THE PETROLOGY AND GEOCHEMISTRY OF THE LOWER OLD RED SANDSTONE LAVAS OF THE SIDLAW HILLS, PERTHSHIRE

by

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Thesis presented for the Degree of Doctor of Philosophy of the University of Edinburgh in the Faculty of Science.

1972

ABSTRACT

The Sidlaw Hills are situated in the Midland Valley of Scotland north-east of Perth. The lava sequence forms a small part of an extensive volcanic province of Lower Old Red Sandstone age in Scotland, and the suite in the Sidlaws consists of a range of lava types including basalt, basaltic-andesite, andesite, and dacite though the more basic rocks predominate. The lavas can be described as calc-alkaline.

Olivine which is always totally altered, is a ubiquitous phenocryst phase in the basalts and basaltic andesites, and is frequently accompanied by plagioclase, and occasionally by clinopyroxene. Orthopyroxene phenocrysts occur rarely in the basalts and in some andesites.

In their major element chemistry, the lavas are reasonably comparable to modern day calc-alkaline lavas, though there is no direct equivalent. The slightly alkalic nature of these rocks compared with modern day calc-alkaline lavas is reflected in the high concentrations of Ba, Sr, Rb, Zr, La, and Ce, though all show considerable variation. Quartz is present in the norms of most of the Sidlaw lavas, and hypersthene is present in all.

The low pressure differentiation of the lavas can be accounted for by fractionation of olivine + plagioclase + minor ore from a chemically variable immediately parental magma. From the close correspondence between observed phenocryst assemblages and liquidus minerals in experimentally melted samples, it is concluded that this fractionation took place at low pressures (c. 1 kb p H_2O). Cumulus enrichment in plagioclase appears to have contributed substantially to the highly aluminous nature of many of these rocks as well as the high contents of/

of Sr.

It is suggested that fractionation of variable amounts of olivine and clinopyroxene at moderately high p H_2O from an olivine tholeiite could give rise to the chemically variable high alumina immediately parental magma.

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NOTE ON UNITS

Unless otherwise stated, oxides are quoted as weight percent (wt %) and elements as parts per million (ppm).

CHAPTER 1

INTRODUCTION

1:1 The Sidlaw Hills

The Sidlaw Hills are situated in the Midland Valley of Scotland between 56° 21' and 56° 37' north, and 3° 03' and 3° 25' west as illustrated in FIG 1-1. As a low lying range of hills, they run north-eastwards from Perth for approximately 34 km, their width varying from 1.5 to 5 km. Their maximum elevation is 376 m above sea level.

The lavas of the Sidlaw Hills form a small part of an extensive though discontinuous sequence of lavas of Lower Old Red Sandstone age, whose present northern limit in Scotland is the Isle of Uya in Shetland, and whose present southern extension includes the Cheviot Hills in Northumberland. The most easterly margin of this Lower Old Red Sandstone lava sequence is defined by the North Sea at Stonehaven while in the west it extends to Lough Erne in Northern Ireland. This whole area embraces the Glencoe lavas, the Lorne Plateau, the Ochil Hills, the Pentland Hills, and the Ayrshire volcanics rocks, and includes approximately 150,000 sq km of Scotland and Northern Ireland. FIG 1-1 illustrates the extent of the Lower Old Red Sandstone lava province.

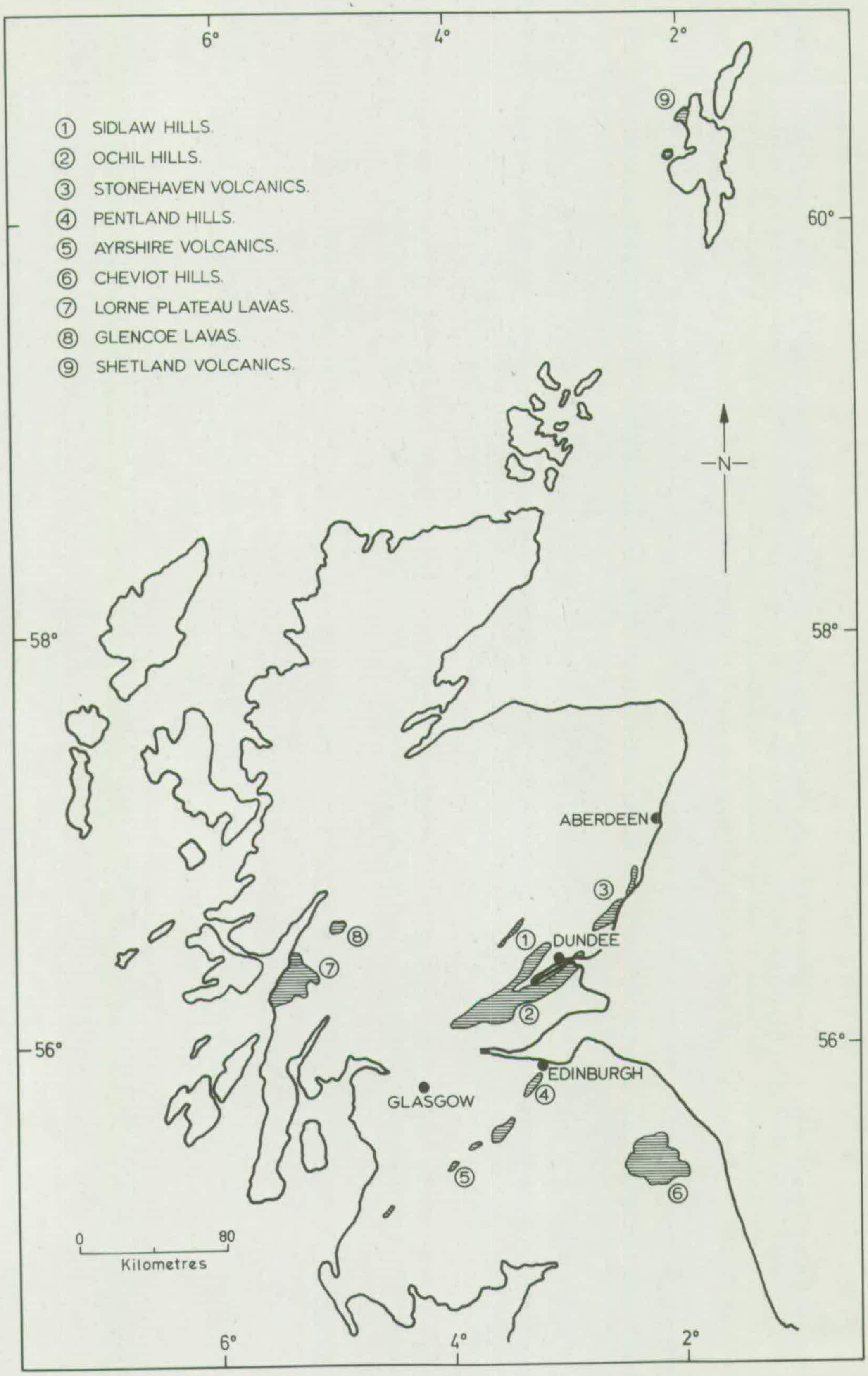
1:2 General Geology

The following discussion is based on field work undertaken in this study, and on information reported by HARRY (1956, 1958) PATERSON and HARRIS (1969), and ARMSTRONG and PATERSON (1970).

The/

FIG. 1-1

Map showing the location of the Sidlaw Hills and distribution of Lower Old Red Sandstone lavas in Scotland


① SIDLAW HILLS.
② OCHIL HILLS.
③ STONEHAVEN VOLCANICS.
④ PENTLAND HILLS.
⑤ AYRSHIRE VOLCANICS.
⑥ CHEVIOT HILLS.
⑦ LORNE PLATEAU LAVAS.
⑧ GLENCOE LAVAS.
⑨ SHETLAND VOLCANICS.
6°
4°
2°
60°
58°
56°
N
ABERDEEN
DUNDEE
EDINBURGH
GLASGOW
0
80
Kilometres

The total thickness of the Lower Old Red Sandstone sequence in the Strathmore region (see FIG 1-1) has been estimated by ARMSTRONG and PATERSON (1970) to be of the order of 9000 m, and in the Sidlaw Hills the thickness is probably greater than 1500 m. However, since the base of the sequence in the Sidlaw Hills is not exposed, an accurate thickness cannot be determined.

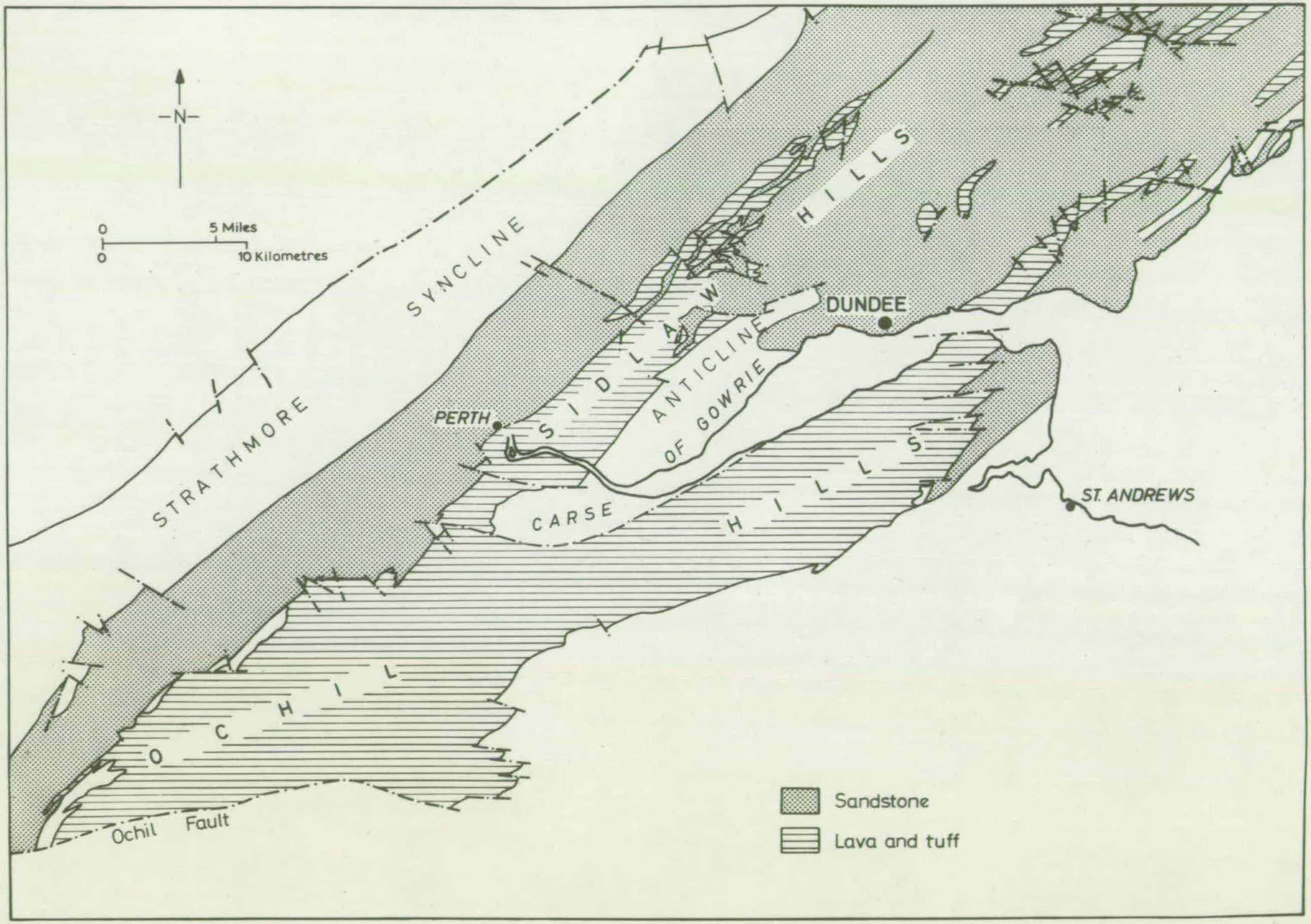
The Lower Old Red Sandstone sequence of the Sidlaw Hills consists of interbedded lavas, sandstones and conglomerates. No pyroclastic deposits have been recognised. The lavas can be divided into groups up to a few hundred metres in thickness separated by sedimentary horizons. Volcanic vents appear to be absent from the Sidlaw Hills, though they are present in the related volcanic sequence of the Ochil Hills. FIG 1-2 illustrates the general geology of the Sidlaw Hills, based on a geological map produced by ARMSTRONG and PATERSON (1970).

1:3 Tectonic Setting

SIR ARCHIBALD GEIKIE (1897) noting the relative position of Lower Devonian sedimentary sequences in the Midland Valley coined the term "Lake Caledonia" for the area, as a region of subsidence. Within this area of subsidence, the volcanic centres have been subjected to minor tectonic movements and in the Sidlaw Hills, folding has produced the Sidlaw Anticline. The Sidlaw Hills form the northern limb of this structure and the Sedimentary rocks and the lavas dip at 10°-15° to the northwest. ARMSTRONG and PATERSON (1970) pointed out that the main folding of the Lower Old Red Sandstone rocks in the Strathmore region took place in mid-Devonian times. The axes of the major folded structures are horizontal, though in the region of Dundee the axis/

FIG. 1-2

Simplified geological map of the Sidlaw Hills and surrounding areas (Based on map published by ARMSTRONG and PATERSON (1970))


N
0 5 Miles
0 10 Kilometres
STRATHMORE SYNCLINE
SIDLAW HILLS
ANTICLINE OF GOWRIE
DUNDEE
PERTH
CARSE
OCHIL HILLS
ST. ANDREWS
Ochil Fault
Sandstone
Lava and tuff

axis of the Sidlaw anticline does change its attitude from a horizontal NE-SW direction to a steep plunge to the southwest.

Faulting within the Sidlaws, generally trending NE-SW, has only been of minor significance, though a major fault does terminate the sequences of lavas in the Carse of Gowrie.

Recently, the whole region of Lower Old Red Sandstone volcanicity in Scotland has been significant in defining the plate tectonic evolution of the Caledonides in theories proposed by DEWEY and PANKHURST (1970), and DEWEY (1971), (see Chapter 8).

1:4 Previous Work

The geology of the Sidlaw Hills first received attention towards the end of the last century, from H. M. Geological Survey. The western Sidlaws were mapped by Professor JAMES GEIKIE, and the eastern extension by H. M. SKAE. The first geological map was published in 1883 as 1" sheet 48 (Perth) on which the lavas were termed "porphyrite". However, when cataloguing the volcanicity of Great Britain, SIR ARCHIBALD GEIKIE (1897) referred to the Sidlaw lavas as "andesites" a description based on information supplied by J. GEIKIE. A. GEIKIE pointed out that the main vents for the extrusive rocks of both the Ochil and Sidlaw Hills probably were situated in the region of Stirling, where the lavas agglomerates and pyroclastic deposits were thought to be more than 10 km thick without their base being exposed.

Although A. GEIKIE described the Sidlaws in relation to other volcanic sequences both structurally and topographically, chemical and petrographic data were limited.

Somewhat more detailed studies of selected areas of the Sidlaws were published/

published by HARRIS (1928) and DAVIDSON (1932). HARRIS (1928), after examination of the extrusive rocks around Dundee, drew attention to the presence of andesite once again, and pointed out that the only surviving high temperature ferro-magnesian minerals in these rocks were ortho- and clinopyroxene, the former usually altered. HARRIS also noted that hornblende bearing lavas, common in other Lower Old Red Sandstone lava sequences, and acid lavas were absent from the Sidlaw Hills. DAVIDSON (1932) was able to distinguish two types of lava in the area of Perth, on the basis of phenocryst size, and the presence or absence of plagioclase phenocrysts namely "Microporphyritic olivine- enstatite basalt, and olivine-enstatite basalt with porphyritic feldspars". Apparently, DAVIDSON was the first person to recognise the presence of olivine in the Sidlaw lavas.

Although neither HARRIS nor DAVIDSON published any complete analyses, the latter author stated "It has been known for some time, however, that the Old Red Sandstone diorites, andesites, and basalts are decidedly richer in potash than the corresponding 'average' rock in the tables of Osann or Washington, and it appears that the affinities of the entire group lie rather with the monzonites than with the true diorites . . . ". Since no analytical data were apparently available for the lavas of the Sidlaw Hills, it is likely that this statement was made on the basis of analyses of lavas from, the Lorne Plateau sequence, and the Glencoe lavas published by H. M. Geological Survey (1916); the Ayrshire volcanics rocks published by H. M. Geological Survey (1930); the Pentland Hills lavas and the Cheviot Hills lavas published by A. GEIKIE (1897). All of the analyses were presented by GUPPY and THOMAS (1931).

The first comprehensive study of the petrography and chemistry of the lavas of the Sidlaw Hills was made by HARRY (1956, 1958) when in turn he mapped the/

the Western, and Eastern Sidlaw Hills. He noted that the lavas were generally fresh, although olivine was always totally altered. HARRY drew attention to several different lava types, namely feldspar-phyric olivine basalt, aphyric olivine basalt, andesite basalt, andesite, and trachyandesite, and recognised their calc-alkaline affinities. The analyses of selected lavas from the Sidlaw Hills quoted by HARRY (1956, 1958) are referred to in Chapter 4, and can be found in TABLE 4-1.

Recently, the Institute of Geological Sciences has begun an extensive re-mapping programme in the Midland Valley of Scotland, the Sidlaw Hills having received attention from ARMSTRONG and PATERSON (1970) and PATERSON (data as yet unpublished).

1:5 Present Research

This project was started in 1969, and field work and sample collection were completed at intervals throughout the first year of study. By collecting samples related "vertically" and "laterally" in the sequence, it was hoped that a comprehensive picture of the petrography, chemistry and geochemistry of the sequence would emerge.

One hundred and fifty samples were collected from the central and eastern Sidlaw Hills to try to obtain a complete range of lava types in this area. Use was made of unpublished I. G. S. field maps produced by I. B. PATERSON, for collecting the freshest possible samples. Certain large quarries were sampled extensively in an attempt to detect any minor chemical and petrographical variations within individual flows and flow units.

A few samples were collected from intrusive bodies apparently of the same age/

age as the lavas in order to detect any differences in composition compared with the lavas.

Thin sections of all the samples collected were examined and 100 lavas and 3 intrusive rocks were analysed for 12 major elements and 7 trace elements. Selected samples were also analysed for Ni, Cr, V, La, and Ce.

Plagioclase phenocrysts were separated from 4 lavas, and orthopyroxene phenocrysts from 3 lavas. Compositions were determined by various techniques reported in Appendix (A). Clinopyroxene and plagioclase were also analysed using an Electron Probe Microanalyser.

Ten lava samples were selected for melting experiments at 1 atmosphere pressure, covering a range of compositions from olivine basalt to hypersthene andesite in order to determine the crystallisation sequence, liquidus temperature, and crystallisation intervals. Two basalts from this group were also selected for preliminary melting experiments at 2 kb pH_2O.

CHAPTER 2

PETROGRAPHY

2:1 Introduction

The first rigorous study of the petrography of the lavas of the Sidlaw Hills was produced by HARRY (1956, 1958) who recognised the calc-alkaline affinities of the lavas. Previous workers such as HARRIS (1928) and DAVIDSON (1932) had classified the lavas into certain groups on the basis of their petrography. However, no strict classification scheme was used by these workers, which must be of importance if comparisons are to be made with other areas of calc-alkaline volcanism.

2:2 Classification

2:2:1 Introduction

It has become apparent during the present study that any classification of the Sidlaw lavas based solely on petrography will be of limited use owing to the variable chemistry of the lavas. Hence, a classification scheme has been erected to take account of both the petrography and the chemistry, and it is based on the classification used by HARRY (1956, 1958). Although a more modern scheme for classifying evolved calc-alkaline lavas has been proposed by STRECKEISEN (1967), it was felt that this scheme would not satisfactorily account for all the lavas of the Sidlaw Hills.

From the literature, it is clear that previous workers on calc-alkaline lavas/

lavas throughout the world have been unable to agree on chemical limits for terms such as basalt, basaltic-andesite and andesite. ANDERSON (1941) described a basaltic-andesite with plagioclase, olivine, augite, and hypersthene phenocrysts with a silica content of 58.7%. The average basaltic-andesite from the Izu-Hakone region of Japan given by KUNO (1959) has a silica percentage of 53.8. WILCOX (1954) regarded the initial lavas of Paricutin as basaltic-andesites having a silica percentage of 55 containing phenocrysts of olivine and plagioclase. COATS (1959) and BYERS (1961) record basaltic-andesite from the Aleutian arc with silica percentages ranging from 53 to 56%. Many of the analyses, quoted by COATS (1968) of basaltic-andesite fall within this silica range, though the so-called basaltic andesites from the Cascades have silica contents around 58%. It is apparent from these reported values that much variability exists in the usage of the term basaltic-andesite. TAYLOR (1969) records calc-alkaline lavas with silica percentages of 53-56 as low Si-andesites.

The classification of andesite has suffered from as much diversity in the literature as has basaltic-andesite. NOCKOLDS (1954) quoted on average silica content of andesite of 54.20% whereas analyses quoted by WASHINGTON (1917), KUNO (1950), TURNER and VERHOOGAN (1960), CHAYES (1965, 1969) and COATS (1968) suggest that a suitable lower silica limit for andesites should be 56%, though they do not propose a definite upper limit. The essential mineralogy of andesites is clinopyroxene and plagioclase though it has been noted by TAYLOR (1969) that olivine occurs in the more basic varieties, and hydrous minerals such as hornblende and biotite are often present in the more siliceous andesites. In this study, this mineralogy is accepted together with a lower limit of 56% SiO_2 for andesites.

Lavas having silica contents in the range 60 to 65% have been grouped separately from the andesites in this study since their petrographical features do not match those of true andesites. This group has been termed dacite to indicate their less siliceous nature than rhyodacites, and rhyolites found in other lava sequences of Lower Old Red Sandstone age in Scotland.

Usage of the term high-alumina basalt must be treated with a certain amount of caution in any classification of calc-alkaline lavas. KUNO (1960) used high alumina basalt to describe aphyric lavas of appropriate composition from Japan though he also termed a few porphyritic lavas as high-alumina basalts. However, KUNO (1960) does regard the aphyric nature of the Japanese basalts as important in the definition as high alumina basalts.

2:2:2 Classification adopted for the Sidlaw lavas

From the above discussion, the following chemical distinctions have been used for classifying the lavas of the Sidlaw Hills, namely basalt (<53% SiO_2), basaltic-andesite (53-56% SiO_2), andesite (56-60% SiO_2) and dacite (60-65% SiO_2). This classification follows that used by TAYLOR (1969), though there are a few minor differences in silica limits. However, a chemical classification based on SiO_2 has proved too limited, and this has been modified to take account of the petrography and the variable K_2O contents. TABLE 2-1 shows the modified chemical classification which includes a distinction between high- and low-K lavas following the classification of TAYLOR (1969), JAKEŠ and SMITH (1970). Strict use of the term aphyric has been adopted in this study, namely for those lavas with no phenocrysts present. On this basis all/

TABLE 2-1

Classification scheme and phenocryst assemblages of Sidlaw lava types

x Phenocrysts present
(x) Phenocrysts rarely present

			PHENOCRYSTS					
LAVA TYPE	% SiO_2	% K_2O	Ol	Pl	Cpx	Opx	Kspar	Ore
Olivine Basalt	< 53	< 2.5	x					
Feldspar-phyric Olivine Basalt	< 53	< 2.5	x	x				(x)
Clinopyroxene-Feldspar-phyric Olivine Basalt	< 53	< 2.5	x	x	x	(x)		
Olivine Basaltic Andesite	53-56	< 2.5	x					
Feldspar-phyric Olivine Basaltic-Andesite	53-56	< 2.5	x	x				
Clinopyroxene-Feldspar-phyric Olivine Basaltic-Andesite	53-56	< 2.5	x	x	x			
High K Basaltic-Andesite	53-56	> 2.5		x				x
Orthopyroxene-phyric Andesite	56-60	< 2.5		x		x		
High K Andesite	56-60	> 2.5	x	x				
Dacite	60-65	> 2.5		x			x	x

all the lavas from the Sidlaw Hills are porphyritic.

2:3 Petrography of the Sidlaw lavas

2:3:1 Introduction

Many of the lava flows in the Sidlaw Hills are massive, though the flow thickness is often indeterminate, due to the lack of continuous exposure. Vesicular lavas are rare, usually forming the tops of individual flows.

Olivine is the most noticeable phenocryst mineral in hand specimen owing to its alteration colour.

In thin section, the lavas are all porphyritic with combinations of olivine, plagioclase, clinopyroxene, orthopyroxene, K-feldspar, and opaque oxides as phenocryst minerals. The most common phenocryst assemblage is olivine + plagioclase. Clinopyroxene occurs infrequently. Orthopyroxene phenocrysts are generally rare, occurring in a few basalts and andesites, and K-feldspar phenocrysts occur only in one dacite. The total phenocryst content of the lavas is usually about 10-15%, though rarely up to 30% phenocrysts occur. The probable order of appearance of minerals in the crystallisation of the basic lavas was as a generalisation, first olivine, then plagioclase, and later clinopyroxene. However, rocks containing phenocrysts of olivine only are not confined to basalt, since some andesitic types also show this assemblage. The sequence of crystallisation is thus a complex problem, and it will be discussed in a later section.

The groundmass of the lavas is fine grained and intergranular, and very rarely glass is present.

Photomicrographs of each rock type described, are presented at the end of this/

this Chapter, and brief descriptions and modal analyses of the analysed lavas can be found in Appendix D. Determinative methods for plagioclase compositions can be found in Appendix A.

2:3:2 Olivine Basalt (PLATE 1)

Olivine basalts are reasonably widespread in the lava sequence of the Sidlaw Hills. In hand specimen, they are usually noticeably porphyritic and contain very few vesicles. The only phenocrysts visible in hand specimen are small patches of iddingsite replacing olivine.

Thin section examination shows that the phenocrysts of olivine are totally pseudomorphed by iddingsite, and are commonly euhedral. Flow alignment of the pseudomorphs with the c-axes of the original olivines parallel to the flow direction is an occasional feature. The phenocrysts of olivine have a maximum length of 1 mm, and display embayments, and "arrowhead" structures which according to the conclusions of DREVER and JOHNSTON (1957) may indicate quenching.

The intergranular groundmass consists of plagioclase (An_{70}), pseudomorphed olivine, clinopyroxene, iron ore, biotite and chlorite, with the feldspar laths occasionally flow aligned. The intimate association of the biotite and chlorite may indicate a reaction relationship, most probably one of alteration of biotite to chlorite.

2:3:3 Feldspar phyric olivine basalt (PLATE 2,3)

Feldspar-phyric olivine basalts are quite common among the lavas of the Sidlaws,/

Sidlaws, especially near the top of the exposed sequence. In hand specimen, the feldspar-phyric olivine basalts are conspicuously porphyritic with plagioclase phenocrysts up to 3 mm in length, and patches of iddingsitised olivines up to 2 mm in length. Vesicular rocks have not been found.

Thin section examination shows euhedral to subhedral phenocrysts of plagioclase (less than 5% of the rock) which commonly display oscillatory and normal zoning from cores of An_{72} to rims of An_{52}. Glomeroporphyritic aggregates of plagioclase are present in certain examples. Alteration of the plagioclase phenocrysts is limited, though in one or two cases, there is evidence of second generation overgrowths on resorbed and altered cores. The composition of the overgrowths appear to be similar to the rims of the unaltered phenocrysts. Olivine forms generally less than 5% of the rock. Once again there is evidence from the crystal form of the olivine phenocrysts of possible quenching. Microphenocrysts of titano-magnetite and magnetite occur rarely in these lavas.

The groundmass is intergranular and consists of plagioclase (An_{46-50}), altered olivine, clinopyroxene, alkali feldspar, iron ore, biotite, hypersthene, titanaugite, and rarely glass. The minor groundmass minerals biotite, hypersthene, and titanaugite are all strongly pleochroic. The alkali feldspar occurs interstitially. Ophitic intergrowths of groundmass plagioclase and clinopyroxene occur fairly infrequently.

2:3:4 Clinopyroxene-Feldspar-phyric Olivine Basalt (PLATES 4,5)

The clinopyroxene-feldspar phyric olivine basalts are rather rare in the Sidlaw Hills, the majority of examples occurring near the top of the exposed sequence./

sequence. A particularly porphyritic example M126 occurs near the base of the sequence. Apart from M126, these lavas are sparsely porphyritic, and exceptionally, plagioclase and clinopyroxene phenocrysts up to 1 cm in length occur.

In thin section, the large phenocryst size is confirmed with plagioclase making up to 15% of the rock and having a maximum length of 6 mm. Glomeroporphyritic aggregates of plagioclase occur fairly frequently. Oscillatory and normal zoning of the plagioclase from cores of An_{60} to rims of An_{50} are common features. Embayments and resorption rims in the plagioclase phenocrysts are common. Euhedral to subhedral phenocrysts of non pleochroic clinopyroxenes are distributed randomly, and usually make up less than 2% of the rock. The clinopyroxene phenocrysts frequently display twinning. Olivine, usually less than 5% of the total rock, shows evidence possibly of two stages of alteration with serpentine cores, and iddingsite rims. The iddingsite rims perhaps reflect a late overgrowth of the altered olivines. The olivine phenocrysts are occasionally enclosed by both plagioclase and clinopyroxene phenocrysts indicating that olivine at least was probably the first phase to crystallise.

Very rare features in these lavas are the occurrence of orthopyroxene xenocrysts, and phenocrysts. These have only been found in lavas M18, and M19 occurring at the top of the sequence. The orthopyroxene is usually surrounded by an aggregate or rarely a single crystal of clinopyroxene, which in turn is surrounded by olivine. Occasionally intergrowths of olivine and clinopyroxene mantle the orthopyroxene. Radial growth of olivine and clinopyroxene from the orthopyroxene is noticeable in a few cases. Since aggregates of olivine and clinopyroxene with no trace of orthopyroxene cores are present

it/

it is likely that resorption of the orthopyroxene has taken place. It is possible that the orthopyroxene cores may be high pressure phenocrysts which have reacted with the liquid at lower pressures. KUNO (1950) and JAMIESON (1969) have described similar features from the Hakone and Nuanetsi lavas respectively though JAMIESON notes that these rare features in the Nuanetsi lavas were probably simply xenocryst overgrowths without resorption. The unmantled orthopyroxene phenocrysts from M18 are euhedral and non-pleochroic, and on petrographic grounds, it is likely that they have a different composition and probably a different origin to xenocrysts.

The intergranular to intersertal groundmass of the clinopyroxene-feldspar phyric olivine basalts consists of pseudomorphed olivine, plagioclase (An_{50}), clinopyroxene, iron ore, and alkali feldspar. Glass is rarely present, and is usually clouded with specks of iron ore.

2:3:5 Olivine Basaltic-Andesite (PLATE 6)

Olivine basaltic-andesite, the slightly more evolved analogue of the olivine basalt in the Sidlaw Hills, occurs both at the top and the base of the exposed sequence. Its appearance in hand specimen is variable especially in grain size, though usually pseudomorphed olivine phenocrysts up to 1 mm in length are noticeable.

The grain size variation is apparent once again in thin section, and frequently the grain size is moderately coarse. Iddingsitised olivine phenocrysts account for less than 8% of the rock. Olivine basaltic-andesite M121 displays a parallel orientation of 'olivine' phenocrysts which are euhedral, with the original c-axes of the olivines indicating flow direction. As with the olivine basalts, there is evidence of possible quenching.

The/

The intergranular groundmass consists of plagioclase (An_{55}) pseudomorphed olivine, non-pleochroic orthopyroxene, clinopyroxene, iron ore with alkali feldspar filling the interstices.

2:3:6 Feldspar-phyric olivine basaltic-andesite (PLATE 7)

Lavas belonging to this group are common in the Sidlaw Hills occurring generally throughout the exposed sequence. Flow thickness vary considerably with a maximum of 30 metres at Collace, though the average is much less. Laterally, these flows often extend several kilometers especially those near the top of the sequence. In hand specimen, the feldspar-phyric olivine basaltic-andesites are sparsely porphyritic with visible feldspar and iddingsitised olivine phenocrysts.

In thin section, the phenocryst sizes and modal percentages appear variable. Plagioclase phenocrysts usually make up less than 10% of the rock, and olivine less than 6%. However there is complete gradation down to near-aphyric varieties. The subhedral plagioclase phenocrysts, up to a maximum length of 6 mm, commonly display oscillatory and normal zoning from cores of An_{60} to rims of An_{48}. Rarely up to 25 distinct zones can be observed. Resorption rims and embayments are common features in the plagioclase phenocrysts. Glomeroporphyritic aggregates of plagioclase occur occasionally. Iddingsitised olivine with a maximum length of 3 mm are usually anhedral and occur sporadically throughout the rock.

The groundmass is normally intergranular but occasionally pilotaxitic and hyalopilitic. Plagioclase (An_{45}), clinopyroxene, iron ore, alkali feldspar and occasionally orthopyroxene and glass (clouded by iron-ore) are present. Ophitic intergrowths/

intergrowths of groundmass plagioclase and clinopyroxene occur rarely.

2:3:7 Clinopyroxene-Feldspar-phyric olivine basaltic-andesite (PLATE 8)

Lavas belonging to this group are fairly common and occur throughout the sequence. Lack of critical exposures make it very difficult to estimate the thickness and lateral extent of the flows. In hand specimen these lavas are occasionally quite coarse grained and rarely vesicular. Plagioclase is generally the most noticeable phenocryst phase.

Considerable variations in modal phenocryst percentage and grain size are apparent in thin section. Plagioclase is the most abundant phenocryst phase rarely making up 20% of the total rock. Olivine makes up usually less than 5% and clinopyroxene less than 3% of the rock, though as with the last group there is complete gradation to near aphyric lavas. Plagioclase phenocrysts are subhedral to euhedral and have a maximum length of 3 mm. They usually display normal zoning from cores of An_{65} to rims of An_{50}, though zoning is not always apparent. Glomeroporphyritic aggregates of plagioclase are fairly common. Pseudomorphed olivine phenocrysts, up to 1 mm in length are anhedral to subhedral and frequently display strong pleochroism from deep red-brown to straw colours and green to colourless. Plagioclase phenocrysts occasionally enclose the olivine. Clinopyroxene phenocrysts occur up to 1 mm in length and are subhedral to euhedral. They are non-pleochroic and do not show signs of zoning. Twinning in the clinopyroxene is common, and the phenocrysts occasionally enclose plagioclase phenocrysts indicating a probable crystallisation order of olivine, first, then plagioclase, and finally clinopyroxene.

The groundmass is usually intergranular but occasionally hyalopilitic,

and/

and consists of iddingsitised olivine, plagioclase (An_{45}) clinopyroxene, iron ore, alkali feldspar and occasionally brown glass.

2:3:8 High-K basaltic andesite (PLATE 9)

High-K basaltic-andesite is apparently the most rare lava type in the Sidlaw Hills, and forms a thick homogeneous flow at Craighead Quarry at the base of the exposed sequence. In hand specimen, this lava is very fine grained and compact, and displays very few feldspar phenocrysts.

The near aphyric nature of the high-K basaltic andesite (M142) is confirmed in thin section. Very rare altered, anhedral alkali-feldspar phenocrysts make up less than 1% of the rock.

The groundmass is intergranular and very fine grained, and appears to consist of alkali feldspar, iron ore, and possibly clinopyroxene and orthopyroxene.

The fact that this lava is extensively altered in thin section may indicate metasomatism, since its outcrop is very close to a Carboniferous Quartz-Dolerite dyke. Hence, the original composition may well have been changed considerably.

This lava was termed trachyandesite by HARRY (1956).

2:3:9 Orthopyroxene-phyric Andesite (PLATE 10)

Orthopyroxene-phyric andesites are uncommon in the lava sequence of the Sidlaw Hills and one flow of unknown thickness and lateral extent has been sampled from Ballo Hill. In hand specimen this rock type is quite coarse/

coarse grained with few poorly developed vesicles.

Thin section examination reveals that the orthopyroxene-phyric andesites are sparsely porphyritic and contain phenocrysts of fresh sub-hedral non-pleochroic orthopyroxene (En_{85}) up to 2 mm in length, and plagioclase (An_{55-60}) up to 1.5 mm long.

The intergranular groundmass consists of plagioclase (An_{48}), clinopyroxene, iron ore, interstitial alkali feldspar, and patches of chloritic material.

2:3:10 High K-andesite (PLATE 11)

High K-andesites are not very common in the Sidlaw Hills, and occur fairly near the top of the exposed sequence, just south of Collace. In hand specimen, these lavas often appear to be considerably altered, and olivine pseudomorphs are the only phenocryst minerals apparent.

Thin section examination show the high-K andesites to be sparsely porphyritic, with plagioclase and olivine phenocrysts making up less than 2% of the rock. Subhedral plagioclase phenocrysts (An_{56-60}), up to 1.5 mm in length have a sub-parallel alignment indicating flow direction. Olivine phenocrysts which are occasionally euhedral have been replaced by a non-pleochroic green alteration product, and the pseudomorphs differ in appearance from those present in the basalts and basaltic-andesites. This factor combined with the fact that these andesites are rather silica rich may tend to indicate that the pseudomorphs were originally relatively fayalitic in composition.

The groundmass has a felted appearance, typical of trachytes and trachyandesites, and consists of plagioclase laths (An_{42}) with a parallel alignment, alkali/

alkali feldspar, minor non-pleochroic clinopyroxene and iron ore.

2:3:11 Dacite (PLATES 12,13)

Dacites have not previously been reported from the lava sequence of the Sidlaw Hills. Two flows or flow units have been sampled from near the base of the exposed sequence at Abernyte, one of which apparently has a thickness in excess of 70 metres. In hand specimen, their appareance is variable, ranging from very fine grained with noticeable feldspar phenocrysts to relatively coarse grained and somewhat vesicular, again with feldspar phenocrysts.

In thin sections this variability of grain size is immediately apparent, though in fact the relatively coarse grained sample contain abundant phenocrysts (~20%). Euhedral plagioclase (An_{32}) occurs up to 2 mm in length, and frequently shows embayments and rounded corners. Alkali feldspar phenocrysts are abundant in only one specimen. Other phenocryst phases include titanomagnetite, and apatite, though apatite only appears near the top of the very thick flow.

The groundmass is pilotaxitic to hyalopilitic and consists of plagioclase (An_{30}), alkali feldspar, iron-ore, rare as a groundmass mineral only in the upper part of the thick flow.

2:4 Petrography of Intrusive Rocks

2:4:1 Introduction

Several large intrusive bodies occur in the Sidlaw Hills, and they have been reported as sills by HARRIS (1927). Three samples were collected from Knapp/

Knapp Quarry near Abernyte, and one sample from Dron Chapel. BALSILLIE (1934) reported dolerite and segregation veins of riebeckite granite from Knapp Quarry.

2:4:2 Dolerite (PLATE 14)

Samples of dolerite from Knapp Quarry and Dron Chapel show little variation in hand specimen, and in the case of Knapp Quarry, two samples were collected, one from the base of the Quarry face, the other from fairly near to the top, in order to detect any variation. The grain size of the specimens is somewhat coarser than the lavas, and plagioclase is the most noticeable mineral. Specks of pyrite are scattered through the samples.

In thin section, the dolerite consists of plagioclase (An_{65}) up to 2 mm in length, and iddingsitised olivine up to 1 mm, set in a groundmass of plagioclase (An_{70}) pseudomorphed olivine, clinopyroxene, iron ore and alkali feldspar. Mineralogically, there appears to be no difference between the dolerites and the feldspar-phyric olivine basalts.

2:4:3 Segregation Veins (PLATE 15)

Segregation veins occur randomly in the quarry face at Knapp Quarry and in hand specimen are quite coarse grained with feldspar up to 1.5 cm in length. The colour of the segregation veins ranges from black to pink, but this appears to be a function of oxidation.

Thin section examination of the segregation veins confirms the coarseness of the grain size. The rock consists of plagioclase (An_{32}), alkali feldspar,/

feldspar, quartz, titanomagnetite, with minor riebeckite, topaz, and apatite. DAVIDSON (1932) has reported similar segregation veins from a dolerite intrusion just west of Perth.

2:5 Summary

From the above discussion the following points can be summarised:-

1) Aphyric lavas are apparently absent in the Sidlaw Hills.
2) Olivine is ubiquitous in the basic lavas both as a phenocryst and a groundmass mineral, and is always totally altered.
3) Clinopyroxene though usually present as a groundmass mineral, occurs fairly infrequently as a phenocryst phase.
4) Orthopyroxene-phyric lavas are rare.
5) Acid lavas in general are rare.
6) Alkali feldspar is a ubiquitous groundmass mineral, and is rare as a phenocryst phase.
7) In the basic lavas the order of first crystallisation of the phenocrysts appears generally to have been olivine first, then plagioclase, and then clinopyroxene. The position of iron ore in this crystallisation scheme is unknown, since it is a rather rare phenocryst phase.

PLATE 1 M24: Olivine Basalt

Note iddingsitised olivine phenocryst

X45

PLATE 2 M13: Feldspar phyric Olivine Basalt

Aggregate of plagioclase phenocrysts.

