picritic liquid plus cumulus olivine. The schematic relationship between four specimens with varying MgO contents is presented in Fig. 7.19. Specimens 52A76 and 77321 are from the same intrusions. However, both 54A76 and 77A76 are from different dykes.

One difficulty pertaining to this hypothesis is that the observed modal abundance of olivine phenocrysts in the thin sections of the group 1 specimens does not always vary sympathetically with the MgO content. This is exemplified by comparison of 53A76 and 71A76, the former has a higher MgO content (20.73 wt% MgO as opposed to 19.59 wt% MgO) but possesses, less olivine phenocrysts (6.4 modal % as opposed to 11.7 modal %). This may possibly be due to the former having a higher MgO content in the interstitial liquid, (ie. the interstitial liquid in 53A76 has suffered less olivine fractionation than the liquid portion of 71A76) but probably reflects the fact that olivine is unevenly distributed in the samples. This means that the thin sections may not be strictly representative of the chemically analysed material. Fortunately the olivine microphenocrysts in 77321 are evenly distributed throughout the sample thus modal analysis of this specimen will give more reliable results than modal analysis of other type 1 picrite specimens.

The type 2 picrites generally contain less MgO than the type 1 picrites (10.7 to 20.4 wt% as opposed to 14.8 to 30.9 wt%) which suggests that the liquid producing these dykes contained less MgO than that involved in the genesis of the type 1 picrites. This

cannot be demonstrated unequivocally due to the uncertainties in the modal analysis procedure discussed above. However, the presence of olivine phenocrysts in the low MgO specimens (eg. 77093 with 10.71 wt% MgO) and the abundant olivine in the higher MgO specimens (77101 contains 21.5 modal % phenocrystic olivine for a MgO content of 20.36 wt%) is in accordance with this interpretation. Unfortunately none of the type 2 picrite specimens are from the chilled margin of these dykes making it impossible to calculate a liquid composition.

The type 3 picrites also possess a lower range of MgO compositions than the type 1 picrites (12.4 to 25.8 wt%). By analogy with the type 2 picrites the liquids involved in these dykes probably contained less MgO than the calculated MgO content of the type 1 picrite liquids. The presence of abundant kaersutite suggests that these magmas contained substantially more H_2O than the other picrite magmas. In addition, these picrites contain significant quantities of normative nepheline and contrast with the hypersthene normative type 1 and type 2 picrites. The relationship of the type 3 picrites to other members of the Rhum minor intrusions suite is not clear and their origins remain obscure.

Several authors (eg. Matthey et al. 1977, Donaldson and Brown 1977, Jakobsson et al. 1979) have suggested that enrichment in cumulus olivine in pyritic rocks can be discerned by comparing the observed core compositions of the olivine phenocrysts with the calculated composition of olivines which would be in equilibrium with the whole rock composition if the latter was indeed a liquid. These calculations are based on the distribution coefficient of FeO and MgO between olivine and the host liquid (see p. 211). The results of the calculations for the type 1 and type 2 picrites excluding the extremely olivine rich rocks 52A76 and 77179 but including the calculated liquid composition of 77321 are presented in Table 7.9. The calculations are based on an $\text{Fe}_2\text{O}_3/\text{Fe}^{\text{O}} + \text{Fe}_2\text{O}_3$ magmatic ratio of 1.5 and a Kd value of 0.30 as recommended by Clarke and O'Hara (1979).

The observed Fo content of the olivine phenocrysts in the type 1 and type 2 picrites range Fo88.5 - Fo85 and Fo88.5 - Fo86 respectively. This suggests that all of the type 1 picrite compositions and more importantly, sample 54A76 and the calculated phenocryst free composition of 77321 which are believed to be ultrabasic liquids in this study are enriched in cumulus olivine. Similarly the type 2 picrites with $\text{MgO} > 13.46$ would also be cumulus enriched by this line of reasoning. It must be

noted however that these calculations are subject to uncertainty in both the estimate of the $\text{Fe}^{3+}/\text{Fe}^{3+}+\text{Fe}^{2+}$ ratio of the magma and also the value of K_d , estimates of the latter vary between 0.26 and 0.39 (Roeder and Emslie 1970; Cawthorn et al. 1973, Sato 1977) with 0.30-0.33 being the generally accepted value (Thompson 1974b, Matthey et al. 1977, Donaldson and Brown 1977). This flexibility allows for an alternative explanation of the discrepancy between the calculated and observed olivine phenocryst compositions. The presence of variolitic groundmass textures in the type 1 and type 2 picrites was noted in Chapter 4 and these were attributed to supercooling. Similarly the unusual olivine textures in 77024 were considered to reflect nucleation and growth in a supercooled ultrabasic liquid. The calculated liquidus olivine composition of 77024 is Fo91.04 and the observed olivine composition is approximately Fo75-Fo76 (Fig. 6.15) thus supercooling causes a considerable reduction in the liquidus olivine composition. Consequently the observed liquidus olivine composition in the type 1 and type 2 picrites may be the result of a small degree of supercooling which produced variolitic textures in the interstitial liquid but did not affect the olivine crystal morphology. The composition of mantle olivines is considered to be between Fo94 and Fo90 (Clarke and

O'Hara 1979). Consequently it is possible that the calculated liquidus olivine compositions of the Rhum ultrabasic rocks indicate that they existed as liquids in equilibrium with mantle olivines. Supporting evidence for this contention comes from the spinel compositions in the type 1 and type 2 picrites, the high Al content of these minerals is considered to reflect crystallisation at depth prior to emplacement in the upper crust (Chapter 6, p. 167).

A comparison of some ultrabasic rocks in the Rhum minor intrusions with the picrite dykes of Skye and some worldwide rocks believed to have existed as high MgO liquids at high crustal levels is presented in Table 7.8. An important feature of Table 7.8 are the differences in the MgO contents of the Rhum rocks (Analyses 1 to 6) and the two picrite dyke chilled margin compositions from Skye (Analyses 7 and 8, Gibb 1976). This relationship is exemplified by the high MgO content of a chilled Rhum picrite (77321 with ~ 22 wt% MgO) and the Skye dykes (~ 10 -15 wt% MgO) and suggests that the picrite dykes of Rhum involved a liquid with higher MgO than that ~~involved a liquid with higher MgO than that~~ involved in the Skye picrites. This is perhaps not surprising as both the basic and intermediate rocks in the Rhum minor intrusion suite are MgO enriched when compared with rocks

of analogous differentiation in other Hebridean suites (see Fig. 8.1).

The remaining analyses in Table 7.8 are from high MgO lavas with olivine phenocrysts. The lava compositions are judged to have existed as liquids within the upper crust and their olivine phenocryst content is believed to reflect equilibration of the initial liquid composition to a low pressure environment.

The peridotite plugs are ultrabasic in composition, and consist of abundant large granular olivines in a coarse grained matrix of interstitial plagioclase and clinopyroxene. These textures suggest that these plugs are not the crystallisation products of extremely MgO rich liquids but are the result of crystallisation of a crystal mush, rich in cumulus olivine and spinel. A possible source for these crystal mushes is the magma chamber responsible for the layered peridotite rocks of Rhum and the compositional similarity between the minerals in one of the plugs (77068) and the minerals in layered series was noted in Chapter 6. Although many of the plugs are petrographically very similar to 77068, others are not. Consequently, the plugs may have tapped a magma source over a period of time and the limited data on the mineral chemistry of the plugs should be treated with caution. It is tentatively suggested that these plugs

represent the flushing of an olivine rich mush from the high level Rhum magma chamber. A corollary of this suggestion is that pure olivine rocks (dunites) which have not yet been observed in the layered peridotites at the present erosion level (Brown 1956, Wadsworth 1961) are present at depth, as abundant dunite xenoliths have been located in one of the peridotite plugs.

b) Assessment of the degree of partial melting.

It is extremely difficult to distinguish between the effects of progressive partial melting and fractional crystallisation in the Rhum minor intrusions with the available data: rare earth element and isotope analyses on critical compositions would no doubt lead to less equivocal interpretations. However, the available evidence suggests that the differentiates are more likely to be the products of fractional crystallisation (cf. the Skye lavas, Thompson et al. 1972, Thompson 1974a) than limited partial melting as proposed for the differentiates in the Mull lava succession (Beckinsale et al. 1978).

Sun et al. (1979) have suggested that plots of Ti ppm against the ratio CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ (Fig. 7.20 and 7.21 respectively) can give an indication of the degree of partial melting for the primitive members of a rock suite. The main points to note in Figs. 7.20

and 7.21 are the low Ti content of the high MgO gabbros and 77024 and the separation of the type 1 and type 2 picrites. The former generally have lower CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (ie. higher CaO and Al_2O_3 contents for a given Ti content).

The trends developed in both Fig. 7.20 and 7.21 are due to increases in the CaO and Al_2O_3 content of the rocks with decreasing TiO_2 . Similar trends in mid-ocean ridge basalts were attributed to various degrees of partial melting by Sun et al. (1979). In their interpretation the rocks with high TiO_2 contents and low CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios were the products of limited partial melting. At these low melting levels the bulk of the Ti (which is an incompatible element) enters the melt but the majority of the CaO and Al_2O_3 is retained in the refractory residue. Increased partial melting increases the CaO and Al_2O_3 contents of the melt and reduces the levels of TiO_2 in the melt by dilution. These relationships indicate that the high MgO gabbros, 77024 and one of the group 2 rocks are the product of substantial partial melting.

The interpretation of the relationships between the compositions with lower TiO_2 contents and higher CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios and the compositions with higher TiO_2 contents in the remaining rocks is much more

difficult. It was stated earlier that the dominant control over the CaO and Al_2O_3 contents of the group 1 to 4 rocks was a calcium rich aluminous clinopyroxene. The trends in Figs. 7.20 and 7.21 could be interpreted as either the result of progressive partial melting of a Ca-rich aluminous mantle clinopyroxene or fractionation of this composition from melts with low TiO_2 contents and high CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios or both.

Another important relationship which comes out of these diagrams is that the high MgO group 1 and 2 magmas have variable TiO_2 contents and CaO/TiO_2 $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios. Although the concentration of TiO_2 in the group 1 rocks will depend largely on the volume of olivine phenocrysts in the sample, the presence of olivine will not affect the CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio of the rock. Note for example that the calculated liquid composition of 77321 after subtraction of 10% olivine increases the TiO_2 content but does not alter the ratios in Figs. 7.20 and 7.21. The group 1 and 2 rocks are MgO rich and probably have not suffered substantial loss of olivine during ascent. This suggests that the TiO_2 levels in these rocks approximate the primary TiO_2 contents of the melt which implies that most of group 1 and 2 are the product of smaller degrees of partial melting than the high MgO gabbros. This interpretation

is consistent with the abundance of the other incompatible elements (Ba, Nb, Zr, Y, Sr, Rb) in these rocks.

It was noted earlier that several of the nepheline normative compositions in the group 4 dolerites contain less K_2O than the hypersthene normative compositions. It is generally accepted that nepheline normative magmas are produced by lower degrees of partial melting than hypersthene normative compositions as this explains the general high abundance of the incompatible elements including K_2O in the former. The anomalous behaviour of K_2O has also been observed in the nepheline and hypersthene normative lavas of Skye (Thompson et al. 1972, Thompson 1974a). These authors suggested that K_2O in the mantle underlying Skye was housed in the K_2O bearing mineral phlogopite making K_2O a compatible, not incompatible, element. In this model small degrees of partial extract small quantities of K_2O from the mantle giving low K_2O nepheline normative basalts. Increased partial melting results in total consumption of the phlogopite giving rise to higher K_2O contents in the hypersthene normative lavas. This interpretation by Thompson and co-workers may also explain the lower K_2O contents of the nepheline normative group 4 rocks on Rhum.

In their studies of the Mull lavas, Beckinsale et al. (1978) found that the intermediate rocks of their

groups 1 and 2 contained less Y and Sr respectively than the related basalt compositions. They suggested that these intermediate rocks were the product of limited partial melting at different levels. In this model the Y and Sr in groups 1 and 2 were retained by the source rock (garnet lherzolite and plagioclase lherzolite respectively) until increased partial melting consumed the garnet and plagioclase fractions of the lherzolite source releasing Y and Sr into the melts. The converse relationship (ie. a general increase in both Y and Sr on differentiation) is found in the Rhum minor intrusions. This contrary relationship may be interpreted as either production of intermediate rocks by limited partial melting of a spinel lherzolite source (as neither Y and Sr would be retained) or the Rhum intermediate rocks were produced by fractional crystallisation.

The presence of intermediate rocks throughout the sequence of minor intrusion on Rhum (see Fig. 5.2) lends support to an origin by fractional crystallisation in that fractionated magmas held within the mantle or lower crust would be available for intrusion throughout the history of the complex. In addition, the phases controlling the chemical trends in the differentiated compositions (calcic aluminium poor clinopyroxene, olivine and plagioclase) are all present as low pressure phenocrysts

in these rocks.

c) Relative depths of the petrogenetic processes.

There are two main factors to be taken into account in this discussion. First, the transitional nature of the Rhum minor intrusion suite as demonstrated in Chapter 3 and second, the suggestion made earlier that the majority of the group 1 and 2 rocks are the product of small degrees of partial melting.

The existence of a thermal divide separating nepheline normative and hypersthene normative compositions along the di-fo-an join in the simplified basalt tetrahedron at one atmosphere has been convincingly demonstrated by several experimental petrologists (Yoder and Tilley 1962, O'Hara 1963, Presnall et al. 1978). This divide effectively separates the crystallisation paths of alkaline basalts and olivine tholeiites and prevents the derivation of alkaline basalt from olivine tholeiite (and vice versa) by fractional crystallisation at atmospheric and low pressures.

This divide is known to break down at higher pressures but the precise depth to which it extends is not known. O'Hara (1968) suggested a limiting pressure of 8 kb for this divide but more recent work by Presnall et al. (1978) in the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$, suggests that it extends

to pressures of only 3 kb. The latter recognised that the effect of Na_2O on their simplified basalt compositions would increase this limiting pressure to approximately 4 kb but did not discuss the effects of iron and TiO_2 . These authors also noted that the disposition of the isothermal surfaces along the join di-fo-an would allow derivation of simplified tholeiite basalt compositions from simplified alkali basalt compositions between 3 and 20 kb total pressure.

Recent geophysical work on the continental margin off Northwest Scotland has shown that the Hebridean crust is approximately 27 km thick (Bott et al. 1979). This is considerably less than the 40 km estimate of Thompson (1974a, p.334). The thermal divide discussed above would extend to approximately 18 km ($\sim$ 4 kb) and consequently would not be operative in the lower crust and upper mantle.

The transitional nature of the Small Isles volcanics (Ridley 1970, 1971), the Ardnamurchan cone sheets (Holland and Brown 1971), the Skye lavas (Thompson et al. 1972, Thompson 1974a), the Mull lavas (Beckinsale et al. 1978) and other world wide transitional basalts (eg. southwestern Australia, Green 1970) is believed to reflect derivation below the low pressure thermal divide in the simplified basalt tetrahedron. A similar explanation is proposed

for the transitional nature of the Rhum minor intrusions. Previous discussions on the depth of origin of the transitional Hebridean basalts (Ridley 1971, Holland and Brown 1971, Thompson et al. 1972) have been based on earlier estimates of the depth extent of the di-fo-an thermal divide which necessitate derivation from pressures greater than 8-10 kb ($\sim$ 35-40 km). However, the evidence presented earlier does not necessitate such deep level control over the petrogenetic processes which produced the Rhum minor intrusion suite. Independent evidence from experimental data led Thompson (1974a) to propose a depth origin of 60 km ($\sim$ 17 kb) for the primitive Skye main lava series basalts. In addition, the geochemical arguments of Beckinsale et al. (1978) require derivation of the group 1 Mull lavas from a garnet lherzolite source. A possible depth estimate of 80 km ($\sim$ 25 kb) for the source of these Mull lavas can be made from the stability field of garnet presented by Carmichael et al. (1973, Fig. 13.1). It was shown earlier (p.224) that the dominant control over the CaO and Al_2O_3 variation in the basic Rhum minor intrusions was probably exercised by an aluminous MgO rich, calcic clinopyroxene which is not, however, preserved as phenocrysts in these rocks. The Al_2O_3 content of clinopyroxenes is believed to increase with increasing pressure (Aoki and

Shiba 1973, Thompson 1974b, Wass 1979) (but see p. 157) and mantle pyroxenes are MgO rich. In addition, the composition of the Group 1 rocks are believed to have been equilibrated with mantle olivines. Consequently it is suggested that the group 1 picrites and the other basic minor intrusions are derived from a high pressure source within the upper mantle.

In the absence of experimental data and any significant geochemical constraints, estimates of the relative source depths of the basic Rhum minor intrusions is purely speculative, however the progression towards alkalinity and the general increase of MgO content with time as noted in Chapter 8 requires explanation. The earliest basic rocks on Rhum are incompatible-depleted gabbros which are considered to be the products of substantial partial melting. These were then followed by the voluminous group 4 and group 8 compositions which account for the bulk of the Rhum minor suite with the MgO rich group 1 and group 2 magmas entering at a later stage (Fig. 5.2). O'Hara et al. (1975) have noted that MgO rich compositions can be produced by limited partial melting of a garnet-lherzolite source at approximately 30 kb (95-100 km), this may well explain the high abundance of incompatibles in the type 1 and type 2 picrites (especially type 1). It is tentatively

proposed that the progression towards alkalinity and high MgO compositions in the Rhum minor intrusions with time reflects a general increase in the depth of partial melting with a limited degree of partial melting at the deeper levels producing more alkalic melts.

The compositional variation within the basic rocks and the coexistence of nepheline normative and hypersthene normative compositions may reflect simultaneous different degrees partial melting at different levels or cyclic reversals in the degree of partial melting at the same depth, or both. In addition mantle heterogeneity may be a contributing factor.

The majority of the intermediate rocks are believed to be the product of low pressure fractional crystallisation of basalt magma at depths up to 15 km (the extent of the fo-an-di thermal divide) as this explains the divergence towards extreme alkaline and tholeiitic compositions. The main phases producing the variation will have been olivine, plagioclase, clinopyroxene and to a lesser extent Fe-Ti oxides. Olivine and Cr-spinel may have also fractionated at high level but slow ascent through the mantle and the lower crust would favour olivine and spinel fractionation en route. The extent of possible deeper level fractional crystallisation cannot be accurately gauged from the available data but

the sparse differentiates following the iron enrichment and MgO depletion trend in Fig. 7.2 are probably the product of higher pressure fractional crystallisation. In addition, the high normative olivine contents of the group 10 rocks (15.8% - 25.3%) suggests these magmas could have been in equilibrium with mantle olivine, implying a higher pressure derivation.

The effects of crustal assimilation.

Recent work on the Nd and Sr isotope ratios of some basalts from Eigg, Muck and Skye (Carter et al., 1978) has shown that crustal contamination has played a role in the genesis of these rocks. In view of the 27 km thick crust underlying Rhum, there is a distinct possibility that there has been interaction of mantle derived magmas with salic crustal rocks during the ascent of magma to high crustal levels. The total absence of mantle derived plutonic nodules in the Rhum minor intrusion suite and in the Hebridean basalts in general lend support to this suggestion as the nodules may have been lost by a settling or filtering process during ascent of magmas through the crust. It is very difficult to assess the extent of crustal contamination in the Rhum minor intrusions. The general lack of gneissose xenoliths and xenocrysts (p. 115) in the Rhum rocks suggests that incorporation of crustal

material may have been limited. In addition Carter et al. (1978) note that the most contaminated lavas did not have SiO_2 contents commensurate with the bulk assimilation of a corresponding proportion of Lewisian gneiss and suggested that Sr and Nd were extracted from basement rocks preferentially with respect to SiO_2 . Whilst the findings of Carter et al. (1978) will be of considerable importance in any isotope study of Hebridean igneous rocks including the Rhum minor intrusions, the extent of crustal contamination on the bulk compositions of the Rhum rocks may have been minimal.

Fig. 7.1 MgO v. iron enrichment in the Rhum minor intrusion suite.
Olivine control line for Kilauea (1959) plotted using data
in Gunn (1971, Table 1).

Key to symbols.

■ Group 1 (Type 1)	● Group 8
■ Group 1 (Type 2)	● Group 9
▢ Group 1 (Type 3)	● Differentiated gabbros
■ Group 1 (77024)	■ Group 10
△ Group 2	■ Group 11
□ Group 3	■ Group 12
▽ Group 4	
+ Low MgO gabbro	
φ High MgO gabbro	

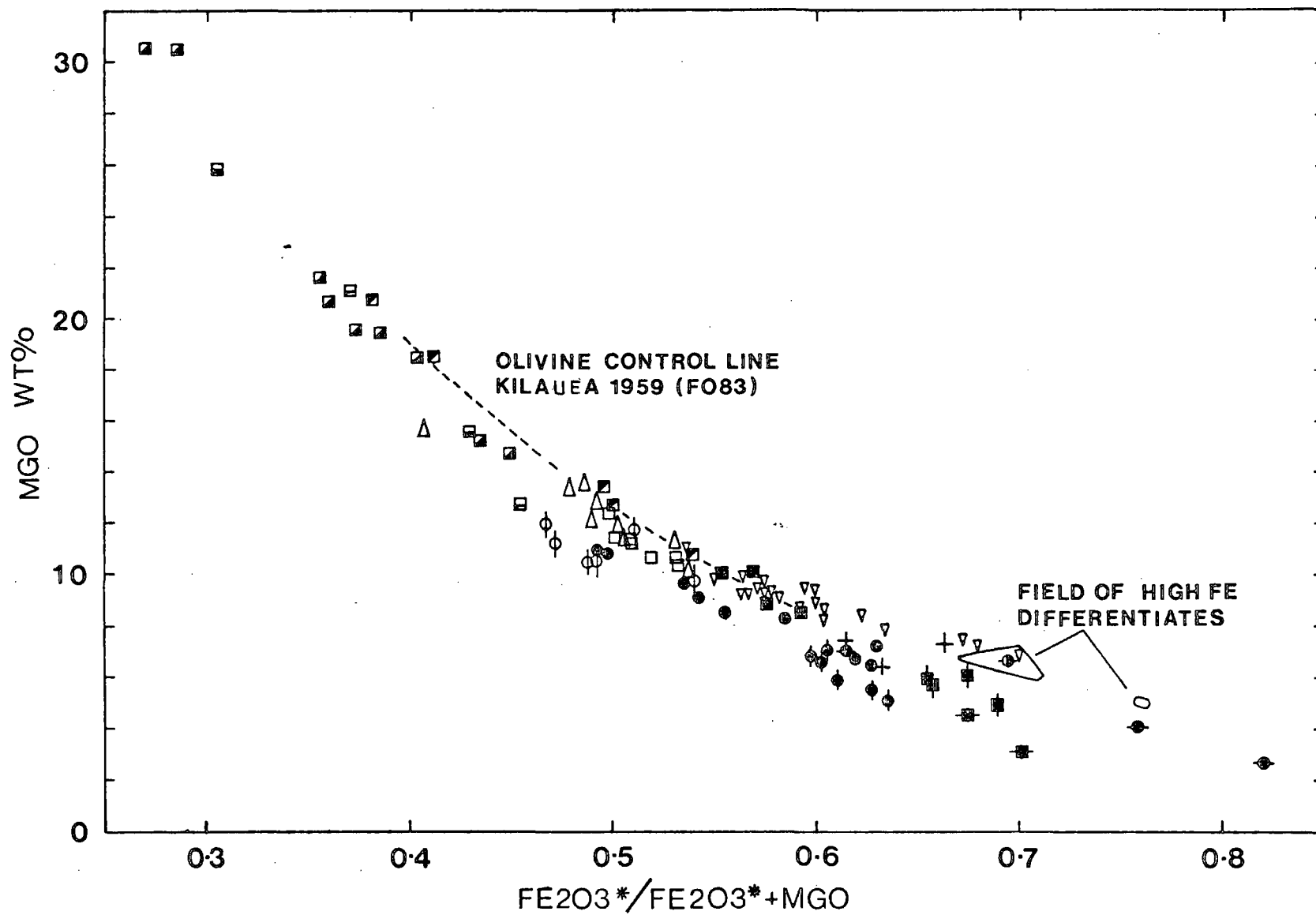


Fig. 7.2 MgO v. Fe_2O_3^* variation in the Rhum minor intrusion²³ suite. Olivine control line for Kilauea (1959) plotted using data in Gunn (1971, Table 1).

Symbols as in Fig. 7.1.

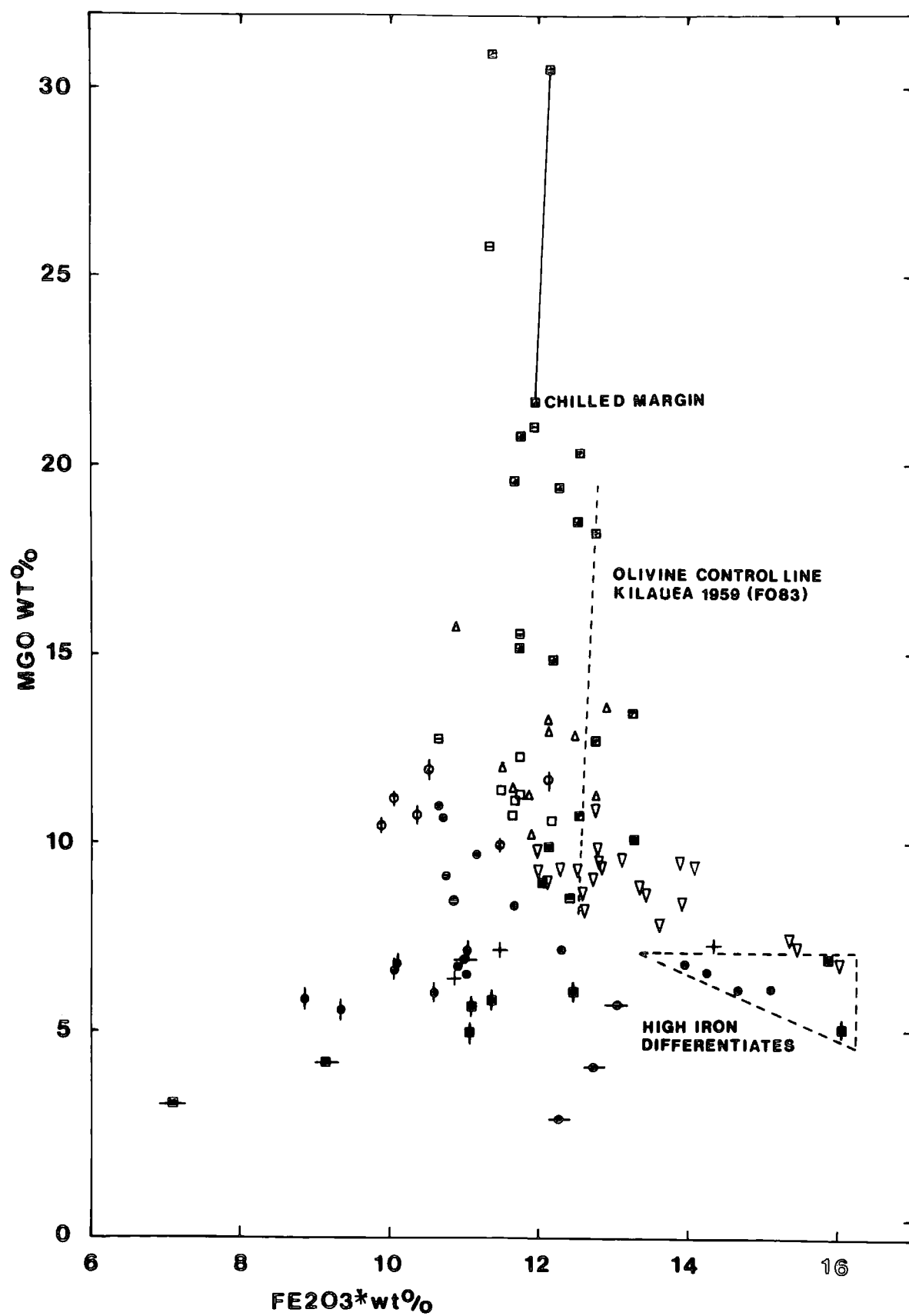


Fig. 7.3 Log Ni v. MgO variation in dolerite groups 1-4.

Symbols as for Fig. 7.1 except:

⊘ = Group 1 type 1

⊞ = Group 1 type 2

⊠ = Group 1 type 3

⊡ = Group 1 (77024)

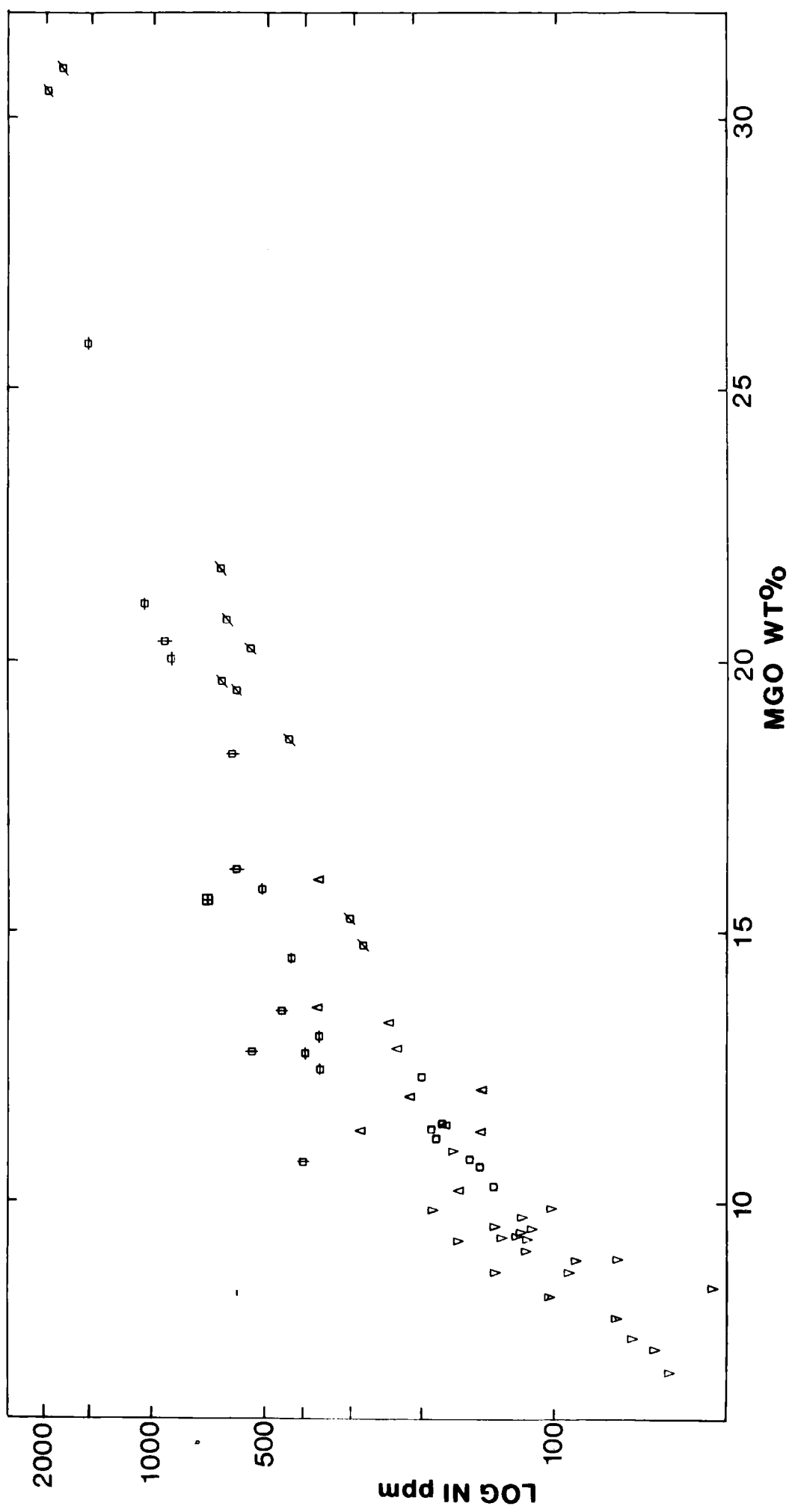


Fig. 7.4 Log Ni v. Log Cr in dolerite groups 1-3.
(Note that this diagram includes all the
picrites listed in appendix 7.2). Symbols
as in Fig. 7.1.

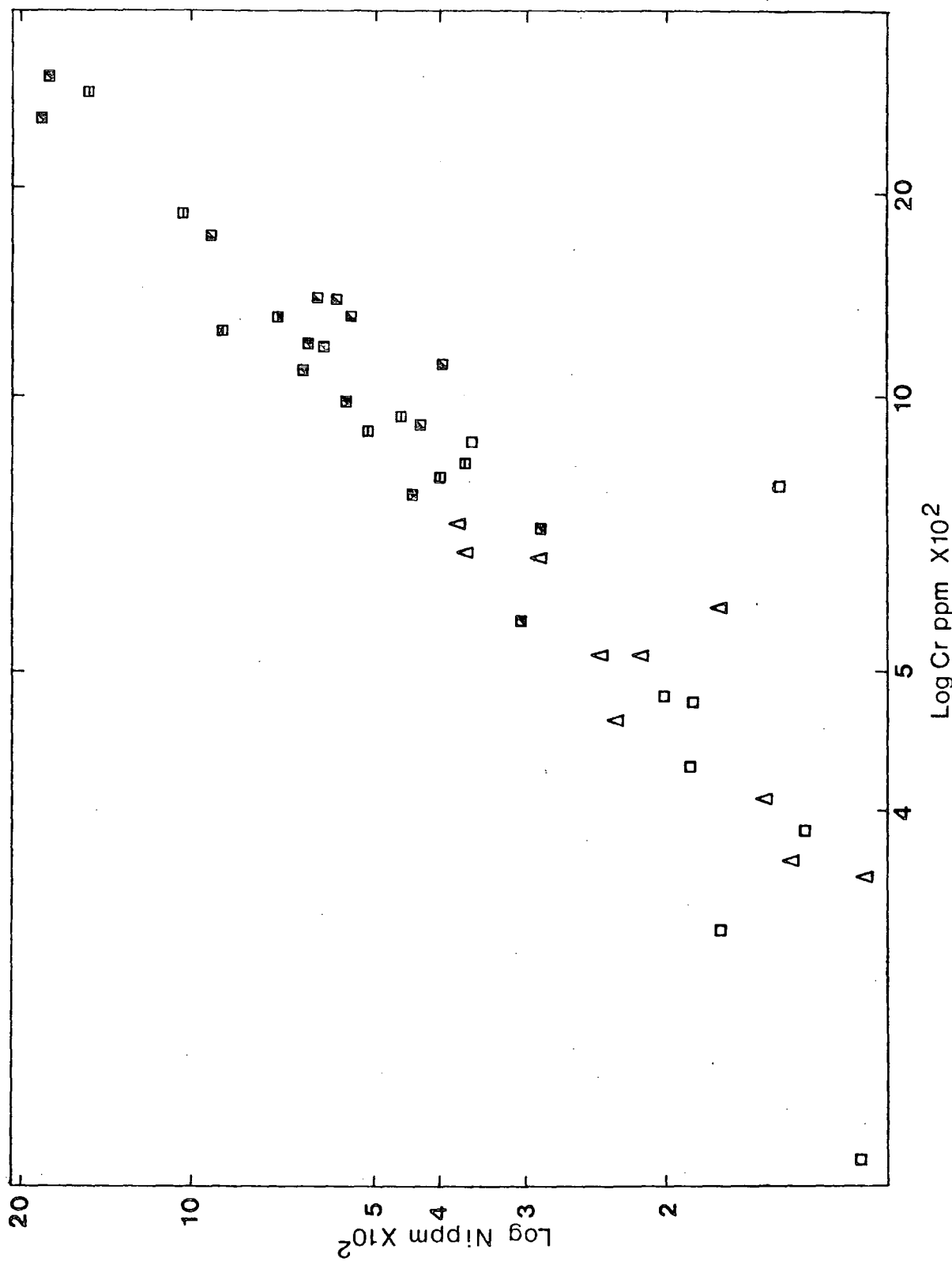


Fig. 7.5 MgO v. Al_2O_3 variation in the Rhum minor intrusion suite. Symbols as in Fig. 7.1 except H = high iron differentiate.

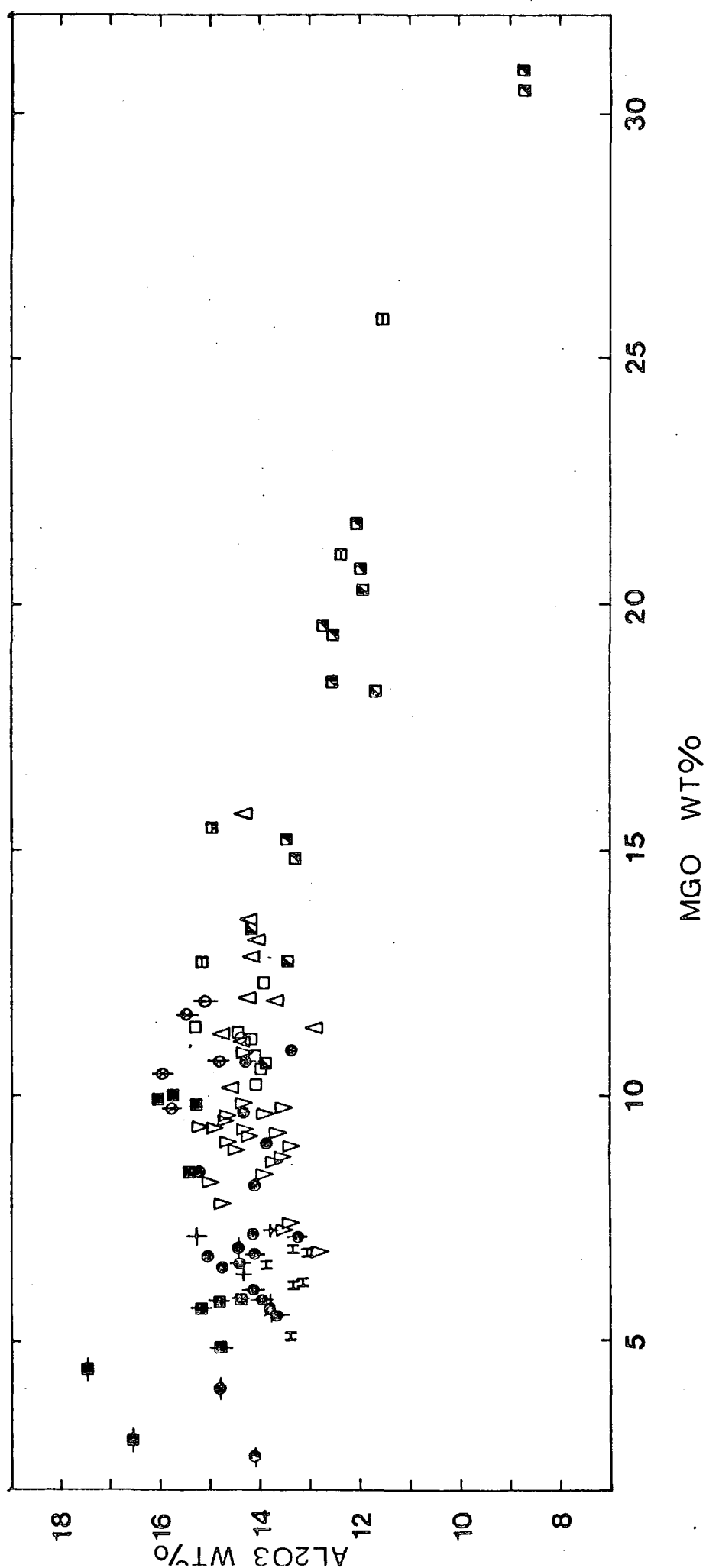


Fig. 7.6 MgO v. CaO variation in the Rhum minor intrusion suite. Symbols as in Fig. 7.1 except H = high iron differentiates.

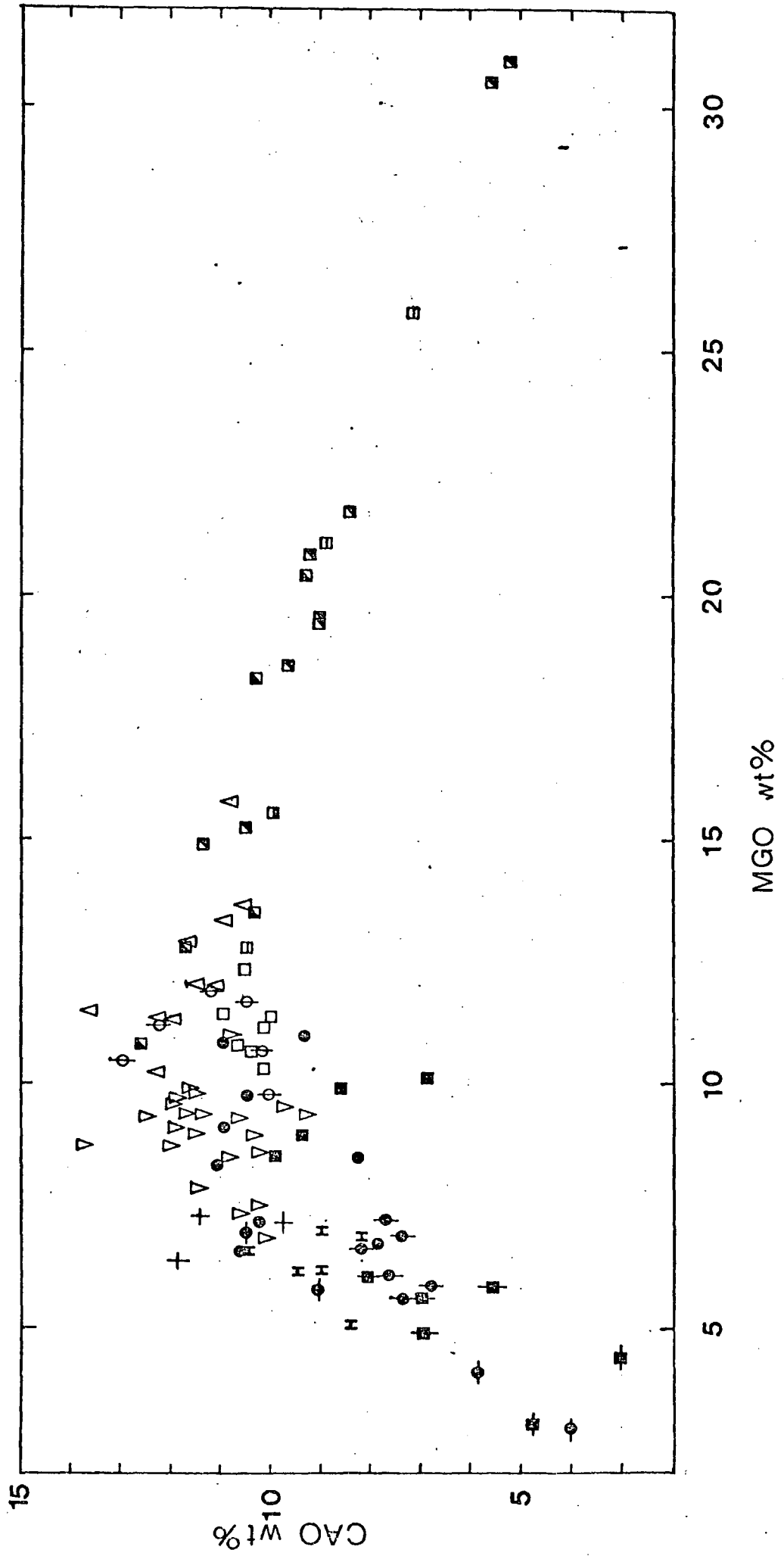


Fig. 7.7 CaO v. iron enrichment in the Rhum
minor intrusion suite. Symbols as
in Fig. 7.1 except H = high iron
differentiates.

