

GEOCHEMISTRY OF SUPRACRUSTAL ROCKS IN THE
SCOURIE - FOINDEE REGION OF THE
N.W. HIGHLANDS, SCOTLAND.

A thesis submitted by
PIUS CSITADINMA OKEKE, B.Sc., M.Sc., D.I.C., F.G.S.

for the degree of DOCTOR OF PHILOSOPHY of the University of London.

May, 1973

Geology Department,
Royal School of Mines,
Imperial College,
London, S.W.7

To my wife

ABSTRACT

The Supracrustal rocks and the associated igneous bodies between Scourie and Foindle occupy north-easterly and north-westerly trending zones respectively within the mainland Lewisian Complex. These rocks are brown-weathering, 'unusual' types of rocks within the complex, and can easily be distinguished from the igneous intrusions. They have been extensively affected by two regional tectono - metamorphic events. An early metamorphism produced medium pressure granulite facies assemblages. They were then retrogressed, which probably increased the abundance of hornblende. The degree of this amphibolitization increases from Scourie in the south to Foindle in the north. Potash metasomatism accompanied this amphibolitization.

Petrographic studies show that the supracrustal rocks are essentially quartz - feldspathic gneisses characterized by the assemblage: quartz + biotite + feldspars + garnet ± muscovite ± sillimanite ± hornblende ± Kyanite ± zircon ± rutile. In the meta-igneous rocks, typical assemblage is: hornblende ± quartz + feldspars ± garnet ± biotite. Few primary igneous minerals or textures have been recognised in some of the rock samples studied.

Geochemical studies reveal that these Supracrustal rocks are metasediments - meta-pelites (in which sillimanite and Kyanite may be preserved), meta-greywackes, and meta-arkoses, - and that the amphibolites are probably meta-basalts of low - alkali tholeiitic type.

On the basis of field evidence, petrography and geochemistry, it is suggested that the metasediments could have been derived from older meta-igneous rocks by normal sedimentary processes. This probably occurred in the early Scourian or pre-Scourian.

ACKNOWLEDGEMENTS

That I started it at all is due to Dr. Gloria Borley whose idea it was, who gave the much needed supervision, and who persuaded me to carry on despite problems. The Federal Government of Nigeria gave me vital financial sponsorship.

I doubt if I would have finished the thesis without the encouragement and help of Professor Janet Watson (in particular), Mr. R. Parker, Mr. H. Thoms, Mr. P. Watkins, Mr. A. Hill, Mr. G. Bullen, Mrs. Susan Parry, Mrs. Ela Kim, and Miss Floretta Taylor. I benefited from useful discussions with my colleagues, Mr. David Savage, and Miss Kate Brodie. Gratitude is due to Drs. A. Barber, A. Beach, and R. Graham, who took me on a visit to the Lewisian Complex in April, 1976, during a trip organised by the Geologists' Association of London, and who introduced me to the geology of the rocks that I studied in this project. The hospitality of Mrs. D. Mackay of the Scourie Lodge cannot also be forgotten.

I am especially grateful to my wife, Clara to whom this thesis is dedicated and my parents. I understood their concern and appreciated their interest.

LIST OF CONTENTS

Page

	ABSTRACT	3
	ACKNOWLEDGEMENTS	4
	LIST OF TABLES	10
	LIST OF PLATES	13
	LIST OF ILLUSTRATIONS	15
CHAPTER 1	INTRODUCTION	20
1.1	The Lewisian Complex	20
1.2	Summary of the Lewisian Complex past studies	23
1.3	Supracrustal rocks in the Lewisian Complex	26
1.4	South Harris metasediments	27
1.5	Previous work in the Scourie - Laxford area	29
1.5.1	Structural geology	29
1.5.2	Mafic and Ultramafic rocks	30
1.5.3	General geochemistry	30
1.5.4	Sedimentary relics	30
1.6	The present work	31
1.7	Methods of study	32
1.8	Format	32
1.9	A note on Terminology	33
CHAPTER 2	FIELD RELATIONSHIPS & STRUCTURES	
2.1	General	40
2.2	Magnetic anomalies in Scourie - Foindole region	42
2.3	Field mapping	42
2.4	Field relationships	43
2.4.1	Meta-igneous bodies	43
(1)	Mafic gneisses/Amphibolites	43
(2)	Ultramafic gneisses	44
(3)	Anorthositic gneiss	44
(4)	Quartz - feldspathic gneisses	45
(5)	Banded acid gneisses	45

		Page
(6)	Scourie dykes (dolerite & metadolerite)	46
(7)	Pegmatites	46
2.4.2	Metamorphosed Supracrustal rocks	47
(1)	Quartzitic gneisses	47
(2)	Feldspathic gneisses	48
(3)	Garnet granulites	48
(4)	Biotite - muscovite - garnet gneisses	48
(5)	Biotite - garnet gneisses	48
(6)	Biotite schists	49
(7)	Quartz - biotite schists	49
(8)	Quartz - biotite - garnet gneisses	49
(9)	Quartz - magnetite gneisses	49
(10)	Quartz - mica schists	50
(11)	Quartz - garnet - mica gneisses	50
(12)	Quartz - feldspathic gneisses with garnet	50
2.5	Structures	
2.5.1	General	51
2.5.2	Folds	51
2.5.3	Foliations	52
2.5.4	Shear zones	52
2.5.5	Lineations	53
2.5.6	Boudins	53
2.5.7	Joints and Faults	53
CHAPTER 3	PETROGRAPHY & MINERALOGICAL CLASSIFICATION	
3.1.	General introduction	62
3.2	Meta-igneous rocks	63
3.2.1	Mafic gneisses	63
3.2.2	Hornblende gneisses (Amphibolites)	64
3.2.3	Ultramafic gneisses	64
3.2.4	Quartz - feldspathic gneisses	65

		Page
3.3	Metamorphosed Supracrustal rocks including metasediments	65
3.3.1	Quartzitic gneisses	65
3.3.2	Feldspathic gneisses	66
3.3.3	Garnet granulites	66
3.3.4	Biotite - muscovite - garnet gneisses	67
3.3.5	Biotite - garnet gneisses	67
3.3.6	Biotite schists	68
3.3.7	Quartz - biotite schists	68
3.3.8	Quartz - biotite - garnet gneisses	68
3.3.9	Quartz - magnetite gneisses	69
3.3.10	Quartz - mica schists	69
3.3.11	Quartz - garnet - mica gneisses	70
3.3.12	Quartz - feldspar - garnet gneisses	70
3.3.13	Quartz - garnet - feldspar gneisses	71
3.4	Conclusions from the petrographic study	71
CHAPTER 4	MAJOR ELEMENT GEOCHEMISTRY	
4.1	Introduction	81
4.2	Meta-igneous rocks including Amphibolites	84
4.3	Supracrustal rocks	86
4.4	FMA	87
4.5	Normative Or-Ab-An	88
4.6	K ₂ O - Na ₂ O - CaO	88
4.7	K ₂ O - SiO ₂	88
4.8	Oxidation Ratio	89
4.9	Summary and Survey of interpretations	90
CHAPTER 5	TRACE ELEMENT GEOCHEMISTRY	
5.1	General	103
5.1.1	K, Rb	105

		Page
5.1.2	K, Sr	106
5.1.3	Ba	107
5.1.4	Ca, Sr	107
5.1.5	Zn, V, Cr, Cu	110
5.1.6	Zr	111
5.1.7	Th	111
5.1.8	Y	112
5.2	Rare-earth elements (REE)	120
5.2.1	Choice of chondrite REE data	122
5.2.2	Normalization	122
5.2.3	Plotting of REE data	126
5.2.4	REE ratios	126
5.2.5	Y and REE	127
5.2.6	Interpretation of REE data	127
(1)	Retrogressed Leuco-gabbro	128
(2)	Granitic gneisses	128
(3)	Amphibolites	129
(4)	Meta-pelites	138
(5)	Meta-greywackes	139
(6)	Meta-arkoses/Impure quartzites	139
5.2.7	Summary of REE geochemistry	141
CHAPTER 6	RECLASSIFICATION OF THE ROCK TYPES ON BASIS OF OVER-all GEOCHEMISTRY	
6.1	Introduction	143
6.2	Niggli values	145
6.3	Triangular diagrams	148
6.4	Major element compositions & Normative Corundum & Quartz	149
6.5	Discriminant functions	169
6.6	Trace element abundances and ratios	172

		Page
6.7	Discrimination of magma types	179
6.8	Summary	187
CHAPTER 7	GENERAL DISCUSSION OF GENESIS AND METAMORPHISM	
7.1	Introduction	189
7.2	Problem of migmatization	189
7.3	Genesis	190
7.4	Metamorphism	197
7.5	Summary of chronological events	216
7.6	Suggestions	222
	CONCLUSIONS	225
	REFERENCES	229
	APPENDIX I	254
	APPENDIX II	260
	APPENDIX III	307
	MAPS	

LIST OF TABLES

Page

1.1	Division of the Lewisian into regions, extent and rock types (after Peach et al. 1907)	35
1.2	Major events in the history of the Lewisian mainland based on Rb-Sr dating (after Moorbath et al. 1969)	36
3.1	Scourian - Laxfordian minerals from rocks between Scourie and Laxford (after Davies, 1974)	74
3.2	Summary of 'representative' assemblages for the rock types in the two sample areas near Scourie and Foindle	75
3.3	Summary of 'representative' fabrics for the rock types in the two sample areas near Scourie and Foindle	76
4.1	Summary of major element analyses for all the rock types.	93
4.2A	Major element compositions (averages & ranges) for rocks in Foindle zone	94
4.2B	Major element compositions (averages & ranges) for rocks in Scourie zone	95
4.3A	CIPW Norms and Niggli values (averages & ranges) for rocks in Foindle zone	96
4.3B	CIPW Norms and Niggli values (averages & ranges) for rocks in Scourie zone	97
5.1	Summary of whole - rock XRF trace element and REE analyses for all the rock types	104
5.2A	XRF trace element compositions (averages & ranges) for rocks in Foindle zone	108
5.2B	XRF trace element compositions (averages & ranges) for rocks in Scourie zone	109

5.3	Rare-earth element abundances (ppm) in chondrite, NASC, and BCR-1 standard	123
5.4	Rare-earth element data (ppm) for the rocks in Scourie - Foindle region	124
5.5	Rare-earth element data (ppm) for rocks used for comparison	125
6.1	Major element compositions (averages & ranges) for rocks (re-classified) in Foindle and Scourie	180
6.2	CIPW Norms (averages and ranges) for rocks (re-classified) in Foindle and Scourie	181
6.3	Niggli values (averages and ranges) for rocks (re-classified) in Foindle and Scourie	182
6.4	XRF trace element compositions (averages and ranges) for rocks (re-classified) in Foindle and Scourie	183
6.5	REE compositions (averages and ranges) for rocks (re-classified) in Foindle and Scourie	184
6.6	Average chemical compositions of selected sedimentary and igneous rocks for comparison	185
7.1	Summary of elemental and oxidation ratios for all rock types	198
7.2	Mineralogy and metamorphism in the Supracrustal rocks in Scourie and Foindle	199
7.3	Average major element compositions for meta-greywacke, meta-pelite, and granitic gneiss	210
7.4	Average XRF trace element compositions for meta-greywacke, meta-pelite, and granitic gneiss	211

		Page
7.5	Average REE compositions for meta-greywacke, meta-pelite, and granitic gneiss	212
7.6	Chronological events in the Scourie - Foindle region	217
7.7	Average chemical compositions for rocks used for comparison and discussion in Chapter 7	218
7.8	Average granulites from type localities	219
7.9	Average grey gneisses from Scotland and Greenland	220
7.10	Average chemical compositions of selected gabbroic rocks	221

LIST OF PLATES

Page

2.1	Scourie dyke (dolerite) deformed by pegmatite, folded and sheared	54
2.2	Interlayering of leucosome and melanosome materials in the Banded acid gneiss, Foindle	54
2.3	Mafic pod (boudin) in quartz - feldspathic gneiss, Foindle	55
2.4	Conformable contact between Amphibolite and Biotite schist, Foindle	55
2.5	Quartz veining in Amphibolite, Foindle	56
2.6	Granular texture garnet granulite, Scourie	56
2.7	Pegmatite vein in Quartz - biotite - garnet gneiss, Foindle - Fanagmore road	57
2.8	Conformable contact between Quartz - biotite - garnet gneiss and mafic gneiss, Foindle	57
2.9	Pegmatite vein in mafic gneiss, Foindle	58
2.10	Shear zone in Biotite schist, Foindle	58
2.11	Isoclinal folds in mafic gneiss, Foindle	59
2.12	Slumping and shearing effects in mafic gneiss, Foindle	59
3.1	Biotite replacing potash - feldspar in Quartz-feldspathic gneiss, Foindle	77
3.2	Granular texture in Feldspathic gneiss, Foindle	77
3.3	Extensive retrogression effects in Biotite - muscovite - garnet gneiss, Foindle	78

3.4	Biotite flakes in Hornblende gneiss (Amphibolite), Foindle	78
3.5	Granular texture and polygonal quartz grains in Quartzitic gneiss, Foindle	79
3.6	Triple junctions and granular texture in Quartz - garnet mica gneiss, Foindle	79
3.7	Retrogression in Ultramafic gneiss, Scourie	80
3.8	Random orientation of biotite in Quartz - garnet - feldspar gneiss, Scourie	80

Fig. No.	LIST OF ILLUSTRATIONS	Page
1.1	Sketch-map showing the mainland Lewisian outcrops (after Watson, 1965)	37
1.2	Sketch-map of the major tectonic structures and foliations in the Lewisian rocks between Scourie and Laxford (after Beach, 1971)	38
1.3	Map illustrating the distribution of pre-Badcallian Basic, Ultrabasic and Supracrustal rocks between Scourie and Laxford of the Scourian Complex (after Davies & Watson, 1977)	39
2.1	Aeromagnetic anomaly map of the Scourie - Foindle region taken from I.G.S one inch survey	60
2.2	Polar diagram for the foliations in Scourie - Foindle region	61
4.1	FMA diagram	98
4.2	Or - Ab - An diagram	99
4.3	K ₂ O - Na ₂ O - CaO diagram	100
4.4	K ₂ O vs SiO ₂ diagram	101
4.5	MgO, CaO, Al ₂ O ₃ , SiO ₂ vs. $\frac{\text{FeO}_t}{\text{FeO}_t + \text{MgO}}$ diagrams	102
5.1	K-Rb plot	115
5.2	K-Sr plot	116
5.3	K-Ba plot	117
5.4a	CaO vs. Y plot (all rock types)	118
5.4b	CaO vs. Y plot (amphibolites)	119