Note oscillatory zoning

X45

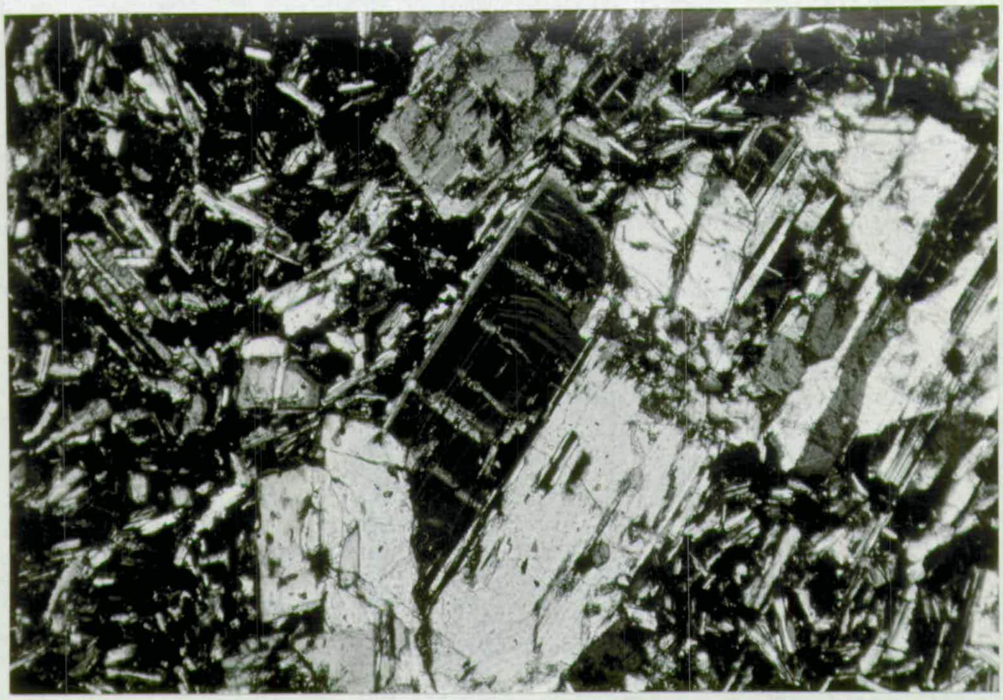


PLATE 3 **M55:** **Feldspar phyric Olivine Basalt**

Note Ophitic intergrowth of groundmass clinopyroxene and plagioclase

X45

PLATE 4 **M19:** **Clinopyroxene-Feldspar phyric Olivine Basalt**

Note:
1) Sub-parallel alignment of plagioclase laths.
2) Iddingsitised olivine
3) Zoned clinopyroxene

X45

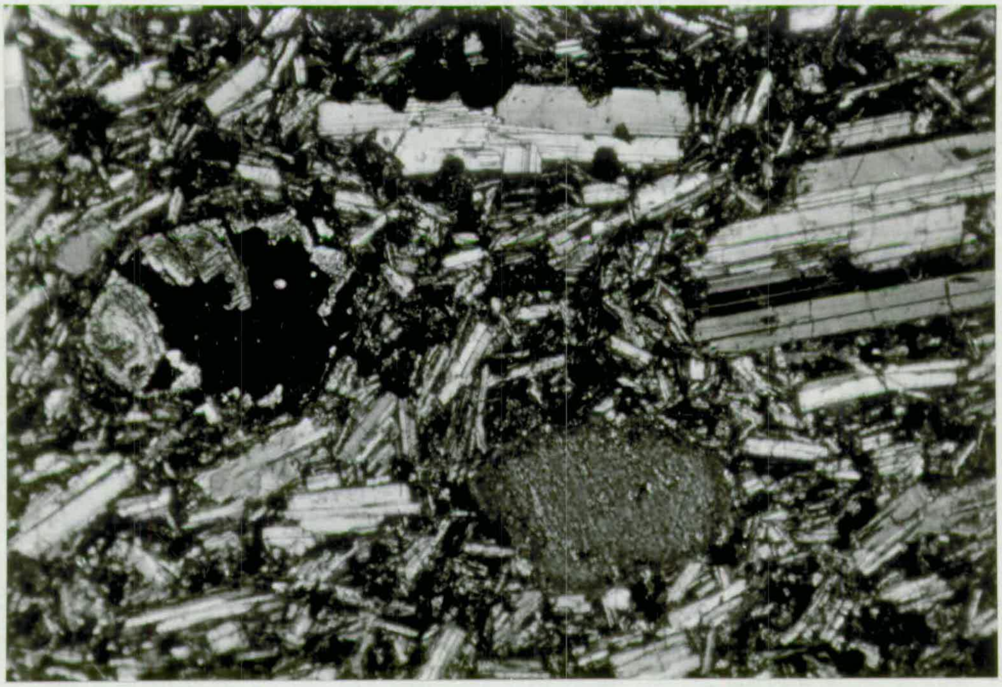
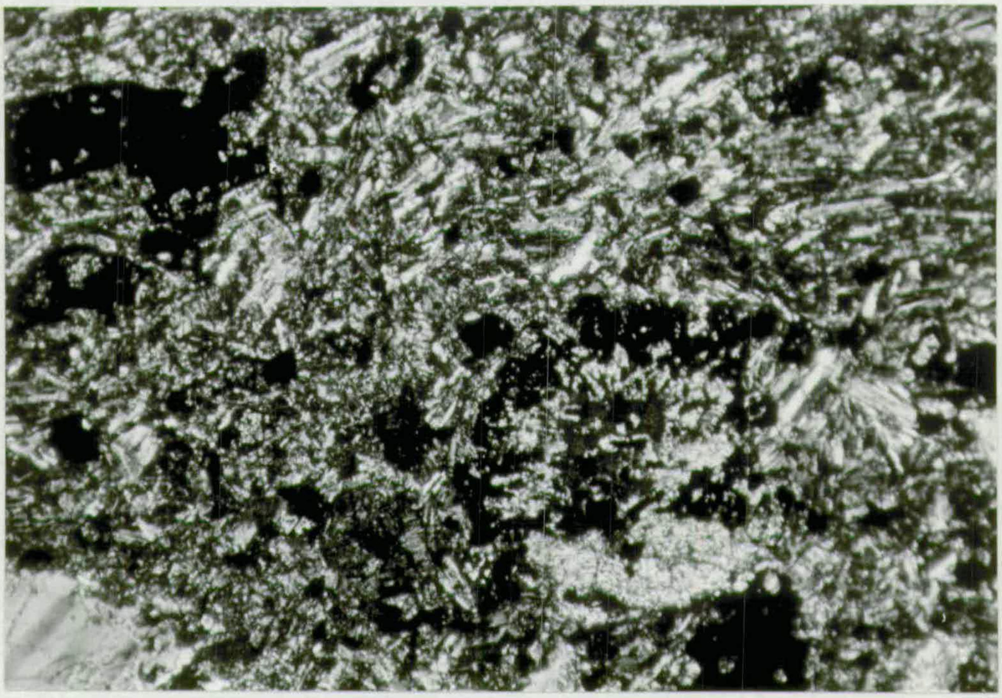


PLATE 5 M18: Clinopyroxene-Feldspar phyric Olivine Basalt
showing rare intergrowths of orthopyroxene
rimmed by clinopyroxene and altered olivine
X45

PLATE 6 M121: Olivine Basaltic-andesite
Note possible quench structure in pseudomorphed
olivine phenocryst
X45



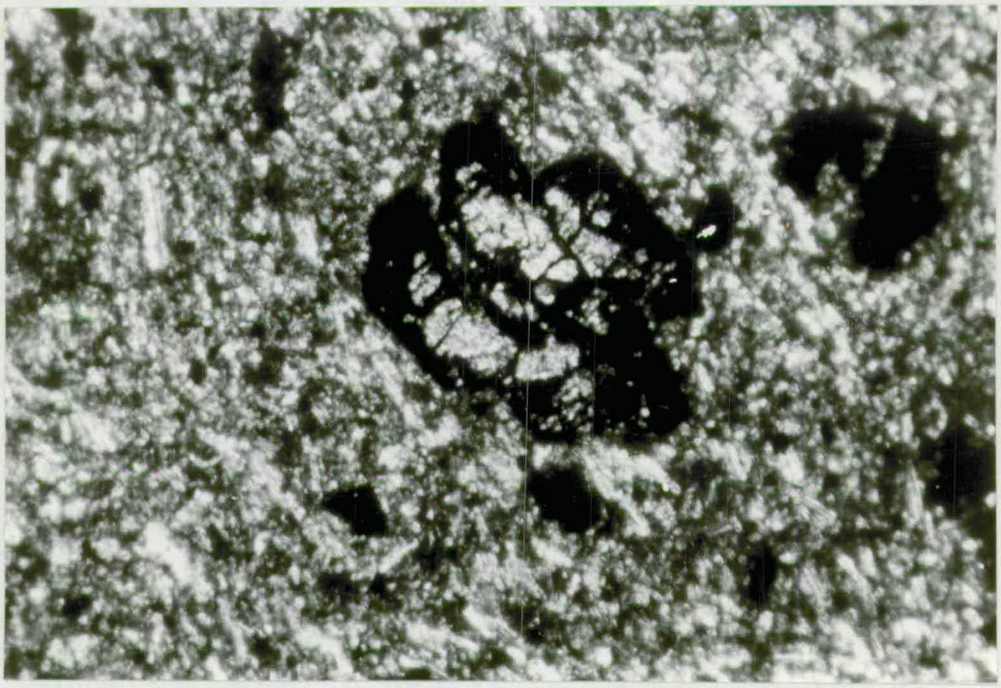
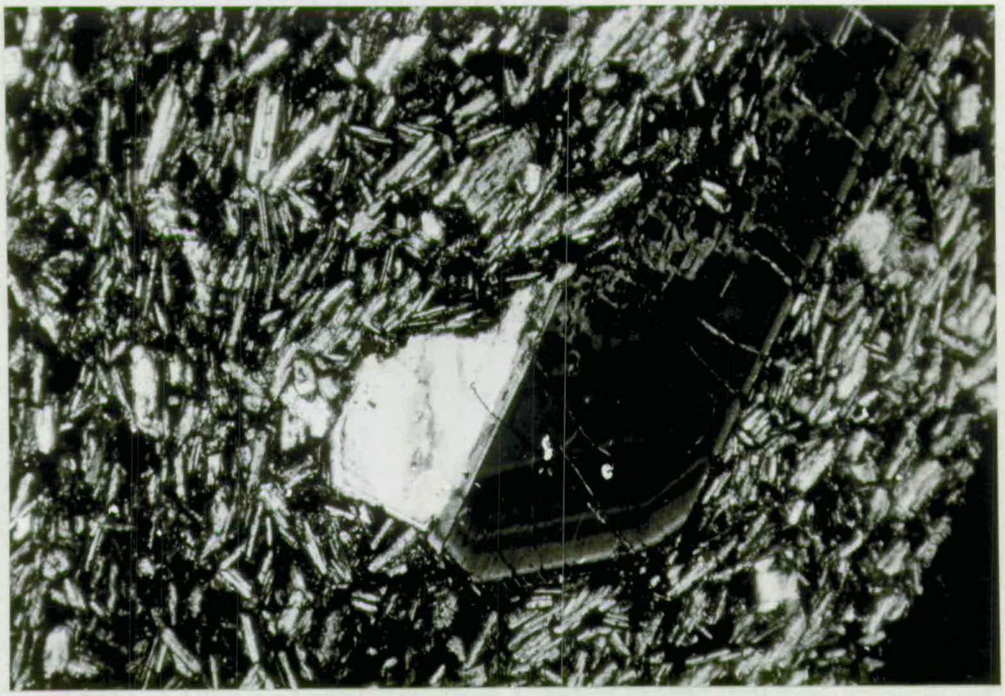


PLATE 7 M105: Feldspar phyric Olivine Basaltic-andesite
illustrating oscillatory zoning and
altered/partially resorbed core
of plagioclase phenocryst
X45

PLATE 8 M83: Clinopyroxene-Feldspar phyric Olivine
Basaltic-andesite
Fresh intergrown plagioclase and clinopyroxene
with iddingsitised olivine set in a glassy
groundmass
X45



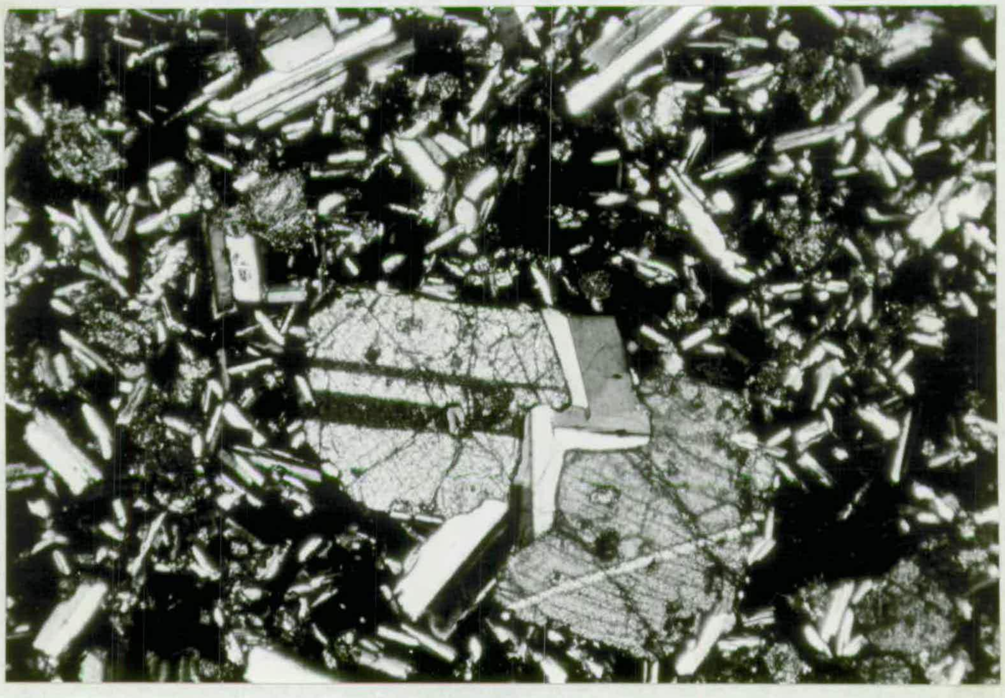


PLATE 9 M142: High-K Basaltic-andesite

Note near aphyric nature of rock

X45

PLATE 10 M95: Orthopyroxene-phyric Andesite

illustrating relatively coarse grain size and rare orthopyroxene phenocryst

X45

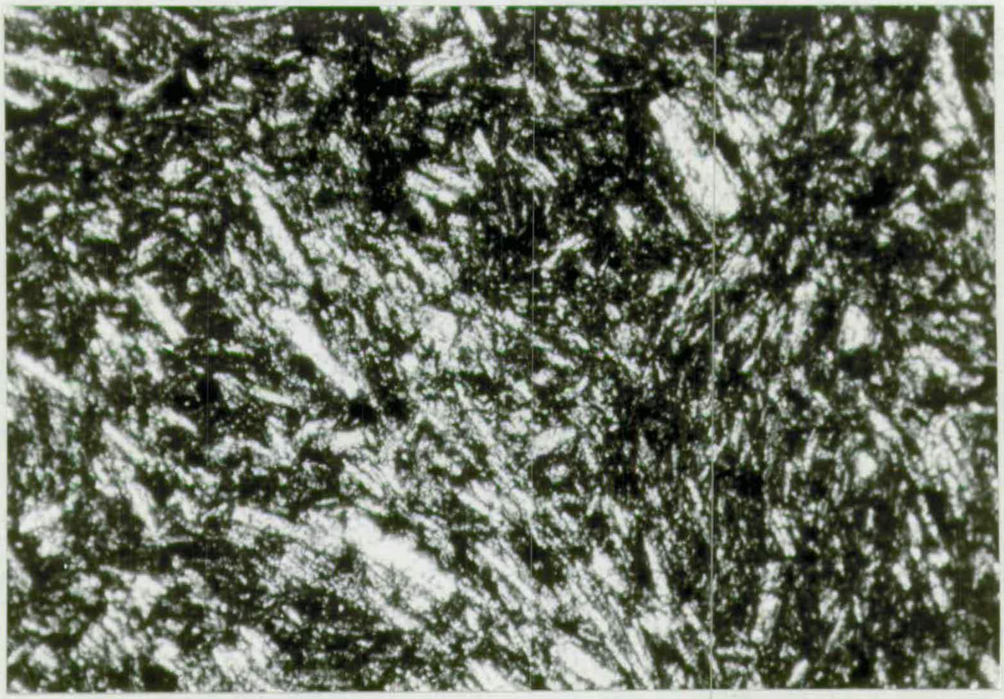


PLATE 11 M140: High-K Andesite

X45

PLATE 12 M100: Dacite

Note: 1) Rounded phenocryst of plagioclase

2) Embayment along twin plane

3) Fine grained groundmass

X45

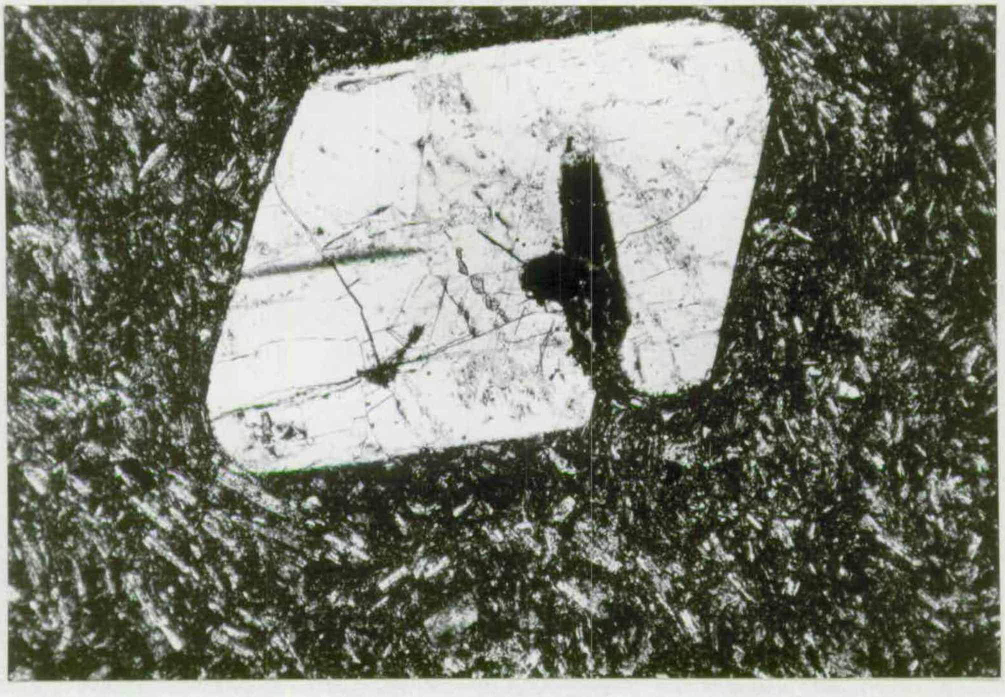


PLATE 13 M107: Dacite

Note alteration and abundance of phenocrysts

(alkali + plagioclase feldspar)

X45

PLATE 14 M111: Dolerite

Note fairly constant grain size

X45

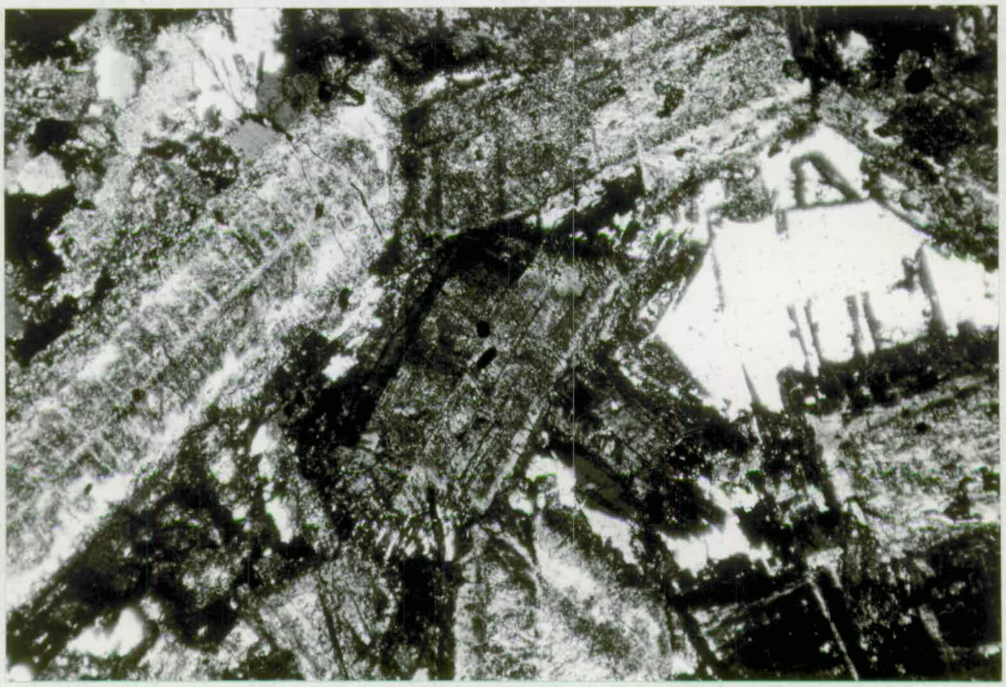
PLATE 15 M114: Segregation Vein

Note: 1) Quartz

2) Altered feldspar

3) Coarse grain size

X45



CHAPTER 3

MINERALOGY

3:1 Introduction

Apart from initial identification of mineral phases in the lavas of the Sidlaw Hills, virtually no data on mineralogy were available before this study was started. BROWN (1967), for example, noted that a knowledge of the chemistry of the important mineral phases in basaltic rocks is necessary to provide a basis for understanding the lava variation and genesis.

Particular attention has been paid to the phenocryst minerals olivine, plagioclase, and clinopyroxene and to a lesser extent orthopyroxene, since these phenocryst minerals may give ideas about fractionation and magmatic variation of the lavas of the Sidlaw Hills. Although olivine is always totally altered, deductions concerning the original composition will be discussed.

Techniques of mineral analysis employed in this study are described in Appendix (A), namely X-R-F analysis, optical analysis, and electron microprobe analysis. Trace element analyses are limited to the XRF determinations.

3:2 Phenocryst Mineralogy

3:2:1 Olivine

One of the more noticeable features of the basic lavas of the sequence of the Sidlaws is the total replacement of olivine by red-brown iddingsite, green bowlingite or hematite. This replacement can be explained by two mechanisms, surface weathering, or magmatic alteration, or more likely a combination/

combination of both. GAY and LE MAITRE (1961) suggest that olivine alteration to iddingsite involves ionic diffusion, and as ferric iron replaces ferrous iron, this diffusion probably took place in an oxidising environment. It has also been pointed out by GAY and LE MAITRE that the alteration is likely to be deuteric, before solidification of the magma, since rims of fresh olivine are found mantling iddingsite in lavas from Gough Island. BAKER and HAGGERTY (1967) report that alteration of olivine under oxidising conditions at low temperature will produce iddingsite, and that post deuteric alteration of iddingsite produces strongly pleochroic assemblages which eventually break down to green alteration products. Since strongly pleochroic alteration assemblages are present in many of the basic lavas of the Sidlaws, it is likely that a combination of both deuteric and post deuteric alteration of the olivine occurred.

The alteration of the olivine in the lavas has proved to be a problem, since any deductions on their original composition is speculative. FAWCETT (1965), has demonstrated that the composition of the iddingsite alteration product of olivine does not give any clues to the original olivine composition, since the breakdown of the olivine is not simply a function of hydration. ROEDER and EMSLIE (1970) have argued that olivine compositions which would crystallise from a liquid of known Mg/Fe^{++} ratio can be deduced by relating the partition coefficients of iron and magnesium between olivine and liquid. However, in the case of the lavas of the Sidlaw Hills, weathering is likely to have altered the iron oxidation ratio, and thus the amount of ferrous iron in the original liquid is in doubt.

It appears that comparisons of lava type and hence olivine compositions might be the most fruitful line of approach in determining the olivine compositions/

compositions of the Sidlaw lavas. Olivine compositions from olivine basalts in calc-alkaline provinces of the West Indies and Japan lie in the range Fo_{70-80}, from the data of KUNO (1950), WILCOX (1954), TURNER and VERHOOGEN (1960), IIDA, KUNO and YAMASAKI (1961) and BAKER (1968). The lavas of the San Juan calc-alkaline province of Colorado which have similar alkali contents to the Sidlaw lavas also have olivine compositions in this range Fo_{70-80} according to LARSEN _et. al_. (1936). On the basis of the above discussion it has been concluded that the original olivine compositions of the Sidlaw basalts may well have fallen into this range Fo_{70-80}.

IIDA, KUNO and YAMASAKI (1961) have recorded an olivine composition of Fo_{17} from an olivine dacite of the Hypersthenic rock series of Japan. It is likely, therefore that the pseudomorphed olivine phenocrysts in the high-K andesites of the Sidlaws, may well have been relatively fayalitic in composition.

3:2:2 _Plagioclase_

Plagioclase phenocrysts were separated from two feldspar-phyric olivine basalts (M66, M67) and two clinopyroxene feldspar-phyric olivine basaltic-andesites (M60, M83). The modal percentages of plagioclase phenocrysts are presented in Appendix (D).

Techniques of separation, purification and analysis are presented in Appendix (A). Complete purification was not achieved, and the analyses have been recalculated to limit the effects of contamination. This recalculation was made by removing normative diopside, hypersthene, olivine, ilmenite and apatite from the determined analyses. The determined and adjusted plagioclase analyses are given in TABLE 3-1 and TABLE 3-2 respectively. Recalculation of/

TABLE 3-1

Chemical analyses of separated plagioclase phenocrysts

Wt%	M60/PL	M66/PL	M67/PL	M83/PL
SiO_2	54.83	52.68	52.20	53.21
TiO_2	0.21	0.25	0.22	0.16
Al_2O_3	28.38	27.69	27.80	29.89
FeO	1.18	2.36	2.10	1.00
MnO	0.03	0.04	0.04	0.02
MgO	0.56	0.62	0.42	0.26
CaO	10.30	10.39	11.00	11.24
Na_2O	4.50	4.40	4.45	4.58
K_2O	0.65	0.76	0.67	0.35
P_2O_5	0.16	0.26	0.21	0.15
TOTAL	100.80	99.45	99.11	100.86
Q	2.84	-	-	0.44
C	1.91	1.37	0.26	1.88
Or	3.81	4.52	3.99	2.05
Ab	37.77	37.43	37.21	38.42
An	49.65	50.12	53.67	54.31
Ne	-	-	0.42	-
Hy	3.24	5.18	-	2.24
Ol	-	-	3.52	-
Mgt	-	-	-	-
Ilm	0.40	0.48	0.42	0.30
Ap	0.38	0.62	0.50	0.35

TABLE 3-2

Adjusted analyses of plagioclase phenocrysts

Wt%	M60/PL	M66/PL	M67/PL	M83/PL
SiO_2	55.43	54.79	54.19	53.59
Al_2O_3	29.00	29.16	29.11	30.25
CaO	10.32	10.61	11.25	11.17
Na_2O	4.60	4.63	4.65	4.63
K_2O	0.66	0.80	0.70	0.35
TOTAL	100.01	99.99	100.00	99.99
Q	4.20	1.86	0.54	1.26
C	1.94	1.33	0.20	1.94
Or	3.89	5.00	3.89	2.22
Ab	38.78	39.30	39.30	39.30
An	51.15	52.54	55.88	55.32
Ba	n.d.	n.d.	n.d.	160
Sr*	1344	1277	1243	1201
Rb	8	n.d.	n.d.	4
Zr	40	n.d.	n.d.	8
Y	12	n.d.	n.d.	8
Normative Composition				
Or	4.1	5.2	3.9	2.3
Ab	41.3	40.6	39.7	40.6
An	54.5	54.2	56.4	57.1
Atomic % Composition				
Or	4.1	4.5	3.8	2.3
Ab	42.9	42.0	41.2	41.8
An	53.0	53.4	54.9	55.9

* Analysis by Atomic Absorption

Remainder by XRF

n.d. not determined

of these analyses on the basis of 32 oxygens indicates that the plagioclases are stoichiometric within the limits of analytical error. The compositions correspond to labradorite with a range An_{53-56}. Plagioclase phenocrysts from a clinopyroxene-feldspar phyric olivine basalt (M19) and from a dacite (M100) have been analysed using an electron microprobe, and the results are presented in TABLE 3-3. The compositions in TABLE 3-3 are based on partial analyses for CaO and K_2O contents of the plagioclase, the CaO content being converted into molecular percent anorthite directly. Correction factors for the CaO and K_2O contents are very small and do not affect the resulting compositions (A. C. Dunham pers. comm.). It can be seen from TABLE 3-3 that the plagioclase phenocrysts exhibit reverse zoning, a feature not commonly observed in the petrography. It was noted however in the case of the dacites, that the plagioclase phenocrysts showed strong evidence of non-equilibrium with the liquid; namely resorption and embayments (see section 2:3:11). The composition determined for plagioclase phenocrysts from M19 compare favourably with the plagioclase compositions from/

TABLE 3-3

				Composition		
		Wt %		Mol %		
Sample No.		CaO	K_2O	An	Ab	Or
M19	core	10.70	0.48	50.7	46.6	2.7
	margin	11.80	0.40	56.4	41.5	2.1
M100	core	7.67	1.32	34.6	57.8	7.6
	margin	9.81	0.90	45.5	49.3	5.2

from separated phenocrysts as shown in TABLE 3-2, though it must be remembered that the separated phenocryst analyses do not take account of zoning. Normative compositions of the plagioclases correspond closely to the molecular compositions. The normal, oscillatory, and reverse zoning features of the plagioclase phenocrysts may well have resulted from variable water pressure during the crystallisation of the magma. YODER (1969) has shown that increasing water pressure will increase the anorthite content of the plagioclase crystallising whereas as increase in dry pressure will produce more sodic plagioclase.

The trace element contents of plagioclase phenocrysts are notably different from values quoted for plagioclase phenocrysts from the Izu/Hakone region by IIDA (1961). Strontium is higher by a factor of 3 in the Sidlaw plagioclase phenocrysts compared with the phenocrysts of similar composition in the hypersthenic rock series of Izu/Hakone. Barium does not differ significantly.

3:2:3 Clinopyroxene

Since the modal percentage of clinopyroxene phenocrysts in the Sidlaw lavas is small, separation by mechanical means was not attempted. Chemical analyses of clinopyroxene phenocrysts from six lavas have been carried out using an electron probe microanalyser. The analyses are presented in TABLE 3-4 together with their C.I.P.W. norms and molecular compositions. All of the clinopyroxenes can be described as augites according to the nomenclature of DEER, HOWIE, and ZUSSMAN (1963). Though the most evolved augite phenocryst compositions occur in a basaltic andesite, there are not systematic variations in augite compositions from basalts to basaltic andesites./

TABLE 3-4 (3 pages)

Electron microprobe analyses of Sidlaw Clinopyroxene phenocrysts

	M18(i) CORE	M18(i) MARGIN	M18(iii) CORE	M18(iii) MARGIN	M18(vi) CORE	M19(i) CORE
SiO_2	52.52	51.65	52.03	51.15	49.96	51.84
TiO_2	0.76	1.00	0.71	0.99	0.61	0.72
Al_2O_3	1.84	2.36	1.76	2.51	5.96	5.97
FeO	9.90	8.98	10.13	9.35	6.51	6.83
MgO	16.49	15.40	15.85	15.39	15.92	16.24
CaO	20.00	20.65	19.30	20.14	20.36	19.55
Na_2O	0.38	0.38	0.35	0.36	0.49	0.56
K_2O	0.01	0.02	0.02	0.01	0.00	0.00
TOTAL	101.90	100.42	100.15	99.90	99.81	101.71
Or	0.06	0.12	0.12	0.06	-	-
Ab	3.16	3.20	2.96	3.05	0.90	4.66
An	3.22	4.65	3.17	5.21	14.09	13.54
Ne	-	-	-	-	1.76	-
Di	75.83	78.29	74.59	76.33	69.52	69.32
Hy	5.75	2.94	10.00	3.88	-	3.42
Ol	10.57	8.91	7.83	9.59	12.57	11.71
La	-	-	-	-	-	-
Ilm	1.42	1.89	1.35	1.88	1.16	1.34
$CaSiO_3$	39.5	42.1	39.2	41.2	42.8	41.2
$MgSiO_3$	45.2	43.7	44.8	43.9	46.5	47.6
$FeSiO_3$	15.3	14.3	16.1	14.9	10.7	11.2

	M19(i) MARGIN	M19(ii) CORE	M83(i) CORE	M83(ii) CORE	M83(ii) MARGIN	M83(iii) CORE	M83(iii) MARGIN
SiO_2	51.68	50.60	53.27	52.53	53.44	53.79	53.87
TiO_2	0.61	0.72	0.66	0.75	0.65	0.52	0.53
Al_2O_3	5.08	6.39	2.23	0.49	2.57	1.79	1.94
FeO	6.97	6.39	7.85	7.77	8.13	7.99	7.82
MgO	16.92	16.27	17.53	16.97	17.51	18.34	18.03
CaO	18.90	19.40	19.48	19.32	18.39	18.53	18.61
Na_2O	0.58	0.64	0.35	0.39	0.32	0.37	0.32
K_2O	0.00	0.01	0.00	0.02	0.03	0.00	0.01
TOTAL	100.74	100.42	100.37	100.24	101.04	101.33	101.13
Or	-	0.06	-	0.12	0.18	-	0.06
Ab	4.87	4.45	2.92	3.29	2.68	3.09	2.68
An	11.17	14.47	4.45	4.97	5.43	3.18	3.78
Ne	-	0.51	-	-	-	-	-
Di	65.38	64.86	72.68	72.51	67.93	70.00	69.96
Hy	4.97	-	11.67	10.54	17.94	16.40	17.98
Ol	12.45	14.29	7.04	7.15	4.62	6.36	4.54
La	-	-	-	-	-	-	-
Ilm	1.15	1.36	1.24	1.42	1.22	0.97	1.00
$CaSiO_3$	39.5	41.2	38.9	39.5	37.5	36.8	37.4
$MgSiO_3$	49.2	48.2	48.8	48.2	49.6	50.8	50.3
$FeSiO_3$	11.4	10.6	12.2	12.4	12.9	12.4	12.3

	M84(i) CORE	M84(ii) CORE	M84(ii) MARGIN	M86(i) CORE	M126(i) CORE	M126(ii) CORE
SiO_2	49.04	49.82	50.78	50.99	50.12	50.71
TiO_2	1.47	1.18	1.00	1.06	1.01	0.93
Al_2O_3	4.37	4.88	2.41	2.39	4.87	4.67
FeO	8.02	6.87	7.80	8.63	7.65	8.01
MgO	14.55	14.88	15.36	15.43	15.94	15.87
CaO	22.23	22.11	21.82	21.32	19.98	19.48
Na_2O	0.31	0.40	0.33	0.44	0.56	0.47
K_2O	0.01	0.00	0.01	0.00	0.02	0.00
TOTAL	100.00	100.14	99.51	100.26	100.15	100.14
Or	-	-	0.06	-	0.12	-
Ab	-	-	0.34	1.46	2.16	3.97
An	10.50	11.50	5.09	4.53	10.70	10.62
Ne	1.42	1.83	1.34	1.22	1.39	-
Di	72.23	73.68	83.08	81.08	70.63	68.82
Hy	-	-	-	-	-	2.46
Ol	10.01	8.96	8.19	9.69	13.08	12.36
La	3.00	1.79	-	-	-	-
Ilm	2.79	2.24	1.91	2.01	1.92	1.76
$CaSiO_3$	45.6	45.9	44.3	43.0	41.5	40.7
$MgSiO_3$	41.5	43.0	43.3	43.4	46.1	46.2
$FeSiO_3$	12.9	11.2	12.4	13.5	12.4	13.0

andesites.

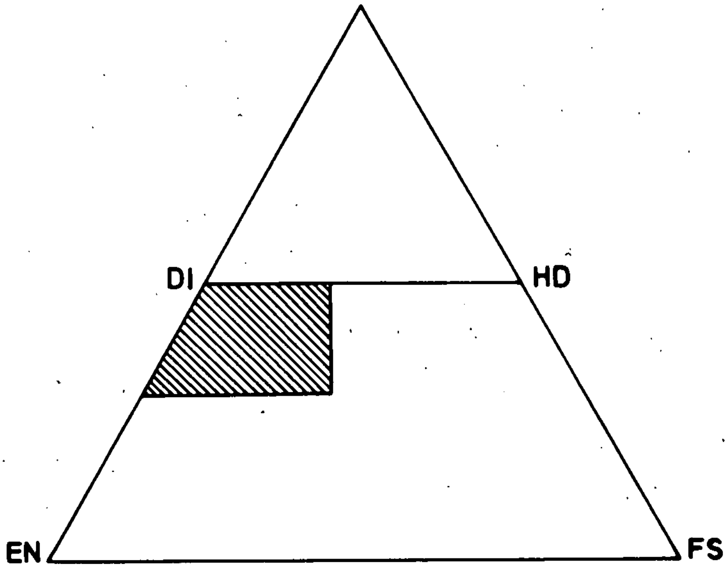
Zoning is apparent from the chemistry of the augites, though it is not particularly strong. The largest relative percentage difference between the core and margin of the augite phenocrysts is in the case of Al_2O_3, which shows both an increase, and a decrease between cores and margins.

A plot of the compositions in the pyroxene quadrilateral is shown in FIG 3-1 and in terms of the molecular ratio Ca: Mg: Fe^{2+}, the largest variation is in the Ca content of the augite phenocrysts. However, variations in the SiO_2, Al_2O_3, and TiO_2 contents are noticeable in the analyses. To assess the variation in more detail, standard Harker variation diagrams for the augite phenocrysts have been constructed in FIG 3-2. It can be seen that as silica increases, MgO increases, whereas CaO decreases. There is also possibly a small increase in FeO content, though TiO_2 decreases. The distribution of Al_2O_3 is worthy of note in that there are two distinct groups, one with greater than 4% Al_2O_3, the other with less than 3% Al_2O_3. The problems associated with the amount of Al_2O_3 in clinopyroxenes have been the subject of debate and research for many years.