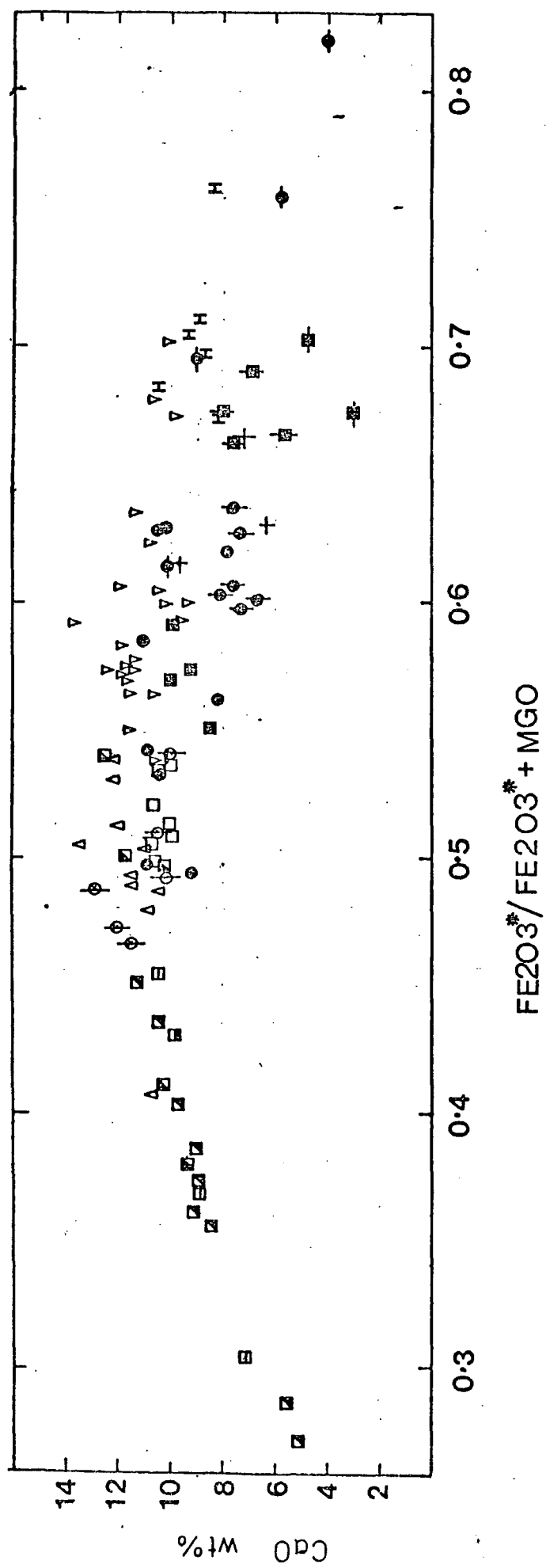


Fig. 7.8 Al_2O_3 v. iron enrichment in the Rhum
miñor intrusion suite. Symbols as in
Fig. 7.1 except:

◻ = Group 1 type 1

⊕ = Group 1 type 2

⊖ = Group 1 type 3

■ = Group 1 77024

H = High iron differentiates

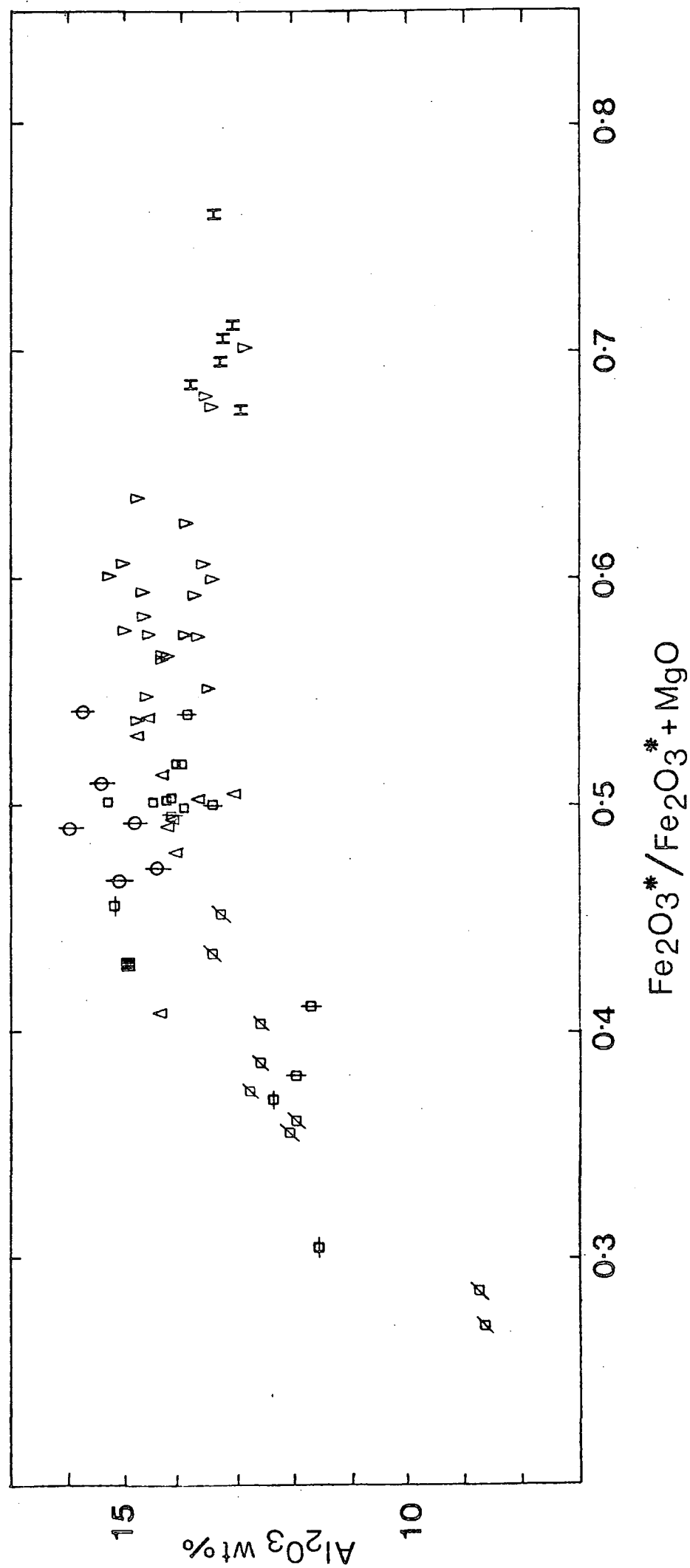


Fig. 7.9 CaO v. $\text{CaO}/\text{Al}_2\text{O}_3$ variation in group 1-4 dolerites and gabbros (excluding gabbroic differentiates). The inset marks the compositional field of the clinopyroxene phenocrysts found in these rocks relative to the trend developed by the gabbros and the dolerite groups 2-4 in the main diagram. See text for discussion. Symbols as in Fig. 7.1.

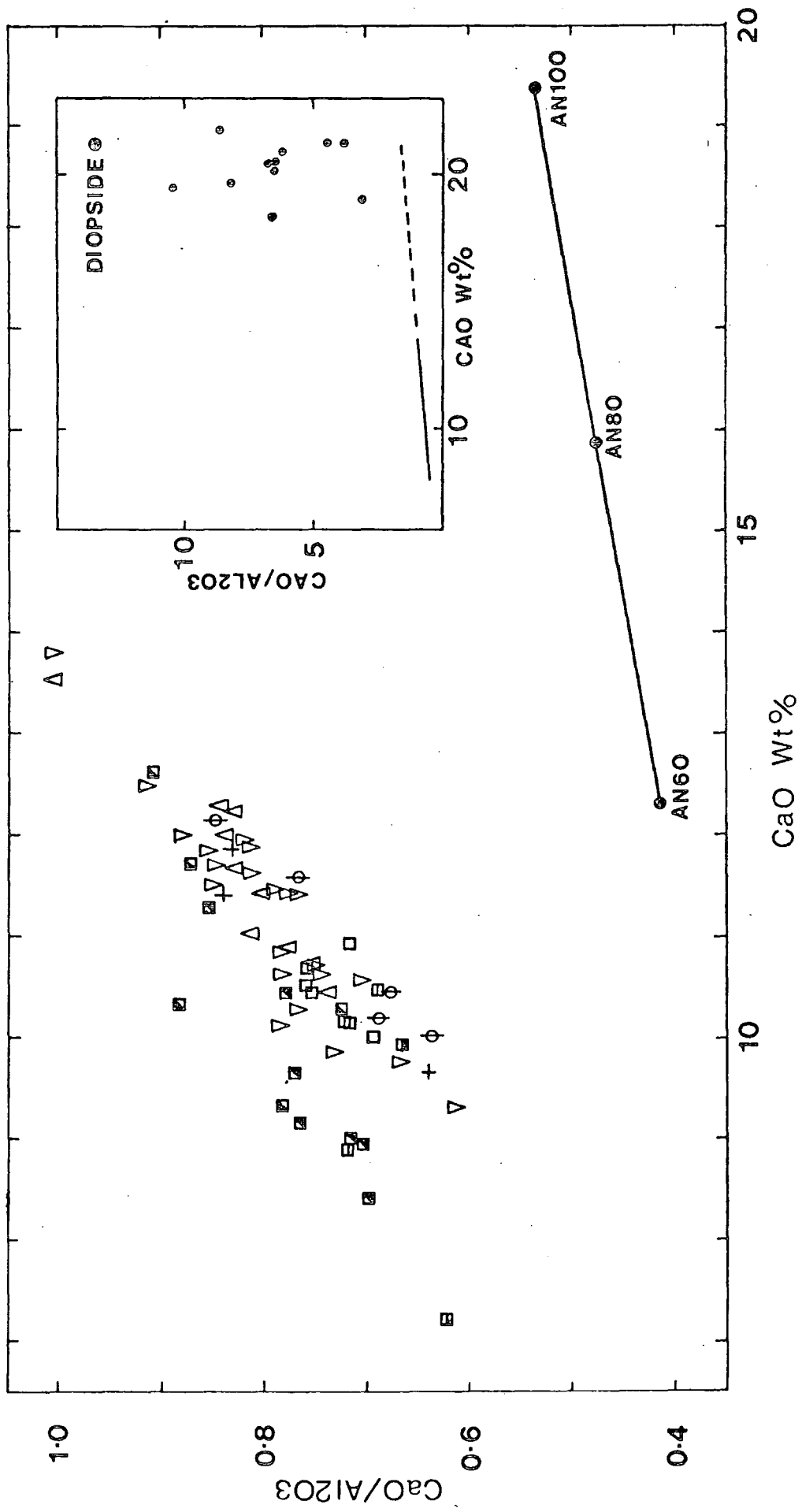


Fig. 7.10 CaO v. Al_2O_3 variation in the dolerite groups 2-4 and the high MgO gabbros. Points X1 and X2 are the calculated residual liquid compositions following 25% subtraction of a calcic pyroxene (CaO = 20%, Al_2O_3 = 2%) and an aluminous calcic pyroxene (CaO = 20%, Al_2O_3 = 10%) respectively from the high lime liquid X. Point X3 is the calculated residual liquid composition after subtraction of 20% plagioclase (An76) from the high lime liquid X. (See discussion on p.223). Symbols as in Fig. 7.1.

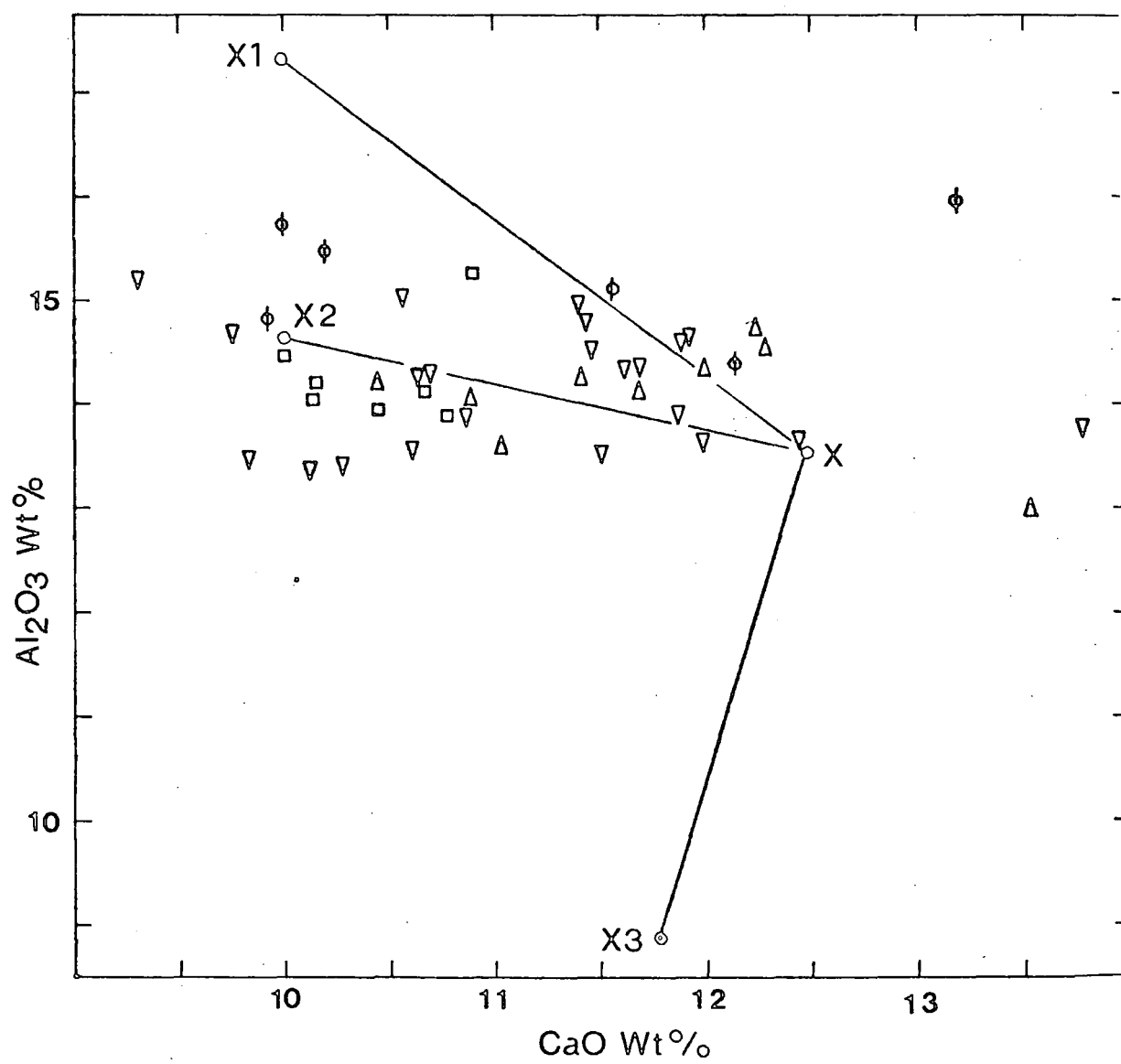


Fig. 7.11 Nb, Y, Sr and Ba v. Zr variation in the Rhum minor intrusion suite. Lines M1 and M2 refer to the trends developed in the Mull lavas (Beckinsale et al., 1978, Fig.5). Symbols as in Fig. 7.1 except:

☒ = all group 1.

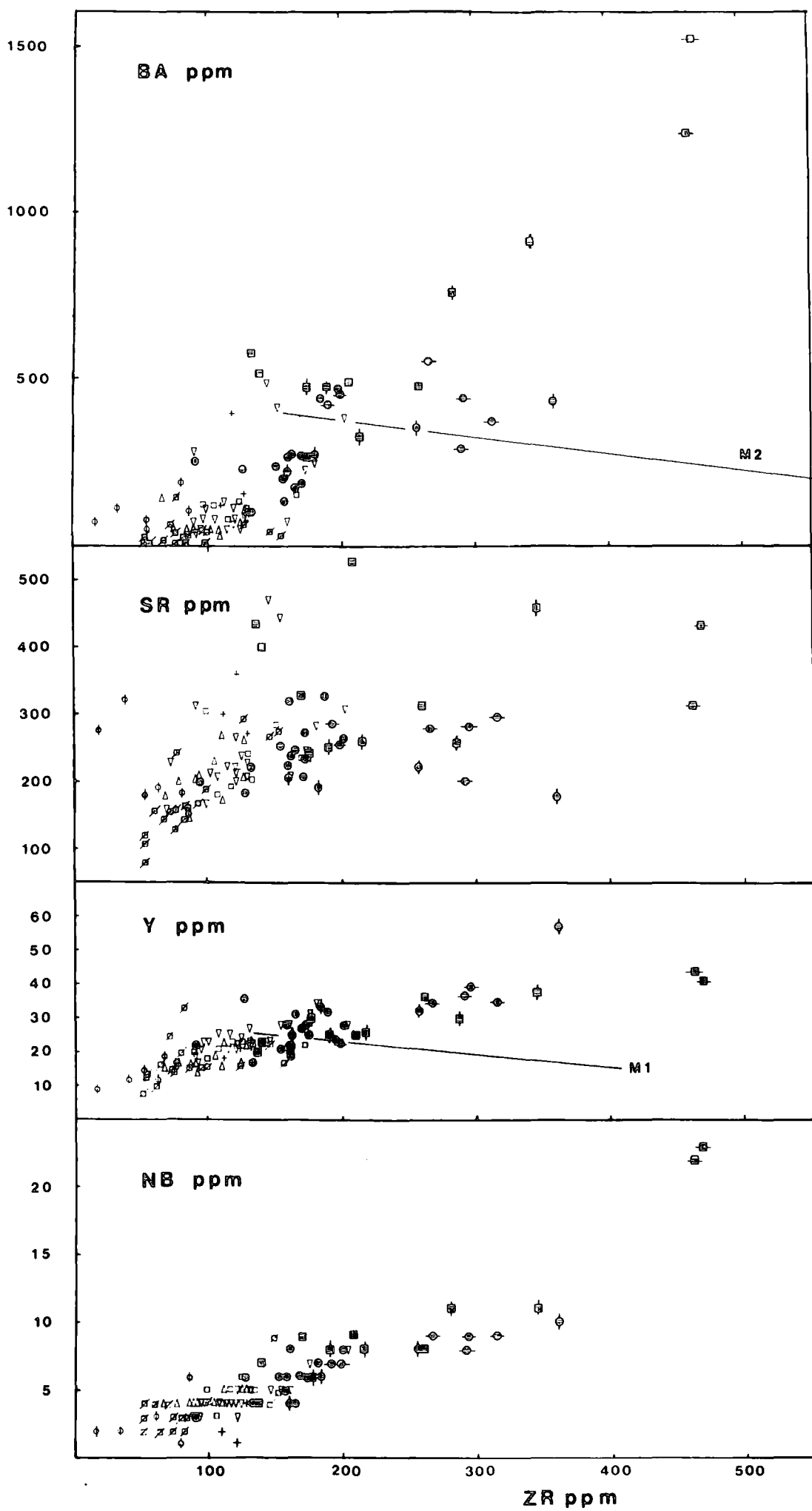
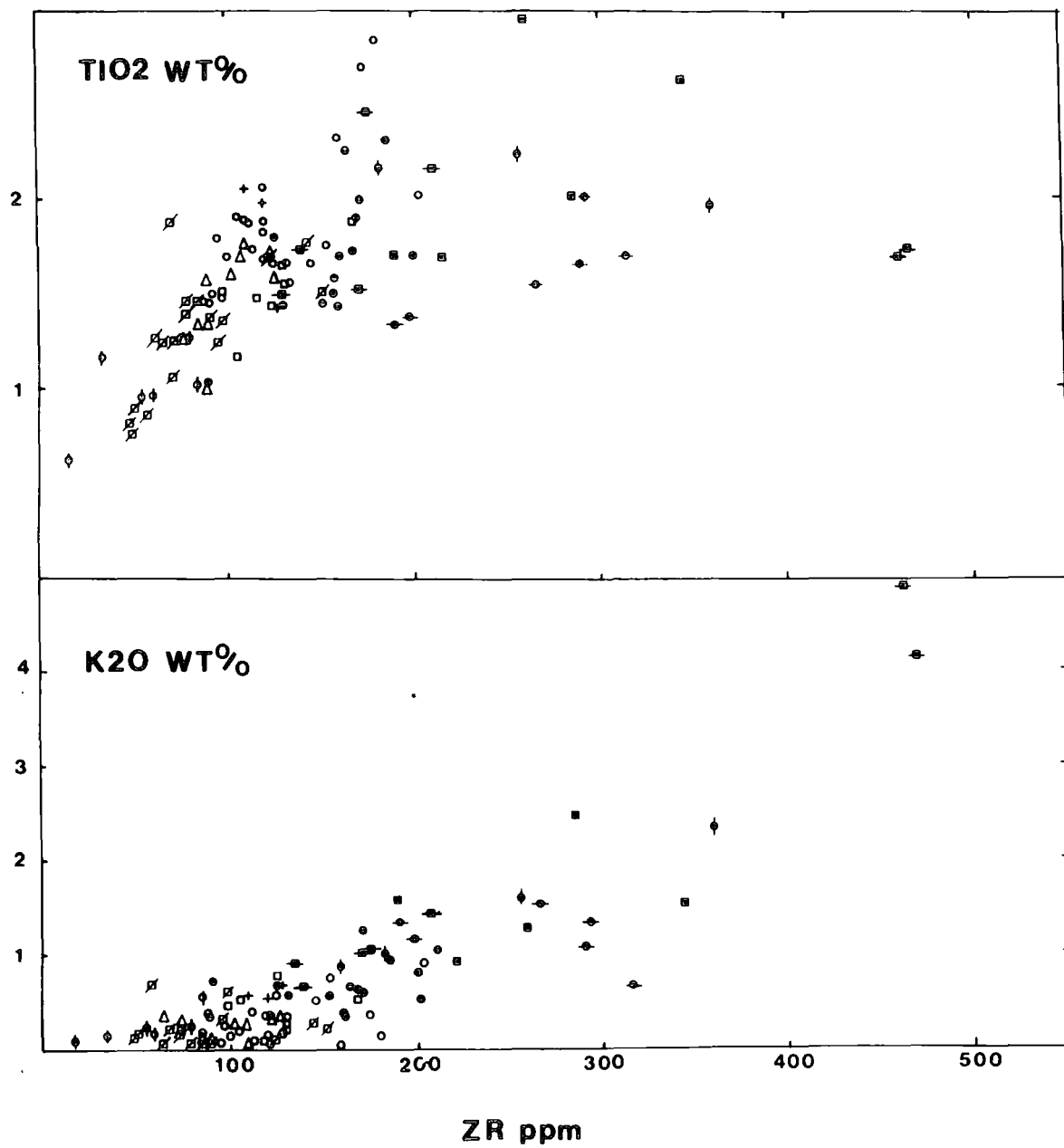


Fig. 7.12 $\text{TiO}_2 + \text{K}_2\text{O}$ v. Zr variation in the Rhum
minor intrusion suite. Symbols as in
Fig. 7.1 except:

Ø = all group 1.



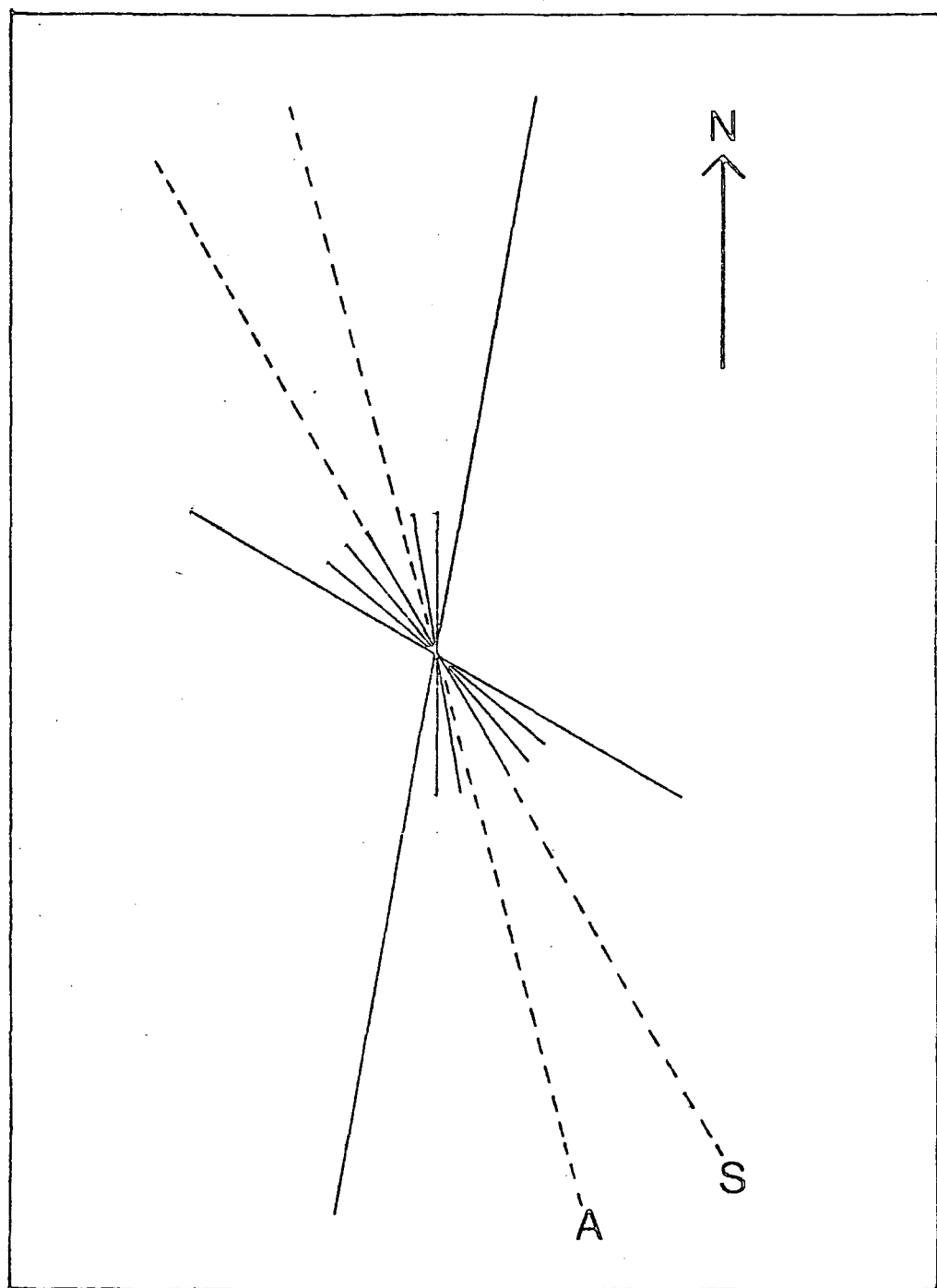


Fig 7-13 Strike orientation of dykes cutting the Rhum lavas. Lines A and S refer to the Skye swarm at Arisaig and Sleat (taken from Matthey et al 1977 fig1)

Fig. 7.14 Major oxide chemical variation in the peridotite plugs. D.I. is the Thornton-Tuttle (1960) Differentiation Index.

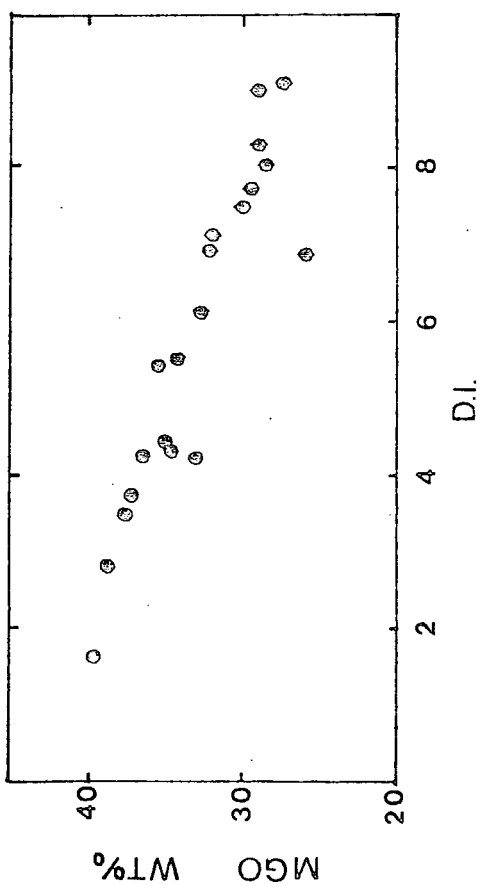
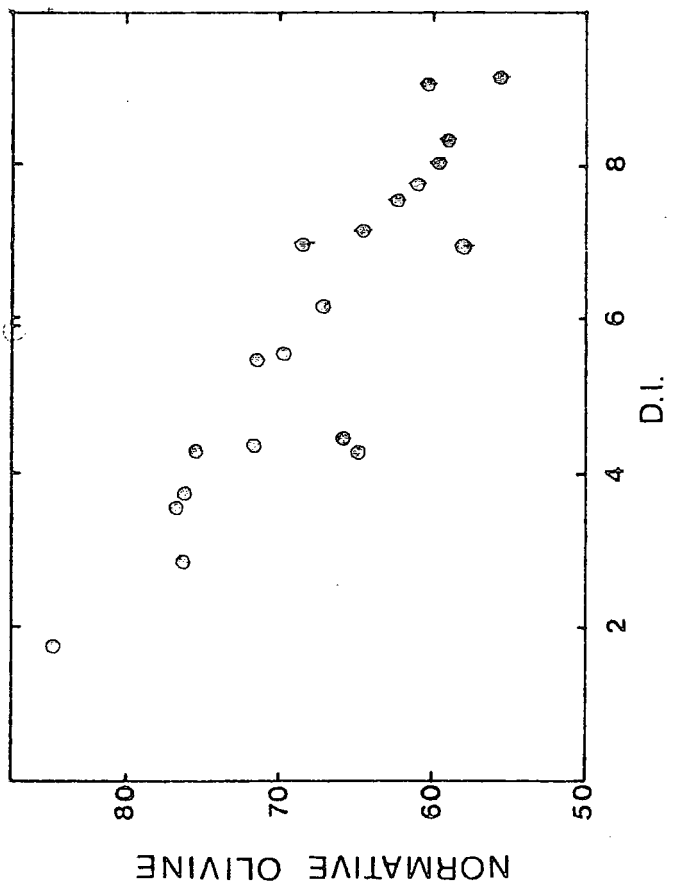
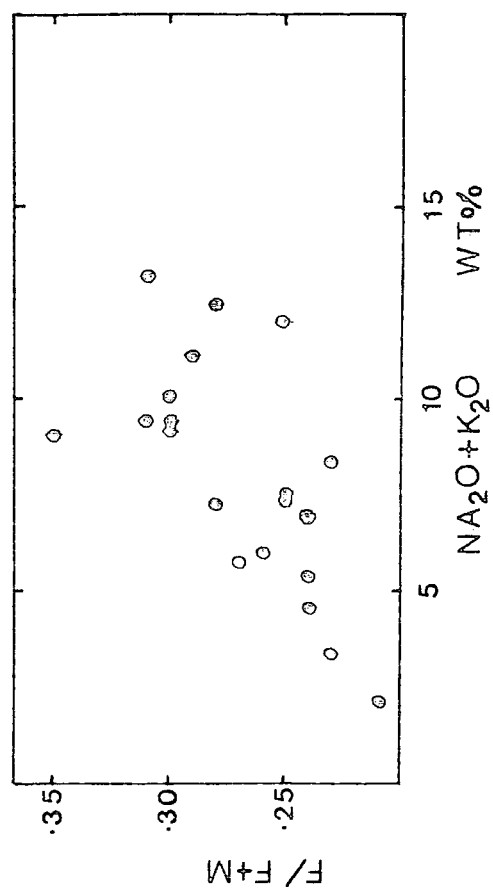
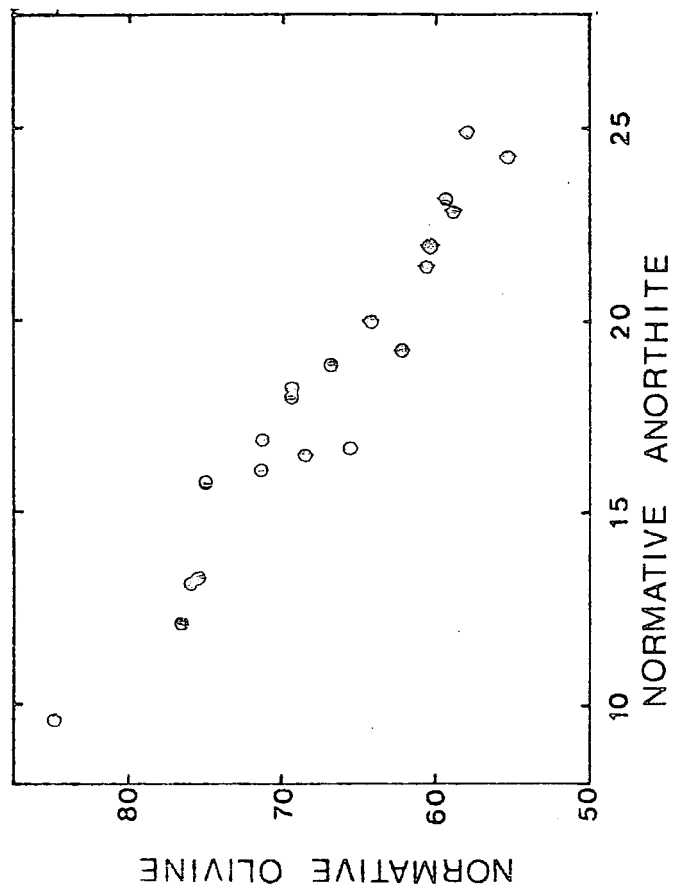


Fig. 7.15 Fe_2O_3^* v. TiO_2 variation in the intermediate
minor intrusions. Symbols as for Fig. 7.1.
High iron differentiates not included.

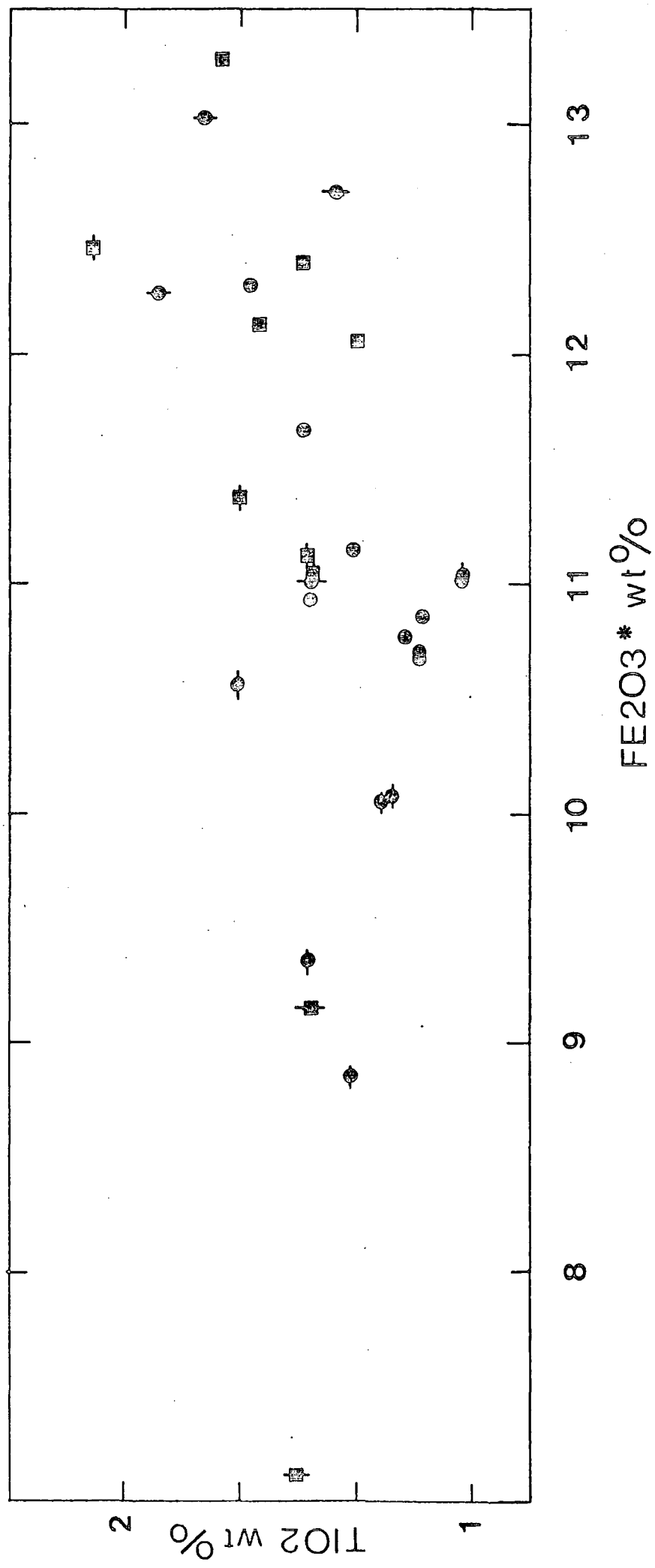


Fig. 7.16 CaO v. Al_2O_3 variation in the intermediate rocks. Direction of fractionation vectors for calcic-clinopyroxene (CC) aluminous-calcic-clinopyroxene (ACC) and plagioclase (An76) taken from Fig. 7.10. Symbols as in Fig. 7.1. High iron differentiates not included.

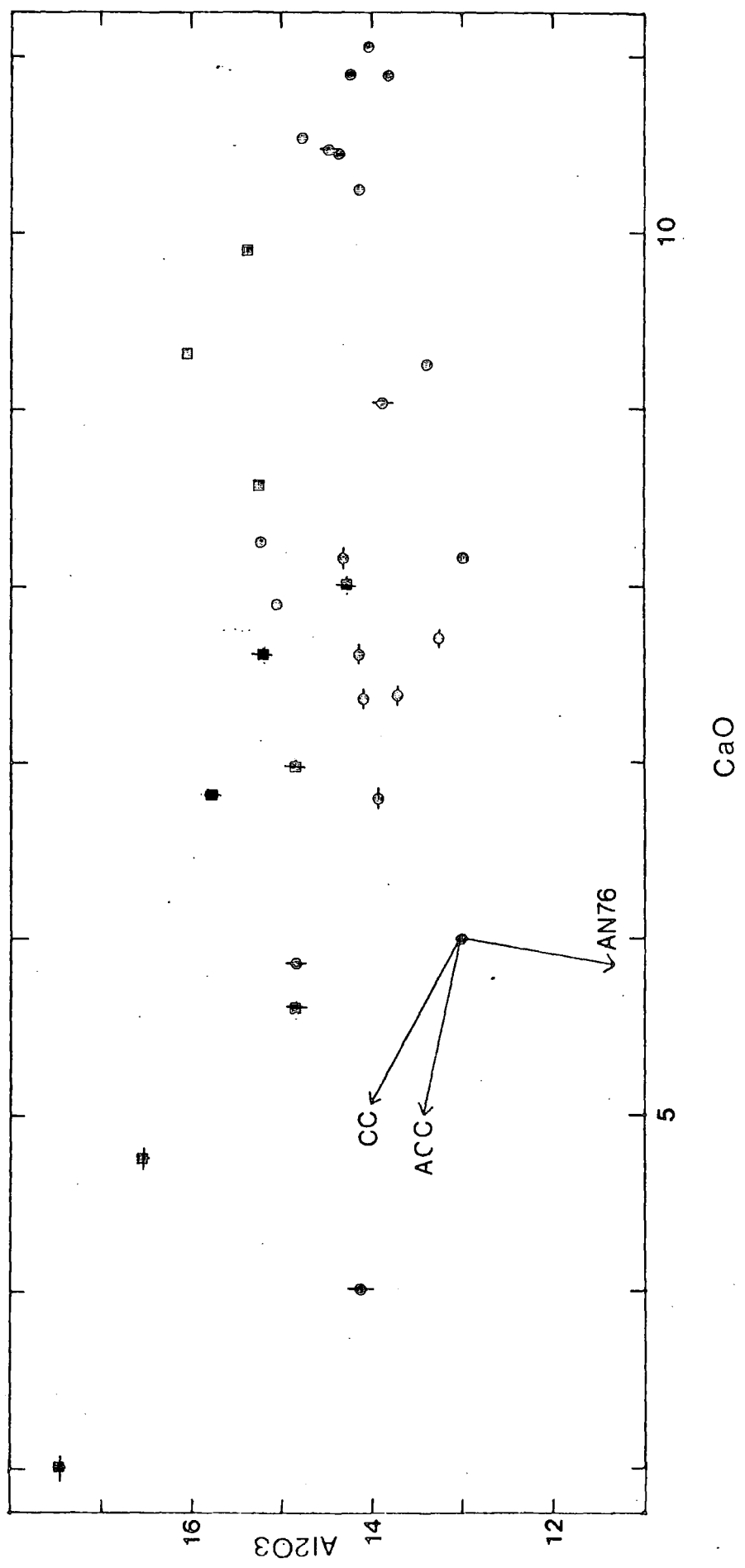
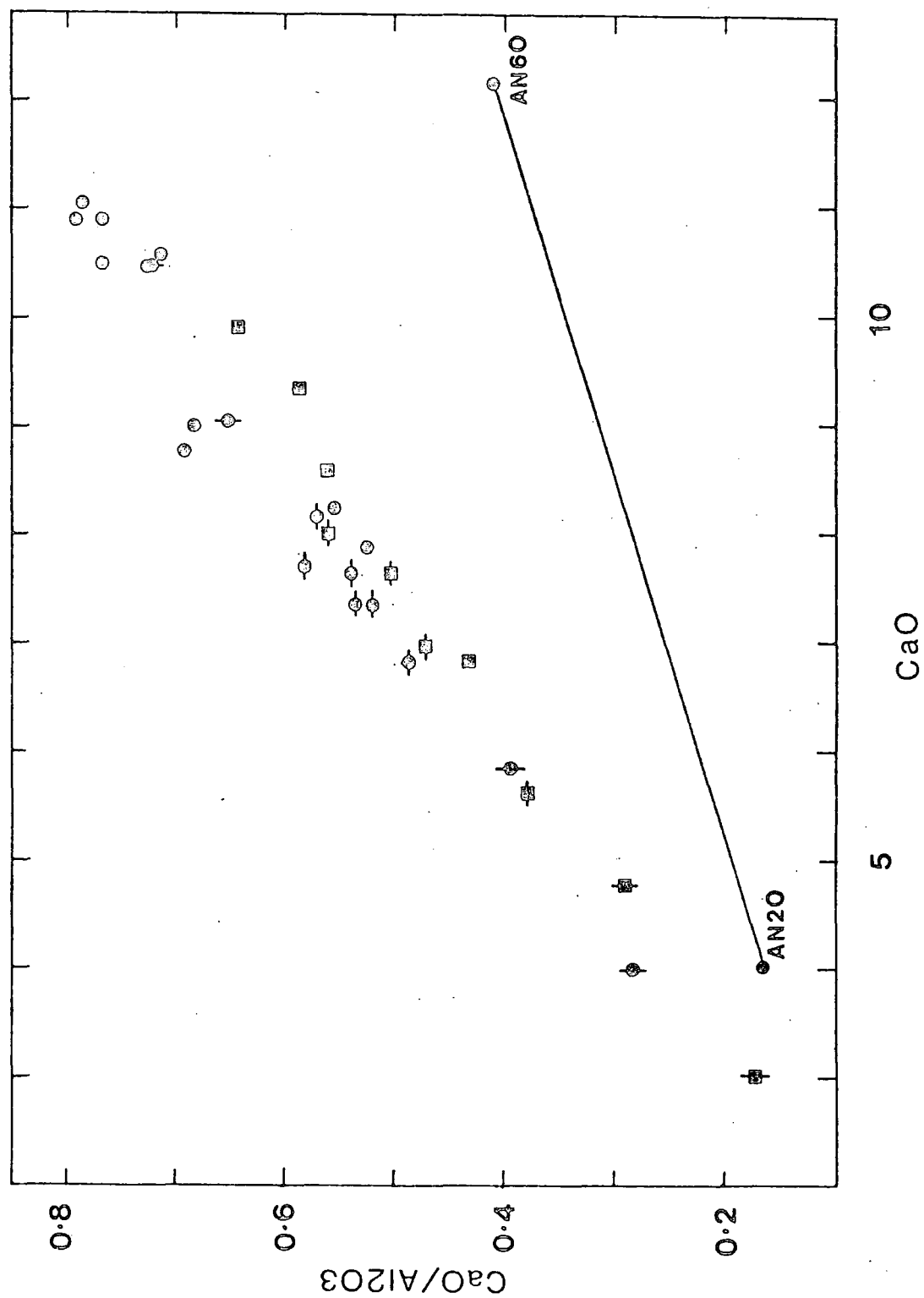


Fig. 7.17 CaO v. $\text{CaO}/\text{Al}_2\text{O}_3$ variation in the intermediate minor intrusions. Solid line refers to a range of plagioclase compositions (An_{20} - An_{60}). Symbols as in Fig. 7.1. High iron differentiates not included.