Fig. No.		Page
5.5	Rare-earth comparison diagrams for Scourie Ultramafic gneiss, Foindle mafic gneiss, Stillwater peridotite etc.	131
5.6	Rare-earth comparison diagrams for the Foindle - Scourie quartz -feldspathic gneiss, Granitic rocks, Finland etc.	132
5.7	Rare-earth comparison diagrams for Foindle amphibolites, and average Archean basalt, Ely Minnesota	133
5.8	Rare-earth comparison diagrams for Foindle - Scourie meta-pelites, Precambrian North American Shales, etc.	134
5.9	Rare-earth comparison diagrams for the Foindle - Scourie meta-greywackes, Wyoming greywackes, etc.	135
5.10	Rare-earth comparison diagrams for Foindle Quartzitic gneiss, Moodie' quartzites, etc.	136
5.11	Plots of Foindle - Scourie metasediments normalized to NASC	137
6.1	Niggli (ti vs. al-alk) and Niggli (ti vs. mg) plots for the meta-igneous rocks	151
6.2	Niggli (ti vs. al-alk) and Niggli (ti vs. mg) plots for the meta-sedimentary rocks	152
6.3	Zr vs Niggli (al-alk) and Zn vs. Niggli mg plots for the meta-igneous rocks	153
6.4	Zr vs Niggli (al-alk) and Zn vs. Niggli mg plots for the meta-sedimentary rocks.	154
6.5	Niggli (al-alk) vs mg, Ni vs mg, and Cr vs mg diagrams for the meta-igneous rocks	155

Fig. No.		Page
6.6	Niggli (al-alk) vs mg, Ni vs mg, and Cr vs mg diagrams for the meta-sedimentary rocks	156
6.7	Log - plots of Chromium & Nickel against Niggli mg for the Amphibolites, Foindle	157
6.8	Niggli mg - c plot	158
6.9	Plots of Niggli values for Foindle amphibolites, calc-silicate rock (Chowdhary et al. 1971)	159
6.10	Log - plots of chromium & Nickel against TiO_2 for the Amphibolites, Foindle	160
6.11	Normative Qtz - Ab - Or diagram	161
6.12	Normative Or - Ab - An diagram	162
6.13	MgO - CaO - Al_2O_3 diagram	163
6.14	MgO and CaO vs. SiO_2 plots	164
6.15	Ti ($\times 10^2$) - Zr - Sr ($\times 0.5$) discrimination diagram	165
6.16	Ti ($\times 10^2$) - Zr - Y ($\times 3$) discrimination diagram	166
6.17	TiO_2 - P_2O_5 - K_2O discrimination diagram	167
6.18	Ti (ppm) vs. Zr ppm discrimination diagram	168
6.19	$Na_2O + K_2O$ vs. SiO_2 diagram	173
6.20	Yb vs. MgO diagram	174
6.21	Ce_n/Yb_n vs Yb_n diagram	175
6.22	A F M diagram	176
7.1	Niggli 100mg - c - (al-alk) diagram	193

Fig. No.

Page

- 7.2 K - Rb plot showing main trend and oceanic
tholeiitic trend 205
- 7.3 Oxidation ratio vs. water (wt. %) diagram 206

Loose Maps in Back Pocket

- Map 1 Geological map of the Supracrustal belt around
Lochan Creige 'Mhail, Scourie (Scale, 1:3520)
- Map 2 Geological map of the Supracrustal belt around
Loch Nam Brac, Foindle (Scale, 1:1000)
- Map 3 Lithological map of the Supracrustal belt
around Lochan Creig 'Mhail, Scourie (Scale,
1:3520)
- Map 4 Lithological map of the Supracrustal belt
around Loch Nam Brac, Foindle (Scale, 1:000)

CHAPTER 1

INTRODUCTION

1.1 The Lewisian Complex (Fig. 1.1).

'Lewisian' is the name given to the Precambrian basement Complex of North-west Scotland (between the Moine thrust and the west coast), and the Outer Hebrides. The Complex together with other gneiss terrains forms the North Atlantic craton, and is also a portion of a larger Precambrian Shield area fragmented by the opening of the North Atlantic in Phanerozoic times. The remnants of this Precambrian craton are now located over much of Greenland, along the coast of Labrador in East Canada and in the Lewisian (Davies, 1974). The craton and the marginal mobile zones incorporate a wide variety of rocks which include migmatites, intrusive igneous bodies and supracrustal rocks which all have a wide range of compositions. The rocks are characterized by granulite or amphibolite facies mineral phases. The oldest rocks of the craton are found in West Greenland to be about 3800 my (McGregor, 1973). Most rocks of the Lewisian Complex are about 2800 my in age.

Within the Lewisian Complex are rocks which have been metamorphosed more than once in their history and which are old enough to represent a very early stage in the evolution of the earth's crust. The two principal groups of metamorphic episodes responsible for the development of the complex have been termed Scourian (older) and Laxfordian (younger) by Sutton & Watson (1951). Lewisian rocks are unconformably overlain by unmetamorphosed Torridonian or Cambrian sediments.

The Lewisian Complex exhibits some lithological variations summarized below:-

- (a) Dominant pyroxene granulites
- (b) Dominant grey gneisses or granite sheets, granitic

gneisses, and

(c) Supracrustal rocks which have resisted incorporation into (a) and (b). These rocks have been found now in increasing number within the Complex (e.g. Coward *et al.* 1969). The outcrops of these Supracrustal rocks range in size from a few square metres to belts many kilometres long, and their preservation reflects a major inhomogeneity in the gneiss - forming process. This thesis is concerned mainly with an investigation of the petrography and chemistry of Supracrustal rocks in part of the mainland Lewisian outcrop. In the Outer Hebrides, the intensity of Laxfordian reworking of Scourian rocks varies markedly even within small areas. In some places Scourian structures and minerals are preserved, while in others, where the gneisses have suffered the full effects of Laxfordian deformation and crystallization, Scourian features are almost totally obliterated (Lisle, 1974; Coward, 1969; Graham, 1969).

Structural aspects of large proportions of the Lewisian Complex have been investigated by many in great detail but little attention has been paid to details of the metamorphic history preserved in the rocks in order to understand the characteristics of the several metamorphic events. An attempt in this line has been made in Dickinson (1974).

In the Lewisian, the intrusion of basic dykes (Scourie dykes) marks a useful event, since the metamorphism and deformation of these dykes can be used to subdivide the Complex into the older (Archean) Scourian and a younger (Proterozoic) Laxfordian Complex (Sutton & Watson, 1951).

The boundaries that separate blocks of the older complex from the areas of 'reworked' complex, occur roughly at intervals of a few tens of kilometres. The areas of reworked complex have been designated "Marginal belts" by Davies (1974) and are mostly north-west trending.

Within the Lewisian Complex, two types of marginal belt have

been distinguished, namely:-

(A) One type of marginal belt lies between an older region that retains granulite facies assemblages and that has remained essentially stable since the end of granulite facies metamorphism, and a reworked zone which has amphibolite facies mineral assemblages and new structural patterns. This type of marginal belt is well developed in the Scourie - Laxford region (Sutton & Watson, 1951), and in the Loch Inver region (Evans & Lambert, 1974).

(B) The other type of marginal belt lies between blocks which retain older structures but have amphibolite facies mineral assemblages, and regions where new structural patterns are developed in conjunction with amphibolite facies mineral assemblages. This type of belt has been encountered most often in the Western Gneisses (Dearnley, 1962) of the Outer Isles and is typified by those of north-west Lewis (Lisle, 1974) of which the Ness belt is an example.

In the Scourie - Laxford area, a north-westerly trending tract of basic and ultrabasic rocks broadly marks the transition zone from pyroxene gneisses in the south around Scourie to the granites and migmatites to the north around Laxford. In the Outer Isles, there are also polycyclic quartz - feldspathic gneiss marked by ultrabasic, basic and anorthositic rocks. This distinctive assemblage of ultrabasic, basic and anorthositic rocks is associated in each region with Supracrustal rocks; similar associations also occur outside the marginal belts and often lie in north-west trending belts as in the north-west Lewis (Lisle, 1974) and Scourie - Laxford area (Davies, 1974).

The origins of some of the major crustal components of the Lewisian are still matters of debate. For example, in the Godthab area of West Greenland, which seems to have escaped the granulite facies metamorphism that affected most of the North

Atlantic craton, the work of McGregor (1973) suggests that the Supracrustal rocks were laid down on a basement of deformed granitic rocks, and that a series of younger ultrabasic, basic and anorthositic intrusions were emplaced into this older complex. The existence of such a basement in Scotland is still in doubt.

1.2 Summary of the Lewisian Complex Past Studies

Extensive studies have gone on for the past 25 years on the Precambrian basement complex. Studies have involved many facets of geology and here an attempt is made to record most of the major findings by different workers.

Peach et al. (1907), were the first to do a systematic mapping of the Lewisian Complex, Scotland over a period of more than 25 years. This work resulted in the publication of the first maps on a scale of 1" to 1 mile and of a geological survey memoir for the mainland region. The authors (op cit. p.37) divided the Lewisian into 3 regions (see Table 1.1). Teall (op cit. p.41) preferred the following grouping based upon rock types:-

- (A) The Fundamental Complex: rocks allied to plutonic igneous rocks, with metamorphosed sediments around Loch Maree and Gairloch
- (B) A series of Pre-Torridonian dykes and sills of basic, ultrabasic, and acid type intruded into Fundamental Complex.

The authors of the memoir demonstrated that in the Central region, the Fundamental Complex is invaded by unmodified dolerite dykes while in the northern and southern regions, dykes of the same suite have been affected by later events and are now incorporated into the complex; they cannot always be distinguished from older basic rocks belonging to the Complex itself. This alteration of the dykes was attributed to the 'terrestrial stresses' which also caused the development of a new north-westerly trending foliation

within the same part of the Complex. It is vital to mention that the work by Peach et al. (1907) has remained a useful guide to later workers on the general geology of the Complex. Some of their results have, to date, remained undisputed.

The next major advance came, after about 50 yrs., from the work of Sutton & Watson (1951). They demonstrated that the period of stress occurring after the dyke intrusion was accompanied by regional metamorphism and migmatization over a very wide area. They therefore recognized two metamorphic complexes within the Lewisian; the older (Scourian) complex predating the dykes and the younger (Laxfordian) complex post-dating them. The Scourian metamorphism was in granulite facies while the Laxfordian metamorphism was in amphibolite facies. During the Scourian metamorphism, a general north-east trending foliation was produced and the Scourian Complex was intruded by a suite of dolerite dykes; in the Central part of the Complex these dykes are unaltered and show igneous textures and mineralogies. Sutton & Watson (op cit), also showed that after the period of dyke intrusion, further episodes of metamorphism in amphibolite facies occurred which reworked parts of the Scourian Complex; injection of granites and pegmatites occurred and the Scourie dykes were deformed, metamorphosed, and incorporated into this new Laxfordian Complex. The Central part of Scourian Complex was, however, not affected by these events and the Scourian minerals and structures were preserved.

Further stimulation in researches into the Lewisian Complex came by the advent of radio-isotopic methods for dating rocks. Gilletti et al. (1961) applied Rb-Sr methods to micas and feldspars from Scourian pegmatites and found they were more than 2500 my old; by similar methods they dated the Laxfordian pegmatites at about 1600 my. A summary of the dating results was provided by Moorbath et al. (1969) and is given in Table 1.2. Pb-isotope

dating by Moorbath et al (op cit) shows that the greater part of the Lewisian Complex was already in existence at 2900 ± 100 my. These research workers also considered that substantial uranium depletion at the time resulted from the granulite facies metamorphism thus giving an older date for this event than that indicated by Rb-Sr and K-Ar methods.

Evans (1963, 1964, 1965) used structural and radiometric evidence to define an amphibolite facies event which locally produced a zone of north - west - south - east trending foliation at about 2200 my (the 'Inverian'). This event reworked the Scourian gneisses, but the Inverian structures which it produced are themselves cut by Scourie dykes.

In the Outer Hebrides Dearnley (1962) was the first to recognise basic dykes, equivalent to the Scourie dyke suite of the mainland, which he used to separate Scourian effects from those of Laxfordian. He proposed a three-fold regional division of the Outer Hebridean Lewisian similar to that of the mainland. This three fold division was not followed by Coward et al. (1970), who maintained that the central zone of the Hebrides, unlike that of the mainland, had suffered considerable, if variable, amounts of Laxfordian deformation.

Myers (1968, 70, 71) studied the Western Harris migmatite complex and the Langavat Supracrustal belt. He showed that the early gneiss complex was developed by extensive recrystallization of a supracrustal sequence, although some supracrustal relics remained. He demonstrated that the main Laxfordian event was in amphibolite facies with granulite assemblages developing further southwards. A later (Laxfordian) synkinematic granite - migmatite complex developed in Western Harris accompanied by widespread hydrous metamorphism, granitization was catalysed by introduction of potash.

Researches in later years on the Lewisian geology have

concentrated more in the fields of geochemistry and geophysics. Lots of geochemical studies have been undertaken on major and minor scales. The researches are so many that they cannot all be enumerated here. They are, therefore, mentioned in this thesis as need entails.

Little geophysical work has been done. A gravity investigation in relation to the structure of the mainland complex has been published in Bott *et al.* (1972). From their gravity profiles across the Ben Stack Line (Peach *et al.* 1907 p.126; Holland & Lambert, 1973), and from the I.G.S. aeromagnetic map, they showed that the Laxfordian biotite gneisses in the north are underlain at a depth of about 3 kilometres by pyroxene granulites similar to those that outcrop in the Scourian complex to the south. A palaeomagnetic study of part of the Lewisian was undertaken by Beckmann (1976). He measured the directions of magnetization in the dykes and gneisses of the Central zone of the mainland Lewisian and in the Laxford granite sheets. Results showed that the paleopole direction for a Scourian granulite fell very close to the mean for the dykes and that a stable magnetization was probably imposed in the late Laxfordian metamorphism at about 1800 m.y.

The results from these studies have helped to confirm the previously held ideas, disprove them or create new ones, but some of the complex problems of the Lewisian geology are still to be solved.

1.3 Supracrustal rocks in the Lewisian Complex

In this section of the thesis, a brief comment is necessary about previous work on those rocks which are the main object of this thesis. These rocks have been recorded in the complex as far back as 1819 by MacCulloch. He found a marble in Rodil (South Harris). Researches in the last ten years have shown that such rocks are more widely distributed than was formerly supposed.