KUSHIRO (1960) and LE BAS (1962) have demonstrated that the Al_2O_3 content of clinopyroxenes increases with increased alkalinity of the magma from which they have crystallised. LE BAS (1962) has shown that by knowing the amount of alumina present in the Z site of the clinopyroxene structure, then with a reasonable degree of accuracy, the affinity of that clinopyroxene, in terms of non-alkaline, alkaline, and peralkaline, can be deduced. BROWN (1967) pointed out that both pressure and temperature of crystallisation of pyroxenes can govern their alumina content, and also reports that a decrease in silica content of/

FIG. 3-1

Sidlaw clinopyroxene compositions


DI
HD
EN
FS

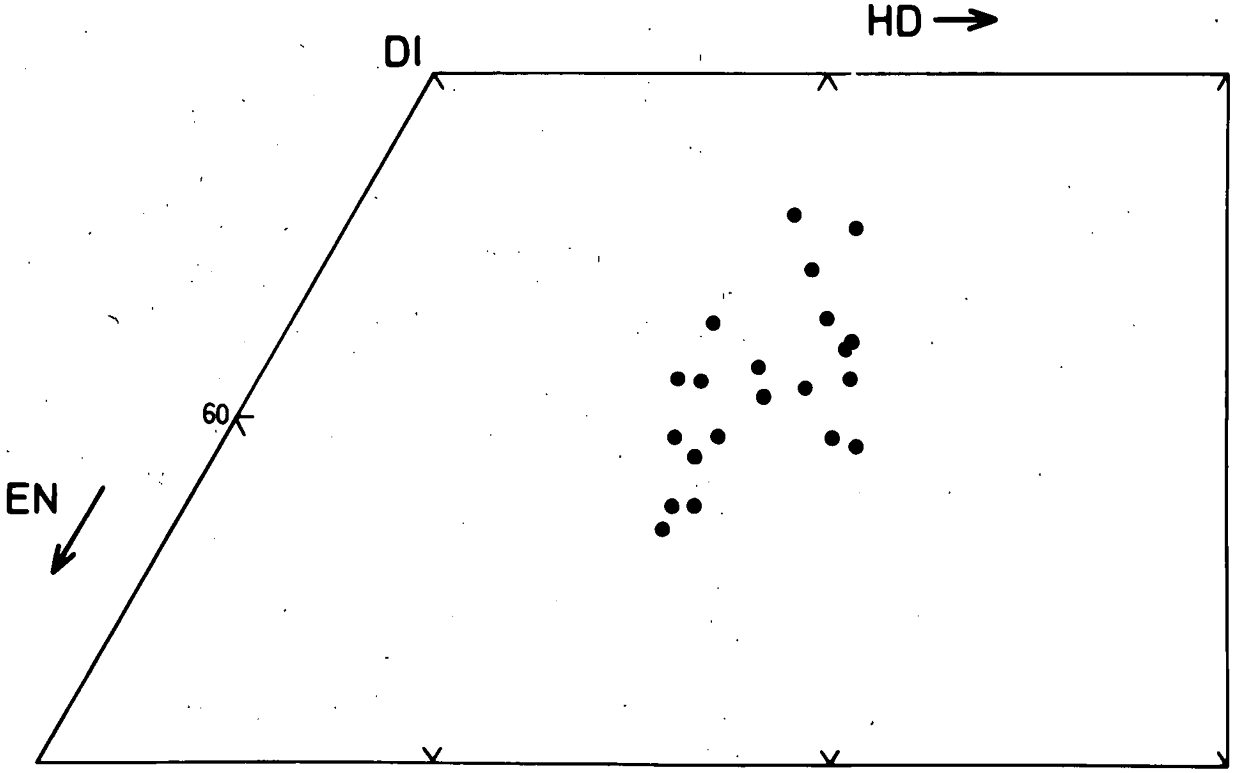
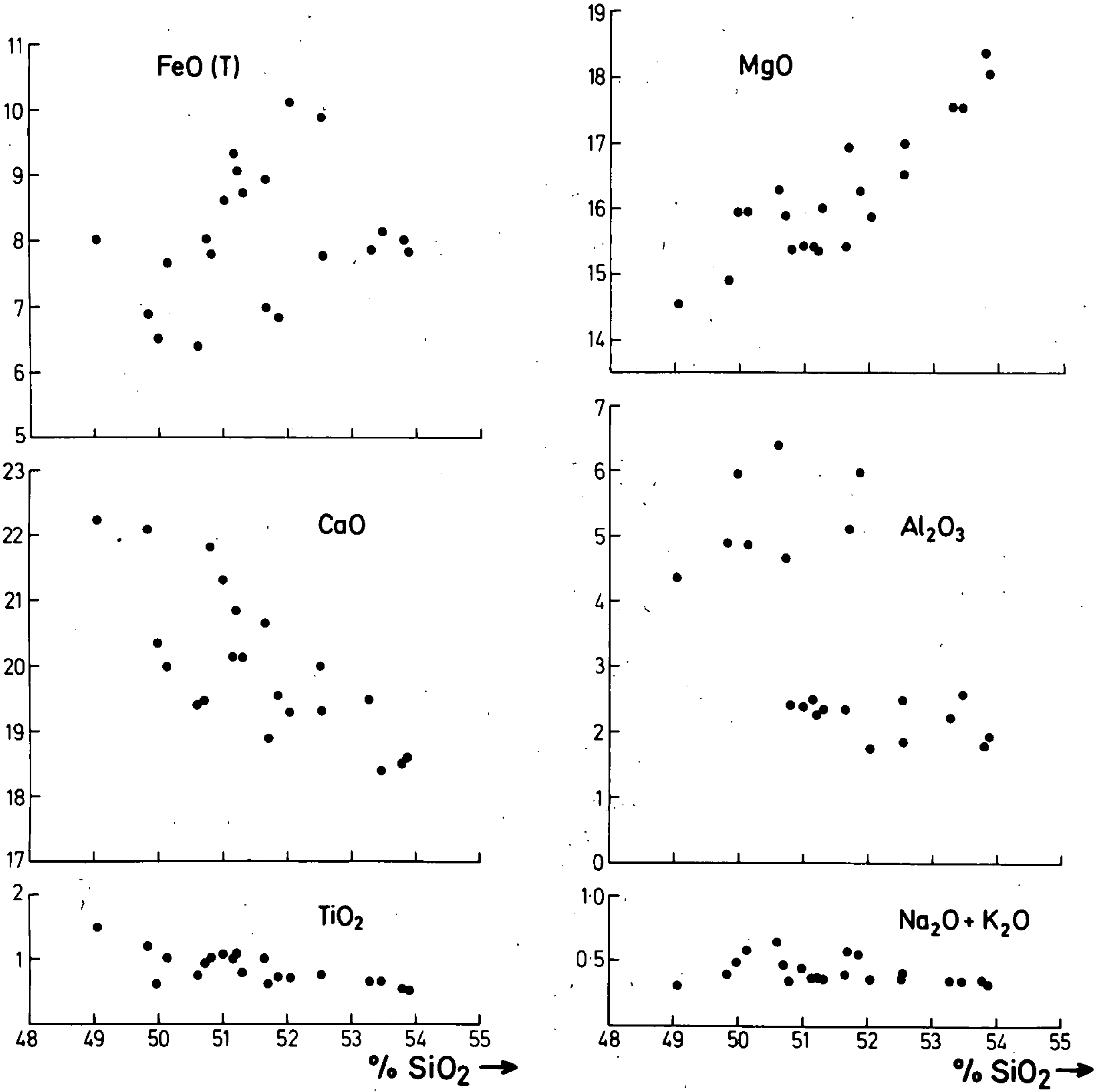

HD →
DI
60
EN

FIG. 3-2

Variation diagrams for Sidlaw clinopyroxene compositions


FeO (T)
CaO
TiO$_2$
MgO
Al$_2$O$_3$
Na$_2$O + K$_2$O
5
6
7
8
9
10
11
17
18
19
20
21
22
23
1
2
14
15
16
17
18
19
0
1
2
3
4
5
6
7
0·5
1·0
48
49
50
51
52
53
54
55
% SiO$_2$ →
% SiO$_2$ →

of clinopyroxene could allow entry of the Ca Tschermaks molecule into the pyroxene structure. This is supported by FIG 3-3 which illustrates the decrease in Al_Z content with increasing silica. However the correlation between total Al_2O_3 content and silica is a little obscure. BIGGAR (pers. comm.) has suggested that both pressure and the rate of cooling could affect the entry of Al_2O_3 into pyroxenes, with high pressure and rapid cooling both increasing the Al_2O_3 content. There appears to be no unique mechanism which is able to account for the variability of Al_2O_3 contents in clinopyroxenes.

According to the data of KUSHIRO (1960), the main role of Titanium in clinopyroxene is to maintain the charge balance which is affected by Al substitution into the Z site of the clinopyroxene structure. LE BAS (1962) has demonstrated the close correlation between Ti content of clinopyroxenes and the amount of Al in the Z site, thus supporting KUSHIRO's statement. FIG 3-4 illustrates the correlation between Al_Z and TiO_2 content of the Sidlaw clinopyroxenes, and it can be seen that once again, two distinct populations of points are present.

Nepheline and rarely calcium orthosilicate are present in the norms of some of the Sidlaw clinopyroxenes, though it should be noted that reduction of all iron to FeO will tend to produce undersaturated norms. The clinopyroxenes fall into the tholeiitic field of COOMBS (1963) though there is some overlap with the alkali field.

3:2:4 Orthopyroxene

Orthopyroxene phenocrysts are rare in the lavas of the Sidlaw Hills, and/

FIG. 3-3

Relationship between Al_Z and silica content of Sidlaw clinopyroxenes

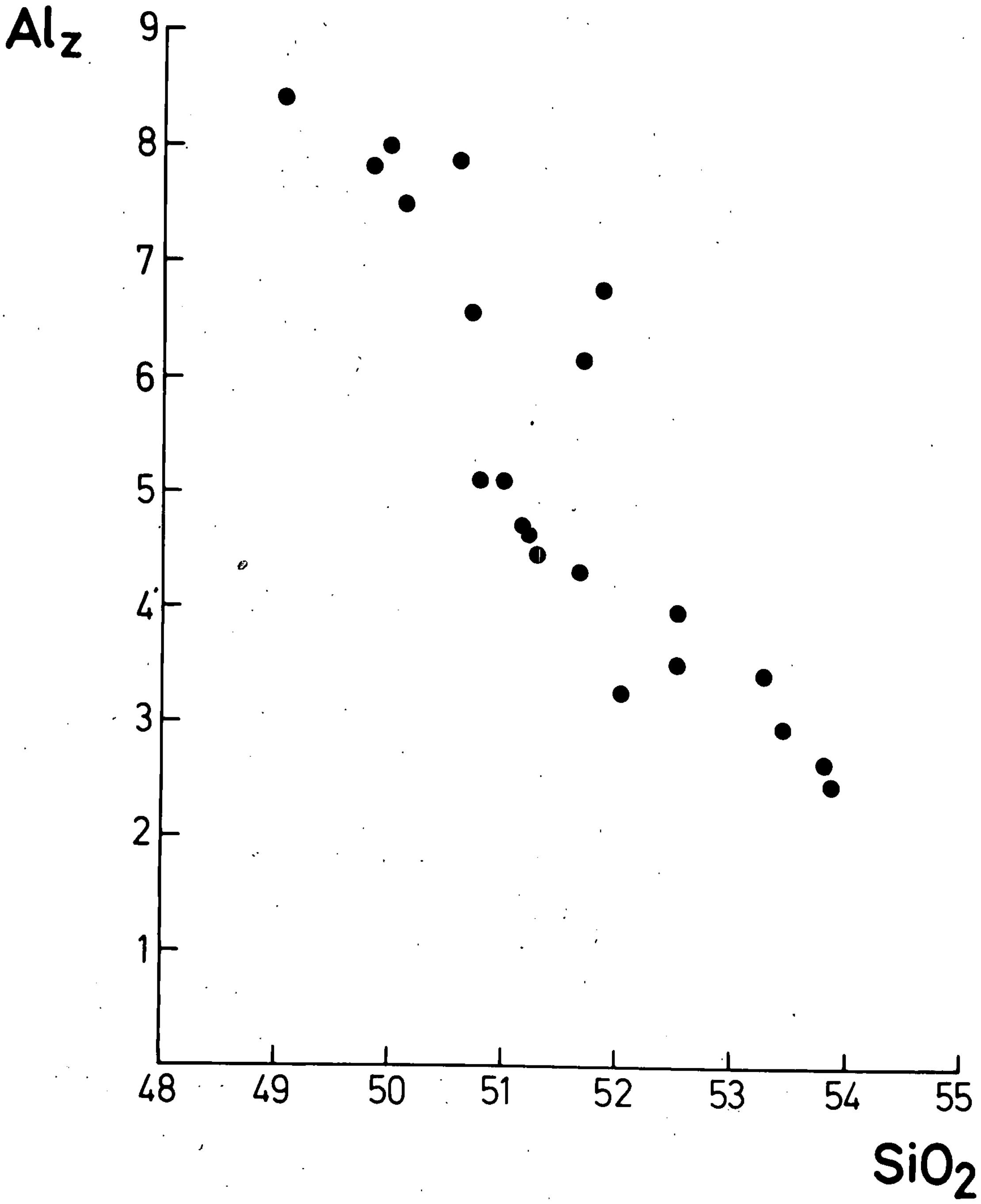
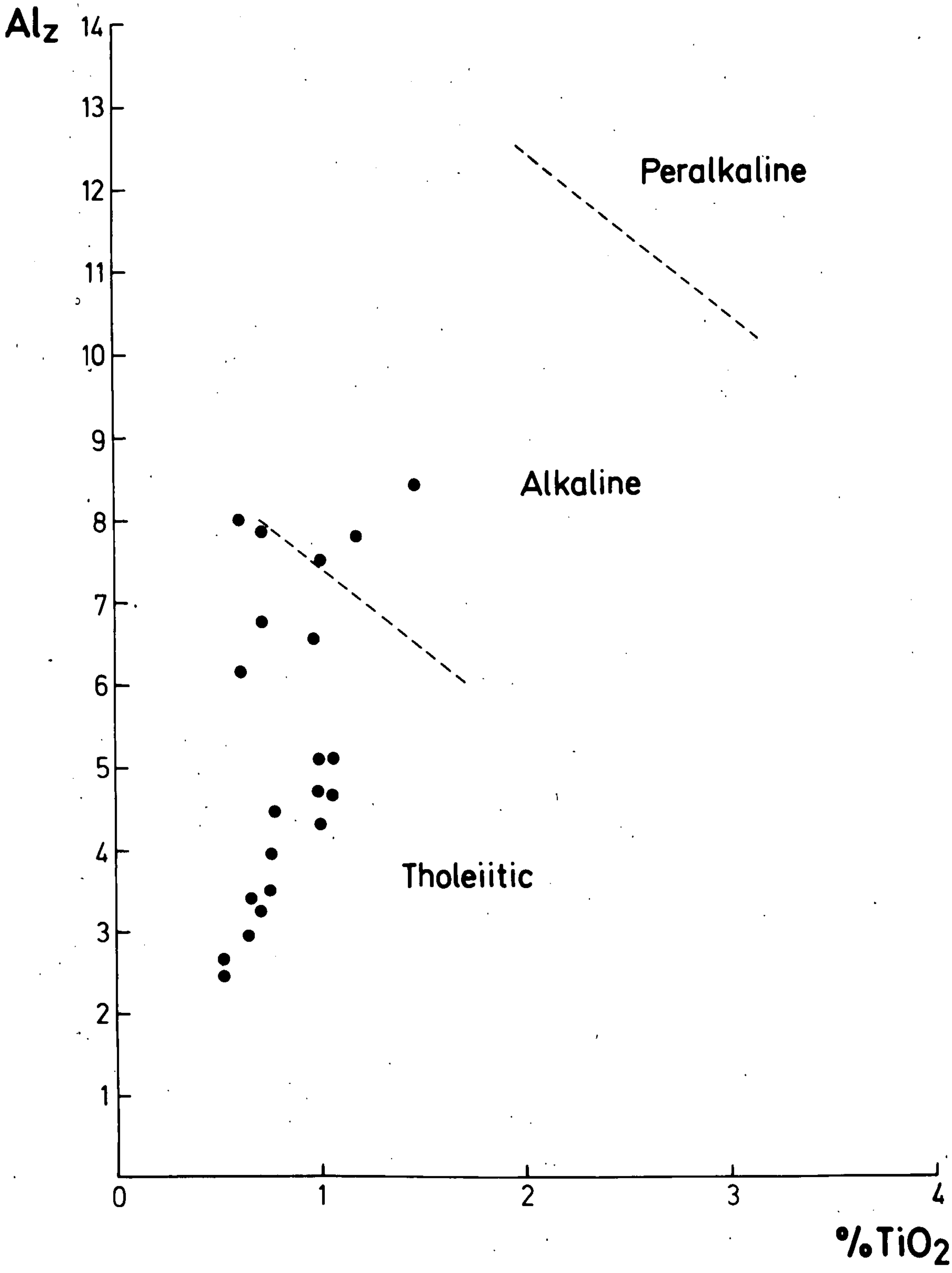

Al$_z$
9
8
7
6
5
4
3
2
1
48
49
50
51
52
53
54
55
SiO$_2$

FIG. 3-4

Relationship between Al_Z and TiO_2 content of Sidlaw clinopyroxenes

(Boundaries from Le BAS (1962))


Alz
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
%TiO2
Peralkaline
Alkaline
Tholeiitic

and only occur in any quantity in the orthopyroxene phyric andesites. Once again mechanical separation of the phenocrysts proved to be difficult, though "hand-picking" of orthopyroxene from impure separated rock fractions was employed for refractive index determinations. Use was made of an electron microprobe for analysis of the rare orthopyroxene phenocrysts from one basalt (M18) from near to the top of the exposed sequence (see section 2:3:4).

The compositions of orthopyroxene phenocrysts from the orthopyroxene-phyric andesites were determined by refractive index measurements on separated grains. The results are given in TABLE 3-5.

TABLE 3-5

Sample No.	R.I.	Mol % En.
M95	1.685	85 - 81
M96	1.681	88 - 84
M97	1.681	88 - 84

The composition has been calculated from determinative curves produced by KUNO (1954) who shows that the compositions depend on the amount of Al_2O_3 present in the orthopyroxene. However the orthopyroxenes from the orthopyroxene-phyric andesite can be described as bronzites according to the nomenclature of DEER, HOWIE, and ZUSSMAN (1963).

Electron microprobe analyses of the rare orthopyroxene phenocrysts and orthopyroxenes mantled by clinopyroxene from the clinopyroxene-feldspar phyric olivine basalt M18 are given in TABLE 3-6 together with the compositions of the clinopyroxene overgrowths. Since the clinopyroxene rims of the orthopyroxene phenocrysts do not differ appreciably in composition to the clinopyroxene rims/

TABLE 3-6

Electron microprobe analyses of Sidlaw orthopyroxenes and clinopyroxene rims

* Unrimmed orthopyroxene phenocryst

	M18(ii) OPX CORE	M18(ii) CPX RIM	M18(iv) OPX CORE	M18(iv) CPX RIM	*M18v OPX
SiO_2	53.41	51.20	52.98	51.29	52.22
TiO_2	0.29	1.06	0.33	0.78	0.00
Al_2O_3	1.07	2.26	1.23	2.35	0.38
FeO	19.59	9.08	18.73	8.75	25.35
MgO	24.02	15.36	23.89	15.99	20.25
CaO	1.73	20.83	2.18	20.14	1.39
Na_2O	0.01	0.36	0.02	0.35	0.00
K_2O	0.00	0.01	0.00	0.02	0.00
TOTAL	100.12	100.16	99.36	99.67	99.59
Or	-	0.06	-	0.12	-
Ab	0.08	3.04	0.17	2.97	-
An	2.87	4.51	3.29	4.80	1.04
Ne	-	-	-	-	-
Di	4.64	79.36	6.17	76.68	4.85
Hy	88.95	0.92	86.52	3.63	91.66
Ol	2.91	10.10	3.22	10.32	2.44
La	-	-	-	-	-
Ilm	0.55	2.01	0.63	1.49	-
$CaSiO_3$	3.4	42.3	4.4	40.9	2.8
$MgSiO_3$	66.2	43.4	66.4	45.2	57.1
$FeSiO_3$	30.3	14.4	29.2	13.9	40.1

rims reported for M18 in TABLE 3-4, it is likely the rims are simply overgrowths rather than reaction products between the orthopyroxene and the liquid. In those examples where the orthopyroxene cores appear to have been replaced by clinopyroxene it is possible that resorption took place before the overgrowth of clinopyroxene. The pyroxene pairs are plotted in the pyroxene quadrilateral in FIG 3-5. Tie-lines have been constructed between the orthopyroxene cores and the clinopyroxene rims.

3:2:5 Other Phenocryst Minerals

No chemical investigations of the phenocryst minerals, alkali feldspar, apatite, and opaque oxides, have been undertaken owing to their frequent alteration, and minor significance.

3:3 Groundmass Minerals

3:3:1 Introduction

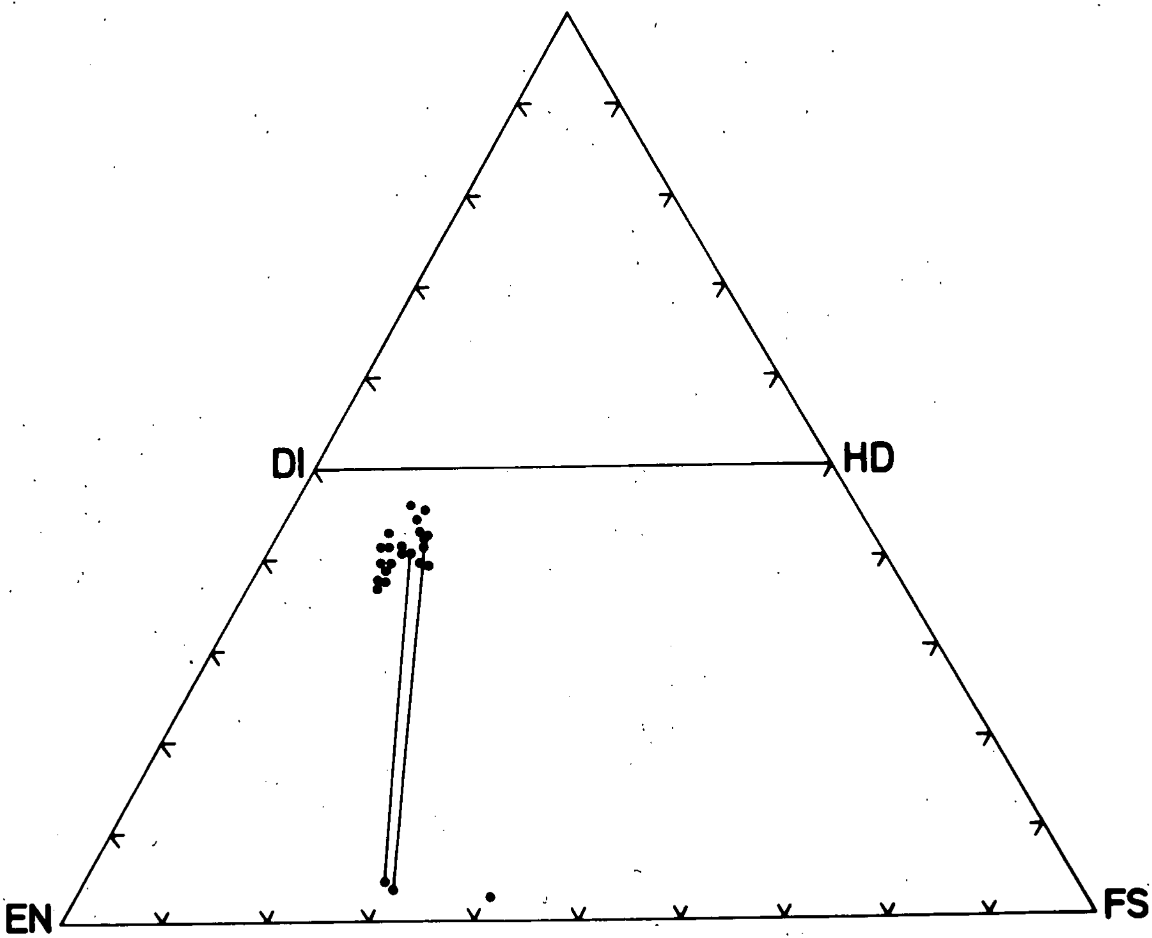
Owing to limited time available for chemical analysis by electron microprobe, investigation of groundmass minerals has been limited to partial analyses for CaO and K_2O of plagioclase and alkali feldspar.

3:3:2 Plagioclase

Groundmass plagioclase has been studied from four lavas ranging from basalt to dacite. The results are presented in TABLE 3-7 and the compositions have been computed from partial analyses of CaO and K_2O. The results are tabulated/

FIG. 3-5

All Sidlaw pyroxenes with tie lines linking orthopyroxene cores and their clinopyroxene rims


DI
HD
EN
FS

tabulated in order of increasing silica content of the whole rock from M19 to M100.

TABLE 3-7

Sample No.	Wt % CaO	Wt % K_2O	Mol % An	Mol % Ab	Mol % Or
M19	12.09	0.49	57.2	39.8	3.0
M129	11.47	0.62	53.9	42.4	3.7
M116	11.18	0.27	53.6	44.8	1.7
M100	5.1	0.80	23.8	71.4	4.8

There is a regular decrease in anorthite content of the groundmass plagioclase from the basalt, through the basaltic-andesites to the dacite, though the orthoclase content is rather variable. It is interesting to note that although the plagioclase phenocrysts in M100 display reverse zoning and strong disequilibrium with resorption and embayments, the groundmass plagioclase is in fact more sodic than the core of the phenocrysts.

3:3:3 Alkali feldspar

Groundmass alkali feldspar has been investigated in three lavas again ranging from basalt to dacite. The results are present in TABLE 3-8 in the same evolutionary order as in TABLE 3-8.

TABLE 3-8/

TABLE 3-8

	Wt %		Mol %		
Sample No.	CaO	K_2O	An	Ab	Or
M19	3.76	5.10	15.2	60.8	24.0
M129	3.12	4.61	11.7	66.1	22.2
M100	1.95	6.08	6.7	59.8	33.5

Though there is a decrease in CaO content from the basalt to the dacite the K_2O content is somewhat variable.

CHAPTER 4

CHEMISTRY - DESCRIPTIVE and COMPARATIVE

4:1 Introduction

One hundred new analyses of lavas and three analyses of intrusive rocks from the Sidlaw Hills are given in Appendix (C). Techniques used in sample preparation and subsequent analysis are presented in Appendix (A).

Chemical analyses of seven lavas from the Sidlaws were reported by HARRY (1956, 1958) and these are presented in TABLE 4-1 with their C.I.P.W. norms. Though of limited use in this study owing to different analytical techniques employed, these analyses have been included to illustrate the oversaturated nature of the lavas, together with their high alumina, and in a few cases high total alkali contents.

The selection of lavas for analysis was based on petrography and freshness.

Two lava flows from Burnside Quarry (see location map) were sampled in detail in an attempt to detect any intra- and inter-flow chemical variation since variations in the petrography were apparent. Significant variations in most major and trace elements were noted, and a summary of this variation is presented in TABLE 4-2. Lateral variation in these flows was impossible to study owing to the lack of continuous exposure.

Analyses representing the different lava types are distributed as follows:-

Olivine basalt	4
Feldspar-phyric olivine basalt/	

TABLE 4-1

Previously published chemical analyses of Sidlaw lavas - HARRY (1956, 1958)

1 = 2-pyroxene basalt

2 = 2-pyroxene basalt

3 = Feldspar-phyric olivine basalt

4 = Olivine free 2-pyroxene basalt

5 = Aphyric basalt

6 = Andesite (basic variety)

7 = Trachyandesite

Wt%	1	2	3	4	5	6	7
SiO_2	51.42	50.97	50.62	48.80	51.46	53.35	54.01
TiO_2	1.76	1.97	1.48	1.77	1.47	1.16	1.38
Al_2O_3	19.30	19.08	16.58	18.03	17.93	15.22	15.10
Fe_2O_3	2.99	2.63	3.77	3.96	7.20	2.14	3.98
FeO	5.62	6.18	3.93	4.28	2.01	4.56	3.39
MnO	0.14	0.15	0.22	0.23	0.12	0.43	0.30
MgO	4.09	3.84	6.87	4.74	4.13	7.42	3.34
CaO	6.58	7.34	8.44	8.02	6.94	6.81	6.37
Na_2O	3.41	3.44	2.78	3.26	3.65	2.92	5.58
K_2O	1.42	1.06	1.12	0.82	1.36	0.76	2.61
H_2O	1.62	2.09	1.64	1.72	1.34	1.98	1.18
H_2O	1.29	0.92	2.16	3.88	1.77	3.27	1.77
P_2O_5	0.21	0.17	0.34	0.26	0.34	0.21	0.67
TOTAL	99.85	99.84	99.95	99.77	99.72	100.23	99.68
Q	4.30	3.61	4.22	3.73	5.95	7.62	-
C	0.71	-	-	-	-	-	-
Or	8.66	6.47	6.88	5.14	8.32	4.73	15.94
Ab	29.76	30.06	24.46	29.29	31.96	26.01	46.69
An	32.26	34.58	30.63	34.12	29.52	27.56	8.73
Ne	-	-	-	-	-	-	1.14
Di	-	1.53	8.36	5.00	2.97	5.25	15.33
Hy	15.89	15.53	16.01	12.39	9.27	22.73	-
Ol	-	-	-	-	-	-	1.87
Mgt	4.46	3.94	5.68	6.10	2.70	3.27	5.96
Hm	-	-	-	-	5.59	-	-
Ilm	3.45	3.86	2.92	3.57	2.89	2.32	2.71
Ap	0.51	0.42	0.84	0.65	0.83	0.52	0.64

TABLE 4-2

Variance analysis of lavas from 2 flows in Burnside Quarry

* = insignificant

	Variance σ^2	% of Total Variance
SiO_2	0.30	10.24
Al_2O_3	0.19	6.55
TiO_2	*	*
FeO(T)	0.96	32.76
MnO	*	*
MgO	0.44	15.01
CaO	0.96	32.76
Na_2O	0.08	2.73
K_2O	*	*
P_2O_5	*	*

Feldspar-phyric olivine basalt	30
Clinopyroxene-feldspar-phyric olivine basalt	5
Olivine basaltic-andesite	4
Feldspar-phyric olivine basaltic-andesite	28
Clinopyroxene-feldspar-phyric olivine basaltic andesite	14
High K basaltic-andesite	1
Orthopyroxene-phyric andesite	3
High K andesite	6
Dacite	5
Intrusive Rocks	3

4:2 Major Element Chemistry

4:2:1 Introduction

Graphical and tabular representation of variation in suites of lavas have frequently proved to be useful in detecting essential chemical variation and frequency distribution. It should be pointed out that average analyses representing suites of lavas are of limited use, since averages only illustrate variation between groups, and take no account of variation within a group of lavas. As the classification adopted in this study relies heavily upon chemical limits, averages for particular groups of lavas are less meaningful, since a restraint has already been placed on their chemistry. Graphical representation of variation by means of histograms and variation diagrams, and statistical analysis of variance have been used in this study to illustrate the chemical variations within the lava suite.

4:2:2/

4:2:2 Histograms

The major element chemical characteristics of the lavas of the Sidlaw Hills are illustrated by histograms in FIG 4-1. These show that the suite is rather basic in nature, though it should be noted that a certain amount of bias is present owing to the multiple sampling of two flows in Burnside Quarry referred to earlier. However, this sampling only accounts for a relatively small proportion of the basalts.

Several important features are displayed in FIG 4-1 apart from the basic nature of the suite. Attention is drawn to the high contents of Na_2O and K_2O, and also the high alumina contents of the lavas, findings very much in agreement with those from analyses quoted by HARRY (1956, 1958), though that author draws little attention to the contents of Na_2O, K_2O, and Al_2O_3.

As noted in section 4:1, sampling was performed on the basis of freshness, and thus it is difficult to draw any firm conclusions regarding the distribution of elements. Hence too much emphasis should not be placed on the apparent bimodal distribution of silica with a possible gap between 59% and 61% SiO_2. GUPPY and SABINE (1956) have tabulated analyses of lavas from the Ochil Hills, which as noted in Chapter 1 are related to the Sidlaw Hills by an anticlinal fold, and these analyses plot within this silica range. Thus, it is unlikely that any significance could be attached to this apparent division.

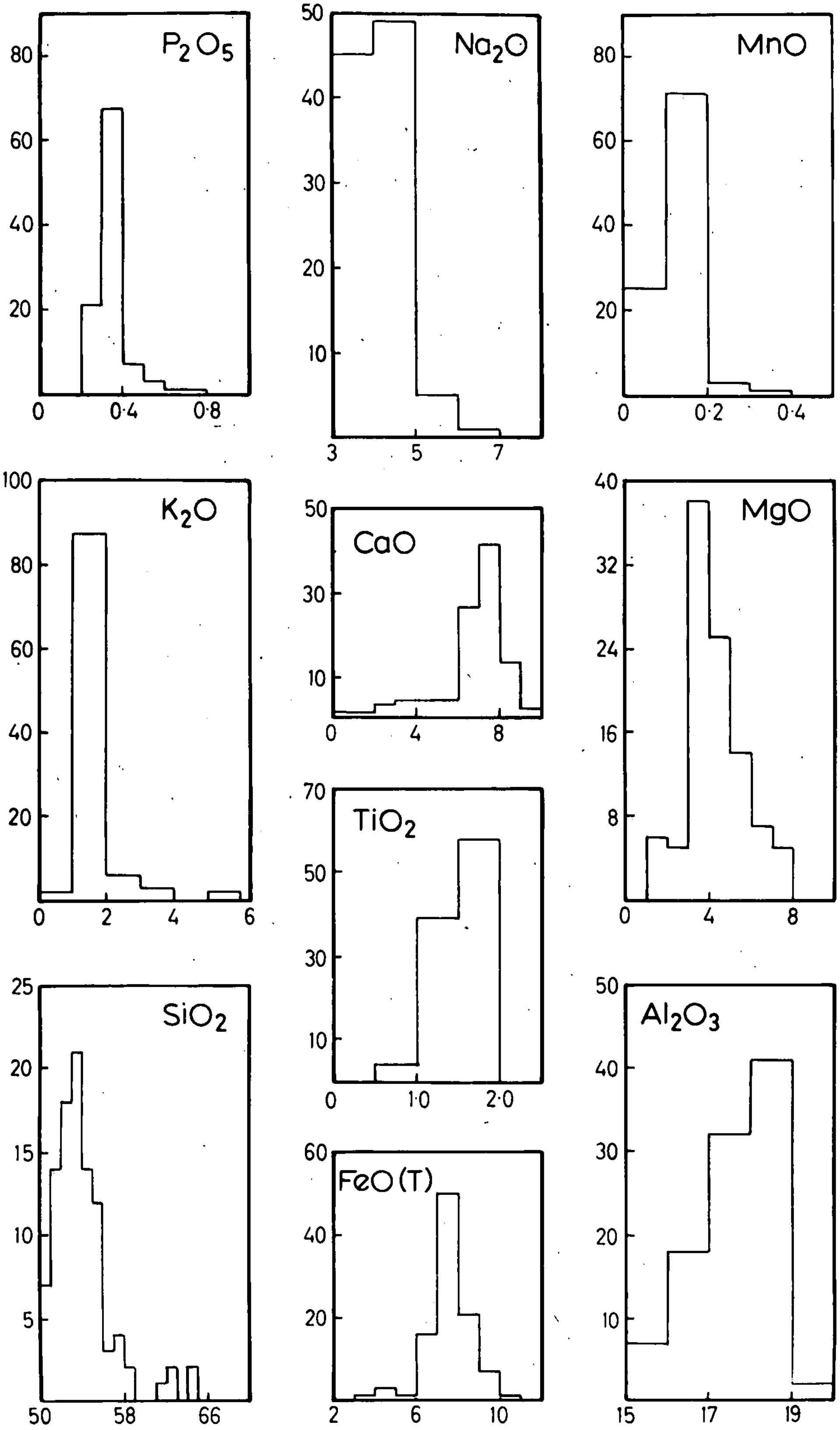
4:2:3 Variance Analysis

Inspection of the analyses of the lavas of the Sidlaw Hills together with/

<u>FIG. 4-1</u>

Histograms of major element distributions.

Vertical scale is frequency


P_2O_5
80
60
40
20
0
0·4
0·8
Na_2O
50
40
30
20
10
3
5
7
MnO
80
60
40
20
0
0·2
0·4
K_2O
100
80
60
40
20
0
2
4
6
CaO
50
30
10
0
4
8
MgO
40
32
24
16
8
0
4
8
TiO_2
70
50
30
10
0
1·0
2·0
SiO_2
25
20
15
10
5
50
58
66
FeO(T)
60
40
20
2
6
10
Al_2O_3
50
40
30
20
10
15
17
19

with the graphical representation of their chemistry by histograms, shows that although the range in silica compositions is quite large (50-65%), the bulk of the values fall within the range 50-56% SiO_2. However, a complete analysis of standard deviation and variance, presented in TABLE 4-3 shows that silica nevertheless makes the largest contribution towards the total variation, namely 52%. This is in agreement with CHAYES (1964) who surveyed the variance and covariance of calc-alkaline basalt-andesite-dacite suites from the Circum-Pacific volcanic belt. The range of contributions made by silica to the total variance of these suites was found to be 37-76% and was the dominant contributor in each case.

Although SiO_2 accounts for 52% of the total variance in this study, 5 variables (SiO_2, CaO, MgO, Al_2O_3 and FeO(T)) contribute nearly 95% towards the total variance of the suite of lavas from the Sidlaws. CHAYES (1960) has pointed out that, since components (variables) of analyses are summed to 100%, this summation imposes a linear restraint which increases negative, but decreases positive covariance. Since often only a few variables contribute vastly towards the total variance, then those variables whose contribution is small may be ignored, as constant sum considerations have little effect upon their correlation. Thus reduction of the number of variables, in this case to 5, can adequately define the variation. However, according to CHAYES (1962), by such a reduction, the correlation between the dominant variable, in this case SiO_2, and the less dominant variables, in this case CaO, MgO, Al_2O_3 and FeO(T) are in some instances likely to be less than the values given in a correlation matrix computed for all variables. This can be illustrated by use of the following equation given by CHAYES (1962).

TABLE 4-3

Variance analysis of all Sidlaw lavas (lavas not analysed for La and Ce have been omitted)

* = insignificant

	Variance σ^2	% of Total Variance
SiO_2	8.29	51.78
Al_2O_3	0.94	5.87
TiO_2	0.06	0.37
FeO(T)	1.46	9.12
MnO	*	*
MgO	1.85	11.56
CaO	2.66	16.62
Na_2O	0.25	1.56
K_2O	0.50	3.12
P_2O_5	*	*
Ba	*	*
Sr	*	*
Rb	*	*
Zr	*	*
Y	*	*
Zn	*	*
Cu	*	*
La	*	*
Ce	*	*

$$E\,(r_{1j}) \quad = \quad \frac{\sigma^{1}}{\sigma_{c}\,(1 - M^{1})}$$

Variable 1 is SiO_2

Variables j = 2-5 are CaO, MgO, Al_2O_3 and FeO(T)

σ^{1} = standard deviation of dominant variable

σ_c = mean of standard deviation of less dominant variables listed above

M^1 = reduced number of variables (= 5 in this case).

Substitution in this equation gives a correlation coefficient of -0.59 which is significantly different from the coefficents between SiO_2 and CaO, MgO, Al_2O_3 and FeO(T) listed in the correlation matrix of TABLE 4-4 and can be attributed solely to the effect of the constant sum factor. Thus the correlation coefficients computed in the correlation matrix of TABLE 4-4 must be treated with slight reservations between the variables SiO_2 and CaO, MgO, Al_2O_3 and FeO(T).

4:2:4 Harker Variation Diagrams

It was noted in the previous section on variance analysis that SiO_2 is the dominant contributor to the chemical variance in the suite of lavas from the Sidlaw Hills, and as such, it is an obvious choice as a simple index of variation/differentiation.

Harker variation diagrams of the type commonly used in petrochemical studies have been constructed for the lavas, and are presented in FIG 4-2. It can be seen from these variation diagrams that there is a somewhat scattered distribution for/

TABLE 4-4 (2 pages)

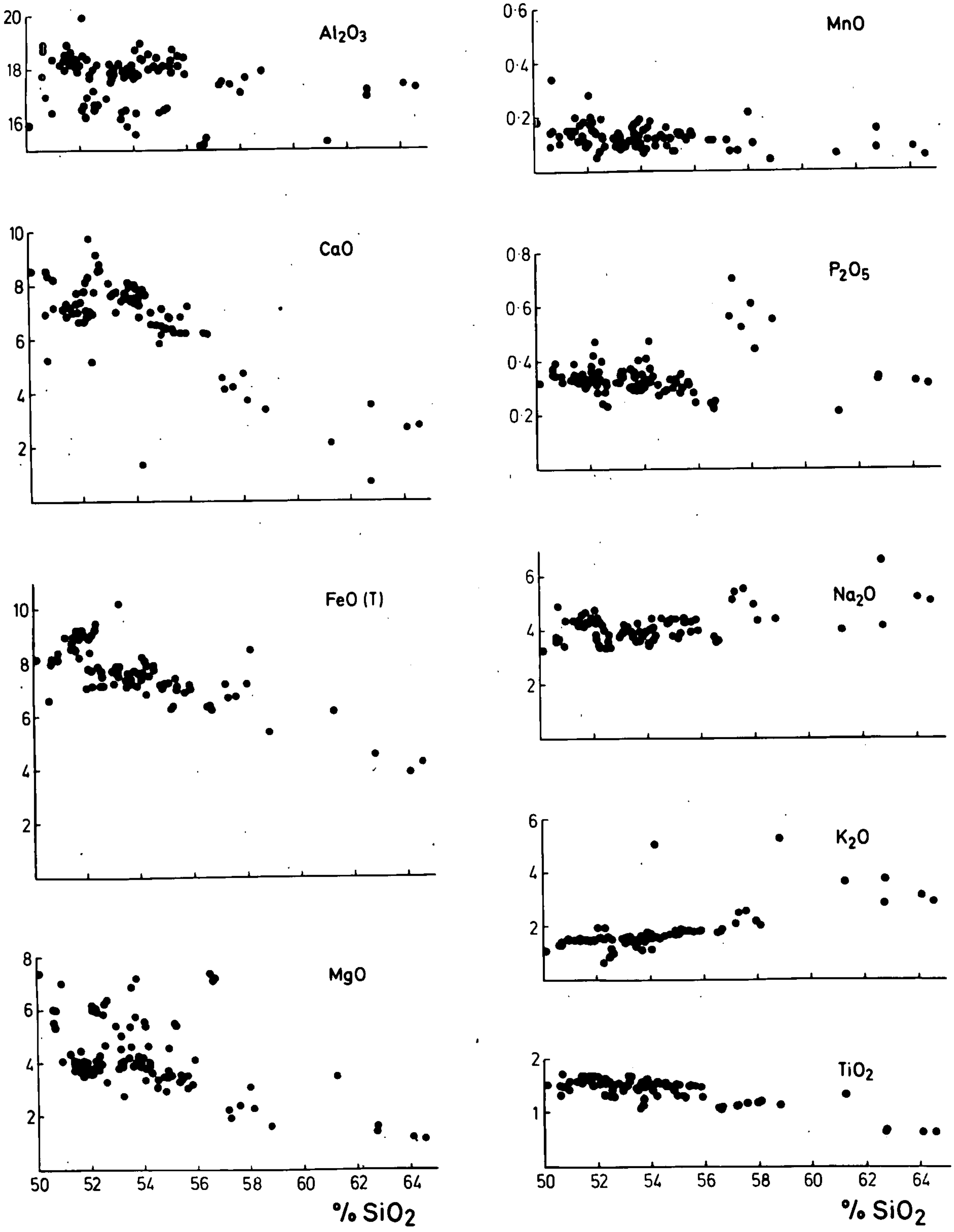
Correlation Matrix for Sidlaw lavas - major and trace elements

SiO_2	1.00									
Al_2O_3	-0.31	1.00								
TiO_2	-0.81	0.51	1.00							
FeO(T)	-0.82	0.34	0.82	1.00						
MnO	-0.39	0.28	0.35	0.24	1.00					
MgO	-0.49	-0.54	0.15	0.21	0.22	1.00				
CaO	-0.70	0.25	0.51	0.45	0.15	0.48	1.00			
Na_2O	0.36	0.48	-0.12	-0.14	0.20	0.67	0.69	1.00		
K_2O	0.65	-0.99	-0.50	-0.47	-0.34	-0.44	-0.81	0.42	1.00	
P_2O_5	-0.11	0.15	0.11	0.11	0.55	-0.17	-0.14	0.17	0.35	1.00
Ba	0.55	-0.21	-0.35	-0.30	-0.22	-0.29	-0.74	0.43	0.62	0.70
Sr	-0.56	0.24	0.52	0.58	0.23	0.13	0.48	-0.95	-0.54	0.26
Rb	0.78	-0.16	-0.55	-0.56	-0.36	-0.50	-0.77	0.43	0.82	0.71
Zr	0.74	-0.14	-0.68	-0.66	-0.27	-0.50	-0.67	0.39	0.72	0.44
Y	0.18	0.32	-0.98	-0.72	-0.11	-0.50	-0.36	0.31	0.48	0.44
Zn	0.41	-0.62	-0.29	-0.37	0.83	-0.18	-0.71	0.48	0.52	-0.13
Cu	-0.14	-0.58	-0.99	-0.45	-0.18	0.44	0.24	-0.48	-0.16	-0.10
La	0.63	-0.39	-0.57	-0.54	-0.26	-0.20	-0.42	0.16	0.52	0.13
Ce	0.41	-0.41	-0.35	-0.25	-0.20	-0.41	-0.46	0.39	0.49	0.33
	SiO_2	Al_2O_3	TiO_2	FeO(T)	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5

Ba	1.00								
Sr	-0.10	1.00							
Rb	0.60	-0.54	1.00						
Zr	0.42	-0.52	0.65	1.00					
Y	0.60	-0.31	0.45	0.47	1.00				
Zn	0.61	-0.47	0.50	0.38	0.17	1.00			
Cu	0.30	0.32	-0.13	-0.82	-0.37	-0.11	1.00		
La	0.36	-0.37	0.50	0.61	0.25	0.23	0.24	1.00	
Ce	0.56	0.73	0.36	0.47	0.14	0.23	-0.99	0.28	1.00
	Ba	Sr	Rb	Zr	Y	Zn	Cu	La	Ce

FIG. 4-2

Variation diagrams of major elements vs. SiO_2


Al$_2$O$_3$
20
18
16
CaO
10
8
6
4
2
FeO (T)
10
8
6
4
2
MgO
8
6
4
2
50
52
54
56
58
60
62
64
% SiO$_2$
MnO
0·6
0·4
0·2
P$_2$O$_5$
0·8
0·6
0·4
0·2
Na$_2$O
6
4
2
K$_2$O
6
4
2
TiO$_2$
2
1
50
52
54
56
58
60
62
64
% SiO$_2$

for most oxides. However, the following points should be noted from FIG 4-2: those oxides which concentrate in olivine, clinopyroxene, basic plagioclase, and ore, all show negative correlation with silica. In general, CaO illustrates quite a strong depletion in the lava series, whilst FeO(Total) and MgO both show a fairly gentle depletion during evolution*. Al_2O_3 remains at a constant level, though there is quite a lot of scattering of compositions in the basic lavas. Na_2O and K_2O show enrichment during evolution, though the Na_2O content of the dacites is rather variable. The K_2O contents of two high-K lavas appear to be anomalously high ($> 5\%$ K_2O). In the case of P_2O_5, there appear to be two distinct populations of composition points. TiO_2 remains at an almost constant level in the basic lavas, though there is substantial depletion in the dacites.