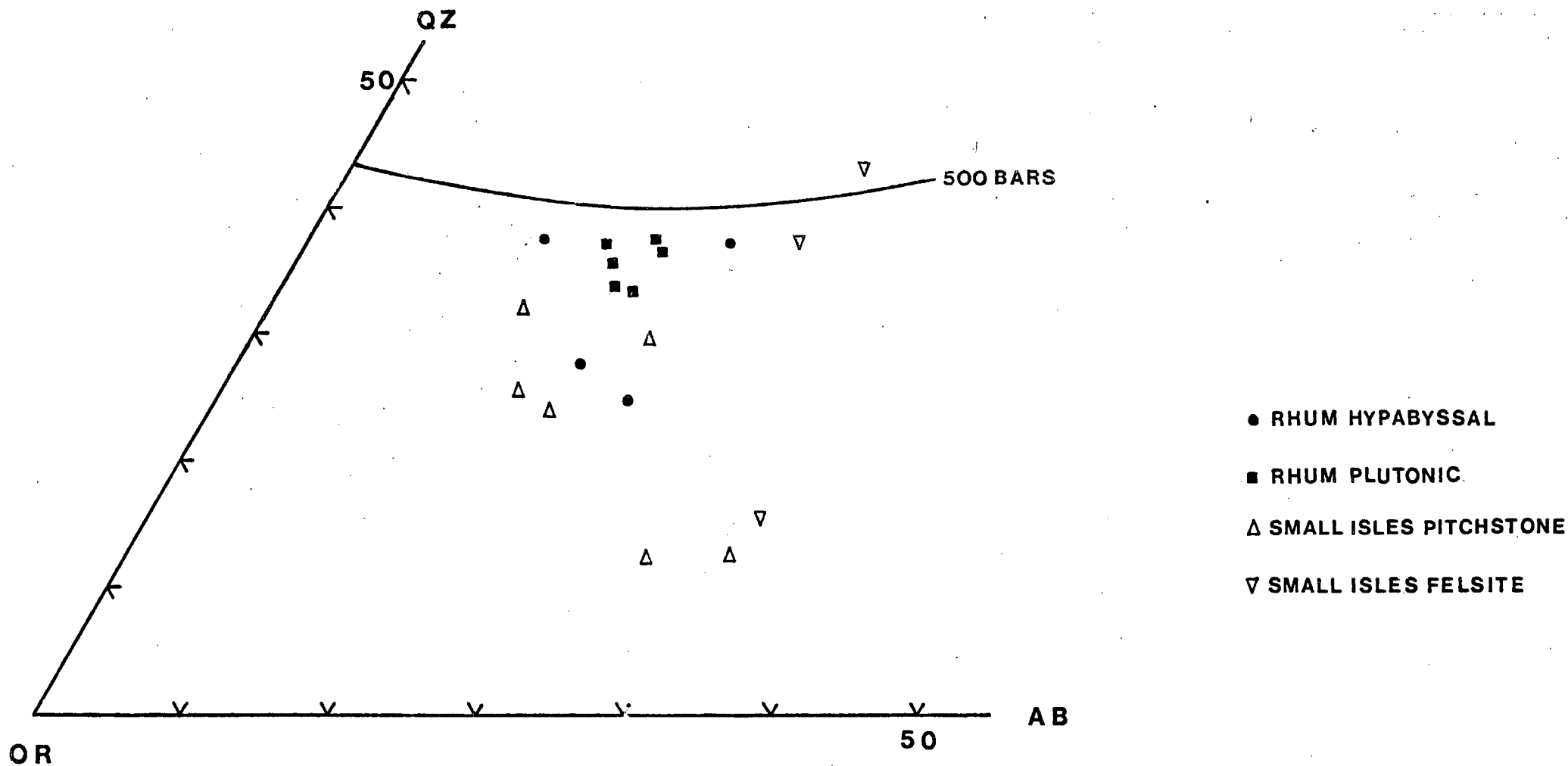


Fig.7.18. Rhum and Small Isle acid rocks projected into the normative system Qz-Or-Ab. The phase boundary feldspar + quartz + liquid at 500 bars is taken from Ridley (1971, Fig.3). Rhum hypabyssal (this study), Rhum plutonic (Dunham 1968, Table 3), Small Isles acid rocks (Ridley 1973, Table 6).

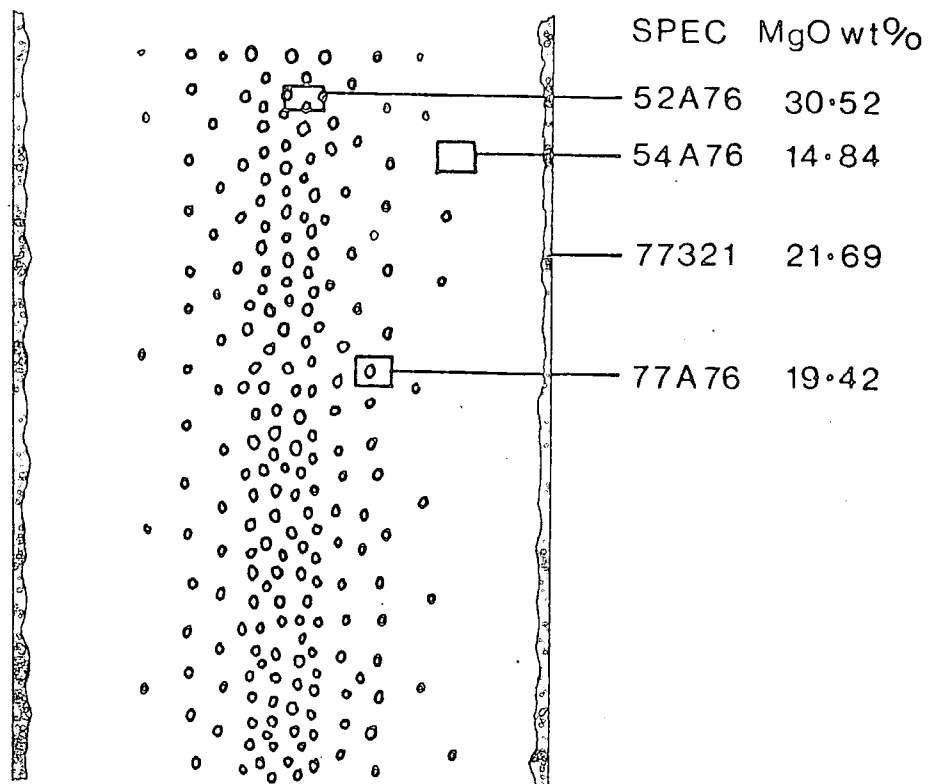
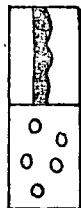


Fig. 7.19 Sketch illustrating the relationship of specimens with varying MgO contents in a flow differentiated picrite dyke.

Key



Chilled margin

Olivine phenocrysts

Fig. 7.20 Ti v. CaO/TiO_2 variation in the dolerite groups 1-4 and the early (high MgO) gabbros, 77104 not included. C refers to the calculated liquid composition of 77321. Symbols as in Fig. 7.1. The field of mid-ocean-ridge basalts (MORB) is taken from Sun et al. (1979, Fig.1).

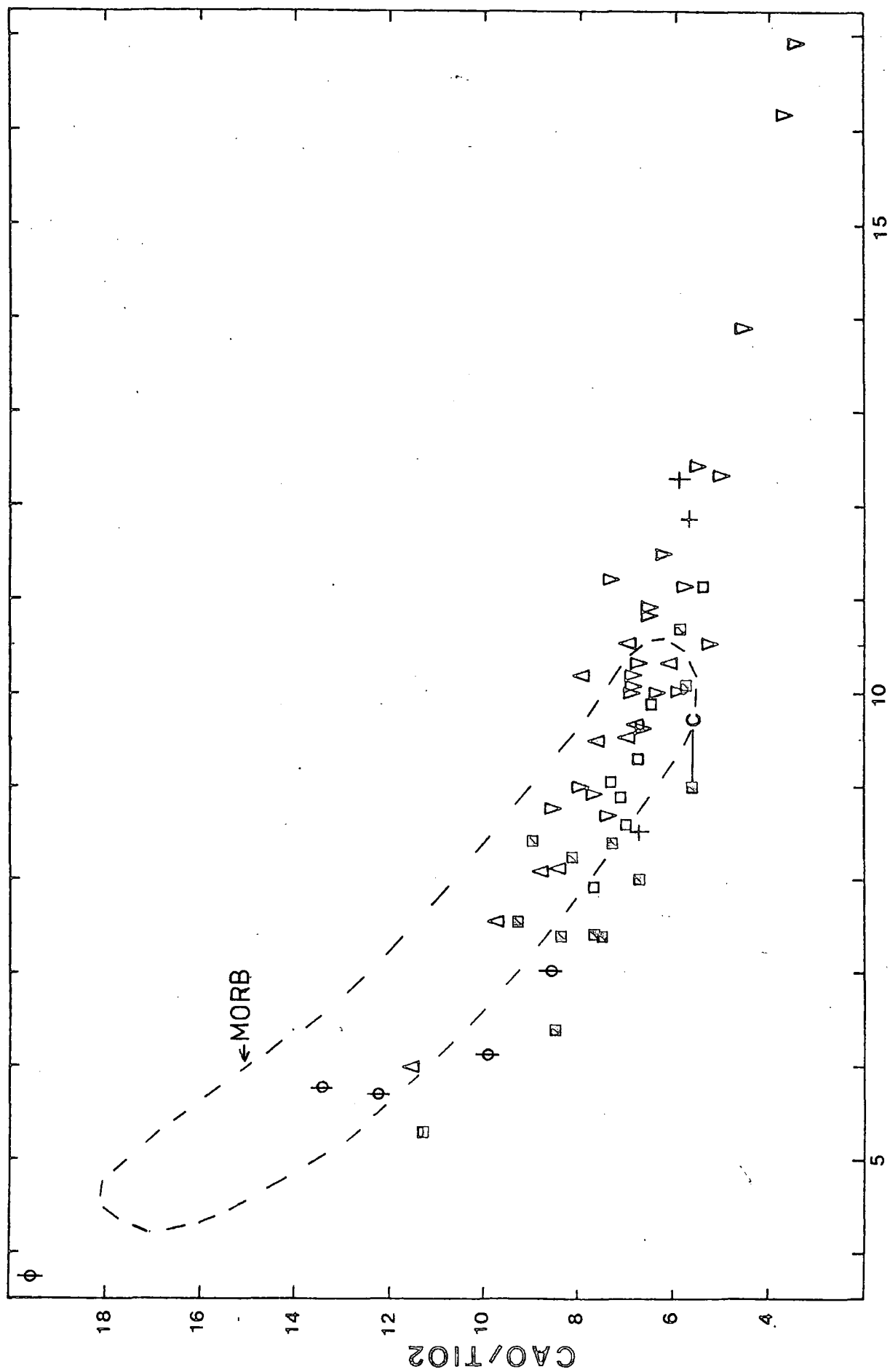
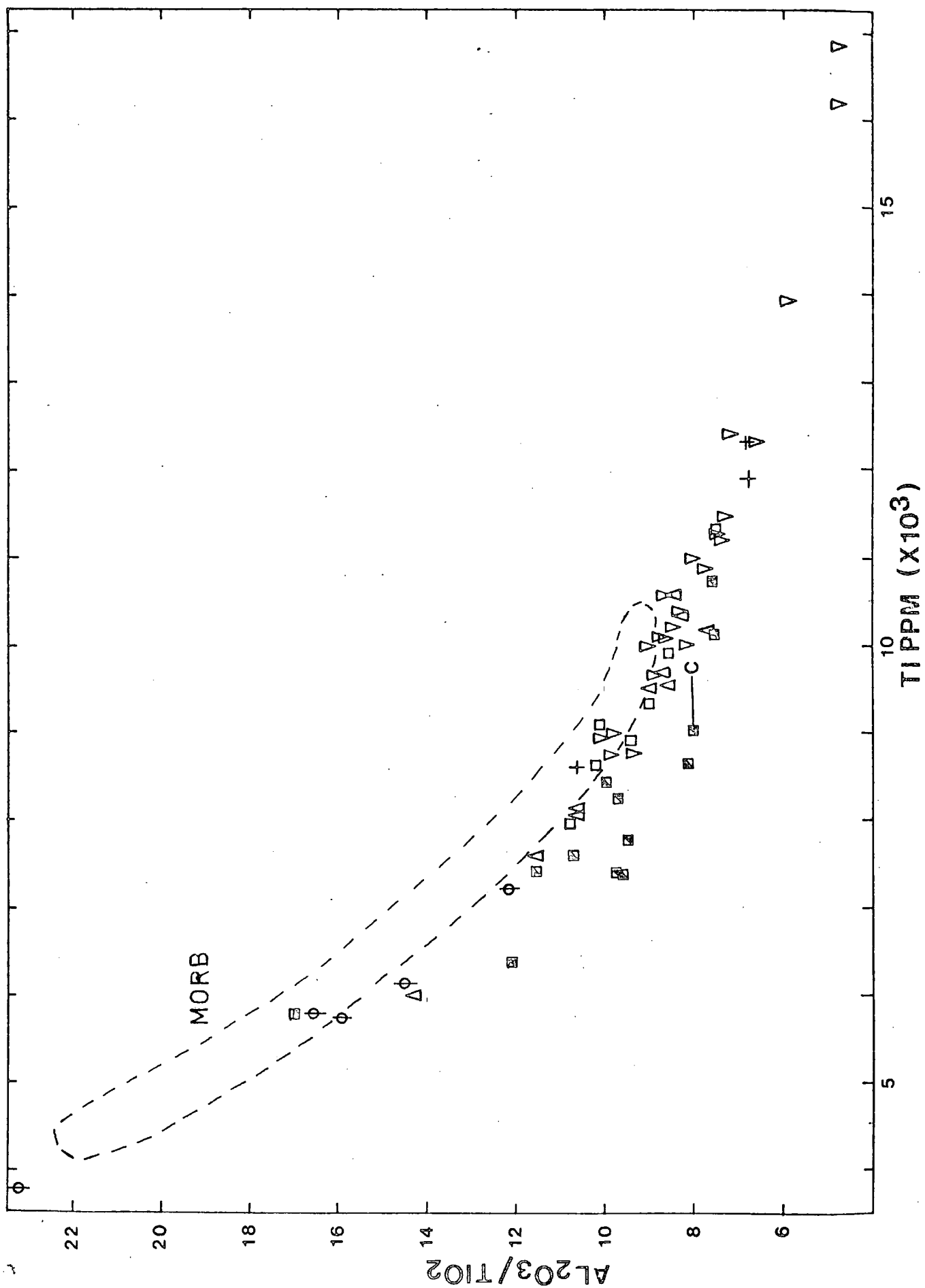
TI PPM (X10³)

Fig. 7.21 Ti v. $\text{Al}_2\text{O}_3/\text{TiO}_2$ variation in the dolerite groups 1-4 and the early (high MgO) gabbros, 77104 not included. C refers to the calculated liquid composition of 77321. Symbols as in Fig. 7.1. The field of mid-ocean-ridge basalts (MORB) is taken from Sun et al. (1979, Fig.1).



Specimen	Fe ₂ O ₃ *	Total alkalis	TiO ₂	MgO
54A76	12.19	1.65	1.38	14.84

Method	Fe ₂ O ₃	FeO	Fe ₂ O ₃ /FeO	Calculated liquidus olivine composition (Fo)
1	2.88	8.38	0.344	91.33
2	1.50	9.62	0.156	90.17
3	1.45	9.66	0.150	90.14
4	1.67	9.46	0.176	90.31

Table 7.1 Calculated Fe₂O₃ ratios and liquidus olivine compositions in 54A76 to show the affects of the various iron oxidation state procedures advocated by different authors.

Method 1 = Irvine and Baragar (1971)

Method 2 = Thompson et al. (1972)

Method 3 = Brooks (1976)

Method 4 = Clarke and O'Hara (1979)

*Total iron as Fe₂O₃

		Skye			Group 5 dolerites					High MgO Gabbros						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	16
Specimen Average		Max	Min	77056	77323	SR151	SR229	SR238	SR284	77031	77033	77257	77292	77320	77104	
wt %	SiO ₂	47.98	46.37	50.03	46.35	46.34	46.57	47.50	46.75	47.61	49.95	49.24	47.15	48.98	46.14	47.42
	Al ₂ O ₃	16.35	13.86	21.34	14.43	15.92	15.78	14.53	16.18	15.05	14.82	14.39	15.12	15.74	15.44	15.94
	Fe ₂ O ₃ *	11.66	7.42	15.22	12.73	12.01	12.41	13.28	12.26	12.44	10.37	10.02	10.52	11.47	12.14	9.97
	MgO	8.34	6.28	11.83	9.92	10.02	9.23	8.39	8.96	8.51	10.71	11.22	11.95	9.74	11.68	10.48
	CaO	12.10	10.87	13.57	13.56	12.49	12.58	12.85	12.58	12.68	10.18	12.14	11.57	9.99	10.45	12.95
	Na ₂ O	2.12	1.71	2.72	1.70	2.01	2.16	1.96	2.04	1.82	2.18	2.02	2.28	2.49	2.36	1.88
	K ₂ O	0.16	0.04	0.22	0.08	0.05	0.05	0.06	0.05	0.05	0.56	0.10	0.22	0.16	0.23	0.17
	TiO ₂	1.02	0.38	1.42	0.97	0.92	0.99	0.16	0.94	1.09	1.02	0.62	0.95	1.17	1.27	0.96
	MnO	0.18	0.10	0.23	0.20	0.18	0.19	0.19	0.19	0.19	0.15	0.16	0.16	0.17	0.16	0.14
	P ₂ O ₅	0.09	0.05	0.14	0.07	0.08	0.08	0.10	0.08	0.10	0.08	0.10	0.10	0.09	0.12	0.09
Total		100.00			100.01	100.02	100.04	100.02	100.03	100.04	100.02	100.01	100.02	100.00	99.99	100.00
ppm	Ni	-	- (121)	- (203)	163	176	149	90	147	108	157	95	215	41	174	209
	Cr	-	- (381)	- (457)	454	484	441	420	418	430	440	337	833	158	321	785
	Ba	-	- (6)	- (16)	29	24	272	45	170	68	101	72	72	117	97	51
	Nb	5	0 (1)	9 (2)	3	3	3	4	3	3	6	2	0	2	1	3
	Zr	49	20 (30)	83 (46)	43	42	45	56	47	47	86	16	56	33	79	61
	Y	25	8 (16)	37 (25)	21	21	25	24	23	23	17	9	15	10	19	12
	Sr	118	95 (106)	167 (143)	119	90	118	101	98	105	149	277	181	323	184	193
	Rb	1	0 (0)	8 -	2	1	2	2	2	1	14	2	6	3	7	3
	Zn	-	- (67)	- (77)	76	74	85	77	74	na.	56	64	60	76	86	46
	Ti/Zr		121	100	144	135	131	132	124	120	139	71	232	102	212	96
Y/Zr		0.51	0.40	0.66	0.49	0.50	0.56	0.43	0.49	0.49	0.20	0.56	0.27	0.30	0.24	0.20
Zr/Nb		9.8	6.8	13.8	14.3	14.0	15.0	14.0	15.7	15.7	14.3	8.0	-	16.5	26.3	20.3

Table 7.2 A comparison of the Skye Preshal Mhor magma type with the Rhum group 5 dolerites and the early gabbros.

Analysis 1 Average of 15 representative Preshal Mhor type dykes and lavas (Mattey *et al.*, 1977 Table IIA) water free

Analyses 2 - 3 Compositional range of Preshal Mhor magma type, (Mattey *et al.*, 1977, Esson *et al.*, 1975).

Trace element data in brackets (I.T. Williamson - unpublished data)

Analyses 4 - 9 Group 5 dolerites (this study)

Analyses 10 - 16 High Mgo gabbros (this study). All but 77104 are either known or inferred to be early in the Rhum sequence.

*Total iron as Fe₂O₃ na = not analysed

	1	2	3	4	5	6	7	8	9
Spec.	SR211	SK291	SK932	SK280	SR141	751210B	A	751218	SK956
SiO ₂	45.76	45.67	44.89	44.81	47.96	47.36	49.44	49.47	48.57
Al ₂ O ₃	16.98	16.28	16.04	15.48	14.69	15.00	14.19	14.35	15.70
Fe ₂ O ₃ *	14.32	13.85	14.76	13.98	14.25	13.12	14.17	13.23	12.98
MgO	7.95	8.43	9.97	10.02	7.53	9.72	5.81	6.48	7.00
CaO	9.70	10.33	9.29	9.91	10.63	11.04	10.50	10.94	10.29
Na ₂ O	3.08	2.83	2.81	2.71	2.72	2.02	3.01	2.92	3.02
K ₂ O	0.11	0.31	0.22	0.25	0.12	0.39	0.71	0.16	0.59
TiO ₂	1.74	1.73	2.05	1.80	1.76	1.44	1.81	2.10	1.41
MnO	0.18	0.22	0.21	0.22	0.16	0.17	0.21	0.19	0.22
wt % P ₂ O ₅	0.19	0.20	0.20	0.19	0.18	0.19	0.22	0.15	0.22
Total	99.01	99.88	100.44	99.37	100.00	100.45	100.07	99.99	100.00
Or	0.7	1.9	1.3	1.5	0.7	2.3	4.2	1.0	2.6
Ab	25.3	22.1	22.0	20.5	23.3	17.2	25.7	25.0	24.0
An	32.6	31.2	30.7	29.9	27.8	30.9	23.4	25.9	30.8
Ne	0.6	1.2	1.0	1.6	-				
Di	12.2	15.8	11.7	15.4	19.9	18.7	23.1	23.0	14.3
Hy	-	-	-	-	11.7	11.4	10.3	15.5	9.9
Ol	21.1	20.3	24.8	23.5	8.8	12.8	5.5	1.7	11.5
Mag	3.9	3.7	4.0	3.8	3.8	3.5	3.8	3.6	3.6
Ilm	3.3	3.3	3.9	3.5	3.4	2.8	3.5	4.0	2.8
Ap	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4
D.I.	26.5	25.1	24.4	23.5	24.0	19.5	30.0	25.9	26.7

Table 7.3 A comparison of selected Skye lavas^{with}/Rhum dolerite group 6.

Analyses 1, 5, 7 Group 6 (This study)

Analyses 2 - 4 and 9 Skye Main Lava Series (Thompson et al. 1972)

Analyses 6 and 8 Skye Main Lava Series (I. T. Williamson unpublished data)

*Total iron as Fe₂O₃, all norms calculated with an Fe₂O₃/Fe₂O₃ + FeO = 0.25

A = average analysis of SR159 SR182 and SR282

Thickness of overburden	Erosion at 680 cm/1000 y	Erosion at 850 cm/1000 y
1.5 km	0.220 my	0.176 my
2.0 km	0.294 my	0.235 my
2.5 km	0.367 my	0.294 my

Table 7.4 Calculated duration of layered ultrabasic rock -
lava eruption interval.

	SPEC 77258	Pl COMPOSITION*	CALCULATED LIQUID
SiO ₂	48.40	47.16	49.60
Al ₂ O ₃	18.89	33.04	6.04
Fe ₂ O ₃	8.38	0.65	15.51
MgO	6.52	0.19	12.28
CaO	14.21	16.97	11.61
Na ₂ O	1.67	2.58	1.77
K ₂ O	0.66	0.02	1.25
TiO ₂	1.04	0.02	1.98
MnO	0.13	-	0.25
wt % P ₂ O ₅	0.09	-	0.17
equivalent wt % pc	49.9**		

* Average of 7 analyses of group 7 phenocrysts

** Modal percent converted to equivalent wt %

Table 7.5 Calculated interstitial liquid composition in a big feldspar (group 7) dolerite.

		Average	Maximum	Minimum
	SiO ₂	40.90	42.14	39.30
	Al ₂ O ₃	7.84	10.81	4.08
	Fe ₂ O ₃ [*]	12.05	14.43	10.55
	MgO	33.13	41.91	26.60
	CaO	4.24	6.57	1.95
	Na ₂ O	0.72	1.15	0.18
	K ₂ O	0.10	0.17	0.03
	TiO ₂	0.48	0.77	0.24
	MnO	0.18	0.20	0.16
wt %	P ₂ O ₅	0.07	0.10	0.03
Total		99.71		
	Ni	1915	2535	1233
	Cr	2398	4456	2214
	Ba	30	91	0
	Nb	2	8	0
	Zr	30	53	13
	Y	6	11	1
	Sr	72	147	22
	Rb	3	5	0
ppm	Zn	74	110	47

Table 7.6 Average composition and the range of compositional variation in the peridotite plugs.

Table 7.7 Comparison of Rhum plutonic, Rhum hypabyssal and Eigg hypabyssal acid rocks.

Analyses 1 - 3 Average and range of Rhum plutonic
(Dunham 1968 Table 3)

Analyses 4 - 8 (this study)

Analysis 9 Cleadale felsite dyke (Ridley 1973 Table 3)

+ (includes 1.8% Acmite)

		1	2	3	4	5	6	8	9
		Average	Max	Min	77159	77239	77241	77180	E6
wt %	SiO ₂	70.74	72.54	69.39	69.52	71.68	69.36	76.13	75.76
	Al ₂ O ₃	12.69	13.82	12.00	13.49	13.03	13.78	12.69	9.44
	Fe ₂ O ₃ *	5.04	5.43	3.50	4.86	4.91	5.22	2.45	3.16
	MgO	0.79	1.14	0.32	1.18	0.36	0.84	0.07	0.36
	CaO	1.74	2.33	0.97	2.03	2.70	1.15	0.07	0.71
	Na ₂ O	4.12	4.28	3.92	4.73	4.41	4.72	3.83	3.21
	K ₂ O	3.21	3.68	2.68	3.18	2.15	3.99	4.56	5.19
	TiO ₂	0.66	0.81	0.42	0.74	0.59	0.71	0.22	0.15
	MnO ₂	0.15	0.36	0.06	0.09	0.10	0.08	0.04	0.05
	P ₂ O ₅	0.13	0.20	0.03	0.19	0.05	0.11	0.02	0.08
	Total	99.27			100.01	99.98	100.16	100.08	98.11
ppm	Ba	1176	1317	1033	896	847	-	161	-
	Nb	-	-	-	14	20	19	24	-
	Zr	324	411	266	349	704	664	524	-
	Y	-	-	-	36	74	59	40	-
	Sr	221	249	197	188	367	130	17	43
	Rb	93	99	59	88	181	115	166	116
	Zn	-	-	-	108	115	-	107	-
	Qz	29.78			22.8	30.2	21.0	35.1	38.9 ⁺
	Cor	0.38			-	-	-	1.4	-
	Or	19.12			18.9	12.8	23.7	27.0	31.4
	Ab	34.68			40.2	37.5	40.1	32.4	20.1
	An	5.97			6.2	9.4	4.7	0.2	2.7
	Di	1.38			2.2	3.1	0.3	2.8	4.7
	Hy	2.20			6.6	4.4	7.2	-	-
	Mt	4.03			1.3	1.3	1.4	0.7	0.3
	Il	1.30			1.4	1.1	1.4	0.4	0.2
	ap	0.3			0.5	0.1	0.3	-	-

TABLE 7.8

COMPARISON OF RHUM HIGH MgO LIQUIDS WITH OTHER HEBRIDEAN AND WORLDWIDE HIGH MgO COMPOSITIONS
 Analyses 1-6 (this study); Analyses 7-8 (Gibb 1976, Table 1); Analyses 9-10 (Clarke 1970, Table 1)
 Analyses 11-12 (Jakobsen et al. 1979)

	1	2	3	4	5	6	7	8	9	10	11	12
Spec	77321	77321L	77024	44A76	54A76	93A76					RE78	RE149
SiO ₂	42.66	42.38	44.51	45.69	45.09	46.62	45.64	46.54	45.6	44.4	46.21	46.21
Al ₂ O ₃	12.06	12.90	14.96	14.31	13.30	12.94	13.11	14.77	10.8	10.2	13.69	13.00
Fe ₂ O ₃ *	11.93	12.87	11.72	10.86	12.18	12.03	11.95	11.36	11.4	12.1	9.32	10.08
MgO	21.69	19.60	15.55	15.73	14.84	14.89	14.58	9.86	19.7	18.6	18.15	18.78
CaO	8.41	8.97	9.93	10.75	11.29	9.85	10.72	12.06	9.2	9.7	10.99	10.79
Na ₂ O	1.16	1.24	2.18	1.08	1.56	1.65	1.39	1.53	1.04	1.37	1.32	1.16
K ₂ O	0.20	0.22	0.05	0.35	0.09	0.30	0.13	0.14	0.08	0.13	0.01	0.05
TiO ₂	1.50	1.60	0.88	1.00	1.37	1.41	0.78	1.17	0.76	1.18	0.41	0.50
MnO	0.16	0.17	0.17	0.14	0.17	0.18	0.16	0.19	0.18	0.17	0.15	0.16
P ₂ O ₅	0.23	0.25	0.08	0.09	0.15	0.13	0.08	0.07	0.09	0.14	0.02	0.05
Total	100.00	100.00	100.03	100.00	100.04	100.00	98.54	97.69	98.85	97.99	100.27	100.78
Or	1.2	1.3	0.3	2.1	0.5	1.8	0.8	0.9	0.5	0.8	0.1	0.3
Ab	9.9	10.0	14.9	9.2	13.3	14.1	12.1	13.4	9.0	12.0	11.2	9.8
An	27.4	29.2	33.0	33.5	29.3	27.3	29.9	34.1	25.1	22.0	31.6	30.1
Di	10.5	11.2	12.3	15.8	21.1	17.0	19.4	22.0	16.7	21.3	18.4	18.4
Hy	1.0	¹	²	10.8	2.8	12.5	10.8	15.8	15.9	5.6	5.3	7.6
Ol	43.4	40.9	32.8	23.6	26.7	21.1	22.8	8.2	28.1	32.4	30.1	30.0
Mt	3.2	3.5	3.1	2.9	3.3	3.2	3.3	3.1	3.1	3.3	2.5	2.7
Il	2.9	3.1	1.6	1.9	2.6	2.7	1.5	2.3	1.5	2.3	0.8	1.0
Ap	0.5	0.6	0.2	0.2	0.4	0.3	0.2	0.2	0.2	0.3	0.0	0.1
D.I.	11.1	11.6	16.9	11.3	13.9	15.9	12.8	14.2	9.5	12.7	11.3	10.1
Modal %	9.1 [‡]	0.0	[‡]	A	1.45	A	~20	A	-	-	22.6	26.8
ol pc												

+¹ includes 0.3%Ne; +² includes 1.8%Ne; *Total iron as Fe₂O₃; ‡ Olivine phyrlic but see Chapter 6; ‡ modal% converted to equivalent wt% to calculate 77321L; All norms calculated water free with an Fe₂O₃/FeO+Fe₂O₃ ratio of 0.25. A = aphyric.

Type 1 Picrite				Type 2 Picrite			
Specimen	Modal % olivine phenocrysts	MgO wt%	Calculated liquids olivine composition (Fo)	Specimen	Modal % olivine phenocrysts	MgO wt %	Calculated liquids olivine composition (Fo)
53A76	6.4	20.73	93.13	77052	15.8	16.14	90.65
54A76	1.45	14.84	90.31	77093	n.d.	10.71	86.76
69A76	n.d.	18.47	91.88	77095	n.d.	12.74	88.44
71A76	n.d.	19.59	92.15	77101	21.9	20.36	92.55
77A76	n.d.	19.42	92.40	77107	n.d.	18.24	91.64
77077	10.2	15.19	90.86	77224	n.d.	13.46	88.60
77321	9.4	21.69	93.29				
77321L ⁺	0	19.60	91.09				
7734L	6.3	15.74	90.62				
Observed range of olivine phenocryst compositions Fo 84.9 - Fo 88.8				Observed range of olivine phenocryst compositions Fo 86.9 - Fo 88.8			

Table 7.9 Calculated liquidus olivine compositions in the type 1 and type 2 picrites; see text for discussion of modal data and interpretation.

⁺calculated olivine phenocryst free composition. n.d. = not determined.

CHAPTER EIGHT

THE PROBLEM OF THE RHUM LAYERED SERIES PARENT MAGMA AND THE RELATIONSHIP TO OTHER HEBRIDEAN SUITES

Introduction

This chapter is split into two sections. Part one deals with the enigmatic question of the composition of the magma parental to the Rhum layered peridotites. The various hypotheses pertaining to this composition are discussed in detail and an alternative hypothesis is presented. The second section compares the Rhum dolerite and Rhum lava suites and the relationship of the former to some other Hebridean basaltic suites is mentioned in brief.

I. THE PROBLEM OF THE RHUM LAYERED SERIES PARENT MAGMA

Introduction

The layered ultrabasic rocks of Rhum consist of a subhorizontal alternation of olivine-rich (feldspathic peridotite) and plagioclase-rich (allivalite) layers that were originally thought to represent a succession of sill-like injections of peridotite and allivalite magma (Harker 1908), but are now interpreted as a cumulate sequence dominated by a large scale alternation of olivine-chrome spinel cumulates and olivine plagioclase⁺ - clinopyroxene cumulates, (Wager and Brown 1968). Each

peridotite layer and the overlying allivalite layer are thought to be the complementary products of a single major episode of crystal accumulation and are referred to as units. Fifteen units have been recognised in the 750m sequence forming the twin peaks of Askival and Hallival in eastern Rhum (Brown 1956). These units vary between 15m and 150m in thickness and the peridotite member is generally considerably thicker than the allivalite. By contrast in Southwest Rhum, only three complete units (B,C,D) varying between 300m and 500m in thickness have been recognised in the 1400m succession of Southwest Rhum (Wadsworth 1961). These are underlain by harrisites and cumulates believed to represent the top of another unit (A). The intervening ground between the two documented areas is presently undergoing detailed research (J. McClurg pers. comm.).

The ultrabasic rocks are thought to represent the uplifted central portion of the high density mass known to underlie Rhum (McQuillin & Tuson, 1963). The absence of a definite chilled margin has led to various hypotheses concerning the composition of the magma responsible for the ultrabasic rocks. As stated earlier Brown (1956), Wadsworth (1961) and Wager and Brown (1968) convincingly demonstrated that the majority of these peridotites were the product of crystal settling and related processes.

Any hypothesis concerning the parent magma composition must take into account the abundant constraints which these and subsequent studies (Donaldson et al. 1973, Donaldson 1975, Henderson and Gejbels 1977, Dunham and Wadsworth, 1978) place on the parent magma composition.

There are four current hypotheses concerning this parent magma and the proposed compositions pertaining to three of these hypotheses are presented in Table 8.1. Having established that the concept of cumulus phases and intercumulus liquids were relevant to the Rhum pluton, Brown (1956) noted the extensive zoning of the interstitial minerals in a specimen from unit 3 and suggested that the interstitial liquid in this ortho-cumulate rock approximated the primary unmodified parent composition. He estimated the composition of this liquid by subtracting the proportion of the chemistry equivalent to the cumulus phases (50%) from the whole rock analysis (Analysis 1, Table 8.1).

An alternative hydrous felspathic peridotite parent magma was proposed by Donaldson et al. (1973) and later discussed in more detail by Donaldson (1975). These authors showed that magmas of this composition were available in the peridotite breccias of western Rhum and were responsible for the production of the poikilo-macro-spherulitic feldspars up to 1m diameter which are best developed in the Dornabac breccia. These feldspars

(composition An80) were considered to reflect rapid growth under conditions of low nucleation density. No zoning was detected between the nucleus and ray extremity and the absence of an overlying liquid precluded an interpretation of these unzoned feldspars as adcumulus growth phenomena. In his later paper Donaldson (1975) emphasised that the unzoned, calcic compositions of the more normal textured plagioclase in other breccias on Rhum could not be explained by the adcumulus growth hypothesis as the matrix liquids were intruded into semi-consolidated peridotite and were consequently not in contact with overlying liquid. In addition he noticed that the calcic anorthosite-gabbro veins which extend from the breccias into the adjacent peridotites were the filter pressed residual liquids from the breccia matrices. These veins contain at least 10% more normative anorthite than basalt and must have been derived from a relatively mafic parent. The Eastern Layered Series peridotites contain a very small proportion of late stage primary hydrous phases and this argues against a hydrous parent. Donaldson (1977) has since restated his opinions and now considers a calcic parent akin to the Preshal Mhor magma type and the eucritic dykes of Skye to be a suitable parent. A hydrous feldspathic peridotite magma is considered to be an unlikely parent composition and is not discussed further.

A detailed hypothesis advocating a eucrite parent (Analyses 2 and 3, Table 8.1) which was intruded with olivine and chrome-spinel phenocrysts at a temperature slightly above the plagioclase liquidus was outlined by Gibb (1976). The main justification for this proposal was the abundance of this type of magma in and around the Skye central complex and the suggestion of Gibb (1976) that the Rhum and Skye centres may have been comagmatic.

Finally, there is a growing body of opinion that a refractory magma akin to the Preshal Mhor magma type of Skye (Mattey et al., 1977) may have parental to both the Rhum layered peridotites (Donaldson 1977, Dunham and Wadsworth 1978) and other Hebridean layered intrusions (Skelhorn et al. 1979, Gamble 1979). There is some confusion in terminology regarding this proposed parent. Dunham and Wadsworth (1978) explicitly state that the low-alkali, high-calcium tholeiite of Esson et al. (1975) (which equals the Preshal Mhor magma type of Mattey et al. 1977) is a likely parent. Similarly Skelhorn et al. (1979) draw attention to the compositional similarity of the chilled margin of the Ben Buie intrusion with the Preshal Mhor magma type. In his account of the anorthosite dykes of northwest Skye, Donaldson (1977) noted the striking similarity of the interstitial liquid in these dykes with Preshal Mhor magma type. However,

in his discussion of the parent magma compositions of the layered basic and ultrabasic rocks of Skye and Rhum he considers "high-lime liquids" (in the sense of Drever and Johnson 1966) to be suitable parents. Despite these difficulties in terminology it is clear that these authors (perhaps with the exception of Donaldson 1977) consider the Preshal Mhor magma type sensu stricto to be the Rhum parent magma. Finally it should be noted that both Dunham and Wadsworth (1978) and Gamble (1979) considered the eucrite parent of Gibb (1976) to be a "high calcium low alkali tholeiite" (Dunham and Wadsworth op.cit. p.355, Gamble op.cit. p. 5); however, it will be shown later that this is clearly not so.

Constraints on the parent magma composition

The most obvious constraint on any parent magma composition is that it must be capable of crystallising phases compositionally identical to those found in the layered peridotites. Whilst this is obviously difficult to show unequivocally, it is a clear feature of the reasoning behind both Brown's (1965) and Gibb's (1976) hypothesis in that these magmas would crystallise the high temperature minerals Cr-spinel, forsteritic olivine, calcic plagioclase and diopsidic pyroxene. Minerals of this composition do occur in the picritic dykes of Skye

(Gibb 1968). The mineralogy of the Preshal Mhor magma type was investigated by Esson et al. (1975) who show that the compositions of the olivine and plagioclase phenocrysts are similar to those in the Rhum layered series and the groundmass pyroxenes are also sufficiently calcic. However, no spinel phenocrysts were observed and the composition of the groundmass spinels is titanomagnetite not Cr-spinel. This discussion is not intended to quibble over minor detail as both Brown (pers. comm. 1976) and Gibb (pers. comm. 1977) presented the analyses quoted in their accounts to illustrate the broad type of magma they were discussing, not the precise parent composition. However, the discrepancy in spinel composition noted above is judged to be significant.

The broad sequence within each unit of olivine Cr-spinel cumulates successively overlaid by olivine-plagioclase and plagioclase-clinopyroxene cumulates infers the following order of low pressure crystallisation:

Olivine - plagioclase - clinopyroxene

In addition, the presence of several discrete Cr-spinel layers at the base of several units (Brown 1956) indicates Cr-spinel preceeded olivine. The sequence of crystallisation $Ol \rightarrow Pl \rightarrow Cpx$ in compositions 1 to 3 (Table 8.1) has been confirmed experimentally at atmospheric pressure by Forster (1978) who also showed spinel preceeded olivine in

compositions 1 and 3. It must be noted however that the melted compositions were Cr free and the crystallisation behaviour of spinel in these charges is consequently not strictly comparable with Cr-bearing compositions. The melting relationships of two Preshal Mhor type basalts was investigated at atmospheric pressure by Esson et al. (1975) who showed that plagioclase was the liquidus phase, closely followed by olivine then clinopyroxene then magnetite. The Rhum magma chamber was emplaced at very high crustal levels (the overburden was estimated to be 1.5 to 2.5 km thick in Chapter 7, p.233). This slight increase in pressure is unlikely to reverse the order of crystallisation determined at atmospheric pressure by Esson et al. (op.cit.). Thus the presence of plagioclase as the first liquidus phase in the Preshal Mhor magma type means this basalt does not satisfy a fundamental requirement of a Rhum layered series parent magma. Note however that Dunham and Wadsworth (1978) consider the crystallisation of each unit begins within the allivalite of the underlying lithological unit (ie. below the allivalite-peridotite phase change which marks the junction between the lithological units) which perhaps surmounts this difficulty.

One of the main points to come out of Brown's (1956) and Wadsworth's (1961) studies was the distinct lack of optically detectable cryptic variation within the Rhum

ultrabasic sequence. Subsequent mineralogical investigations by electron microprobe analysis has shown there is slight but significant cryptic variation within each of peridotite units (Dunham and Wadsworth 1978) with the phases in each unit attaining a temperature minimum some way below the lithological top of each unit. Brown (1956) considered each unit to be a product of the accumulation of unzoned high temperature minerals from a basaltic parent, the absence of complementary differentiates necessitating an open system fractionation environment. To explain the lack of cryptic variation Brown (1956) cited the synthetic system Di-An-Fo (Osborn and Tait 1952, in Brown op.cit.) which indicated there would be a small drop in temperature from the liquidus to the three phase cotectic. However, more extensive experimental investigation in the system Di-Fo-An-Ab (Yoder and Tilley 1962) showed that there would be a considerable drop in temperature to the three phase cotectic. This work prompted Wager and Brown (1968) to invoke the process of delayed crystal nucleation in a supersaturated magma to explain the lack of cryptic variation. This hypothesis was questioned by Gibb (1976) who considered in the light of his previous work on this topic (Gibb, 1974), that supersaturation of plagioclase was unlikely to occur in a slow cooling plutonic body the size of the Rhum intrusion. It should

be noted, however, that delayed nucleation of olivine in supercooled liquids has been invoked to explain the peculiar textured olivines (harrisite) in the Rhum intrusion (Donaldson 1974) showing that supercooling is a viable petrogenetic process within the Rhum peridotites. The fall in temperature from the olivine liquidus to the clinopyroxene liquidus in Brown's (1956) proposed parent was shown to be in the order of 100°C by Forster (1978) which suggests that considerable cryptic variation (greater than that found by Dunham and Wadsworth, 1978) would be expected if a basalt was the parent magma (but see later discussion, p.333).

The fall in temperature from the olivine liquidus to the clinopyroxene liquidus is substantially reduced in Gibb's (1976) hypothesis in that the magma enters the chamber with olivine and Cr-spinel in suspension at a temperature just above the plagioclase liquidus. In this model the Cr-spinel and olivine are precipitated to form the sp-olivine cumulates and the olivines are thought to re-equilibrate to slightly lower temperatures during descent. Crystallisation and settling of plagioclase then clinopyroxene ensues, producing the ol-pl and pl-cpx cumulates. Early experimental work on this type of magma (Gibb 1971) showed that the temperature drop from the entry of plagioclase to the

entry of clinopyroxene was probably small ($\sim 10^{\circ}\text{C}$). However, subsequent work has shown this to be erroneous and the plagioclase-clinopyroxene temperature interval is estimated to be in the order of 45°C (Biggar and Gibb, 1976). Experimental work on Analyses 2 and 3 (Table 8.1) has shown an even greater plagioclase-clinopyroxene temperature interval of approximately 80° (Forster 1978). The main conclusion that can be drawn from these experimental investigations is that the fall in temperature from the plagioclase liquidus to the clinopyroxene liquidus in the Skye picrites is not compatible with the limited cryptic variation encountered in the Rhum layered peridotites.

An alternative explanation of the lack of cryptic variation in the Rhum peridotites has been advanced by Usselman and Hodge (1978). These authors believed that the thermal history of the liquid involved in open system fractionation could be modelled numerically. They showed that a limited number of replenishing intervals and volumes can produce the situation where heat lost during cooling equals the heat of input on replenishment. Thermal modelling of the Rhum magma chamber, showed that the constancy of process producing the individual units yielded a steady thermal fractionating state with a limited temperature interval. This has important

repercussions for the proposed Rhum layered series parents (especially Brown's 1956 basic parent) as the small fluctuations (less than 10°C) around the olivine-plagioclase cotectic (Usselman and Hodge 1978, Fig.7) show that little cryptic variation would be expected in these phases in passing from unit to unit. Unfortunately Usselman and Hodge did not show the effect of clinopyroxene crystallisation on their model as this may upset the delicate thermal balance attained along the olivine-plagioclase cotectic, however the prior crystallisation of spinel before olivine may reflect the rapid cooling of magma on entry into the open system magma chamber. These difficulties withstanding, the thermal model discussed above does seem to provide a viable explanation of the limited cryptic variation within each unit and explains the constancy of composition between successive units within the peridotite sequence.

One feature of the Rhum ultrabasic rocks is the complete separation of the Cr-spinel, into distinct seams at various levels within these rocks. The calculated settling rates of olivine and Cr-spinel through a basic magma is presented in Table 8.2. (For discussion of the methods used in these calculations see Appendix 8.1). The gross differences between the settling rate of olivine and Cr-spinel (chiefly a

function of their disparate size) suggest that the latter would not be capable of forming a separate cumulate horizon and argue in favour of in situ crystallisation of all the phases in the magma chamber. In addition both Henderson and Gejbels (1977) and J. McClurg (pers. comm.) have noted the presence of olivine cumulates both overlain and underlain by thin spinel seams which once again is not compatible with Gibbs (1976) hypothesis.