Distinctive areas of metasediments are recorded from

- (A) Gairloch and Loch Maree districts (Peach *et al.* 1907; Bowes & Battacharjee, 1967; Park, 1964)
- (B) The Leverburgh and Langavat belts of South Harris (Jehu & Craig, 1927; Davidson, 1943; Dearnley, 1959, 1963; Coward *et al.* 1969)
- (C) The Ness district of Lewis (Watson, 1969)
- (D) Glenelg (Clough, 1910), and
- (E) Scourie and Laxford (fig. 1.3; Davies & Watson, 1977).

Smaller patches of similar material are recorded throughout the Outer Hebrides (Coward *et al.* 1969; Lisle, 1974); from the area between Loch Laxford and Durness (Chowdhary *et al.* 1971), south east of Scourie (Barooah, 1970), and from Scourie More (Savage, pers. communication). Sheraton (1969) concluded from geochemical evidence that many of the gneisses in the Drumbeg area had originated as dacitic and andesitic lavas which were intercalated with thin sedimentary horizons.

Some, if not all, of the Supracrustal rocks existed before the Scourian metamorphism, 2900 m.a (Coward *et al.* 1969; Coward *et al.* 1970) and their relationships with other rocks are of great importance in a study of the entire complex.

1.4 South Harris metasediments

The metasediments are probably among the oldest rocks in the Outer Isles, and are either Scourian or pre-Scourian (Skinner, 1970). These rocks from South Harris deserve special mention because they represent at the present time, what may be referred to as 'obvious' metasediments in the Lewisian. They include

- (a) forsterite marbles
- (b) diopside rich calc - silicates,
- (c) graphite schists,
- (d) Quartzites, and

(e) Kyanite or sillimanite gneisses.

Usually the carbonate and calc-silicate rocks are found in discontinuous lenticular patches. Pelitic and psammitic gneisses are much more abundant. They consist essentially of quartz, one or two feldspars, biotite, garnet and kyanite with occasional muscovite, sillimanite, hornblende or rutile. This assemblage is high grade but the occasional presence of muscovite must preclude granulite facies temperatures, and could be due to the retrogression of the early granulites. Cordierite was reported by Davidson (1943), more recently by Coward et al. (1969), and by Cunningham (pers. communication) in South Harris, but it has not been seen in any of the specimens collected by the writer in the Foindle and Scourie region of the mainland. The mineral assemblages observed in these metasediments are rarely seen unmodified. The sediments are not intimately intruded by an igneous complex. They show a strong retrogression, and in some cases complete recrystallization. The garnets are frequently seen altering to biotite, this time a pale-yellow brown or yellow-green biotite in contrast to the brownish-yellow primary metamorphic biotite. The foliation is often seen rotated by this post garnet formation such that it is at variance with a relict foliation retained within the garnets. In the most spectacular examples large kyanite crystals are seen bent around the euhedral garnets. Some examples are retrogressed and crystallized that they are composed entirely of quartz, feldspar and biotite, the last mineral showing a marked preferred orientation. Dearnley (1963) and Witty (1975) consider that there is evidence for two periods of garnet growth corresponding to granulite facies metamorphism in the Scourian and Laxfordian. Davidson (1943) did not recognise a super-position of events, but both agree that the present assemblage was formed at the time of the metamorphism of the Igneous Complex which intrudes them.

1.5 Previous work in the Scourie - Laxford area

The Scourie - Laxford area forms a transition zone between the Scourian gneisses cut by basic dykes to the south and the Laxfordian polycyclic gneisses in the north. Many studies have been made on the rocks within this transition zone. Here, an attempt will be made to summarize what are considered to be the contributions from various workers under the headings: Structural geology, general geochemistry, and sedimentary relics.

1.5.1 Structural geology

Several maps (e.g. fig. 1.2) from the area have been published and structural interpretations given: e.g. in Peach *et al.* (1907); Watson (1949; Sutton & Watson (1951); Sutton & Watson (1961); Beach (1974); Beach *et al.* (1974); Holland (1966); and Davies (1974, 1976). A major controversy arising from this work has been over the 'best' interpretations for the evolution of the Laxford front with particular emphasis on the emplacement of the migmatites. There are two schools of thought. Holland (1966) believes that the migmatites were folded into a basement of pyroxene granulites. Beach (1974), on the basis of existing geological and geophysical data, suggested that the development of the shear zones followed regional north-ward overthrusting (of unknown extent) which emplaced the Scourian granulites above what are now Laxfordian migmatites. The Laxford front is a zone of complex rotational deformation which separates intensely deformed Laxfordian migmatites from heterogeneously deformed pyroxene granulites (Beach *et al.* 1974). The dominant sense of movement as inferred from the shear zones is sinistral and north-side upwards. This implies that the migmatites were moving upwards from beneath the Scourian granulites (i.e. overthrusting).

However, in general, all previous workers in the area accept the fact that there have been two major phases of deformation and

that the Laxford front marks a zone of exceptionally high strain. Almost all authors also agree that modified Scourian rocks extend as far north as the outcrop of the Laxford granite sheets; most regard rocks of the Laxfordian complex north of these sheets as time - equivalents of the Scourian granulites, differing from the latter in metamorphic history.

1.5.2 Mafic and Ultramafic rocks

Valuable mineralogical and chemical studies were made by O'Hara (1961a, b), Muecke (1969) and Bowdidge (1969) on the Scourian ultrabasic and basic gneiss masses at Scourie. These layered igneous bodies have been interpreted by some of these workers to be cumulates. Bailey (1951), and Burns (1966) also studied the dykes. Burns (op. cit) in his study on the chemical and mineralogical changes associated with the Laxfordian metamorphism of dolerite dykes in the area showed that introduction of components was limited, only potassium showing a marked increase in concentration.

1.5.3 General geochemistry

Holland (1966) used 400 chemical analyses in his geochemical study of the Lewisian rocks of the Scourie - Laxford area. On the basis of his data, he suggested that a geochemical boundary between Scourie and Laxford lay within the presently accepted Laxford front, but such a boundary is not easy to establish on the ground. Beach et al. (1974) also hold the same view as Holland (op. cit).

1.5.4 Sedimentary relics

The existence of possible sedimentary relics between Scourie and Laxford has gradually been confirmed, and petrographic and chemical evidence on this subject is summarized below. All examples, except (2), are from work on the Scourie Complex.

(1) Barooah (1970) describes 3 rock types, namely calc-silicate granulite, meta-arkose, and chlorite schist. The calc-silicate granulite, a diopside - garnet - calcite - plagioclase rock, is of particularly convincing sedimentary appearance, both in hand specimen and thin section.

(2) Chowdhary et al. (1971) describe two occurrences of quartzites in the Laxfordian Complex near Rhinconich.

(3) Clough et al. (1907) in the Geological Survey of Scotland, 6" sheet Sutherland 39, note the irregular sill of saussurite. They also recognised two occurrences of limestone between Scourie and Kylesku and existence of garnetiferous rocks (garnet - biotite schists) near Ben Stack.

(4) Davies (1974) mapped a series of 'brown schists'. He interpreted them as metamorphosed Supracrustal rocks with mineral assemblages (sillimanite and kyanite) characteristic of aluminous metasediments, and also calc-silicate gneiss.

The field occurrences of these rocks between Scourie and Laxford and within the entire Lewisian, suggesting sedimentary origin render the hypothesis of direct derivation of the entire complex from the mantle some what less palusible. The existence seems significant in the interpretation of the Lewisian history.

1.6 The present work

A major difficulty in the Scourie - Laxford region has been to produce satisfactory criteria by which the nature and origin of large number of supracrustal rocks could be established. The work discussed in this thesis is therefore an attempt to

- (a) define the characteristics of the Scourie - Foindle Supracrustal rocks
- (b) describe those textural features of the rocks which give valuable information on the mode of deformation that prevailed during their history

- (c) elucidate the nature of the metasomatism that affected them
- (d) use chemical evidence to
 - (1) classify them
 - (2) suggest what rock types they were before metamorphism and deformation, and
 - (3) propose a source and how they were derived.

1.7 Methods of study

The localities shown in fig. 2.1 were mapped on a scale of 1:1000 over an area of about 5.59 sq. km around Loch Nam Brac, in the region of Foindale, and on a scale of 1:3520 over an area of 0.56 sq. km around Lochan Creige 'Mhail, in the region of Scourie. In situ exposures were poor due to the effects of glaciation which has obscured some of the solid geology.

Samples were collected by random sampling. As a result of the inhomogeneity of the rocks, the choice of representative samples was a matter of personal judgement. However, it is considered that the collection can be regarded as representative for the region.

Laboratory work included a petrographic study of 116 thin sections of the rocks from both areas, and analysis of 56 selected rock samples by X-ray fluorescence, wet chemical, and instrumental Neutron Activation techniques.

1.3 Format

The metric system of measurement has been adopted throughout the thesis. All diagrams are termed figures, photographs are referred to as plates while tables still remain tables. These are numbered sequentially within each chapter. The numbers of the thin sections which appear in photographs (Chapter 3) refer to the thin section numbers in the Department of Geology collection, Imperial College.

1.9 A note on terminology

The terms 'Scourian' and 'Laxfordian' were introduced by Sutton & Watson (1951) to refer to pre-dyke and post-dyke events; and were defined to include all events which fell into these two divisions of time. In view of the increasing knowledge of the complexity of the history of the Lewisian, as well as the fact that there are several types of basic dykes present in the Lewisian (Tarney, 1963; O'Hara, 1961a; Sutton & Watson, 1951; Clough *et al.* 1907); and the possibility that these dykes may be of more than one age (Bowes & Ghaly, 1964; Bowes & Khoury, 1965; Evans & Tarney, 1964; Park, 1964), it may be more desirable to have specific names to separate phases of metamorphism, which are not defined in terms of their relations to any dykes. The method of isotopic dating makes it feasible to adopt this nomenclature.

In this thesis, the terms 'Scourian' and 'Laxfordian' are used in much the same sense as they were used by Sutton & Watson (1951) but not in the broad sense that their strict definition would imply. They will refer to groups of rocks, Scourian gneisses (Scourian Complex) formed in single metamorphic episode and their metamorphic effects are best seen at or near Scourie and dated at about 2600 my while the Laxfordian gneisses (Laxfordian Complex) refer to those later rocks typically seen around Laxford and about 1600 my old. Therefore, 'Scourian' could be said to represent the period from the accumulation of the Supracrustal pile which may rest upon an earlier basement to the onset of the intrusion of the Scourie dyke suite at or before about 2190 my, and 'Laxfordian' denotes the period from 2190 to 1400 my (Dickinson, 1974). Such terms as Badcallian (Park, 1970) and Inverian (Evans, 1965) which refer to more narrowly defined episodes on the mainland have been avoided in this thesis in order not to create a confusion of taking them to be either distinct orogenies or episodes of metamorphism and/or deformation.

A few terms are used without introduction. 'Foliation' and 'gneiss' are used in the sense of Harker (1939) to apply to any planar structure, and any coarse grained metamorphic rock showing this structure. 'Banding' is considered as a variety of foliation. 'Granulite' is used exclusively to refer to the granulite facies.

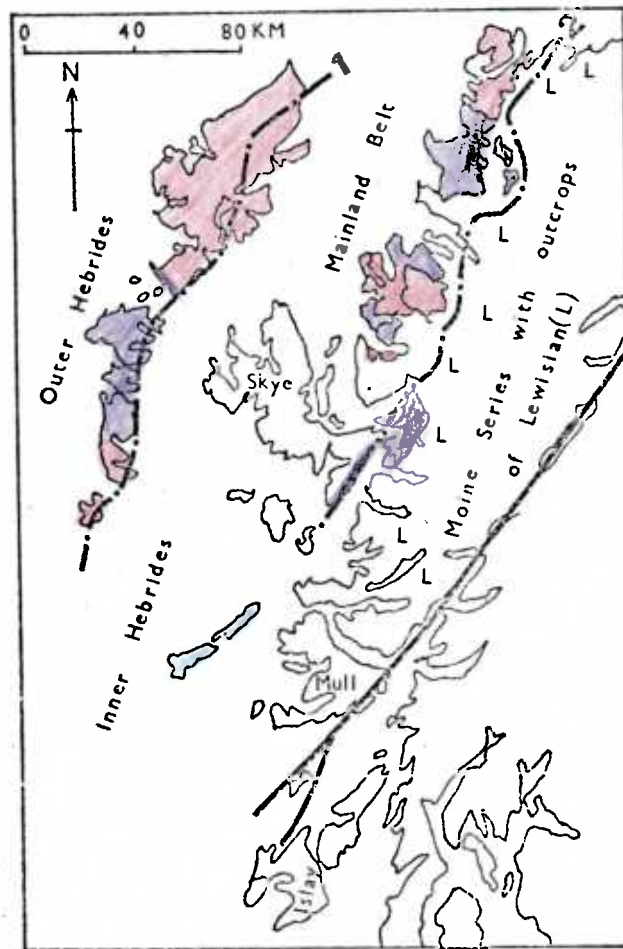
All abbreviations used are explained in the Appendix 1, and are either conventional or self-explanatory.

Table 1.1 Division of the Lewisian into regions, extent and rock types (after Peach et al. 1907)

Region	Extent	Main rock types
1. NORTHERN	Cape wrath to Loch Laxford	Hornblende and Biotite gneisses
2. CENTRAL	North of Scourie to Loch Broom	Pyroxene gneisses
3. SOUTHERN	Guinard Bay to Loch Torrindon and Island of Raasay	Hornblende & Biotite gneisses Augen gneisses Sedimentary rocks in the neighbourhood of Gairloch

Table 1.2 Major Events in the History of the Lewisian Complex of the mainland based on the Rb-Sr dating from Moorbath et al (1969).

Age	Events
2,600 my (minimum)	Early Scourian metamorphism; structures of the north - east - south - west trend
2,5400 - 2,310 my	Intrusion of dyke - like potash pegmatites of north-east trend with cut Scourian structures and are locally folded by later events
2,190 - 1,900 my (?)	Intrusion of Scourie dyke suite
1,800 - 1,700 my (minimum)	Laxfordian amphibolites facies metamorphism; structures of north-west trend
1,700 - 1,6500 my	Laxfordian pegmatites and granites
1,450 - 1,400 my	Termination of radiogenic organ and strontium diffusion.