FIG 4-3 illustrates the behaviour of total alkalis when plotted against SiO_2. Field boundaries, from KUNO (1969) separating tholeiitic, calc-alkalic, and alkalic lavas have been included. From this diagram, the lavas appear to be transitional between calc-alkaline, and alkaline.

4:2:5 Correlation Coefficients

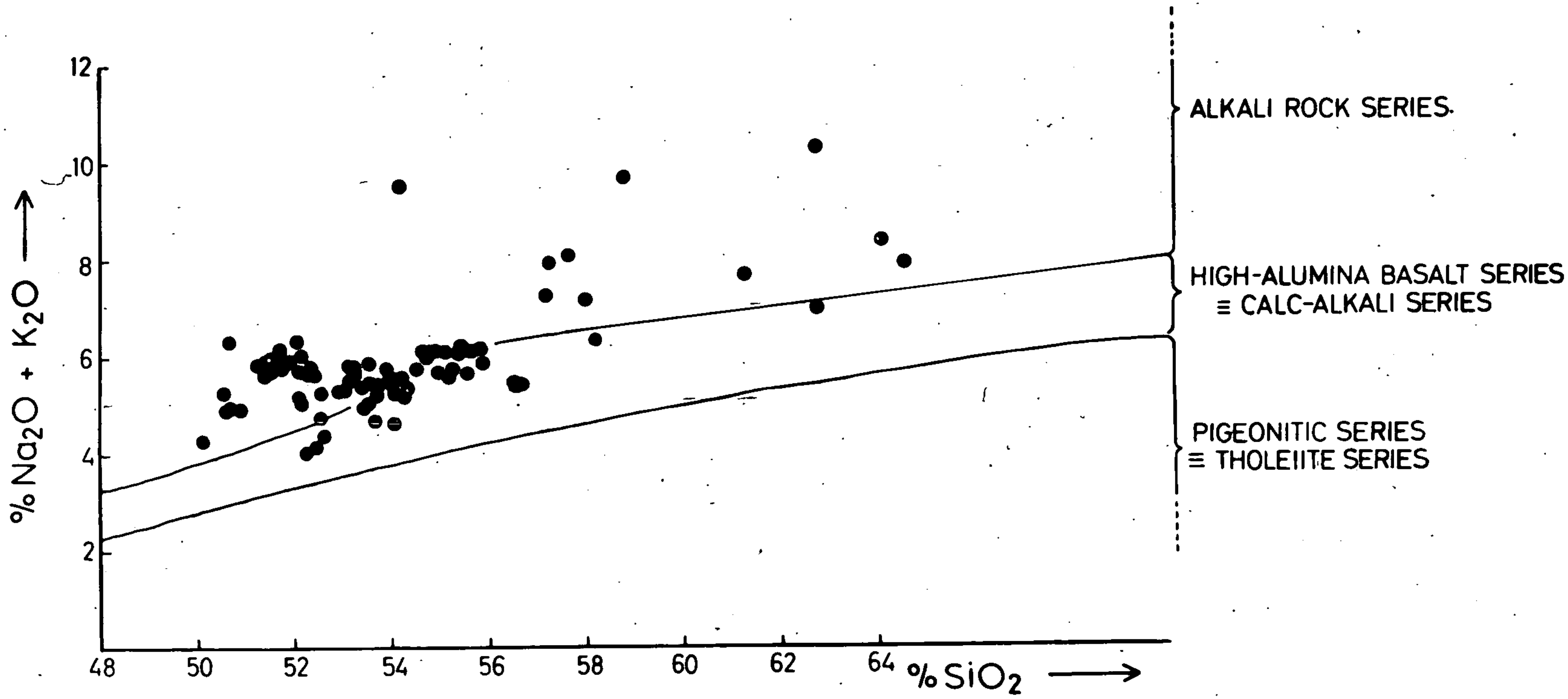
Examination of TABLE 4-4 shows that the correlation coefficients between SiO_2 and Na_2O, K_2O, and P_2O_5 are all positive indicating enrichment during evolution, though in the case of Na_2O, the enrichment is rather small. However, the correlation coefficients between SiO_2 and Al_2O_3, TiO_2, FeO(Total), MnO,/

* For present purposes, it is taken as a convenient assumption that the lava series is evolutionary in nature and that the more basic rocks (rocks poor in SiO_2 and rich in MgO and CaO) broadly represent the parental material from which the other rocks (rich in SiO_2 poor in MgO and CaO) are derived).

FIG. 4-3

Variation diagram of total alkalis vs. SiO_2

(Boundaries from KUNO (1969))


12
10
8
6
4
2
% Na_2O + K_2O →
48
50
52
54
56
58
60
62
64
% SiO_2 →
ALKALI ROCK SERIES.
HIGH-ALUMINA BASALT SERIES
≡ CALC-ALKALI SERIES
PIGEONITIC SERIES
≡ THOLEIITE SERIES

MnO, MgO and CaO are all negative and quite large apart from Al_2O_3 which, even taking into account the constant sum factor referred to in section 4:2:3, indicate quite strong depletion during evolution.

4:2:6 Three-Component Variation Diagrams

Though construction of a complete series of 2-component Harker variation diagrams will yield a comprehensive picture of magmatic variation, it is often useful to construct triangular variation diagrams to demonstrate additional variations not readily observable from Harker diagrams. FIG 4-4 illustrates an 'FMA' diagram for all lavas of the Sidlaw Hills. Superimposed onto FIG 4-4 are comparitive trends from the calc-alkaline lavas of the Cascade province after CARMICHAEL (1964), of Japan after KUNO (1969) and the Scottish Caledonian igneous rocks after NOCKOLDS and ALLEN (1953). It is interesting to note that although there is no iron enrichment in the lavas when plotted against SiO_2 (FIG 4-2), iron-enrichment is apparent in the basic lavas in the FMA plot of FIG 4-4. This is due to the fact that during evolution of the lavas series of the Sidlaw Hills the MgO depletion is strong initially, and less apparent in later stages. Hence, the FeC/MgO ratio will increase in the basalts but decrease relatively in the more evolved lavas, thus giving apparent iron-enrichment. It should be noted that the bulk of the lavas plot within the calc-alkaline field according to the field boundaries of KUNO (1969).

In FIG 4-5, the lava compositions are plotted in terms of their K_2O, Na_2O, and CaO contents. Trends from CARMICHAEL (1964), and also NOCKOLDS/

FIG. 4-4

F.M.A. variation diagram for Sidlaw lavas

———	for Japan from KUNO (1969)
— × —	for Cascades from CARMICHAEL (1964)
— • —	for Scottish Caledonian from NOCKOLDS and ALLEN (1953)

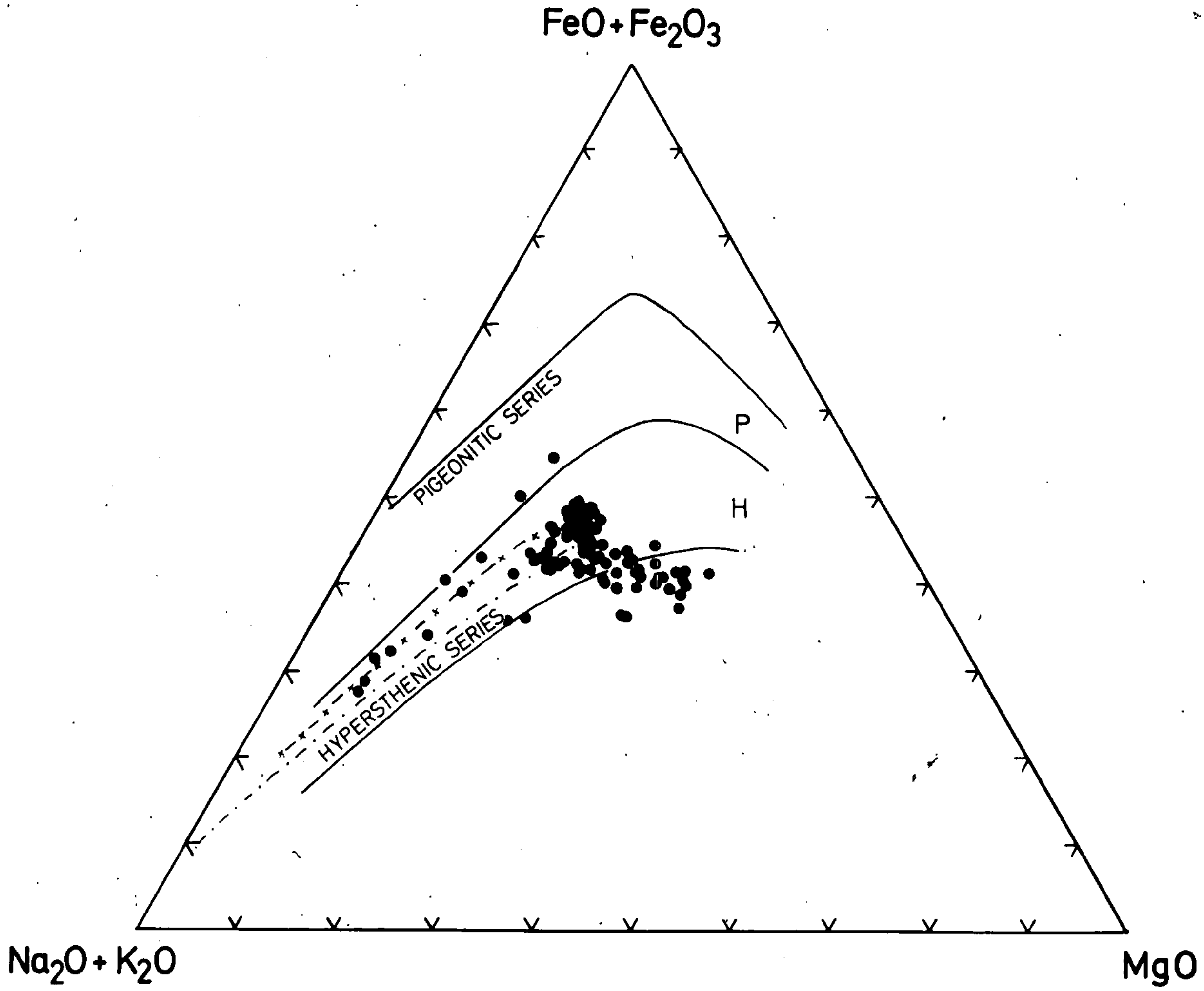
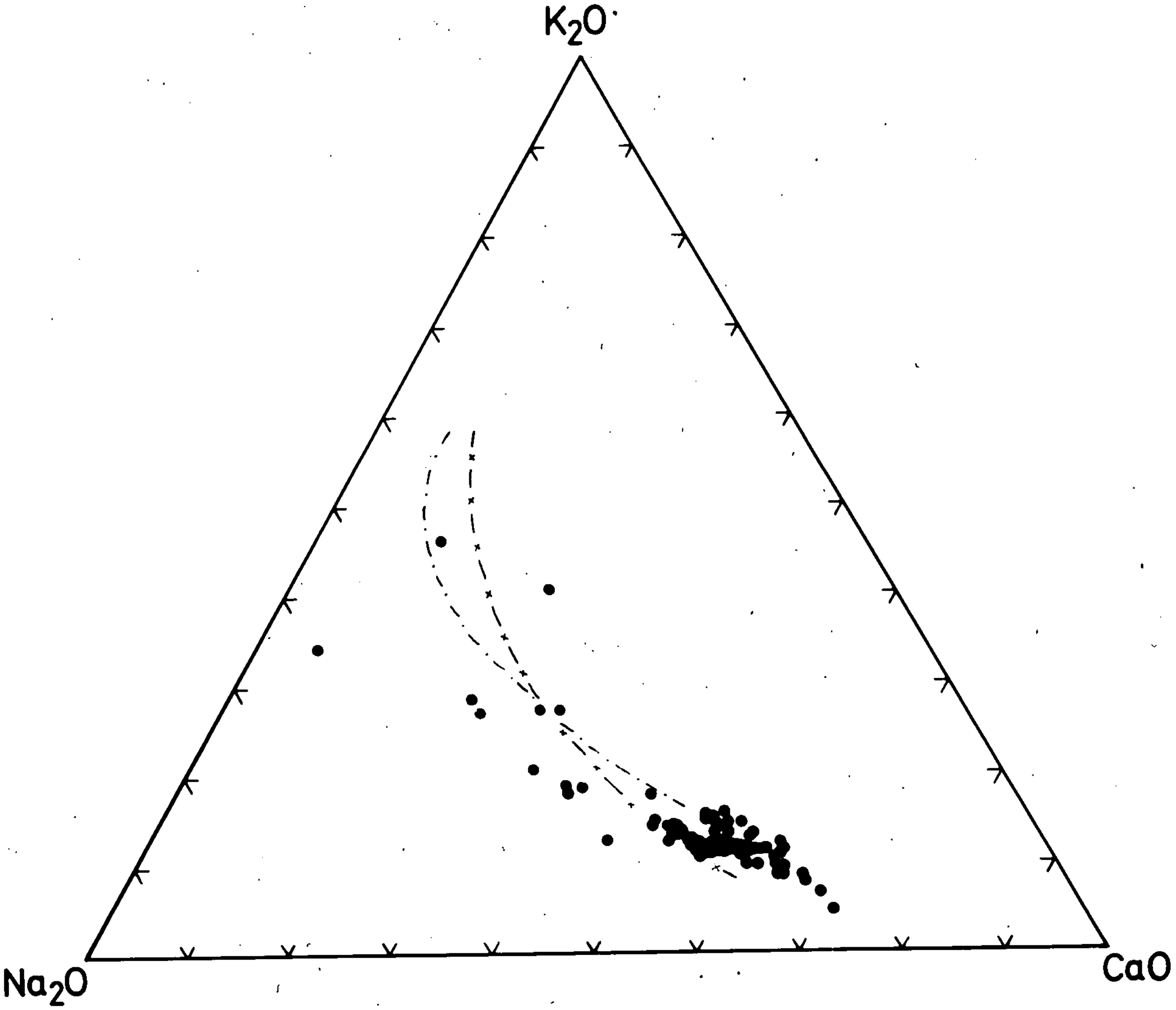

FeO + Fe_2O_3
PIGEONITIC SERIES
P
H
HYPERSTHENIC SERIES
$Na_2O + K_2O$
MgO

FIG. 4-5

K.N.C. variation diagram for Sidlaw lavas

—— × —— Cascades from CARMICHAEL (1964)

—— • —— Scottish Caledonian from NOCKOLDS and ALLEN (1953)


K$_2$O
Na$_2$O
CaO

NOCKOLDS and ALLEN (1953) are superimposed onto the diagrams. The lavas closely follow the trends from the other provinces especially the Scottish Caledonian trend. The large variation in alkali content noted in FIG 4-2 is also apparent in the KNC plots of FIG. 4-5.

4:2:7 C.I.P.W. Norms

It was noted in Chapter 2 that all the lavas from the Sidlaw Hills show some signs of alteration. The mean value of the natural oxidation ratios of the lavas is 0.600, compared with an average of 0.423 for 1775 Cenozoic andesites quoted by CHAYES (1969). This value of 0.423 is comparable with the freshest of the Sidlaw lavas, though even this lava shows some alteration petrographically. Consequently, the natural oxidation ratios of the Sidlaw lavas have been adjusted to a value 0.350, and the calculated norms of the lavas with this oxidation ratio are presented in Appendix (C).

The following points should be noted from the norms.

1. The oversaturated nature (i.e. quartz normative) of many of the basalts, and all of the more evolved rocks. This feature is illustrated diagramatically in FIG 4-6 where the lava compositions are plotted in terms of normative olivine, diopside, and quartz in molecular percent.
2. Normative albite and orthoclase increase at the expense of normative anorthite during evolution, this being illustrated in FIG 4-7.
3. Corundum is present in the norm of very few lavas; those generally showing anomalous alkali contents, though corundum is ubiquitous in the/

FIG. 4-6

Normative Olivine-Diopside-Quartz diagram illustrating the oversaturated nature of most of the lavas

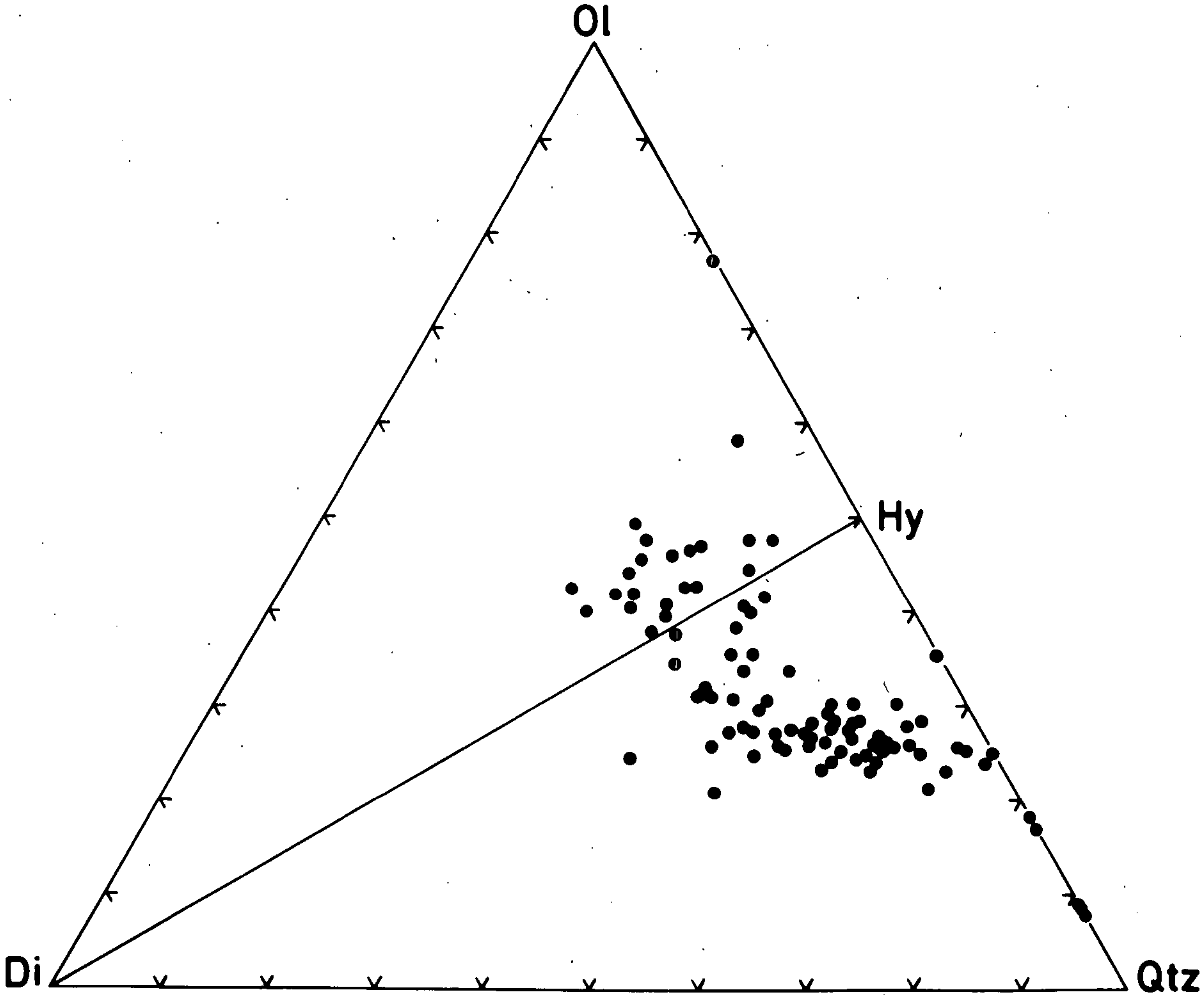
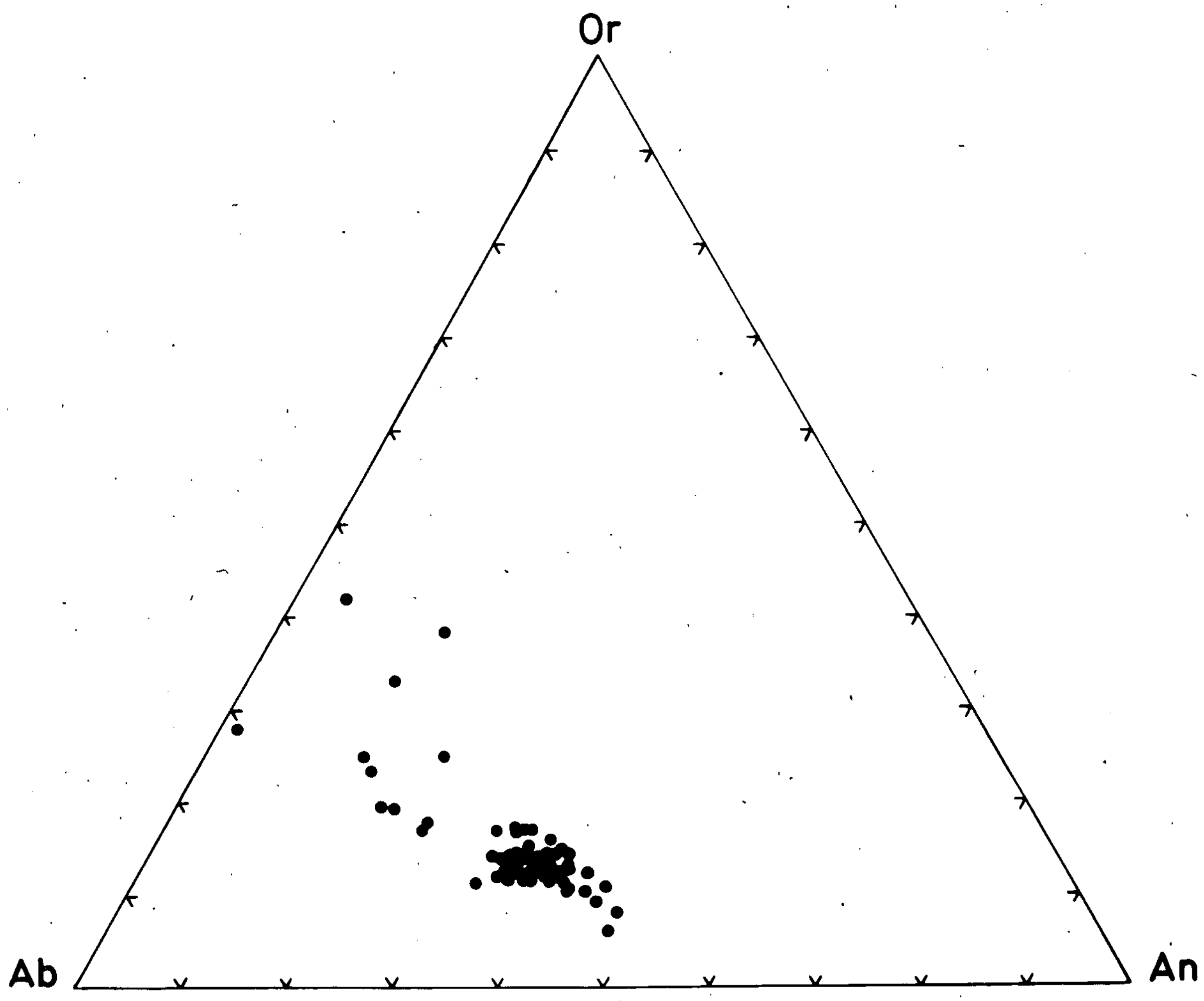

Ol
Hy
Di
Qtz

FIG. 4-7

Normative feldspar diagram


Or
Ab
An

the norms of the dacites. CHAYES (1969) has noted that corundum normative andesites and dacites are fairly common in Cenozoic lavas of the Circum-Pacific belt.

4:3 Trace Element Chemistry

4:3:1 Introduction

TAYLOR (1969) has stressed the importance of trace element studies and their application to problems of petrogenesis of calc-alkaline suites. The association of calc-alkaline rocks with orogenic areas, and their possible derivation from the mantle have stimulated much geochemical research in recent years.

Element behaviour in liquids is controlled by several processes, and important one of which is the stability of mineral phases under various conditions, such as temperature and pressure. The rejection of elements by certain mineral phases under specific temperature/pressure environments gives rise to concentrations of those elements in the liquid, and thus provides clues to the effects of fractionation of mineral phases. Those elements which are rejected by mafic mineral phases such as olivine and clinopyroxene have been termed "incompatible elements" by GREEN andRINGWOOD (1967). These incompatible elements include Ba, Rb, Sr, Y, etc., i.e. those elements which are rejected by most minerals until late stages of fractionation.

No previous research has been undertaken on the trace element concentrations in the lavas of the Sidlaw Hills, and in this study, suitable trace elements have been investigated to detect the role played by fractionation of olivine, plagioclase, and minor clinopyroxene.

4:3:2 Histograms

The distributions of trace elements in the lavas of the Sidlaw Hills are shown in FIG 4-8. In section 4:2:2 it was noted that the Sidlaw lavas were rich in Na_2O and K_2O. Trace elements associated with Na_2O and K_2O similarly show high levels, and are notably higher than the averages for calc-alkaline lavas quoted by TAYLOR (1969). Though most of the trace element concentrations in the Sidlaw lavas are higher than TAYLOR'S averages, too much emphasis should not be placed on the differences since different analytical techniques for the trace elements have been used.

4:3:3 Variation diagrams

The trace element variation in the lavas of the Sidlaw Hills is shown in FIG 4-9, and as with the major element Harker variation diagrams, SiO_2 has been used as an index of magmatic variation. The behaviour of each trace element will be described separately following the suggestions of TAYLOR (1965).

Barium: Owing to the ionic radius of Ba, this element substitutes only for K^+ among common cations, and concentrates especially in K-feldspar. In the lavas, the Ba content increases with evolution, though concentrations are quite variable.

Strontium: TAYLOR (1965) has noted that Sr will enter plagioclase, and thus this element should be a useful indicator of plagioclase fractionation. The lavas in general show a steady depletion in Sr with evolution, though there is considerable variation. The five analysed dacites have relatively high/

FIG. 4-8

Histograms of trace element distribution.

Vertical scale is frequency

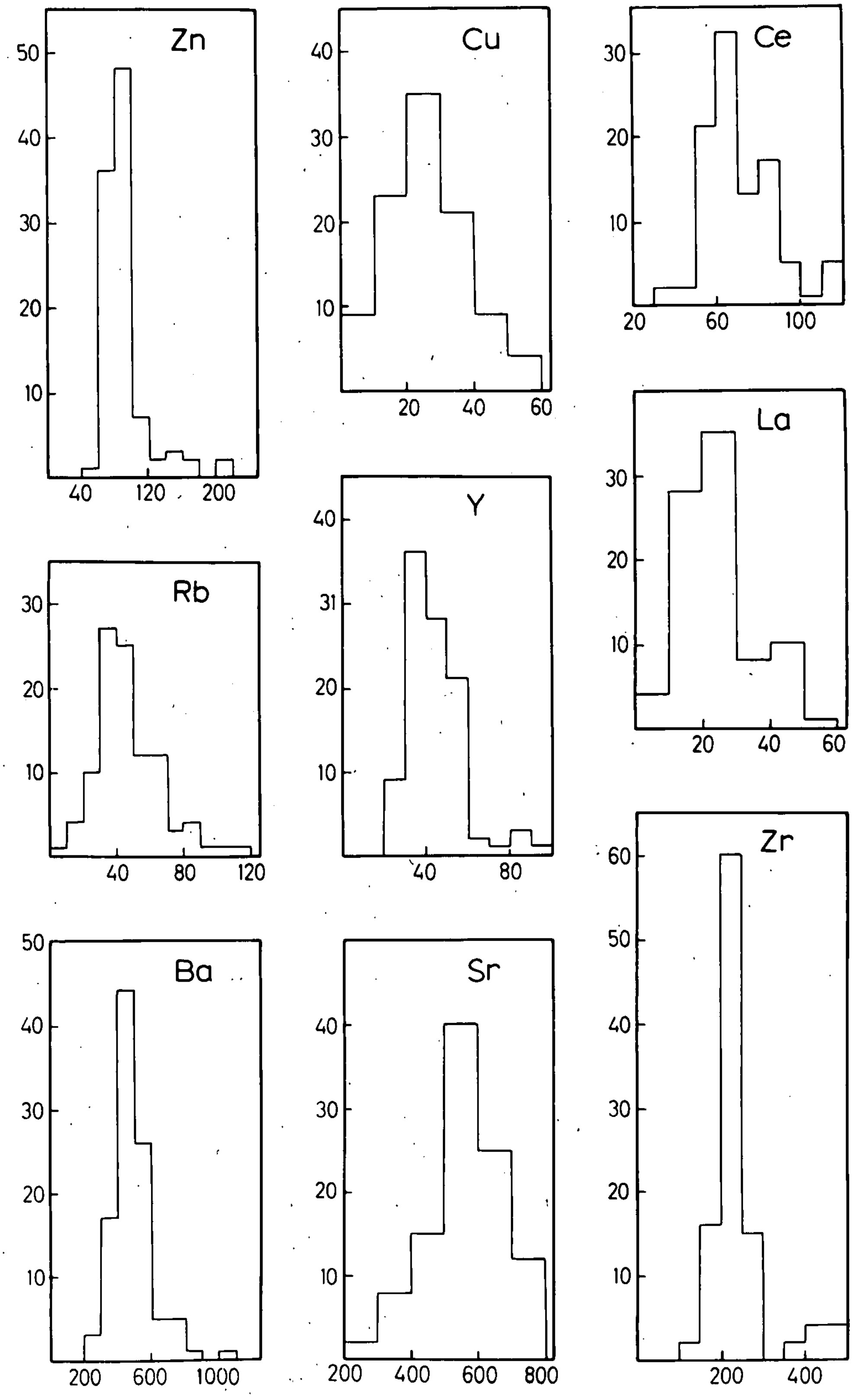
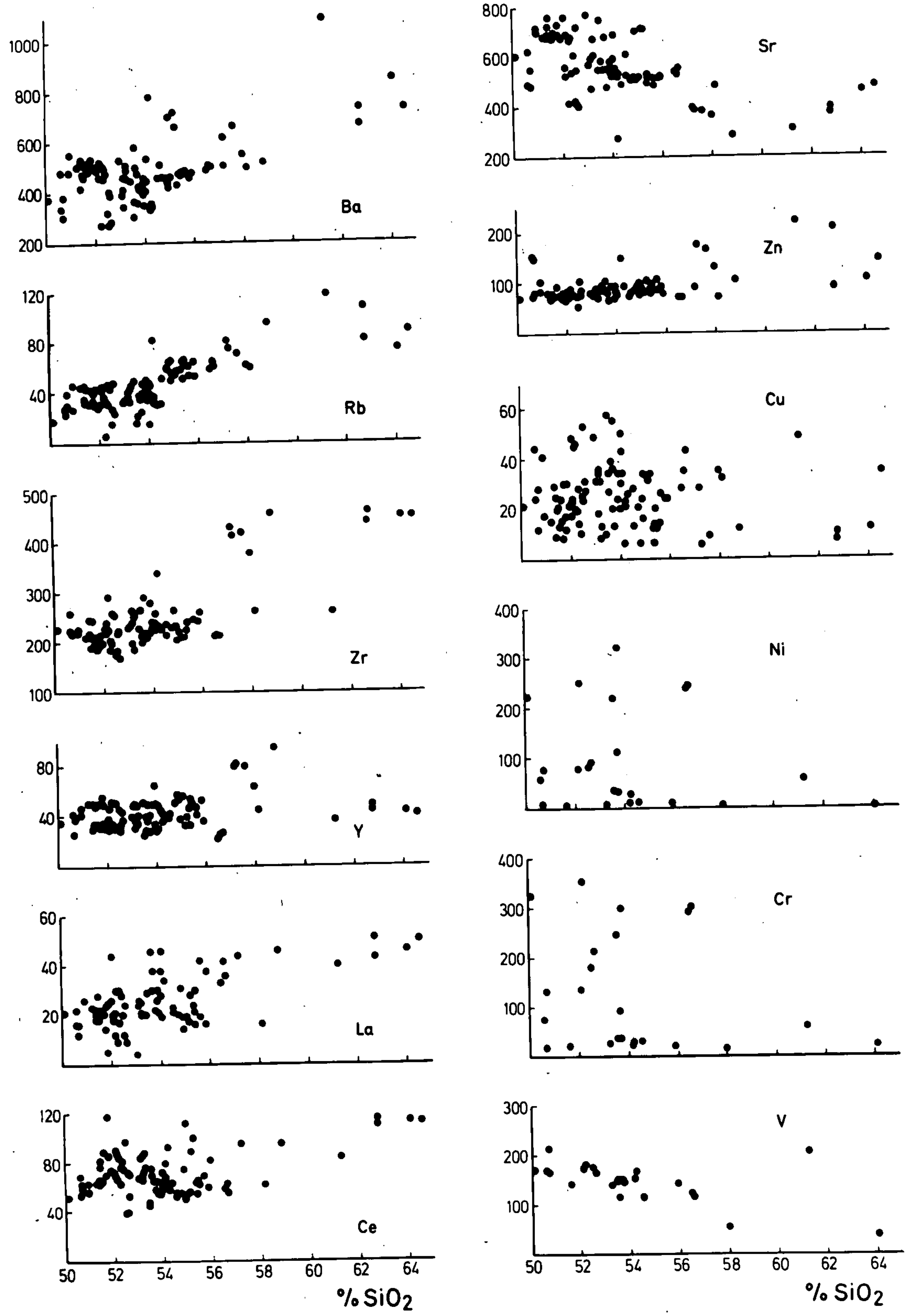

Zn
50
40
30
20
10
40
120
200
Cu
40
30
20
10
20
40
60
Ce
30
20
10
20
60
100
La
30
20
10
20
40
60
Rb
30
20
10
40
80
120
Y
40
31
20
10
40
80
Zr
60
50
40
30
20
10
200
400
Ba
50
40
30
20
10
200
600
1000
Sr
40
30
20
10
200
400
600
800

FIG. 4-9

Variation diagrams of trace elements vs. SiO_2


Ba
1000
800
600
400
200
Rb
120
80
40
Zr
500
400
300
200
100
Y
80
40
La
60
40
20
Ce
120
80
40
50
52
54
56
58
60
62
64
% SiO2
Sr
800
600
400
200
Zn
200
100
Cu
60
40
20
Ni
400
300
200
100
Cr
400
300
200
100
V
300
200
100
50
52
54
56
58
60
62
64
% SiO2

high CaO contents, considering their SiO_2 content, and this is accompanied by high Sr.

<u>Rubidium</u>: This element is very similar in size and chemical character to potassium, and as such it is excluded from mafic mineral phases such as olivine and clinopyroxene. In the Sidlaw lavas, rubidium shows a steady increase in concentration with evolution. TAYLOR (1965) has shown that the K/Rb ratio is often a useful clue to fractionation of a suite of rocks. According to GAST (1965) the K/Rb ratio in many common rocks is constant (~ 300), though there is wide variation in some oceanic tholeiites. In the Sidlaw lavas, there is a slight decrease in the K/Rb ratio with evolution as shown in FIG 4-10. The preferential removal of K in the dacites by alkali feldspar will lower the K/Rb ratio. The occasional high values of the K/Rb ratio in a few of the Sidlaw basalts is likely to be a function of the rather low Rb content in those lavas.

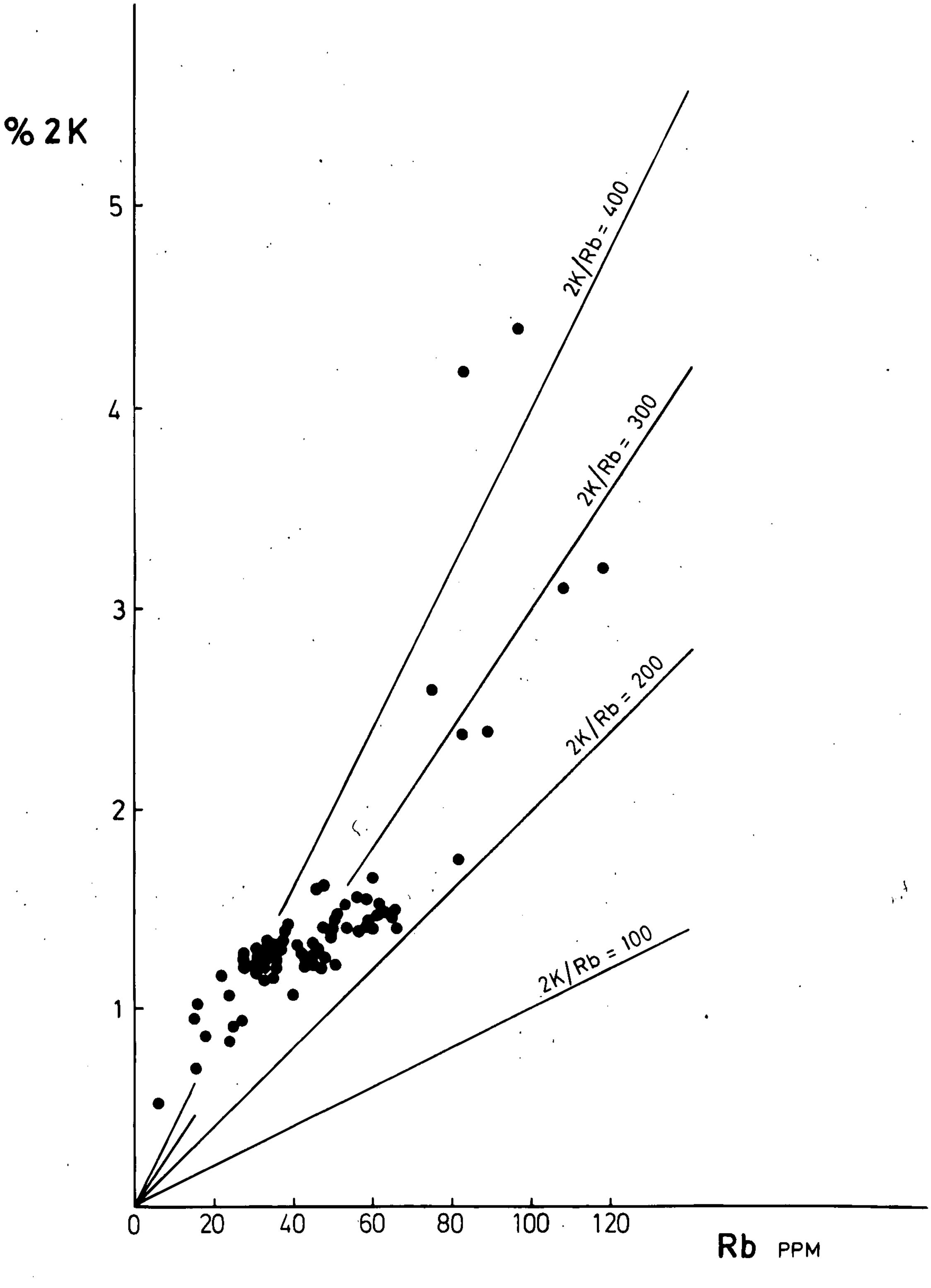
<u>Zirconium</u>: Common rock forming minerals do not readily accept zirconium into their structure due to its ionic size, and hence during evolution the concentration of zirconium is likely to increase. In the Sidlaw lavas, there is evidence of concentration, though the cloudiness of the distribution makes it difficult to assess the full behaviour of zirconium.