Another constraint on the parent magma composition was given by Henderson and Gejbels (1977) who showed the plagioclase within the Rhum peridotite are characterised by light REE enrichment, which is strong evidence for a light REE enriched parent. In their discussion of this observation Henderson and Gejbels (op.cit.) considered this argued in favour of a basaltic parent produced by limited partial melting and argues against a Preshal Mhor magma type parent as these have light REE depleted patterns (Mattey et al. 1977) and are believed to be products of substantial partial melting (Thompson et al. 1972; Thompson 1974a; Mattey et al. 1977; Wood 1979). There is no REE data concerning the eucritic picrite dykes of Skye.

Estimates of the volumes of basalt magma (Analysis 1, Table 8.1) which produced the exposed peridotite sequence on Rhum have been made by Henderson and Gejbels 1977. Calculations

based on an assumed Ni Kd coefficient of 10 between olivine and magma (reasonable in view of the data in Hart and Davis (1979, Fig.5)) and a NiO content of olivine in the range 0.23-0.25 wt%; indicate large volumes of basalt magma ($2,200 \text{ km}^3$) are required by a basalt parent. This volume estimate is probably too high as Dunham and Wadsworth (1978), show the Rhum olivines can possess up to 0.4 wt% NiO. Nevertheless a large volume of magma is a prerequisite of a basalt parent. The high Ni content of the eucrite parent (Analysis 2 and 3, Table 8.1) drastically reduce the necessary volume of the parent liquid. The peridotite sequence in the eastern and western layered series is known to be approximately 2.2km thick (Dunham and Wadsworth 1978) but is believed to be underlayed by 15km of high density rocks (McQuillan and Tuson, 1963). Although the underlying rocks probably contain a proportion of differentiated material, a basalt parent will require that enormous volumes of differentiates ($\sim 40 \times 10^3 \text{ km}^3$) would have been expelled from the magma chamber, and the bulk of these rocks must have been removed prior to the eruption of the lavas of western Rhum (p.233). A high MgO parent with an attendant low NiO olivine-magma Kd (between 3 and 6, Hart and Davis 1979, Fig.7) and high bulk magma Ni content will drastically reduce the volume requirements of the parent magma.

Donaldson (1974) has shown that olivine textures very similar to those in the harrisitic or crescumulate peridotites of Rhum can be reproduced experimentally in supercooled magmas with low nucleation densities and high normative olivine. It can be argued that these crescumulate olivines are the product of upward growth of olivine from the magma chamber floor in a stagnant basalt magma (Wager et al. 1960) but the evidence presented by Donaldson (1974, 1976) is more convincing, thus a high normative olivine content (20-30%) appears to be a requisite of the Rhum parent magma. High normative olivine is a feature of one of the Skye picrites (Analysis 3, Table 8.1) but Gibb's (1976) model envisaged crystallisation of olivine prior to entry into the magma chamber and cannot explain these crescumulate textured rocks. The Preshal Mhor magma type (Analysis 1, Table 7.2) has a normative olivine content of approximately 15 wt% and does crystallise olivine but the Ni and Cr contents are relatively low. Donaldson (1977) explicitly states that these low trace element abundances support the proposition that these magmas "have fractionated large amounts of olivine and Cr-spinel during ascent from the mantle". Thus it appears that this magma type would be incapable of crystallising the large volumes of olivine encountered in the Rhum peridotites and possibly could not produce

the crescumulate textured olivines.

Finally, any proposed parent will gain credence if magmas of similar composition are known to exist on Rhum. The similarity of the proposed basalt parent to the marginal gabbro of the northeastern margin of the peridotite sequence was noted by Wager and Brown (1968) and this study has shown that magmas broadly similar to the Preshal Mhor magma type were available at an early stage in the evolution of the complex. In addition Preshal Mhor type magmas have been located as dykes cutting the Rhum lavas but these are considered to postdate the evolution of the Rhum magma chamber (see detailed discussion in Chapter 7, p.239) and consequently may not have been available during the formation of the Rhum layered peridotites. The broad similarities of the Rhum group picrites with the Skye picrites was noted in Chapter 7, p. 259, but the latter are different in detail (especially the lower MgO content) with respect to the Rhum picrites.

The existence of high MgO liquids on Rhum has been demonstrated in this study (see Table 7.8 and discussion in relevant text) and it is suggested that magmas of this type are the parent magma to the Rhum layered peridotites as they satisfy the necessary requirements of a Rhum parent magma discussed above.

These ultrabasic liquids crystallise minerals of the correct type (Cr-spinel, forsteritic olivine etc.) and by analogy with experimental work on rocks of similar composition (Gibb 1971, Forster 1978) will crystallise these minerals in the requisite order. Note however that the compositional dissimilarity of the Cr-spinel compositions in the type 1 and type 2 picrites (and the Rhum lavas) with respect to the primary spinels from the layered peridotites (Fig. 6.13) suggest that the former are not the precise parental magma type. These ultrabasic magmas (with high normative olivine) will be capable of producing crescumulate textured olivines on supercooling and their high MgO and Ni contents are commensurate with the production of limited volumes of differentiates. One problem which has not been convincingly overcome is the limited cryptic variation within the peridotite units, however, if the thermal model of Usselman and Hodge (1978) is applicable to Rhum then this ultrabasic liquid parent will be as applicable as a basaltic parent. Confirmation of this however requires more detailed experimental and thermal modelling to produce an unequivocal interpretation.

In conclusion the Preshal Mhor magma type is believed to be an unsuitable parent magma for the Rhum layered peridotites. The basalt parent of Brown (1956) and the

euclitic parent with olivine + Cr-spinel in suspension of Gibb (1976) have certain disadvantages which are overcome by a high MgO - high CaO ultrabasic parent. Magmas of the latter composition have been shown to have existed on Rhum during the Tertiary, consequently it is suggested that these Rhum magmas are the parent magma to the Rhum layered peridotites.

II. A COMPARISON OF THE RHUM DOLERITES WITH THE RHUM LAVAS AND OTHER HEBRIDEAN SUITES.

The geochemistry of the Rhum lavas has been presented in the revised Rhum Memoir (Dunham et al., in press) and the comparisons made here are consequently based on as yet unpublished data. Four series of mineralogically and chemically distinct lava flows of olivine basalt, hawaiite, basaltic-andesite and icelandite have been distinguished on Rhum and these are referred to as the lava groups 2 to 5 respectively (Emeleus 1976, Dunham et al., in press). Another basalt type geochemically distinct from the former occurs as clasts in the conglomerates associated with the lavas (Group 1, Dunham et al., in press). The current investigation of the petrographic and compositional variation of all the rock types found as clasts in these conglomerates is very important, as these conglomerates are the only key to a better understanding of the geological history of

Rhum in post ultrabasic emplacement and pre-lava times.

Although both the lava and the dolerite suites contain a mixed assemblage of transitional basalts (Chapter 3, Fig. 3.6) and basaltic differentiates, comparisons of the dolerite groups with the lava groups of analogous composition has revealed important differences between the two suites. In addition, the dolerite groups 1-3 and the differentiated dolerite groups 11 and 12 have no analog^{ue}s in the Rhum lava pile.

The tholeiitic lava group 1 basalts are similar in some respects to the more tholeiitic members of the dolerite group 4. However, there are differences in the Al_2O_3 , MgO and Na_2O abundances, the Al_2O_3 content of the dykes is somewhat lower and the MgO and Na_2O contents higher than the levels in the lava group 1 basalts. Comparisons of the Al_2O_3 and MgO contents of the lava group 2 basalts and the more alkalic group 4 dolerites, the Hawaiites of lava group 3 and dolerite group 10 and the basaltic andesites of lava group 4 and the dolerite group 8 reveal similar discrepancies. The difference in MgO content of the two suites gives lower iron enrichment values for the dolerites (Fig. 8.1).

Although the icelandite lava group 5 and the dolerite group 9 rocks have similar SiO_2 contents they differ greatly in the relative abundances of Al_2O_3 , MgO , CaO ,

K_2O , TiO_2 and P_2O_5 these being lower (with the exception of MgO and CaO) in the dolerite dykes.

Some of the dolerite specimens were collected from dykes believed to have acted as feeders to overlying lavas (p.27). The geochemical differences outlined above suggest that these dykes did not feed the lavas now preserved in situ or in the conglomerates of western Rhum, but to earlier lavas which were eroded prior to the eruption of the lavas of western Rhum. This emphasises the point made in Chapter 7 (p.232) that there is a considerable erosion interval postdating the emplacement of the dykes and preceeding the eruption of the lavas.

The high levels of MgO in the Rhum dolerite suite when compared with other Hebridean suites has been mentioned in Chapter 3 (p. 79). The well documented magma types of Skye (Thompson et al. 1972; Matthey et al. 1977) and some average compositions of the tholeiitic Ardnamurchan cone sheets (Holland and Brown, 1971) have been plotted along with the Rhum dolerites and the Rhum lavas in Fig. 8.1. This standard plot is generally used to illustrate the differences between tholeiitic differentiation (Fe-enrichment with limited alkali enrichment) and alkalic differentiation (little Fe-

enrichment for large increases in total alkalis) but is used here to emphasise the dissimilarity between the Rhum dolerite suite and the other Hebridean suites. Note that the group 1 and group 2 lavas of Mull (Beckinsale et al. 1978) are compositionally similar to the Skye Main Lavas Series basalts (Beckinsale et al. 1978, p. 421).

Two other points of interest concerning the Rhum minor intrusion suite in its Hebridean context merit discussion. The Rhum dolerites are characterised by fairly low concentrations of the incompatible elements (Ti, K, P, Nb, Zr and Y) and Morrison (1978) has shown this is also a feature of the Mull and Skye lavas. This suggests that the mantle underlying the Hebridean centres was depleted in incompatible elements prior to the generation of the Tertiary magmas. This may be a primary feature of this mantle which accreted with low incompatible element concentrations early in the Earth's history or may reflect thorough leaching of incompatibles during an earlier regional partial melting event. The presence of Permo-Carboniferous dykes in the Hebrides has been noted by Speight (1972) and Permo-Carboniferous dykes in general are known to be alkalic in composition (MacGregor, 1948). It is possible that the Permo-Carboniferous partial melting event removed the bulk of

the incompatible elements leaving only an incompatible depleted residue available for the Tertiary partial melting event.

The zoning of the Skye lava pile from alkalic basalt to tholeiitic basalt was considered to reflect a progressive increase in the degree of partial melting by Thompson et al. 1972 and Wood 1979. Similar zoning of lava piles in Iceland and Troodos led Gibson et al. (1976) to propose this was ^ageneral feature of basalts from extensional tectonic environments. The Rhum minor intrusion suite however shows the reverse situation in that the earliest known igneous rocks on Rhum are incompatible-depleted tholeiitic gabbros ($\simeq$ Preshal Mhor tholeiite of Skye) and there is a progression towards more alkalic (and more magnesian) compositions with decreasing age. In view of the known differences in the sequence of intrusion of analogous rocks on Rhum and Skye (the generalised sequence lavas - basic and ultrabasic intrusives - granophyre on Skye is the reverse of the Rhum sequence), it is perhaps not surprising that the trends of basic magma composition associated with the centres are so dissimilar.

Fig. 8.1 $\text{Fe}_2\text{O}_3^*/\text{Fe}_2\text{O}_3^* + \text{MgO}$ v. $\text{Na}_2\text{O} + \text{K}_2\text{O}$ variation in some Hébridean suites.

Key to symbols

- Rhum dolerite suite (this study)
- Average composition of Rhum Lava groups (Emeleus in Dunham et al. (in press)).
- ☑ Skye Preshal Mhor magma type (Mattey et al., 1977, Table IA).
- Skye Fairy Bridge Magma type (Mattey et al., 1977, Table V).
- Skye Main Lava Series magma type (Thompson et al., 1972, Table 1).
- △ Average composition of Ardnamurchan cone sheets (Holland and Brown, 1971, Table 1).

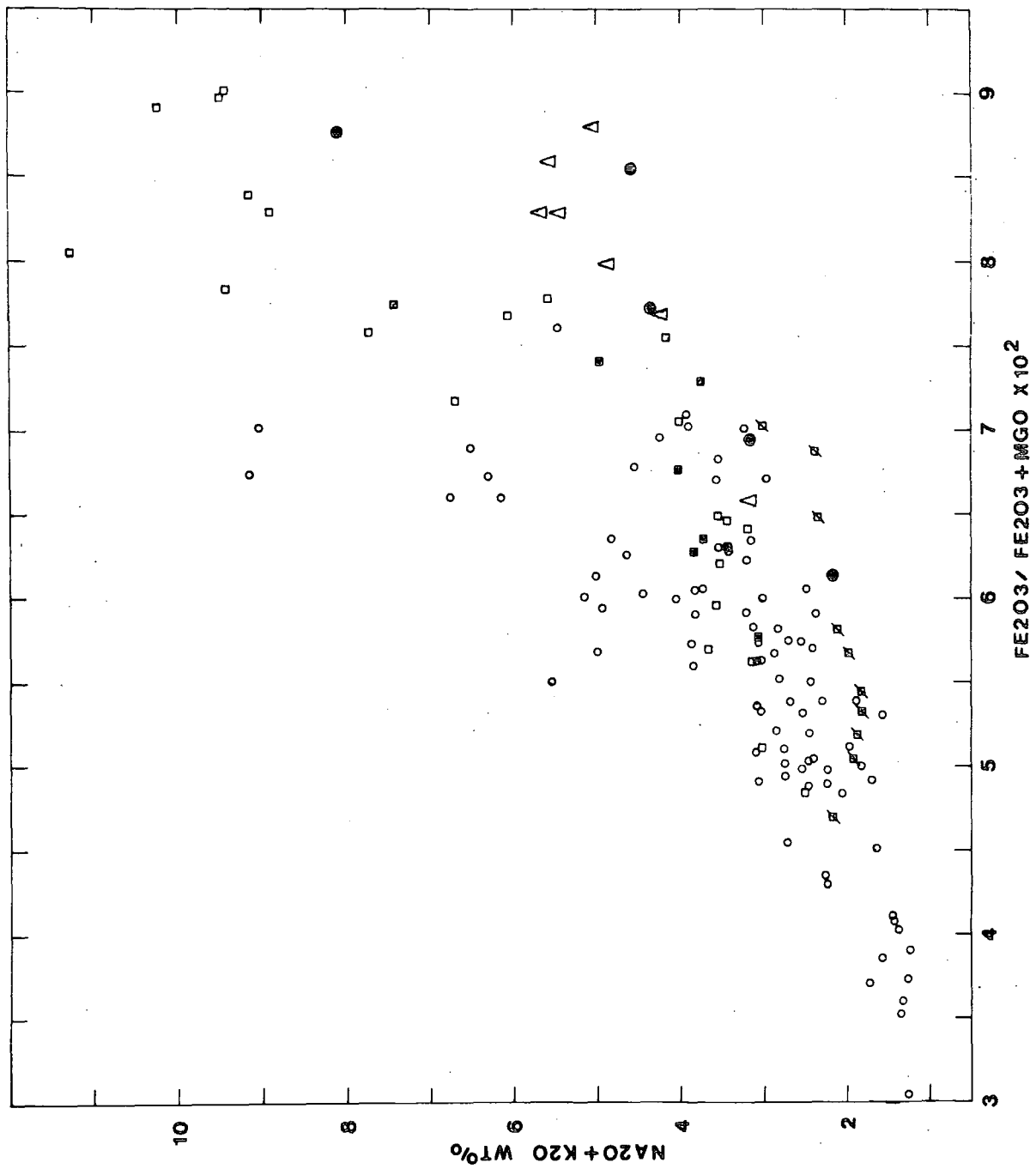


TABLE 8.1

SOME PROPOSED RHUM LAYERED SERIES PARENT MAGMAS

Analysis 1 Brown (1956, Table 8, anal.1)

Analysis 2-3 Gibb (1976, Table 1, B,c)

	1	2	3
SiO ₂	46.80	46.54	45.64
Al ₂ O ₃	18.60	14.77	13.11
Fe ₂ O ₃	1.40	3.75	3.69
FeO	7.70	6.85	7.43
MgO	10.90	9.86	14.58
CaO	10.60	12.06	10.72
Na ₂ O	2.70	1.53	1.39
K ₂ O	0.30	0.14	0.13
TiO ₂	0.80	1.17	0.78
P ₂ O ₅	0.04	0.07	0.08
MnO	0.0	0.19	0.16
Wt% Cr ₂ O ₃	0.04	440 ppm	0.14
Or	1.8	0.9	0.8
Ab	19.2	13.4	12.1
An ⁻	37.8	34.1	29.9
Ni	2.0*	—	—
Di	11.9	22.0	19.4
Hy	—	15.8	10.8
Ol	23.2	8.2	22.2
Mt	2.7	3.1	3.3
Ilm	1.5	2.3	1.5
Ap	0.1	0.2	0.2

*All norms calculated with a fixed Fe₂O₃/Fe₂O₃+FeO ratio of 0.25. Analysis 1 is hypersthene normative if the norm is calculated with the Fe₂O₃ and FeO values quoted by Brown (1956).

	Particle diameter	Viscosity (poises)	Viscosity (poises)	Viscosity (poises)	Viscosity (poises)	Viscosity (poises)
		100	300	500	1000	3000
		cm/sec	cm/sec	cm/sec	cm/sec	cm/sec
Olivine (Fo85)	1 mm	0.2287	0.0762	0.0457	0.0228	0.0076
	3 mm	2.0580	0.6860	0.4116	0.2058	0.0686
Cr-spinel	0.3 mm	0.0848	0.0283	0.0170	0.0085	0.0028
	0.4 mm	0.1507	0.0502	0.0301	0.0151	0.0050

Table 8.2. Comparison of calculated settling rates (cm/sec) for olivines and Cr-spinels in the Rhum layered series to illustrate that olivine will settle much faster than the latter. For discussion of the calculation method see Appendix 8.1.

SUMMARY OF IMPORTANT POINTS

Several interesting facts concerning the Rhum minor intrusions have resulted from this investigation. A wide range of rock types came under scrutiny and the synthesis of their field relationships as expressed in Chapters 2 and 5 has allowed appraisal of the probable sequence of magma evolution on Rhum. The contrast between the Rhum sequence and that found in other well studied Hebridean centres (e.g. Skye, Thompson et al., 1972; Mull, Beckinsale et al., 1978) emphasises the complexity of mantle processes which can operate in a small area over a relatively short period of geological time.

The Discriminant Function Analysis technique applied to basalt classification in Chapter 3 has shown that there are real and distinct differences between the tholeiite, alkali olivine basalt and calc-alkali basalt magma types. Although the existence of basalts compositionally transitional between alkali olivine basalt and tholeiite basalt has been appreciated for several years this, statistical approach produced a method for numerically defining their transitional nature and allows for numeric comparisons of the departure of any basalt composition from the typical alkali olivine basalt or tholeiite basalt compositions.

The petrographic and mineralogical studies show that mineral textural and compositional variation in the Rhum

minor intrusions can be related to a variety of magmatic processes. The unusual texture of the minerals occurring in several of the dykes are similar to those produced in experimental charges and suggest that supercooling has played a role in the genesis of several of the Rhum dykes. Previous studies of compositional variation in spinel minerals has shown they are sensitive indicators of magmatic change and providing the effects of primary and secondary variation can be disentangled they can be useful petrogenetic indicators. If future experimental studies concentrate on the roles of compositional variation and pressure in spinel genesis it is possible that this mineral type may offer great insight into magma genesis.

The geochemical data presented in Chapter 7 shows that liquids with approximately 15 wt% MgO were not uncommon on Rhum during the Tertiary and may alleviate several difficulties concerning the genesis of the Rhum layered peridotites and possibly the layered basic rocks in other Hebridean centres. Two principal trends are developed by the basic and intermediate rocks of Rhum, these being an iron enrichment - MgO depletion trend and an iron depletion - MgO depletion trend as exemplified in Fig. 7.2. These are broadly considered to reflect the differences between mantle and crustal petrogenetic processes. The petrogenetic discussion of these trends

in Chapter 7 attempted to distinguish between mantle and crustal processes but the lack of more sophisticated geochemical data (especially REE) precludes an unequivocal interpretation.

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Appendices

Note that all references cited in the appendices, except those in appendices 3.1 - 3.3, are included in the reference list for the main text. References in appendices 3.1 - 3.3 are located on p.373 unless marked otherwise.

Appendix 1.1

List of publications made during the course of this study.

Forster, R.M. 1978. Preliminary atmospheric pressure melting relations of some proposed Rhum parent magmas. Prog. in Experimental Petrology, N.E.R.C. Rpt. 4, p.200-201.

Emeleus, C.H. & Forster, R.M. 1979. Field guide to the Tertiary Igneous rocks of Rhum. Nature Conservancy Council, pp.44.

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Appendix 2.1 Strike orientations plotted in Fig 2.1

STRIKE (°)	270-279	280-289	290-299	300-309	310-319	320-329	330-339	340-349	350-359	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
ROSE 1			4	10	7	2	8	4		1		1			2	2	2	
ROSE 2	10	4	5	1	1	3	1	4	3	2	2	1	4	4	5	10	6	5
ROSE 3			1	1	3		5	13	5	20	12	8	2		2		1	
ROSE 4	1	3	4	6	8	5		1	2			1	1					
ROSE 5	14	12	8	16	7	7	4	1			2	3	3	4	4	5	3	5
ROSE 6	9	7	6	2	7	5	4	4	3	1		3	2	2	2	4		6
ROSE 7	1	1	4	2	1	1	1	1	2	1	2					1		
ROSE 8	5	6	3	10	3	1	1				2							
ROSE 9	6	5	10	6	1	5		3		2	3	4	9	7	9	3		2
ROSE 10	2	5	5	11				1		1	3	2	2	7	6	2		3
ROSE 11	2		1							1	4	1	2	2	1	1		1
ROSE 12			2	3		4	3	7	11	11	6	2	3		2			
ROSE 13	7	2	2	1				1		6		3		1		1	1	

Strike	Dip
165	60E
10	60W
85	55S
30	15NW
30	35NW
45	25NW
10	15NW
45	20NW
85	15NW
135	20NE
125	60SW
115	25SW
90	30SE
110	45SW
135	50SW
155	30SW
105	40SW
110	55SW
110	45SW
115	45SW
145	45SW
115	45SW
110	45SW
85	20SW
110	65SW
125	45SW
125	45SW
115	40SW
120	40SW
115	40SW
105	30SW
130	35SW
105	40SW
120	50SW
120	50SW
115	40SW
125	15NE
125	45SW
115	70SW
110	30SW
110	35SW
105	30SW
110	40SW
115	40SW
120	35SW
115	35SW
115	40SW
105	40SW
130	45SW
130	40SW
110	40SW
130	35SW
90	30SW
100	40SW

Strike	Dip
140	70SW
110	45SW
105	45SW
110	45SW
105	55SW

Rose 12

Strike	Dip
170	65E
140	45E
135	60E
0	60W
0	60W
50	25NW
5	45E
30	45SE
20	55SE
170	60E
170	60W
15	65E
170	65W
165	40W
100	25N
110	25NW

Appendix 3.1

DATA SOURCES FOR BASALT ANALYSES USED IN THE DISCRIMINANT
ANALYSIS WITH THE NUMBER OF ANALYSES USED FROM EACH SOURCE

I Tholeiites

Continental		Ocean Floor	
Brooks and Nielson (1978)	3	Baragar et al. (1977)	4
Cox and Horung (1966)	3	Cann (1970)	3
Cox et al. (1967)	2	Engel and Engel (1964)	2
Dunham and Kaye (1965)	5	Engel et al. (1965)	4
Holmes (1936)	1	Fisher et al. (1968)	2
Holmes and Harwood (1929)	1	Kay et al. (1970)	1
Lipman and Moench (1972)	3	Muir and Tilley (1966)	3
Sukeswala and Poldevart (1958)	2	Ridley et al. (1974)*	3
Wilkinson (1968)	4		
Oceanic island (includes Iceland)			
Baker et al. (1974)	3	MacDonald and Katsura (1964)	4
Carmichael (1964)	5	McBirney and Williams (1969)	3
Gass et al. (1973)	3	Sigvald. (1974)	5
Gunn et al. (1971)	6	Wood (1978)	3

II Alkaline

Continental		Oceanic (includes Grenada)	
Baker et al. (1973)	3	Arculus (1976)	4
Barber et al. (1970)	4	Baker (1969)	4
Brown and Carmichael (1971)	3	Baxter (1976)	3
Gass and Mallick (1968)	4	Gass et al. (1973)	3
Gibb and Henderson (1978)	4	Gunn and Watkins (1976)	2
Kesson (1973)	3	Gunn et al. (1970)	2
Lipman (1969)	4	Irrabalo (1969)	3
Saggerson (1970)	5	MacDonald and Katsura (1964)	4
		McBirney and Williams (1969)	3
		Strong (1972)	3

III Calk-alkaline

Beddoe-Stephens (1977)*	4	Keller (1974)	2
Brothers and Martin (1970)	7	Kuno (1960)	3
Fitton (1971)	4	Lowder and Carmichael (1970)	3
Gill (1970)	2	Lopez-Escobar and Frey (1977)	4
Gunn and Mooser (1970)	2	Nichols (1971)	7
Hemming (1974)	4	Smith and Carmichael (1968)	3
Jakes and Smith (1970)	1	Wise (1969)	5

IV World-wide transitional

Baker et al. (1977)	12	Hei. et al. (1966)	2
Bass (1972)*	2	Lipman and Moench (1972)	6
Cox et al. (1970)	4	Tonguy (1978)	3
Gass et al. (1973)	6	Waters (1961)	5
Green (1970)*	4		

V Hebridean

Beckinsale et al. (1978)*	11	Mitchell et al. (1976)	8
Holland (unpublished data)	16	Ridley (1973)*	47
Mattey et al. (1977)	25	Thompson et al. (1972)*	43

*Cited at end of main text

STATISTICS ON SOURCE BASALT COMPOSITIONS

THOLEIITE BASALTS TOTAL NUMBER OF CASES=78

VARIABLE	NO OF CASES WITH VARIABLE	MEAN	ST-DEV	MAXIMUM	MINIMUM	SKEWNESS
SiO ₂	78	49.73	1.13	53.77	46.28	0.69
Al ₂ O ₃	78	15.78	1.53	19.15	11.99	0.18
TOTAL FEO	78	11.16	1.74	14.71	7.72	0.25
MgO	78	6.74	1.55	12.20	3.40	0.37
CaO	78	10.80	1.44	14.51	7.29	0.18
Na ₂ O	78	2.72	0.43	3.57	1.82	0.46
K ₂ O	78	0.46	0.32	1.85	0.04	1.47
TiO ₂	78	1.97	0.83	4.34	0.47	0.62
MnO	78	0.90	0.34	2.34	0.11	1.22
P ₂ O ₅	75	0.25	0.19	1.17	0.03	2.18
NI	55	0.27	0.68	3.30	15.30	0.42
CR	38	243.79	125.22	552.00	44.40	0.23
BA	43	137.88	84.30	312.00	5.00	0.38
NB	19	17.00	10.00	42.00	2.00	0.79
ZR	46	128.30	70.55	326.00	35.00	0.68
Y	35	32.99	14.23	62.00	10.00	0.26
SR	52	232.77	109.76	484.00	40.00	0.56
RB	34	9.53	6.22	26.00	1.00	0.59
ZN	18	100.17	25.55	141.00	57.00	0.07

ALKALI OLIVINE BASALTS TOTAL NUMBER OF CASES=62

VARIABLE	NO OF CASES WITH VARIABLE	MEAN	ST-DEV	MAXIMUM	MINIMUM	SKEWNESS
SiO ₂	62	47.39	1.79	52.88	44.68	1.29
Al ₂ O ₃	62	15.61	1.41	17.94	10.27	-0.90
TOTAL FEO	62	11.44	1.34	14.69	8.53	-0.95
MgO	62	7.87	2.63	15.14	3.71	-0.59
CaO	62	10.08	1.50	13.85	6.18	-0.35
Na ₂ O	62	3.27	0.85	5.97	1.98	1.30
K ₂ O	62	1.01	0.50	2.40	0.16	0.25
TiO ₂	62	2.44	0.83	4.25	0.81	0.04
MnO	62	0.17	0.34	0.28	0.01	-0.93
P ₂ O ₅	62	0.46	0.21	1.46	0.14	0.80
NI	25	182.76	134.79	495.00	26.00	0.67
CR	27	198.44	144.39	540.00	15.00	0.62
BA	43	363.20	170.63	720.00	48.00	0.44
NB	22	38.05	25.58	100.00	2.00	0.47
ZR	35	173.06	79.99	300.00	68.00	0.84
Y	27	29.59	12.28	60.00	15.00	0.86
SR	40	595.35	287.87	1500.00	261.00	1.95
RB	32	21.25	11.35	40.00	3.00	-0.20
ZN	19	83.42	15.85	110.00	50.00	-0.10

CALC-ALKALI BASALTS TOTAL NUMBER OF CASES=51

VARIABLE	NO OF CASES WITH VARIABLE	MEAN	ST-DEV	MAXIMUM	MINIMUM	SKEWNESS
SiO ₂	51	50.49	0.97	52.21	48.54	-0.32
Al ₂ O ₃	51	17.50	2.13	22.35	11.38	-1.00
TOTAL FEO	51	9.49	1.32	12.86	7.35	-0.99
MgO	51	6.53	1.87	11.33	3.12	0.71
CaO	51	10.69	1.52	13.77	7.77	0.14
Na ₂ O	51	2.64	0.74	3.89	0.84	-0.49
K ₂ O	51	1.01	0.73	3.33	0.22	1.76
TiO ₂	51	1.01	0.38	1.90	0.19	0.65
MnO	51	0.18	0.34	0.28	0.12	0.63
P ₂ O ₅	46	0.23	0.18	0.47	0.10	0.64
NI	23	87.29	84.42	337.00	10.00	1.46
CR	25	148.28	155.46	634.00	10.00	1.58
BA	23	368.43	197.42	901.00	107.00	1.17
NB	14	5.86	4.32	13.00	1.00	0.47
ZR	23	71.95	45.44	158.00	19.00	0.75
Y	19	18.32	8.12	35.00	5.00	0.95
SR	23	586.52	226.43	984.00	130.00	0.46
RB	22	47.86	45.68	150.00	5.00	1.50
ZN	19	84.68	16.12	138.00	71.00	0.32

Appendix 3.1

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Appendix 3.2

Discriminant function analysis

The analysis was performed using the procedure discriminant in the Northern Universities Multiple Access computer (NUMAC) SPSS statistical package version 8 at Durham University (Nie et al., 1975). The first stage in the analytical procedure was the recalculation of $\text{Fe}_2\text{O}_3 + \text{FeO}$ to total iron as FeO the major oxides in all analyses were then normalised to total 100%. The second stage in the analytical procedure was standardisation of the data variables (both major oxide and trace elements) to Z scores by subtracting the mean of the distribution for each variable i and dividing by the standard deviation.

$$Z_i = \frac{X_i - \bar{X}_i}{S_i}$$

This standardisation equally weights the variability of say SiO_2 at 45-52 (wt %) and the variability of Rb (0-50 ppm) about their respective common means. In accordance with standard trace element procedure a Log_{10} transformation was performed on the trace elements to produce a normal population distribution.

Discriminant analysis then acts on these standardised variables and forms one or more linear "functions in the

form:

$$D_i = d_{i1}Z_1 + d_{i2}Z_2 + \dots + d_{ip}Z_p$$

where D_i is the score on the discriminant function i , the d 's are weighting coefficients and the Z 's are the standardised values of p discriminating variables. Option 1 of procedure Discriminant (Nie et al., op.cit) was invoked to include cases with missing values.

The classification functions were in the form:

$$C_i = C_{i1}V_1 + C_{i2}V_2 + C_{ip}V_p + C_{i0}$$

where C_i is the classification score for each class, the C_{ij} 's are the classification coefficients with C_{i0} being the constant and the V 's are the raw scores on the discriminating variables. A separate classification function was derived for each class and each function weighted according to the size of the class. These classification functions were derived from the individual group covariance matrices.

Procedure discriminant produces two probability statistics during the classification of a case into a group. The value $P(X/G)$ gives the probability of a case in a group which has a location as far from the group centroid (see below) as the case in question. The value $P(G/X)$ is the probability of that case belonging to the group it has been classified into.

A high $P(G/X)$ value indicates that the case in question is more likely to belong to that group than any of the other groups and providing the $P(X/G)$ value is also high the classification is valid. This latter probability provides the necessary constraint on for example classification of an igneous suite which includes intermediate rocks with high SiO_2 . These would be preferentially classified as tholeiite as opposed to alkali basalt (in that SiO_2 is an important component in the discriminant function) but they would lie a long way from the group centroid (ie. low $P(X/G)$ and the mis-classification would be detected.

The value known as the group centroid is the mean of the discriminant score for each group on its respective function(s), ie. the most likely situation of a member of that group with respect to the discriminant function(s).

Appendix 3.3

Standardised Canonical Discriminant Functions

MAJOR OXIDES ONLY

	FUNC 1	FUNC 2		FUNC 1
SiO ₂	-2.55413	-2.30421	SiO ₂	-2.45367
Al ₂ O ₃	-2.15715	-1.89696	Al ₂ O ₃	-1.71555
TOTALFeO	-2.00173	-2.24044	TOTALFeO	-1.81133
MgO	-2.20393	-2.82525	MgO	-1.64695
CaO	-2.13883	-2.34856	CaO	-1.70922
Na ₂ O	-0.52234	-1.03540	Na ₂ O	-0.11566
K ₂ O	-0.50462	-0.01291	K ₂ O	0.18248
TiO ₂	-0.76063	-1.87916	TiO ₂	-0.95737
MnO	-0.56885	0.06925	MnO	-0.42719
P ₂ O ₅	0.21650	-0.01302	P ₂ O ₅	0.01778

Group Centroid

Group Centroid

	FUNC 1	FUNC 2	FUNC 1
Tholeiite	-0.77349	-0.97010	-1.53514
Alkali	2.15513	0.22543	1.93131
Calc-alkali	-1.43698	1.20963	

MAJOR OXIDES AND TRACE ELEMENTS

	FUNC 1	FUNC 2		FUNC 1
SiO ₂	1.56944	1.87389	SiO ₂	1.37565
Al ₂ O ₃	1.14233	1.41384	Al ₂ O ₃	0.70378
TOTALFeO	0.93003	1.73647	TOTALFeO	0.65459
MgO	0.89251	1.99830	MgO	0.17576
CaO	1.10176	1.80435	CaO	0.69055
Na ₂ O	0.11080	0.65778	Na ₂ O	-0.33114
K ₂ O	0.25193	-0.11967	K ₂ O	-0.40389
TiO ₂	0.08724	1.54733	TiO ₂	0.27646
MnO	0.67999	-0.07930	MnO	0.49545
P ₂ O ₅	-0.21569	0.01949	P ₂ O ₅	-0.10802
Ni	0.38956	0.30412	Ni	0.23780
Cr	0.51407	-0.45891	Cr	0.24169
Ba	-0.56523	-0.15776	Ba	-0.57506
Nb	0.32225	-0.19077	Nb	0.20345
Zr	-0.15130	0.14434	Zr	-0.06704
Y	-0.28276	0.19448	Y	-0.14930
Sr	-0.35734	0.71693	Sr	0.24242
Rb	0.13891	-0.18489	Rb	-0.05511
Zn	-0.01709	-0.32845	Zn	-0.11609

Group Centroid

Group Centroid

	FUNC 1	FUNC 2		FUNC 1
Tholeiite	0.63726	1.02875	Tholeiite	-1.60125
Alkali	-2.31720	-0.44057	Alkali	-2.01447
Calc-alkali	1.84237	-1.31308		

Unstandardised Canonical Discriminant Functions

These are derived in an analogous manner to the standardised functions listed previously but will operate on data which has not been normalised to z scores providing the penultimate product is multiplied by the constant listed at the end of each discriminant function.

MAJOR OXIDES ONLY

	FUNC 1	FUNC 2		FUNC 1
SiO ₂	-1.898049	-1.712328	SiO ₂	-1.682596
Al ₂ O ₃	-1.287582	-1.132277	Al ₂ O ₃	-1.161031
TOTALFEO	-1.322826	-1.480578	TOTALFEO	-1.148963
MgO	-1.080723	-1.385393	MgO	-0.7849087
CaO	-1.445055	-1.586755	CaO	-1.165026
Na ₂ O	-0.7757832	-1.537783	Na ₂ O	-0.1787287
K ₂ O	-1.007275	-0.2576487E-01*	K ₂ O	0.4473243
TiO ₂	-1.028659	-2.541340	TiO ₂	-1.150076
MnO	-13.38699	1.629625	MnO	-9.857938
P ₂ O ₅	0.7172462	-0.4312484E-01	P ₂ O ₅	0.6661001E-01
(CONSTANT)	158.4481	153.8755	(CONSTANT)	135.4631

MAJOR OXIDES AND TRACE ELEMENTS

	FUNC 1	FUNC 2		FUNC 1
SiO ₂	1.166300	1.392542	SiO ₂	0.9433487
Al ₂ O ₃	0.6818425	0.8439041	Al ₂ O ₃	0.4762943
TOTALFEO	0.6146039	1.147533	TOTALFEO	0.4152199
MgO	0.4376528	0.9798891	MgO	0.8376549E-01
CaO	0.7443850	1.219076	CaO	0.4706844
Na ₂ O	0.1645537	0.9769390	Na ₂ O	-0.5117261
K ₂ O	0.5028897	-0.2388704	K ₂ O	-0.9900758
TiO ₂	0.1179788	2.092575	TiO ₂	0.3321041
MnO	16.00260	-1.866279	MnO	11.43313
P ₂ O ₅	-0.7145491	0.6455399E-01	P ₂ O ₅	-0.4047525
Ni	0.1002807	0.7828676E-01	Ni	0.6129370E-01
Cr	0.1252376	0.1118012	Cr	0.5842955E-01
Ba	-0.1385052	-0.3865885E-01	Ba	-0.1435192
Nb	0.9957589E-01*	-0.5894766E-01	Nb	0.6130612E-01
Zr	-0.3798900E-01	0.3624231E-01	Zr	-0.1661615E-01
Y	-0.7689975E-01	0.5289183E-01	Y	-0.4003399E-01
Sr	-0.8600952E-01	0.1725599	Sr	0.5959392E-01
Rb	0.3864681E-01	-0.5143928E-01	Rb	-0.1561139E-01
Zn	-0.4727808E-02	-0.9085518E-01	Zn	-0.3299191E-01
(CONSTANT)	-89.35329	-120.9608	(CONSTANT)	-64.04783

*computer notation E-01 = 10⁻¹

Appendix 5.1

Specimen list with compositional type, location, enclosing country rock (CR), structural type (SR) and relevant cross-cutting relationships.

Key to compositional types.

1-12 Dolerite groups, F denotes a high variant.