LEGEND

- Scourian complexes
- Laxfordian complexes
- Undated complexes on forland
- L
L
 Undated complexes of Caledonian orogenic belt
- 1 Outer Isle Thrust-plane
- 2 Moine Thrust plane

Fig. 1.1 Sketch-map showing the mainland Lewisian outcrops
(after Watson, 1965)

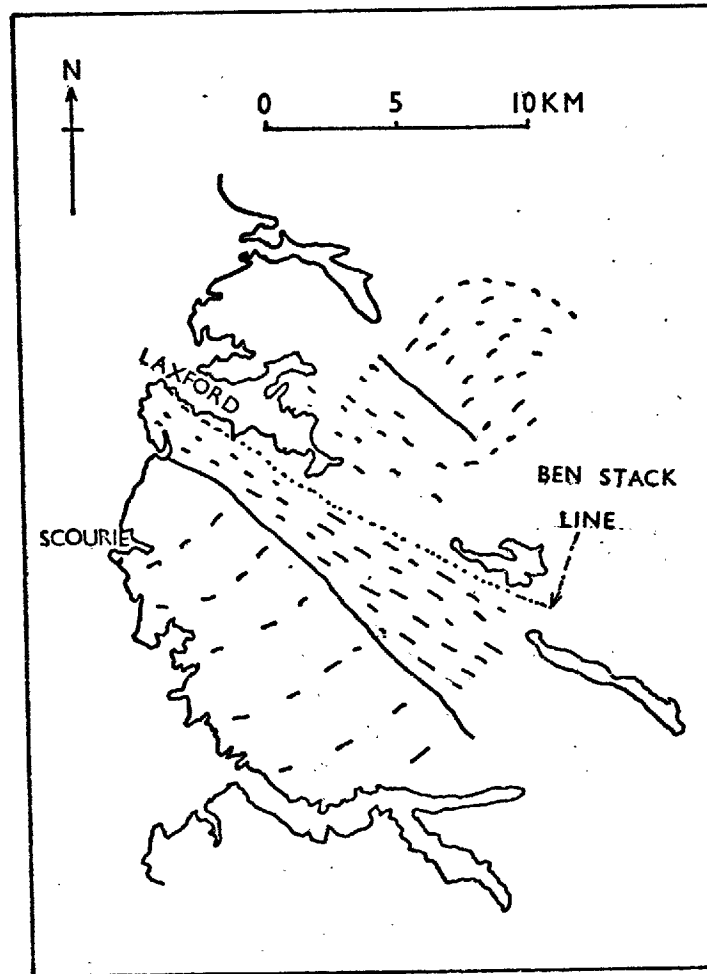
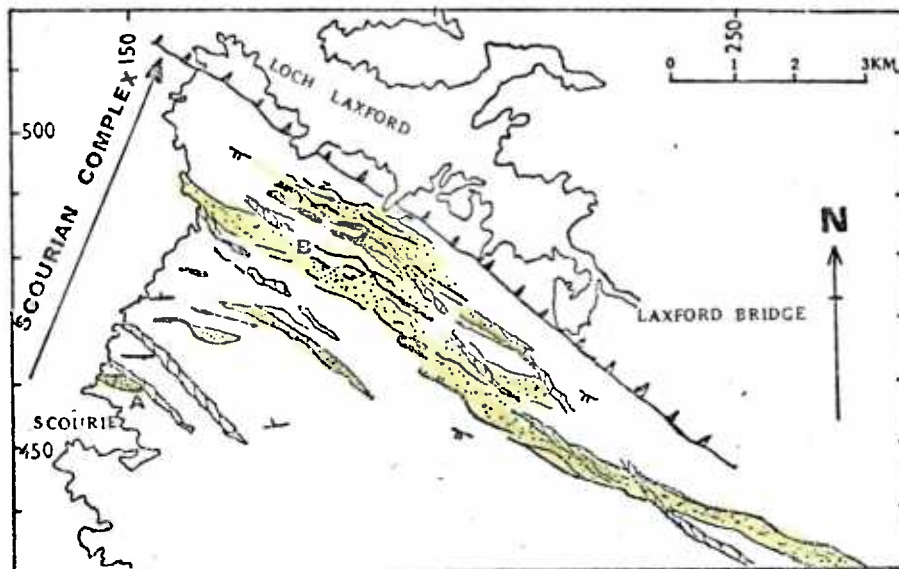


Fig. 1.2 Sketch-map of the major tectonic structures and foliations in the Lewisian rocks between Scourie and Laxford (after Beach, 1971).



LEGEND



Pre - Badcallian (early Scourian) ultrabasic and basic assemblages



Supracrustal rocks



Quartz - feldspathic gneisses



Scourie dykes and meta-dolerites



Southern Limit of Laxfordian granites



Foliation dip $< 45^\circ$



Foliation dip $> 45^\circ$

Fig. 1.3 Map illustrating the distribution of pre - badcallian basic, ultrabasic and supracrustal rocks between Scourie and Laxford of the Scourian complex (after Davies & Watson, 1977). A and B are the supracrustal belts studied.

FIELD RELATIONSHIPS & STRUCTURES2.1 General

The areas studied in this thesis are shown in fig. 1.2 which gives a synthesis of the major tectonic structures that have been mapped in the area between Scourie and Laxford. The source of information for this compilation is Beach *et al.* (1974). The transition zone in the Scourie - Laxford region is of fundamental importance, as was recognised by Peach *et al.* (1907). Since Evans (1963) suggested that the Lochinver antiform was of late Scourian age, the real age of the geometrically similar structures in the Scourie - Laxford region has been in dispute. One of the principal results of remapping in the latter area has been the recognition that certain tectonic structures, regarded as Laxfordian by Sutton & Watson (1951) were formed prior to dyke intrusion and were therefore late Scourian in age. A series of Scourian folds was mapped in this transition zone by Beach *et al.* (1974), and it was found that strong Laxfordian deformation is concentrated in the northern part of this fold belt. The Ben Stack Line, shown in fig. 1.2, is based on the work of Holland (1966) and marks a geochemical boundary defined by him in terms of rock chemistry. It thus forms the southern limit of the maximum development of the Laxfordian granites, and as such was recognised by Peach *et al.* (1907). The tectonic significance of this line is difficult to judge (Beach, 1971). Peach *et al.* (1907, p.126) reported it as being regionally transgressive to the foliation. The two areas chosen for this study provide samples, firstly, of the rocks near the southern boundary of the transition zone, where late Scourian and Laxfordian modifications are relatively slight, and, secondly, of the rocks from the northern part of the transition zone, where these modifications are strong.

Since the work of Clough (in Peach *et al.* 1907), systematic

mapping of the tectonic structures in the whole of the Scourie - Laxford area has been carried out by Beach *et al.* (1974), and Davies (1974). Beach *et al.* (1974) mapped a large number of lithologic units which included components of the Scourian basic/ultrabasic intrusive complexes. The greatest concentration of metamorphosed basic and ultrabasic bodies is in the Foindle zone of Sutton & Watson (1951) and in its south - eastward extension. Frequently in this area gneisses consisting of garnet - biotite - plagioclase - quartz - sulphide assemblage are closely associated with the igneous bodies. These are the 'brown gneisses' of Sutton & Watson (1951) and their distinctive weathering is a result of the decomposition of metallic sulphide phases. A similar association of gneisses of igneous bodies has been described in the Lewisian of the Outer Hebrides by Coward *et al.* (1969) who interpreted the brown gneisses as relicts of metasedimentary rocks because of their similarity to the undoubted metasediments of South Harris. The igneous bodies of the Foindle area undoubtedly predate the granulite facies metamorphism since they contain granulite facies mineral assemblages although these are frequently altered to more hydrous assemblages.

Davies (1974) working in the same area recorded the following rock types:-

- (a) A suite of ultrabasic, basic and anorthositic rocks consisting of
 - (1) Ultramafic rocks
 - (2) meta-gabbros (including leuco-gabbros and mafic gabbros)
 - (3) meta-anorthosite
- (b) Rusty weathering Quartz - feldspathic schists and gneisses consisting of
 - (1) garnet + sillimanite schists and mica schists
 - (2) quartz rich rocks
 - (3) calc-silicate gneisses
 - (4) amphibolites

- (c) Quartzo - feldspathic gneisses consisting of
 - (1) homogeneous quartzo - feldspathic gneisses
 - (2) banded migmatitic gneisses
- (d) Scourie dyke (dolerite and metadolerite), and
- (e) Pegmatites (Late Scourian and Laxfordian).

2.2 Magnetic Anomalies in Scourie - Foindle region

Fig. 2.1 is part of the original one inch aeromagnetic survey map of Great Britain published by I.G.S. It shows the magnetic anomalies in the area between Scourie and Foindle. It is evident from a study of the magnetic anomalies in the region that the most pronounced positive anomalies correspond very closely with the known outcrops of Scourian granulites. The area of Scourie More (south of Scourie Bay) has an anomaly on the regional map of about + 400 γ . There is a very steep magnetic gradient northwards across Scourie Bay until near Foindle and Fanagmore where there is a magnetic low of -250/200 γ on the regional survey. The fall off in magnetism of the rocks is a result of the granulites in this region being amphibolitized (Beach, 1974). Thus the magnetic gradient across Scourie Bay coincides with the southern limit of major development of hornblende in former granulite facies rocks.

2.3 Field mapping

A large amount of field data has already been published on the area in which the present work was carried out, and the published information provided the structural frame work within which the present study was planned. As part of this study, two areas as shown in fig. 2.1 were selected. The rock types and major structures were mapped and recorded in geological maps (Maps 1 & 2). The field observations which provide a frame work for the detailed petrographic studies in the next chapter are now reported. This account is given in two categories, namely, Field relationships and Structures.

2.4 Field relationships

Here, the main lithologic units and their field relationships are briefly described. The names given to the rocks were initially field names subject to later confirmation by microscopic studies as reported in Chapter 3. Gneisses and schists in Foindle and Scourie are of varying mineralogical compositions. Following the work of Davies (1974) the rocks were divided in the field into two groups provisionally regarded as genetically distinct:

- A. Meta-igneous bodies and
- B. Metamorphosed Supracrustal rocks including metasediments.

2.4.1 Meta-igneous bodies

Meta-igneous bodies in Scourie and Foindle include

- (1) Mafic gneisses/Amphibolites
- (2) Ultramafic gneisses
- (3) Anorthositic gneiss (only in Foindle)
- (4) Quartz feldspathic gneisses
- (5) Banded acid gneisses
- (6) Scourie dykes (dolerite and metadolerite), and
- (7) Pegmatites.

(1) Mafic gneisses/Amphibolites

On the basis of field evidence, it was not easy to draw a boundary between these rocks. This is because in Foindle, almost all of the original pyroxene has been converted to hornblende. One significant observation is that the amount of hornblende varies from specimen. As a result, specimens with hornblende concentrations estimated to be $>80\%$ are referred to as Amphibolites whilst those with $<80\%$ hornblende are referred to as mafic gneisses. In general, specimens with more hornblende have been characterized by less amount of garnet. This is likely due to retrogression. They are widely distributed as layers, lenses, or pods (Plate 2.3) and in Foindle

have concordant relationship with the foliation of the adjacent rock type as illustrated in Plate 2.4. Samples of these rocks were taken with the aim of comparing their compositions. The amphibolites can also be distinguished from similar mafic gneisses by the presence of yellow sulphide - bearing horizons, quartz - rich layers and by the fact that they rarely contain garnet. Dark-green hornblende, biotite and plagioclase are common. The origin of the amphibolites is not certain but their close association with supracrustal rocks may indicate a similar origin (Davies, 1974). In some localities, foliation is caused by segregation of light and dark coloured minerals into layers or clots. Alignment of hornblende crystals within the layers also locally defines a lineation. The foliation of these rocks and conformable habit of their occurrence (Plate 2.4) distinguished them from more massive and cross-cutting meta-dolerite. Often these rocks are veined by quartz (Plate 2.5), pegmatite (Plate 2.9) and are sheared.

(2) Ultramafic and (3) Anorthositic gneisses

Rocks ranging from ultrabasic to anorthositic in composition are associated with the supracrustal rocks in Foindle. They are also present in extensive regions of quartz - feldspathic (acid) gneisses. However, ultrabasic rocks are more prevalent than the anorthositic gneiss which occupies effectively a minimal area (see Map 2). In fact the only rock that is anorthositic in composition is found around LNB 85 sample locality in Foindle. No rock of that composition was recognised in Scourie. Davies (1974; Chapter 4) outlines the evidence that these rocks (anorthosites) form parts of deformed sheet-like igneous complexes, which were originally composed of cumulates and associated differentiates formed before the Scourian granulite facies metamorphism and modified during successive tectono - metamorphic events. The Foindle anorthositic gneiss is rich in hornblende and plagioclase. The ultramafics in

Scourie still retain some crystals of green pyroxene and opaques. Signs of hornblende replacing pyroxene are seen in a few hand specimens. The hornblende increases in abundance from Scourie towards Foindle and there is also a progressive increase in alteration of olivine to serpentine. These data suggest retrogressive effects on anhydrous granulite facies mineral phases.

(4) Quartz - feldspathic gneisses

These rocks often alternate with mafic gneisses or the early basic and anorthositic masses (Davies, 1974). They are massive and light coloured and possess a few species of mafic minerals such as biotite. The dominant feldspar is plagioclase which often occurs as augen from a few millimetres up to 3 cm long. Often, mafic pods (Plate 2.3) are found enclosed in them. They occupy about 20% of the entire region. In Foindle where the effects of Laxfordian deformation are more pronounced chlorite and epidote are present. The minerals might have been derived from biotite and plagioclase respectively, which were the early mineral phases. Occasionally the rocks grade into banded acid gneisses.

(5) Banded acid gneisses

Banded acid gneisses ('migmatitic gneisses', (Davies, 1974), are composed of alternating layers of quartz - feldspathic (leucosome) and amphibole-rich (melanosome) minerals (Plate 2.2). They may be the hydrous equivalents of the pyroxene granulites which predominate near Scourie. Pyroxene is not however seen in the outcrops of the gneisses within the Supracrustal belts since such minerals have been replaced by other later assemblages during the process of retrogression. Banded acid gneisses are only seen in Foindle which is very close to the migmatite complex at Laxford. They occupy about 10% of the entire Foindle area and are usually associated with the acid/quartz - feldspathic sheets. The early

history of the banded acid gneiss is a matter of personal interpretation of available data. Coward *et al.* (1969) consider them to be of Supracrustal origin. Bridgwater *et al.* (1973) and Davies (1974) uphold the idea that the rocks be considered as the metamorphosed derivative of several generations of acid igneous rocks which, on the basis of their present compositions, would correspond to tonalites.