<u>Yttrium</u>: TAYLOR (1965) noted that although Y^{3+} was close in size to Ca^{2+}, it only substituted for Ca^{2+} to any extent in apatite. Thus Y^{3+} contents of lavas should give clues to the effects of apatite fractionation. During evolution of the Sidlaw lavas, Y^{3+} shows a gradual increase in content until the high-K andesites, at which point apatite microphenocrysts occur. The Y^{3+} concentration decreases from the high-K andesites to the dacites.

<u>Zinc</u>: This element has a rather random distribution in the Sidlaw lavas, though/

FIG. 4-10

Plot of 2K (wt %) vs. Rb (ppm) for the Sidlaw lavas


%2K
5
4
3
2
1
0
20
40
60
80
100
120
Rb PPM
2K/Rb = 400
2K/Rb = 300
2K/Rb = 200
2K/Rb = 100

though there is possibly an increase with evolution. According to TAYLOR (1965), zinc concentration is usually controlled by a sulphide phase, and TAUSON and KRAVCHENKO (1956) have pointed out that zonc is often present in plagioclase, usually as small grains of sphalerite.

Copper: Copper enters many rock forming minerals, substituting for sodium in plagioclase, Ca in apatite and Fe^{2+} in olivines and pyroxenes. Thus its contents in lavas are likely to be variable. This variability is shown in the Sidlaw lavas, though there is slight depletion during evolution.

Lanthanum: The concentration of this element in the Sidlaw lavas is notably higher than the average values quoted by TAYLOR (1969). Though the distribution of La in the Sidlaw lavas is variable, its concentration does increase with evolution.

Cerium: The distribution of cerium closely parallels that of Lanthanum, though there is slightly less variability in its concentrations. Once again Ce is enriched in the Sidlaw lavas compared with the average of TAYLOR (1969).

Nickel: Though only selected lavas have been analysed for Ni, it is clear from FIG 4-9 that the transition from basalt to basaltic andesite is accompanied by strong depletion of Ni which then maintains an almost constant low value in the more evolved lavas. The affect of deuteric alteration of the olivine on the Ni content of the lavas is unknown.

Chromium: This element has an almost identical distribution pattern to Ni, with high chromium contents in the basalts and strong depletion during evolution.

Vanadium: There is a steady depletion of vanadium in the lavas which probably reflects the minor role of ore fractionation.

4:3:4/

4:3:4 Multiple Component Variation Diagrams

To assess the variation of all trace-elements and to detect varieties of trace element distributions, factor analysis has been employed following the method of PRINZ (1967). Each trace element is treated as a variable, and comparison is made between all variables. Only those lavas with analyses of Ba, Sr, Rb, Sr, Y, Zn, Cu, Cr, Ni, and V have been used to obtain a full picture of the variation. A description of the method employed can be found in Appendix C. The trace elements are related to four end members which are dominated by Sr, Cr (and Ni), Ba (with V and Zr) and V (with Ba and Zr). Thus each whole rock composition can be plotted as a point in a tetrahedron, but following PRINZ (1967), the analytical points are projected onto two faces of that tetrahedron, thus allowing comparisons with other suites. FIG 4-11 illustrates the trace element variation of the Sidlaw lavas in terms of the 4 end members listed above, and for comparison, trends for other calc-alkaline lavas have been superimposed.

Inspection of FIG 4-11 shows that the variation of all the trace elements considered together supports the individual variations shown in FIG 4-9 with depletion of elements having basic affinities during evolution, and enrichment in those elements not accepted into mafic mineral phases.

4:4 Chemistry of the Intrusive Rocks

Three samples of intrusive rocks from Knapp Quarry (see location map), M111, M112, and M114 have been analysed for major and trace elements (see Appendix (C)).

Chemically, the dolerites M111 and M112 are very similar to the lavas having/

FIG. 4-11

Multiple component variation in the trace element contents of the lavas

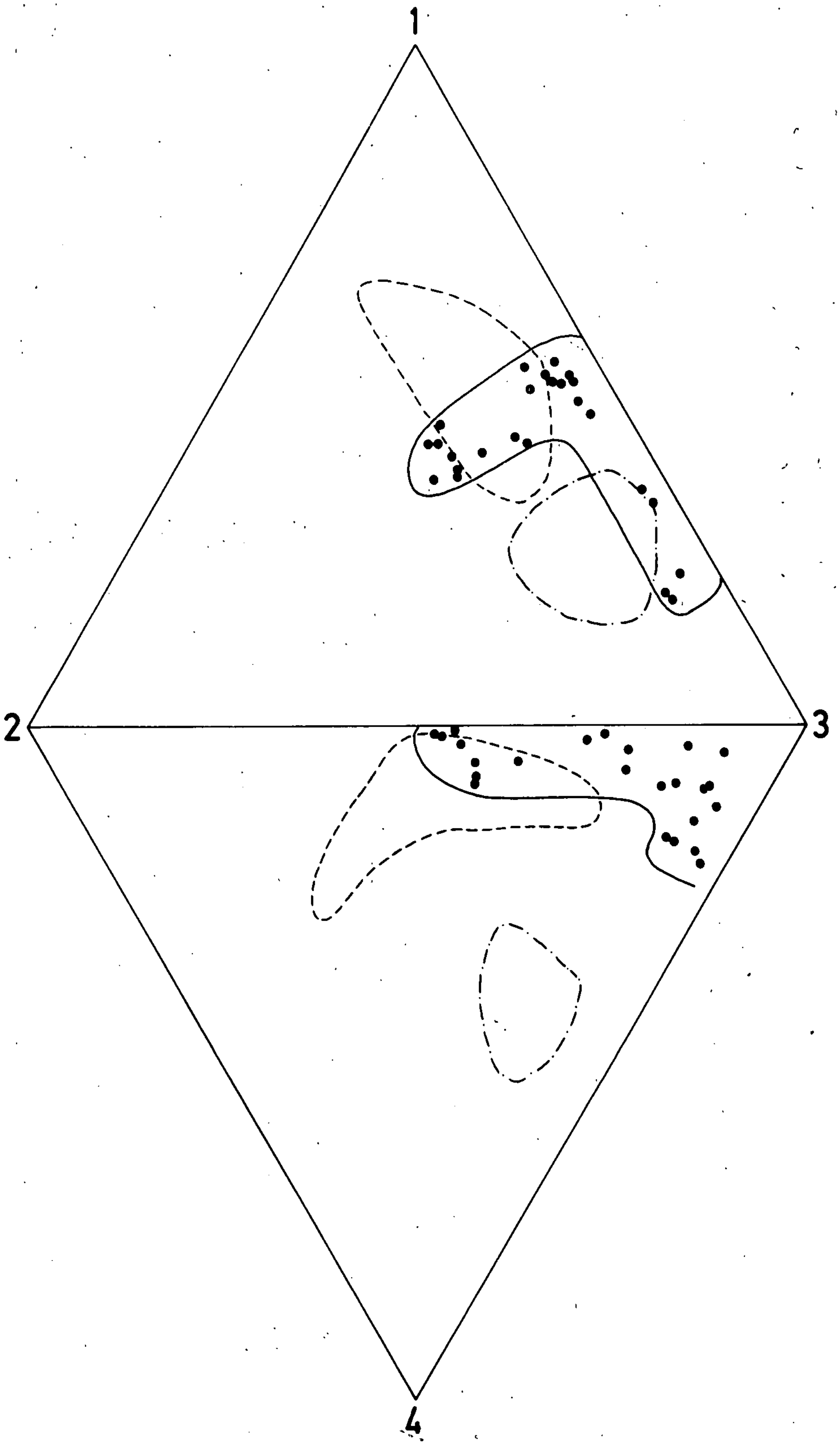
1 = Sr

2 = Cr (and Ni)

3 = Ba (with V and Zr)

4 = V (with Ba and Zr)

◌ Hakone hypersthenic series)
)
) PRINZ (1967)
)
◌ Lassen Peak)


1
2
3
4

having high alumina and high alkali contents and are oversaturated with quartz in the norm. Their trace element chemistry similarly corresponds closely to the lavas of similar silica content.

The striking mineralogy of the segregation vein (M114) is born out in its chemistry, with high contents of silica and K_2O. The trace element chemistry similarly shows large concentrations of those elements enriched by fractionation, namely Ba, Rb, Zr, La, and Ce.

4:5 Variation of Lava Chemistry with height in the sequence

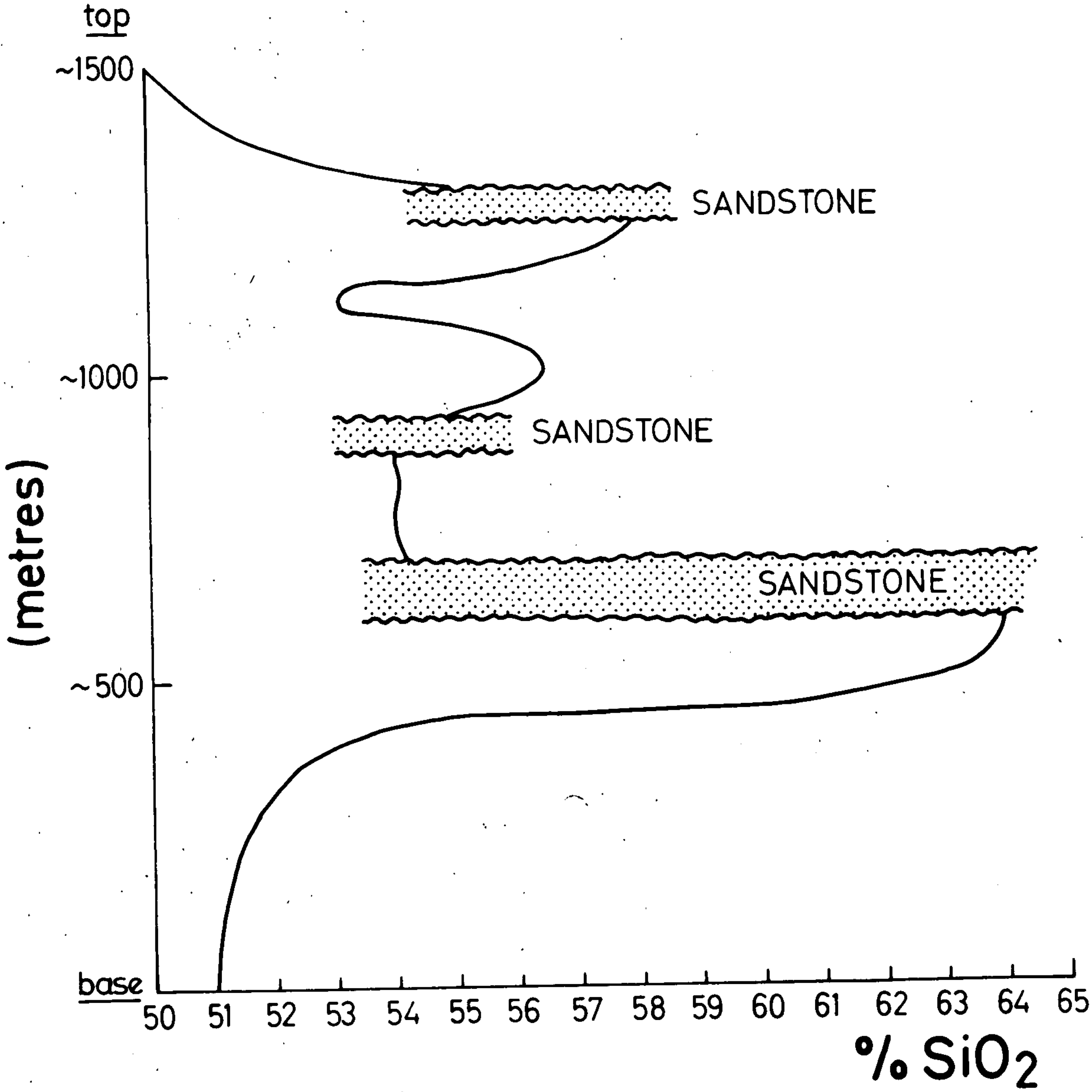
The lack of continuous vertical exposure in the lava sequence of the Sidlaw Hills makes any deductions on the chemical variation of the lavas with height somewhat speculative. However, by considering the lava units (i.e. series of flows, each series being separated by a sedimentary horizon) as a whole, a reasonably complete picture of the chemical variation can be obtained. FIG 4-12 illustrates the chemical variation of the lavas with height using SiO_2 as an index of magmatic variation. It is apparent from FIG 4-12 that the more evolved lavas occur near the middle of the exposed sequence, and the most basic at the top.

4:6 Comparison with other calc-alkaline lava suites

In general, basaltic lavas are subordinate in occurrence to andesites and rhyolites in calc-alkaline provinces throughout the world, and although the lava sequence in the Sidlaw Hills is rather basic, the Lower Old Red Sandstone lava province in Scotland as a whole contains compositions from basalt/

FIG. 4-12

Simplified variation in lava chemistry with height in the exposed sequence, using SiO_2 as a simple index of variation


top
~1500
~1000
~500
base
(metres)
SANDSTONE
SANDSTONE
SANDSTONE
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
% SiO_2

basalt to rhyolite.

Chemically, the Sidlaw lavas have higher contents of alkali elements and slightly higher Al_2O_3 contents when compared with Circum-Pacific calc-alkaline lavas of the same SiO_2 content, though in the case of Al_2O_3, considerable variation is present. The Sidlaw lavas have enrichment factors of about 1.5 for Na_2O and 4 for K_2O in comparison to average analyses of Circum-Pacific and West Indian calc-alkaline lavas with the same SiO_2 content quoted by TAYLOR (1969) and BAKER (1968) respectively. Trace elements associated with K_2O confirm this enrichment. However, LARSEN and CROSS (1956), JAKEŠ and SMITH (1971) and TAYLOR (1969) have reported high-K calc-alkaline andesites from North America and Indonesia with potassium contents similar or slightly higher than in the Sidlaw andesites. It should be pointed out that these high-K lavas from North America and Indonesia contain amphibole phenocrysts which are apparently absent from the Sidlaws.

There appears to be no direct equivalent of the lavas of the Sidlaw Hills in modern calc-alkaline lava suites, though they show typical calc-alkaline characteristics in the Sidlaw lavas such as high alumina contents, silica saturation in the norm, and lack of iron enrichment.

4:7 Summary

The lavas of the Sidlaw Hills can be described as calc-alkaline with higher potash contents than averages of modern lavas quoted by TAYLOR (1969). Many of the basalts, and all of the more evolved lavas are silica saturated and all the lavas contain hypersthene in their norms.

CHAPTER 5

FRACTIONATION MODELS

5:1 Introduction

Having described the general features of the chemistry of the Sidlaw lavas, the following discussion is concerned with construction of plausible fractionation models to explain the chemical variation.

5:2 Fractionation Models

5:2:1 Major Elements

From the variation diagrams of FIG 4-2, it can be seen that there is depletion of MgO, CaO, FeO(T), Al_2O_3 and TiO_2 and enrichment in Na_2O and K_2O as SiO_2 increases, and it is suggested that fractionation of olivine, plagioclase, ilmenite, and possibly clinopyroxene may have given rise to the observed sequence.

To test hypotheses of fractionation, it is initially simpler to consider those lavas which show no signs of cumulus enrichment since they are more likely to represent liquid compositions. The distinction between cumulus enriched and non-cumulus enriched lavas has been made solely on the phenocryst content of the lavas; less than 5% modal phenocrysts present being used to indicate non-cumulus enriched lavas.

Harker variation diagrams have been constructed for the selected phenocryst-poor lavas (FIG 5-1). It is clear from these diagrams that there is/

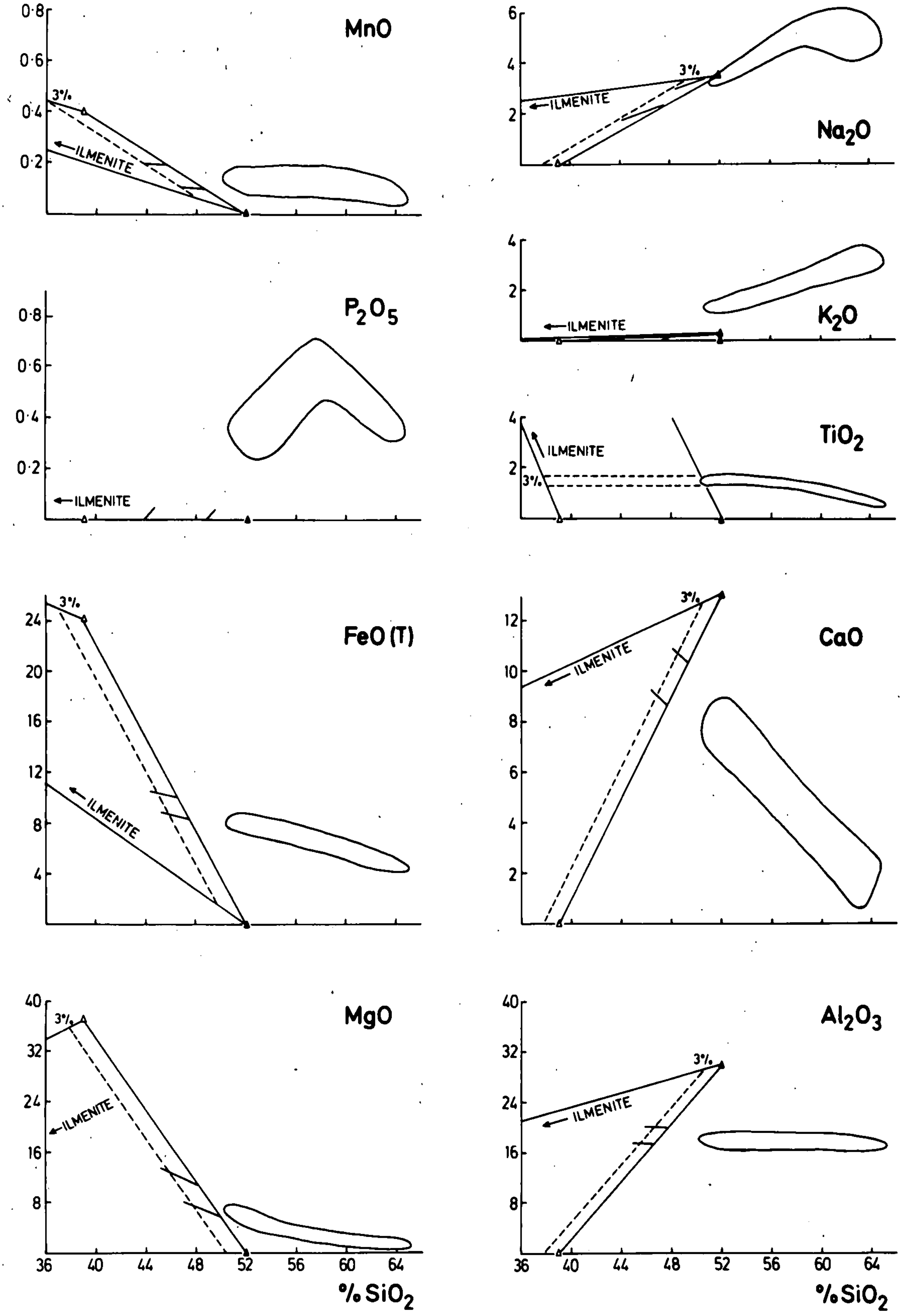
FIG. 5-1

Variation/extract diagram for phenocryst-poor lavas (major elements)

△ = Olivine

▲ = Plagioclase

⬭ = Trend of Phenocryst poor lavas


MnO
0·8
0·6
0·4
0·2
3%
ILMENITE
P2O5
0·8
0·6
0·4
0·2
ILMENITE
FeO (T)
24
20
16
12
8
4
3%
ILMENITE
MgO
40
32
24
16
8
3%
ILMENITE
36
40
44
48
52
56
60
64
% SiO2
Na2O
6
4
2
3%
ILMENITE
K2O
4
2
ILMENITE
TiO2
4
2
3%
ILMENITE
CaO
12
10
8
6
4
2
3%
ILMENITE
Al2O3
40
32
24
16
8
3%
ILMENITE
36
40
44
48
52
56
60
64
% SiO2

is a fairly close correlation between most oxides and silica, and since the phenocryst assemblage in the basic lavas is in general olivine + plagioclase + rare ilmenite, the composition points of these minerals have been added to each diagram. Olivine and ilmenite compositions are taken from DEER, HOWIE and ZUSSMAN (1963), the olivine selected being Fo_{70} (see Chapter 3). The plagioclase composition used is that of the most basic plagioclase phenocrysts from the Sidlaw lavas. The back projection of the TiO_2 vs SiO_2 trend into the three-phase triangle gives the probable amount of ilmenite in the extract as about 3%. Superimposing this value on the remaining 3-phase triangles suggest that extraction of olivine, plagioclase, and ilmenite in the ratio 27:70:3 from the most basic lava composition and/or addition of these phases to more siliceous compositions could approximately explain the observed trends. This ratio corresponds fairly closely to the calculated average olivine:plagioclase:ilmenite phenocryst ratio from the modal percentages of 34:66:trace. The model thus appears to be a simple crystal fractionation/accumulation model.

To assess this fractionation model in more detail, groundmass (and hence approximate liquid) compositions have been calculated for selected basic lavas and are presented in Appendix (C). FIG 5-2 illustrates the liquid-whole rock tie lines in Harker variation diagrams. If processes of crystal fractionation or accumulation have operated then the liquid-whole rock tie lines should plot along the whole rock trends. From FIG 5-2 it can be seen that in general the tie lines show the expected behaviour, though no special significance can be attached to it in the Na_2O, K_2O, and P_2O_5 diagrams since it is conditioned by the position of the phenocryst triangles relative to the whole-rock trends. The scattering of direction in the other diagrams can be accounted/

FIG. 5-2

Whole rock - groundmass compositions for selected Sidlaw lavas

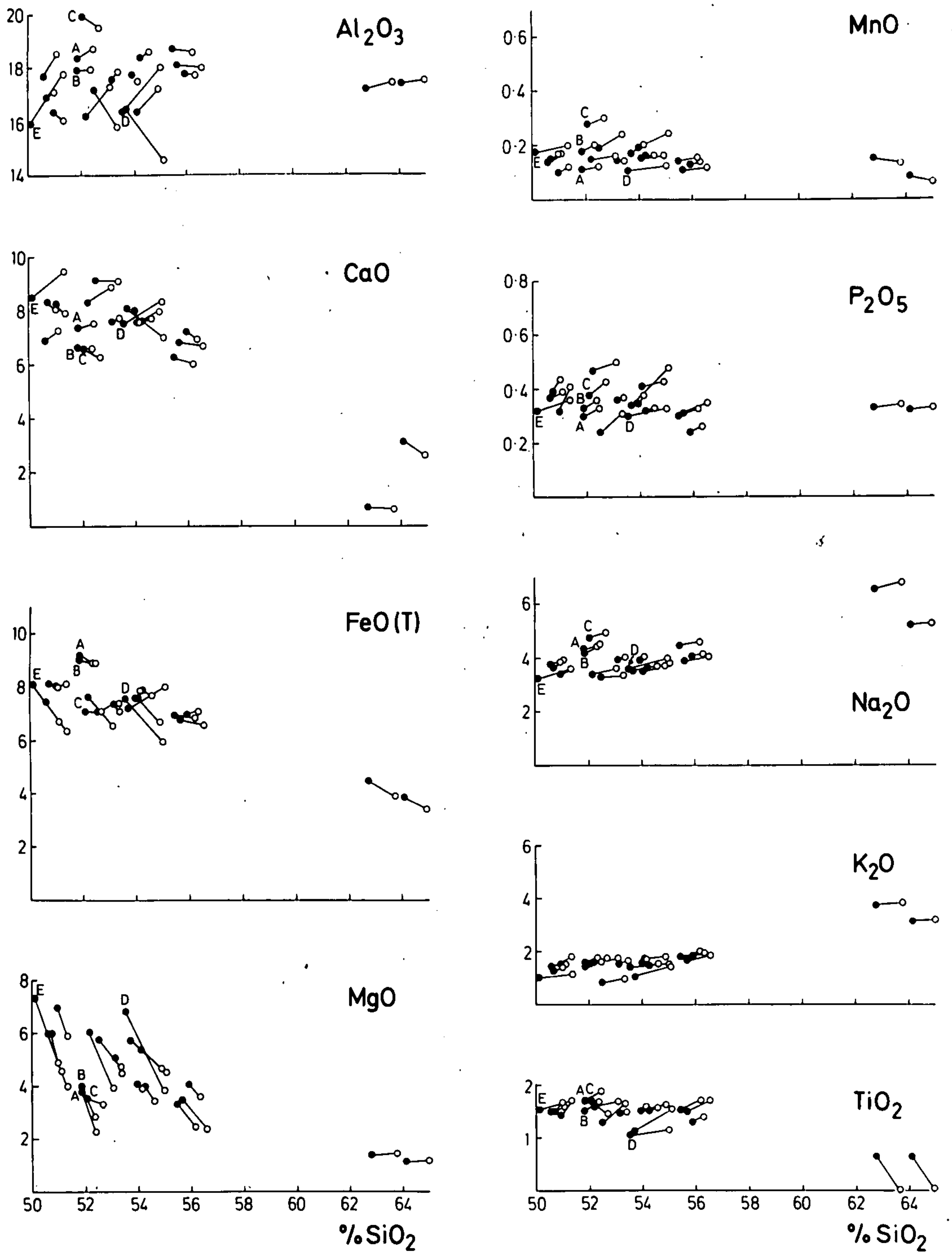
● = Whole rock

o = Groundmass

A, B, C, = Samples from one flow

D = Olivine Basaltic andesite

E = Olivine Basalt


Al_2O_3
20
18
16
14
CaO
10
8
6
4
2
FeO (T)
10
8
6
4
2
MgO
8
6
4
2
50
52
54
56
58
60
62
64
% SiO_2
MnO
0·6
0·4
0·2
P_2O_5
0·8
0·6
0·4
0·2
Na_2O
6
4
2
K_2O
6
4
2
TiO_2
2
1
50
52
54
56
58
60
62
64
% SiO_2
A
B
C
D
E

accounted for by assuming that in the individual specimens examined the olivine-plagioclase phenocryst ratio fluctuates randomly on either side of the average. This is probably a reflection of relatively small scale inhomogeneity in the samples or in the flows sampled. It may well for example be significant that the three samples (A, B, C in FIG 5-2) from a single flow show an average tie-line direction which is along the whole-rock trend though individual samples deviate from this.

FIG 5-3 illustrates all the analysed Sidlaw lavas, and shows that the phenocryst rocks in general follow the same trend as the phenocryst-poor.

"Cross-trend" Scatter

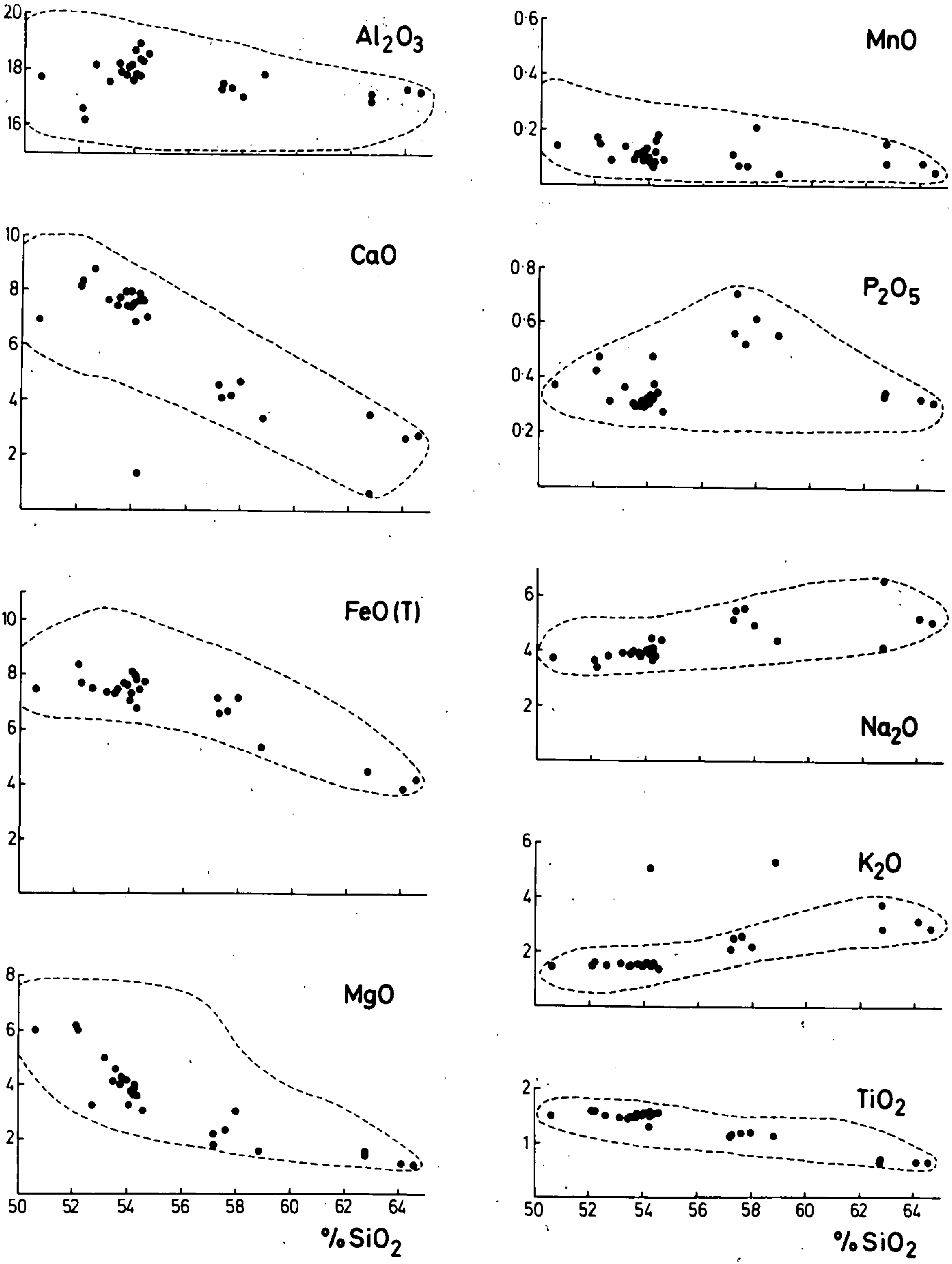
From the liquid-whole rock variation diagrams of FIG 5-2 it is apparent that the generation of some lavas from others by olivine + plagioclase + ilmenite fractionation is impossible (e.g. generation of D from E). Thus it is concluded that even the most basic Sidlaw lavas must have been derived from a variable range of immediately parental and more basic magmas. The parental magmas must have had a substantial range of SiO_2 ($\pm$ 2%), MgO ($\pm$ 1%), CaO ($\pm$ 5%) and K_2O ($\pm$ 0.4%) contents. Note that it is this feature which accounts for the apparent "repetition" of phenocryst assemblages noted in Chapter 2. Here the rocks were classified initially on the basis of their SiO_2 contents and it is clear that this parameter alone is insufficient to produce simple relationships between phenocryst assemblage and rock name. For example lavas carrying only olivine phenocrysts are found both in the basaltic group ($SiO_2 < 53\%$) and amongst basaltic-andesites (SiO_2 53-56%). In this latter group, however, such assemblages are found only in highly magnesian rocks.

FIG. 5-3

Comparison between phenocryst rich and phenocryst poor lava trends

● Phenocryst poor lavas

◌ Trend of all lavas


Al_2O_3
20
18
16
CaO
10
8
6
4
2
FeO (T)
10
8
6
4
2
MgO
8
6
4
2
50
52
54
56
58
60
62
64
% SiO_2
MnO
0·6
0·4
0·2
P_2O_5
0·8
0·6
0·4
0·2
Na_2O
6
4
2
K_2O
6
4
2
TiO_2
2
1
50
52
54
56
58
60
62
64
% SiO_2

5:2:2 Trace Elements

FIG 5-4 illustrates the trace element variation diagram on which are superimposed the three mineral composition points used in FIG 5-1. Though more uncertainty exists in the trace element contents of the minerals, it is clear that a fractionation model as envisaged above could account for the trace element variation in the lavas.

5:3 Cumulus Enrichment

In section 5:2, it was considered that those lavas with > 5% modal phenocrysts were probably cumulus enriched. The following discussion examines the possible chemical effects of cumulus enrichment. FIG 5-5 illustrates the proposed cumulus enriched and non-cumulus enriched lavas, and shows that cumulus enrichment has a somewhat random effect on the basic lavas. Plagioclase accumulation is likely to have increased Al_2O_3 and CaO contents and decreased MgO and FeO compared with non-cumulus enriched lavas with the same silica percentage. Olivine accumulation would have the opposite effect. In FIG 5-6, the trace element relationships of phenocryst rich and phenocryst poor rocks are shown. The cumulus enriched basalts have higher Sr contents than the non-cumulus enriched basalts, which may well reflect plagioclase accumulation.

5:4 The role of clinopyroxene in Fractionation Models

As noted in Chapter 2, clinopyroxene phenocrysts occur infrequently in the Sidlaw lavas and it has been suggested that clinopyroxene may be the third phase to appear in the crystallisation scheme. Fractionation of clinopyroxene alone/

<u>FIG. 5-4</u>

Variation/extract diagram for phenocryst poor lavas (trace elements)

symbols as for FIG. 5-1

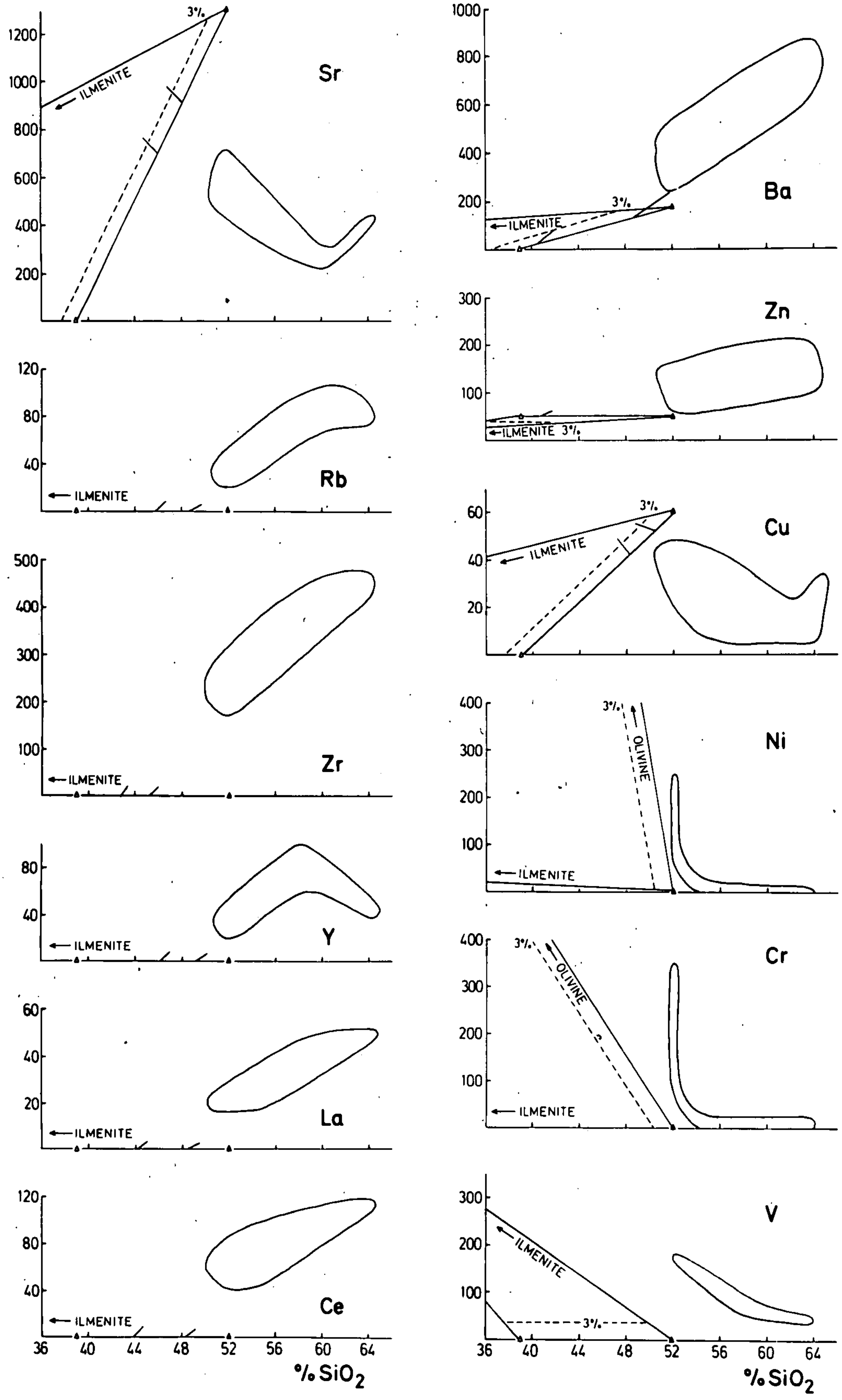
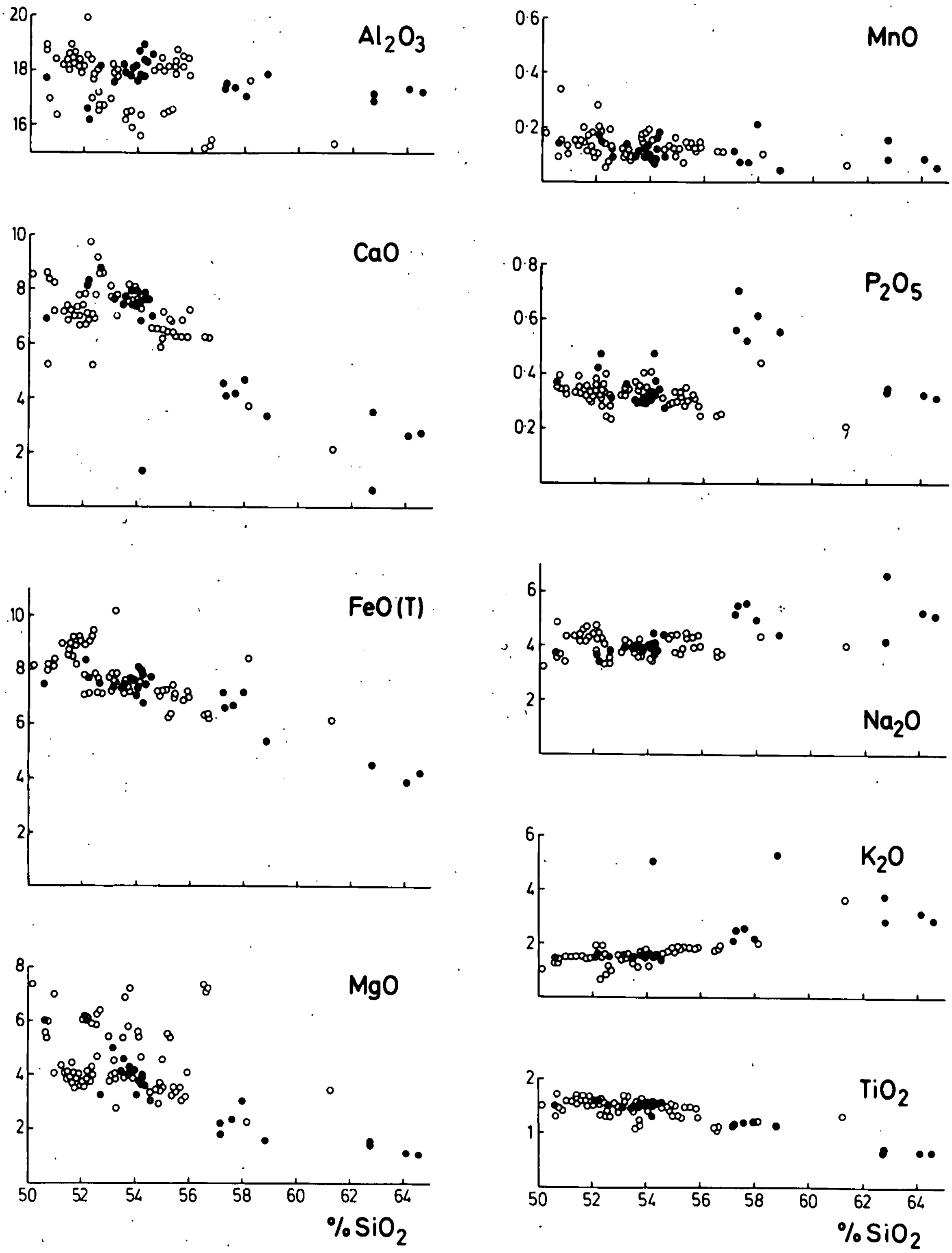