HMG High MgO Gabbro

LMG Low MgO Gabbro

P Peridotite

A Acid

Key to country rocks

LA Lavas

PE Layered peridotites

MG Marginal gabbros

GR Granophyre

TU Tuffisite

FE Felsite

EX Explosion breccia

TB Torridonian inside MRF

TO Torridonian outside MRF

LE Lewisian gneiss

Key to structural types

DY Dyke

IS Inclined sheet

TCS Thin conformable sheet

THC Thick conformable sheet

PIS Parallel inclined sheet

PI Plug

Spec	Type	Location	CR	ST	X-Cutting
10A76	4F	NM40849985	TO	DY	
12A76	7	Fig 2.11	EX	DY	Cuts an early gabbro
14A76	4F	NM40479978	TO	TCS	
15A76	8	NM40509982	TO	TCS	
16A76	8	NM40559984	TO	DY	
18A76	8	NM40619984	TO	TCS	
20A76	8	NM40669984	TO	DY	
21A76	4	NM40669984	TO	DY	Cuts 22A76
22A76	4	NM40719982	TO	TCS	
23A76	8	NM40839985	TO	TCS	
25A76	8F	NM40899986	TO	TCS	
26A76	4	NM40919986	TO	DY	
29A76	9	NM39459865	TO	TCS	
32A76	10	NM35489968	PE	DY	
35A76	8	NM35349975	GR	DY	
38A76	4F	NG35430048	TO	DY	Cuts 41A76
40A76	2	"	TO	DY	Cuts 38A76
41A76	4	"	TO	DY	
44A76	2	NG35370045	TO	DY	
46A76	2	NM39319828	TO	DY	Cut by MRF
47A76	4	NM39319829	TO	PIS	
48A76	8	"	TO	DY	
49A76	8	"	TO	PIS	
50A76	8	"	TO	DY	
51A76	8	NM39309831	TO	DY	
52A76	1	Fig 2.9	TO	DY	
53A76	1	"	TO	DY	
54A76	1	"	TO	DY	Cuts 50A76
55A76	9	NM39359835	TO	DY	
56A76	1	Fig 2.9	TO	DY	
60A76	4	NM39369839	TO	DY	
61A76	4	NM39569894	TO	PIS	
62A76	4	NM39579899	TO	PIS ?	
63A76	4	"	TO	PIS ?	
64A76	8	NM38389845	TO	PIS	
65A76	2	"	TO	PIS	
66A76	3	"	TO	PIS	
69A76	1	Fig 2.9	TO	DY	
70A76	2	NM39369841	TO	DY	
71A76	1	Fig 2.9	TO	DY	
72A76	3	NM39419847	TO	PIS	
73A76	3	NM "	TO	PIS	
74A76	3	"	TO	PIS	
75A76	8	NM39419846	TO	PIS	
76A76	9	NM39419845	TO	PIS	
77A76	1	Fig 2.9	TO	DY	Cuts PIS
79A76	8	NM39439850	TO	PIS	
81A76	9	NM39439852	TO	DY	
82A76	4	"	TO	DY	Cuts 81A76?
83A76	10F	NM "	TO	PIS	
85A76	1	Fig 2.9	TO	DY	
87A76	3	NM39459868	TO	PIS	
89A76	3	NM39469860	TO	PIS	
92A76	3	NM39439855	TO	PIS	

Spec	Type	Location	CR	ST	X-Cutting
93A76	2	NM39459859	TO	PIS	
94A76	4	NM39519877	TO	DY	Cuts 95A76, 77316
95A76	4	NM	TO	PIS	
77002	4F	NM41099646	TB	DY	
77003	8	NM40929550	PE	DY	
77004	8	NM40849574	PE	DY	
77005	11	NM40849575	PE	DY	
77006	8	NM40849576	PE	DY	
77007	8	NM40839580	PE	DY	
77008	11	NM40819593	PE	DY	
77010	4	Fig 2.6	GR	DY	
77011	4	"	GR	DY	
77012	4	"	GR	DY	
77013	4	NM	GR	DY	
77014	7	"	GR	DY	Also on Fig 2.11
77015	4	"	GR	DY	
77017	1	"	GR-PE	DY	Also on Fig 2.9
77019	2	NM35559360	PE	DY	
77023	11F	NM35359716	PE	DY	Cuts Dornabac breccia
77024	1	Fig 2.9	PE	DY	
77031	HMG	Fig 2.11	TO	PL	
77032	4	NM39169725	PE	DY	
77033	HMG	Fig 2.11	PL		
77034	9	NM38599860	EX	DY	Cuts 77033
77035	4	"	EX	DY	Cuts 77033
77036	1	Fig 2.9	EX	DY	Cuts 77033
77039	2	NM38569866	EX	DY	Cuts 77033
77040	8	NM38499840	FE	DY	
77042	2	NM38509831	FE	DY	
77044	4	NM38519850	FE	DY	Cuts 77046
77046	3	"	FE	DY	
77047	7	Fig 2.11	FE	DY	
77048	3	NM38419852	FE	DY	Cuts 77047
77049	4F	NG35690130	TO	DY	Cuts 77361 (PP)
77051	P	Fig 2.11	TO	PL	
77052	1	Fig 2.9	TO	DY	Cuts 77051 (PP)
77054	P	Fig 2.11	TO	PL	
77055	P	Fig 2.11	TO	PL	
77056	5	NG34300221	TO	DY	Cuts 77055 (PP)
77058	10	NM33839399	FE	DY	
77061	8F	NM38549350	EX-FE	DY	Liq-liq contact with FE
77064	8	NM38619351	FE	DY	
77066	P	Fig 2.11	TO	PL	
77067	LMG	Fig 2.11	TO	PL	
77068	4	NG42200020	TO	DY	
77070	4	NG42290053	TO	TCS	
77071	4	NM38599349	FE	DY	
77073	4	NM38599349	FE	DY	
77075	8F	NM39369806	TB	DY	
77076	4	"	TB	DY	Cuts 77075
77077	1	Fig 2.9	TB	DY	Cuts 77075
77078	8	NM39429807	TB	DY	
77080	3	NM39309807	TB	DY	
77082	3	NM39359801	TB	DY	

Spec	Type	Location	CR	ST	X-Cutting
77084	2	NG32720202	TO	DY	
77086	4	NG32690204	TO	DY	
77087	4F	NG32840224	TO	DY	Cuts 77078
77088	9	"	TO	DY	
77089	P	Fig 2.11	TO	PL	
77090	10	NG36800395	TO	DY	
77091	4	"	TO	DY	
77092	8	Fig 2.11	TO	THC	Kilmory type
77093	1	Fig 2.9	TO	DY	
77095	1	"	TO	DY	
77097	P	Fig 2.11	TO	PL	
77098	HMG	"	TO	PL	Pos'n WRT MRF ?
77099	P	"	TO	PL	
77100	LMG	"	GR	PL	
77101	1	Fig 2.9	LE	DY	
77102	QG	Fig 2.11	TB-EX-LE		Dunham 1968 Pl. 25
77103	QG	Fig 2.11	TB		
77104	HMG	Fig 2.11	TO	PL	Extremely fresh
77105	8	"	TO	THC	Kilmory type
77107	1	Fig 2.9	TO	DY	
77108	8	Fig 2.11	TO	THC	Kilmory type
77109	P	Fig 2.11	TO	PL	
77116	2	NM38639356	FE	DY	
77120	4	NM38539381	TB	DY	
77121	2	NM38439248	EX	DY	
77122	2	NM38349260	EX	DY	
77123	2	"	EX	DY	
77124	8	NM38239354	EX	DY	
77125	4	Fig 2.6	FE	DY	Cuts 77335
77127	8F	"	FE		Liq-liq contact with FE
77132	12	NM36579176	TO-MG	IS	
77136	P	Fig 2.11	TO	PL	
77137	10	NM36639184	MG	DY	
77138	P	Fig 2.11	MG		
77145	8F	NM38559350	EX-FE	DY	Liq-liq contact with FE
77148	4	Fig 2.6	FE	DY	
77149	8	"	FE	DY	
77155	8	NM37889494	PE	DY	
77158	2	"	PE	DY	
77159	A	Fig 2.11	TB	DY	Cut by a basic dyke
77160	7	"	GR	DY	
77174	8F	"	TO	THC	Papadil type
77175	4	NM38029186	TO	DY	
77176	4	"	TO	DY	
77177	12	NM36759121	TO	IS	
77178	3	NM36769110	TO	DY	Cuts 77179?
77179	1	Fig 2.9	TO	DY	
77180	A	Fig 2.11	TO	DY	
77181	P	"	TO	PL	
77182	P	"	MG	PL	
77183	P	"	MG	PL	
77184	10	NM36159176	MG	DY	
77191	3	NM36119181	MG	DY	
77192	1	Fig 2.9	MG	DY	

Spec	Type	Location	CR	ST	X-Cutting
77196	1	Fig 2.9	MG	DY	
77197	1	"	MG	DY	
77204	4	NM36849140	TO	IS	Cuts 77245
77205	4	NM1	TO	IS	Cuts 77204,77245
77208	4	NM39379259	TO	DY	
77209	9	"	TB	DY	Cuts 77208
77210	4F	NM39439266	TB	DY	
77212	2	"	TB	DY	
77214	2	"	TB	DY	Cuts 77212
77215	4	NM39379259	TB	DY	
77221	1	Fig 2.9	MG	DY	
77224	1	Fig 2.9	PE	DY	
77225	1	"	MG	DY	
77231	4	NM34459826	GR	DY	
77235	1	Fig 2.9	MG	DY	
77236	1	"	MG	DY	
77237	1	"	MG	DY	
77239	A	Fig 2.11	GR	DY	
77240	2	NM33309562	GR	DY	
77241	A	Fig 2.11	GR	DY	
77243	8F	Fig 2.11	TO	THC	Cut by a Gp 7 DY
77244	8F	"	TO	THC	Papadil type
77245	2	NM36849140	TO	DY	Cut by 77205
77246	LMG	Fig 2.11	TO	PL	
77249	3	NM39259785	TB-TU	DY	Cuts 77251
77250	8	"	TB-TU	DY	
77251	3	"	TB-TU	DY	
77252	HMG	Fig 2.11	FE-MG	PL	
77256	HMG	Fig 2.11	TO	PL	
77257	HMG	"	TO	PL	
77258	7	"	TO	PL	
77259	P	"	TO	PL	
77261	LMG	"	TO	PL	
77264	PD	"	TO	PL	
77265	LMG	"	TO	PL	
77267	LMG	"	TO	PL	
77268	P	"	TO	PL	
77269	4	NG34790175	TO	TCS	
77270	LMG	Fig 2.11	TO	PL	
77271	8	"	TO	THC	Kilmory type
77272	8	"	TTO	THC	Kilmory type
77273	LMG	"	TO	PL	
77274	GD	"	TO	PL	
77279	11	NM36279973	PE	DY	
77280	HMG	Fig 2.11	PE	PL	
77281	P	"	GR	PL?	
77282	LMG	"	TO	PL	
77283	LMG	"	TO	PL	
77284	4	NG34920143	TO	TCS	Cut by 77268 (Pp)
77286	P	Fig 2.11	TO	PL	
77287	LMG	"	GR	PL	
77288	HMG	"	TO	PL	
77290	P	"	TB-EX	PL	

Spec	Type	Location	CR	ST	X-cutting
77292	HMG	Fig 2.11	EX	PL	
77295	HMG	"	EX	PL	
77296	LMG	"	TB	PL	
77306	8F	NM38559350	EX-FE	DY	Liq-liq contact with FE
77309	P	Fig 2.11	TO	PL	
77314	4	NM39189713	PE	DY	
77315	8	NM39069685	PE	DY	
77316	8	NM39409846	TO	PIS	
77318	3	"	TO	PIS	
77320	HMG	Fig 2.11	TO	PIS	
77321	1	Fig 2.9	TO	DY	Chill to 52A76
77322	4F	NM33459558	GR	DY	
77323	5	NM33129564	GR	DY	
77324	4	NM33109563	GR	DY	Cuts 77325
77325	8	"	GR	DY	
77327	4	NM33939562	PE	DY	
77330	4	Fig 2.6	FE	IS	Cuts 77335
77331	4	"	FE	DY	Cuts 77343,77149,77339,77333
77332	4	"	FEE	DY	
77333	4	"	FE	IS	
77334	4F	"	FE	DY	
77335	4	"	FE	IS	Cuts 77332
77337	4	"	FE	IS	Cuts 77149,77334,77335,77343
77339	8	"	FE	IS	Cuts 77343
77340	4	"	FE	IS	Cuts 77339
77341	1	"	FE	DY	Cuts 77339 Also on Fig 2.9
77342	11	"	FE	IS	Cuts 77339
77343	4	"	FE	DY	
77344	4	"	FE	DY	Cuts 77339,77343
77346	9	"	FE	DY	
77348	4	"	FE	IS	Cuts 77343,77350
77349	8	"	FE	DY	
77350	8	"	FE	DY	
77351	4	"	FE	IS	Cuts 77149
77352	2	"	FE	DY	Cuts 77149
77356	3	NM39409846	TO	PIS	
77359	4	NG35700416	TO	DY	Cuts 77359, cut by a THC
77360	4	"	TO	DY	CHE pers collection
SR141	6		LA	DY	
SR151	5		LA	DY	"
SR159	6		LA	DY	"
SR182	6		LA	DY	"
SR211	6		LA	DY	"
SR229	5		LA	DY	"
SR238	5		LA	DY	"
SR282	6		LA	DY	"
SR284	5		LA	DY	"

APPENDIX 6.1

ELECTRON MICROPROBE ANALYSIS

The machine used was a Cambridge Instrument Company Geoscan Mark II operated at an accelerating voltage of 15 KV and a specimen current of 40 nanoamps. The focussed beam diameter is in the order of $2-5\mu$.

Samples were prepared as polished thin sections and where possible were simultaneously carbon coated with the standards to ensure a uniform carbon coat thickness. Both standards and samples were stored in a dessicator between analysing sessions to prevent deterioration of the carbon coat.

All analyses were made on a wavelength dispersive system with three analysing crystals - LiF, K.A.P. and P.E.T. Analyses prior to January 1979 were made using a single spectrometer, all subsequent analyses made simultaneous use of two spectrometers. The general analysing conditions for each element are shown in Table A6.1.

Data handling follows the general method described by Sweatman and Long (1969) and was performed by an on-line Varian 620 L/100 computer. The program Tim 3 (written by Dr. A. Peckett) performs a ZAF (Atomic number, Mass absorbtion, Fluorescence) correction on peak and background data for samples and standard. In general 4 to 6 ten-second count accumulations are obtained and averaged for each peak and background position, for each element. Background values determined for each mineral type were used throughout each analytical session.

Calculated detection limits for the elements in Table A6.1 are believed to be 200-500 pm and overall accuracy for the major constituents (> 10 wt%) is estimated to be $\pm 2\%$ (Pinsent, 1974).

TABLE A6.1

OPTIMUM ANALYSING CONDITIONS AND STANDARDS USED IN ELECTRON MICROPROBE ANALYSIS

Z	Element	Line	Analysing crystal	Counter	Peak	Background	Standard
11	Na	K α 1	K.A.P.	Flow	53 $^{\circ}$ 14'	$\begin{smallmatrix} + \\ - \end{smallmatrix}$ 2 $^{\circ}$	Jadeite
12	Mg	"	"	"	43 $^{\circ}$ 42'	"	MgO
13	Al	"	"	"	36 $^{\circ}$ 32'	"	Al ₂ O ₃
14	Si	"	P.E.T.	"	109 $^{\circ}$ 18'	"	Wollastonite
19	K	"	"	"	50 $^{\circ}$ 20'	"	K-feldspar
20	Ca	"	LiF	"	113 $^{\circ}$ 02'	"	Wollastonite
22	Ti	"	"	"	86 $^{\circ}$ 05'	"	TiO ₂
24	Cr	"	"	"	69 $^{\circ}$ 16'	"	Cr ₂ O ₃
25	Mn	"	"	"	62 $^{\circ}$ 48'	"	Rhodonite
26	Fe	"	"	"	57 $^{\circ}$ 20'	"	Fe
28	Ni	"	"	"	48 $^{\circ}$ 34'	"	Ni

APPENDIX 6.2

TABLE SHOWING WHICH MINERAL TYPES WERE ANALYSED IN EACH SPECIMEN
 OL=OLIVINE, PL=PLAGIOCLASE, CP=CLINOPYROXENE,
 OP=OPAQUE OXIDES, OPX=ORTHOPYROXENE, A=AMPHIBOLE
 TY=SPECIMEN TYPE, GP=GROUND PLUG, PP=PERIDOTITE PLUG

SPEC	TY	PHENOCRYSTS				OL	GROUNDMASS			OPX	A
		OL	PL	CP	OP		OL	PL	CP		
12A76	7		X				X	X			
32A76	10						X	X	X		
46A76	2						X	X	X		
52A76	1	X			X			X	X		
53A76	1	X					X	X			
55A76	9		X	X			X				
62A76	4			X				X	X		
66A76	1				X			X	X		
85A76	1	X			X		X	X			
95A76	4						X	X		X	
77027	8		X	X				X			
77023	1						X	X			
77024	1	X			X	X	X	X			
77039	2				X		X	X		X	
77044	4			X				X			
77047	7		X								
77052	1	X									
77058	10							X			
77067	GP							X			
77068	4							X		X	
77082	3		X	X			X	X		X	
77084	2		X					X			
77090	10		X					X			
77092	8			X			X	X			
77093	1	X			X	X		X			
77095	1	X			X		X	X			
77105	8		X	X							
77132	12						X				
77155	8						X	X		X	
77184	10				X			X			
77209	9			X							
77212	2						X	X			
77214	2		X	X			X	X		X	
77236	1										
77251	3			X			X	X			X
77258	7		X					X		X	
77268	PP							X		X	
77279	1					X	X	X			
77292	GP						X	X			
77321	1				X		X	X		X	
77341	1						X	X			
SR266	6						X	X			

Appendix 6.3

Table of mineral analyses. The specimens in each mineral type are arranged in the ascending order of their respective dolerite groups, with the gabbro and peridotite mineral analyses located at the end of each section. Note that iron is given as Fe^{2+} in all analyses, (including the opaque oxides), NA= not analysed.

Guide to analysis numbers.

The first 5 characters refer to the specimen number.

01,02 etc refer to the mineral analysis number for that specimen.

G and P refer to groundmass and phenocrysts respectively.

CLINOPYROXENES

	52A7601G	52A7602G	53A7601G	53A7602G	53A7603G	7732101G	7732103G	7734101G
WT %								
SiO ₂	47.30	46.34	48.56	47.89	47.47	43.62	44.06	45.62
TiO ₂	2.45	2.15	1.92	1.95	2.53	3.88	3.53	2.42
Al ₂ O ₃	6.15	6.32	6.62	6.49	7.50	8.56	9.55	8.86
Cr ₂ O ₃	0.15	0.19	0.14	0.16	0.40	0.02	NA	NA
FeO	12.30	8.99	8.79	9.74	8.26	10.96	10.67	10.15
MnO	2.30	0.15	0.20	0.20	0.12	0.16	0.18	0.12
MgO	11.53	12.42	12.46	11.53	12.52	10.24	10.15	10.28
CaO	24.68	21.95	21.90	21.32	21.98	20.72	20.41	24.25
Na ₂ O	0.20	0.42	0.36	0.91	0.24	0.85	0.89	0.73
NiO	0.22	0.83	0.11	0.14	0.23	NA	NA	NA
TOTAL	98.54	98.87	101.26	99.89	100.65	98.99	98.04	98.43
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.737	1.755	1.798	1.835	1.749	1.684	1.691	1.745
Ti	0.273	0.362	0.353	0.355	0.471	0.112	0.102	0.370
Al	0.275	0.284	0.289	0.278	0.328	0.388	0.409	0.309
Cr	0.045	0.033	0.004	0.022	0.012	0.001	0.000	0.020
Fe ²⁺	0.332	0.287	0.272	0.336	0.250	0.353	0.342	0.325
Mn	0.001	0.005	0.006	0.006	0.004	0.005	0.006	0.004
Mg	0.657	0.706	0.638	0.653	0.694	0.588	0.581	0.566
Ca	0.847	0.898	0.869	0.851	0.875	0.854	0.830	0.830
Na	0.015	0.031	0.026	0.057	0.017	0.063	0.066	0.054
Ni	0.001	0.001	0.003	0.004	0.007	0.000	0.000	0.000
ATOMIC PROPORTIONS								
Ca	46.13	47.58	47.51	47.30	48.11	47.59	47.62	47.68
Fe	18.29	15.16	14.88	16.80	13.77	19.67	19.43	18.65
Mg	35.78	37.34	37.60	35.90	38.12	32.75	32.95	33.67
MG-NUMBER								
M/M+F	65.42	71.12	71.64	68.12	73.47	62.48	62.90	64.35

CLINOPYROXENES

	7734102G	7709501G	85A7601G	85A7602G	69A7602G	69A7603G	7702411G	7702412G
WT %								
SiO ₂	45.72	45.16	49.21	49.45	48.61	48.59	47.66	47.40
TiO ₂	2.59	1.97	1.95	1.25	2.36	1.58	1.66	1.91
Al ₂ O ₃	6.62	8.50	5.47	4.13	4.54	4.15	5.73	5.09
Cr ₂ O ₃	2.94	0.16	0.02	0.29	0.17	0.13	0.20	0.21
FeO	11.87	9.43	10.03	8.44	8.28	8.18	8.85	9.31
MnO	0.21	0.17	0.30	0.17	0.14	0.19	0.36	0.28
MgO	11.17	11.69	14.47	14.55	13.50	13.76	12.24	11.35
CaO	19.80	20.21	18.85	19.97	21.77	21.82	22.98	23.46
Na ₂ O	0.65	0.55	0.40	0.33	0.40	0.22	0.55	0.47
NiO	NA	NA	NA	NA	0.19	0.15	NA	NA
TOTAL	98.67	97.84	100.70	98.58	100.16	98.77	100.43	100.08

ATOMIC PROPORTIONS BASED ON 6 OXYGENS

Si	1.762	1.735	1.824	1.866	1.816	1.843	1.708	1.791
Ti	0.075	0.057	0.054	0.035	0.066	0.045	0.047	0.054
Al	0.331	0.385	0.239	0.184	0.244	0.185	0.254	0.271
Cr	0.001	0.005	0.001	0.000	0.005	0.004	0.006	0.006
Fe ₂	0.383	0.303	0.311	0.266	0.259	0.259	0.278	0.294
Mn	0.007	0.005	0.009	0.005	0.004	0.006	0.011	0.009
Mg	0.642	0.670	0.800	0.818	0.757	0.777	0.686	0.630
Ca	0.818	0.832	0.749	0.807	0.871	0.885	0.925	0.934
Na	0.049	0.041	0.029	0.024	0.029	0.016	0.040	0.034
Ni	0.000	0.000	0.000	0.000	0.006	0.005	0.000	0.000

ATOMIC PROPORTIONS

Ca	44.39	46.11	40.27	42.67	46.17	46.09	48.98	50.40
Fe	23.77	16.79	16.72	14.08	13.71	13.48	14.72	15.76
Mg	34.84	37.10	43.01	43.25	40.12	40.43	36.29	34.24

MG-NUMBER

M/M.F.	62.65	68.84	72.00	75.45	74.54	74.99	71.14	68.48

CLINDPYROXENES

	46A7621G	46A7622G	77A3901G	77A3902G	77A8401G	77A8403G	7721201G	7721202G
WT. %								
SiO ₂	46.98	46.72	47.11	48.33	47.89	47.51	46.57	45.33
TiO ₂	1.45	1.33	1.67	0.95	1.52	1.38	1.73	1.72
Al ₂ O ₃	6.38	5.64	5.81	4.41	5.75	4.58	5.87	5.88
Cr ₂ O ₃	NA	0.44	0.14	0.32	0.15	0.26	0.03	0.32
FeO	7.87	8.25	9.45	10.49	8.58	11.49	9.85	10.58
MnO	0.84	0.18	0.19	0.25	0.15	0.27	0.23	0.34
MgO	13.71	13.65	12.82	13.29	13.26	13.12	12.70	12.62
CaO	23.83	22.74	21.43	22.72	21.85	19.68	21.57	22.24
Na ₂ O	0.45	0.46	0.50	0.53	0.36	0.54	0.57	0.70
NiO	0.28	0.24	NA	0.05	NA	NA	0.06	0.12
TOTAL	97.46	97.07	98.72	98.74	99.61	98.23	99.07	98.63
ATOMIC PROPORTIONS BASED ON 5 OXYGENS								
Si	1.797	1.831	1.796	1.836	1.823	1.828	1.772	1.777
Ti	0.042	0.039	0.048	0.027	0.046	0.040	0.050	0.052
Al	0.274	0.255	0.261	0.199	0.255	0.228	0.264	0.266
Cr	0.000	0.001	0.004	0.001	0.004	0.002	0.001	0.001
Fe ₂	0.252	0.255	0.341	0.335	0.270	0.357	0.315	0.340
Mn	0.010	0.006	0.006	0.006	0.005	0.009	0.007	0.011
Mg	0.782	0.785	0.729	0.757	0.744	0.752	0.728	0.721
Ca	0.854	0.857	0.859	0.849	0.881	0.811	0.863	0.832
Na	0.033	0.034	0.037	0.039	0.026	0.040	0.042	0.052
Ni	0.003	0.001	0.000	0.002	0.000	0.000	0.002	0.003
ATOMIC PROPORTIONS								
Ca	45.24	44.92	45.48	43.72	46.50	42.24	45.84	43.73
Fe	13.34	13.95	15.95	17.27	14.25	18.58	16.34	13.35
Mg	41.42	41.14	38.57	39.01	39.25	39.18	37.82	37.93
MG-NUMBER								
M/H+P	75.64	74.67	70.74	69.31	73.37	67.83	69.83	67.42

CLINOPYROXENES

	7721401P	7721402P	7721403P	7721404G	7721405P	7721406G	7721407G	7721408P
WT %								
SiO ₂	51.31	51.27	51.36	49.15	49.25	49.57	48.60	45.50
TiO ₂	0.82	0.78	0.56	1.35	1.33	1.33	1.29	2.34
Al ₂ O ₃	2.58	1.89	2.53	5.49	5.61	4.49	5.37	5.57
Cr ₂ O ₃	0.17	0.06	0.42	0.26	0.46	NA	0.18	0.17
FeO	9.50	10.17	7.31	7.51	6.50	10.01	7.94	8.01
MnO	0.21	0.19	0.15	0.11	0.16	0.17	0.13	0.14
MgO	15.24	14.91	17.20	14.88	13.80	12.95	14.00	12.51
CaO	19.69	19.56	19.31	21.88	22.01	21.21	21.55	21.40
Na ₂ O	0.25	0.24	0.22	0.29	0.00	0.00	0.27	0.00
NiO	NA	NA	NA	NA	NA	NA	NA	NA
TOTAL	99.77	99.07	99.00	100.13	99.22	99.73	99.33	97.20
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.915	1.932	1.910	1.827	1.838	1.863	1.824	1.810
Ti	0.023	0.022	0.014	0.036	0.037	0.038	0.036	0.058
Al	0.113	0.084	0.111	0.240	0.247	0.199	0.238	0.254
Cr	0.005	0.002	0.012	0.008	0.014	0.000	0.005	0.005
Fe ²⁺	0.295	0.321	0.227	0.233	0.206	0.315	0.249	0.285
Mn	0.007	0.006	0.005	0.003	0.005	0.005	0.004	0.005
Mg	2.848	2.838	2.958	2.787	2.768	2.726	2.783	2.720
Ca	2.787	2.790	2.769	3.871	3.880	3.854	3.867	3.886
Na	0.018	0.018	0.016	0.021	0.000	0.000	0.020	0.000
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ATOMIC PROPORTIONS								
Ca	40.76	40.55	39.35	46.23	47.48	45.09	45.63	46.85
Fe	15.35	16.45	11.63	12.38	11.11	16.61	13.12	15.45
Mg	43.89	43.00	49.02	41.39	41.41	38.30	41.24	38.10
Mg=NUMBER								
M/M+F	74.09	72.32	80.83	76.97	78.84	69.75	75.86	71.68

CLINOPYROXENES

	7708202P	7708204G	7725101G	7725102G	7725103P	7725104P	7704401P	7704403P
WT. %								
SiO ₂	47.66	47.12	51.63	46.60	50.07	49.28	51.19	51.71
TiO ₂	1.61	2.23	4.86	2.35	1.18	1.13	0.04	0.60
Al ₂ O ₃	4.73	5.73	3.01	5.42	2.44	2.51	4.74	2.71
Cr ₂ O ₃	0.17	0.22	0.20	NA	0.10	NA	0.58	0.27
FeO	8.92	9.28	8.32	10.80	9.69	9.23	6.44	7.58
MnO	0.19	0.18	0.12	0.17	0.35	0.26	0.14	0.23
MgO	12.73	12.65	15.33	11.68	14.46	14.31	15.71	17.10
CaO	21.29	21.14	20.43	21.00	19.60	21.85	20.38	18.24
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.26
NiO	NA	NA	NA	NA	NA	NA	0.10	0.05
TOTAL	97.28	96.37	99.90	98.02	97.85	98.57	100.48	98.83
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.837	1.797	1.913	1.790	1.911	1.879	1.872	1.921
Ti	0.047	0.066	0.024	0.068	0.034	0.032	0.026	0.010
Al	0.215	0.258	0.131	0.247	0.108	0.113	0.204	0.119
Cr	0.005	0.007	0.006	0.000	0.003	0.000	0.017	0.008
Fe ₂	0.287	0.290	0.258	0.349	0.309	0.294	0.107	0.236
Mn	0.006	0.006	0.004	0.006	0.011	0.008	0.004	0.007
Mg	0.731	0.719	0.847	0.672	0.823	0.813	0.856	0.947
Ca	0.879	0.862	0.811	0.869	0.801	0.893	0.708	0.726
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.019
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.002
ATOMIC PROPORTIONS								
Ca	46.34	46.09	42.34	45.97	41.46	44.63	43.12	38.85
Fe	15.12	15.48	13.46	18.45	16.00	14.71	10.64	12.34
Mg	38.54	38.44	44.20	35.57	42.55	40.56	46.24	49.68
MG-NUMBER								
M/M+F	71.83	71.29	76.66	65.84	72.68	73.43	81.30	80.07

CLINOPYROXENES

	7704404P	7706001G	7706002G	95A7501G	95A7602G	95A7603G	95A7604G	62A7601P
WT %								
SiO ₂	49.61	46.77	48.03	47.96	49.18	48.26	48.24	57.47
TiO ₂	1.43	2.41	1.32	1.54	1.43	2.19	2.19	0.80
Al ₂ O ₃	6.31	5.14	4.79	5.58	4.48	4.87	4.97	3.20
Cr ₂ O ₃	0.06	0.03	NA	0.06	0.04	0.08	0.07	0.22
FeO	8.40	12.64	11.72	10.59	11.74	12.35	11.02	8.21
MnO	0.24	0.29	0.34	0.25	0.39	0.28	0.25	0.44
MgO	12.86	12.15	12.84	13.56	12.77	12.36	12.67	15.41
CaO	18.99	19.91	18.40	19.10	17.60	19.29	19.51	20.47
Na ₂ O	0.66	0.41	0.68	0.48	0.45	0.45	0.60	0.30
NiO	NA	NA	NA	NA	NA	NA	NA	NA
TOTAL	98.76	99.35	98.08	99.22	98.08	100.13	99.91	98.99
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.858	1.795	1.847	1.815	1.860	1.825	1.827	1.804
Ti	0.044	0.058	0.038	0.044	0.041	0.062	0.062	0.025
Al	0.279	0.232	0.217	0.249	0.242	0.217	0.222	0.137
Cr	0.002	0.001	0.000	0.002	0.001	0.002	0.002	0.007
Fe ₂	0.263	0.406	0.377	0.335	0.375	0.391	0.378	0.258
Mn	0.008	0.009	0.011	0.008	0.014	0.009	0.008	0.013
Mg	0.718	0.695	0.734	0.771	0.728	0.697	0.682	0.841
Ca	0.762	0.819	0.758	0.775	0.721	0.782	0.792	0.824
Na	0.062	0.031	0.051	0.035	0.033	0.033	0.051	0.022
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ATOMIC PROPORTIONS								
Ca	43.72	42.65	47.67	41.19	39.53	41.82	42.78	42.86
Fe	15.00	21.14	20.17	17.83	20.58	20.90	20.40	13.42
Mg	41.19	36.21	39.26	40.98	39.90	37.28	36.82	43.72
MG#NUMBER								
M/M+F	73.18	63.14	66.06	69.69	65.97	64.08	64.35	75.52

CLINOPYROXENES

	62A7602P	62A7603G	62A7604G	62A7605G	SR28201G	SR28202G	SP28203G	12A7601G
WT. %								
SiO ₂	51.13	48.79	50.03	51.43	50.20	51.57	50.70	49.50
TiO ₂	2.88	1.54	1.48	0.82	1.25	0.69	0.73	1.54
Al ₂ O ₃	3.15	4.23	4.62	3.35	4.65	2.31	4.25	5.27
Cr ₂ O ₃	2.18	2.04	0.05	0.23	2.39	0.15	2.32	2.09
FeO	8.02	11.14	8.64	6.47	8.04	8.24	7.82	9.13
MnO	0.54	0.84	0.54	0.40	0.22	0.30	0.18	0.23
MgO	14.87	13.04	14.32	15.19	15.11	16.08	15.02	13.91
CaO	20.27	19.65	20.53	20.85	19.83	19.39	19.69	20.97
Na ₂ O	0.32	0.37	0.23	0.26	0.23	0.21	0.24	0.35
NiO	NA	NA	NA	NA	0.12	0.13	0.08	NA
TOTAL	99.34	99.64	100.44	99.00	99.84	99.07	99.93	100.79
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.939	1.849	1.856	1.913	1.861	1.924	1.874	1.836
Ti	0.025	0.044	0.041	0.023	0.029	0.019	0.020	0.043
Al	0.139	0.189	0.202	0.147	0.223	0.102	0.185	0.222
Cr	0.045	0.031	0.041	0.007	0.011	0.004	0.009	0.003
Fe ₂	0.250	0.353	0.268	0.201	0.249	0.257	0.242	0.283
Mn	0.017	0.027	0.017	0.013	0.017	0.009	0.006	0.007
Mg	0.828	0.737	0.792	0.842	0.835	0.894	0.877	0.769
Ca	0.811	0.798	0.816	0.831	0.788	0.775	0.780	0.833
Na	0.023	0.027	0.017	0.019	0.017	0.015	0.017	0.025
Ni	0.000	0.000	0.000	0.000	0.004	0.004	0.002	0.000
ATOMIC PROPORTIONS								
Ca	42.94	42.27	43.50	44.33	42.08	40.24	41.07	44.20
Fe	13.23	18.70	14.29	10.74	13.32	13.35	12.73	15.02
Mg	43.83	39.02	42.21	44.93	44.60	46.42	46.20	40.78
MG-NUMBER								
M/M+F	76.81	67.60	74.71	80.71	77.01	77.57	78.40	73.09

CLINOPYROXYENES

	12A7532G	12A7533G	7709221G	7709222G	7709223P	7709224P	7712531P	7715531G
WT %								
SiO ₂	49.62	50.25	52.57	53.36	53.26	53.39	53.59	51.61
TiO ₂	1.62	1.49	0.54	0.38	2.36	0.33	2.31	0.61
Al ₂ O ₃	5.86	6.41	3.42	2.64	2.47	2.25	2.38	1.87
Cr ₂ O ₃	2.25	2.25	0.48	0.26	0.22	0.21	0.37	0.46
FeO	7.48	6.27	7.43	7.68	6.37	6.38	5.92	10.26
MnO	2.14	2.17	2.14	2.16	2.13	0.23	2.13	0.22
MgO	13.53	13.53	16.21	16.96	18.43	17.98	17.68	15.55
CaO	21.17	20.93	19.11	16.41	19.43	18.28	19.64	19.23
Na ₂ O	0.31	0.33	0.22	0.21	0.22	0.27	0.17	0.33
NiO	NA	NA	NA	NA	NA	NA	0.10	NA
TOTAL	99.45	99.18	99.52	99.56	107.89	98.82	100.20	99.71
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.848	1.852	1.935	1.955	1.929	1.955	1.947	1.931
Ti	0.045	0.042	0.015	0.010	0.010	0.009	0.028	0.017
Al	0.257	0.262	0.148	0.114	0.105	0.098	0.102	0.082
Cr	0.034	0.033	0.002	0.002	0.006	0.006	0.011	0.002
Fe ²⁺	0.233	0.194	0.229	0.235	0.193	0.197	0.180	0.321
Mn	0.004	0.005	0.004	0.005	0.004	0.001	0.004	0.007
Mg	0.724	0.747	0.879	0.926	0.995	0.987	0.958	0.867
Ca	0.845	0.833	0.754	0.723	0.754	0.721	0.765	0.771
Na	0.022	0.022	0.016	0.015	0.015	0.019	0.012	0.022
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000
ATOMIC PROPORTIONS								
Ca	46.92	45.84	48.50	38.36	38.63	37.87	40.20	39.35
Fe	12.93	10.97	12.29	12.49	9.94	10.32	9.46	16.39
Mg	40.16	42.19	47.21	49.16	51.24	51.82	50.34	44.26
MG=NUMBER								
M/M+F	75.64	79.37	79.34	79.74	83.76	83.40	84.18	72.98

CLINOPYROXENES

	7715502G	7715503G	7700601P	55A7601P	55A7602P	55A7603P	7720901P	7720902P
WT %								
SiO ₂	49.23	49.45	51.20	51.34	51.28	51.43	52.03	53.70
TiO ₂	1.18	1.29	2.02	2.89	1.27	1.09	2.92	2.88
Al ₂ O ₃	3.78	3.62	3.60	2.55	2.25	3.17	2.74	2.64
Cr ₂ O ₃	2.26	2.28	2.89	2.12	2.11	2.16	2.69	2.12
FeO	12.54	12.64	8.75	12.24	12.56	12.23	11.44	11.31
MnO	2.23	2.27	2.21	2.21	2.25	2.23	2.95	2.79
MgO	14.17	14.23	15.61	14.37	16.62	15.62	16.13	15.71
CaO	23.23	18.15	19.21	19.94	17.29	18.84	15.57	18.75
Na ₂ O	0.42	0.42	2.00	0.26	2.33	0.30	2.24	2.19
NiO	NA	NA	NA	NA	NA	NA	NA	NA
TOTAL	99.44	99.93	100.29	100.28	100.56	100.60	99.91	101.28
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.855	1.867	1.888	1.910	1.896	1.890	1.901	1.888
Ti	0.034	0.037	0.026	0.025	0.032	0.030	0.026	0.025
Al	0.169	0.161	0.157	0.116	0.129	0.135	0.121	0.116
Cr	0.022	0.022	0.026	0.024	0.023	0.025	0.023	0.021
Fe ²⁺	0.333	0.399	0.271	0.313	0.330	0.311	0.358	0.352
Mn	0.027	0.029	0.027	0.027	0.028	0.027	0.030	0.025
Mg	0.799	0.792	0.862	0.825	0.916	0.873	0.809	0.873
Ca	0.812	0.734	0.761	0.796	0.685	0.748	0.664	0.747
Na	0.031	0.029	0.032	0.019	0.024	0.022	0.017	0.014
Ni	0.000	0.000	0.030	0.020	0.040	0.020	0.000	0.020
ATOMIC PROPORTIONS								
Ca	41.76	38.18	42.22	41.15	35.48	38.70	34.57	37.93
Fe	17.15	22.75	14.31	16.17	17.27	16.28	18.63	17.86
Mg	41.29	41.06	45.47	42.69	47.45	45.21	45.81	44.21
MG=NUMBER								
M/M+F	72.56	66.42	76.05	72.53	73.54	73.76	71.54	71.23

CLINOPYROXENES

	7720903P	7720904P	7705801G	7705802G	7709001G	7709002G	32A7601G	32A7602G
WT. %								
SiO ₂	51.55	52.71	48.36	47.98	46.14	46.45	46.96	45.58
TiO ₂	2.72	2.79	1.94	1.80	3.15	2.98	2.69	3.31
Al ₂ O ₃	2.49	2.34	5.58	5.60	4.88	4.85	4.14	5.53
Cr ₂ O ₃	2.12	2.12	2.16	0.38	3.09	0.12	2.02	2.28
FeO	12.39	10.35	9.51	8.44	12.35	10.58	9.28	9.93
MnO	2.83	0.83	0.18	0.13	0.78	0.59	0.30	2.33
MgO	16.42	15.67	13.41	13.57	10.99	11.11	10.39	9.30
CaO	17.91	18.66	21.27	21.31	19.65	21.32	24.82	24.75
Na ₂ O	3.24	0.25	0.41	0.47	0.49	0.00	0.64	0.24
NiO	NA	NA	NA	NA	NA	NA	NA	NA
TOTAL	100.67	100.93	100.92	99.68	98.52	98.10	99.24	99.32
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.909	1.923	1.802	1.803	1.790	1.799	1.806	1.758
Ti	0.020	0.022	0.054	0.051	0.092	0.087	0.078	0.096
Al	0.109	0.102	0.245	0.248	0.223	0.221	0.188	0.256
Cr	0.004	0.003	0.005	0.011	0.003	0.004	0.001	0.009
Fe ₂	0.322	0.320	0.299	0.255	0.401	0.346	0.298	0.320
Mn	0.026	0.026	0.006	0.004	0.026	0.019	0.010	0.010
Mg	0.026	0.026	0.074	0.075	0.036	0.041	0.056	0.035
Ca	0.711	0.739	0.849	0.856	0.817	0.885	1.023	1.023
Na	0.017	0.018	0.030	0.034	0.037	0.000	0.048	0.018
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ATOMIC PROPORTIONS								
Ca	36.65	38.52	44.85	45.56	44.08	47.26	53.36	54.47
Fe	16.60	16.68	15.82	14.38	21.62	18.48	15.57	17.06
Mg	46.75	44.80	39.34	40.36	34.30	34.26	31.07	28.47
MG=NUMBER								
M/M+F	73.80	72.87	71.32	74.13	61.33	64.96	66.62	62.54

CLINOPYROXENES

	7727901G	7727902G	7727903G	7727904G	7702301P	7702302P	7706701G	7706702G
WT %								
SiO ₂	52.99	49.76	51.61	50.27	47.64	47.71	51.37	49.72
TiO ₂	1.17	1.24	0.91	0.63	2.21	2.47	0.76	0.70
Al ₂ O ₃	3.12	3.26	2.69	1.32	3.58	4.07	2.51	3.29
Cr ₂ O ₃	0.42	0.13	0.17	0.07	0.05	0.00	0.06	0.09
FeO	9.77	9.61	9.48	11.31	9.64	10.53	7.57	6.39
MnO	0.69	0.93	0.80	0.51	0.27	0.31	0.30	0.19
MgO	14.83	15.28	15.10	13.17	11.64	9.85	16.31	16.30
CaO	19.11	18.66	18.60	23.35	23.42	23.23	22.88	21.71
Na ₂ O	0.29	0.29	0.34	0.31	0.37	0.36	0.31	0.21
NiO	NA	NA	NA	NA	NA	NA	0.17	0.12
TOTAL	99.99	98.96	99.69	101.04	98.62	98.33	100.24	99.32
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	1.001	1.080	1.024	1.009	1.035	1.045	1.009	1.057
Ti	0.033	0.034	0.026	0.018	0.054	0.072	0.021	0.020
Al	0.137	0.145	0.118	0.059	0.162	0.186	0.109	0.145
Cr	0.001	0.004	0.005	0.002	0.002	0.000	0.002	0.002
Fe ²⁺	0.305	0.304	0.296	0.357	0.310	0.341	0.234	0.200
Mn	0.022	0.030	0.025	0.020	0.009	0.010	0.009	0.006
Mg	0.824	0.849	0.839	0.742	0.668	0.550	0.899	0.907
Ca	0.764	0.764	0.743	0.945	0.966	0.955	0.827	0.869
Na	0.021	0.021	0.025	0.023	0.028	0.027	0.022	0.015
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.004
ATOMIC PROPORTIONS								
Ca	40.35	39.84	39.58	46.24	49.59	51.23	42.20	43.97
Fe	16.10	15.84	15.75	17.48	15.96	18.28	11.04	12.10
Mg	43.56	44.32	44.67	36.28	34.35	30.48	45.86	45.93
MG=NUMBER								
M/M+F	73.01	73.66	73.94	67.49	68.29	62.51	79.34	81.97

CLINOPYROXENES

	7729201G	7729202G	7729203G	7726804G	7726805G	7726806G
WT. %						
SiO ₂	50.50	51.16	51.28	50.36	50.98	51.34
TiO ₂	0.72	0.87	0.86	0.56	0.55	0.56
Al ₂ O ₃	2.42	2.45	2.05	4.42	3.77	3.71
Cr ₂ O ₃	0.15	0.22	0.26	1.43	1.32	1.29
FeO	13.95	11.86	11.86	4.43	4.45	4.50
MnO	0.36	0.34	0.38	0.28	0.17	0.17
MgO	15.36	14.47	14.76	16.34	16.99	15.39
CaO	18.74	19.71	19.36	21.44	21.38	21.59
Na ₂ O	0.32	0.34	0.37	0.27	0.33	0.34
NiO	0.10	0.15	0.22	0.47	0.49	0.04
TOTAL	99.67	99.81	100.42	99.10	99.13	99.99
ATOMIC PROPORTIONS BASED ON 6 OXYGENS						
Si	1.898	1.918	1.914	1.866	1.885	1.883
Ti	0.024	0.025	0.024	0.016	0.015	0.015
Al	0.137	0.129	0.093	0.176	0.164	0.164
Cr	0.034	0.041	0.032	0.041	0.039	0.037
Fe ₂	0.344	0.347	0.346	0.136	0.138	0.138
Mn	0.011	0.011	0.012	0.009	0.005	0.005
Mg	0.860	0.845	0.821	0.932	0.887	0.896
Ca	0.753	0.764	0.774	0.850	0.847	0.853
Na	0.023	0.025	0.027	0.019	0.024	0.021
Ni	0.006	0.006	0.007	0.002	0.003	0.001
ATOMIC PROPORTIONS						
Ca	38.47	39.87	39.88	44.90	45.26	45.18
Fe	17.58	18.11	17.82	7.22	7.35	7.32
Mg	43.95	42.02	42.30	47.79	47.39	47.50
MG-NUMBER						
M/M+F	71.43	69.89	70.36	86.88	86.57	86.65

ORTHOPYROXENES IN THE EARLY (HIGH MGO) GABBROS

	7729204G	7729205G	7729206G
WT %			
SiO ₂	52.52	53.45	53.22
TiO ₂	1.35	2.47	2.46
Al ₂ O ₃	1.41	1.45	1.42
Cr ₂ O ₃	3.33	2.04	3.34
FeO	19.41	18.12	18.43
MnO	2.52	2.54	2.56
MgO	23.31	23.95	24.72
CaO	2.29	1.98	1.92
Na ₂ O	2.17	2.21	2.21
NiO	2.10	2.13	2.10
TOTAL	122.33	122.12	122.48
ATOMIC PROPORTIONS BASED ON 6 OXYGENS			
Si	1.935	1.956	1.943
Ti	2.029	2.013	2.013
Al	2.061	2.063	2.061
Cr	2.021	2.021	2.021
Fe ₂	2.598	2.554	2.559
Mn	2.016	2.017	2.017
Mg	1.254	1.327	1.345
Ca	2.083	2.078	2.075
Na	2.027	2.021	2.021
Ni	2.006	2.024	2.023
ATOMIC PROPORTIONS			
Ca	4.24	4.21	3.81
Fe	32.76	28.58	27.93
Mg	65.22	67.41	68.26
MG=NUMBER			
M/M+F	57.88	70.22	70.96

AMPHIBOLES IN THE GROUP 1 (TYPE 3) PICRITES

	7723601G	7723602G	7723603G
WT %			
SiO ₂	42.44	41.37	41.87
TiO ₂	4.94	4.73	5.21
Al ₂ O ₃	11.49	11.74	11.26
Cr ₂ O ₃	0.03	0.15	0.07
FeO	9.03	8.75	8.88
MnO	0.14	0.12	0.14
MgO	14.97	15.08	14.75
CaO	11.87	11.86	11.92
Na ₂ O	3.13	2.97	2.50
K ₂ O	0.41	0.42	0.46
TOTAL	98.45	97.19	97.06
ATOMIC PROPORTIONS BASED ON 23 OXYGENS			
Si	6.152	6.078	6.150
Ti	2.539	2.523	2.575
Al	1.963	2.033	1.940
Cr	0.003	0.017	0.008
Fe ²⁺	1.095	1.075	1.091
Mn	0.017	0.015	0.017
Mg	3.235	3.323	3.229
Ca	1.844	1.867	1.876
Na	0.880	0.846	0.712
K	0.076	0.079	0.086
MG=NUMBER			
M/M+F	74.71	75.44	74.75

OLIVINES GROUP 1 TYPE 1

	52A7603P	52A7604P	53A7604P	53A7605P	53A7606P	53A7607P
WT %						
SiO ₂	40.88	40.94	40.65	38.50	39.54	40.60
Cr ₂ O ₃	0.00	0.11	0.11	0.00	0.00	0.10
FeO	11.10	11.26	12.88	13.23	14.54	12.90
MnO	0.17	0.15	0.20	0.16	0.22	0.23
MgO	47.73	46.99	46.37	46.45	45.36	45.85
CaO	0.33	0.37	0.34	0.32	0.40	0.36
NiO	0.36	0.37	0.43	0.46	0.34	0.39
TOTAL	100.66	100.19	100.98	99.12	100.40	100.43
ATOMIC PROPORTIONS BASED ON 4 OXYGENS						
Si	0.996	1.002	0.995	0.955	0.984	0.999
Cr	0.002	0.002	0.002	0.000	0.000	0.002
Fe ₂	0.226	0.231	0.264	0.277	0.303	0.266
Mn	0.004	0.003	0.004	0.003	0.005	0.005
Mg	1.734	1.715	1.691	1.736	1.683	1.682
Ca	0.009	0.010	0.009	0.009	0.011	0.009
Ni	0.527	0.544	0.632	0.693	0.508	0.577
MG=NUMBER						
M/MOF	88.46	88.15	86.52	86.22	84.76	86.37