(6) Scourie dykes (dolerite and metadolerite)

In Scourie a dolerite dyke forms the northern limit of the map area (see Map 1). The dyke runs from the Minch coast across the entire area towards inland. It is north-west trending and has sharp contacts with surrounding gneisses. The width is about 50 metres. A specimen collected from it shows some igneous mineral phases (plagioclase and green pyroxene) and a sub-ophitic texture is obvious. The same dyke is deformed by Laxfordian pegmatite and shears (Plate 2.1). Typical mineral assemblages according to Sutton & Watson (1951) are:

Andesine/Labradorite + augite + hypersthene + ores. Sutton & Watson (*op cit*) also listed the changes in mineral assemblages and textures of the dykes across the Scourie - Laxford transition zone as a result of Laxfordian tectono - metamorphic activity. All the dykes in Foindle area are meta-dolerites. All vary in thickness from a few metres to tens of metres. In general thinner bodies are more altered than the thicker ones. Typical mineral assemblages of the meta-dolerites of this area are:

Hornblende + plagioclase + quartz ± biotite.

(7) Pegmatites

These are preserved in the basic igneous rocks and supracrustal rocks. They are of late Scourian or Laxfordian age and usually occur as veins (Plate 2.7). The pegmatites have perthitic

feldspars often pink in colour intergrown with quartz. Biotite, and, rarely, garnet occur as accessories.

2.4.2. Metamorphosed Supracrustal rocks

Metamorphosed Supracrustal rocks around Lochan Creige 'Mhail in Scourie include:

Garnet granulite

Quartz - garnet - feldspar gneiss

Quartz feldspar - garnet gneiss

Quartz - biotite - garnet gneiss

Biotite - garnet gneiss.

Such rocks around Loch Nam Brac in Foindle include:

Quartzitic gneiss

Feldspathic gneiss

Quartz - magnetite gneiss

Biotite - muscovite - garnet gneiss

Quartz - biotite - garnet gneiss

Biotite schist

Quartz - biotite schist

Quartz - mica schist

Quartz - garnet - mica gneiss.

(1) Quartzitic gneisses

These rocks, dominantly rich in quartz (>80%), are found in one area only (see Map 2). With increasing amount of mafic minerals and feldspar, they are referred to as 'quartzitic gneisses' in preference to quartzites. Another acceptable name is 'impure quartzites'. Characteristically, they are light coloured with occasional mineral banding defined by some feldspathic layers, and biotite. Quartz occurs as elongated grains up to 1 cm long but generally between 0.5 mm and 1 mm. Possibly this is the group of monomineralic rocks found as part of the Supracrustal series and

interpreted by Sutton & Watson (1951) as being of metasomatic origin, and derived from the 'early basic' rocks. Beach et al. (1974) identified them also as supracrustal rocks. The mineral content and proportions suggest a sedimentary origin, and if so, the rocks could range from semi-pelites to impure psammites, or could even be of volcanoclastic origin. Confirmation of their origin and a possible mechanism of derivation are discussed in Chapters 5, 6, and 7.

(2) Feldspathic gneisses

These light coloured rocks which only occur in Foindle resemble impure marbles. But petrographic study (next chapter) shows that they are extremely rich in plagioclase feldspar. The outcrops form a small lens of about 150 cm long.

(3) Garnet granulites

Garnet granulites are exposed in Scourie. They are rich in garnet (>50%), up to 2 cm long, with hornblende as the main mafic mineral. They are coarse grained (Plate 2.6) and have conformable contact with the adjacent mafic gneisses.

(4) Biotite - muscovite - garnet gneisses

Gneisses of this type are found in Foindle. Micas (black, biotite and white, muscovite) are prevalent with garnets (≈ 1 cm). Some outcrops form lenticular bands with the mica flakes clearly defining a lineation pattern. This linear arrangement of mafic assemblages is attributed to be the effects of intense Laxfordian deformation in Foindle area.

(5) Biotite - garnet gneisses

Biotite is dominant in these gneisses which also contain pinkish garnets (≈ 1 cm). These rocks are slightly coarser

grained than the average gneisses of the Scourie region where they have been recognised.

(6) Biotite schists

In Foindle, quartz - biotite - garnet gneisses grade into biotite schists. Abundant biotite occurs, the average grain size being 0.5 mm. The grains are sub-parallel and define an obvious lineation.

(7) Quartz - biotite schists

With a greater proportion of quartz, the biotite schists grade into Quartz - biotite schists in Foindle. Quartz grains are about 1 cm. Foliation planes, defined by biotite are still preserved.

(8) Quartz - biotite - garnet gneisses

In Foindle and Scourie, these gneisses are found as lenses in mafic gneisses and are often coarse grained. Abundance of quartz and biotite is obvious with a minimal amount of garnet. Occasionally the foliation is cut by Laxfordian pegmatite veins (Plate 2.7). In Foindle the rocks are concordant with the adjacent mafic gneiss (Plate 2.8). The mafic gneisses (same plate) is itself a small layer (≈ 5 cm) sandwiched in the Quartz - biotite - garnet gneiss. This position of the mafic gneiss within the Quartz - biotite - garnet gneiss (supracrustal) is interpreted to represent tectonic emplacement.

(9) Quartz - magnetite gneisses

These are dark coloured rocks with appreciable amount ($\approx 20\%$) of magnetite. The rocks are exposed on the west of Loch Nam Brac (around LNB 90 sample locality) in Foindle, where they have a concordant relationship with the adjacent mafic sheets. These gneisses are distinguished from the nearly dark-coloured mafic rocks

by the presence of red garnets. The mafic bodies are more massive and have no garnets.

(10) Quartz - mica schists

In Foindle, where the effects of Laxfordian deformation are seen, these rocks, light brown in colour, can be recognised by their clear-cut foliations, defined by the presence of muscovite and biotite, and by their banding. Quartz grains are greatly reduced in size (≈ 0.5 cm). Adjacent to these schists are rocks which are also enriched in micas, but with smaller proportions of quartz.

(11) Quartz - garnet - mica gneisses

These gneisses are similar to the preceding type except that they have some garnet grains. They are medium grained and have no defined banding as have the quartz - mica schists. They have a mottled colour.

(12) Quartz - feldspathic gneisses with garnet

Near Scourie, are gneisses which on macroscopic grounds have been grouped as Quartz - garnet - feldspar gneiss and Quartz - feldspar garnet gneiss (see Map 1). In the field it was difficult to separate the two rock types. Both rock types are rich in quartz, garnet and feldspar. The only problem was the proportion of garnet or feldspar in each. This could not be estimated from field observations. The separation as shown on the map is based on petrographic studies (Chapter 3) and over-all whole - rock chemistry (Chapters 4 & 5).

2.5

STRUCTURES2.5.1 General

The presence of a major fold structure in the Scourie - Laxford region has been proposed by Holland (1966). Beach (1974) describes a structure similar to the antiform dated as late Scourian by Evans (1963, 1965) at Lochinver, and very different from that described by Sutton & Watson (1951, 1961). Beach et al. (1974) also demonstrated the existence of a series of folds of Scourian age. In general rocks in Scourie trend north-east while those in Foindle must have been tilted almost at 90° to give an approximately north-westerly trend. The two areas have been affected by 2 main phases of deformation (F_1 , F_2). Deformation was by folding, penetrative shearing and ductile faulting and also indicated by the development of boudins, joints and lineations. The structures are both Scourian and Laxfordian in age and are now briefly described as they were seen during the field mapping.

2.5.2 Folds

Two fold phases are recognised in both areas (1st and 2nd).

(1) 1st fold phase

The first folding (F_1 deformation) led to the formation of open antiforms and synforms in much of the region between Scourie and the southern edge of the Foindle zone. Scourie dykes clearly cross-cut a series of regularly spaced upright antiforms and synforms (Beach et al. 1974). In Foindle area, the minor folds are sometimes isoclinal (Plate 2.11) and have the same fold axes as the synforms and antiforms. The isoclinal folds became more open to the south (towards the Tarbet road). In the south of Loch Nam Brac, where these folds have been least modified by later deformation, their axes are nearly horizontal and their axial surfaces also strike north - west - south - east and dip steeply to

the south-west. Around Lochan Creige 'Mhail near Scourie, the axial surfaces of the major folds (antiforms and synforms) strike north - east - south - west parallel to the trend of Scourian foliations. Isoclinal folds near Scourie also have the same axial surface trend.

(2) 2nd fold phase (F_2 deformation)

The F_2 deformation was probably the first to affect the Scourie dykes with the development of penetrative fabrics; many of the shear structures within the dykes (e.g Plate 2.1) are also of this age (Beach et al. (1974)). F_2 folds are tight and are more prevalent in Foindle where Laxfordian deformation has been more intense. The axial surfaces of these F_2 folds are oblique to those of F_1 (Davies, 1974). This change, with time, in deformation style could imply that the Scourie zone acted as a competent block during the second deformation when minor folds were developed.

2.5.3 Foliations

Foliations in the Scourie zone are mainly Scourian, whilst those in Foindle are Laxfordian in age. The banding in the rocks in Scourie trend north-east while that in Foindle is north-west. The foliations in Foindle have a fairly constant north-westerly trend, parallel to the axial planes of the F_1 folds but in Scourie there is a degree of scatter of foliation directions but can be said to be approximately north-east. Fig. 2.2 is a polar diagram for the foliations in Foindle and Scourie region. Steeper foliations in Foindle rocks ($>45^\circ$) are obvious.

2 5.4 Shear zones

Shear belts are narrow tracts in which deformation and, often, metamorphism is much more intense than in the surrounding rocks. They may be parallel or oblique to the regional foliation and they

have the geometrical effect of faults or thrusts (Watson, 1949 pp. 89). Shear zones are common in the two areas (Foindle and Scourie). Most of the shears are oblique to the foliations (Plate 2.10). They are dominantly Laxfordian in age as exemplified in Scourie where they deform a Scourie dyke (Plate 2.1). All shear zones are characterized by a linear arrangement of fabrics. In Foindle (Plate 2.12), the shearing in the mafic gneiss was probably accompanied by slumping and quartz veining through the plane of weakness (shear plane).

2.5.5 Lineations

No strong linear structures were found in the Scourie area (except in shear zones), but in Foindle, where the effects of Laxfordian deformation are more pronounced, they are common. The linear mafic fabrics (defined by the orientation of biotite) trend north-west which is the same orientation as that of the Laxfordian foliation.

2.5.6 Boudins

Mafic boudins are common within the country igneous bodies in both areas (Plate 2.3). The more competent mafic gneiss (often amphibolite) are usually enclosed within the less competent quartz-feldspathic gneisses). Formation of the boudins is assumed to be tectonic, and to have resulted in the separation of originally continuous competent layers with strings of pods.

2.5.7 Joints and Faults

The last phase of the structural history (probably post F₂ deformation) resulted in the formation of vertical joints and faults almost perpendicular to the fold axes. The best examples are seen in rocks of the Foindle area.



Plate 2.1 Scourie dyke (Dolerite) deformed by pegmatite, folded and sheared, Scourie. A is pegmatite. Camera cap is along the shear plane.



Plate 2.2 Interlayering of leucosome and melanosome materials in the Banded acid gneiss, Foindle.



Plate 2.3 Mafic pod (boudin) in quartz-feldspathic gneiss, Scourie.



Plate 2.4 Conformable contact between amphibolite and Biotite schist,
Foindle.



Plate 2.5 Quartz veins in amphibolite, Rindale.



Plate 2.6 Granular texture in garnet granulite, Scourie.



Plate 2.7 Pegmatite vein in Quartz - biotite - garnet gneiss,
Foindle - Fanagmore road.



Plate 2.8 Conformable contact between Quartz - biotite - garnet
gneiss and Mafic gneiss, Fiondle.



Plate 2.9 Pegmatite vein in Mafic gneiss, Foindle



Plate 2.10 Shear zone in Biotite schist, Foindle.



Plate 2.11 Isoclinal fold in mafic gneiss, Poindie. Laxfordian pegmatite (x) cut across the foliations of the country mafic gneiss.



Plate 2.12 Slumping and shearing effects in mafic gneiss, Poindie.