Sr
3%
ILMENITE
1200
1000
800
600
400
200
Rb
ILMENITE
120
80
40
Zr
ILMENITE
500
400
300
200
100
Y
ILMENITE
80
40
La
ILMENITE
60
40
20
Ce
ILMENITE
120
80
40
36
40
44
48
52
56
60
64
% SiO2
Ba
3%
ILMENITE
1000
800
600
400
200
Zn
ILMENITE 3%
300
200
100
Cu
3%
ILMENITE
60
40
20
Ni
3%
OLIVINE
ILMENITE
400
300
200
100
Cr
3%
OLIVINE
ILMENITE
400
300
200
100
V
ILMENITE
3%
300
200
100
36
40
44
48
52
56
60
64
% SiO2

FIG. 5-5

Illustration of the effect of cumulus enrichment (major elements)

o Cumulus enriched lavas (> 5% phenocrysts)

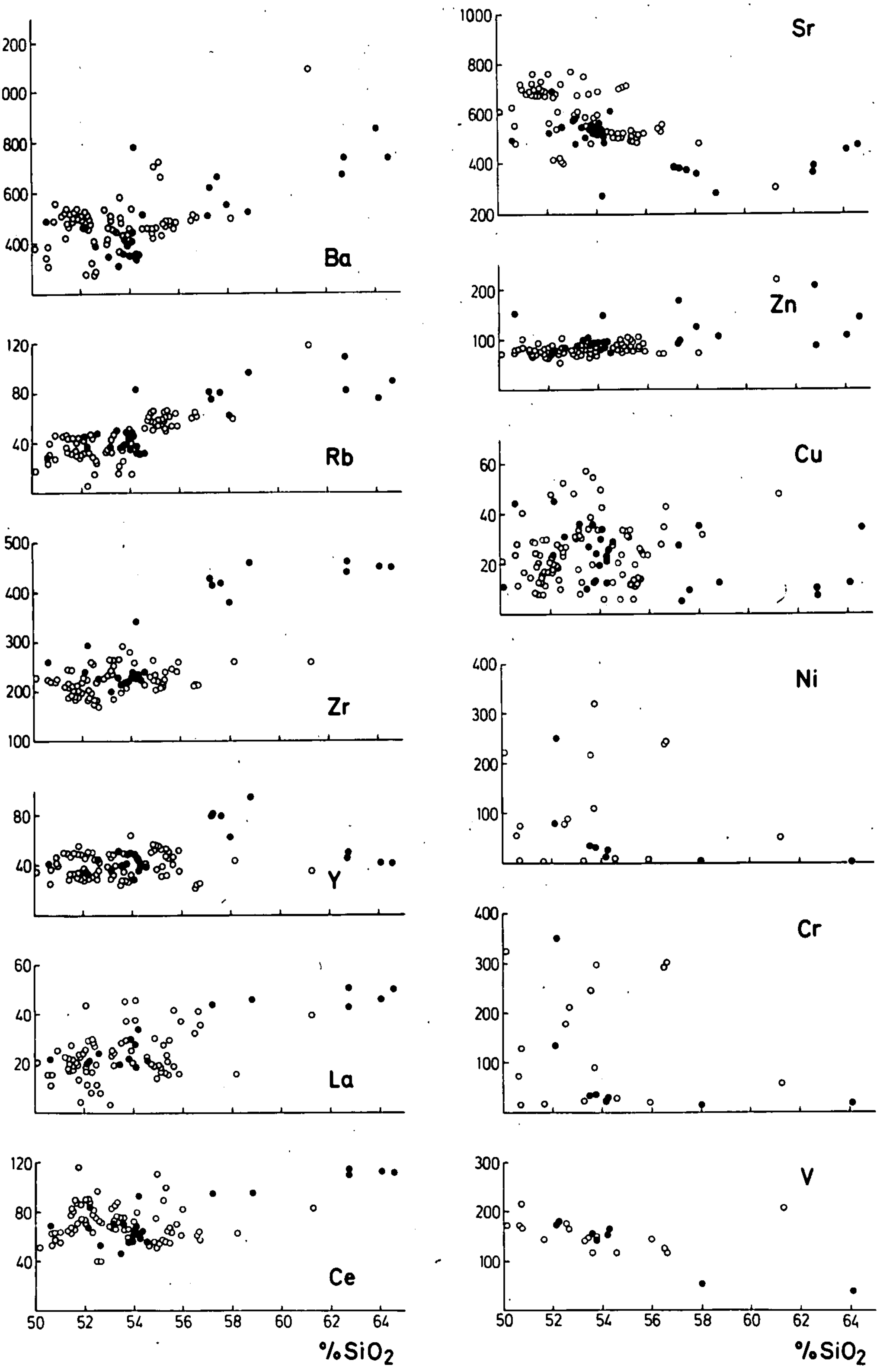
● Non-cumulus enriched lavas (< 5% phenocrysts)


Al$_2$O$_3$
20
18
16
CaO
10
8
6
4
2
FeO(T)
10
8
6
4
2
MgO
8
6
4
2
50
52
54
56
58
60
62
64
% SiO$_2$
MnO
0·6
0·4
0·2
P$_2$O$_5$
0·8
0·6
0·4
0·2
Na$_2$O
6
4
2
K$_2$O
6
4
2
TiO$_2$
2
1
50
52
54
56
58
60
62
64
% SiO$_2$

<u>FIG. 5-6</u>

Illustration of the effect of cumulus enrichment (minor elements)

Symbols as for FIG. 5-5


1200
1000
800
600
400
Ba
120
80
40
Rb
500
400
300
200
100
Zr
80
40
Y
60
40
20
La
120
80
40
Ce
50
52
54
56
58
60
62
64
%SiO2
1000
800
600
400
200
Sr
200
100
Zn
60
40
20
Cu
400
300
200
100
Ni
400
300
200
100
Cr
300
200
100
V
50
52
54
56
58
60
62
64
%SiO2

alone will not explain the variation in lava chemistry, but when it is considered in combination with olivine, plagioclase and ilmenite, it is possible that the magmatic trends could be accounted for. However, the amount of clinopyroxene in the non-cumulus enriched lavas is very small and it occurs in only one lava. Thus, it is concluded that if clinopyroxene had fractionated, it was of minor importance.

5:5 Summary

It is considered that fractionation of olivine, plagioclase and ilmenite (with possible minor clinopyroxene) could satisfactorily account for the chemical variation in the non-cumulus enriched lavas, and that the scatter in the whole rock variation diagrams is a function of:-

1) Slight variability in the cumulus enrichment process. Some samples have more than average contents of plagioclase whilst others have more than average contents of olivine phenocrysts.
2) Wide range of immediately parental magmas.

It is important to note that the present data do not disprove the simple straightforward Low Pressure crystal fractionation/accumulation model.

Other models, for example involving amphibole fractionation have been considered, but in view of the above, it is impossible to decide whether they any importance.

CHAPTER 6

EXPERIMENTAL MELTING DATA

6:1 Introduction

In Chapter 5, it was suggested that the fractionation of olivine, plagioclase and ilmenite could explain the observed chemical variation in the Sidlaw lavas. In this Chapter the possible pressure regime in which this fractionation took place is discussed with reference to melting data for selected lavas from the Sidlaw Hills.

6:2 Melting Studies

6:2:1 Introduction

The problems of basalt-magma genesis have led petrologists to consider the implications of phase equilibria studies on silicate systems. Though simple silicate melting studies have provided a foundation on which to base theories of magma evolution, these silicate systems suffer from the drawback of lacking many important constituents of natural rocks.

However, attempts were made by BOWEN (1914, 1928) to relate the phase relations in more complex synthetic systems such as $CaMgSi_2O_6$ - Mg_2SiO_4 - $CaAl_2Si_2O_8$ - SiO_2 to the features observed in basic igneous rocks, though it can be seen from this system that only 4 major oxides are included. As more oxides are added to synthetic systems deductions concerning the phase relations within natural compositions become less speculative.

Experimental/

Experimental melting studies on natural basalts have aided greatly in understanding phase relations, and crystallisation behaviour, within this complex multi-component basaltic system. The basaltic compositions used in most of these melting experiments by YODER and TILLEY (1962), TILLEY, YODER and SCHAIRER (1963, 1964, 1965, 1966) were tholeiitic basalts from Hawaii, Japan, and Iceland, though a high alumina basalt from Medicine Lake, in the United States, and high-alumina basalt, basaltic andesite, and hypersthene andesite lavas from Paricutin in Mexico have also been studied.

Recently BROWN and SCHAIRER (1967, 1971) reported the melting relations of a series of calc-alkaline lavas from the Solomon Islands, and the West Indies. It is clear from these studies on natural lavas, that phase relationships determined are more valid than for synthetic "simple" systems, though synthetic studies are still of considerable value in defining probable phase equilibria.

Ten lavas from the Sidlaw Hills, ranging from olivine basalt to hypersthene andesite were selected for melting experiments at 1 atmosphere pressure, and the techniques employed are presented in Appendix (B). Experimental run data are presented in Appendix (B). All analyses of lavas from the Sidlaws have been recalculated with all iron as FeO, since the conditions under which melting was conducted were totally reduced.

6:3 Atmospheric Pressure Studies

The chemical compositions and the C.I.P.W. norms of the Sidlaw lavas used in melting experiments are presented in TABLE 6-1 and TABLE 6-2 respectively. Since these analyses have been recalculated with all Fe as FeO,/

<u>TABLE 6-1</u>

Chemical composition of Sidlaw lavas used in melting experiments

	M1	M20	M24	M32	M34	M39	M44	M61	M87	M96
SiO_2	54.65	52.18	50.11	51.63	53.26	50.69	51.72	55.18	52.48	56.69
TiO_2	1.60	1.59	1.53	1.66	1.67	1.73	1.64	1.32	1.30	1.09
Al_2O_3	18.03	16.19	15.97	18.64	17.78	18.89	18.32	16.46	17.15	15.42
FeO	7.79	7.67	8.11	9.14	10.13	7.92	8.15	6.21	7.08	6.18
MnO	0.12	0.15	0.18	0.11	0.08	0.34	0.17	0.07	0.19	0.11
MgO	3.42	6.07	7.34	4.44	2.72	5.30	3.43	5.49	5.80	7.23
CaO	6.43	8.30	8.50	6.99	7.01	5.21	7.28	6.80	9.10	6.15
Na_2O	4.43	3.40	3.24	4.14	4.17	4.90	4.64	3.65	3.30	3.61
K_2O	1.70	1.62	1.04	1.53	1.46	1.42	1.48	1.88	0.85	1.84
H_2O	1.52	2.29	3.03	1.30	0.74	2.85	1.33	1.49	2.00	1.08
P_2O_5	0.33	0.47	0.32	0.34	0.34	0.34	0.34	0.33	0.24	0.25
TOTAL	100.02	99.93	99.37	99.92	99.36	99.59	98.50	98.88	99.49	99.65
$\frac{FeO}{FeO+MgO}$	0.695	0.558	0.525	0.673	0.788	0.599	0.704	0.531	0.550	0.461

TABLE 6-2

C.I.P.W. norms of Sidlaw lavas of TABLE 6-1

	M1	M20	M24	M32	M34	M39	M44	M61	M87	M96
Q	-	-	-	-	-	-	-	2.60	0.52	2.82
C	-	-	-	-	-	0.65	-	-	-	-
Or	10.20	9.80	6.38	9.17	8.75	8.67	9.00	11.40	5.15	11.03
Ab	33.05	29.46	28.45	35.51	35.77	42.38	40.37	31.71	28.64	30.99
An	24.66	24.71	26.94	28.14	25.84	24.42	25.51	23.59	30.23	20.73
Ne	-	-	-	-	-	0.25	0.01	-	-	-
Di	4.63	11.74	11.98	3.98	6.10	-	7.86	7.22	11.87	6.95
Hy	18.39	15.50	12.05	6.37	18.12	-	-	20.11	20.48	24.79
Ol	-	4.56	10.40	12.82	1.39	19.39	13.22	-	-	-
Ilm	3.08	3.09	3.02	3.20	3.22	3.40	3.20	2.57	2.53	2.10
Ap	0.79	1.14	0.79	0.82	0.82	0.83	0.83	0.80	0.58	0.60
D.I	48.44	39.26	34.83	44.68	44.52	51.31	49.39	45.71	34.31	44.84

FeO, two lavas M39, and M44 are slightly nepheline normative. The remaining lavas are either olivine-hypersthene or quartz-hypersthene normative.

The liquidus phase, the order of appearance of mineral phases and their approximate temperatures of appearance are given in TABLE 6-3. Olivine is the liquidus phase in only two lavas, both of which can be described as olivine basalts and contain only olivine as phenocrysts. Clinopyroxene was the third phase to crystallise in 8 of the lavas and was not found in the lowest temperature runs for the other two. The order of appearance of clinopyroxene is in agreement with the data on high-alumina basalt of YODER and TILLEY (1962). Since the phases crystallising in the melting experiments on the lavas from the Sidlaw Hills correspond closely with their petrography in the case of olivine and plagioclase, and occasionally in the case of clinopyroxene it is likely that the observed phenocrysts in the lavas have a low pressure origin, and that in most cases the lavas were erupted before the incoming temperature of clinopyroxene was reached.

FIG 6-1 illustrates the lack of rational relationship between iron enrichment and liquidus temperature. However, a linear trend should not necessarily result in this diagram as different liquidus phases occur, and more than one phase is causing fractionation. Superimposed on to this diagram is the liquidus temperature - iron enrichment trend of continental margin calc-alkaline series from YODER (1969), TILLEY, YODER and SCHAIRER (1966) and it can be seen that in general the liquidus temperatures for a given FeO/FeO + MgO ratio are the same value for both the Sidlaw lavas and the temperature of appearance of plagioclase as a liquidus phase in the Sidlaw lavas corresponds closely to the continental margin calc-alkaline series.

The change of liquidus phase in calc-alkaline lavas has been discussed

by/

TABLE 6-3

Liquidus phase and order and temperature of appearance of phases in experimental runs

SAMPLE	HIGHEST TEMPERATURE OF CRYSTALLISATION OF PHASES
M1	PL(1190°), OL(1150°), CPX(1105°)
M20	PL(1190°), OL(1190°), CPX(1150°)
M24	OL(1225°), PL(1190°), CPX(1150°)
M32	PL(1190°), OL(1170°), CPX(1105°)
M34	PL(1190°), OL(1130°)
M39	PL(1190°), OL(1150°), CPX(1150°)
M44	PL(1210°), OL(1150°), CPX(1130°)
M61	PL(1190°), OL(1190°), CPX(1150°)
M87	PL(1210°), OL(1190°), CPX(1150°)
M96	OPX(1200°)

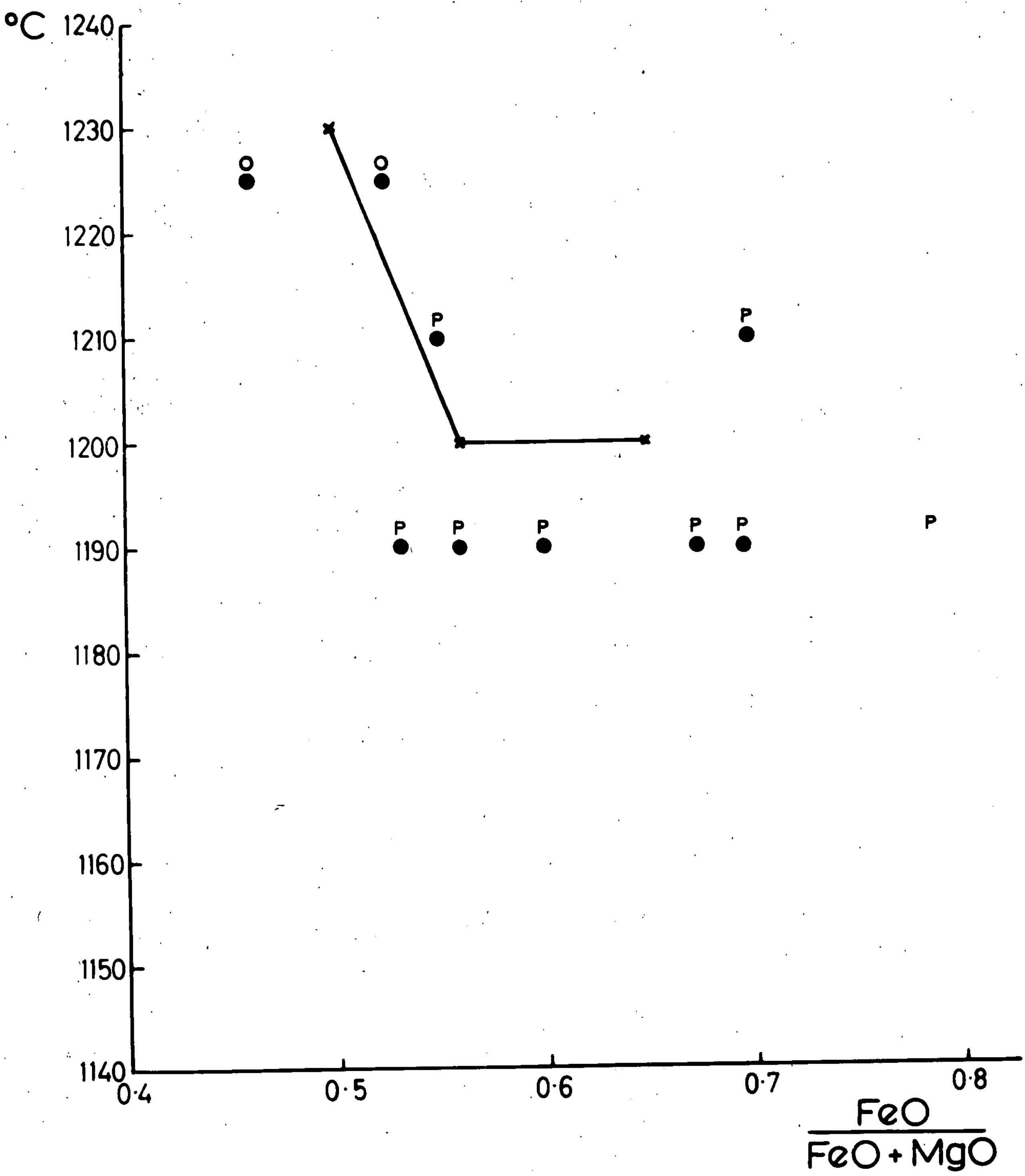
Temperatures ± 10°C

FIG. 6-1

Plot of iron enrichment vs. liquidus temperature for experimentally melted Sidlaw lavas

P = Plagioclase liquidus
O = Olivine liquidus

Superimposed trend from YODER (1969)


°C
1240
1230
1220
1210
1200
1190
1180
1170
1160
1150
1140
0·4
0·5
0·6
0·7
0·8
$\frac{FeO}{FeO + MgO}$
O
O
P
P
P
P
P
P
P
P

by YODER (1969), who concluded that the presence of water in the lava delayed the incoming of plagioclase. This conclusion is particularly important when considering the behaviour of M20 (see TABLE 6-1) which has modal olivine phenocrysts only, but has both olivine and plagioclase on the liquidus at 1190°C. The presence of modal olivine phenocrysts only, and plagioclase co-existing with olivine on the liquidus in this lava suggests that olivine is the true liquidus phase at the point of origin, and that substantial amounts of water may have been present during the crystallisation of M20 on its way to the surface.

The relationship between the temperature of appearance of olivine either as liquidus phase or 'second' phase to crystallise and the MgO content of the lavas is shown in FIG 6-2.

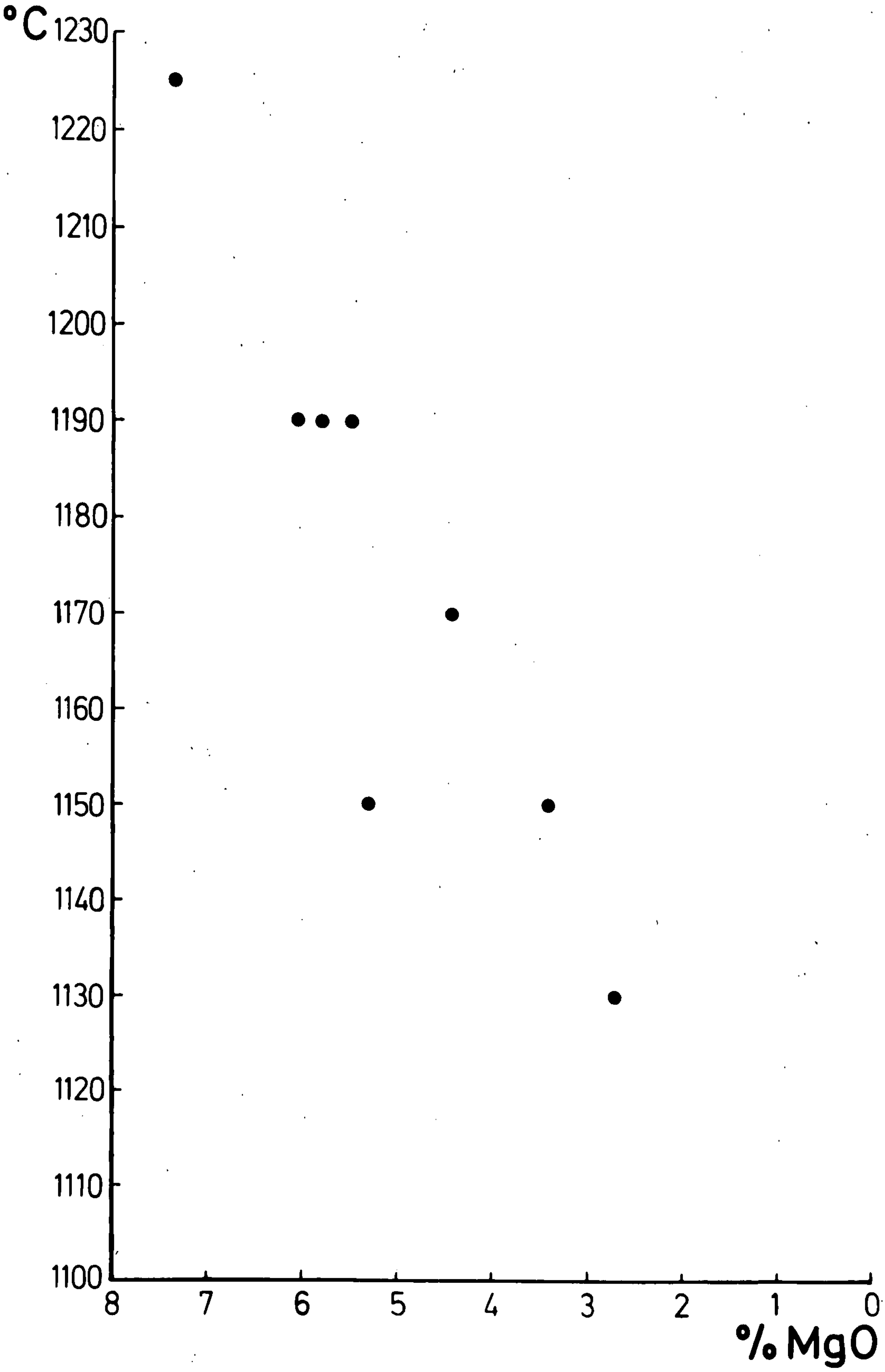
6:4 Elevated Pressure Studies

From TABLE 6-3 it can be seen that the liquidus temperatures of the lavas of the Sidlaw Hills at 1 atmosphere pressure are all greater than 1190°C, a value which is considerably higher than that observed in nature for calc-alkaline lavas from Paricutin (1080°C) reported by FOSHAG and GONZALES (1954). BROWN and SCHAIRER (1967, 1971) have reported reduction of the liquidus temperature of calc-alkaline lavas from St. Kitts, and St. Lucia in the West Indies by as much as 200°C by melting of the lavas under hydrothermal conditions at 2 kb water pressure. The liquidus temperature found under the higher pressure conditions were in the range 1010° - 1050°, values very much in agreement with FOSHAG and GONSALES (1954).

Preliminary runs at 2 kb water pressure have been made on the Sidlaw lavas/

FIG. 6-2

Relationship between temperature of appearance of olivine and MgO content of lavas


°C
1230
1220
1210
1200
1190
1180
1170
1160
1150
1140
1130
1120
1110
1100
8
7
6
5
4
3
2
1
0
% MgO

lavas M24 and M39 (see TABLE 6-1), and the results are given in TABLE 6-4. Several important points emerge from this study. The liquidus temperatures are reduced considerably, and it can be seen that in the case of M39, the liquidus has not been reached even at 1000°C. The suppression of the temperature of crystallisation of plagioclase in M24 is in agreement with the data of YODER and TILLEY (1962) for high alumina basalt. Buffering of runs was achieved by using a mixture of Wüstite/Magnetite, and a description of techniques is presented in Appendix (B). The experimental run data is tabulated in Appendix (B).

6:5 Summary

The close correspondence between the observed phenocryst assemblages and the order of appearance of phases in the melting experiments at 1 atmosphere pressure suggest that fractionation in the Sidlaw lavas was a low pressure phenomenon, and probably took place in the presence of water. The importance of olivine-plagioclase fractionation and the relative unimportance of clinopyroxene fractionation (see Chapter 5) is confirmed.

TABLE 6-4

Experimental results from 2 kb melting

	TEMP	PHASES RECORDED
M24	1147	LIQUID
	1098	LIQUID + OLIVINE + SPINEL
	1047	LIQUID + OLIVINE + CLINOPYROXENE
	1000	LIQUID + OLIVINE + CLINOPYROXENE + PLAGIOCLASE
M39	1147	LIQUID
	1098	LIQUID
	1047	LIQUID
	1000	LIQUID

Wüstite/Magnetite Buffer

Temperatures ± 10°C

CHAPTER 7

GENERAL ASPECTS OF PETROGENESIS

7:1 Introduction

Petrologists have for many years been aware of the problems associated with the genesis of calc-alkaline magmas, and many theories have been proposed for their origin. Before the advent of extensive phase-equilibria and melting studies, theories on the origin of calc-alkaline magmas could be grouped into three main categories, which have been outlined by BEST (1969). These are listed below.

1) Mixing of Magmas:

This theory was proposed by LARSEN et. al. (1938) to explain the formation of the lavas of the San Juan volcanic province. However, the mechanism of magma mixing is unlikely to be of importance since Strontium isotope data, and trace element data in general suggest mantle derivation of calc-alkaline magmas, and preclude the possibility of mixing of magmas.

2) Crustal Anatexis:

The hypothesis of anatexis in the formation of calc-alkaline magmas suffers from several drawbacks. Partial melting of crustal material is likely to produce moderately siliceous liquids and would fail to provide sufficient basaltic material. BEST (1969) has pointed out that the order of emplacement of plutonic calc-alkaline rocks is the reverse from that which would be expected if anatexis had operated. Strontium isotope/

isotope studies by TAYLOR and WHITE (1965) and TAYLOR (1969) indicate a mantle origin for the calc-alkaline magmas. TAYLOR (1969) has shown that trace element data, and geophysical data do not support theories of anatexis.

3) Assimilation of Crustal Material:

As with anatexis, isotopic and trace element studies by TAYLOR (1969), do not support theories of assimilation proposed by HOLMES (1932) and TURNER and VERHOOGEN (1960).

Studies on synthetic compositions and systems, and more recently on natural compositions, have provided much needed information relating to the genesis of calc-alkaline magmas. Consequently numerous hypotheses concerned with the origin of calc-alkaline magmas have produced, many of which propose a mantle origin. O'HARA (1965, 1968), YODER (1965, 1966, 1969), and KUSHIRO (1972) have shown that the initial partial melting products of Upper Mantle Peridotite under water saturated conditions up to 25 kb are quartz normative and rich in alumina. With increasing degrees of partial melting, or with gradual loss of water, the liquid in equilibrium with the peridotite changes its composition and becomes less silicic.

OSBORN (1959, 1962) proposed derivation of the calc-alkaline lava series by fractional crystallisation of high-alumina basalt under hydrous conditions and a high partial pressure of oxygen. OSBORN has shown from work on the MgO-FeO-Fe_2O_3-SiO_2 that if a magma crystallises as a closed system, the residual liquids will become strongly enriched in iron, and the partial pressure of oxygen will drop. If, however, the partial pressure of oxygen is buffered, magnetite precipitation will result, leaving a residual liquid depleted in iron, and more akin to calc-alkaline liquids. The above 4-component/

4-component system investigated by OSBORN (1959, 1962) suffered from lack of basaltic components, though by the addition of CaO and Al_2O_3, and later Na_2O, OSBORN (1969) achieved more appropriate results. Fractional crystallisation of olivine, plagioclase, clinopyroxene, and magnetite from an olivine basalt with concomitant gain of water and loss of hydrogen from the system, could produce andesitic liquids (Osborn pers. Comm.). However, the general hypothesis is not supported on geochemical grounds by TAYLOR (1969). Similarly, there is no geophysical evidence from regions of calc-alkaline volcanism which supports large scale precipitation of magnetite.

GREEN and RINGWOOD (1966) have suggested a quartz eclogite parental material for calc-alkaline magmas and argued that partial melting of the quartz eclogite at pressures of about 30 kb might produce a dry andesite. More recently, JAKEŠ and SMITH (1970) proposed partial melting of mantle material in which a low melting-point mica phase was involved, coupled with fractionation of hydrous minerals such as amphibole and mica to explain the evolution of the potassium-rich calc-alkaline lavas of New Guinea.

The role of amphibole fractionation in the genesis of calc-alkaline magmas has been discussed by HOLLOWAY and BURNHAM (1972) who show a close correspondance between the compositions of experimental liquids and natural hornblende andesites, and conclude that derivation of evolved calc-alkaline lavas from a tholeiitic basalt is a plausible mechanism.

It is likely, that no single hypothesis will be sufficient to explain each calc-alkaline province owing to the considerable chemical variation between provinces.

7:2 Genesis of the Sidlaw Lavas/

7:2 Genesis of the Sidlaw Lavas

TAYLOR (1969) has pointed out that unlike alkali or tholeiitic lavas, calc-alkaline lavas are not found in ocean basins or in shield volcanic regions, and hence, derivation of calc-alkaline magmas by a single process from the mantle is unlikely. TAYLOR also points out that trace element data on calc-alkaline magmas are consistent with a multiple stage derivation from the upper mantle. The contents of Ni and Cr are very low in many of the basaltic andesites and andesites from the Sidlaw Hills, though in the basalts, the concentrations of these elements are variable. As shown in Chapter 4, it is unlikely that removal of olivine and plagioclase from the most basic liquid could account for such a rapid depletion of Ni and Cr in the basalts, and cause virtually no depletion in the range basaltic-andesite to dacite. This, according to the argument put forward by TAYLOR (1969), would tend to favour multiple stage derivation of the Sidlaw lavas from the upper mantle.

Production of silicic high alumina liquids by hydrous partial melting of upper mantle garnet lherzolite has been recognised by O'HARA (1965, 1968), YODER (1969), and KUSHIRO (1972) as a possible mechanism for the generation of andesitic and dacitic calc-alkaline lavas, and they all note that more basic liquids could be produced by either advanced partial melting or by loss of hydrous conditions. Thus it seems likely that in formation of aluminous basic liquids, the role of water content must be an important consideration. However, it was noted in Chapters 1 and 2 that the amount of water in the erupted magmas may not have been too large, since pyroclastic deposits and hydrous minerals are apparently absent from the Sidlaw lava sequence.//

sequence. Consequently, theories of origin of the Sidlaw lavas by both dry and wet partial melting of upper mantle garnet lherzolite will be outlined.

YODER (1969) has demonstrated that under hydrous conditions, the initial partial melt product of a peridotite (olivine + clinopyroxene + orthopyroxene) at 20 kb will be a liquid which if separated would crystallise as the assemblage clinopyroxene + orthopyroxene + quartz. YODER goes on to suggest that if this initial liquid was erupted, a calc-alkaline andesite could result, though O'HARA (1965, 1968), YODER (1969), and KUSHIRO (1972) have indicated that this liquid would be siliceous, and likely to crystallise as andesite or dacite. Owing to the comparitive rarity of andesites and dacites in the Sidlaw lava sequence, it is concluded that this process may not have been of great importance in this area.

Dry partial melting of a four phase garnet lherzolite at 20 kb and 1640°C has been shown by YODER (1969) and KUSHIRO (1972) to yield a liquid which would crystallise as olivine and sub-calcic augite, though if this liquid was erupted, it would most likely crystallise as an olivine tholeiite. Its normative olivine content would depend greatly on the degree of partial melting which takes place. O'HARA (1968) has pointed out, that the first liquid produced by dry partial melting of upper mantle peridotite is likely to be picritic and that olivine will fractionate on ascent of this picrite to produce an olivine tholeiite. This production of olivine tholeiite is accepted as a possible first stage in the formation of the Sidlaw lava sequence.

KUSHIRO (1972) has shown that fractionation of olivine and clinopyroxene from an olivine tholeiite will give rise to aluminous liquids under hydrous conditions/

conditions at 13-15 kb, and it is likely that this mechanism could operate at lower pressures. YODER and DICKEY (1971) demonstrated that with increasing water pressure, the orthopyroxene primary phase volume diminishes at the expense of the clinopyroxene and plagioclase volumes, though the clinopyroxene volume does expand to a certain extent relative to plagioclase. Data on M24, the most basic lava composition in the Sidlaw sequence, shows that at 2 kb water pressure, the plagioclase liquidus is suppressed with clinopyroxene being the second rather than third phase to crystallise. This feature has also been observed by YODER and TILLEY (1962). Thus, it is concluded that water pressure will delay plagioclase crystallisation. Derivation of high-alumina basalt from the olivine tholeiite by hydrous fractionation of olivine and clinopyroxene is accepted. It was noted above that formation of an olivine tholeiite from the upper mantle required dry partial melting of garnet lherzolite. Upward migration of this olivine tholeiite liquid to a region where water may be able to control the fractionation is necessary. Such a zone where water becomes an important accessory may be the base of an orogen containing wet sediments or a region of deep faulting allowing entry of water into the system.

The low water pressures envisaged above for the derivation of the high-alumina basalt from the olivine tholeiite as a precursor to the low pressure differentiation of the Sidlaw sequence, tend to support the apparent lack of pyroclastic deposits and hydrous minerals. HOLLOWAY and BURNHAM (1972) and CAWTHORN (pers. comm.) have demonstrated that amphibole crystallisation takes place at fairly low water pressures, and thus it is concluded that if olivine tholeiite is the immediately parental magma of the Sidlaw lava sequence, derivation of high-alumina basalt from that parent took place at shallow/

shallow depths possibly less than 10 km.

One of the most important considerations of any petrogenetic scheme is to test whether the parent/daughter chemical relationships are valid. This can only be done in a most approximate way, but it is worthwhile to check that the idea is not totally implausible. For this purpose, major element data for a range of olivine tholeiites have been taken from TURNER and VERHOOGEN (1960), MANSON (1967) and JAMIESON and CLARKE (1970). The chemical composition of the high-alumina basalt has been taken from the most basic lava in the sequence from the Sidlaw Hills. FIG 7-1 shows the major element relationships between the postulated olivine tholeiite compositional range and the high-alumina basalt. Olivine (Fo_{70}) and clinopyroxene (from Chapter 3) composition points have been added to each variation diagram. It can be seen that extraction of approximately 40% olivine and 60% clinopyroxene from the olivine tholeiite compositions could account for the major element chemistry of the high-alumina basalt. Trace element relationships have not been considered since the trace element contents of the olivine, clinopyroxene, and olivine tholeiites are not known in detail. How the range of high-alumina basalt liquids (see Chapter 5) can be produced is not clear though fluctuating proportions of olivine and clinopyroxene could partially account for it.

7:3 Petrogenetic Summary

The following petrogenetic scheme is envisaged as a series of possible mechanisms for production of the Sidlaw lava sequence.

1) Dry partial melting of upper mantle garnet lherzolite to produce picritic/

FIG. 7-1

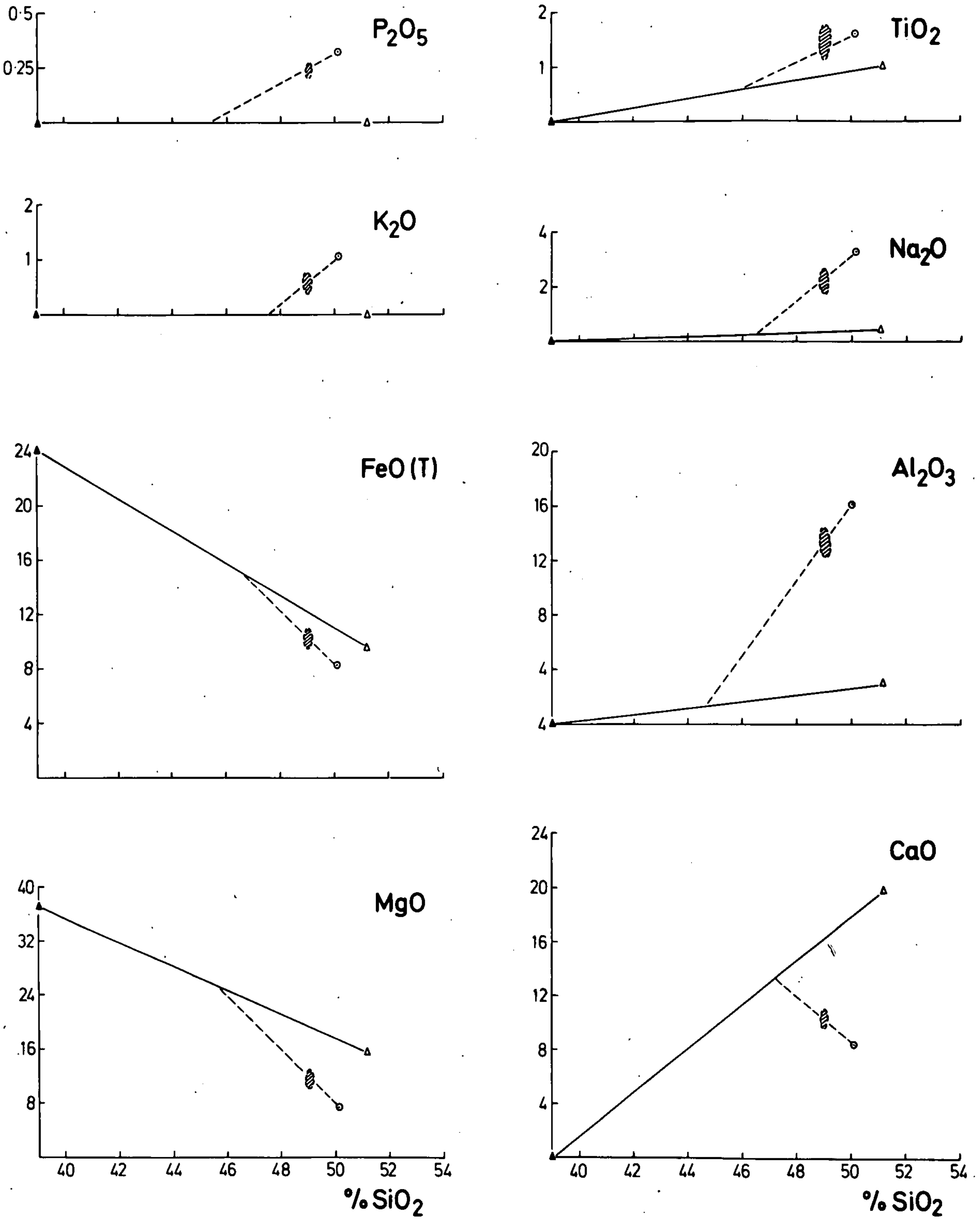
Extract diagram illustrating the proposed derivation of high alumina basalt from olivine tholeiite

▨ = Ol tholeiite compositional range

▲ = Olivine

△ = Clinopyroxene

⊙ = High Alumina Basalt (M24)



P$_2$O$_5$
0·5
0·25
TiO$_2$
2
1
K$_2$O
2
1
Na$_2$O
4
2
FeO (T)
24
20
16
12
8
4
Al$_2$O$_3$
20
16
12
8
4
4
MgO
40
32
24
.16
8
CaO
24
20
16
12
8
4
40
42
44
46
48
50
52
54
% SiO$_2$
40
42
44
46
48
50
52
54
% SiO$_2$

picritic liquid.