OLIVINES GROUP 1 TYPE 2

	7705201P	7705223P	7709301P	7709302P	7709323P	7709304G	7709502P	7709503P
WT %								
SiO2	41.98	41.85	43.52	39.65	39.77	39.76	39.66	39.63
FeO	10.94	11.95	12.82	11.87	11.35	14.84	12.76	12.79
MnO	0.27	0.19	0.19	0.17	0.15	0.27	0.18	0.22
MgO	46.85	47.34	46.95	48.10	47.04	44.83	46.88	47.14
CaO	0.32	0.23	0.36	0.35	0.40	0.67	0.36	0.38
NiO	0.37	0.39	0.32	0.40	0.35	0.25	0.37	0.36
TOTAL	100.66	101.96	101.26	100.54	99.06	100.58	100.21	100.52
ATOMIC PROPORTIONS BASED ON 4 OXYGENS								
Si	1.019	1.008	0.993	0.973	0.988	0.990	0.980	0.977
Fe2	0.222	0.241	0.262	0.244	0.236	0.338	0.264	0.264
Mn	0.004	0.004	0.004	0.004	0.003	0.006	0.004	0.005
Mg	1.0695	1.0698	1.0710	1.0760	1.0742	1.0664	1.0728	1.0733
Ca	0.008	0.007	0.009	0.009	0.011	0.018	0.010	0.010
Ni	0.0539	0.0550	0.0470	0.0590	0.0522	0.0374	0.0550	0.0534
MG=NUMBER								
M/MOF	88.42	87.58	86.72	87.84	88.08	84.37	86.75	86.79

OLIVINES GROUP 1

	85A7602P	85A7603P	7702401P	7702402P	7702403P	7702405P	7702406P	7702407P
WT. %								
SiO ₂	40.45	39.86	38.95	39.55	37.05	38.34	38.76	37.84
FeO	11.68	13.98	21.62	20.22	21.82	23.13	22.31	21.75
MnO	0.13	0.22	0.39	0.36	0.36	0.44	0.47	0.42
MgO	45.23	45.21	38.86	38.72	38.91	38.47	38.64	39.12
CaO	0.33	0.44	0.32	0.42	0.44	0.24	0.51	0.27
NiO	0.34	0.33	0.22	0.15	0.21	0.18	0.20	0.20
TOTAL	99.16	100.04	100.36	99.22	98.79	100.80	100.89	99.60
ATOMIC PROPORTIONS BASED ON 4 OXYGENS								
Si	1.003	0.992	1.003	1.021	0.976	0.991	0.997	0.986
Fe ₂	0.242	0.291	0.465	0.432	0.480	0.520	0.480	0.474
Mn	0.003	0.005	0.009	0.008	0.008	0.010	0.010	0.009
Mg	1.0709	1.0677	1.0491	1.0491	1.0527	1.0483	1.0482	1.0519
Ca	0.009	0.012	0.009	0.012	0.012	0.007	0.014	0.008
Ni	0.007	0.004	0.003	0.003	0.003	0.002	0.003	0.003
MG-NUMBER								
M/M+F	87.59	85.22	76.21	77.51	76.07	74.78	75.53	76.22

OLIVINES GROUP 1 AND PERIDOTITE PLUG

	7722410G	7726801P	7726802P	7726803P
WT. %				
SiO ₂	38.72	40.24	40.01	40.60
FeO	22.90	14.23	14.33	14.60
MnO	2.53	0.26	2.10	0.01
MgO	36.86	45.12	44.60	44.33
CaO	0.54	0.26	0.26	0.16
NiO	0.17	0.37	0.45	0.33
TOTAL	99.72	100.25	99.75	100.03
ATOMIC PROPORTIONS BASED ON 4 OXYGENS				
Si	1.011	0.998	0.997	1.000
Fe ₂	0.500	0.290	0.299	0.304
Mn	0.012	0.005	0.002	0.000
Mg	1.435	1.668	1.656	1.643
Ca	0.015	0.007	0.007	0.004
Ni	0.027	0.051	0.064	0.049
MG=NUMBER				
M/M+F	74.15	85.17	84.73	84.40

PLAGIOCLASE

	53A7609G	85A7608G	85A7609G	7702415G	7702416G	7702417G	7700378G	7709511G
WT %								
SiO ₂	49.00	49.55	50.23	50.30	58.92	51.34	49.75	48.70
Al ₂ O ₃	30.58	30.24	30.23	29.98	25.16	30.09	28.93	30.24
FeO	0.57	0.80	0.79	0.52	0.51	0.79	1.74	1.42
MgO	0.40	0.38	1.16	0.22	0.27	0.31	1.55	0.86
CaO	15.32	13.31	14.00	13.75	7.94	13.13	13.62	14.50
Na ₂ O	2.64	3.24	2.66	3.78	6.26	3.93	2.70	2.68
K ₂ O	0.26	0.13	0.09	0.09	0.23	0.11	0.05	0.44
TOTAL	98.37	98.12	99.16	98.73	99.25	99.70	98.34	98.49
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	9.129	9.217	9.240	9.320	10.601	9.394	9.273	9.085
Al	6.714	6.629	6.554	6.534	5.335	6.485	6.355	6.639
Fe ²⁺	0.089	0.124	0.122	0.080	0.077	0.121	0.271	0.222
Mg	0.000	0.044	0.318	0.061	0.072	0.085	0.431	0.239
Ca	3.058	2.653	2.760	2.725	1.523	2.573	2.720	2.916
Na	1.026	1.169	0.949	1.356	2.184	1.394	0.976	0.969
K	0.014	0.024	0.021	0.021	0.053	0.026	0.012	0.010
ATOMIC PROPORTIONS								
Ca	74.62	68.99	73.99	66.43	40.51	64.45	73.36	74.87
Na	25.03	30.39	25.44	33.05	58.09	34.91	26.32	24.89
K	0.35	0.62	0.57	0.52	1.40	0.64	0.32	0.24

PLAGIOCLASE

	7732104G	7732105G	7734103G	7734104G	46A7608G	46A7609G	7723910G	7703811G
WT %								
SiO ₂	52.35	52.39	47.55	48.55	48.88	55.23	51.23	52.55
Al ₂ O ₃	27.07	26.88	32.40	29.92	32.74	27.33	28.38	28.74
FeO	1.87	2.24	1.36	1.51	2.76	0.93	1.39	1.29
MgO	1.07	2.92	1.25	0.94	0.18	0.49	0.86	0.90
CaO	11.62	12.53	15.25	15.39	14.65	10.69	14.13	13.92
Na ₂ O	4.67	5.49	3.22	2.79	3.17	4.75	3.59	3.23
K ₂ O	2.19	0.17	0.13	0.10	0.29	0.21	0.14	0.20
TOTAL	98.85	100.72	98.84	98.98	98.47	99.63	99.72	98.72
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	9.693	9.626	8.898	9.350	9.122	10.215	9.432	9.381
Al	5.926	5.828	6.724	6.558	6.745	5.842	6.158	6.285
Fe ²⁺	0.293	0.343	0.213	0.251	0.118	0.136	0.214	0.200
Mg	0.295	0.251	0.293	0.251	0.050	0.132	0.236	0.249
Ca	2.325	2.491	3.060	3.014	2.923	2.077	2.788	2.764
Na	1.676	1.952	1.121	1.028	1.145	1.672	1.282	1.162
K	0.245	0.042	0.031	0.024	0.021	0.049	0.033	0.021
ATOMIC PROPORTIONS								
Ca	57.25	55.47	72.64	74.49	71.49	54.72	67.96	73.32
Na	41.64	43.64	26.62	24.92	27.99	44.24	31.24	29.44
K	1.11	0.89	0.74	0.59	0.52	1.28	0.80	0.54

PLAGIOCLASE

	7721204G	7721205G	7721206G	7708408P	7721405P	7721406G	7724107P	7721408P
WT. %								
SiO ₂	53.29	49.69	49.49	50.66	49.36	55.41	52.25	46.72
Al ₂ O ₃	28.32	30.18	32.54	29.45	31.36	26.63	26.02	33.21
FeO	1.37	1.35	1.27	1.29	0.54	0.63	0.91	0.46
MgO	0.41	0.54	0.41	0.44	NA	NA	NA	NA
CaO	12.78	16.25	15.00	15.33	14.88	9.69	11.10	17.33
Na ₂ O	4.53	2.86	2.65	3.12	3.92	6.96	6.47	2.21
K ₂ O	0.09	0.04	0.01	0.09	0.09	0.14	0.09	0.08
TOTAL	100.79	100.98	99.17	100.18	100.15	99.46	97.74	99.81
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	9.658	9.094	9.147	9.291	9.055	10.494	9.772	8.636
Al	6.049	6.509	6.652	6.365	6.780	5.717	5.933	7.234
Fe ²⁺	0.208	0.207	0.165	0.167	0.083	0.096	0.142	0.071
Mg	0.111	0.136	0.113	0.122	0.000	0.000	0.000	0.000
Ca	2.482	3.189	2.971	3.013	2.925	1.891	2.225	3.432
Na	1.092	1.015	0.950	1.110	1.394	2.458	2.346	0.720
K	0.021	0.009	0.002	0.021	0.021	0.033	0.021	0.019
ATOMIC PROPORTIONS								
Ca	60.61	75.59	75.73	72.71	67.39	43.16	48.44	82.28
Na	38.88	24.09	24.21	26.78	32.13	56.10	51.09	17.27
K	0.51	0.22	0.06	0.51	0.49	0.74	0.47	0.45

PLAGIOCLASE

	7721429P	7708205G	7708206G	7708206G	7708239G	7708212P	7725105G	7725106G
WT. %								
SiO ₂	52.24	49.34	53.67	49.52	54.31	46.81	49.05	52.43
Al ₂ O ₃	29.14	30.93	28.33	30.49	28.21	32.79	32.82	31.36
FeO	0.65	0.67	1.05	0.63	0.69	0.50	0.64	0.62
MgO	NA	NA	NA	NA	NA	NA	NA	NA
CaO	12.93	14.48	11.11	14.07	12.82	16.66	14.44	14.44
Na ₂ O	4.67	4.01	5.02	4.42	7.30	1.86	4.15	3.92
K ₂ O	0.13	0.06	0.19	0.08	0.16	0.21	0.03	ND
TOTAL	97.96	99.49	100.27	99.31	101.40	98.54	99.13	100.47
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	9.391	9.105	9.753	9.173	9.775	8.733	9.001	9.101
Al	6.419	6.727	6.067	6.642	5.984	7.189	6.732	6.671
Fe ₂	0.133	0.103	0.160	0.097	0.090	0.278	0.099	0.095
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	2.590	2.864	2.163	2.787	2.087	3.330	2.868	2.820
Na	1.693	1.435	2.006	1.584	2.548	0.673	1.401	1.385
K	0.031	0.014	0.044	0.019	0.037	0.022	0.007	0.000
ATOMIC PROPORTIONS								
Ca	63.04	66.40	58.39	63.48	44.67	83.14	65.68	67.26
Na	39.24	33.27	48.59	36.09	54.54	16.80	34.16	32.94
K	0.72	0.33	1.03	0.43	0.79	0.06	0.16	0.00

PLAGIOCLASE

	95A7605G	95A7606G	12A7604P	12A7605P	12A7606G	12A7607G	7724702P	7725001P
WT. %								
SiO ₂	57.22	58.52	46.85	46.95	59.31	59.12	45.52	47.32
Al ₂ O ₃	25.81	24.63	32.48	32.38	25.04	24.99	33.98	32.91
FeO	0.72	1.21	0.55	0.30	1.41	1.38	0.58	0.54
MgO	0.12	0.79	0.25	0.00	0.44	0.40	0.05	0.19
CaO	8.79	8.35	17.47	16.99	7.86	7.85	17.32	17.38
Na ₂ O	6.42	5.50	1.33	1.79	5.94	6.72	1.56	1.31
K ₂ O	0.19	0.17	0.00	0.02	0.11	0.13	0.03	0.01
TOTAL	99.27	99.88	98.98	98.43	99.81	100.59	99.04	99.66
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	10.366	10.530	8.715	8.767	10.585	10.557	7.865	8.729
Al	5.510	5.223	7.120	7.125	5.293	5.259	6.919	7.154
Fe ²⁺	0.109	0.182	0.086	0.047	0.212	0.206	0.084	0.083
Mg	0.032	0.212	0.069	0.000	0.118	0.126	0.031	0.052
Ca	1.706	1.554	3.482	3.399	1.511	1.502	3.207	3.435
Na	2.255	2.268	0.498	0.648	2.056	2.327	0.523	0.469
K	0.044	0.039	0.000	0.005	0.025	0.030	0.007	0.002
ATOMIC PROPORTIONS								
Ca	42.60	40.25	87.49	83.89	41.94	38.93	85.83	87.94
Na	56.30	58.74	12.51	15.99	57.36	60.30	13.99	12.00
K	1.10	1.01	0.00	0.12	0.70	0.77	0.18	0.06

PLAGIOCLASE

	7725802P	7725803P	7725804P	7709205G	7709206G	7710502P	7710503P	7710504P
WT %								
SiO ₂	46.81	48.20	47.97	52.80	52.02	46.78	49.78	48.84
Al ₂ O ₃	32.54	32.93	32.84	29.20	29.50	31.92	30.46	31.22
FeO	0.70	0.53	0.57	1.18	0.91	0.55	0.63	0.53
MgO	0.28	0.19	0.22	0.33	0.30	NA	NA	NA
CaO	16.69	16.70	16.75	13.17	13.34	19.03	15.18	15.75
Na ₂ O	1.61	1.56	1.71	3.34	3.67	2.55	2.72	2.42
K ₂ O	0.02	0.01	ND	0.17	0.18	0.08	0.12	0.09
TOTAL	98.65	100.12	100.06	100.19	99.92	100.91	98.89	99.15
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	8.728	8.825	8.800	9.590	9.491	8.634	9.211	9.037
Al	7.150	7.105	7.100	6.250	6.343	6.943	6.642	6.808
Fe ²⁺	0.109	0.081	0.087	0.179	0.139	0.085	0.007	0.082
Mg	0.078	0.052	0.060	0.089	0.082	0.000	0.000	0.000
Ca	3.334	3.276	3.293	2.563	2.638	3.763	3.010	3.182
Na	0.582	0.554	0.608	1.176	1.298	0.913	0.976	0.868
K	0.005	0.002	0.000	0.039	0.042	0.019	0.028	0.021
ATOMIC PROPORTIONS								
Ca	85.03	85.49	84.41	67.83	66.75	80.16	74.98	78.15
Na	14.84	14.45	15.59	31.13	32.88	19.44	24.31	21.32
K	0.12	0.06	0.00	1.04	1.06	0.40	0.71	0.52

PLAGIOCLASE

	7717505P	7715524G	7715525G	7715506G	7715507G	7722604P	7722625P	55A7604P
WT. %								
SiO ₂	49.74	56.55	59.20	56.80	61.46	51.22	54.23	54.12
Al ₂ O ₃	32.92	25.94	23.56	25.39	23.12	29.45	27.67	27.57
FeO	2.76	2.59	2.78	0.58	0.51	0.54	2.86	2.57
MgO	NA	NA	NA	NA	NA	NA	NA	NA
CaO	16.27	8.88	6.37	8.32	5.62	12.57	13.46	11.21
Na ₂ O	2.72	6.52	7.90	6.99	8.25	5.38	7.24	5.11
K ₂ O	0.09	0.44	2.73	0.47	0.81	0.37	2.14	2.22
TOTAL	122.30	98.92	98.54	98.25	99.57	99.63	102.60	98.60
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	9.110	10.326	12.784	12.427	11.013	9.421	9.836	9.020
Al	6.674	5.571	5.258	5.482	4.882	6.383	5.914	5.955
Fe ²⁺	2.116	2.292	2.119	2.289	2.276	2.298	2.130	2.287
Mg	2.222	2.222	2.222	2.222	2.222	2.222	2.222	2.222
Ca	3.154	1.734	1.243	1.574	1.079	2.477	2.433	2.222
Na	2.955	2.324	2.792	2.483	2.797	1.919	2.545	1.816
K	2.021	2.102	2.172	2.110	2.185	2.287	2.232	2.251
ATOMIC PROPORTIONS								
Ca	76.16	41.88	29.58	37.78	26.57	55.26	44.08	54.11
Na	23.33	55.65	66.38	59.58	68.87	42.82	55.21	44.63
K	0.51	2.47	4.04	2.64	4.56	1.94	0.70	1.26

PLAGIOCLASE

	55A7605P	55A7606G	55A7607G	7709003P	7709004P	32A7601G	32A7602G	7702303G
WT %								
SiO ₂	55.45	57.69	54.56	50.07	50.86	68.06	67.18	59.84
Al ₂ O ₃	25.82	25.96	25.05	29.90	29.07	17.13	16.46	21.25
FeO	0.83	0.75	0.72	0.45	0.65	0.50	0.11	0.59
MgO	NA	NA	NA	0.13	0.28	NA	NA	NA
CaO	10.12	9.47	10.15	12.54	11.47	1.08	0.03	5.77
Na ₂ O	6.64	5.79	0.86	2.90	3.52	7.57	0.12	7.20
K ₂ O	0.26	0.30	0.20	0.20	0.22	0.44	15.18	0.36
TOTAL	99.12	99.97	93.44	96.29	96.07	94.78	99.08	96.01
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	10.157	10.378	10.317	9.421	9.577	12.422	12.398	11.110
Al	5.573	5.504	6.006	6.630	6.451	3.679	3.580	4.653
Fe ₂	0.127	0.114	0.114	0.071	0.102	0.076	0.017	0.092
Mg	0.000	0.000	0.000	0.036	0.079	0.000	0.000	0.000
Ca	1.006	1.025	2.057	2.548	2.314	0.211	0.006	1.348
Na	2.358	2.020	0.315	1.058	1.285	2.675	0.043	2.594
K	0.061	0.059	0.048	0.048	0.053	0.102	3.574	0.085
ATOMIC PROPORTIONS								
Ca	45.09	45.64	84.98	69.73	63.36	7.06	0.16	33.47
Na	53.53	51.60	13.03	28.95	35.19	89.52	1.19	64.41
K	1.38	1.76	1.99	1.31	1.45	3.42	98.65	2.12

PLAGIOCLASE

	7702304G	7727906G	7713201G	7713202G	7713203G
WT %					
SiO ₂	65.72	63.34	67.58	67.77	64.95
Al ₂ O ₃	15.92	22.13	18.93	18.45	18.44
FeO	3.25	0.14	0.73	0.70	1.10
MgO	NA	NA	NA	NA	0.24
CaO	0.01	2.17	0.32	0.19	0.33
Na ₂ O	0.14	6.92	6.01	5.55	6.67
K ₂ O	15.04	0.11	6.81	8.22	6.86
TOTAL	97.29	94.81	102.38	100.71	98.39
ATOMIC PROPORTIONS BASED ON 32 OXYGENS					
Si	12.423	11.579	12.030	12.082	11.898
Al	3.541	4.768	3.971	3.876	3.981
Fe ₂	0.041	0.021	0.100	0.104	0.160
Mg	0.000	0.000	0.000	0.000	0.011
Ca	0.002	0.425	0.061	0.036	0.065
Na	0.051	2.453	2.074	1.020	2.369
K	3.621	0.025	1.547	1.624	1.603
ATOMIC PROPORTIONS					
Ca	0.06	14.64	1.66	0.96	1.60
Na	1.39	84.48	56.34	50.90	50.68
K	98.55	0.88	42.00	48.14	39.71

OPAQUE OXIDES: CHROME SPINELS

	52A7505P	52A7606P	52A7607P	52A7608P	69A7601P	7732107P	7709306P	7709307P
WT. %								
SiO ₂	0.13	0.04	0.07	0.05	0.11	0.23	0.02	0.02
TiO ₂	0.95	1.07	0.91	1.03	0.45	1.05	0.56	0.54
Al ₂ O ₃	24.47	25.41	24.29	27.08	26.73	28.75	31.58	30.47
Cr ₂ O ₃	38.15	34.62	37.62	33.51	33.22	32.31	30.51	32.34
FeO	19.71	22.08	18.02	20.00	21.85	18.13	20.49	17.17
MnO	0.60	0.40	0.61	0.60	0.57	0.55	0.58	0.48
MgO	15.89	15.50	15.03	15.68	15.62	16.71	15.37	17.41
CaO	0.03	0.02	0.03	0.01	0.02	0.08	0.06	0.02
TOTAL	99.90	97.28	97.38	98.05	98.17	97.81	99.17	98.45
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	0.033	0.000	0.024	0.017	0.037	0.075	0.006	0.007
Al	0.367	0.422	0.360	0.401	0.420	0.405	0.213	0.207
Cr	6.347	6.731	6.450	7.076	7.047	7.436	8.077	7.853
Fe ₂	10.467	9.701	10.568	9.263	9.264	8.839	8.254	8.816
Mn	5.477	5.699	5.127	5.624	6.171	5.024	5.615	4.741
Mg	0.293	0.245	0.305	0.296	0.283	0.268	0.280	0.233
Ca	5.586	5.597	5.697	5.553	5.581	5.857	5.328	6.081
	0.591	0.403	0.605	0.199	0.401	1.573	1.166	0.192
MOLECULAR PROPORTIONS								
RO ₂	0.13	0.00	0.00	0.07	0.15	0.31	0.03	0.03
R ₂ O ₃	13.32	14.41	13.55	15.27	14.21	16.35	17.54	16.86
RO	86.55	85.59	86.35	84.67	85.65	83.34	82.43	83.12
MG-NUMBER								
M/M+F	2.73	2.46	2.81	3.09	2.97	2.94	3.28	2.58

OPAQUE OXIDES: CHROME SPINELS

	7709504P	7709505P	7709506P	7709507P	7709508P	7709509P	7709510P	85A7604P
WT. %								
SiO ₂	0.01	0.01	0.02	0.37	0.47	0.25	0.47	0.26
TiO ₂	0.68	1.06	0.81	0.56	0.65	0.51	0.63	0.68
Al ₂ O ₃	32.82	29.11	29.72	33.93	32.14	29.89	33.57	24.47
Cr ₂ O ₃	29.19	29.47	31.96	28.33	30.07	31.82	27.97	37.94
FeO	18.54	22.07	19.35	18.93	17.49	19.10	18.68	19.49
MnO	0.72	0.37	0.41	0.40	0.53	0.57	0.64	0.30
MgO	16.66	15.40	16.00	16.34	17.13	15.84	16.63	15.27
CaO	0.02	0.03	0.04	0.17	0.26	0.11	0.14	0.07
TOTAL	98.62	97.52	98.31	99.22	98.74	98.28	98.73	98.38
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	0.003	0.003	0.007	0.118	0.150	0.082	0.150	0.027
Al	0.258	0.412	0.312	0.247	0.244	0.234	0.237	0.268
Cr	0.367	0.598	0.692	0.523	0.628	0.706	0.461	0.371
Fe ₂	7.872	8.137	8.750	7.525	8.024	8.678	7.457	10.623
Mn	5.054	6.172	5.355	5.093	4.727	5.344	5.044	5.527
Mg	2.336	0.182	2.200	0.232	0.252	0.277	0.304	0.150
Ca	5.756	5.448	5.612	5.561	5.856	5.535	5.680	5.478
	0.388	0.595	0.787	3.244	4.985	2.155	2.682	1.448
MOLECULAR PROPORTIONS								
RO ₂	0.01	0.01	0.03	0.51	0.65	0.34	0.65	0.35
R ₂ O ₃	18.47	16.73	16.72	19.13	18.01	16.65	18.92	13.18
RO	81.51	83.26	83.25	80.35	81.34	83.01	80.43	85.47
MG=NUMBER								
M/M+F	4.10	2.19	2.24	2.99	3.05	3.09	3.92	1.39

OPAQUE OXIDES: CHROME SPINELS

	85A7605P	7703912P	7703913P	7718401P	7718402P	32A7605G	32A7607G	7702413P
WT. %								
SiO ₂	2.64	2.39	2.34	0.23	2.21	4.20	1.11	2.89
TiO ₂	2.64	2.71	18.37	1.69	2.38	1.91	13.05	1.12
Al ₂ O ₃	23.96	26.65	1.37	19.61	27.34	1.50	2.64	16.25
Cr ₂ O ₃	29.69	34.24	2.54	22.53	23.44	7.15	2.91	24.62
FeO	21.49	17.86	67.12	44.61	39.22	76.12	74.14	47.96
MnO	2.24	2.65	2.06	1.19	0.68	0.99	2.07	1.84
MgO	14.67	15.62	2.35	4.60	7.48	2.26	2.45	5.52
CaO	2.28	NA	NA	2.25	2.24	2.29	2.22	NA
TOTAL	97.41	95.82	92.15	94.42	95.81	88.22	91.40	97.22
ATOMIC PROPORTIONS BASED ON 32 OXYGENS								
Si	2.212	0.232	2.114	0.011	0.423	2.282	0.385	2.312
Al	2.248	0.283	7.250	0.729	0.356	0.925	5.327	0.463
Cr	7.786	7.135	2.363	5.517	7.427	2.487	0.175	4.453
Fe ₂	8.161	9.697	2.151	6.725	5.855	2.456	0.264	7.226
Mn	5.983	5.123	19.042	13.446	11.342	26.488	21.755	14.257
Mg	2.118	0.328	1.228	0.631	0.348	2.546	0.501	2.430
Ca	5.167	5.661	2.126	1.788	2.750	2.226	2.167	2.076
	1.582	0.222	2.020	1.059	0.825	2.222	4.582	2.322
MOLECULAR PROPORTIONS								
RO ₂	2.89	2.12	2.47	0.24	2.21	2.27	1.40	1.17
R ₂ O ₃	16.98	15.11	15.69	12.12	16.25	2.32	12.66	9.18
RO	82.13	84.77	83.84	87.84	83.93	97.40	87.86	89.65
MG-NUMBER								
M/M+F	1.42	3.27	87.18	8.60	5.61	19.79	65.52	5.73

OPAQUE OXIDES: CHROME SPINELS

	7702414P	7726807P	7726808P	7726809P
WT. %				
SiO ₂	0.99	0.46	3.44	0.51
TiO ₂	1.49	1.26	1.48	1.54
Al ₂ O ₃	12.68	19.62	18.63	16.58
Cr ₂ O ₃	21.67	35.93	36.86	36.35
FeO	54.28	27.28	28.40	28.63
MnO	0.76	0.72	0.99	0.78
MgO	3.52	12.23	12.12	12.13
CaO	NA	NA	NA	NA
TOTAL	95.37	97.27	99.03	98.62
ATOMIC PROPORTIONS BASED ON 32 OXYGENS				
Si	0.367	0.157	3.148	0.172
Al	0.634	0.588	3.587	0.613
Cr	3.619	5.338	5.912	4.990
Fe ²⁺	5.542	10.283	10.379	10.271
Mn	15.598	7.928	8.899	8.193
Mg	0.430	0.357	0.452	0.393
Ca	1.354	4.422	4.372	4.391
	0.000	0.000	0.000	0.000
MOLECULAR PROPORTIONS				
RO ₂	1.32	0.52	0.56	0.56
R ₂ O ₃	7.76	11.18	10.67	10.68
RO	92.93	88.22	88.77	88.66
MG=NUMBER				
M/M+F	5.88	3.45	4.17	3.68

OPAQUE OXIDES "ILMENITES"

	46A7605G	46A7606G	7703908P	7703809P	7708406G	7725107G	95A7608G	95A7609G
WT %								
SiO ₂	0.04	0.37	2.68	2.77	3.08	0.31	0.02	0.01
TiO ₂	4.17	8.64	18.74	15.87	15.76	42.01	18.97	17.95
Al ₂ O ₃	0.28	0.90	2.28	2.33	3.81	0.00	1.23	0.11
Cr ₂ O ₃	0.09	0.05	0.08	0.03	0.07	0.00	0.09	0.04
FeO	84.01	77.64	67.34	65.79	67.37	54.40	71.64	73.22
MnO	0.45	0.75	1.47	1.11	1.95	2.68	1.64	1.60
MgO	0.02	0.38	1.26	2.47	0.54	0.00	0.07	0.00
CaO	0.05	0.00	0.00	0.00	0.00	0.00	0.12	0.00
NiO	0.00	0.41	0.13	0.13	0.13	0.00	0.00	0.00
TOTAL	89.11	89.14	93.98	90.50	92.71	99.40	93.78	92.93
ATOMIC PROPORTIONS BASED ON 6 OXYGENS								
Si	0.003	0.027	0.165	0.177	0.193	0.017	0.001	0.001
Ti	0.242	0.469	0.866	0.754	0.741	1.699	0.926	0.901
Al	0.025	0.077	0.165	0.176	0.281	0.000	0.004	0.000
Cr	0.005	0.003	0.004	0.002	0.003	0.000	0.005	0.002
Fe ₂	5.427	4.690	3.462	3.523	3.522	2.446	3.891	4.089
Mn	0.029	0.046	0.077	0.050	0.103	0.122	0.090	0.090
Mg	0.002	0.041	0.115	0.236	0.050	0.000	0.007	0.000
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.000
	0.000	1.780	0.480	0.500	0.488	0.000	0.000	0.000
MOLECULAR PROPORTIONS								
RO ₂	4.29	9.34	21.62	19.42	19.65	40.05	18.66	17.73
R ₂ O ₃	0.27	0.75	1.77	1.83	2.99	0.00	0.99	0.11
RO	95.44	89.91	76.61	78.75	77.36	59.95	80.35	82.16
MG-NUMBER								
M/M+F	0.04	0.86	3.23	6.27	1.41	0.00	0.17	0.00

OPAQUE OXIDES

"ILMENITES"

	7706803G	7727907P	7727908P
WT %			
SiO ₂	4.54	0.12	0.11
TiO ₂	16.30	45.25	47.53
Al ₂ O ₃	4.13	0.35	0.32
Cr ₂ O ₃	0.16	0.13	0.13
FeO	68.06	46.82	45.32
MnO	0.06	4.13	4.00
MgO	0.83	1.17	1.63
CaO	0.00	0.14	0.10
NiO	0.20	0.04	0.00
TOTAL	94.28	98.04	99.14
ATOMIC PROPORTIONS BASED ON 6 OXYGENS			
Si	0.272	0.005	0.006
Ti	0.735	1.798	1.845
Al	0.292	0.022	0.019
Cr	0.008	0.004	0.005
Fe ₂	3.413	2.050	1.956
Mn	0.003	0.185	0.175
Mg	0.074	0.092	0.125
Ca	0.000	0.005	0.005
	0.721	0.000	0.000
MOLECULAR PROPORTIONS			
RO ₂	21.67	43.28	44.86
R ₂ O ₃	3.22	0.31	0.30
RO	75.10	55.41	54.84
MG-NUMBER			
M/M+F	2.13	4.26	5.02

OPAQUE OXIDES

"MAGNETITES"

	7721404G	7721406G	7708213G	7708214G	7725108G	7715508G	7715509G
WT. %							
SiO ₂	0.33	0.27	0.00	0.26	0.35	0.28	0.59
TiO ₂	19.36	22.19	33.28	6.28	1.60	23.25	19.99
Al ₂ O ₃	0.37	1.27	0.00	0.00	0.00	1.22	1.53
Cr ₂ O ₃	0.12	0.00	0.00	0.00	0.10	0.15	0.16
FeO	76.56	72.48	64.24	89.42	91.53	70.73	72.70
MnO	1.55	1.64	2.19	0.21	0.00	0.90	0.03
MgO	0.43	0.00	0.00	0.00	0.00	0.60	0.57
CaO	0.11	0.26	0.00	0.24	0.13	0.14	0.14
TOTAL	98.83	98.04	99.51	96.37	93.71	96.87	96.61
ATOMIC PROPORTIONS BASED ON 32 OXYGENS							
Si	0.100	0.088	0.000	0.008	0.140	0.091	0.105
Ti	4.819	5.431	7.557	1.775	0.482	5.650	4.973
Al	0.144	0.460	0.000	0.000	0.000	0.392	0.596
Cr	0.031	0.000	0.000	0.000	0.032	0.039	0.042
Fe ₂	21.192	19.727	16.320	28.105	30.650	19.280	20.113
Mn	0.435	0.452	0.564	0.067	0.000	0.248	0.261
Mg	0.212	0.000	0.000	0.000	0.000	0.292	0.281
Ca	0.039	0.091	0.000	0.081	0.056	0.040	0.050
MOLECULAR PROPORTIONS							
RO ₂	18.32	21.21	30.92	6.22	1.98	22.23	19.73
R ₂ O ₃	0.33	0.88	0.00	0.00	0.05	0.83	1.22
RO	81.35	77.90	69.08	93.78	97.97	76.94	79.05
MG=NUMBER							
M/M+F	0.99	0.00	0.00	0.00	0.00	1.49	1.38

APPENDIX 7.1

X-ray Fluorescence Analysis

Samples were fragmented and stripped of weathering using a Cutrock Engineering hydraulic splitter. Further fragmentation to an aggregate of < 1cm chips was achieved with a Sturtevant 2"x 6" Roll Jaw Crusher. Grinding of this aggregate to a fine powder was accomplished in a Tema Laboratory Disc Mill with a tungsten-carbide grinding barrel. Grinding took 1-4 minutes.

Several grams of powder were then compressed into briquettes using a hydraulic press, operated at 800-900 kg/cm² (5-6 tons/inch²). A few drops of an inert organic binding material (Mowiol) was added to the powder, prior to compression to aid cohesion.

Major and trace elements (excluding some Nb and Rb) were analysed on a Philips PW1212 automatic spectrometer into which the briquettes were loaded by a Torrens Industries TEL08 Automatic Sample Loader. Routine operating conditions for this machine are given by Reeves (1971).

The major and minor elements Si, Al, Fe, Mg, Na, K, Ti and P were determined in a single analytical session using a Cr target and an evacuated tube. Mn was determined separately using W radiation. The accumulation of counts for the unknowns was based on a 'fixed count' time for a

monitor. This minimises machine drift or instability.

Data handling was performed using an iterative procedure described by Holland and Brindle (1966) and Reeves (1971). Standards used in this calibration were the international standards, AGV1, BCRI, BR, DTS1, G1, GH, GR, PCC1, SY-1 and W-1 (for compositions see Flanagan, 1973). The departmental secondary standard Na-1 with 20-50 wt% Al_2O_3 was used to control Al_2O_3 calibration beyond the range of the international standards (17.25 wt%). K_2O in specimens with < 0.07 wt% K_2O was redetermined with longer (100 seconds) counting times to increase the precision of the K_2O determination at low concentrations.

Three checks were made to elucidate the scope of variation possible for each quoted major oxide determination thus giving an estimate of the precision of the procedures outlined above, these are as follows:

- (1) Two separate briquettes were made from the same powdered sample (77192, an olivine phyric dolerite). The replicate analyses are presented in Table A7.1. Only small differences occur in the values quoted for the replicate determination excluding perhaps Na_2O which varies from 2.31-2.52 wt%.
- (2) Two samples (52A76, 77047) which were analysed on the first day were re-analysed at the end of the last

day to estimate any variability within the run due to machine instability. The replicate analyses on these two specimens are also presented in Table A7.1 where slight variations can be seen in the values quoted for each element.

- (3) The percentage error due to the variation in the counts of standards (each of which was analysed four times during the run) were assessed for 6 representative standard compositions. The compositions of these standards and the error for each major oxide determination are presented on Table A7.2. It is clear that although precision declines with decreasing concentration the errors on the standards in Table A7.2 are generally small. An exception being the composition G1 which exhibits larger errors.

The checks outlined above suggest that small variations in run conditions over a period of days do occur but these do not significantly affect the reliability of the results. The reasons for the larger errors on G1 are not clear but inhomogeneity within the briquette is one possible explanation. It must be stressed that these results are based on limited data and can only be viewed as a rough guide to the precision of data produced by the PW1212. A rigorous check of the precision of

PW1400 prior to its routine use as an operating instrument and the discontinued use of standard G1 is recommended.

The trace elements Ba, Nb, Zr, Y, Sr, Rb, Zn, Ni and Cr were determined using W radiation. Nb and Rb were redetermined on a PW1400 using Rh radiation and longer counting times (100 seconds) in samples with < 6 ppm and 10 ppm respectively. Peaks and backgrounds obtained for standards and unknowns were converted to the function $(P/B-1)$. This function when plotted against standard concentrations produces a straight line from which unknown concentrations can be directly obtained. This calculation was performed using the program TRATIO (written by R.C.O. Gill). Mass absorption and matrix effects are compensated for by the $(P/B-1)$ function using scattered background radiation as an internal standard. TRATIO also allows correction for the interferences of Sr $K\alpha$ on Zr $K\alpha$, Rb $K\alpha$ on Y $K\alpha$ and Y $K\alpha$ on Nb $K\alpha$ using experimentally determined interference factors. The redetermined Nb and Rb values were calculated using the function $(P/B-1)$, direct and were in tolerable agreement with the earlier determinations. The longer counting times over one peak and two background positions lowered the detection limit of these elements to 1 ppm with an estimated error of ± 0.5 ppm at this concentration.

The standards used were synthetic, spiked glasses produced by the Pilkington Research Laboratory for use in lunar investigations (Brown et al., 1970).

TABLE A3.1

REPLICATE DETERMINATIONS OF MAJOR OXIDE ANALYSES

Analyses 1 and 2: Analyses of two different brickettes made from the same finely crushed sample

Analyses 3 and 4: Analyses of the same brickette at the beginning and end of the same run

Analyses 5 and 6: " " " " " " " " " " " "

	1	2		3	4		5	6	
Spec.	77192 (a)	77192 (b)	Deviation from mean	77047	77047	Deviation from mean	52A76	52A76	Deviation from mean
SiO ₂	46.54	46.61	+ 0.04	49.99	49.70	+ 0.15	41.18	41.21	+ 0.02
Al ₂ O ₃	15.04	15.08	+ 0.02	18.94	18.95	+ 0.01	8.77	8.74	+ 0.02
Fe ₂ O ₃ *	11.20	11.02	+ 0.09	7.18	7.24	+ 0.03	12.16	12.15	+ 0.01
MgO	12.99	12.78	+ 0.11	5.62	5.66	+ 0.02	30.52	30.44	+ 0.04
CaO	10.05	10.02	+ 0.02	15.10	15.28	+ 0.09	5.58	5.64	+ 0.03
Na ₂ O	2.31	2.52	+ 0.11	1.98	1.98		0.62	0.67	+ 0.03
K ₂ O	0.46	0.46		0.08	0.08		0.14	0.14	
TiO ₂	1.20	1.20		0.91	0.91		0.82	0.82	+ 0.01
MnO	0.16	0.17	+ 0.01	0.10	0.10		0.17	0.17	
P ₂ O ₅	0.12	0.14	+ 0.01	0.08	0.09	+ 0.01	0.08	0.08	

BR				BCR1			
Wt%	Comp	Mean Counts	Range of %ge error (+)	Comp	Mean Counts	Range of %ge error (+)	
SiO ₂	38.20	67923	0.14-0.38	54.50	103424	0.22-0.29	
Al ₂ O ₃	10.20	86680	0.21-0.39	13.61	122427	0.21-0.48	
Fe ₂ O ₃	12.88	100780	0.35-0.53	13.40	114147	0.38-0.47	
MgO	13.28	96292	0.93-1.29	3.46	19039	1.22-1.62	
CaO	13.80	179566	0.51-0.55	6.92	86876	0.04-0.23	
Na ₂ O	3.05	28343	1.16-3.23	3.27	28572	0.44-0.96	
K ₂ O	1.40	56617	0.40-0.84	1.70	64615	0.67-0.86	
TiO ₂	2.60	127306	0.25-0.46	2.20	116977	0.73-0.89	
P ₂ O ₅	1.04	13878	2.02-2.16	0.36	3804	2.70-3.19	

W1				GR			
Wt%	Comp	Mean Counts	Range of %ge error (+)	Comp	Mean Counts	Range of %ge error (+)	
SiO ₂	52.64	94908	0.44-0.67	65.90	134043	0.94-1.12	
Al ₂ O ₃	15.00	141896	0.72-1.34	14.75	133556	0.37-0.44	
Fe ₂ O ₃	11.09	95819	0.21-0.33	4.05	39061	0.64-0.67	
MgO	6.62	41064	1.08-1.61	2.40	22130	1.28-2.00	
CaO	10.96	139079	0.35-0.53	2.50	30477	0.27-0.48	
Na ₂ O	2.15	20248	0.64-0.79	3.80	31562	1.04-1.69	
K ₂ O	0.64	26252	0.77-0.89	4.50	156947	0.41-0.43	
TiO ₂	1.07	52847	0.46-0.72	0.65	37429	0.55-1.20	
P ₂ O ₅	0.14	1751	0.40-0.40	0.28	2794	9.24-13.28	

DTS1				G1			
Wt%	Comp	Mean Counts	Range of %ge error (+)	Comp	Mean Counts	Range of %ge error (+)	
SiO ₂	40.50	57770	0.21-0.22	72.64	150040	2.65-3.63	
Al ₂ O ₃	0.24	2016	3.05-3.94	14.04	129702	6.06-6.39	
Fe ₂ O ₃	8.64	107481	0.68-0.40	1.94	17638	0.46-0.61	
MgO	49.80	418756	0.94-1.24	0.38	4226	9.80-11.17	
CaO	0.15	2456	1.75-2.61	1.39	16086	3.31-8.16	
Na ₂ O	0.01	788	11.37-16.19	3.32	28544	4.66-5.05	
K ₂ O	0.00	715	2.94-2.73	5.48	176739	5.58-6.01	
TiO ₂	0.01	837	0.42-1.19	0.26	14419	1.47-3.19	
P ₂ O ₅	00.00	32	68.25-157.1	0.09	732	24.34-17.04	

Table A3.2 Estimated precision of the major oxide determinations
based on the range of error around the mean counts value

Appendix 7.2

Table of major oxide and trace element analyses.

These are arranged in ascending order of the dolerite groups with D.I. followed by the high MgO gabbros, the low MgO gabbros and the peridotite plug analyses. The CIPW norms are presented on p458

* indicates an analysis plotted in Chapter 7.

The following average analyses were also plotted in Chapter 7

Group 3

The average of 4 similar parallel inclined sheets, (72A76, 73A76, 77318, 77356).

Group 8

Average of 5 Kilmory thick conformable sheets, (77092, 77105, 77108, 77271, 77272).

Average of 3 Papadil thick conformable sheets, (77174, 77243, 77244).

Average of 4 dykes with liquid-liquid contacts with felsite in Stony Corrie, Dibidil, (77061, 77127, 77145, 77306).