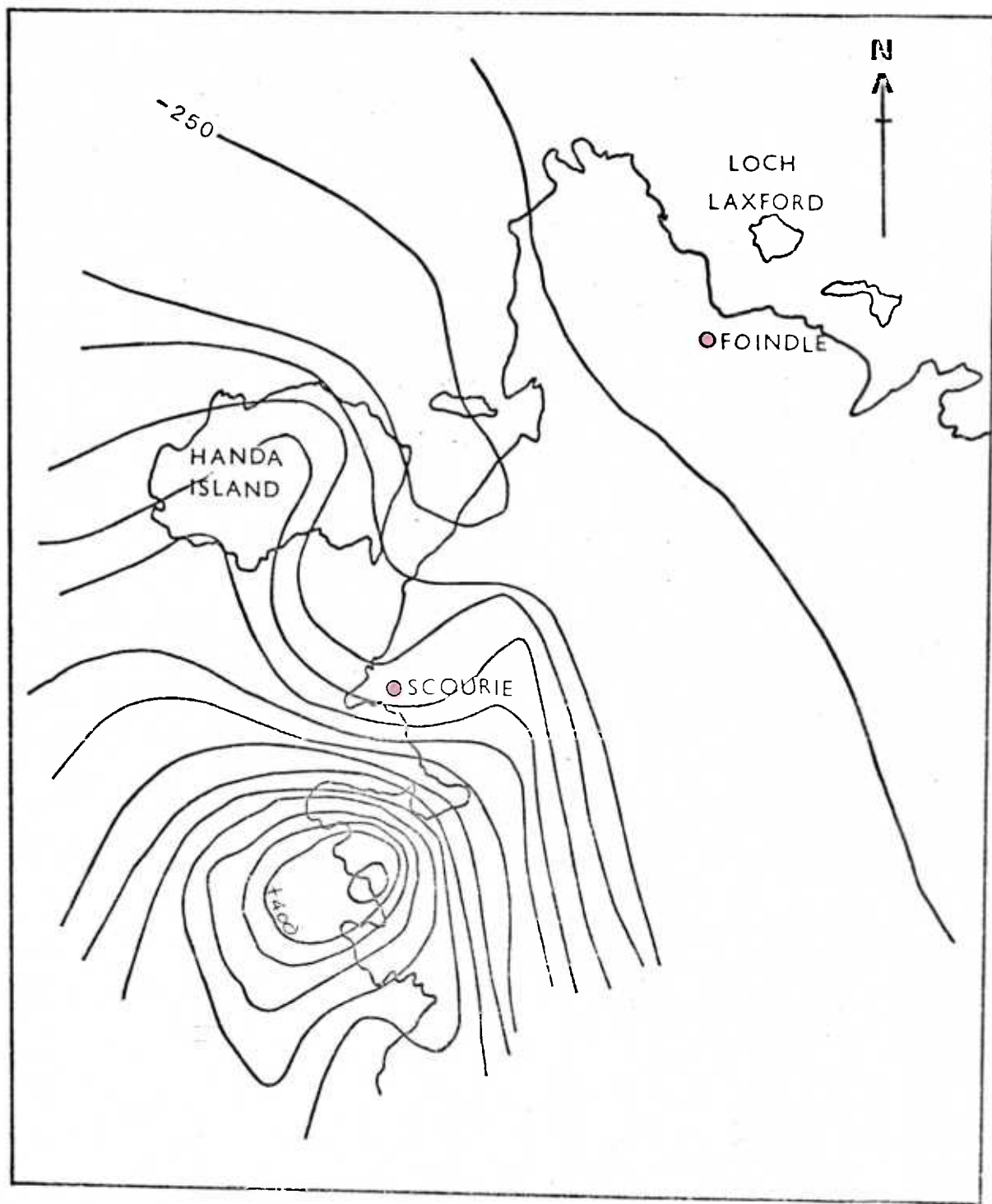
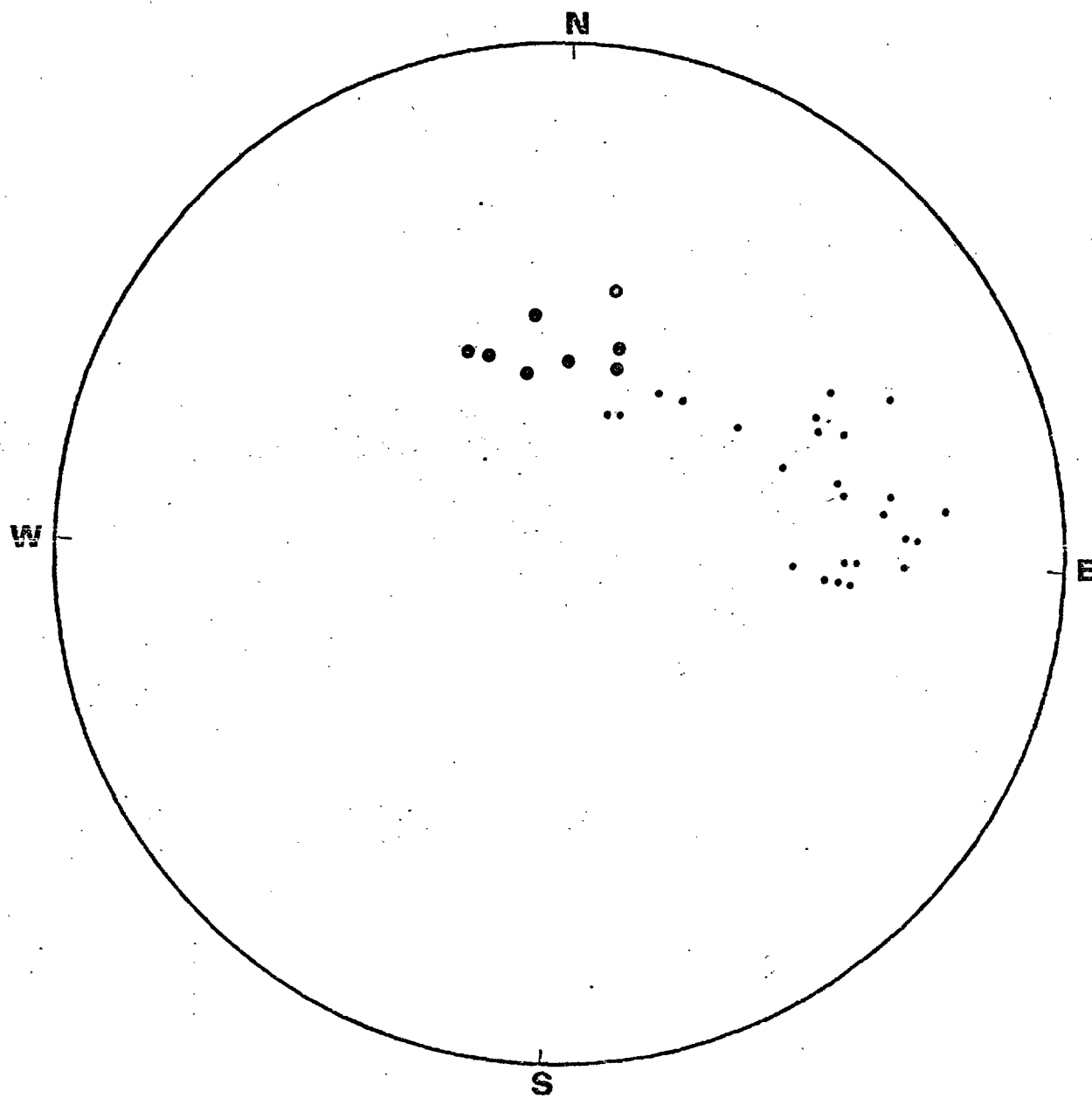


Fig. 2.1 Aeromagnetic anomaly map of the Scourie - Foindle region taken from I.G.S. one inch survey. Scale: 1 inch = 1 mile; contour interval = 50 gammas.



- Foindle foliations
- Scourie foliations

Fig. 2.2 Polar diagram for the foliations in Foindle - Scourie region.

CHAPTER 3PETROGRAPHY AND MINERALOGICAL CLASSIFICATION3.1 General Introduction

Beach (1971) summarized the mineral assemblages found in different parts of the Scourie - Laxford area. For the amphibolitized or retrogressed Scourie rocks the following principal assemblages were identified:

hornblende - (opx - plag - biot)

hornblende - plag - opx - (qtz - ap - epid - zir)

hornblende - plag - qtz - opx - (ap - biot).

The Laxfordian shear zones had the following assemblages:

biot - hbl - plag - qtz - opx - ap - rut

hbl - biot - cal - epid

hbl - epid - plag - qtz - haem - il

gar - biot - plag - qtz - Ky - opx - (str-sph-cor-mus-haem)

Sutton & Watson (1951) found the following assemblages in the Claisfearn and Foindle zones of the mainland Lewisian:

plag - qtz - hbl ± biot - (opx)

hbl - epid - plag - qtz - (chl - haem)

gar - biot - plag - qtz - sulphides

plag - Kfsp - qtz - mus - (biot)

plag - Kfsp - hbl - cpx - sph

plag - pyx - gar

plag - qtz - (biot)

gar - qtz

Anth - talc - trem

The above mineral assemblages immediately suggest either igneous or sedimentary parental rocks. An attempt to summarize the mineral fabrics in the Supracrustal and igneous rocks between Scourie & Laxford was also made by Davies (1974). Table 3.1 records the main fabrics found by him.

Petrographic studies made as part of the present research resulted in identification of 'representative' assemblages for the various rock types, and these are represented in Table 3.2. It should be noted that the field names as given in Chapter 2 are still maintained. Rocks have been classified purely on the basis of their mineralogy. Descriptions are given only for those rocks whose compositions are presented in the Appendix. Plagioclase compositions were determined by Michel - Levy's method (see Kerr, 1959; pp. 258).

The remainder of this chapter will deal with the petrographic observations and at the end, some conclusions which were drawn from the study will be given. These conclusions will be drawn on again in later chapters that deal with the chemical characteristics of the rocks.

3.2 Meta-igneous rocks

3.2.1 Mafic gneisses

In the Scourie area as a whole, mafic gneisses usually contain opx + garnet, showing varying degrees of retrogression. Brownish hornblende, different from the green pleichroic hornblende often seen replacing the clino-pyroxene is occasionally found. The hornblende crystals are granular in texture.

There is no visible pyroxene still preserved in the rocks from the Foundle mafic gneisses. Hornblendes are granular in texture, but occasionally have schistose texture also, and were possibly derived from clino pyroxene similar to that seen in Scourian granulites. Green pleichroic amphibole is the most abundant mineral associated with biotite, plagioclase (An₃₈), epidote, iron oxides, K-feldspar and minor quartz. Other effects of retrogression, as deduced from the petrography include:

- (a) biotite replacing hornblende

(b) myrmekitic texture.

This is an intergrowth of quartz and plagioclase feldspar in which the quartz occurs as worm-like rods within the feldspar. This is due to replacement of K-feldspar by a soda-rich feldspar with the separation of excess quartz (Whitten & Brook, 1972; pp. 311).

Garnet is also prominent.

3.2.2 Hornblende gneisses (Amphibolites)

The amphibolites which occur chiefly in the Foindle area contain predominantly anhedral mineral grains, the exceptions being sub-hedral prisms of hornblende and granoblastic aggregates of plagioclase and quartz. Individual grains of hornblende are usually small (1 - 2 mm long), but hornblende clusters up to 1½ cm in diameter are present in a few samples. Some thin sections show tight folds in which unbroken hornblende laths occur in granoblastic quartz and plagioclase.

Plagioclase composition is difficult to estimate because of extensive 'clouding'. Faint normal zoning can be seen in a few thin sections. Most plagioclase show some degree of alteration to zoisite. The zoisite is fine grained, laths not exceeding 0.5 mm in length. The original outline of the feldspar grains are in some cases outlined by flakes of sericitic mica (Plate 3.4) which is probably a secondary mineral formed by hydrothermal alteration of the plagioclase feldspar.

Other minerals found in the thin sections are boitite and iron oxide. Biotite rims around hornblende are also a common feature.

3.2.3 Ultramafic gneisses

Pale green and subhedral crystals of ortho-pyroxene, and dark-green hornblende are the dominant minerals in the samples examined. Other minerals include: garnet, biotite, plagioclase, and iron - oxides. The rocks are characterized by granular texture.

Indications of retrogression include:

- (a) development of brown biotite along the grain boundaries of hornblende (Plate 3.7)
- (b) hornblende enclosing remnants of clino-pyroxene (oblique extinction).

Brownish-yellow scapolite that lacks twinning, has parallel extinction, and rather strong birefringence is also found.

Scapolite occurring in some gabbros as a high temperature alteration of plagioclase has been noted by Kerr (1959; pp. 290).

3.2.4 Quartz - feldspathic gneisses

Quartz is the most abundant mineral in these rocks. Granular and polygonal quartz grains have straight boundaries and triple junctions. Other minerals found in the sections studied include:

biotite, K-feldspar, plagioclase, garnet, sphene, hornblende, + iron oxides. In the rocks from Scourie, brownish-yellow alteration products of biotite occur around the porphyroblastic garnet. Plagioclase is An₄₆ in composition. Clino-pyroxene which grades into green clino-amphibole is characteristic of some sections. Occasionally, as in Plate 3.1, biotite replaces K-feldspar, and it may form rim round the iron oxides.

3.3 Metamorphosed Supracrustal rocks including metasediments

3.3.1 Quartzitic gneisses

Quartz ($\approx$ 30% of rock by volume) is the major mineral and it has a granoblastic habit (Plate 3.5). Other minerals include: biotite, chlorite, K-feldspar, iron oxide, sphene, epidote + garnet. Triple junctions are a common feature and imply equilibrium recrystallization (Spry, 1974). The grain boundaries are almost straight. Crystals of brown biotite occur as inclusions in K-feldspar and this is a characteristic of the rocks. Evidence of

intensive deformation of the rocks is seen by the occasional linear arrangement of biotite fabrics. Also, biotite crystals sometimes respond to the effect of folding. Garnet is rimmed by biotite in some thin sections. With decreasing amount of mafic minerals, and feldspars, these rocks might have been quartzites, but have now graded into quartzitic gneisses. The origin of these gneisses is further discussed in Chapters 5, 6 & 7.

3.3.2 Feldspathic gneisses

These gneisses are very rich in feldspars (plagioclase > K-feldspar). Euhedral plagioclase crystals have compositions ranging from An₃₃ to An₃₆. Granular texture is common (Plate 3.2). The crystals are occasionally oriented in different directions. This is attributed to the complex structural history of the Foindle area.

Other minerals include:

quartz, light brown muscovite, and zircon. Zircon crystals occur as inclusions in the feldspathic groundmass. Intergrowths of K-feldspar and plagioclase are also observed in some thin sections.

3.3.3 Garnet granulites

Garnet is the most prominent mineral and it occurs as euhedral crystals. Granular textures are also well developed in these rocks.

Retrogression effects include:

- (a) epidote rimmed by biotite
 - (b) biotite inclusions in garnet (common feature)
 - (c) quartz inclusions in garnet
 - (d) biotite flakes along irregular partings of garnet
 - (f) minute sillimanite crystals occurring as inclusions in garnet.
- These are characterized by their parallel cleavages, transverse to the irregular fractures of garnet.

3.3.4 Biotite - muscovite - garnet gneisses

Rocks of this type are confined to the Foindle area. They are characterized by equidimensional grains of quartz although micas are the dominant minerals. Muscovite occurs as colourless to pale-green thin tabular crystals with perfect cleavage. Biotite flakes are yellowish brown, sometimes with zircon inclusions. Other minerals include:

quartz, K-feldspar (microcline), garnet, plagioclase and iron oxide.

Possible effects of retrogression are:

- (a) biotite rimming and penetrating polygonal quartz grains (Plate 3.3)
- (b) K-feldspar replacing plagioclase
- (c) brownish biotite replacing euhedral garnet

In some sections, foliations are defined by biotite crystals which themselves are also folded around quartz grains. Muscovite folded round K-feldspar is also seen. In one section (No. 50373), the micas are aligned in two directions, probably a response to the two main phases of deformation discussed in Chapter 2.

3.3.5 Biotite - garnet gneisses

In these generally granular gneisses, garnets, pink in thin section, frequently contain inclusions of biotite and quartz. In general, blue - green hornblende is more or less completely replaced by biotite (brownish yellow pleichroism). Accessory minerals include plagioclase, iron oxide, zircon and rutile. Broken plagioclase (An₄₀) grains, up to 2 mm in diameter, have twin lamellae that are often bent. Quartz grains are of a similar size, and they show marked undulatory extinction and sub-grain structures.

Replacement and recrystallization are indicated by the following observations:

- (a) biotite replacing K-feldspar

- (b) sericitization of plagioclase, and
- (c) reddish-brown and needle - like rutile inclusion in garnet.