2) Upward migration of this picritic liquid with concomitant loss of olivine to give rise to an olivine tholeiite.

3) Low to moderate pressure wet fractionation of olivine and clinopyroxene from the olivine tholeiite giving a range of high alumina basaltic liquids.

4) Medium to low pressure fractionation of olivine + plagioclase + ilmenite + very minor clinopyroxene from the high alumina basalts to give the observed lava sequence of the Sidlaw Hills.

CHAPTER 8

SIDLAW LAVAS IN RELATION TO PLATE TECTONICS

8:1 Introduction

Though there is very little geophysical data connected with the origin of the Lower Old Red Sandstone lavas of Scotland, it is necessary to review the current theories on the geophysical evidence related to calc-alkaline magma genesis in order to relate the Lower Old Red Sandstone volcanicity to the structural evolution of the Caledonides.

In the last decade, attention has been paid to the possibility that andesite volcanism may be related to a zone of seismic activity dipping towards the continents from a region on the continental side of a geosynclinal trench. This zone of seismic activity was first recognised by BENIOFF (1954), though only recently have the implications of its connection with andesite volcansim been recognised. RAYLEIGH and LEE (1969), amongst many others, have discussed the possible relationships between calc-alkaline volcanism and earthquake zones produced during subduction of oceanic plate down a Benioff zone.

8:2 Evolution of the Caledonides

DEWEY and PANKHURST (1970), and DEWEY (1971) have outlined models for the evolution of the Scottish Caledonides based on isotopic age patterns, and structural and stratigraphic relationships. The above authors concluded that/

that the presence of a northwards dipping Benioff zone beneath the Midland Valley of Scotland could explain the observed magmatic sequence in the area. The exact location of the trench where oceanic plate was consumed is in doubt, though DEWEY (1971) proposed a trench along the present northern boundary of the Southern Uplands.

In contrast, FITTON and HUGHES (1970) have suggested that a southerly dipping Benioff zone of Ordovician age could explain the evolution of the tholeiitic, calc-alkaline, and alkalic volcanic suites of the Lake District and Wales, and propose that the trench should be located in the Moffat region. By accepting the theories proposed above, it is tempting to conclude that the magmatic variation within the Caledonides could be explained by two Benioff zones, a conlusion which would require the approach of two continental land masses with associated consumption of oceanic plate. DICKINSON and HATHERTON (1967, 1969) have demonstrated that the potassium contents of lavas increase with distance away from the oceanic trench, and hence increase with increased depth of consumed oceanic plate beneath the volcanic centre. The feature applies only to those lavas apparently associated with subduction of oceanic plate. The potassium contents of the Lower Old Red Sandstone basalts ($< 53\%$ SiO_2) in Scotland is rather variable as shown in TABLE 8-1, although data at present available are very few for most areas.

On the basis of the uncertainty concerning K_2O contents of the lavas, and the fact that a subduction zone in the Southern Uplands as envisaged by DEWEY and PANKHURST (1972) and DEWEY (1971) would not take account of the Cheviot lavas (since they would have been generated on top of oceanic plate) it is concluded that, it would be premature to postulate the existance/

TABLE 8-1

K_2O contents of basalts of Lower Old Red Sandstone age from various lava sequences in Scotland

Locality	Range in K_2O	No. of analyses
Sidlaws	0.6 - 2.0	37
Ochils	1.3 - 2.0	4
Ayrshire	1.51	1
Stonehaven	2.34	1
Lorne	2.10	1
Pentland Hills	1.0 - 3.0	2

existance of a Benioff zone to explain the Lower Old Red Sandstone lavas of Scotland.

ACKNOWLEDGEMENTS

I am indebted to my supervisor, Dr. K. G. Cox for suggesting this project and for his helpful advice on many of the problems associated with it. I am especially grateful to him for much valuable discussion and constructive criticism of the thesis manuscript.

For much useful criticism and discussion I should also like to thank Professor M. J. O'Hara, Drs B. G. J. Upton, K. R. Gill, G. M. Biggar and Mr. R. G. Cawthorn.

I wish to thank Mr. I. B. Paterson of the Institute of Geological Sciences for providing field maps of the Sidlaw Hills, and for much useful discussion of the problems involved with sample collection.

Analyses of lavas were carried out under the expert guidance of Messrs G. R. Angell and M. J. Saunders.

The assistance of Professor M. J. O'Hara, Dr. G. M. Biggar, and Messrs C. E. Ford and D. J. Humphries with experimental petrological techniques is gratefully acknowledged.

I am very grateful for the assistance of Mr. Colin Chaplin and his technical staff, especially Miss Margaret Muir, and Mr. Ian Bowler who helped with diagrams and produced the photographs in this thesis respectively.

Dr. A. C. Dunham and Mr. F. Wilkinson of the Department of Geology, Manchester University, kindly provided electron microprobe analytical facilities, and I wish to thank them for their assistance.

I am very grateful to Professors F. H. Stewart and G. Y. Craig for placing the excellent facilities of the Grant Institute of Geology at my disposal.

My thanks are due to Miss Angela E. Bulloch for typing this thesis.

This work was carried out during the tenure of an N.E.R.C. Research Studentship (1969-1972).

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APPENDIX A

SAMPLE PREPARATION AND ANALYTICAL TECHNIQUES

A:1 Sample Preparation

A:2 X-ray Fluorescence Analysis

A:3 Wet Chemical Methods

A:4 Electron Microprobe Analysis

A:5 Optical Determinations

A:6 Modal Analysis

APPENDIX A

SAMPLE PREPARATION AND ANALYTICAL METHODS

A:1 Sample Preparation

Samples selected for analysis were washed in water and scrubbed with a hard brush in order to remove loose fragments and as much of the weathered surface as possible. After drying, the samples were split into small fragments (~ 2cm) using a Cutrock hydraulic rock splitter. Care was taken to remove weathered fragments, and those which showed signs of contamination from the rock splitter. This contamination was evident from small coatings of steel on the fragments. Since the lavas are fine grained and compact, very little powder was produced during sample splitting. As the lavas appeared to be homogeneous in thin section and hand specimen, large quantities of sample were not required.

The 2 cm sized chips were reduced to ~5 mm fragments using a STURTEVANT Jaw Crusher. The fine powder resulting from this initial crushing was retained. Final grinding of the samples was achieved using a steel TEMA disc mill. After grinding for 60 seconds, and sieving through nylon nets it was found that the powder grain size was less than -100 mesh, and sieving was discontinued.

STRONG (1970) has shown by contamination tests that Ni and Cr appear to be the main contaminants produced by grinding in a steel TEMA, and therefore samples selected for analysis of Ni and Cr were ground in a tungsten carbide TEMA disc mill. Although the WC TEMA contaminates the samples with small amounts/

amounts of W and Co, this does not affect the present study.

For separation of plagioclase phenocrysts, the rocks were ground to -15 mesh and the fine grains were passed through a magnetic separator at fairly low current. Repeated magnetic separation resulted in an impure plagioclase separate, though it was difficult to remove all impurities due to inclusions in the feldspar. The impure separate was ground to -100 mesh in a WC TEMA and the powder passed through the separator once more. Final purification was not achieved and impurities such as rutile, clinopyroxene, and altered olivine were estimated in one sample studied in detail (M83) by point counting to be 0.5%. 1% and 1% respectively.

A:2 X-Ray Fluorescence Analysis

A:2:1 Major Element Analysis

A fusion method of sample preparation for analysis of major elements was adopted in this study, and this method has been outlined by ROSE et. al. (1963). The absolute weight of fusion constituents used is not critical providing the ratio 1:1:8 of sample : La_2O_3 : $Li_2B_4O_7$ is maintained. The weights chosen in this study were 0.75 gms sample, 0.75 gms La_2O_5, and 6 gms $Li_2B_4O_7$ each constituent being dried thoroughly before use. The mixtures were placed in graphite crucibles and fused at 1050°C in a muffle furnace. After fusion, the glass beads were allowed to cool. Any bead which showed signs of incomplete fusion (indicated by white La_2O_3 on the surface) were discarded, and the fusion repeated. After the beads had cooled sufficently, they were placed in clean dried glass jars inside a dessicator. Finally their weights were made up to exactly 7.5 gms using dried $Li_2B_4O_7$, and the

samples/

samples were stored in firmly stoppered glass bottles. Before use, the glass beads were ground to -200 mesh in a WC TEMA. The powders were dried at 110°C, and just prior to analysis they were compressed into discs with a boric acid backing. Care was taken to achieve a smooth unbroken disc surface, any poor discs being discarded and replaced. This method of preparation reduces matrix effects and thus corrections for the matrix are not required. Another feature of this method is the linear relationship which results between fluorescent intensity and element concentration for all elements with an atomic number greater than 11.

The analyses were carried out using a Phillips PW1212 Automatic X-ray Fluorescence Spectrometer. The operating conditions for analysis of major elements are presented in TABLE A-1. Each of the major element oxides analysed by this technique was determined using a Cr tube, and the results were computed against standards (prepared and analysed by exactly the same techniques, as the samples) using a computer programme available in the Grant Institute of Geology. MnO was determined using a W tube. The standards used in this study were both U.S.G.S. standards (AGV-1, BCR-1) and Edinburgh University standards. These are shown in TABLE A-2 and the values used were those quoted by FLANAGAN (1969).

To estimate the precision of the XRF analyses, five fusions of M1 were prepared. The results of this precision test are presented in TABLE A-3. The precision data are compared with those given by APPLETON (1970).

A:2:2 Trace Element Analysis

Trace element determinations were carried out on the rock powder (ground

to/

TABLE A-1

Element and Line		Kv	mA	Crystal	Method	Counter	Time (secs)	Collimator	Vacuum
Si	K	60	24	PE	P	Flow	20	Coarse	Yes
Ti	K	60	24	PE	P	"	10	"	Yes
Al	K	60	24	PE	P	"	20	"	Yes
Fe	K	60	24	PE	P	Scint	20	"	Yes
Mg	K	40	32	KAP	P-B	Flow	100	"	Yes
Ca	K	40	24	PE	P	"	10	Fine	Yes
K	K	60	24	PE	P	"	10	"	Yes
P	K	60	24	PE	P-B	"	40	"	Yes

Method

P = Peak

B = Background

TABLE A-2

Standards for Major Elements

AGV-1	NBS 88a
BCR-1	NBS 98a
E1	629
E2	630
T1	KI B&C
N-357	520

TABLE A-3

Precision of Major Element Analyses

						Appleton (1970)	
	M	R	S	C	N	M	C
SiO_2	54.54	54.12-54.77	0.22	0.40	5	48.37	0.32
Al_2O_3	17.97	17.71-18.10	0.40	2.25	5	16.34	1.09
Fe_2O_3	8.69	8.61-8.91	0.21	2.38	5	8.74	0.93
MgO	3.32	2.88-3.46	0.15	4.46	5	4.45	1.85
CaO	6.52	6.36-6.71	0.12	1.87	5	9.73	0.26
K_2O	1.67	1.63-1.73	0.03	1.92	5	7.71	0.49
P_2O_5	0.29	0.29-0.31	0.02	6.90	5	0.48	3.40
TiO_2	1.52	1.43-1.60	0.07	4.67	5	0.81	1.11

M = Mean

R = Range

S = Standard Deviation

C = Coefficient of variation (%)

N = Number of determinations

to -100 mesh or less) using the PW1212 spectrometer. The powder was supported on mylar inside the spectrometer. Care was taken to ensure that sufficient sample was used since penetration by the X-rays is quite deep, and small amounts of powder might result in anomalous determinations. Ba, Sr, Rb, Y, Zn and Cu, were determined on all samples; La and Ce on most of the samples, and Ni, Cr, and V on selected samples. The operating conditions are presented in TABLE A-4 and the standards used in the determinations were AGV-1, BCR-1, GSP-1, G1, G2, DTS-1, T1, W1, SY2 most of which are U.S.G.S. standards. The standard values chosen were those quoted by FLANAGAN (1969), and are shown in TABLE A-5.

Precision tests were carried out on samples M1 (5 determinations), and the results of this test are presented in TABLE A-6.

A:3 Wet Chemical Methods

Ferrous iron was determined according to the method of WILSON (1955). The precision of FeO analyses is presented in TABLE A-7.

Na_2O was determined using an EEL flame photometer. The samples were dissolved in concentrated HNO_3 and HF and evaporated to dryness on a hotplate. This step is repeated once, and the sample finally taken into solution with dilute H_2SO_4. The sample solutions were diluted to give concentrations in the range 1-25 ppm Na_2O to correspond with standard solutions used. The exact concentration of Na_2O was determined by bracketing between two standard solutions. Interference by Ca was removed by using a double Na filter. The precision of Na_2O analyses is presented in TABLE A-8.

H_2O/

TABLE A-4

Element and Line		Kv	mA	Crystal	Method	Counter	Time (Secs)	Collimator	Vacuum
Ba	K	80	24	LiF	P/B	Scint	20	Fine	No
Sr	K	80	24	LiF	P/B	"	20	"	No
Rb	K	80	24	LiF	P/B	"	20	"	No
Zr	K	80	24	LiF	P/B	"	20	"	No
Y	K	80	24	LiF	P/B	"	20	"	No
Zn	K	80	24	LiF	P/B	"	40	"	No
Cu	K	80	24	LiF	P/B	"	40	"	No
La	K	80	24	LiF	P/B	Flow	40	"	Yes
Ce	K	80	24	LiF	P/B	"	40	"	Yes
Ni	K	80	24	LiF	P/B	"	40	"	Yes
Cr	K	80	24	LiF	P/B	"	40	"	Yes
V	K	80	24	LiF	P/B	"	40	"	Yes

TABLE A-5

Standards for Trace Elements

AGV-1
BCR-1
DTS-1
G1
G2
GSP-1
T1
W1
SY-2
NBS 1a
NBS 1011
NBS 1014

TABLE A-6

Precision of Trace Element Analyses

						Appleton (1970)	
	M	R	S	C	N	M	C
Ba	461	440-485	16.55	3.59	5	1291	1.7
Sr	522	494-585	33.07	6.33	5	1867	1.3
Rb	52	47-58	3.66	7.04	5	483	3.3
Zr	215	206-238	12.09	5.62	5	291	2.5
Y	43	36-52	6.24	14.51	5	57	6.9
Zn	78	75-84	3.19	4.09	5	62	5.7
Cu	13	6-20	4.49	34.50	5	-	-
La	23	21-25	2.86	12.40	4	-	-
Ce	53	48-59	4.80	9.10	4	-	-

H_2O was determined by a similar method to that proposed by SHAPIRO and BRANNOCK (1962) where 1 gm of sample is fused with 3 gms of flux (lead oxide/lead chromate) in a pyrex tube. The precision of this method is shown in TABLE A-9.

Sr was determined on the plagioclase separates by Atomic Absorption Spectroscopy in the presence of La_2O_3 and KCl using synthetic standards. The U.S.G.S. standard AGV-1 was used as a test for accuracy. The results of the Atomic Absorption determinations are compared with X-R-F results in TABLE A-10.

A:4 Electron Microprobe Analysis

The electron microprobe analyses of pyroxene presented in Chapter 3 were carried out at Manchester University under the supervision of Dr. A. C. Dunham and Mr. F. Wilkinson. The standards used in the determinations were both synthetic and natural compositions and the results were corrected both for machine drift and "dead-time".

The feldspar compositions of Chapter 3 were computed from partial analyses by electron microprobe for CaO and K_2O, using synthetic and natural feldspar standards. By using appropriate standard compositions, errors in the determination of unknown compositions are small (Dr. Dunham, pers. comm.). CaO and K_2O can be converted into Mol % Anorthite and Mol % Orthoclase directly.

A:5 Optical Determinations/

TABLE A-7

Precision of FeO determinations

						Appleton (1970)	
	M	R	S	C	N	M	C
FeO	3.55	3.52-3.58	0.019	0.54	5	4.19	1.01

TABLE A-8

Precision of Na_2O determinations

						Appleton (1970)	
	M	R	S	C	N	M	C
Na_2O	4.43	4.39-4.49	0.033	0.75	5	1.79	0.44

TABLE A-9

Precision of H_2O determinations

	M	R	S	C	N
H_2O	1.52	1.41-1.62	0.084	5.53	4

TABLE A-10

Accuracy of Sr determinations

	Flanagan (1969)	A.A. (This study)
AGV-1	657 ppm	665 ppm

	ppm Sr (A.A)	ppm Sr (XRF)
M60	1344	1440
M83	1201	1300

A:5 Optical Determinations

Determinations of the anorthite content of plagioclase were made using the Michel Levy method on a flat microscope stage and on a universal stage using the high temperature determinative curves of VAN DER KAADEN (1951), SLEMMONS (1962), BURRI, PARKER and WENK (1967), and MUIR (1955).

Refractive Indices of orthopyroxenes were determined on crushed grains in sodium light.

A:6 Modal Analysis

Data on the modal analysis was obtained by point counting on a Shadowmaster projection microscope. 2400 points were counted on each view of the sample slide. Additional determination on duplicate slides of about 25% of the specimens were carried out to obtain more representative modal analysis.

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APPENDIX B

EXPERIMENTAL PETROLOGY TECHNIQUES

B:1 Atomspheric Pressure Experiments

B:2 Elevated Pressure Experiments

APPENDIX B

EXPERIMENTAL PETROLOGY TECHNIQUES

B:1 Atmospheric Pressure Experiments

Samples selected for melting at 1 atmosphere pressure were ground to -325 mesh in a WC TEMA, to lessen the possibility of residual grains remaining after the runs. Approximately 10-15 mg of sample were placed in Mo tubes. The powder was tamped down and the tubes were left unsealed. They were loaded with open end upwards into a Pt carrier and run at various temperatures between 1050°C and 1225°C in an atmosphere of H_2/CO_2 for between 5 and 7 hours depending on the temperature. The runs were made under the supervision of D. J. Humphries. Calibration of temperatures were made using the melting points of Au and Li_2SiO_3 and errors were found to be ± 4°C at 1064° and ± 9.5 at 1208°.

After quenching, the capsules were opened. Care was taken to ensure that all the sample had been removed from the capsule in case crystal sinking in the liquids had occurred. The samples were examined optically in oil of known Refractive Index. As far as could be ascertained all the crystals observed in the 1 atmosphere runs were primary and not quench products.

The atmospheric pressure run data are presented in TABLE B-1.

B:2 Elavated Pressure Experiments

As with the atmospheric pressure experiments, selected powders were ground

to/

TABLE B-1

Atmospheric pressure melting data

TEMP (°C)	1224	1200	1180	1163	1147	1123	1100	1065
M1	GL	GL	GL+P	GL+P	GL+P+Ol	GL+P+Cl	GL+P+Ol+Cp	GL+P+Ol+Cp
M20	GL	GL	GL+P+Ol	GL+P+Ol	GL+P+Ol+Cp	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M24	GL+Ol	GL+Ol	GL+P+Ol	GL+P+Ol	GL+P+Ol+Cp	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M32	GL	GL	GL+P	GL+P+Ol	GL+P+Ol+Cp	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M34	GL	GL	GL+P	GL+P	GL+P	GL+P+Ol	GL+P+Ol	-
M39	GL	GL	GL+P	GL+P	GL+P+Ol+Cp	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M44	GL	GL+P	GL+P	GL+P	GL+P+Ol	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M61	GL	GL	GL+P+Ol	GL+P+Ol	GL+P+Ol+Cp	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M87	GL	GL+P	GL+P+Ol	GL+P+Ol	GL+P+Ol+Cp	GL+P+Ol+Cp	GL+P+Ol+Cp	-
M96	GL	GL+P	GL+OP	-	-	-	-	GL+P+OP+Cp

to -325 mesh. 2 mg of deionised water were syringed into a small Pt capsule. The capsule was then filled with 10-15 mg of sample. The top of the capsule was cleaned, crimped with pliers and welded with a carbon electrode. Care was taken to ensure that complete welding had occurred. The capsule was weighed, heated on a hotplate for 1 hour, and weighed again. Any capsules which lost weight were discarded and renewed. In order to buffer the partial pressure of water, a large Pt capsule was selected, filled with 10 mg of water, excess buffer mixture (either Wüstite/Magnetite or Ni/NiO), the sample capsule, and sealed by welding. Experimental runs at 2 kb were made using a Yoder Bomb (for a full description see FORD (1972)). The gas atmosphere used in the experiments was H_2/Ar, and the temperature was controlled and measure using Pt/Rh thermocouples. As with the atmospheric pressure experiments, temperature calibration was made using Au and Li_2SiO_3. After quenching, capsules were opened, and examined optically and by X-ray Diffraction. The buffer mixture was checked by X-ray Diffraction after each run to ensure that the required oxygen fugacity was maintained throughout the runs.

Quench crystals of mica were found in all runs. Other quench phases were apparent but these were distinguished from primary minerals partially by the crystal form. The assistance of Professor M. J. O'Hara and Mr. C. E. Ford with this distinction is gratefully acknowledged.

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TABLE B-2

Elevated pressure melting data

TABLE B-2

TEMP	PH_2O	M24	M39
1147	2 kb	Gl+Quench Mica above liquidus	Gl+Quench Mica above liquidus
1098	2 kb	Gl+Ol+Sp+Quench Mica LIQ+Ol+Sp	Gl+Quench Mica above liquidus
1047	2.1 kb	Gl+Ol+Cpx+Quench Mica LIQ+Ol+Cpx	Gl+Quench Mica above liquidus
1000	2 kb	Gl+Ol+Cpx+Pl+Amph? LIQ+Ol+Cpx+Pl	Gl+Quench Mica above liquidus

APPENDIX C

TABLES OF CHEMICAL DATA FOR SIDLAW LAVAS

TABLE C-1 Lava Analyses

TABLE C-2 Calculated Groundmass Analyses

TABLE C-3 Intrusive Rock Analyses

KEY TO TABLE C-1

M1	Feldspar phyric Olivine Basaltic Andesite
M2	" " " " "
M3	" " " " "
M7	Feldspar phyric Olivine Basalt
M10	" " " "
M13	" " " "
M18	Clinopyroxene-Feldspar phyric Olivine Basalt
M19	" " " " "
M20	Olivine Basalt
M23	Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite
M24	Olivine Basalt
M26	High K Andesite
M28	Feldspar-phyric Olivine Basalt
M29	" " " "
M30	Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite
M31	" " " " " "
M32	Feldspar-phyric Olivine Basalt
M33	" " " "
M34	Feldspar-phyric Olivine Basaltic Andesite
M35	Feldspar-phyric Olivine Basalt
M36	" " " "
M37	" " " "
M38	" " " "
M39	" " " "

M41/

M41	Feldspar-phyric Olivine Basalt
M42	" " " "
M43	" " " "
M44	" " " "
M49	" " " "
M50	" " " "
M53	" " " "
M54	" " " "
M55	" " " "
M56	Feldspar-phyric Olivine Basaltic Andesite
M58	" " " " "
M59	Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite
M60	" " " " " "
M61	" " " " " "
M62	Dacite
M64	Feldspar-phyric Olivine Basalt
M65	" " " "
M66	" " " "
M67	" " " "
M68	" " " "
M69	" " " "
M70	" " " "
M71	Feldspar-phyric Olivine Basaltic Andesite
M72	" " " " "
M73	" " " " "
M74	" " " " "

M75/

M75	Feldspar-phyric Olivine Basaltic Andesite
M76	" " " " "
M77	" " " " "
M78	" " " " "
M79	" " " " "
M80	" " " " "
M81	High-K Andesite
M82	" " "
M83	Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite
M84	" " " " " "
M85	" " " " " "
M86	" " " " " "
M87	Clinopyroxene-Feldspar-phyric Olivine Basalt
M88	Feldspar-phyric Olivine Basaltic Andesite
M89	Feldspar-phyric Olivine Basalt
M90	Feldspar-phyric Olivine Basaltic Andesite
M91	" " " " "
M92	" " " " "
M94	" " " " "
M95	Orthopyroxene-phyric Andesite
M96	" " "
M97	" " "
M98	Dacite
M99	"
M100	"
M101/	

M101 Feldspar-phyric Olivine Basaltic Andesite

M102 Olivine Basalt

M104 Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite

M105 Feldspar-phyric Olivine Basaltic Andesite

M107 Dacite

M110 Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite

M116 Olivine Basaltic Andesite

M117 Clinopyroxene-Feldspar phyric Olivine Basaltic Andesite

M118 Olivine Basalt

M119 Olivine Basaltic Andesite

M121 " " "

M126 Clinopyroxene-Feldspar phyric Olivine Basalt

M127 Feldspar-phyric Olivine Basalt

M128 Clinopyroxene Feldspar phyric Olivine Basalt

M129 Olivine Basaltic Andesite

M131 Feldspar phyric Olivine Basaltic Andesite

M132 " " " " "

M133 " " " " "

M134 " " " " "

M135 " " " " "

M136 " " " " "

M138 High K Andesite

M139 " " "

M140 " " "

M142 High K Basaltic Andesite

TABLE C-1.

	M1.	M2.	M3.	M7.	M10.	M13.	M18.	M19.
SIO2	54.54	54.94	55.39	52.57	52.26	50.62	52.10	50.72
TIO2	1.52	1.54	1.51	1.36	1.32	1.32	1.58	1.50
AL2O3	17.97	17.91	17.83	16.64	16.91	18.71	16.61	16.92
FE2O3	5.93	3.12	4.65	3.93	3.45	3.34	4.46	4.22
FEO	2.49	4.34	2.76	3.55	3.97	3.56	4.32	4.30
MNO	0.12	0.16	0.13	0.13	0.15	0.09	0.17	0.15
MGO	3.32	3.70	3.52	6.21	5.89	5.47	6.16	5.96
CAO	6.52	6.48	6.22	8.51	9.68	8.50	8.08	8.31
NA2O	4.46	4.42	4.43	3.59	3.35	3.60	3.64	3.66
K2O	1.67	1.69	1.78	1.13	0.63	1.29	1.52	1.29
H2O	1.52	1.05	1.19	2.20	2.29	3.31	2.05	2.77
P2O5	0.31	0.33	0.35	0.28	0.28	0.35	0.42	0.39
TOTAL	100.37	99.68	99.86	100.10	100.18	100.16	101.11	100.19

CIPW NORMS.

	M1.	M2.	M3.	M7.	M10.	M13.	M18.	M19.
Q	3.30	3.72	4.57	1.81	3.32	-	0.19	-
C	-	-	-	-	-	-	-	-
OR	10.01	10.16	10.72	6.85	3.82	7.90	9.11	7.86
AB	37.73	38.03	38.20	31.15	29.06	31.55	31.22	31.92
AN	23.91	24.44	23.96	26.61	29.97	32.20	24.83	26.73
DI	5.19	4.89	4.17	11.82	13.90	7.28	10.44	10.54
HY	10.53	11.31	11.02	14.74	13.01	12.78	15.87	13.05
OL	-	-	-	-	-	1.38	-	1.78
MGT	4.18	3.69	3.59	3.69	3.67	3.45	4.29	4.23
ILM	2.89	2.97	2.92	2.65	2.57	2.60	3.04	2.94
AP	0.67	0.79	0.84	0.68	0.68	0.86	1.01	0.95

PPM

	M1.	M2.	M3.	M7.	M10.	M13.	M18.	M19.
BA	461	420	475	272	272	340	460	385
SR	522	507	491	410	412	624	518	480
RB	52	50	51	27	6	24	45	40
ZR	215	234	242	182	185	226	240	218
Y	43	37	34	33	30	26	36	38
ZN	78	76	81	76	75	74	74	82
CU	13	16	14	23	46	24	24	29
LA	23	19	24	12	30	16	20	16
CE	53	54	55	40	63	54	67	58
NI	12					52	82	77
CR	29					75	136	132
V	116					165	172	166
K/RB	266	280	290	347	870	446	280	267
D.I.	51.04	51.90	53.49	39.81	36.19	39.45	40.52	39.78

TABLE C-1 (CONTD)

	M20.	M23.	M24.	M26.	M28.	M29.	M30.	M31.
SIO2	52.18	53.97	50.11	58.15	51.38	51.51	53.25	53.13
TIO2	1.59	1.50	1.53	1.23	1.69	1.69	1.70	1.70
AL2O3	16.19	17.72	15.97	17.67	18.56	18.90	18.00	17.82
FE2O3	4.73	3.70	4.05	4.98	5.38	5.05	4.73	4.83
FEO	3.41	4.20	4.46	3.50	3.58	4.02	3.56	3.44
MNO	0.15	0.19	0.18	0.10	0.13	0.20	0.11	0.11
MGO	6.07	4.11	7.34	2.26	3.96	3.93	4.05	4.51
CAO	8.30	8.00	8.50	3.68	7.10	7.17	7.72	7.70
NA2O	3.40	3.95	3.24	4.33	4.17	4.19	4.16	4.22
K2O	1.62	1.59	1.04	1.99	1.45	1.47	1.62	1.59
H2O	2.29	1.34	3.03	1.21	2.30	1.57	1.06	0.84
P2O5	0.47	0.35	0.32	0.44	0.39	0.32	0.36	0.35
TOTAL	100.40	100.62	99.77	99.54	100.09	100.02	100.32	100.04

CIPW NORMS.

	M20.	M23.	M24.	M26.	M28.	M29.	M30.	M31.
Q	1.67	3.01	-	12.48	0.35	-	1.49	0.61
C	-	-	-	2.65	-	-	-	-
OR	9.80	9.50	6.38	11.68	8.81	8.87	9.69	9.50
AB	29.46	33.79	28.45	36.68	36.27	36.19	35.63	36.09
AN	24.71	26.21	26.94	15.57	28.42	29.01	25.97	25.25
DI	11.45	9.37	11.70	-	4.19	4.19	8.41	8.89
HY	14.71	10.56	17.77	11.77	13.31	12.87	10.68	11.57
OL	-	-	0.68	-	-	0.38	-	-
MGT	3.98	3.85	4.27	4.41	4.40	4.44	4.01	3.99
ILM	3.09	2.88	3.02	2.28	3.30	3.28	3.27	3.26
AP	1.14	0.84	0.79	1.01	0.95	0.77	0.86	0.84

PPM

	M20.	M23.	M24.	M26.	M28.	M29.	M30.	M31.
BA	462	460	380	496	422	460	490	460
SR	692	549	607	473	675	685	607	593
RB	37	41	18	60	36	32	33	35
ZR	293	243	228	262	248	246	250	238
Y	33	34	35	45	30	48	34	31
ZN	78	68	72	68	67	72	84	87
CU	45	34	21	32	9	21	13	18
LA	21	21	21	16	20	18	21	24
CE	84	58	52	62	63	65	88	86
NI	252		224					
CR	352		325					
V	178		169					
K/RB	358	322	480	275	334	380	401	377
D.I.	40.93	46.29	34.83	54.66	45.44	45.06	46.81	46.20

TABLE C-1 (CONTD)

	M32.	M33.	M34.	M35.	M36.	M37.	M38.	M39.
SIO2	51.63	51.74	53.26	51.84	51.48	51.93	52.28	50.69
TIO2	1.66	1.70	1.67	1.70	1.71	1.68	1.64	1.73
AL2O3	18.64	18.37	17.78	18.33	18.49	18.13	18.35	18.89
FE2O3	6.52	6.63	7.93	6.00	4.99	6.47	4.95	4.82
FEO	3.27	2.89	2.99	3.75	4.42	3.10	4.65	3.58
MNO	0.11	0.11	0.08	0.11	0.14	0.09	0.14	0.34
MGO	4.44	4.03	2.72	3.80	4.04	3.55	4.00	5.30
CAO	6.99	7.70	7.01	7.37	7.08	7.32	7.02	5.21
NA2O	4.14	4.28	4.17	4.32	4.34	4.43	4.26	4.90
K2O	1.53	1.48	1.46	1.47	1.47	1.48	1.52	1.42
H2O	1.30	1.09	0.74	1.22	1.57	1.33	1.36	2.85
P2O5	0.34	0.32	0.34	0.30	0.33	0.31	0.31	0.34
TOTAL	100.57	99.34	100.15	100.21	100.06	99.82	100.48	100.07
CIPW NORMS.								
Q	-	-	3.90	-	-	-	0.29	-
C	-	-	-	-	-	-	-	0.65
OR	9.17	8.87	8.75	8.83	8.86	8.94	9.11	8.67
AB	35.51	36.73	35.78	37.15	37.47	38.31	36.54	42.85
AN	28.14	26.92	25.84	26.71	27.17	25.76	26.82	24.42
DI	3.86	7.87	5.93	6.88	5.25	7.56	5.23	-
HY	13.16	8.80	10.58	10.87	10.40	10.44	13.42	5.44
OL	1.44	2.21	-	0.85	2.12	0.37	-	9.59
MGT	4.70	4.56	5.20	4.71	4.62	4.62	4.69	4.15
ILM	3.20	3.27	3.22	3.28	3.31	3.26	3.16	3.40
AP	0.82	0.77	0.82	0.72	0.80	0.75	0.74	0.83
PPM								
BA	518	485	510	500	475	502	504	305
SR	677	692	671	691	689	675	670	550
RB	31	33	43	30	33	28	33	30
ZR	198	185	184	192	196	198	204	220
Y	34	31	41	35	34	31	34	38
ZN	96	75	68	70	76	64	73	148
CU	15	30	31	30	20	21	20	12
LA	21	20	20	24	28	25	9	12
CE	70	85	76	73	66	72	76	63
NI	6		7					8
CR	18		25					17
V	141		138					213
K/RB	410	367	282	407	370	439	377	386
D.I.	44.68	45.60	48.42	45.97	46.33	47.24	45.94	51.52

TABLE C-1 (CONTD)

	M41.	M42.	M43.	M44.	M49.	M50.	M53.	M54.
SIO2	52.05	52.35	51.57	51.72	52.11	52.19	52.43	52.36
TIO2	1.69	1.64	1.61	1.64	1.55	1.65	1.61	1.58
AL2O3	19.90	17.74	18.30	18.32	18.51	18.43	17.93	17.63
FE2O3	4.84	5.67	4.93	5.48	5.04	4.27	5.18	8.88
FEO	2.66	4.09	4.00	3.21	4.29	5.14	3.09	1.39
MNO	0.28	0.14	0.15	0.17	0.20	0.18	0.07	0.05
MGO	3.53	3.70	3.83	3.43	3.75	4.06	3.93	4.24
CAO	6.62	6.91	7.07	7.28	7.08	6.81	7.73	5.11
NA2O	4.75	4.17	4.53	4.64	4.25	4.44	4.01	3.84
K2O	1.57	1.48	1.44	1.48	1.51	1.60	1.61	1.95
H2O	1.56	1.50	1.63	1.33	1.84	1.48	1.43	1.93
P2O5	0.38	0.33	0.34	0.34	0.33	0.34	0.40	0.36
TOTAL	99.83	99.72	99.40	99.04	100.46	100.59	99.42	99.32

CIPW NORMS.

	M41.	M42.	M43.	M44.	M49.	M50.	M53.	M54.
Q	-	1.89	-	-	0.44	-	1.72	3.71
C	-	-	-	-	-	-	-	0.80
OR	9.49	8.95	8.75	9.00	9.09	9.58	9.76	11.94
AB	41.10	36.13	39.40	40.40	36.64	38.06	34.80	33.66
AN	28.98	25.92	26.05	25.51	27.48	25.97	26.84	23.83
DI	1.67	5.69	6.27	7.62	4.98	4.88	7.93	-
HY	7.23	12.66	8.56	6.49	13.00	10.80	10.81	17.13
OL	3.70	-	2.61	2.69	-	2.10	-	-
MGT	3.63	4.78	4.40	4.25	4.57	4.61	4.03	4.93
ILM	3.28	3.19	3.14	3.20	3.00	3.17	3.14	3.11
AP	0.92	0.80	0.83	0.83	0.80	0.82	0.97	0.88

PPM

	M41.	M42.	M43.	M44.	M49.	M50.	M53.	M54.
BA	500	498	468	526	490	525	475	455
SR	759	677	696	693	694	683	603	534
RB	31	32	33	30	43	45	44	47
ZR	230	200	197	205	220	224	255	260
Y	38	30	33	32	47	52	51	51
ZN	85	73	70	74	86	88	53	71
CU	17	14	13	8	24	20	10	28
LA	26	30	22	20	18	12	28	17
CE	90	81	88	117	87	85	97	75
NI								
CR								
V								
K/RB	421	384	362	409	292	295	300	341
D.I.	50.58	46.97	48.15	49.40	46.18	47.64	46.28	49.32

TABLE C-1 (CONTD)

	M55.	M56.	M58.	M59.	M60.	M61.	M62.	M64.
SIO2	52.65	54.11	53.07	54.96	55.27	55.18	62.78	51.84
TIO2	1.30	1.52	1.48	1.31	1.30	1.32	0.69	1.51
AL2O3	16.67	17.79	18.18	16.37	16.50	16.46	16.91	17.90
FE2O3	4.00	6.76	4.02	5.20	4.76	4.69	2.57	4.47
FEO	3.48	2.01	3.52	2.42	2.04	1.99	2.17	4.99
MNO	0.09	0.07	0.09	0.09	0.07	0.07	0.08	0.18
MGO	6.34	3.73	3.77	4.53	5.39	5.49	1.62	4.01
CAO	8.57	6.82	7.61	7.09	6.75	6.80	3.49	6.62
NA2O	3.33	3.98	3.92	3.78	3.86	3.65	4.12	4.24
K2O	1.01	1.57	1.39	1.88	1.86	1.88	2.87	1.58
H2O	1.59	1.29	1.78	1.43	1.63	1.49	2.33	1.36
P2O5	0.23	0.33	0.32	0.33	0.32	0.33	0.34	0.33
TOTAL	99.25	99.98	99.15	99.39	99.85	99.35	99.97	98.83
CIPW NORMS.								
Q	3.23	4.77	3.81	5.23	4.51	5.30	17.97	0.37
C	-	-	-	-	-	-	1.53	-
OR	6.13	9.46	8.47	11.40	11.25	11.40	17.41	9.60
AB	28.96	34.36	34.20	32.82	33.45	31.71	35.79	36.90
AN	28.32	26.56	28.77	22.73	22.73	23.59	15.50	25.86
DI	11.04	4.67	6.46	8.98	7.52	7.04	-	4.64
HY	15.51	12.25	10.87	11.80	13.96	14.36	7.28	14.18
OL	-	-	-	-	-	-	-	-
MGT	3.70	4.19	3.74	3.69	3.28	3.23	2.34	4.70
ILM	2.54	2.94	2.90	2.55	2.53	2.57	1.35	2.95
AP	0.56	0.80	0.78	0.80	0.78	0.80	0.83	0.80
PPM								
BA	285	445	390	700	660	720	665	535
SR	401	548	568	698	704	709	386	697
RB	24	46	35	56	58	58	82	44
ZR	167	228	234	205	212	210	462	214
Y	37	49	49	38	39	33	49	50
ZN	80	78	75	93	106	80	88	78
CU	27	34	31	34	34	31	7	12
LA	9	19	4	14	28	17	43	5
CE	70	68	84	112	100	89	110	86
NI	92							
CR	214							
V	163							
K/RB	349	283	329	279	263	267	289	294
D.I.	38.33	48.59	46.48	49.46	49.21	48.41	71.18	46.87

TABLE C-1 (CONTD)

	M65.	M66.	M67.	M68.	M69.	M70.	M71.	M72.
SIO2	51.40	51.79	51.38	51.24	51.61	50.94	55.87	55.36
TIO2	1.57	1.58	1.56	1.59	1.64	1.58	1.47	1.52
AL2O3	17.95	18.04	18.34	18.18	18.18	18.36	18.39	18.08
FE2O3	4.59	4.77	5.65	4.50	5.72	5.18	3.60	3.37
FEO	4.51	4.49	3.65	4.83	3.87	3.66	3.86	4.29
MNO	0.15	0.13	0.13	0.15	0.11	0.13	0.14	0.14
MGO	4.04	4.00	3.68	4.30	3.65	4.06	3.17	3.27
CAO	6.80	6.98	7.30	7.08	7.14	7.15	6.21	6.37
NA2O	4.43	4.35	4.40	4.38	4.21	4.34	4.39	4.43
K2O	1.53	1.54	1.50	1.47	1.50	1.45	1.80	1.70
H2O	1.50	1.24	1.47	1.64	1.49	2.22	1.03	1.01
P2O5	0.33	0.35	0.35	0.33	0.34	0.32	0.28	0.28
TOTAL	98.80	99.26	99.41	99.69	99.46	99.39	100.21	99.80
CIPW NORMS.								
Q	-	-	-	-	0.53	-	5.15	4.58
C	-	-	-	-	-	-	-	-
OR	9.33	9.33	9.10	8.90	9.10	8.86	10.76	10.20
AB	38.70	37.73	38.23	37.97	36.57	37.99	37.59	38.06
AN	25.37	25.78	26.55	26.23	26.98	27.24	25.46	24.80
DI	5.87	5.99	6.75	6.12	5.79	5.91	3.14	4.40
HY	9.90	11.80	8.49	8.19	12.31	8.60	10.77	10.58
OL	2.42	0.89	2.44	4.09	-	3.14	-	-
MGT	4.52	4.56	4.56	4.62	4.69	4.36	3.64	3.77
ILM	3.08	3.08	3.04	3.09	3.20	3.10	2.82	2.93
AP	0.81	0.85	0.85	0.80	0.83	0.78	0.67	0.67
PPM								
BA	535	520	515	505	502	485	455	430
SR	723	730	760	680	708	700	512	496
RB	44	42	46	45	44	47	65	58
ZR	219	214	214	213	212	220	243	224
Y	51	56	52	51	50	47	53	47
ZN	81	74	78	81	70	102	93	89
CU	25	17	29	15	24	17	24	12
LA	18	14	22	23	21	26	16	24
CE	81	87	76	63	61	56	60	65
NI								
CR								
V								
K/RB	283	304	270	268	280	256	228	241
D.I.	48.04	47.06	47.33	46.86	46.20	46.85	53.51	52.84

TABLE C-1 (CONTD)

	M73.	M74.	M75.	M76.	M77.	M78.	M79.	M80.
SIO2	54.85	55.46	55.64	55.40	54.76	55.09	54.91	55.43
TIO2	1.42	1.53	1.49	1.54	1.49	1.53	1.41	1.49
AL2O3	18.38	18.69	18.44	18.30	18.05	18.05	17.94	18.17
FE2O3	4.56	3.38	3.47	3.50	3.89	5.73	6.29	4.34
FEO	2.90	3.85	3.67	3.89	3.60	2.02	1.52	2.94
MNO	0.12	0.14	0.12	0.14	0.13	0.12	0.11	0.13
MGO	2.89	3.35	3.00	3.41	3.44	3.49	3.40	3.31
CAO	5.81	6.25	6.20	6.31	6.52	6.38	6.13	6.28
NA2O	4.35	4.44	4.31	4.30	4.28	4.42	4.44	4.42
K2O	1.78	1.79	1.78	1.76	1.69	1.68	1.69	1.77
H2O	1.38	1.29	1.19	1.15	0.99	1.12	1.46	1.25
P2O5	0.29	0.30	0.32	0.30	0.28	0.30	0.29	0.29
TOTAL	98.73	100.47	99.63	100.00	99.12	99.93	99.59	99.82

CIPW NORMS.