RHUM DOLERITE GROUPS 1-12

	52A76★	53A76★	54A76★	55A76	69A76★	71A76	77A76★	77077★	77179★	77321★
WT%										
SiO ₂	41.20	43.55	45.09	43.75	43.29	44.45	43.53	44.77	41.70	42.66
Al ₂ O ₃	9.76	11.98	13.30	11.87	12.55	12.77	12.56	13.44	8.60	12.46
Fe ₂ O ₃	12.16	11.71	12.18	11.68	12.49	11.63	12.22	11.69	11.36	11.93
MgO	32.48	20.73	14.84	20.22	18.47	19.59	19.42	15.19	30.92	21.69
CaO	5.51	9.17	11.29	9.67	9.55	8.99	9.00	10.47	5.23	8.41
Na ₂ O	0.65	1.02	1.56	1.01	1.36	1.13	3.96	2.00	0.25	1.15
K ₂ O	0.14	0.31	0.09	0.23	0.12	0.13	0.63	0.29	0.72	0.20
TiO ₂	0.83	1.23	1.37	1.27	1.68	1.46	1.33	1.78	0.86	1.50
MnO	0.17	0.15	0.17	0.15	0.17	0.15	0.18	0.16	0.16	0.16
P ₂ O ₅	0.08	0.15	0.15	0.15	0.22	0.10	0.15	0.21	0.11	0.23
PPM										
NI	1846	535	285	554	438	654	605	345	1771	659
CR	2628	1172	687	982	731	1258	1166	555	3083	4
BA	13	4	40	29	70	13	47	48	37	35
NB	4	4	4	5	9	3	4	4	4	5
ZR	51	98	93	90	124	73	120	144	50	153
Y	8	16	20	15	16	14	16	23	10	17
SR	107	200	159	194	298	159	192	260	100	276
RB	2	6	5	3	4	4	12	6	31	1
ZN	71	59	70	55	123	87	95	77	66	79
GROUP	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1

RHUM DOLERITE GROUPS 1-12

	77341	77052	77093*	77095*	77101*	77107*	77224*	77192	77196	77197*
WT%										
SiO ₂	44.35	44.03	46.67	46.13	43.15	43.89	44.54	46.58	45.01	41.84
Al ₂ O ₃	13.21	12.89	13.88	13.44	11.91	11.66	14.19	15.06	14.92	11.57
Fe ₂ O ₃	12.48	12.74	12.51	12.73	12.53	12.73	13.24	11.11	11.95	11.32
MgO	15.74	16.14	17.71	12.74	20.36	18.24	13.46	12.89	14.47	25.82
CaO	10.80	11.43	12.56	11.68	9.30	10.28	10.27	10.04	9.23	7.18
Na ₂ O	1.27	1.20	1.92	1.75	1.04	1.35	2.55	2.42	2.22	1.09
K ₂ O	0.48	0.10	0.06	0.46	0.20	0.12	0.23	0.46	0.55	0.17
TiO ₂	1.53	1.18	1.40	1.26	1.23	1.44	1.23	1.20	1.47	0.77
MnO	0.19	0.18	0.21	0.17	0.10	0.18	0.18	0.17	0.17	0.17
P ₂ O ₅	0.15	0.09	0.10	0.09	0.09	0.12	0.11	0.13	0.21	0.08
PPM										
NI	385	600	391	548	928	622	437	367	453	1504
CR	1059	1364	1104	1288	1729	1385	914	868	936	3009
BA	51	77	10	19	30	30	53	302	217	28
NR	4	2	2	2	3	3	4	4	6	2
ZR	106	65	79	64	73	83	69	74	112	52
Y	19	12	24	16	15	16	25	17	10	14
SR	183	168	147	145	129	162	156	407	272	83
RB	25	6	0	0	0	4	2	5	8	3
ZN	153	79	80	78	72	74	98	74	86	74
GROUP	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3

RHUM DOLERITE GROUPS 1-12

	77221	77225	77235	77236*	77237*	85A76	77017	77024*	77036	48A76

WT%

SiO2	42.25	43.98	44.96	41.63	46.89	43.40	43.75	44.41	44.74	46.78
Al2O3	13.26	13.07	15.35	12.39	15.19	9.21	13.28	14.95	13.34	14.66
Fe2O3	12.63	12.24	11.43	12.40	10.66	11.56	13.47	11.72	12.59	10.92
MgO	20.00	15.77	12.43	21.04	12.76	28.44	14.87	15.55	15.08	13.05
CaO	8.25	9.92	11.22	8.88	10.45	5.50	10.54	9.93	10.39	11.35
Na2O	1.83	2.64	2.56	1.69	2.55	0.82	1.89	2.18	1.58	1.62
K2O	0.14	0.40	0.19	0.12	0.18	0.13	0.15	0.05	0.19	0.18
TiO2	1.32	1.66	1.52	1.45	1.87	0.69	1.79	0.88	1.76	1.14
HNO	0.18	0.16	0.18	0.17	0.14	0.16	0.18	0.17	0.18	0.16
P2O5	0.15	0.16	0.17	0.25	0.09	0.09	0.16	0.08	0.16	0.13

PPM

NI	890	513	364	1341	390	1599	410	717	351	243
CR	1263	893	814	1878	788	2559	696	1296	674	854
BA	17	48	34	29	140	27	75	11	46	27
NB	2	5	3	3	2	5	6	3	5	4
ZR	83	107	104	81	73	56	120	53	123	84
Y	17	18	16	33	16	10	17	13	20	18
SR	198	218	243	167	246	104	255	123	230	227
RB	3	17	8	0	3	6	2	1	3	7
ZN	82	45	75	53	64	75	87	77	88	72

GROUP	1.3	1.3	1.3	1.3	1.3	1	1	1	1	2

RHUM DOLERITE GROUPS 1-12

	44A75★	46A76★	65A76★	72A76	93A76	77019★	77339	77042	77084★	77116★
WTX										
SiO2	45.69	45.97	46.91	46.71	45.62	44.32	46.32	44.28	46.74	46.86
Al2O3	14.31	12.98	14.26	13.82	12.94	14.20	13.50	13.48	14.33	13.61
Fe2O3	12.86	11.63	11.49	12.34	12.23	12.91	11.19	13.63	11.85	12.12
MgO	15.73	11.41	12.01	11.11	14.89	13.60	15.62	12.59	11.25	11.96
CaO	10.75	13.54	11.42	12.11	9.85	10.45	12.23	11.44	12.31	11.34
Na2O	1.08	2.15	2.16	2.35	1.65	2.17	1.70	2.13	1.86	2.12
K2O	0.35	0.25	0.10	0.19	0.37	0.31	0.30	0.11	0.10	0.36
TiO2	1.00	1.70	1.35	1.63	1.41	1.72	1.08	2.00	1.58	1.59
MnO	0.14	0.19	0.16	0.19	0.18	0.18	0.16	0.18	0.19	0.17
P2O5	0.29	0.18	0.14	0.15	0.13	0.15	0.10	0.16	0.11	0.14
PPM										
NI	368	176	143	148	335	372	425	283	284	214
CR	649	565	368	379	693	697	872	584	639	517
BA	140	46	56	47	82	70	58	92	54	112
NB	4	5	4	5	5	5	4	6	4	5
ZR	66	108	90	114	110	123	79	126	89	127
Y	15	16	14	20	17	17	18	21	17	22
SR	182	269	205	241	175	261	138	312	212	248
RB	10	4	4	8	9	6	5	4	1	12
ZN	52	58	73	102	104	76	76	96	79	101
GROUP	2	2	2	2	2	2	2	2	2	2

RHUM DOLERITE GROUPS 1-12

	77121	77122	77123	77158*	77212*	77214*	77240	77245	77352*	66476*
NY%										
IO2	45.53	44.98	45.89	45.54	45.41	47.19	44.95	45.85	45.48	47.14
AL2O3	13.74	12.87	13.76	14.34	14.73	14.56	14.41	15.49	14.15	13.91
FE2O3	12.26	12.73	12.16	12.24	12.75	11.89	12.54	11.52	12.48	12.23
CaO	14.93	14.99	13.50	13.29	11.28	19.20	13.39	11.64	12.84	12.28
SiO2	10.45	10.98	11.37	10.89	12.22	12.29	11.78	11.95	11.70	10.52
Na2O	1.69	1.35	1.65	1.82	1.52	2.21	1.10	1.62	1.60	2.14
K2O	0.12	0.36	0.12	0.25	0.24	0.30	0.74	0.51	0.11	0.13
IO2	1.12	1.45	1.31	1.61	1.76	1.26	1.47	1.17	1.34	1.45
MNO	0.18	0.19	0.17	0.17	0.18	0.17	0.21	0.17	0.17	0.15
205	0.09	0.10	0.10	0.14	0.14	0.12	0.12	0.09	0.14	0.14
PPM										
NY	353	372	275	239	146	164	289	193	229	234
IR	811	895	661	516	374	404	618	373	458	476
AA	41	22	27	52	34	56	45	182	52	82
UB	4	5	3	4	4	4	4	3	4	5
VR	72	91	82	123	110	77	80	50	85	116
Y	19	18	21	19	23	17	19	16	17	23
SR	138	154	178	230	172	203	170	228	147	194
RB	4	22	4	4	2	17	36	19	8	3
EN	74	79	71	91	75	70	97	81	129	95
GROUP	2	2	2	2	2	2	2	2	2	3

RHUM DOLERITE GROUPS 1-12

	72A76	73A76	74A76	87A76*	89A76*	92A76	77246*	77248	77280	77282*
WT%										
SiO ₂	48.56	48.56	47.24	47.51	48.31	47.13	48.39	47.48	48.53	48.42
Al ₂ O ₃	14.71	13.92	13.77	14.48	14.37	14.18	14.21	13.83	14.33	14.13
Fe ₂ O ₃	12.34	11.72	12.21	11.74	11.86	11.80	11.68	11.51	11.46	11.61
MgO	13.63	11.31	12.82	11.31	12.25	11.49	11.17	11.61	12.25	12.73
CaO	12.85	12.38	11.28	12.22	12.16	11.28	12.16	12.06	12.85	12.68
Na ₂ O	2.28	2.32	2.48	2.33	2.59	2.13	2.23	2.12	2.57	2.18
K ₂ O	0.26	0.21	0.17	0.78	0.51	0.25	0.53	0.66	0.22	0.28
TiO ₂	1.55	1.51	1.73	1.43	1.88	1.44	1.32	1.52	1.41	1.65
MnO	0.17	0.16	0.17	0.17	0.17	0.18	0.17	0.17	0.17	0.17
P ₂ O ₅	0.17	0.13	0.15	0.16	0.21	0.12	0.13	0.15	0.12	0.16
PPM										
NI	152	148	147	192	133	179	186	241	113	153
CR	381	396	367	399	333	422	472	575	361	771
BA	127	126	73	134	156	91	125	139	116	142
NB	5	5	5	6	6	4	3	5	5	5
ZR	133	126	126	124	168	125	126	114	111	129
Y	24	19	22	23	22	19	21	25	22	23
SR	199	224	211	255	235	191	182	228	222	241
RB	8	8	8	67	26	13	15	21	5	7
ZN	99	92	93	91	84	82	121	91	92	99
GROUP	3	3	3	3	3	3	3	3	3	3

RHUM DOLERITE GROUPS 1-12

	77178	77191*	77249	77251	77318	77356	21A76	22A76*	41A76	47A76*
WT%										
SiO ₂	45.13	46.24	46.95	46.57	48.12	48.41	48.66	47.55	47.63	48.68
Al ₂ O ₃	14.90	15.29	13.68	14.14	13.90	13.96	13.91	13.59	14.71	13.54
Fe ₂ O ₃	12.92	11.47	12.66	11.93	12.50	11.01	12.22	13.44	13.35	11.09
MgO	17.32	11.40	11.33	11.97	10.32	10.86	9.11	8.70	5.36	0.81
CaO	9.55	10.91	10.25	10.63	10.51	10.54	11.52	11.09	11.43	11.51
Na ₂ O	3.17	2.40	2.47	2.20	2.47	2.34	2.41	2.29	2.40	2.25
K ₂ O	0.50	0.46	0.48	0.32	0.18	0.17	0.39	0.23	0.10	0.20
TiO ₂	1.96	1.51	2.15	1.87	1.60	1.52	1.56	1.01	1.73	1.67
MnO	0.16	0.15	0.17	0.17	0.18	0.18	0.18	0.18	0.20	0.17
P ₂ O ₅	0.28	0.16	0.20	0.20	0.13	0.14	0.14	0.18	0.10	0.17
PPM										
NI	144	175	160	182	146	130	125	93	98	105
CR	381	350	357	339	404	393	380	265	334	354
BA	314	128	137	90	103	115	136	82	46	00
NB	5	5	6	5	4	4	5	4	4	5
ZR	166	98	166	145	131	130	118	106	76	129
Y	26	18	24	22	20	23	22	25	27	22
SR	408	305	329	223	205	205	202	209	204	205
RB	21	5	9	6	6	5	8	3	10	10
ZN	83	76	102	97	113	98	76	72	114	87
GROUP	3	3	3	3	3	3	4	4	4	4

RHUM DOLERITE GROUPS 1-12

	60A76	61A76	62A76	63A76	77312	77013	77032	77035	77044☆	77068☆
WT%										
SiO2	43.69	47.24	46.96	46.87	47.21	47.53	48.29	48.87	47.81	46.64
Al2O3	13.90	13.78	14.26	13.83	14.34	15.03	13.64	14.28	14.56	14.31
Fe2O3	12.23	13.48	13.15	13.48	12.64	11.87	12.79	11.97	12.39	12.77
MgO	9.46	9.44	9.47	9.58	9.56	9.76	8.80	9.26	8.97	10.95
CaO	11.17	11.78	12.29	11.94	11.95	10.70	11.08	10.64	11.48	10.72
Na2O	2.41	2.18	2.22	2.12	2.43	2.56	2.88	2.75	2.74	2.45
K2O	0.19	0.33	0.38	0.33	0.18	0.63	0.38	0.32	0.34	0.34
YtO2	1.63	1.66	1.56	1.50	1.63	1.59	1.95	1.61	1.68	1.45
MnO	0.18	0.22	0.24	0.19	0.22	0.17	0.18	0.17	0.18	0.19
P2O5	0.15	0.14	0.12	0.13	0.14	0.15	0.22	0.13	0.15	0.16
PPM										
NI	141	84	114	111	151	216	88	162	90	172
CR	382	335	359	352	373	526	284	465	332	314
BA	83	42	36	51	24	128	112	87	115	283
NB	5	4	4	3	4	4	5	5	4	3
ZR	138	67	62	61	121	146	139	129	119	89
Y	29	22	23	20	20	23	25	27	21	18
SR	179	212	211	217	213	218	213	217	225	314
RB	6	11	15	12	6	22	8	7	12	2
ZN	120	95	92	100	263	86	90	94	85	63
GROUP	4	4	4	4	4	4	4	4	4	4

KROM DOLERITE GROUPS 1-12

	77076	77125	77148*	77175*	77176*	77204	77208	77231	77269	77284
NT%										
SI02	48.15	47.67	46.83	46.83	46.82	47.21	45.91	47.30	47.66	46.17
AL2O3	13.49	14.04	14.63	14.64	15.21	13.92	15.37	14.82	14.35	15.24
FE2O3	12.59	12.53	12.80	13.98	14.26	13.83	13.23	12.07	13.19	12.41
MGO	8.83	8.95	9.57	9.52	9.39	9.79	9.23	9.56	8.36	9.49
CAO	11.64	12.68	11.95	9.76	9.30	9.97	12.31	11.83	11.87	12.84
NA2O	2.34	1.96	2.27	2.73	2.25	2.55	1.99	2.14	2.30	1.97
K2O	0.68	0.34	0.14	0.54	0.76	0.66	0.33	0.37	0.17	0.22
TI02	1.89	1.51	1.50	1.67	1.76	1.68	1.65	1.55	1.75	1.78
MNO	0.19	0.20	0.18	0.20	0.17	0.19	0.18	0.17	0.18	0.19
P2O5	0.19	0.12	0.15	0.26	0.26	0.19	0.15	0.19	0.16	0.15
PPM										
NI	90	140	137	111	116	61	117	145	96	107
CR	200	397	383	94	267	61	294	363	331	391
BA	219	50	44	484	414	389	40	67	325	96
WB	4	3	3	5	5	6	4	3	4	4
ZR	127	68	92	145	153	150	106	99	173	111
Y	24	19	21	23	28	24	22	28	21	24
ER	280	195	158	459	445	269	188	267	271	242
RB	19	26	8	10	19	23	13	14	5	4
ZN	100	96	77	60	114	132	68	91	81	85
GROUP	4	4	4	4	4	4	4	4	4	4

RHUM DOLERITE GROUPS 1-12

	77327	77330*	77332	77333	77336	77337	77351	26A76*	82A76	94A76
WT%										
SiO ₂	47.19	47.74	47.28	48.12	46.21	47.27	47.45	46.58	47.40	47.33
Al ₂ O ₃	14.21	13.67	14.51	14.15	14.75	14.60	14.41	13.02	13.51	15.81
Fe ₂ O ₃	13.50	12.52	12.45	12.31	12.62	12.54	12.36	13.10	13.54	12.33
MgO	9.58	9.28	9.74	9.70	9.46	9.49	9.33	9.68	8.62	8.23
CaO	9.85	12.48	11.19	11.58	11.47	11.04	11.85	11.86	10.91	11.30
Na ₂ O	2.78	2.18	2.53	2.33	2.80	2.51	2.42	2.63	3.14	2.66
K ₂ O	0.49	0.37	0.31	0.37	0.25	0.60	0.44	0.08	0.25	0.50
TiO ₂	1.38	1.46	1.63	1.41	2.03	1.61	1.42	1.80	2.13	1.73
MnO	0.19	0.19	0.19	0.20	0.18	0.20	0.19	0.19	0.24	0.16
P ₂ O ₅	0.22	0.11	0.15	0.12	0.21	0.13	0.12	0.15	0.17	0.15
PPM										
NI	153	113	123	125	100	108	117	120	70	128
CR	336	359	309	377	291	307	386	297	171	317
BA	353	74	110	156	70	154	121	54	96	54
NB	5	4	5	3	6	5	4	4	6	4
ZR	127	88	120	80	149	120	89	95	160	128
Y	24	18	23	20	23	23	17	23	30	20
SR	396	207	213	197	282	205	211	231	218	282
RB	2	14	20	17	17	42	20	2	11	30
ZN	102	86	115	107	100	167	106	68	75	74
GROUP	4	4	4	4	4	4	4	4	4	4

RHUM DOLERITE GROUPS 1-12

	95A76*	77010	77011	77015	77070	77071	77073	77074	77086	77091*
WT%										
SiO2	47.73	47.32	46.84	47.47	46.36	46.33	46.88	46.55	46.72	46.57
Al2O3	15.72	13.99	13.86	14.36	13.68	13.47	14.53	14.81	14.93	13.75
Fe2O3	12.61	13.32	13.37	13.14	13.09	15.12	12.69	12.84	12.51	12.62
MgO	9.24	8.20	8.81	8.16	7.82	8.33	9.56	9.77	8.92	8.69
CaO	10.57	11.47	11.28	11.21	12.87	10.67	10.53	10.48	11.92	13.78
Na2O	3.25	3.05	3.48	3.22	2.61	3.19	3.02	2.97	2.94	2.22
K2O	0.58	0.34	0.25	0.27	0.13	0.07	0.26	0.26	0.08	0.15
YtO2	1.66	1.91	1.94	1.86	1.96	2.40	1.86	1.86	1.59	1.87
MnO	0.18	0.21	0.20	0.20	0.21	0.22	0.18	0.19	0.20	0.19
P2O5	0.15	0.18	0.19	0.18	0.16	0.20	0.22	0.25	0.13	0.16
PPM										
NI	104	87	86	74	127	76	117	109	125	137
CR	279	279	282	293	362	158	258	365	341	373
BA	56	58	40	43	82	84	238	248	76	89
NB	4	5	5	5	4	5	6	6	4	4
ZR	123	133	131	132	94	146	142	136	99	120
Y	24	27	24	27	21	31	25	21	10	22
SR	240	205	209	209	286	215	322	317	228	203
RB	25	11	0	10	1	2	8	9	1	2
ZN	76	155	101	194	97	130	108	98	86	65
GROUP	4	4	4	4	4	4	4	4	4	4

RHUM DOLERITE GROUPS 1-12

	77120	77225☆	77215	77313	77314☆	77324	77331☆	77335	77340	77343
WT%										
SiO ₂	45.58	47.53	46.68	45.43	46.24	46.41	45.79	47.33	46.19	47.22
Al ₂ O ₃	14.67	13.42	14.14	14.77	14.33	14.39	14.96	13.24	14.11	13.05
Fe ₂ O ₃	12.72	13.36	13.68	13.38	12.78	13.69	12.79	13.42	13.25	13.47
MgO	9.99	8.86	8.15	13.83	9.89	9.13	9.38	9.25	9.60	9.55
CaO	11.92	12.28	12.26	11.96	11.63	11.81	11.41	11.97	11.80	11.40
Na ₂ O	2.48	3.13	2.26	2.65	3.38	2.23	2.58	2.69	2.56	2.61
K ₂ O	0.35	2.90	0.81	2.44	2.29	0.47	0.24	0.24	0.15	0.28
TiO ₂	1.63	2.45	1.84	1.71	1.73	1.87	1.49	1.77	0.94	1.79
MnO	0.18	2.22	0.18	0.19	0.19	0.21	0.21	0.24	0.21	0.24
P ₂ O ₅	0.17	0.25	0.16	0.15	0.15	0.19	0.14	0.17	0.19	0.13
PPM										
NI	116	75	122	87	131	108	121	58	97	05
CR	343	187	324	342	287	276	312	124	349	349
BA	71	386	122	58	38	70	89	97	50	124
NB	3	8	4	4	4	4	4	3	4	4
ZR	120	223	129	118	113	123	97	113	125	124
Y	22	28	42	19	21	27	23	26	22	21
SR	268	307	258	227	225	206	168	205	232	227
RB	23	20	24	8	1	29	17	12	8	18
ZN	81	238	91	75	88	153	237	118	154	99
GROUP	4	4	4	4	4	4	4	4	4	4

RHUM DOLERITE GROUPS 1-12

	77344	77348	77359*	13A76	14A76	38A76	77332	77049*	77087*	77210
WT%										
SiO ₂	47.56	47.06	47.42	47.82	46.12	47.28	47.31	45.75	47.65	46.47
Al ₂ O ₃	15.77	14.84	14.35	12.87	13.17	14.66	14.65	13.59	13.47	14.34
Fe ₂ O ₃	11.73	12.07	12.26	16.31	15.69	13.98	14.30	15.45	15.34	14.91
MgO	8.49	9.84	9.34	6.82	7.58	7.52	7.31	7.29	7.46	7.61
CaO	11.68	11.14	11.71	12.12	12.87	10.28	11.26	12.62	9.83	11.42
Na ₂ O	2.83	2.61	2.74	2.87	3.28	3.73	2.65	4.54	2.84	1.06
K ₂ O	0.16	0.54	0.13	0.36	0.31	0.04	0.06	0.03	0.13	1.46
TiO ₂	1.45	1.57	1.70	2.70	2.72	2.15	2.19	2.32	2.81	1.97
MnO	0.17	0.18	0.18	0.24	0.22	0.20	0.21	0.22	0.23	0.23
P ₂ O ₅	0.15	0.15	0.16	0.19	0.24	0.19	0.22	0.20	0.22	0.14
PPM										
NI	94	99	132	61	48	68	69	64	71	93
CR	298	327	623	56	244	98	178	71	139	223
BA	53	188	115	227	81	35	25	74	244	184
NB	4	5	4	7	6	5	5	5	6	3
ZR	97	120	120	173	178	149	143	159	181	111
Y	18	22	19	31	32	31	31	28	34	24
SR	221	231	216	241	259	375	212	209	284	183
RB	13	34	1	9	9	0	2	1	1	62
ZN	92	106	61	116	78	113	95	106	115	87
GROUP	4	4	4	4	4	4	4	4	4	4

RHUM DOLERITE GROUPS 1-12

	77322	77334	77360*	77356	77323	SR151	SR229	SR238	SR284	SR141
VT%										
SI02	45.30	47.42	45.72	46.35	46.34	46.57	47.50	46.75	47.61	47.06
L203	13.71	13.92	14.78	14.43	15.92	15.78	14.53	16.18	15.25	14.69
E203	14.13	13.91	13.62	12.73	12.71	12.41	13.28	12.26	12.94	14.25
GO	8.52	8.43	7.83	9.92	10.32	9.23	8.39	8.96	8.51	7.53
AO	11.79	10.86	11.44	13.56	12.49	12.58	12.85	12.58	12.88	10.63
A20	2.85	2.83	3.28	1.70	2.21	2.16	1.96	2.34	1.82	2.72
20	0.20	0.39	0.29	0.28	0.25	0.45	0.26	0.45	0.25	0.12
IO2	1.99	1.88	2.07	0.97	0.92	0.99	1.16	0.94	1.29	1.76
NO	0.23	0.21	0.18	0.20	0.18	0.19	0.19	0.19	0.19	0.15
205	0.17	0.13	0.20	0.47	0.08	0.08	0.10	0.08	0.10	0.18
PPM										
NI	67	54	76	153	176	149	90	147	128	396
RI	288	86	185	454	484	441	420	418	433	726
AA	95	137	66	29	24	272	45	171	68	72
VB	6	4	5	3	3	3	4	3	3	4
RI	129	112	121	43	42	45	56	47	47	101
RI	23	25	22	21	21	25	24	23	23	23
SR	207	216	214	119	90	118	121	98	125	213
BB	7	22	0	2	1	2	2	2	1	2
ZN	330	123	86	76	74	85	77	74	0	0
GROUP	4	4	4	5	5	5	5	5	5	6

RHUM DOLERITE GROUPS 1-12

	SR159	SR182	SR211	SR282	12A76	77W14	77B47	7715W	77258	16A76*
WT%										
SiO2	49.42	49.24	45.76	49.45	47.52	46.94	49.80	47.33	48.47	49.78
Al2O3	14.23	14.23	16.98	14.26	15.42	16.19	18.95	17.45	18.89	14.43
Fe2O3	13.95	14.25	14.32	14.31	11.21	11.34	7.21	9.85	8.38	11.65
MgO	5.24	5.65	7.95	5.54	9.35	9.10	5.64	8.16	6.52	8.31
CaO	17.58	17.51	9.79	17.42	12.71	12.36	15.19	13.51	14.21	11.25
Na2O	2.96	3.11	3.28	2.97	2.21	2.21	1.98	1.72	1.57	2.49
K2O	0.67	0.73	0.11	0.74	0.23	0.54	0.48	0.54	0.66	0.64
TiO2	1.73	1.82	1.74	1.88	1.25	1.29	0.91	1.19	1.24	1.72
MnO	0.20	0.21	0.18	0.21	0.17	0.16	0.10	0.14	0.13	0.15
P2O5	0.21	0.23	0.19	0.22	0.11	0.11	0.09	0.10	0.09	0.16
PPM										
NI	55	44	122	45	121	134	53	112	70	144
CR	158	132	287	128	374	398	266	404	313	414
BA	261	254	21	253	47	102	35	115	125	173
NB	6	7	4	7	3	3	3	3	2	6
ZR	138	139	110	135	80	76	48	58	54	168
Y	37	43	27	39	19	17	11	12	14	27
SR	197	199	183	194	259	233	265	218	351	235
RB	15	16	1	16	9	17	6	14	27	14
ZN	189	189	183	117	75	68	45	52	50	81
GROUP	5	6	6	6	7	7	7	7	7	8

RHUM DOLERITE GROUPS 1-12

	18A76	22A76	23A76	35A76	48A76*	49A76	50A76*	51A76*	64A76	79A76
WT%										
SiO2	51.25	52.71	50.69	52.26	49.28	49.36	50.67	50.41	52.11	49.06
Al2O3	13.56	13.41	13.45	14.53	14.22	13.31	13.83	14.12	14.38	13.42
Fe2O3	11.85	12.21	11.91	12.41	12.69	11.34	12.76	12.29	12.78	11.97
MgO	7.52	7.88	8.16	4.94	12.80	10.47	9.11	7.18	7.45	8.01
CaO	12.78	12.89	10.37	8.22	12.90	11.12	12.91	12.21	8.87	12.69
Na2O	2.49	2.64	2.52	4.14	2.18	2.16	2.45	2.04	3.20	2.55
K2O	0.63	0.92	0.75	1.24	0.37	0.25	0.39	0.60	0.86	0.38
YtO2	1.79	1.83	1.84	2.13	1.44	1.65	1.58	1.02	1.96	1.78
MnO	0.18	0.18	0.17	0.20	0.15	0.16	0.15	0.18	0.15	0.19
P2O5	0.16	0.15	0.17	0.20	0.16	0.17	0.17	0.18	0.24	0.15
PPM										
NI	79	99	92	37	143	112	121	73	94	134
CR	271	333	256	49	347	346	361	168	255	313
BA	273	387	226	373	121	70	137	122	275	169
NB	6	5	6	8	4	5	5	6	6	5
ZR	173	172	175	225	131	154	158	172	224	143
Y	29	32	31	28	17	23	22	28	32	24
SR	210	232	229	229	234	235	242	229	246	282
RR	13	21	17	31	12	9	11	17	25	16
ZN	76	86	76	150	89	71	94	125	129	1241
GROUP	8	8	8	8	8	8	8	8	8	8

RHUM DOLERITE GROUPS 1-12

77003 77004* 77006* 77007 77040 77075* 77078 77092 77105 77108

WT%

SiO2	51.43	52.40	51.66	51.28	49.91	50.98	51.21	52.65	50.83	51.51
Al2O3	13.64	15.03	15.21	15.21	13.77	13.36	13.87	14.74	14.51	15.52
Fe2O3	11.79	12.92	10.83	11.13	10.94	14.65	12.58	14.63	11.75	10.35
MgO	7.79	6.72	8.48	7.45	11.19	10.96	7.24	6.53	7.23	6.75
CaO	3.78	7.87	8.24	9.35	9.42	9.25	9.22	10.53	10.71	9.82
Na2O	3.34	4.22	3.49	3.18	2.42	2.47	2.96	2.86	2.82	3.25
K2O	0.95	0.82	0.35	0.95	0.94	0.57	0.64	0.67	0.70	1.20
TiO2	1.93	1.70	1.43	1.51	1.19	1.45	1.86	1.07	1.12	1.19
MnO	0.16	0.14	0.14	0.16	0.16	0.15	0.22	0.15	0.20	0.15
P2O5	0.19	0.20	0.18	0.17	0.12	0.15	0.23	0.11	0.12	0.24

PPM

NI	62	88	177	113	270	250	63	47	49	74
CR	134	197	344	314	643	628	166	115	114	247
BA	331	453	262	281	218	241	252	250	237	487
NR	8	8	8	6	5	6	8	4	4	5
ZR	193	199	159	141	130	152	228	83	88	120
Y	26	28	19	18	24	21	37	24	22	19
SR	256	256	321	277	190	255	236	207	243	381
RB	24	28	9	16	33	16	10	12	9	21
ZN	109	89	87	84	100	101	126	74	82	75

GROUP

8 8 8 8 8 8 8 8 8 8

RHUM DOLERITE GROUPS 1-12

	77124	77145	77149	77250	77281	77272	77316	77325	77339	77349
WT%										
SiO ₂	52.16	49.53	49.53	52.17	52.86	53.27	49.72	53.51	52.36	49.45
Al ₂ O ₃	14.27	12.73	13.59	13.34	14.74	15.01	14.38	13.84	15.75	14.36
Fe ₂ O ₃	12.55	15.68	11.77	14.53	11.10	12.55	12.73	11.99	12.55	11.13
MgO	5.92	5.94	9.51	6.84	5.16	6.42	6.94	5.89	7.85	9.73
CaO	7.21	9.35	11.25	8.97	13.48	12.47	9.78	7.63	7.02	12.45
Na ₂ O	3.49	3.01	2.33	2.91	2.53	2.59	3.53	3.74	3.26	2.49
K ₂ O	1.59	2.89	0.46	2.48	0.75	2.79	0.75	1.17	1.23	0.53
TiO ₂	2.46	2.41	1.40	2.32	1.27	1.22	1.83	1.67	1.49	1.53
MnO	2.18	2.23	0.18	0.22	0.20	0.16	2.19	2.23	2.15	0.18
P ₂ O ₅	0.26	0.23	0.10	0.25	0.10	0.12	0.19	0.34	0.14	0.16
PPM										
NI	19	36	122	21	45	39	71	28	122	147
CR	36	85	354	79	108	90	126	161	263	365
BA	396	259	182	221	267	265	180	459	462	231
VB	9	5	6	6	4	4	6	9	7	5
ZR	224	155	119	162	93	88	166	325	164	157
Y	29	32	20	29	22	22	27	56	21	23
SR	239	239	214	261	196	207	236	199	285	226
BB	36	35	29	27	18	19	28	44	53	24
ZN	131	123	107	196	93	63	124	286	123	128
GROUP	B	B	B	B	B	B	B	B	B	A

RHUM DOLERITE GROUPS 1-12

	77350	15A76	25A76*	75A76	77061	77064	77127	77148	77155*	77243
WT%										
SiO2	49.82	52.53	49.86	52.74	52.45	49.92	50.51	51.61	49.28	49.17
Al2O3	13.32	13.42	13.32	13.37	13.25	13.09	13.55	12.54	13.85	13.87
Fe2O3	11.90	13.05	14.63	14.22	14.53	13.11	14.39	14.05	14.24	14.23
MgO	9.63	6.22	6.14	6.52	6.26	6.72	6.32	6.82	6.58	7.42
CaO	10.75	9.78	9.44	8.52	8.83	10.02	8.64	8.77	10.49	9.93
Na2O	2.38	2.50	2.95	3.62	3.34	3.44	3.58	2.60	2.85	2.55
K2O	0.49	1.03	0.94	0.97	0.63	0.42	0.34	1.14	0.69	0.77
TiO2	1.37	2.14	2.31	2.51	2.23	2.01	2.20	2.03	1.81	1.68
MnO	0.20	0.19	0.24	0.20	0.20	0.19	0.21	0.21	0.22	0.21
P2O5	0.12	0.22	0.19	0.23	0.27	0.18	0.25	0.22	0.17	0.17
PPM										
NI	123	72	50	28	31	66	27	18	45	28
CR.	354	124	106	50	93	177	88	33	138	32
BA	265	387	442	294	274	216	285	347	231	171
NB	3	7	7	8	3	6	4	6	6	4
ZR	163	182	186	219	159	179	175	176	126	127
Y	26	35	32	32	30	29	35	28	36	24
SR	223	321	329	231	251	217	245	272	183	244
RR	25	24	25	31	29	11	20	36	16	20
ZN	100	87	121	137	123	104	142	127	97	99
GROUP	8	8	8	8	8	8	8	8	8	8

RHUM DOLERITE GROUPS 1-12

	77346	32A75★	83A76★	77058★	77090★	77137	77184	77005	77008★	77023
WT%										
SiO ₂	54.72	46.34	47.74	47.79	47.88	47.49	46.26	52.27	53.71	48.04
Al ₂ O ₃	14.30	15.76	13.34	15.37	16.04	14.65	15.24	15.18	14.80	13.46
Fe ₂ O ₃	10.05	13.27	15.86	12.38	12.06	11.85	12.12	11.08	11.73	16.04
MgO	6.61	12.05	6.93	8.53	8.96	11.52	9.89	5.66	4.96	5.05
CaO	8.16	6.41	8.99	9.90	9.32	7.30	8.56	7.60	6.97	8.40
Na ₂ O	3.30	3.55	3.20	3.19	2.97	3.25	4.53	4.58	5.60	4.20
K ₂ O	1.16	1.44	1.05	0.54	0.91	1.46	1.01	1.58	0.91	1.29
TiO ₂	1.38	2.16	2.45	1.73	1.49	1.88	1.92	1.71	1.69	2.94
MnO	0.14	0.18	0.22	0.17	0.16	0.14	0.17	0.14	0.11	0.22
P ₂ O ₅	0.16	0.43	0.21	0.29	0.21	0.46	0.30	0.20	0.21	0.35
PPM										
NI	100	173	42	104	124	240	199	95	40	10
CR	218	207	63	224	145	267	357	182	60	23
BA	471	487	266	515	571	870	367	476	325	474
NB	7	9	6	7	4	11	9	8	8	8
ZR	197	207	176	139	135	258	169	189	215	260
Y	23	25	30	23	21	28	26	25	26	36
SR	255	526	241	401	435	452	327	252	258	314
RB	37	22	55	16	13	27	15	26	16	20
ZN	100	132	213	153	87	120	112	97	23	145
GROUP	9	10	10	10	10	10	10	11	11	11

RHUM DOLERITE GROUPS 1-12

	77244	77326	77315	29476★	55A76★	76A76★	81A76★	77034★	77288	77229
NTX										
SI02	51.71	49.16	49.71	55.11	57.50	54.43	57.43	55.13	52.94	55.28
AL203	13.45	12.88	13.22	13.21	13.92	14.13	13.60	14.09	13.70	14.22
FE203	13.85	15.71	13.30	11.32	8.85	10.56	9.33	10.07	13.42	10.98
MG0	6.82	6.17	7.43	7.15	5.88	6.04	5.56	6.81	6.27	4.57
CAO	7.50	9.38	9.58	7.69	6.78	7.61	7.34	7.33	7.31	7.35
NA20	2.95	3.05	3.31	2.69	3.64	3.49	3.99	3.58	3.27	3.64
K20	1.37	0.82	0.91	1.46	1.53	1.34	0.57	1.35	0.18	1.82
TI02	1.97	2.40	2.31	1.56	1.54	2.01	1.70	1.34	2.32	1.74
MNO	0.17	0.23	0.20	0.23	0.12	0.16	0.14	0.14	0.20	0.16
P205	0.22	0.22	0.23	0.16	0.22	0.25	0.18	0.16	0.31	0.22
PPM										
NI	24	23	39	97	71	57	79	167	28	42
CR	128	84	71	247	163	141	96	367	138	99
BA	392	289	230	294	551	440	373	421	336	550
NB	6	5	6	8	9	9	9	7	8	9
ZR	166	152	202	289	266	293	314	191	295	465
Y	21	29	30	37	34	39	35	24	44	32
SR	275	258	223	235	280	282	293	286	393	276
RB	37	30	20	54	45	39	30	34	2	42
ZN	132	159	119	114	110	125	52	97	123	103
GROUP	8	8	8	9	9	9	9	9	9	9

RHUM DOLERITE GROUPS 1-12

77279☆ 77342☆ 77132☆ 77177☆

AT 2

53.28	49.35	56.86	54.23
14.81	14.27	16.54	17.45
11.37	12.45	7.10	9.14
5.83	5.02	3.22	4.43
5.59	3.21	4.75	3.23
4.39	4.25	4.85	4.25
2.47	2.25	4.18	4.23
1.99	2.63	1.74	1.69
2.16	2.19	0.12	2.15
2.27	2.75	0.54	2.92

AT 4

35	28	3	5
35	28	1	37
759	915	1524	1233
11	11	23	22
255	344	453	452
33	33	41	44
258	459	431	314
49	61	63	93
128	172	136	119

AT 10P 11 11 12 12

RHUM GABBRD PLUGS

	77031*	77033*	77104*	77256	77257	77292*	77295	77320*	77252	77284
WTZ										
SiO2	49.95	49.24	47.42	46.10	47.15	48.98	48.78	46.15	43.78	43.85
Al2O3	14.82	14.39	15.94	15.68	15.12	15.74	15.38	15.44	14.22	15.01
Fe2O3	10.37	10.02	9.97	11.39	10.52	11.47	10.58	12.14	11.65	13.07
MgO	10.71	11.22	10.48	11.03	11.95	9.74	10.05	11.68	17.23	13.46
CaO	10.18	12.14	12.95	10.32	11.57	9.99	12.22	10.45	9.19	9.97
Na2O	2.18	2.02	1.88	2.92	2.28	2.49	2.58	2.36	2.05	2.40
K2O	0.56	0.10	0.17	0.38	0.22	0.16	0.44	0.23	0.16	0.21
TiO2	1.02	0.52	0.96	1.80	0.95	1.17	1.56	1.27	1.41	1.68
MnO	0.15	0.16	0.14	0.16	0.16	0.17	0.14	0.16	0.15	0.18
P2O5	0.08	0.10	0.09	0.24	0.10	0.09	0.25	0.12	0.15	0.17
PPM										
NI	157	95	229	152	215	41	126	174	422	370
CR	440	337	785	319	833	158	347	321	858	720
BA	101	72	51	71	72	117	118	97	105	76
NB	6	2	3	4	0	2	1	1	0	1
ZR	86	16	61	144	56	33	146	79	83	115
Y	17	9	12	20	15	10	24	19	16	17
SR	149	277	193	330	181	323	256	184	288	253
RB	14	2	3	6	6	3	10	7	3	3
ZN	56	64	46	47	60	76	44	86	66	103

RHUM GABBRO PLUGS

	77288	77067	77098	77100	77246*	77261	77265	77267*	77270	77273
WT%										
SiO ₂	46.82	52.29	49.35	40.79	47.63	48.50	46.75	49.68	48.33	47.74
Al ₂ O ₃	15.24	15.25	14.25	13.78	13.55	15.59	15.27	14.32	16.32	15.13
Fe ₂ O ₃	8.25	11.47	10.15	11.49	14.33	12.94	13.34	10.85	11.93	12.63
MgO	14.91	7.17	7.27	7.83	7.29	6.40	8.32	6.38	8.21	7.91
CaO	13.28	9.72	13.26	12.63	11.48	9.72	10.89	11.87	9.46	10.50
Na ₂ O	0.95	3.64	3.45	2.88	2.69	3.43	3.19	3.92	3.28	3.63
K ₂ O	0.25	2.69	3.32	0.32	0.55	1.04	0.11	0.58	0.97	0.25
TiO ₂	0.54	1.43	1.64	1.58	1.98	1.03	2.03	2.05	1.52	1.84
MnO	0.11	0.16	0.15	0.18	0.20	0.16	0.18	0.15	0.16	0.17
P ₂ O ₅	0.27	0.17	0.15	0.18	0.28	0.31	0.22	0.19	0.22	0.23
PPM										
NI	337	92	91	88	69	58	122	72	78	96
CR	1955	395	146	434	124	189	277	326	226	221
BA	58	156	43	53	395	473	56	120	328	85
NB	0	4	4	5	1	4	5	2	6	3
ZK	33	128	57	125	123	164	128	113	131	121
Y	6	23	18	22	21	27	21	18	20	23
SR	199	272	281	204	350	517	592	300	488	304
RB	0	11	8	8	11	27	2	9	21	5
ZN	34	35	47	53	104	72	79	50	66	64

77282 77283 77287 77296 77102* 77103* 77274* 77264* 33A76 77163

WT%

SiO ₂	49.24	48.43	47.96	48.06	51.81	51.42	53.71	58.15	51.22	51.41
Al ₂ O ₃	14.28	14.67	16.23	15.19	14.47	13.84	14.81	14.10	13.77	14.67
Fe ₂ O ₃	11.44	12.04	11.26	10.92	10.90	13.02	12.71	12.26	10.25	10.47
MgO	7.42	8.26	8.86	8.53	6.92	5.72	4.25	2.69	6.94	7.88
CaO	12.21	11.15	12.18	11.44	10.47	9.03	5.84	3.99	12.78	10.64
Na ₂ O	3.14	2.89	3.42	3.20	2.44	3.38	4.59	4.03	2.53	2.62
K ₂ O	0.33	0.87	0.44	0.18	0.87	1.01	1.50	2.36	0.57	0.50
TiO ₂	1.83	1.55	1.51	1.98	1.69	2.17	2.22	1.97	1.67	1.52
MnO	0.15	0.17	0.14	0.17	0.17	0.21	0.18	0.17	0.15	0.19
P ₂ O ₅	0.18	0.15	0.18	0.31	0.16	0.20	0.20	0.25	0.13	0.10

PPM

NI	70	77	130	81	93	32	4	0	68	126
CR	49	258	318	325	227	25	5	0	118	207
BA	79	125	132	50	228	272	351	431	101	200
NR	0	4	5	3	4	6	8	10	5	0
ZR	82	96	165	175	159	182	256	359	98	105
Y	19	22	23	26	25	33	32	57	20	25
SR	249	314	348	221	207	190	222	178	238	223
RB	6	21	9	7	24	25	46	58	11	12
ZN	53	72	69	53	61	107	98	160	52	87

77328

77353

Wt%

SiO ₂	49.85	45.49
Al ₂ O ₃	18.64	22.18
Fe ₂ O ₃	5.71	8.57
MgO	7.12	17.83
CaO	15.27	12.96
Na ₂ O	1.78	1.38
K ₂ O	0.28	0.03
TiO ₂	0.63	0.43
MnO	0.28	0.11
P ₂ O ₅	0.27	0.23

PPM

NI	88	272
CR	416	358
BA	39	32
NB	0	1
ZR	28	4
Y	6	4
SR	320	283
RB	1	1
ZN	16	33

PERIDOTITE PLUGS

	77181	77182	77183	77259	77268	77281	77286	77290	77309	77357
WT%										
SiO ₂	41.37	47.61	40.89	41.67	41.43	42.13	41.24	47.03	41.77	39.63
Al ₂ O ₃	9.19	10.38	10.04	9.82	7.53	6.90	8.50	6.84	0.14	4.08
Fe ₂ O ₃	12.68	14.43	12.70	11.82	11.26	10.98	11.03	11.79	10.76	11.81
MgO	29.71	25.60	28.65	28.76	32.71	35.16	32.91	36.76	32.11	41.91
CaO	5.10	6.22	5.39	5.99	5.97	3.78	4.56	3.42	5.22	1.95
Na ₂ O	0.82	0.76	1.15	1.22	0.53	0.47	0.66	0.66	1.09	0.18
K ₂ O	0.12	0.15	0.17	0.09	0.07	0.07	0.07	0.04	0.12	0.03
TiO ₂	0.77	0.57	0.73	0.62	0.33	0.32	0.47	0.28	0.32	0.24
MnO	0.18	0.20	0.18	0.16	0.17	0.20	0.17	0.18	0.17	0.17
P ₂ O ₅	0.10	0.08	0.10	0.09	0.06	0.06	0.05	0.04	0.06	0.04
PPM										
NI	1570	1233	1446	1476	1796	2247	1887	2306	1823	2465
CR	2559	2394	2854	2214	3035	3399	2565	2799	3179	2885
BA	22	91	65	27	25	36	14	15	42	16
NB	2	1	1	3	0	0	0	1	0	2
ZR	53	28	44	43	20	19	30	13	19	19
Y	10	2	6	8	4	5	6	6	4	1
SR	112	132	147	98	45	55	68	30	55	22
CO	3	4	4	1	0	4	2	0	4	1
ZN	66	110	85	72	67	68	77	77	68	70

PERIDOTITE PLUGS

	77051	77054	77055	77066	77089	77097	77099	77129	77136	77138
WT%										
SiO ₂	40.70	41.00	40.78	41.47	42.14	41.26	39.30	40.75	40.27	40.37
Al ₂ O ₃	5.49	7.44	5.29	8.36	10.81	10.16	5.53	7.70	7.34	6.71
Fe ₂ O ₃	12.13	17.55	11.31	12.95	10.83	12.12	12.53	11.52	14.18	12.66
MgO	37.71	35.67	38.76	30.77	27.56	28.69	37.72	34.24	32.26	34.87
CaO	3.77	4.11	3.24	5.43	6.57	5.81	3.39	4.29	4.10	4.14
Na ₂ O	0.37	0.74	0.29	0.78	1.15	1.01	0.54	0.62	0.81	0.48
K ₂ O	0.00	0.10	0.06	0.14	0.10	0.10	0.12	0.13	0.13	0.10
TiO ₂	0.28	0.27	0.29	0.58	0.64	0.65	0.59	0.57	0.61	0.50
MnO	0.18	0.16	0.18	0.19	0.16	0.18	0.18	0.17	0.20	0.19
P ₂ O ₅	0.04	0.03	0.06	0.07	0.07	0.07	0.06	0.08	0.09	0.06
PPM										
NI	2411	2535	2483	1727	1742	1523	2393	2035	1420	1842
CR	3528	3257	4456	2560	3466	2632	2668	3161	2215	2852
BA	23	29	18	45	42	21	0	10	43	25
NB	2	4	4	1	2	8	1	2	3	1
ZR	16	14	20	34	42	34	26	38	41	31
Y	4	5	5	7	11	9	5	7	8	7
SR	32	32	35	70	80	83	73	104	103	69
RB	4	5	4	1	3	2	1	3	5	1
ZN	70	47	58	75	69	78	76	74	105	76

Table of CIPW Norms.