3.3.6 Biotite schists

This group which is well represented in the Foindle area is characterized by major amount of biotite together with minor amounts of garnet, quartz, K-feldspar and iron oxide. Biotite is more or regularly distributed through the rock, the foliation of which is defined by parallel alignment of biotite and by elongation of quartz and feldspar grains. Biotite flakes average 0.5 mm in length with pale - yellow pleichroism. In a few sections, biotite crystals occur as inclusions in garnet. Quartz grains are slightly elongated (between 0.5 and 1 mm long). Grains boundaries are sharp. Longer crystals frequently have a well developed sub-grain structure, whilst smaller grains show undulatory extinction. Microcline showing cross-hatch twinning, occurs in grains averaging 1.5 mm in diameter.

3.3.7 Quartz - biotite schists

The predominant minerals in rocks of this group are quartz ($\approx 40\%$ of rock by volume) + biotite. Accessory minerals are apatite, K-feldspar, plagioclase, garnets, iron oxide and sphene. Sub-idioblastic flakes of biotite are well developed. In some thin sections the biotite flakes are near to define a foliation. The matrix is composed of equi - granular quartz, about 0.3 mm in diameter, together with abundant K-feldspar and small amounts of twinned plagioclase (An_{36}). Sphene occurs as irregular grains and has high relief.

3.3.8 Quartz - biotite - garnet gneisses

Granular quartz grains form almost 40% (by volume) of the rocks

in this group. Other minerals include:

hornblende, biotite, apatite, K-feldspar, plagioclase, garnet, iron oxide, zircon, and although not always kyanite. Quartz crystals form triple junctions with straight grain boundaries. Garnet with clear irregular partings under crossed nicols, often encloses quartz. Kyanite (colourless to pale blue with high relief) also occurs as minute blades (≈ 0.5 mm in length) in garnet. The cross-hatch twinning of the K-feldspar, typical of microcline, is also observed. Apatite occurs as small prismatic crystals with parallel extinction.

3.3.9 Quartz - magnetite gneisses

Main minerals are garnet, quartz, and iron oxide (probably magnetite). The accessories are biotite, plagioclase, rutile and zircon. Reddish brown rutile needles occur in garnet. Non-pleichroic clino-zoisite is also observed.

Retrogression effects include:

- (a) clino-zoisite rim around the magnetite
- (b) quartz inclusions in garnet
- (c) biotite and rutile inclusions in garnet
- (d) biotite rims around garnet

Triple junctions formed by granular quartz are common. The boundaries are sometimes occupied by brownish biotite.

3.3.10 Quartz - mica schists

These schists are characterized by abundant quartz and micas (biotite and muscovite). The accessories include epidote, K-feldspar, plagioclase (An₃₃), iron oxide, and zircon. The matrix consists of granular quartz (≈ 0.5 mm in diameter), together with abundant K-feldspar and plagioclase. Plagioclase twins are slightly bent and some twin lamellae appear to have been destroyed by metamorphic reactions. Stress orientations in two directions are

deduced from biotite and muscovite textures. Muscovite occurs as tabular crystals aligned in one direction, and in some thin sections, muscovite crystals are seen to cut across the biotite fabric. These observations suggest that there might have been two phases of deformation or that muscovite crystallized at a late stage under static conditions.

Replacement and recrystallization reactions are:

- (a) minute green epidote inclusions in biotite
- (b) iron oxide rims on epidote
- (c) formation of K-feldspar around zircon grains

3.3.11 Quartz - garnet - mica gneisses

Quartz is the most abundant mineral. Granular texture and triple junctions formed by almost straight grain boundaries are characteristic of the rocks (Plate 3.6). Other minerals include biotite, muscovite, K-feldspar, plagioclase, garnet, sphene, $\pm$ kyanite. The most pronounced retrogression effect is the brownish - yellow alteration of biotite around porphyroblastic garnet. Plagioclase compositions (where lamellae have not been destroyed completely) range from An₄₂ to An₄₆.

3.3.12 Quartz - feldspar - garnet gneisses

These gneisses are characterized by equidimensional quartz (about 1 mm in diameter), whose grain boundaries meet at triple points. Other minerals include:

biotite, garnet, iron oxide, sphene, K-feldspar (microcline) and plagioclase.

Faint cross-hatch twinning is typical of the microcline. Garnet occurs as xenoblastic grains whose boundaries are frequently embayed by quartz. Quartz inclusions within garnet are common. Garnet is also altered marginally to biotite. Biotite occurs as flakes, 1 - 2 cm long. Irregular, pale - green crystals of sphene do not

show complete extinction, and this may be due to the strong dispersion shown by the mineral.

3.3.13 Quartz - garnet - feldspar gneisses

These gneisses are greatly enriched in quartz. Major and minor components include:

garnet, biotite, K-feldspar, plagioclase, and iron oxide.

Development of biotite crystals in random orientation is common (Plate 3.8). Where the coarse - grained quartz crystals are seen unaltered, grain boundaries are straight and meet at triple points. In some samples, these grain boundaries are slightly curved.

Biotite replacement of K-feldspar is the most pronounced alteration effect. Others may include:

- (a) K-feldspar occurring in plagioclase host
- (b) biotite inclusions in garnet.

3.4 Conclusions from the petrographic study

A number of conclusions drawn from the petrographic study are given below, and they will be referred to again in Chapters 4, 5 & 6 which deal with the chemical characteristics of these rocks.

- (a) Almost all the rocks classified as Supracrustal contain garnet. Where there is an appreciable proportion of garnet, aluminous mineral phases like kyanite and sillimanite have been observed.
- (b) All Supracrustal rocks contain quartz and feldspar, and most of them contain biotite
- (c) Granular textures are typical of most rocks with the exception of those that have suffered the intensive deformation.
- (d) The occurrence of clino-zoisite is interesting.

Clino-zoisite is a product of retrogressive metamorphism of amphibolites, hornblende - schists, glaucophane schists

(Kerr, 1959 pp. 336).

- (e) The occurrence of Zircon in some of the Supracrustal rocks may help to provide a petrogenetic classification of this group of rocks (see Chapter 6. & 7 for further discussions).
- (f) Retrogression is more intense in the Foindle rocks than in those from Scourie. The appearance of chlorite and muscovite in some of the Foindle rocks supports this observation and suggests that a lower grade metamorphism than that prevalent in Scourie was responsible for this. Textures from similar rocks from both areas are also significantly different. (see Table 3.3).
- (g) Replacement and recrystallization are more pronounced in the quartz - feldspathic Supracrustal rocks than in the meta-igneous rocks. In the meta-igneous suites, replacement and recrystallization are also more pronounced in the acid rocks than in the basic or ultrabasic rocks.

Mineralogical variations within the Supracrustal rocks are of

3 types:

- (1) variations in the relative proportions of quartz, feldspar, alumino - silicates and mafic minerals present in the different rock types.
- (2) Similar variation to those in (1) occur between bands or lenses within the same rock type
- (3) variations in the abundance of each of the alumino - silicates and mafic minerals in relation to their total amount in any one rock.
- (h) Rocks from the shear zones are more enriched in biotite, and sometimes muscovite, than similar rocks from outside the zones.
- (1) The plagioclase is saussuritized, partially replaced by

chlorite in (Foindle), and exhibits poorly developed twins.

In general, there is overprinting of deformation and metamorphic events in the rocks studied from both areas (i.e only a few primary igneous minerals or textures have been observed). Thin sections from rocks in Foindle area show that pyroxene (characteristic of unaltered Scourian granulites) has been completely replaced by hornblende and biotite. This common feature suggests that the rocks from Foindle area could contain more potassium than their equivalents from Scourie. Chemical evidence in favour this suggestion is discussed in Chapters 4 and 7.

Table 3.1. Scourian and Laxfordian minerals from rocks between Scourie and Laxford (after Davies, 1974).

	SCOURIAN MINERALS	LAXFORDIAN MINERALS
SUPRACRUSTAL ROCKS	Quartz	Quartz
	Plagioclase	Plagioclase
	Biotite	Biotite
	Garnet	Garnet
	Hornblende	Hornblende
	Kyanite	Sillimanite
	Sillimanite	Chlorite
	Diopside	
LAYERED ULTRABASIC, BASIC, AND ANORTHOSITIC ROCKS	Labradorite	Andesine
	Clino-pyroxene	Clino-pyroxene
	Spinel	Biotite
	Red-garnet	Serpentine
	Olivine	
BANDED MIGMATITIC GNEISSES	Quartz	Quartz
	Plagioclase	Plagioclase
	Biotite	Biotite
	Orthopyroxene	Chlorite
	K-feldspar	Hornblende
		Epidote

Table 3.3. Summary of 'representative' fabrics for the rock types in the two sample areas near Scourie and Foindle

	SCOURIE		FOINDLE	
	Typical assemblage	Texture	Typical assemblage	Texture
1. META-IGNEOUS ROCKS				
(a) Mafic gneisses	(i) feldspar + cpx + brownish Hbl → garnet (ii) cpx → hbl ± qtz (iii) iron → hbl + biot oxide	Garnet rim; Hbl not entirely replacing cpx; Granular	No cpx; ± garnet	Mainly schistose Hbl with clusters of qtz inclusions probably, replacing cpx
(b) Quartz-feldspathic gneisses	(i) cpx → biot (ii) cpx + opx + plag(anti-perthite) + qtz (iii) qtz + garnet + biot + magnetite	No schistosity; Granular Tripple junctions	No cpx; No anti-perthite	schistosity; cpx completely replaced by hbl
2. METAMORPHOSED SUPRACRUSTAL ROCKS	Anti-perthitic feldspars; qtz with rutile rods + garnets → biot + clear qtz. No muscovite	Granular; Tripple junctions	No anti-perthite; qtz + feldspar + biot + mus + epidote + chlorite	Essentially schistose; garnet → biot in irre- gular partings

N. B. → means replaced by



Plate 3.1. Biotite replacing potash feldspar in quartz feldspathic gneiss, Foindle. Slide No. 51610. x 160. Crossed Nicols.

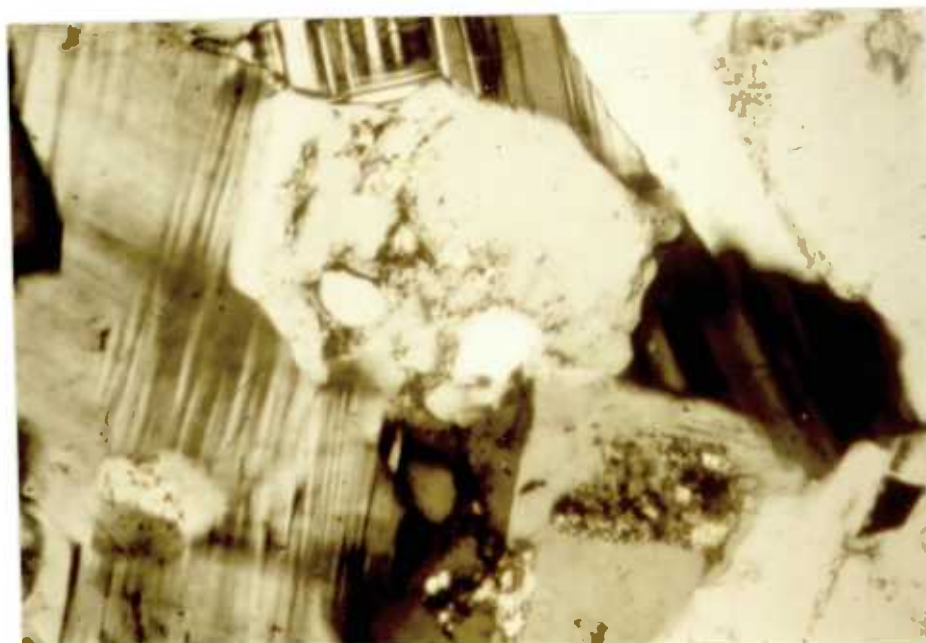


Plate 3.2. Granular texture in Feldspathic gneiss, Foindle. Slide No. 51609. x 160. Crossed Nicols.

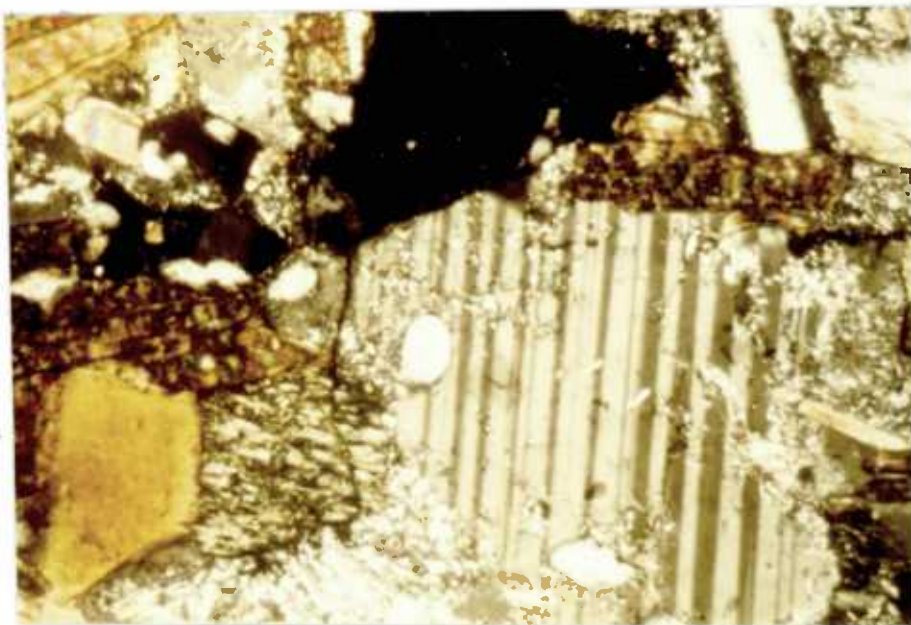


Plate 3.3 Extensive retrogression effects in Biotite - muscovite - garnet gneiss, Foindle. Slide No. 50143. X 160. Crossed nicols.