	M73.	M74.	M75.	M76.	M77.	M78.	M79.	M80.
Q	5.38	4.19	5.88	4.95	4.46	4.23	3.67	4.67
C	-	-	-	-	-	-	-	-
OR	10.85	10.70	10.72	10.56	10.22	10.10	10.38	10.66
AB	37.98	38.00	37.17	36.93	37.05	38.07	39.05	38.11
AN	26.18	26.08	26.21	25.82	25.62	24.88	24.97	24.97
DI	1.31	2.67	2.44	3.21	4.53	4.32	2.53	3.92
HY	11.13	11.16	10.40	11.22	10.87	11.01	12.13	10.56
OL	-	-	-	-	-	-	-	-
MGT	3.67	3.53	3.52	3.62	3.68	3.70	3.78	3.53
ILM	2.78	2.94	2.88	2.97	2.89	2.96	2.78	2.88
AP	0.71	0.72	0.77	0.72	0.68	0.72	0.71	0.70

PPM

	M73.	M74.	M75.	M76.	M77.	M78.	M79.	M80.
BA	452	467	475	475	460	460	440	475
SR	514	513	510	523	500	515	517	501
RB	65	63	61	65	60	56	66	66
ZR	266	239	245	238	228	220	226	239
Y	58	50	47	54	51	56	54	53
ZN	94	84	107	80	85	88	99	99
CU	6	12	14	6	20	33	24	20
LA	31	16	19	21	20	19	19	30
CE	75	63	70	66	55	56	51	62
NI								
CR								
V								
K/RB	227	233	240	223	233	247	212	222
D.I.	54.22	52.89	53.77	52.44	51.73	52.40	53.09	53.44

TABLE C-1 (CONTD)

	M81.	M82.	M83.	M84.	M85.	M86.	M87.	M88.
SIO2	58.81	57.20	53.70	53.89	53.15	53.21	52.48	53.43
TIO2	1.15	1.13	1.12	1.65	1.52	1.58	1.30	1.46
AL2O3	17.84	17.32	16.45	18.01	17.50	17.61	17.15	18.18
FE2O3	5.27	5.40	3.72	5.66	4.23	3.70	4.40	5.37
FEO	0.62	2.29	3.83	1.96	3.97	4.13	3.12	2.46
MNO	0.04	0.11	0.17	0.18	0.13	0.13	0.19	0.09
MGO	1.59	2.21	5.74	3.91	3.96	3.85	5.80	4.17
CAO	3.33	4.54	8.10	7.50	7.68	7.69	9.10	7.40
NA2O	4.38	5.13	3.57	3.97	3.94	3.95	3.30	3.92
K2O	5.29	2.11	1.10	1.75	1.56	1.56	0.85	1.47
H2O	1.32	1.47	2.07	1.38	1.45	1.30	2.00	1.57
P2O5	0.55	0.56	0.34	0.40	0.39	0.36	0.24	0.30
TOTAL	100.19	99.47	99.91	100.26	99.48	99.07	99.93	99.82

CIPW NORMS.

	M81.	M82.	M83.	M84.	M85.	M86.	M87.	M88.
Q	3.82	5.99	4.29	3.40	3.09	3.33	3.60	3.40
C	0.17	-	-	-	-	-	-	-
OR	31.78	12.79	6.67	10.52	9.44	9.46	5.15	8.89
AB	37.68	44.53	30.99	34.16	34.15	34.31	28.64	33.94
AN	13.14	18.46	26.27	26.60	26.08	26.39	30.23	28.31
DI	-	0.73	10.16	6.91	8.37	8.36	11.58	5.84
HY	7.09	10.22	14.87	10.62	10.93	10.30	14.00	12.27
OL	-	-	-	-	-	-	-	-
MGT	2.77	3.72	3.73	3.64	4.04	3.88	3.69	3.78
ILM	2.22	2.20	2.18	3.18	2.96	3.08	2.53	2.84
AP	1.32	1.36	0.83	0.96	0.95	0.88	0.58	0.73

PPM

	M81.	M82.	M83.	M84.	M85.	M86.	M87.	M88.
BA	520	505	475	432	417	455	322	445
SR	278	390	677	581	587	583	421	544
RB	96	81	25	50	41	46	15	50
ZR	458	428	218	280	266	262	176	228
Y	95	80	50	65	51	49	46	51
ZN	104	90	65	91	83	76	103	97
CU	12	28	20	24	34	8	25	10
LA	46	44	30	26	26	25	20	20
CE	95	95	58	72	66	73	39	46
NI			112				82	
CR			91				181	
V			151				174	
K/RB	255	215	365	287	312	278	254	241
D.I.	73.28	63.30	41.95	48.08	46.68	47.10	37.39	46.23

TABLE C-1 (CONTD)

	M89.	M90.	M91.	M92.	M94.	M95.	M96.	M97.
SIO2	52.62	53.78	53.91	54.05	54.52	56.50	56.69	56.62
TIO2	1.51	1.54	1.52	1.56	1.57	1.08	1.09	1.08
AL2O3	18.16	18.03	18.17	18.69	18.56	15.11	15.42	15.12
FE2O3	5.45	3.93	4.20	4.89	5.87	2.33	2.53	2.49
FEO	2.56	4.13	3.81	2.92	2.40	4.20	3.90	4.10
MNO	0.09	0.09	0.13	0.08	0.09	0.11	0.11	0.11
MGO	3.25	4.25	4.12	3.30	3.05	7.34	7.23	7.05
CAO	8.74	7.41	7.36	7.48	6.98	6.21	6.15	6.23
NA2O	3.79	3.82	3.96	3.94	4.38	3.73	3.61	3.56
K2O	1.49	1.47	1.48	1.50	1.38	1.74	1.84	1.76
H2O	1.65	1.44	1.47	1.73	1.43	1.10	1.08	1.10
P2O5	0.31	0.31	0.29	0.30	0.27	0.24	0.25	0.22
TOTAL	99.62	100.20	100.42	100.44	100.50	99.67	99.90	99.44
CIPW NORMS.								
Q	3.09	4.11	3.63	4.82	4.32	4.92	5.49	6.19
C	-	-	-	-	-	-	-	-
OR	9.04	8.83	8.87	9.02	8.28	10.45	11.03	10.60
AB	32.91	32.86	34.00	33.94	37.63	32.09	30.99	30.71
AN	28.88	28.16	27.84	29.40	27.32	19.67	20.73	20.47
DI	10.99	5.76	5.89	5.17	4.92	8.00	6.81	7.62
HY	7.51	12.61	12.23	10.14	9.90	18.97	19.08	18.51
OL	-	-	-	-	-	-	-	-
MGT	3.88	3.95	3.91	3.78	3.96	3.24	3.18	3.28
ILM	2.94	2.97	2.93	3.02	3.03	2.09	2.10	2.09
AP	0.75	0.75	0.70	0.72	0.65	0.58	0.60	0.53
PPM								
BA	387	412	397	405	512	485	500	510
SR	539	544	535	526	604	534	550	526
RB	48	48	44	48	32	59	61	65
ZR	226	219	222	240	238	213	214	216
Y	45	49	50	29	39	22	27	26
ZN	83	92	85	80	73	69	70	69
CU	31	13	24	30	28	28	43	35
LA	24	22	30	28	21	33	36	42
CE	53	56	56	65	55	59	56	63
NI						240		246
CR						290		301
V						122		115
K/RB	255	254	276	259	352	245	248	225
D.I.	45.04	45.79	46.51	47.78	50.22	47.46	47.51	47.50

TABLE C-1 (CONTD)

	M98.	M99.	M100.	M101.	M102.	M104.	M105.	M107.
SIO2	62.74	64.55	64.08	53.50	50.59	53.67	55.65	61.27
TIO2	0.66	0.65	0.66	1.43	1.51	1.58	1.51	1.34
AL2O3	17.17	17.24	17.37	16.09	17.70	17.64	18.04	15.22
FE2O3	3.42	2.85	2.65	3.81	6.19	5.16	3.67	3.41
FEO	1.38	1.64	1.49	3.63	1.87	2.45	3.46	3.06
MNO	0.15	0.05	0.08	0.13	0.14	0.16	0.11	0.06
MGO	1.39	1.08	1.15	5.34	6.00	3.85	3.48	3.45
CAO	0.67	2.74	2.65	7.46	6.92	7.50	6.81	2.10
NA2O	6.54	5.05	5.21	3.74	3.73	4.21	3.92	4.04
K2O	3.75	2.88	3.13	1.23	1.46	1.68	1.69	3.64
H2O	1.53	1.41	1.28	2.51	2.71	1.33	1.50	2.62
P2O5	0.33	0.31	0.32	0.37	0.37	0.36	0.31	0.21
TOTAL	99.73	100.45	100.07	99.24	99.19	99.63	100.15	100.42
CIPW NORMS.								
Q	6.44	16.47	14.35	4.77	-	2.23	6.96	13.57
C	1.97	1.59	1.38	-	-	-	-	1.35
OR	22.64	17.23	18.77	7.54	9.00	10.15	10.16	22.07
AB	56.54	43.27	44.74	32.84	32.92	36.77	33.74	35.08
AN	1.20	11.71	11.22	24.37	28.41	24.63	27.10	9.28
DI	-	-	-	9.23	3.90	8.87	4.21	-
HY	6.83	5.58	5.52	13.81	16.71	9.72	10.67	12.35
OL	-	-	-	-	1.23	-	-	-
MGT	2.31	2.16	1.99	3.72	3.93	3.68	3.50	3.18
ILM	1.28	1.25	1.27	2.82	2.99	3.07	2.92	2.61
AP	0.80	0.74	0.77	0.91	0.91	0.87	0.75	0.51
PPM								
BA	730	730	845	580	485	500	485	1085
SR	364	472	452	747	490	542	478	301
RB	108	89	75	16	28	38	53	118
ZR	439	450	451	265	261	290	247	261
Y	45	41	42	25	42	36	41	37
ZN	206	143	104	84	154	80	84	219
CU	10	34	12	57	44	39	26	48
LA	51	50	46	29	22	46	42	40
CE	115	112	113	75	69	65	71	84
NI			-					57
CR			18					58
V			37					204
K/RB	288	279	346	637	432	367	262	256
D.I.	85.62	76.96	77.86	45.15	41.92	49.15	50.87	70.71

TABLE C-1 (CONTD)

	M110.	M116.	M117.	M118.	M119.	M121.	M126.	M127.
SIO2	53.75	54.09	55.90	52.07	54.05	53.56	50.94	52.56
TIO2	1.26	1.55	1.30	1.53	1.40	1.06	1.43	1.41
AL2O3	15.81	16.32	17.74	16.48	15.54	16.37	16.37	16.45
FE2O3	4.28	4.71	3.57	6.29	7.55	4.89	6.82	6.26
FEO	3.46	3.30	3.76	2.05	1.38	3.17	1.89	2.03
MNO	0.14	0.15	0.13	0.10	0.07	0.11	0.10	0.12
MGO	7.18	5.39	4.09	5.99	5.53	6.83	6.98	4.63
CAO	7.41	7.55	7.21	7.76	7.27	7.55	8.22	8.71
NA2O	3.59	3.52	4.02	3.80	3.45	3.62	3.39	3.72
K2O	1.64	1.72	1.84	1.93	1.16	1.41	1.51	1.54
H2O	2.12	1.98	1.16	2.48	2.09	1.52	2.58	1.50
P2O5	0.29	0.41	0.24	0.36	0.29	0.30	0.34	0.32
TOTAL	100.93	100.69	100.96	100.84	99.78	100.39	100.57	99.25

CIPW NORMS.

Q	1.41	4.39	4.63	-	6.68	1.64	-	2.00
C	-	-	-	-	-	-	-	-
OR	9.85	10.34	10.93	11.67	7.07	8.47	9.17	9.37
AB	30.87	30.31	34.20	32.89	30.11	31.13	29.47	32.40
AN	22.54	24.07	25.06	22.72	24.23	24.65	25.68	24.33
DI	10.28	9.08	7.52	11.41	8.86	9.14	11.14	14.50
HY	18.14	13.93	11.04	10.71	15.32	18.30	14.13	9.85
OL	-	-	-	2.75	-	-	2.61	-
MGT	3.77	3.90	3.56	4.00	4.28	3.90	4.19	4.00
ILM	2.43	3.00	2.48	2.97	2.74	2.05	2.79	2.76
AP	0.70	0.99	0.57	0.87	0.71	0.72	0.83	0.78

PPM

BA	425	535	475	512	440	365	555	462
SR	474	684	522	557	593	580	712	718
RB	49	38	53	45	15	22	27	27
ZR	210	261	262	240	228	202	228	218
Y	27	30	36	30	27	28	41	33
ZN	82	79	77	80	80	90	84	81
CU	55	43	24	48	50	34	41	53
LA	38	46	38	44	38			
CE	65	80	82	70	66	48	63	72
NI	322		12			220		
CR	298		20			246		
V	147		142			116		
K/RB	275	370	288	352	641	532	455	465
D.I.	42.13	45.05	49.77	44.56	43.86	41.23	38.64	43.77

TABLE C-1 (CONTD)

	M128.	M129.	M131.	M132.	M133.	M134.	M135.	M136.
SIO2	52.98	53.16	53.53	53.98	54.37	53.74	54.26	54.26
TIO2	1.42	1.47	1.48	1.52	1.55	1.48	1.58	1.52
AL2O3	16.87	17.54	17.91	17.62	18.30	17.79	18.95	18.35
FE2O3	5.92	3.69	6.20	5.67	4.46	5.02	4.47	3.21
FEO	2.31	4.02	1.82	1.92	3.42	3.06	2.75	4.98
MNO	0.12	0.14	0.11	0.10	0.18	0.12	0.12	0.16
MGO	5.38	5.01	4.61	4.19	3.58	4.02	3.93	4.01
CAO	8.07	7.58	7.69	7.92	7.63	7.90	7.84	7.62
NA2O	3.74	3.95	3.95	3.99	3.79	3.90	4.09	3.65
K2O	1.55	1.57	1.50	1.55	1.53	1.47	1.50	1.50
H2O	1.83	1.56	1.64	1.63	1.79	1.39	1.74	1.02
P2O5	0.32	0.36	0.29	0.32	0.34	0.29	0.37	0.32
TOTAL	100.51	100.05	100.73	100.41	100.94	100.18	101.60	100.60

CIPW NORMS.

	M128.	M129.	M131.	M132.	M133.	M134.	M135.	M136.
Q	1.61	1.58	2.35	3.26	5.32	3.57	3.06	5.09
C	-	-	-	-	-	-	-	-
OR	9.34	9.45	9.00	9.32	9.16	8.85	8.91	8.93
AB	32.26	34.06	33.94	34.37	32.49	33.57	34.81	31.11
AN	25.14	25.97	27.12	26.05	28.77	27.16	29.08	29.47
DI	10.87	7.98	7.80	9.51	5.93	8.72	6.11	5.26
HY	13.32	13.44	12.43	10.14	10.71	10.68	10.66	12.45
OL	-	-	-	-	-	-	-	-
MGT	3.95	3.80	3.81	3.63	3.82	3.91	3.46	4.02
ILM	2.75	2.85	2.85	2.94	2.98	2.86	3.02	2.91
AP	0.77	0.87	0.70	0.77	0.82	0.70	0.88	0.76

PPM

	M128.	M129.	M131.	M132.	M133.	M134.	M135.	M136.
BA	530	345	305	350	345	360	355	335
SR	764	472	500	518	486	536	531	513
RB	33	37	36	35	31	39	37	31
ZR	229	199	214	230	226	221	228	234
Y	40	36	40	48	40	41	36	44
ZN	81	87	103	93	94	90	91	82
CU	49	36	27	20	26	36	23	21
LA								
CE	67	70	70	61	64	55	62	58
NI			36			32		27
CR			35			36		29
V			154			142		166
K/RB	389	352	346	367	403	309	332	401
D.I.	43.20	45.09	45.29	46.96	46.97	45.98	46.79	45.13

TABLE C-1 (CONTD)

	M138.	M139.	M140.	M142.
SIO2	57.28	57.63	57.98	54.20
TIO2	1.16	1.18	1.20	1.31
AL2O3	17.50	17.37	17.05	17.75
FE2O3	6.66	6.91	4.00	5.63
FEO	0.62	0.46	3.54	2.92
MNO	0.07	0.07	0.21	0.08
MGO	1.82	2.34	3.05	4.64
CAO	4.08	4.15	4.70	1.32
NA2O	5.44	5.52	4.95	4.45
K2O	2.50	2.55	2.19	5.04
H2O	1.41	1.35	1.39	2.69
P2O5	0.70	0.52	0.61	0.47
TOTAL	99.24	100.05	100.87	100.50
CIPW NORMS.				
Q	4.81	3.45	6.07	-
C	0.10	-	-	3.80
OR	15.20	15.37	13.06	30.62
AB	47.36	47.64	42.26	38.71
AN	16.12	15.39	17.99	3.58
DI	-	1.76	1.23	-
HY	8.99	9.39	11.97	10.69
OL	-	-	-	4.74
MGT	3.45	3.46	3.66	4.16
ILM	2.27	2.29	2.30	2.56
AP	1.71	1.26	1.46	1.14
PPM				
BA	615	660	550	785
SR	380	373	360	269
RB	75	71	62	92
ZR	415	418	378	342
Y	82	80	64	45
ZN	176	166	128	148
CU	5	9	35	12
LA				34
CE				93
NI			5	12
CR			14	21
V			53	153
K/RB	277	298	293	504
D.I.	67.37	66.46	61.39	69.33

TABLE C-2.

	M19A.	M20A.	M23A.	M24A.	M35A.	M41A.	M64A.
SIO2	50.99	53.09	54.17	51.36	52.46	52.68	52.33
TIO2	1.67	1.70	1.60	1.70	1.88	1.44	1.67
AL2O3	17.11	17.31	17.50	17.77	18.69	19.45	17.96
FEO	8.02	6.53	7.82	6.31	8.85	7.05	8.90
MNO	0.17	0.16	0.20	0.20	0.12	0.30	0.20
MGO	4.87	3.93	3.91	4.02	2.25	3.31	2.82
CAO	8.07	8.88	7.54	9.46	7.50	6.23	6.56
NA2O	3.85	3.64	4.03	3.60	4.55	4.94	4.43
K2O	1.44	1.73	1.71	1.16	1.62	1.76	1.73
H2O	2.90	2.40	1.38	3.20	1.25	1.60	1.40
P2O5	0.44	0.50	0.38	0.36	0.33	0.43	0.36
TOTAL	99.53	99.87	100.24	99.14	99.50	99.19	98.36

CIPW NORMS.

Q	-	0.76	-	-	-	-	-
C	-	-	-	-	-	-	-
OR	8.80	10.49	10.22	7.14	9.74	10.65	10.54
AB	33.70	31.59	34.49	31.74	39.18	42.82	38.65
AN	26.02	26.44	24.89	30.12	26.24	26.33	24.76
DI	10.29	12.72	8.69	13.48	8.03	2.06	5.40
HY	7.48	13.47	17.71	13.12	3.81	1.32	9.37
OL	9.35	-	0.02	0.14	8.57	12.98	7.13
MGT	-	-	-	-	-	-	-
ILM	3.28	3.31	3.07	3.36	3.63	2.80	3.27
AP	1.08	1.21	0.91	0.89	0.80	1.04	0.88
D.I.	42.51	42.84	44.71	38.89	48.92	53.48	49.19

TABLE C-2 (CONTD)

	M74A.	M83A.	M87A.	M98A.	M100A.	M102A.	M105A.
SIO2	56.21	55.09	53.33	63.76	64.97	51.11	56.54
TIO2	1.70	1.56	1.66	0.00	0.04	1.58	1.68
AL2O3	18.53	14.54	15.80	17.35	17.47	18.50	17.95
FEO	6.80	7.99	7.33	3.88	3.39	6.69	6.55
MNO	0.15	0.24	0.24	0.13	0.06	0.17	0.12
MGO	2.43	4.56	4.77	1.42	1.18	4.61	2.33
CAO	6.02	7.00	9.07	0.61	2.61	7.23	6.70
NA2O	4.61	3.79	3.35	6.77	5.26	3.90	4.06
K2O	1.98	1.47	1.02	3.84	3.21	1.53	1.88
H2O	1.31	2.17	2.10	1.61	1.32	2.81	1.55
P2O5	0.33	0.48	0.31	0.34	0.33	0.39	0.35
TOTAL	100.07	98.89	98.98	99.71	99.84	98.52	99.71

CIPW NORMS.

	M74A.	M83A.	M87A.	M98A.	M100A.	M102A.	M105A.
Q	2.52	4.27	3.15	3.94	13.00	-	5.92
C	-	-	-	1.79	1.41	-	-
OR	11.84	8.98	6.22	23.13	19.25	9.44	11.23
AB	39.49	33.15	29.25	58.38	45.17	34.47	34.99
AN	24.32	18.94	25.86	0.82	10.95	29.72	25.67
DI	3.14	11.39	15.26	-	-	4.19	4.93
HY	14.63	19.04	16.24	11.11	9.35	11.75	13.08
OL	-	-	-	-	-	6.33	-
MGT	-	-	-	-	-	-	-
ILM	3.27	3.06	3.25	-	0.08	3.13	3.25
AP	0.79	1.18	0.76	0.82	0.79	0.96	0.84
D.I.	53.85	46.40	38.63	85.45	77.42	43.92	52.23

TABLE C-2 (CONTD)

	M116A.	M117A.	M121A.	M126A.	M129A.	M136A.
SIO2	54.90	56.32	55.00	51.35	53.38	54.58
TIO2	1.63	1.38	1.16	1.67	1.49	1.57
AL2O3	17.20	17.69	17.99	16.06	17.82	18.55
FEO	6.65	7.02	5.93	8.07	7.07	7.66
MNO	0.16	0.14	0.12	0.12	0.14	0.16
MGO	3.70	3.62	3.86	5.95	4.49	3.42
CAO	7.95	6.91	8.30	7.91	7.70	7.70
NA2O	3.71	4.12	3.98	3.55	4.01	3.71
K2O	1.81	1.96	1.55	1.78	1.59	1.55
H2O	2.03	1.20	1.55	2.68	1.60	1.04
P2O5	0.43	0.26	0.33	0.40	0.37	0.33
TOTAL	100.17	100.62	99.77	99.54	99.66	100.27
CIPW NORMS.						
Q	3.17	2.30	1.83	-	-	2.50
C	-	-	-	-	-	-
OR	10.90	11.65	9.32	10.86	9.58	9.23
AB	31.98	35.06	34.28	31.01	34.60	31.63
AN	25.40	24.12	27.12	23.36	26.43	29.61
DI	9.88	7.20	10.41	11.88	8.30	5.61
HY	14.48	16.41	14.00	9.08	14.58	17.63
OL	-	-	-	9.57	2.73	-
MGT	-	-	-	-	-	-
ILM	3.15	2.64	2.24	3.27	2.89	3.00
AP	1.04	0.62	0.80	0.98	0.89	0.79
D.I.	46.04	49.01	45.43	41.86	44.17	43.36

TABLE C-3

M111 = Dolerite

M112 = Dolerite

M114 = Segregation Vein

TABLE C-3.

	M111.	M112.	M114.
SIO2	52.94	52.50	65.14
TIO2	1.40	1.42	0.79
AL2O3	17.71	17.74	14.53
FE2O3	4.57	4.66	2.29
FEO	3.46	3.21	2.05
MNO	0.09	0.09	0.08
MGO	5.17	5.48	1.69
CAO	7.36	6.61	2.04
NA2O	4.21	4.38	3.69
K2O	1.53	1.77	5.92
H2O	2.46	2.67	1.17
P2O5	0.31	0.28	0.19
TOTAL	101.21	100.81	99.58
CIPW NORMS.			
Q	2.04	1.38	15.30
C	-	-	-
OR	8.90	10.56	35.03
AB	35.63	37.20	30.92
AN	25.02	23.35	5.56
DI	7.37	5.83	2.94
HY	9.60	9.00	3.30
OL	-	-	-
MGT	6.73	6.26	3.25
HM	-	0.32	-
ILM	2.74	2.74	1.52
AP	0.67	0.67	0.34
PPM			
BA	370	410	750
SR	568	589	217
RB	46	48	127
ZR	213	228	499
Y	27	31	55
ZN	81	127	55
CU	41	32	44
LA	28	48	64
CE	65	68	116
K/RB	276	306	387

APPENDIX D

MODAL DATA AND LOCATION OF SAMPLES FROM THE SIDLAW HILLS

Key to TABLE D-1

OB	Olivine Basalt
FOB	Feldspar phyric Olivine Basalt
CFOB	Clinopyroxene-feldspar phyric Olivine Basalt
OBA	Olivine Basaltic-andesite
FOBA	Feldspar phyric Olivine Basaltic-andesite
CFOBA	Clinopyroxene-feldspar phyric Olivine Basaltic-andesite
HKBA	High-K Basaltic-andesite
OA	Orthopyroxene phyric Andesite
HKA	High-K Andesite
D	Dacite
*	National Grid Reference on 6" sheets

Modal Phenocryst Data (Volume %)

Ol = Olivine

Pl = Plagioclase

Cpx = Clinopyroxene

Opx = Orthopyroxene

Kspar = Alkali feldspar

Ore = Fe/Ti oxide

tr = Trace

TABLE D-1

M1	FOBA	Collace Quarry	NO 20853160*	Ol 2.0, Pl 6.3, Ore 1.2
M2	FOBA	Collace Quarry	NO 20843160	Ol 2.8, Pl 6.9
M3	FOBA	Collace Quarry	NO 20803160	Ol 1.1, Pl 5.3, Ore 0.7
M7	FOB	Black Hill	NO 22153170	Ol 4.2, Pl 6.0
M10	FOB	Black Hill	NO 22123171	Ol 4.9, Pl 5.9
M13	FOB	Nr Craighead Quarry	NO 24102814	Ol 1.7, Pl 4.9
M18	CFOB	Denend	NO 31024171	Ol 1.5, Pl 1.9, Cpx 0.5, Opx 0.2
M19	CFOB	Denend	NO 31064165	Ol 2.6, Pl 5.4, Cpx 2.0
M20	OB	Denend	NO 31204152	Ol 5.1
M23	CFOBA	Denend	NO 31414130	Ol 0.4, Pl 5.0, Cpx 1.5
M24	OB	Denend	NO 31454114	Ol 8.0
M26	HKA	Denend Burn	NO 31854082	Ol 2.1, Pl 3.3
M28	FOB	Denend Burn	NO 32324105	Ol 2.4, Pl 6.3
M29	FOB	Denend Burn	NO 32334103	Ol 1.4, Pl 6.7
M30	CFOBA	Northballo Quarry	NO 24693540	Ol 2.7, Pl 10.3, Cpx 0.1
M31	CFOBA	Northballo Quarry	NO 24693542	Ol 4.1, Pl 6.7, Cpx 0.3
M32	FOB	Burnside Quarry	NO 30574011	Ol 3.4, Pl 4.8
M33	FOB	Burnside Quarry	NO 30564010	Ol 3.5, Pl 7.1
M34	FOBA	Burnside Quarry	NO 30554009	Ol 3.9, Pl 6.1
M35	FOB	Burnside Quarry	NO 30544008	Ol 3.9, Pl 6.0
M36	FOB	Burnside Quarry	NO 30534005	Ol 3.1, Pl 6.0
M37	FOB	Burnside Quarry	NO 30514003	Ol 3.6, Pl 3.7
M38	FOB	Burnside Quarry	NO 30504002	Ol 3.0, Pl 6.8, Ore 0.3

M39/

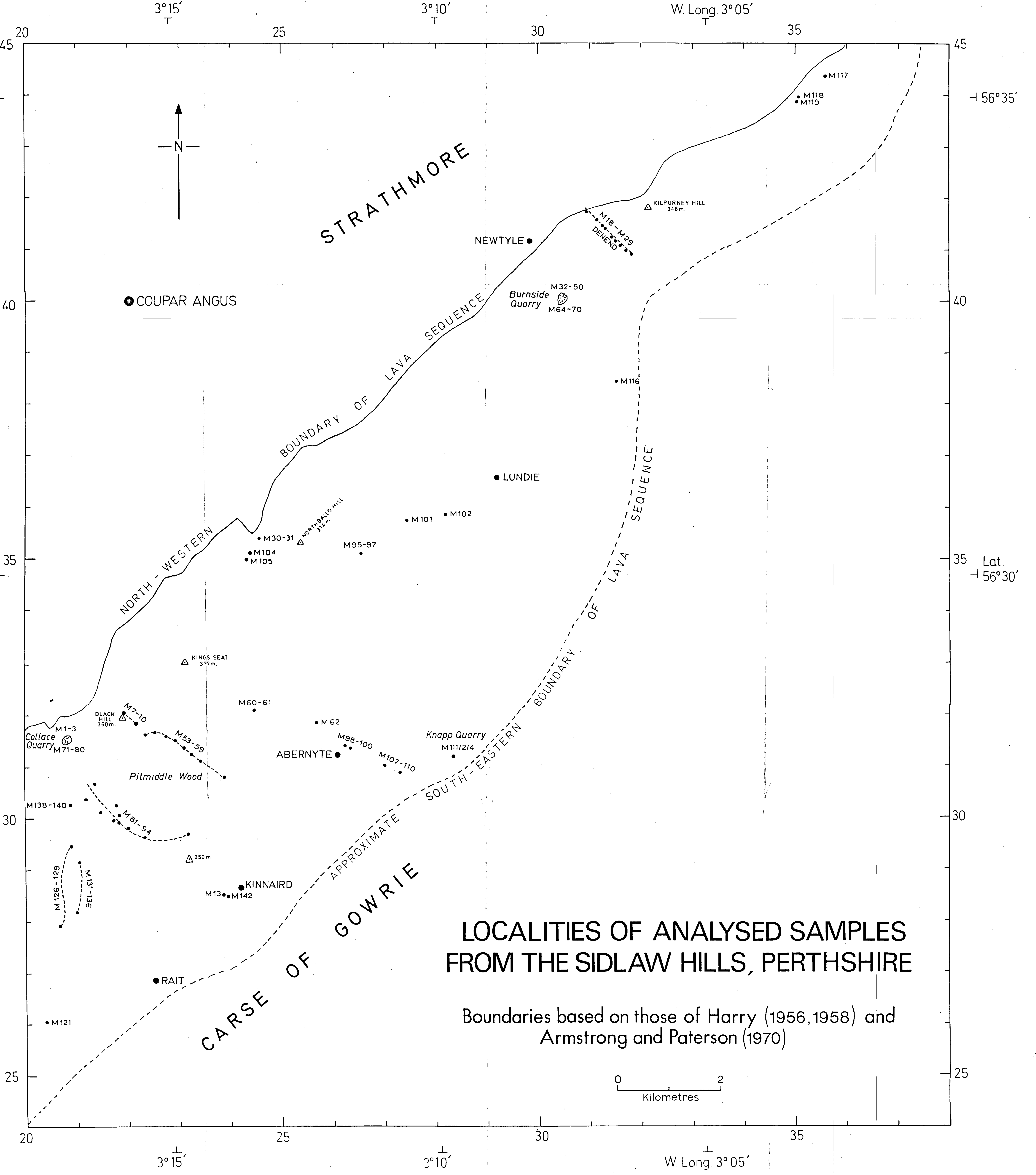
M39	FOB	Burnside Quarry	NO 30484000	Ol 2.2, Pl 8.4, Ore 0.5
M41	FOB	Burnside Quarry	NO 30453995	Ol 1.3, Pl 9.4, Ore 0.5
M42	FOB	Burnside Quarry	NO 30443992	Ol 4.3, Pl 5.8
M43	FOB	Burnside Quarry	NO 30423991	Ol 3.5, Pl 5.8
M44	FOB	Burnside Quarry	NO 30403990	Ol 2.2, Pl 4.6
M49	FOB	Burnside Quarry	NO 30513991	Ol 2.3, Pl 6.0, Ore 0.1
M50	FOB	Burnside Quarry	NO 30523995	Ol 2.7, Pl 4.2
M53	FOB	Pitmiddle Wood	NO 22503145	Ol 4.2, Pl 7.3
M54	FOB	Pitmiddle Wood	NO 22503146	Ol 4.2, Pl 9.4
M55	FOB	Pitmiddle Wood	NO 23163120	Ol 5.7, Pl 9.7
M56	FOBA	Hoole Hill	NO 23423110	Ol 1.0, Pl 1.2
M58	FOBA	Hoole Hill	NO 23423111	Ol 2.5, Pl 4.7
M59	CFOBA	Pitmiddle Hill	NO 23843062	Ol 3.8, Pl 11.8 Cpx 1.3
M60	CFOBA	Nr Pitmiddle Hill	NO 24423209	Ol 3.2, Pl 12.6, Cpx 0.9
M61	CFOBA	Nr Pitmiddle Hill	NO 24423209	Ol 2.8, Pl 12.5, Cpx 1.6
M62	D	Kirkton Hill Wood	NO 25753174	Pl 0.7, Ore 1.0
M64	FOB	Burnside Quarry	NO 30573997	Ol 3.1, Pl 5.6
M65	FOB	Burnside Quarry	NO 30604000	Ol 4.4, Pl 6.1
M66	FOB	Burnside Quarry	NO 30644005	Ol 2.8, Pl 4.5
M67	FOB	Burnside Quarry	NO 30684110	Ol 2.7, Pl 6.2
M68	FOB	Burnside Quarry	NO 30714041	Ol 3.1, Pl 8.2
M69	FOB	Burnside Quarry	NO 30654017	Ol 3.4, Pl 9.2
M70	FOB	Burnside Quarry	NO 30614016	Ol 3.1, Pl 5.9
M71	FOBA	Collace	NO 20783153	Ol 2.0, Pl 8.1
M72	FOBA	Collace	NO 20813153	Ol 1.8, Pl 6.3
M73	FOBA	Collace	NO 20843154	Ol 2.0, Pl 4.8

M74/

M74	FOBA	Collace	NO 20863155	Ol 2.3, Pl 6.3
M75	FOBA	Collace	NO 20863157	Ol 1.3, Pl 6.7
M76	FOBA	Collace	NO 20853158	Ol 1.9, Pl 7.0
M77	FOBA	Collace	NO 20853159	Ol 3.4, Pl 8.2
M78	FOBA	Collace	NO 20833160	Ol 1.6, Pl 6.2
M79	FOBA	Collace	NO 20803161	Ol 1.8, Pl 3.7
M80	FOBA	Collace	NO 20783162	Ol 1.8, Pl 6.7
M81	HKA	Nr Hoole Farm	NO 21323065	Ol 1.4, Pl 0.1
M82	HKA	Nr Hoole Farm	NO 21183031	Ol 0.8, Pl 0.4
M83	CFOBA	Nr Pitmiddle Wood	NO 21453010	Ol 4.4, Pl 21.9, Cpx 2.3
M84	CFOBA	Nr Pitmiddle Wood	NO 21743123	Ol 1.8, Pl 2.8, Cpx 0.4
M85	CFOBA	Nr Pitmiddle Wood	NO 20803002	Ol 3.9, Pl 6.8, Cpx 0.2
M86	CFOBA	Nr Pitmiddle Wood	NO 20702995	Ol 3.1, Pl 6.7, Cpx 0.5
M87	CFOB	Nr Pitmiddle Wood	NO 21752990	Ol 4.3, Pl 16.2, Cpx 0.1
M88	FOBA	Nr Pitmiddle Wood	NO 22002980	Ol 2.0, Pl 0.9
M89	FOB	Nr Pitmiddle Wood	NO 22302960	Ol 2.4, Pl 2.3
M90	FOBA	Nr Pitmiddle Wood	NO 22322960	Ol 2.8, Pl 2.1
M91	FOBA	Nr Westlaws	NO 22402950	Ol 2.2, Pl 1.5
M92	FOBA	Nr Westlaws	NO 22522968	Ol 2.1, Pl 1.7
M94	FOBA	Nr Woodburn Head	NO 23082970	Ol 1.1, Pl 4.0
M95	OA	Ballo Quarry	NO 26513514	Pl 2.4, Opx 3.4
M96	OA	Ballo Quarry	NO 26503516	Pl 3.1 Opx 1.5
M97	OA	Ballo Quarry	NO 26493514	Pl 1.8, Opx 2.5
M98	D	Kirkton Craig	NO 26113137	Pl 0.9, Ore 0.8
M99	D	Kirkton Craig	NO 26133135	Pl 0.5, Ore 0.7
M100	D	Kirkton Craig	NO 26153136	Pl 1.3, Ore 0.7

M101/

M101	FOBA	Lochindores Quarry	NO 27423579	Ol 5.8, Pl 1.8
M102	OB	Balshando	NO 28183588	Ol 3.4, Ore tr.
M104	CFOBA	Gask Hill	NO 24243550	Ol 1.7, Pl 6.3, Cpx 0.1
M105	FOBA	Gask Hill	NO 24273492	Ol 2.8 Pl 6.3
M107	D	Milton	NO 31333090	Pl 3.5 Kspar 12.4
M110	CFOBA	Milton	NO 31493095	Ol 4.9 Pl 0.2, Cpx 0.1
M116	OBA	Newton Quarry	NO 31583837	Ol 3.9, Ore tr.
M117	CFOBA	Little Law Quarry	NO 35644472	Ol 1.0, Pl 4.0 Cpx 1.0
M118	OB	Wester Denoon	NO 34764295	Ol 4.4
M119	OBA	Wester Denoon	NO 34734285	Ol 5.1
M121	OBA	Nr Evelick Castle	NO 20632597	Ol 7.2
M126	CFOB	Swirlhead	NO 20602782	Ol 3.5, Pl 9.5, Cpx 1.7
M127	FOB	Nr Swirlhead	NO 20752797	Ol 2.0, Pl 7.8
M128	CFOB	Nr. Swirlhead	NO 20822810	Ol 2.8, Pl 11.3, Cpx 0.6
M129	OBA	Whitmyre Wood	NO 20592885	Ol 1.2
M131	FOBA	Nr Franklyden	NO 21082915	Ol 0.8, Pl 0.6
M132	FOBA	Nr Franklyden	NO 20972913	Ol 1.6, Pl 0.3
M133	FOBA	Nr Franklyden	NO 20972912	Ol 1.2, Pl 1.3
M134	FOBA	Nr Franklyden	NO 21062901	Ol 1.9, Pl 1.2
M135	FOBA	Nr Whitmyre Wood	NO 21032877	Ol 2.9, Pl 4.1
M136	FOBA	Nr Whitmyre Wood	NO 20722852	Ol 1.5, Pl 1.4
M138	HKA	Nr Hoole Farm	NO 21373067	Ol 0.5, Pl 0.5
M139	HKA	Nr Bandirran	NO 21383069	Ol 0.8, Pl 0.3
M140	HKA	Nr Bandirran	NO 21183035	Ol 0.6, Pl 0.9
M142	HKBA	Craig Head Quarry	NO 24102810	Kspar 0.2, Ore 0.9



LOCALITIES OF ANALYSED SAMPLES FROM THE SIDLAW HILLS, PERTHSHIRE

Boundaries based on those of Harry (1956, 1958) and Armstrong and Paterson (1970)