These were calculated using the program NORMCAL, written by R.C.O.Gill, with a fixed $\text{Fe}_2\text{O}_3 / \text{FeO}$ ratio of 0.25. DI refers to the Thornton-Tuttle (1960) Differentiation Index.

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

52A76★ 53A76★ 54A76★ 56A76 69A76★ 71A76 77A76★ 77077★ 77179★ 77321★ 77341 77052

ORTHOCLASE	0.8	1.8	2.5	1.4	0.7	0.8	3.8	1.7	4.3	1.2	2.9	0.6
ALBITE	5.6	8.7	13.3	8.6	11.6	9.7	8.2	14.5	2.1	9.9	10.9	10.3
ANORTHITE	20.8	27.5	29.3	27.4	28.1	29.7	28.4	27.1	20.7	27.4	28.7	29.8
NEPHELINE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0
DIOPSIDE	5.0	13.9	21.1	15.9	15.0	11.7	12.5	19.2	3.8	13.5	19.6	21.6
HYPERSTHENE	0.7	2.9	2.8	3.5	0.9	9.0	3.5	0.0	4.3	1.0	1.4	0.6
OLIVINE	62.1	39.3	26.7	37.2	36.5	33.8	37.4	29.0	59.9	43.4	32.0	31.2
MAGNETITE	3.3	3.1	3.3	3.1	3.4	3.1	3.3	3.1	3.1	3.2	3.4	3.4
ILMENITE	1.6	2.4	2.6	2.4	2.2	2.0	2.6	3.4	1.6	2.0	2.9	2.3
APATITE	0.2	0.4	0.4	0.4	0.5	0.2	0.4	0.5	0.3	0.6	0.4	0.2
DIFF. INDEX	6.4	10.6	13.9	10.0	12.3	10.4	12.0	17.6	6.4	11.1	13.7	10.9

77093★ 77095★ 77101★ 77107★ 77224★ 77192 77196 77197★ 77221 77225 77235 77236★

ORTHOCLASE	0.4	0.4	1.2	0.7	1.4	2.7	3.3	1.0	0.8	2.4	1.1	0.7
ALBITE	16.4	15.0	8.9	11.5	13.9	19.6	17.2	6.1	9.5	10.5	14.3	6.1
ANORTHITE	29.4	28.9	27.5	25.7	26.9	29.1	30.3	26.4	27.8	22.9	30.1	26.1
NEPHELINE	0.0	0.0	0.0	0.0	0.0	0.6	0.0	1.7	3.3	6.6	4.1	4.5
DIOPSIDE	26.6	23.4	14.7	20.0	19.3	16.3	11.7	7.1	10.0	20.6	20.0	13.3
HYPERSTHENE	4.4	5.4	1.5	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OLIVINE	16.5	20.9	40.2	35.6	28.1	26.1	30.0	52.9	42.2	30.0	23.9	40.0
MAGNETITE	3.4	3.4	3.4	3.4	3.6	3.3	3.0	3.0	3.4	3.3	3.1	3.3
ILMENITE	2.7	2.4	2.4	2.8	2.4	2.3	2.0	1.5	2.5	3.0	2.9	2.0
APATITE	0.2	0.2	0.2	0.3	0.3	0.3	0.5	0.2	0.4	0.4	0.4	0.6
DIFF. INDEX	16.8	15.3	10.1	12.2	19.6	22.9	20.5	8.9	13.7	19.4	19.5	11.3

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

77237★ 85A76 77017 77024★ 77035 40A76 44A76★ 46A76★ 65A76★ 70A76 93A76 77019★

ORTHOCLASE	1.1	0.8	0.9	0.3	1.1	1.1	2.1	1.5	0.6	1.1	1.8	1.9
ALBITE	19.6	7.3	12.9	14.3	13.5	13.8	39.2	12.4	18.4	17.5	14.1	14.0
ANORTHITE	29.7	21.3	27.4	31.2	29.0	32.5	33.5	25.3	29.2	28.2	27.3	28.4
NEPHELINE	1.0	0.9	1.0	2.0	0.9	0.9	0.9	3.3	0.9	0.9	0.9	0.9
DIOPSIDE	17.6	24.5	19.6	14.5	17.6	18.8	15.8	33.3	21.8	25.4	17.9	18.5
HYPERSTHENE	0.3	1.7	0.3	0.0	0.6	0.4	0.8	0.9	4.1	3.1	12.5	0.9
OLIVINE	24.2	5.1	34.3	32.5	27.0	18.0	23.6	17.5	19.8	17.9	21.1	27.7
MAGNETITE	2.0	0.1	3.6	3.2	3.4	2.0	2.9	3.1	3.1	3.2	3.2	3.5
ILMENITE	3.6	1.3	3.4	1.7	3.4	2.2	0.9	3.1	2.6	3.1	2.7	3.3
APATITE	0.2	0.2	0.4	0.2	0.4	0.3	0.2	0.4	0.3	0.4	0.3	0.4
DIFF. INDEX	21.8	7.8	15.5	16.8	14.6	14.9	11.3	17.1	19.0	18.7	15.9	18.3

77093★ 77095★ 77101★ 77107★ 77224★ 77192 77196 77197★ 77221 77225 77235 77236★

ORTHOCLASE	0.4	0.4	1.2	0.7	1.4	2.7	3.3	1.0	0.8	2.4	1.1	0.7
ALBITE	16.4	15.9	18.9	11.5	13.9	19.6	17.2	6.1	9.9	2.5	14.3	0.6
ANORTHITE	29.4	28.9	27.5	25.7	26.9	29.1	30.3	26.4	27.8	22.9	30.4	26.4
NEPHELINE	0.0	0.9	0.9	0.9	0.3	0.6	0.9	1.7	0.9	0.6	0.9	0.9
DIOPSIDE	26.6	23.4	14.7	20.9	19.3	16.3	11.7	0.9	18.9	20.6	20.9	1.1
HYPERSTHENE	4.4	5.4	1.5	3.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9
OLIVINE	16.5	20.9	40.2	35.6	28.1	26.1	31.0	5.0	42.0	3.0	2.0	4.0
MAGNETITE	0.4	0.4	0.4	0.4	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8
ILMENITE	2.7	2.4	2.4	2.8	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
APATITE	0.2	0.2	0.2	0.3	0.3	0.3	0.5	0.3	0.4	0.4	0.4	0.6
DIFF. INDEX	16.8	15.3	10.1	12.2	19.6	22.9	20.5	8.9	13.7	19.4	19.5	11.3

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

	77352*	66A76*	72A76	73A76	74A76	87A76*	89A76*	92A76	77046*	77048	77080	77082*
ORTHOCLASE	20.7	20.6	10.5	10.3	10.2	4.7	3.0	10.5	3.2	3.9	10.3	10.7
ALBITE	13.7	18.3	19.5	19.6	21.2	19.9	22.1	18.2	19.1	18.1	21.9	18.6
ANORTHITE	31.4	28.3	27.5	27.3	25.2	27.0	25.5	28.7	27.5	26.5	27.2	28.2
DIOPSIDE	21.2	18.9	17.6	19.2	23.7	17.8	19.4	21.8	18.2	22.0	21.3	19.5
HYPERSTHENE	4.9	9.6	17.6	15.5	2.6	4.7	8.9	5.5	12.1	4.3	8.9	15.3
OLIVINE	21.9	17.9	9.6	10.8	18.4	19.7	13.8	18.1	14.1	18.7	13.3	18.0
MAGNETITE	3.4	3.3	3.3	3.2	3.3	3.2	3.2	3.2	3.1	3.1	3.1	3.1
ILMENITE	2.6	2.8	3.4	2.9	3.3	2.7	3.6	2.8	2.5	2.9	2.7	3.2
APATITE	0.3	0.3	0.4	0.3	0.4	0.4	0.5	0.3	0.3	0.4	0.3	0.4
DIFF. INDEX	14.3	18.9	21.7	20.9	22.2	24.6	25.2	19.7	22.2	22.0	23.3	20.3

	77178	77191*	77249	77251	77318	77356
ORTHOCLASE	3.0	2.7	2.9	1.0	1.1	1.0
ALBITE	21.8	18.3	21.1	18.8	21.1	19.7
ANORTHITE	25.2	29.9	25.1	28.0	26.6	27.5
NEPHELINE	2.9	1.2	0.0	0.0	0.0	0.0
DIOPSIDE	17.3	19.1	20.1	19.2	21.7	19.7
HYPERSTHENE	0.0	0.0	4.0	4.0	10.1	14.4
OLIVINE	21.9	22.4	18.8	19.9	12.7	11.3
MAGNETITE	3.5	3.1	3.4	3.2	3.4	3.2
ILMENITE	3.8	2.9	4.1	3.6	3.1	2.9
APATITE	0.7	0.4	0.5	0.5	0.3	0.3
DIFF. INDEX	27.7	22.2	24.0	20.7	22.2	20.7

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

	77A56	77A23	SR151	SR229	SR238	SR284	SR141	SR159	SR182	SR211	SR282	12A76
ORTHOCLASE	0.5	0.3	0.3	0.4	0.3	0.3	0.7	4.0	4.4	0.7	4.4	1.4
ALBITE	14.5	17.2	18.5	16.8	17.4	15.6	23.3	25.3	26.6	25.3	25.4	17.2
ANORTHITE	31.8	34.6	33.5	31.0	35.2	33.1	27.8	23.3	23.0	32.6	23.7	32.7
NEPHELINE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
DIOPSIDE	29.0	22.2	23.6	26.8	22.2	24.3	20.1	23.4	23.4	12.2	22.5	24.5
HYPERSTHENE	1.9	1.4	0.8	9.7	4.2	13.4	11.7	10.3	7.7	0.0	12.1	6.0
OLIVINE	16.8	19.1	18.0	9.3	15.4	7.5	8.9	6.0	7.1	21.1	3.9	12.6
MAGNETITE	3.4	3.2	3.3	3.6	3.3	3.5	3.8	3.8	3.8	3.9	3.9	3.0
ILMENITE	1.9	1.8	1.9	2.2	1.8	2.1	3.4	3.3	3.5	3.3	3.5	2.4
APATITE	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.5	0.6	0.5	0.5	0.3
DIFF. INDEX	15.0	17.5	18.8	17.1	17.7	15.0	24.0	29.3	31.0	26.5	29.0	18.5

	77A14	77A47	7716A	7725B	16A76*	18A76	20A76	23A76	35A76	48A76*	49A75	50A76*
QUARTZ	0.0	1.0	0.4	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
ORTHOCLASE	3.2	0.5	3.2	3.0	3.8	3.8	5.5	4.5	7.4	2.2	1.5	2.3
ALBITE	17.2	16.8	14.7	14.2	21.3	21.3	22.6	21.4	35.0	18.6	18.4	20.9
ANORTHITE	33.9	42.8	38.6	42.4	25.5	24.2	22.2	23.5	17.7	28.2	26.1	25.7
DIOPSIDE	22.1	26.2	22.9	22.7	23.4	23.4	22.2	22.2	18.3	20.4	22.9	22.4
HYPERSTHENE	1.8	8.8	4.5	7.9	14.4	19.2	18.4	21.2	9.3	15.6	18.9	21.2
OLIVINE	16.1	0.0	10.9	4.4	4.8	0.0	1.9	0.1	4.3	9.1	5.5	1.1
MAGNETITE	3.0	1.9	2.6	2.2	3.1	3.2	3.3	3.2	3.3	2.9	3.4	2.9
ILMENITE	2.5	1.7	2.3	2.4	3.3	3.4	3.5	3.5	4.1	2.8	3.2	3.0
APATITE	0.3	0.2	0.2	0.2	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4
DIFF. INDEX	20.4	18.3	17.9	18.2	25.1	26.2	28.0	25.8	42.4	20.8	19.9	23.2

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

	51A76*	64A76	79A76	77003	77004*	77006*	77007	77009	77075*	77078	77092	77105
QUARTZ	0.0	0.6	0.0	0.0	0.3	0.0	0.3	4.0	0.0	0.7	1.9	0.0
ORTHOCLASE	3.6	5.1	2.3	5.7	4.9	2.1	5.7	5.4	3.4	3.8	4.0	4.2
ALBITE	25.1	27.3	21.8	28.5	35.9	29.8	27.2	20.7	21.1	25.3	24.4	24.1
ANORTHITE	23.8	22.5	24.3	19.6	19.9	25.0	24.1	24.3	23.9	22.0	25.6	25.1
DIOPSIDE	21.4	16.5	22.9	18.8	14.8	12.2	17.6	17.8	17.2	17.8	21.5	22.8
HYPERSTHENE	16.3	20.8	18.0	15.5	11.4	20.9	13.4	14.4	24.3	22.0	17.3	14.1
OLIVINE	2.4	0.0	3.7	4.5	6.5	4.0	5.9	12.0	4.1	0.0	0.3	4.3
MAGNETITE	3.3	2.9	3.2	3.2	2.9	2.9	3.8	2.9	2.9	3.4	2.9	3.2
ILMENITE	3.6	3.8	3.4	3.7	3.3	2.7	2.9	2.3	2.8	3.6	2.1	2.1
APATITE	0.4	0.6	0.4	0.5	0.5	0.4	0.4	0.3	0.4	0.6	0.3	0.2
DIFF. INDEX	28.7	33.0	24.1	34.2	44.7	31.0	32.8	26.0	24.5	29.8	30.3	28.3

	77108	77124	77145	77149	77250	77281	77272	77316	77325	77339	77349	77350
QUARTZ	0.0	0.5	0.0	0.0	0.0	3.9	4.2	0.0	1.6	0.0	0.0	0.0
ORTHOCLASE	7.2	0.5	5.3	0.7	2.9	4.5	4.7	4.5	7.0	7.4	3.2	2.0
ALBITE	27.8	29.8	25.8	19.9	24.9	21.6	22.1	29.9	32.0	27.8	21.3	20.3
ANORTHITE	24.4	18.2	18.8	25.8	22.1	26.9	27.2	21.5	17.7	23.0	26.7	24.5
DIOPSIDE	18.9	13.3	22.1	23.5	17.5	20.4	20.8	21.5	15.0	12.7	19.0	23.2
HYPERSTHENE	9.7	19.9	15.1	14.8	22.8	17.4	16.7	3.1	19.6	20.5	13.9	16.4
OLIVINE	6.5	0.0	2.5	7.3	0.0	0.0	0.0	12.1	0.0	2.6	8.8	6.6
MAGNETITE	2.8	3.4	4.2	3.2	3.9	3.0	2.8	3.4	3.2	2.8	3.0	3.2
ILMENITE	2.3	4.7	4.6	2.7	4.5	2.1	2.0	3.5	3.2	2.9	2.9	2.5
APATITE	0.6	0.6	0.6	0.2	0.6	0.2	0.3	0.5	0.8	0.3	0.4	0.3
DIFF. INDEX	35.0	39.8	31.1	22.7	28.7	29.9	31.1	34.4	40.5	35.2	24.4	23.3

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

	15A76	25A76*	75A76	77061	77064	77127	77148	77155A	77243	77244	77326	77315
QUARTZ	1.2	2.0	2.2	2.4	0.3	2.0	2.4	2.5	0.0	1.1	2.4	0.0
ORTHOCLASE	6.2	5.6	5.8	3.8	0.5	2.0	6.8	4.1	4.6	8.2	4.8	5.4
ALBITE	22.3	25.3	31.2	28.6	29.4	32.7	22.3	24.4	21.8	25.2	26.1	28.3
ANORTHITE	22.2	20.5	17.5	19.5	21.7	20.2	19.4	23.2	24.4	19.6	19.3	21.2
DIOPSIDE	21.6	21.1	19.4	19.2	22.4	17.6	19.4	23.3	20.0	13.6	21.8	23.2
HYPERSTHENE	19.2	16.6	8.9	19.2	8.9	19.0	21.8	10.2	16.3	24.2	13.9	6.5
OLIVINE	0.0	2.0	0.1	1.1	7.3	1.6	0.4	7.4	5.4	0.6	4.7	9.8
MAGNETITE	3.8	3.9	3.8	3.9	3.5	3.0	3.8	3.8	3.8	3.7	4.2	3.0
ILMENITE	4.1	4.4	4.8	4.3	3.9	4.2	3.9	3.5	3.2	3.3	4.6	4.4
APATITE	0.5	0.5	0.6	0.6	0.4	0.6	0.5	0.4	0.4	0.5	0.5	0.6
DIFF. INDEX	29.6	30.9	36.8	32.4	31.9	32.7	31.5	28.5	26.4	34.5	30.9	33.7

	29A76*	55A76*	76A76*	81A76*	77034*	77088	77209	77346	32A76*	83A76*	77058*	77090*
QUARTZ	7.3	7.3	3.8	8.1	2.8	6.0	4.3	3.7	0.0	0.0	0.0	0.0
ORTHOCLASE	6.3	9.1	8.2	4.3	8.2	1.1	10.9	6.0	8.6	6.3	8.3	0.0
ALBITE	23.0	31.0	29.8	34.8	30.5	28.0	31.1	28.2	24.4	27.4	23.3	25.4
ANORTHITE	21.0	17.3	19.1	17.6	18.5	22.7	17.2	21.0	23.1	19.2	26.0	28.0
NEPHELINE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DIOPSIDE	13.4	12.3	14.1	14.6	13.0	9.8	14.9	15.3	6.7	0.0	17.7	14.0
HYPERSTHENE	22.5	17.1	18.0	15.5	20.5	23.0	14.8	19.2	0.0	1.5	10.0	0.4
OLIVINE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAGNETITE	3.0	2.4	2.8	2.5	2.7	3.0	3.3	2.6	25.3	15.8	18.4	2.1
ILMENITE	3.2	2.9	3.0	3.3	2.6	4.5	3.3	2.6	3.5	4.3	3.3	3.2
APATITE	0.4	0.5	0.6	0.4	0.4	0.7	0.5	0.4	1.0	0.5	0.7	0.5
DIFF. INDEX	36.6	47.5	41.5	46.1	41.4	35.0	46.2	38.8	36.2	33.7	30.6	30.8

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

	77137	77184	77205	77208*	77223	77279*	77342*	77132*	77177*
CORUNDUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
ORTHOCLASE	8.7	6.0	9.4	5.4	7.7	14.7	12.2	24.8	29.3
ALBITE	25.1	18.7	37.8	46.5	30.0	36.7	29.8	41.3	36.3
ANORTHITE	21.3	18.4	15.3	12.7	14.3	13.9	13.9	11.1	8.9
NEPHELINE	1.4	10.8	2.7	0.7	3.3	0.0	3.5	0.0	0.0
DIOPSIDE	9.9	18.2	15.7	17.2	21.3	10.0	17.4	5.9	0.0
HYPERSTHENE	0.0	0.0	0.0	0.0	0.0	7.7	0.0	7.5	5.0
OLIVINE	25.7	20.2	12.3	14.8	12.6	9.3	12.9	2.2	10.7
MAGNETITE	3.2	3.3	3.3	3.0	4.5	3.1	3.3	1.9	2.5
ILMENITE	3.6	3.7	3.3	3.2	5.7	3.8	5.0	3.3	3.2
APATITE	1.1	0.7	0.5	0.5	0.8	0.6	1.8	2.0	2.2
DIFF. INDEX	35.3	35.6	47.9	52.7	41.0	51.5	45.6	66.1	65.6

	21A76	22A76*	41A76	47A76*	60A76	61A76	62A76	63A76	77012	77013	77032	77035
ORTHOCLASE	2.3	1.2	1.1	1.2	1.1	2.0	2.3	2.0	0.6	3.8	2.3	1.9
ALBITE	20.6	19.6	21.3	19.2	20.6	18.7	17.3	18.1	20.6	21.9	24.6	23.5
ANORTHITE	26.2	26.5	23.7	26.5	26.8	27.1	28.5	27.5	28.2	27.9	23.4	25.9
DIOPSIDE	25.2	26.4	22.3	24.3	22.8	25.2	25.5	25.6	25.0	20.0	25.0	21.5
HYPERSTHENE	8.9	8.4	8.0	14.0	13.2	5.3	5.2	4.2	1.9	1.4	2.2	8.9
OLIVINE	10.2	10.2	11.2	7.9	8.6	14.6	14.5	15.5	16.7	18.5	14.7	11.7
MAGNETITE	3.2	3.6	3.5	3.2	3.3	3.6	3.5	3.6	3.4	3.2	3.4	3.2
ILMENITE	3.0	3.7	3.3	3.2	3.1	3.2	3.0	3.1	3.1	3.0	3.7	3.1
APATITE	0.3	0.4	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.4	0.5	0.3
DIFF. INDEX	22.9	20.8	22.4	20.4	21.7	20.6	19.5	20.1	21.4	25.6	26.9	25.4

RHOM DOLERITE GROUPS 1-12 CIPW NORMS

77044* 77068* 77076 77125 77148* 77175* 77176* 77204 77208 77231 77269 77284

ORTHOCLASE	2.2	2.4	4.1	2.4	0.8	3.4	4.5	3.4	1.8	2.2	1.2	1.3
ALBITE	23.4	21.0	20.0	16.8	19.4	23.4	19.3	21.8	17.2	18.3	19.7	16.8
ANORTHITE	26.7	27.3	24.6	28.8	29.5	26.5	29.5	24.9	32.5	32.0	28.6	32.4
DIOPSIDE	24.2	20.6	26.4	27.7	23.9	16.9	12.6	19.4	21.8	22.7	24.3	24.9
HYPERSTHENE	0.6	0.2	5.0	7.8	3.4	2.7	11.3	3.9	3.2	6.3	9.6	2.2
OLIVINE	16.2	22.3	11.5	10.3	10.3	24.0	15.0	18.6	16.9	13.9	9.4	15.2
MAGNETITE	3.3	3.4	3.4	3.4	3.4	3.7	3.8	3.7	3.6	3.2	3.6	3.3
ILMENITE	3.2	2.8	3.6	2.9	2.9	3.2	3.4	3.2	3.2	3.0	3.4	3.4
APATITE	0.4	0.4	0.5	0.2	0.4	0.6	0.6	0.5	0.4	0.5	0.4	0.4
DIFF. INDEX	25.4	23.1	24.1	18.8	20.2	26.4	23.8	25.8	18.8	22.5	23.7	18.2

77327 77330* 77332 77333 77335 77337 77351 26A76* 82A76 94A76 95A76* 77010

ORTHOCLASE	2.9	2.2	1.9	2.2	1.5	3.6	2.6	0.5	1.5	3.5	3.5	2.0
ALBITE	23.8	18.6	21.6	17.4	20.1	21.5	20.7	20.8	25.1	22.2	23.9	22.9
ANORTHITE	25.1	26.7	27.6	20.7	27.2	27.1	27.4	26.2	22.3	29.8	24.9	23.7
NEPHELINE	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	1.3	0.3	2.1	1.7
DIOPSIDE	18.6	28.5	22.3	23.2	23.4	22.2	25.3	26.2	25.5	21.0	22.0	26.6
HYPERSTHENE	3.2	4.1	2.3	12.3	0.0	0.1	0.4	0.0	0.0	0.0	0.0	0.0
OLIVINE	18.6	13.4	17.4	10.0	17.9	18.7	17.3	18.0	16.5	16.3	16.6	15.3
MAGNETITE	3.7	3.4	3.3	3.3	3.4	3.4	3.3	3.5	3.7	3.2	3.4	3.6
ILMENITE	3.6	2.8	3.1	2.7	3.9	3.1	2.7	3.5	4.1	3.3	3.2	3.7
APATITE	0.5	0.3	0.4	0.3	0.5	0.3	0.3	0.4	0.4	0.4	0.4	0.4
DIFF. INDEX	26.7	20.8	23.5	19.6	23.7	25.0	23.3	22.2	27.5	26.0	29.5	26.7

RHUM DOLERITE GROUPS 1-12 CIPW NORMS

	77011	77015	77070	77071	77073	77074	77086	77091*	77120	77205*	77215	77313
ORTHOCLASE	0.3	1.6	0.8	0.4	1.6	1.6	0.5	4.9	2.1	5.4	4.8	2.6
ALBITE	22.6	23.9	18.6	24.8	23.8	23.1	20.6	16.9	19.8	22.7	18.0	14.2
ANORTHITE	22.3	24.2	24.6	22.5	26.3	26.6	27.6	27.4	28.2	20.1	26.3	25.5
NEPHELINE	3.9	2.0	2.9	1.4	1.1	1.2	2.5	1.1	0.7	2.2	0.7	4.6
DIOPSIDE	26.9	25.1	31.8	24.3	20.3	19.7	25.4	33.3	24.8	24.2	27.1	27.2
OLIVINE	16.3	15.6	13.3	17.4	19.4	20.2	16.8	13.3	17.1	17.2	15.4	18.7
MAGNETITE	3.6	3.5	3.8	4.1	3.4	3.5	3.4	3.4	3.4	3.6	3.7	3.6
ILMENITE	3.7	3.6	3.8	4.6	3.6	3.6	3.1	3.6	3.5	3.9	3.5	3.3
APATITE	0.5	0.4	0.4	0.5	0.5	0.6	0.3	0.4	0.4	0.6	0.4	0.4
DIFF. INDEX	26.8	27.5	22.4	26.6	26.4	26.9	23.5	18.9	22.7	30.3	23.6	21.4

	77314*	77324	77331*	77335	77340	77343	77344	77348	77359*	13A76	14A76	38A76
ORTHOCLASE	0.5	2.8	1.4	1.4	0.9	1.7	1.0	3.2	0.8	2.2	1.9	0.2
ALBITE	19.1	18.5	21.5	22.0	20.1	22.0	23.6	20.5	23.2	24.6	23.7	27.8
ANORTHITE	25.6	28.2	28.8	23.5	26.9	25.8	30.1	27.5	26.7	21.5	21.5	23.4
NEPHELINE	3.6	0.3	0.3	0.6	1.0	0.2	0.3	1.0	0.1	0.0	1.5	2.2
DIOPSIDE	25.7	24.3	22.3	28.8	25.2	24.8	22.2	22.2	25.4	23.2	25.9	22.0
HYPERSTHENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.7	0.0	0.0
OLIVINE	18.4	18.2	19.0	16.3	18.2	18.3	16.4	19.1	17.2	6.9	15.6	16.0
MAGNETITE	3.4	3.7	3.4	3.6	3.6	3.5	3.2	3.2	3.3	4.3	4.2	3.8
ILMENITE	3.3	3.6	2.9	3.4	3.7	3.4	3.8	3.0	3.3	5.2	5.2	4.1
APATITE	0.4	0.5	0.3	0.4	0.5	0.3	0.4	0.4	0.4	0.5	0.6	0.5
DIFF. INDEX	23.2	21.6	23.2	24.0	22.0	23.9	24.9	24.7	24.1	26.8	27.0	30.3

RHUM GABBRD PLUGS CIPW NORMS

	77031*	77033*	77104*	77256	77257	77292*	77295	77320*	77252	77280	77288	77067
ORTHOCLASE	3.3	0.6	1.0	2.3	1.3	1.0	2.6	1.4	1.0	1.3	0.3	4.1
ALBITE	18.6	17.2	16.0	20.0	19.2	21.3	22.0	24.2	13.3	14.3	8.2	31.1
ANORTHITE	20.2	34.1	34.8	28.8	30.6	31.6	29.3	31.2	29.4	29.0	37.4	23.5
NEPHELINE	0.0	0.0	0.0	2.6	0.1	0.0	0.0	0.0	2.3	3.4	0.0	0.0
DIOPSIDE	17.0	24.1	23.6	17.1	21.4	14.4	16.2	16.5	12.5	15.3	22.7	19.7
HYPERSTHENE	19.2	13.2	4.5	0.0	0.0	16.0	11.6	0.2	0.0	0.0	9.5	2.6
OLIVINE	7.6	10.6	15.2	22.0	22.4	9.3	11.8	24.6	35.4	28.8	18.7	12.8
MAGNETITE	2.8	2.7	2.7	3.1	2.8	3.1	2.8	3.3	3.1	3.5	2.2	3.1
ILMENITE	2.0	1.2	1.8	3.4	1.8	2.2	3.0	2.4	2.7	3.2	1.8	2.7
APATITE	0.2	0.2	0.2	0.6	0.2	0.2	0.6	0.3	0.4	0.4	0.2	0.4
DIFF. INDEX	21.9	17.8	17.1	25.0	20.7	22.2	24.6	21.5	16.5	18.9	8.5	35.2

	77002	77049*	77287*	77210	77322	77334	77360*
ORTHOCLASE	0.4	0.2	0.8	8.4	1.2	2.3	0.5
ALBITE	22.7	21.1	24.3	16.8	20.3	24.2	23.7
ANORTHITE	28.2	16.8	23.9	26.4	24.3	24.4	26.5
NEPHELINE	0.0	0.7	0.0	0.0	2.2	0.0	1.4
DIOPSIDE	21.2	28.9	19.7	23.0	27.6	23.0	24.1
HYPERSTHENE	10.2	0.0	15.0	1.5	0.0	0.8	0.0
OLIVINE	8.8	14.2	6.2	15.8	16.4	16.7	15.5
MAGNETITE	3.0	4.2	4.1	4.0	3.8	3.7	3.7
ILMENITE	4.2	4.5	5.4	3.8	3.8	3.6	4.0
APATITE	0.5	0.5	0.5	0.3	0.4	0.3	0.5
DIFF. INDEX	23.0	30.9	25.1	25.2	23.7	26.6	25.7

RHUM GABBRO PLUGS CIPW NORMS

	77208	77144	77246*	77261	77265	77267*	77270	77273	77282	77283	77287	77296
ORTHOCLASE	1.9	1.9	3.3	6.2	0.7	3.5	5.8	1.5	1.8	5.2	2.6	1.1
ALBITE	22.9	24.6	23.3	28.3	24.5	26.5	26.3	26.4	26.3	23.1	25.5	26.2
ANORTHITE	22.6	23.9	23.3	24.5	27.3	19.0	27.3	24.6	24.2	24.7	27.9	26.3
NEPHELINE	3.6	0.0	0.0	0.6	1.5	3.8	0.0	2.3	0.3	0.9	2.0	0.6
DIOPSIDE	34.6	31.2	25.9	18.2	21.3	31.1	15.2	21.8	29.1	24.5	17.7	23.0
HYPERSTHENE	0.0	0.4	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OLIVINE	8.2	11.4	12.1	14.6	17.2	7.9	17.3	15.9	11.3	15.4	18.2	14.9
MAGNETITE	2.7	3.1	3.9	3.5	3.5	2.9	3.2	3.4	3.1	3.2	3.3	2.9
ILMENITE	3.1	3.0	3.8	3.7	3.9	3.9	3.1	3.5	3.5	3.4	2.9	3.8
APATITE	0.4	0.4	0.7	0.7	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.7
DIFF. INDEX	28.3	26.5	26.3	34.0	26.7	33.7	32.1	34.3	28.4	29.2	30.1	27.9

RHUM GABBRD PLUGS CIPW NORMS

	77102*	77103*	77274*	77264*	33A76	77163	77328	77353
QUARTZ	2.5	0.1	1.3	0.6	0.7	0.7	0.1	0.0
ORTHOCLASE	5.2	6.0	9.5	14.1	3.4	3.0	3.5	3.2
ALBITE	23.8	28.9	39.2	34.5	21.6	22.4	15.1	11.8
ANORTHITE	26.2	19.8	15.2	13.6	24.7	27.0	42.9	49.1
DIOGENITE	24.5	10.9	12.1	4.8	31.2	20.7	25.6	12.4
HYPERSTHENE	18.2	17.1	17.2	16.6	12.2	20.2	12.7	3.7
OLIVINE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7
MAGNETITE	3.0	3.5	3.4	3.3	2.8	2.8	1.8	2.3
ILMENITE	3.2	4.2	4.3	3.8	3.2	2.9	1.2	0.8
APATITE	2.4	0.5	0.7	0.6	0.3	0.2	0.2	0.1
DIFF. INDEX	28.6	35.0	49.1	58.1	25.7	26.1	15.7	11.9

PERIDOTITE PLUGS CIPW NORMS

	77351*	77354*	77355	77366	77389	77397	77399	77129	77136	77138	77181	77182
ORTHOCLASE	0.5	0.6	0.4	0.8	0.6	0.6	0.0	0.8	0.8	0.6	0.7	0.9
ALBITE	3.2	3.1	2.5	6.6	7.3	6.0	2.2	4.1	5.1	3.3	7.2	5.4
ANORTHITE	13.2	16.8	13.1	19.1	24.2	23.1	12.2	18.2	16.2	16.0	21.3	24.8
LEUCITE	0.0	0.0	0.0	0.2	0.3	0.0	0.6	0.0	0.0	0.0	0.2	0.0
NEPHELINE	2.0	1.7	2.0	0.0	1.5	1.4	3.8	0.6	1.0	2.4	3.0	0.6
DIOPSIDE	1.5	2.8	1.4	6.1	6.5	4.4	2.8	2.3	3.0	3.4	2.9	4.7
HYPERSTHENE	2.0	0.0	2.7	0.0	0.0	0.0	2.2	0.0	0.0	0.0	1.8	0.0
OLIVINE	75.7	71.5	76.3	62.6	55.8	59.8	76.7	69.8	68.7	71.7	61.3	58.4
CAL ORTHOSIL	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
MAGNETITE	0.3	2.8	3.0	3.5	2.9	3.3	3.4	3.1	3.8	3.4	3.4	3.9
ILMENITE	0.5	0.8	0.6	1.1	1.2	1.2	1.1	1.1	1.0	1.0	1.5	1.1
APATITE	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.2
DIFF. INDEX	3.7	5.4	2.8	7.5	9.1	8.0	3.5	5.5	6.9	4.3	7.7	6.9

PERIDOTITE PLUGS CIPW NORMS

	77183	77259	77268	77281	77286	77290	77309	77357
CORUNDUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
ORTHOCLASE	1.0	0.5	0.4	0.4	0.4	0.2	0.7	0.2
ALBITE	35.7	6.7	2.9	4.0	5.6	2.0	2.8	1.4
ANORTHITE	22.0	22.2	18.1	16.6	18.8	15.7	19.9	9.5
NEPHELINE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DIOPSIDE	3.5	5.7	9.2	1.5	2.9	2.0	4.6	0.0
HYPERSTHENE	0.0	0.0	4.2	7.8	2.8	0.0	0.0	0.0
OLIVINE	60.5	59.2	64.9	66.0	62.2	75.4	64.0	84.8
MAGNETITE	3.4	3.2	3.3	2.0	3.2	3.2	2.9	3.2
ILMENITE	1.4	1.2	0.6	0.6	0.9	0.5	0.0	0.5
APATITE	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
DIFF. INDEX	9.0	8.3	4.2	4.4	6.1	4.2	7.1	1.7

Appendix 8.1

Calculated olivine and spinel settling rates in basaltic magmas.

The behaviour of fluids interacting with dispersed particles can be predicted from the Reynolds Number (N_R) of the system. This is the ratio of inertial force to viscous force and can be expressed as follows:

$$N_R = \frac{UL\rho}{\mu}$$

where U is the relative velocity of fluid and particles (cm sec^{-1})

L is the particle diameter (cm)

ρ is the density of the fluid (g cm^{-3})

μ is the viscosity of the fluid (poises)

Large values of Reynolds Number ($N_R > 10,000$) imply only slightly viscous behaviour and the development of turbulent flow, while small values indicate highly viscous behaviour and the operation of a laminar flow regime.

Natural systems involving magma and crystals have very small Reynolds Number (< 0.1) and under these circumstances it has been suggested that Stokes Law may be used to estimate the settling velocity of crystals in a basaltic liquid (Wadsworth 1973, Donaldson 1974). The assumption that basalt liquidus phases will sink in a basalt liquid is a fundamental premise of the cumulus theory in igneous

systems advocated by Wager and co-workers (e.g. Wager et al., 1960, Wager and Brown, 1968) which has recently been challenged by McBirney and Noyes (1979). These authors note that the olivine crystals in the Kilauea Iki 1959 crater lava lake in Hawaii had not settled in the years following this lake's emplacement and suggested that Stokes Law was not applicable to crystals in igneous melts. It is beyond the scope of this thesis to reassess the role of crystal settling in the genesis of the Rhum layered peridotites. However, it may be pertinent that the mafic parent advocated in Chapter 8 of this thesis would be less viscous than a basalt parent and consequently may be less susceptible to the criticisms of the role of crystal settling in the Skaergaard parent levelled by McBirney and Noyes (1979).

Stokes Law may be stated as follows:

$$U = \frac{D^2 (\rho_P - \rho_F)g}{18\mu}$$

where U is the terminal settling velocity of the particle (cm sec⁻¹)

D is the particle diameter (cm)

ρ_P is the particle density (gm cm⁻³)

ρ_F is the fluid density (gm cm⁻³)

g is the acceleration due to gravity (980 cm sec⁻²)

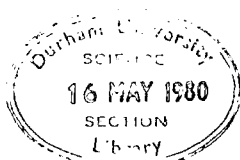
μ is the viscosity of the fluid (poises) and is applicable to streamline motion of spherical particles. The olivines and chromites in the Rhum layered series are not spherical but Wadsworth (1973) suggests that providing the grains do not have extreme shapes the calculated results for a sphere of equivalent diameter hold reasonably well (within 20%). In addition the lack of data concerning magma density and viscosity introduce more uncertainty into the results presented in Table 8.2 consequently these figures can only be viewed on a comparative basis (ie. large olivines will settle faster than small olivines).

The mineral density value ρ_P at 1000°C for olivine (Fo85) and Cr-spinel used in the calculations was 3.22 and 4.53 respectively (Birch et al., 1942). Various estimates for magma viscosity ranging from 300 to approximately 3000 poises have been made (Macdonald 1963, Bottinga and Weill 1970, McBirney and Noyes 1979) so the calculations were made for a range of magma viscosities. Various estimates have also been made for magma densities (ρ_F), these are: 2.7-2.8 Dunham and Emeleus (1967), 2.64-2.78 Bottinga and Weill (1970), 2.58 Wadsworth (1973). The calculations made here assumed a magma density of 2.8, whilst this may lead to difficulties with respect to the cumulus theory in that plagioclase may not sink in a magma of this density it does not affect the conclusion drawn from Table 8.2 that

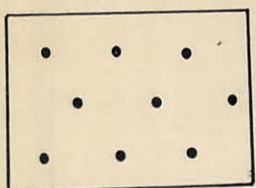
olivine will sink much faster than Cr-spinel. The settling rates for both minerals will increase if a lower magma density value had been chosen. A comparison of olivine and spinel settling rates in a magma of density 2.5 and 2.8 respectively is made below to illustrate this point.

Mineral type	ρ_P	ρ_F	Particle diameter	Viscosity (poises)	Settling rate
Ol	3.22	2.8	1 mm	300	0.0762 cm/sec
Ol	"	2.5	1 mm	"	0.1307 "
Ol	"	2.8	3 mm	"	0.6860 "
Ol	"	2.5	3 mm	"	1.1760 "
Cr-Sp		2.8	0.3 mm	"	0.0283 "
Cr-Sp		2.5	0.3 mm	"	0.0332 "
Cr-Sp		2.8	0.4 mm	"	0.0502 "
Cr-Sp		2.5	0.4 mm	"	0.0589 "

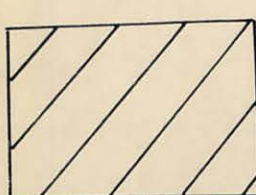
The particle diameters for Cr-spinel and olivines were measured in three thin sections from the Unit 11/ Unit 12 junction in the Durham University collections. The olivines range from 0.8-3.0mm in size and the largest spinels were 0.4mm diameter.



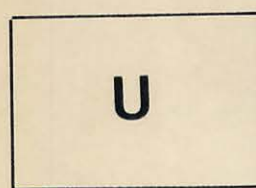
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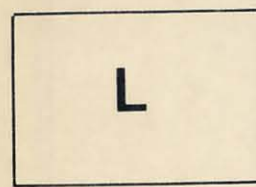
TORRIDONIAN AND TRIASSIC
OUTSIDE THE MAIN RING FAULT



ACID AND ASSOCIATED ROCKS



LAYERED ULTRABASIC ROCKS



LAVAS



APPROXIMATE LOCATION OF
TRAVERSE

FIG 2.1 RHUM DYKE STRIKE ORIENTATIONS

N

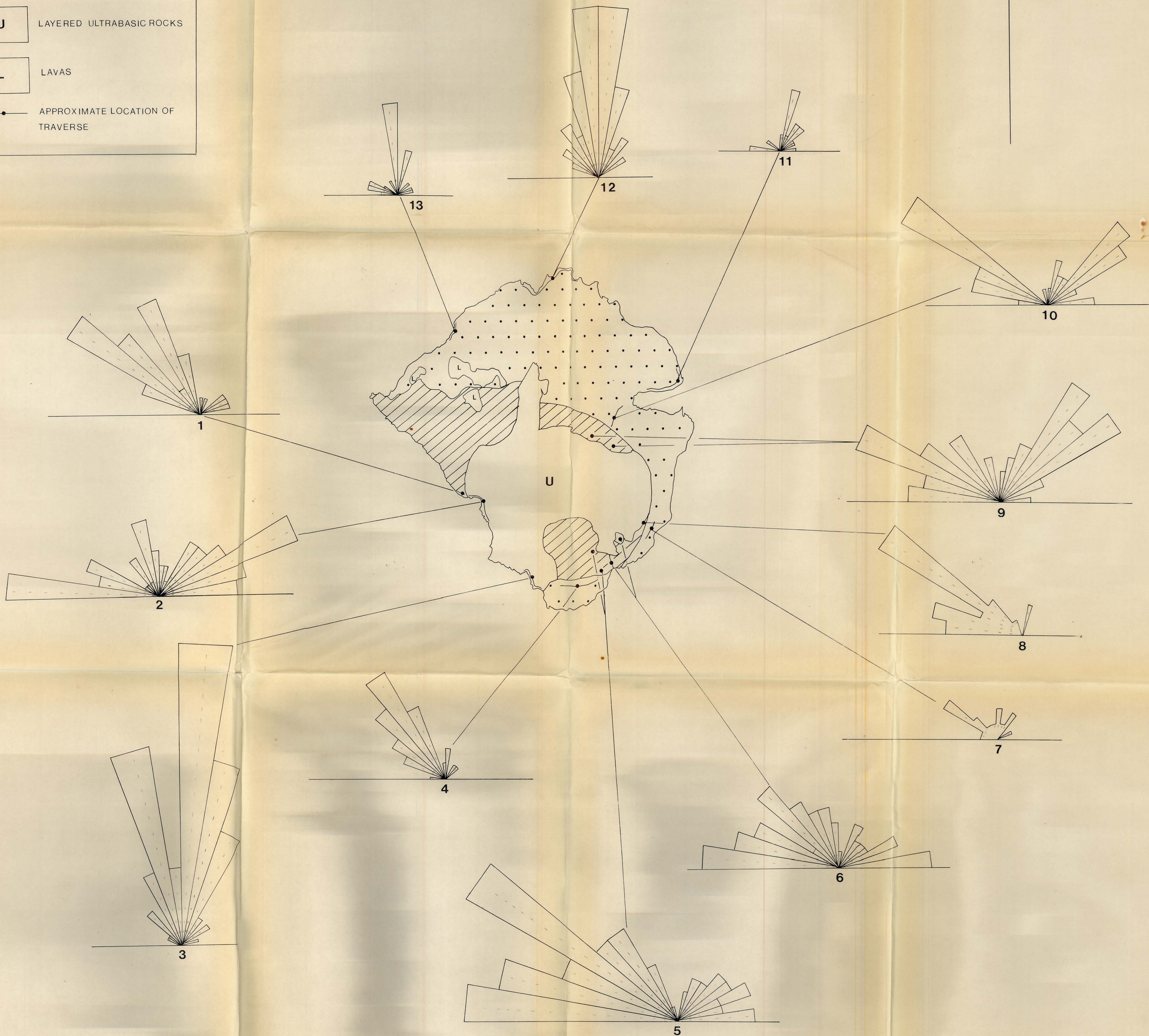
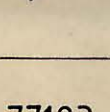




Fig. 2.II Location map of some Rhum minor intrusions.

KEY

L	LAVAS AND CONGLOMERATES
U	LAYERED ULTRABASIC ROCKS
A	ACID AND ASSOCIATED ROCKS
Tr	TRIASSIC
T	TORRIDONIAN OUTSIDE THE MAIN RING FAULT
	GABBRO PLUG
	PERIDOTITE PLUG
	ACID DYKE
	THICK CONFORMABLE SHEET
	BIG FELDSPAR DYKE
77123	SPECIMEN NUMBER