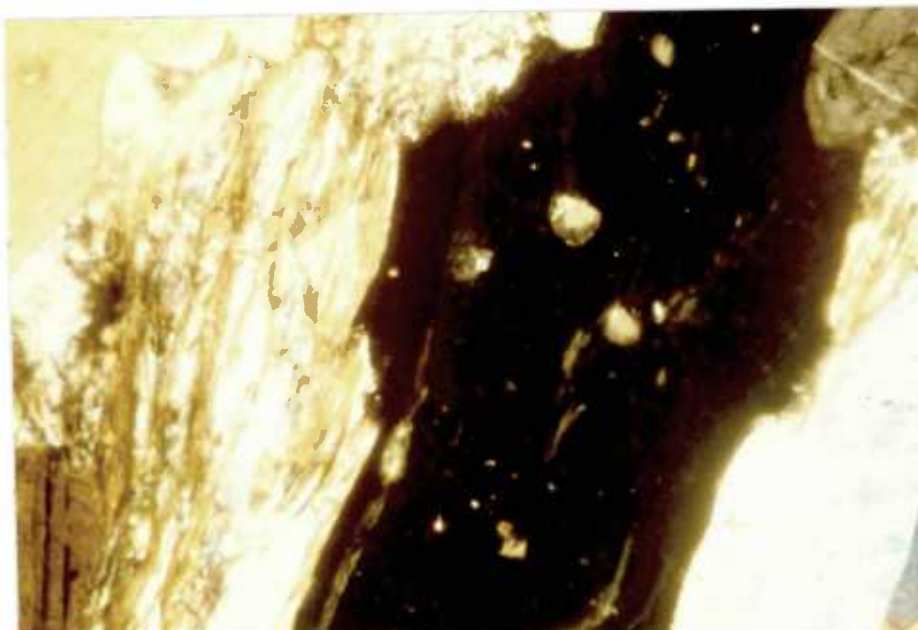


Plate 3.4 Sericitic mica replacing plagioclase in Hornblende gneiss (Amphibolite), Foindle. Slide No. 51059. X160. Crossed nicols.

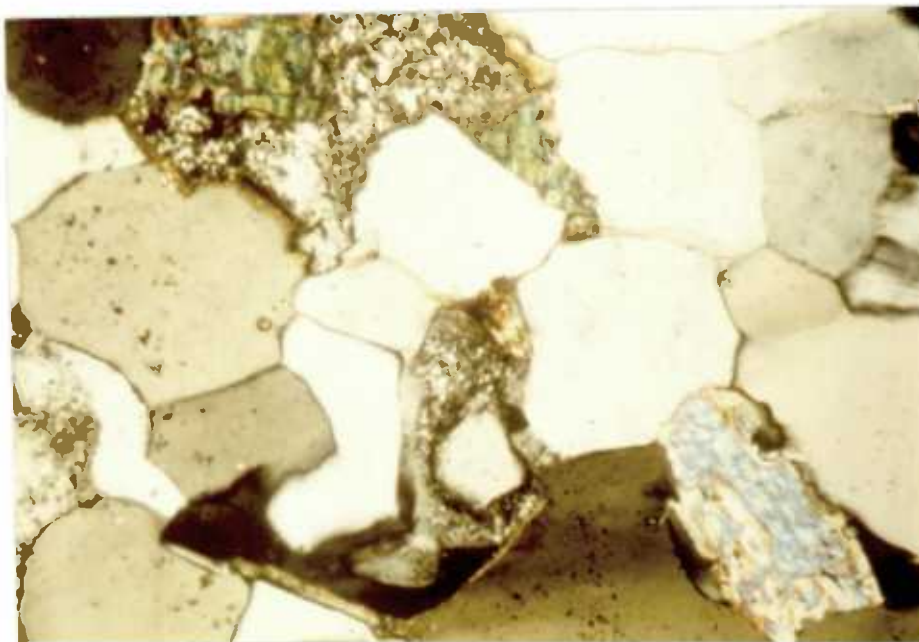


Plate 3.5. Granular texture and polygonal quartz grains
in Quartzitic gneiss, Foindle.

Slide No. 51047. x 160. Crossed Nicols.

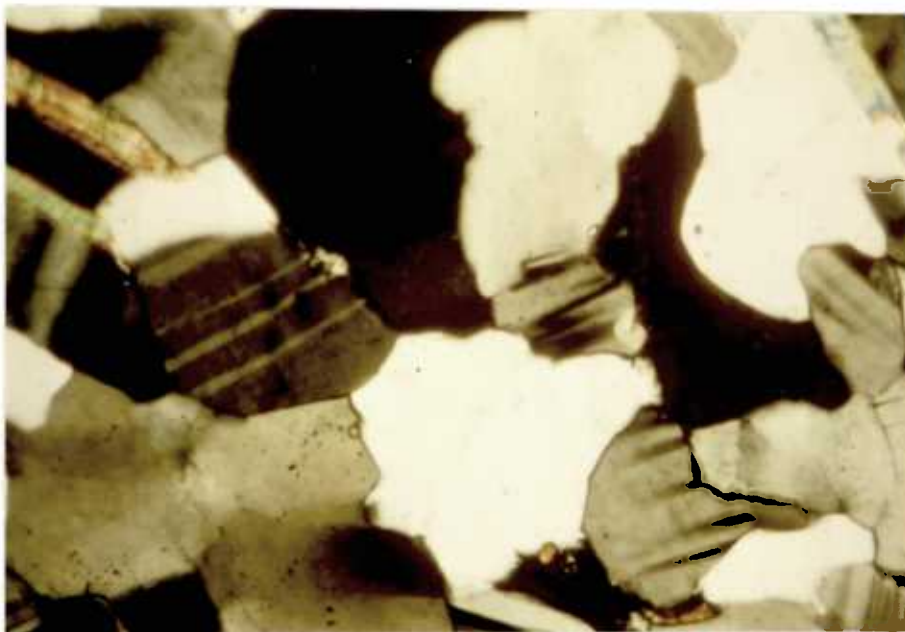


Plate 3.6. Tripple junctions and granular texture in
Quartz - garnet - mica gneiss, Foindle.

Slide No. 51045. x 160. Crossed Nicols.

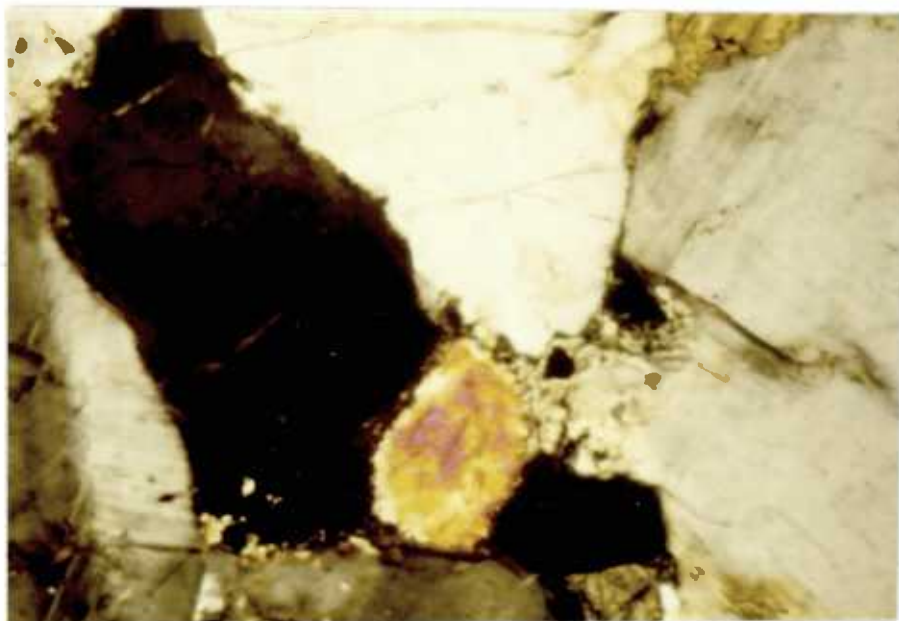


Plate 3.7. Retrogression in Ultramafic gneiss, Scurie.
Slide No. 51624. x 160. Crossed Nicols.

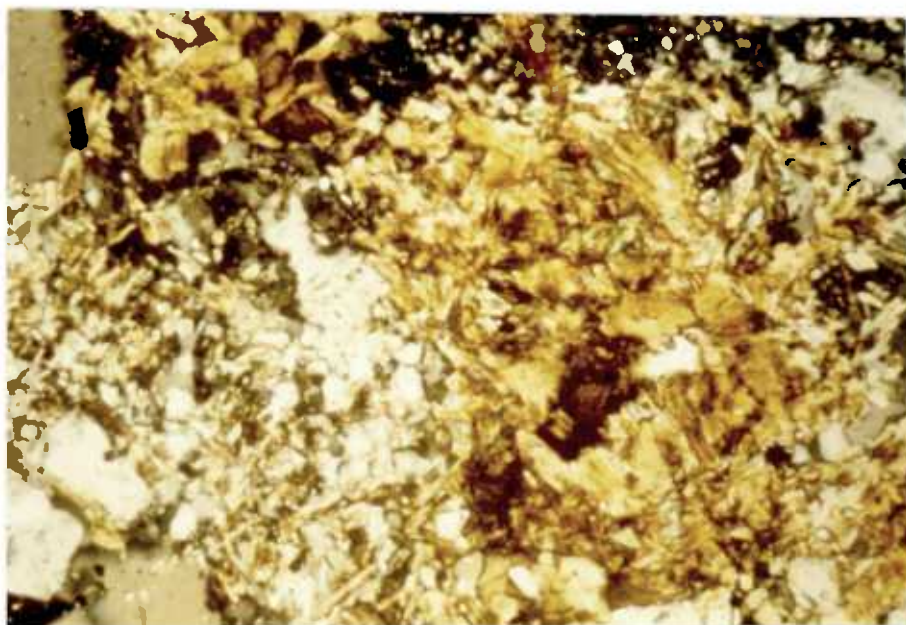


Plate 3.8. Random orientation of biotite in Quartz-garnet-
feldspar gneiss, Scurie. Slide No. 51061.
x 160. Crossed Nicols.

CHAPTER 4MAJOR ELEMENT GEOCHEMISTRY4.1 Introduction

A description of the geochemical relationships between the various analysed rock types is now presented. Attention is focused on major elements only and trace elements are dealt with in chapter 5. Table 4.1 presents a summary of the available analyses for the rock types discussed in this chapter. The chemical analyses (major & trace element compositions), CIPW norms, and Niggli values are tabulated as to major rock units, classified on the basis of their mineralogy, in Appendix IIB. Tables 4.2A, 4.3A, and 4.2B, 4.3B present the averages and ranges of compositions, CIPW norms, and Niggli values for the rocks in Foindle and Scourie respectively. Determination of the oxidation state of the iron has allowed the calculation of CIPW norms for all analyses. If Fe^{2+} or Fe^{3+} is expressed as total iron, CIPW norm calculations could lead to gross errors (Witty, 1975). Fe^{2+} is found to be always $>$ Fe^{3+} .

The interpretation of the data has been limited to a study of the trends, comparisons, and contrasts, shown by the various groupings. The groupings are based on obvious lithological differences and inferences as to possible initial petrologic type. Rock analyses from previous geochemical studies of the Lewisian Scottish mainland and Outer Hebrides are compared with those for similar rock types (meta-igneous and meta-sedimentary) studied by the present author. Analyses of rocks from other areas are also quoted for comparison (see Tables in Chapters 6 & 7) as the need arises.

The most interesting data have been plotted on Bivariate or triangular diagrams. They were selected either because they showed variation within or between groups or because they are related to standard parameters used by other workers. The graphs included are:

FMA	(fig 4.1)
Or-Ab-An	(fig. 4.2)
K ₂ O-Na ₂ O-CaO	(fig. 4.3)
K ₂ O vs SiO ₂	(fig. 4.4)
MgO, CaO, Al ₂ O ₃ , SiO ₂ vs $\frac{\text{FeO}_t}{\text{FeO}_t + \text{MgO}}$	(fig 4.5)

Two interesting problems in the interpretation of major element data are, firstly, to examine the elemental composition and elemental ratios of each group of similar analyses in relation to the known ranges of different types of possible parent rocks and, secondly, to account for variations in either elemental composition or elemental ratios amongst members of any rock group. These problems are, however, complicated by the fact that available geochemical data are for "end - product" rocks which have suffered both deformation and metamorphism twice. Therefore, the major element data do not necessarily reflect the original chemistry of the rocks.

Comparisons are difficult as compositional variations could be caused by a variety of factors such as:

- (a) sedimentary differentiation or volcanic activity prior to metamorphism of the rocks in the granulite facies
- (b) migrations of material during granulite facies metamorphism
- (c) the retrogression that followed the granulite facies metamorphism

The third factor is immediately favoured as being an important factor in producing compositional variations as there appear to be consistent differences between the analysed samples from Area A and Area B (for details, see Tables 4.2 & 4.3). The textural changes reported in the preceding chapter might have been brought about by a fluid medium. If this fluid was a hydrothermal solution (e.g. H₂O rich,

although fluid enriched in, say, Co_2 is also possible), then alkalis could not be relied on as a guide to the original chemistry of the rocks. Leaching of alkalis, or their redistribution, could easily have occurred during metamorphism in the presence of a fluid medium. Beach (1974) favoured a water phase as the fluid that brought about the textured changes in rocks from the region studied in this thesis, and he considered there was relationship between degree of metasomatism and deformation in the rocks. This close relationship between deformation and metamorphism has also been postulated by Brown and Fyfe (1972) who suggested that water can penetrate granulites along tectonically deformed zones. Beach (op. cit) supported the view of these workers and suggested that water penetrates anhydrous rock system most easily by a process of hydraulic fracturing (a cataclastic process). This diffusion of fluid along the intergranular boundaries of minerals occurred during amphibolitization and resulted in over-all loss of Ca, Mg and gain in Na. From Table 7.3, it can be seen that retrogression in the supracrustal rocks discussed here resulted in loss of Ca, Mg, and Na in the granitic gneiss (meta-igneous) and enrichment of Ca, Mg with loss of Na. Enrichment of potassium occurs in all rock types. There is no significant gain in Na as reported by Beach (1974) for his rocks. However, it must be pointed out that Beach might have compared unaltered Scourian granulite facies rocks (not encountered in the present study) with amphibolite facies ones in order to establish the extent of amphibolitization; furthermore although he mentioned kyanite bearing rocks, there is no evidence that he analysed any supracrustal rocks. Rocks studied in the sampling areas within the Scourie and Foindle are essentially retrogressed granulites, with the degree of alteration more intense in Foindle (see preceding chapter). The reader is referred to Chapter 7 for further discussions.

Where possible, chemical characteristics of rocks are described in groups thought to be genetically related. In certain cases, this is difficult; hence an attempt is made by descriptions of variation diagrams.

4.2 Meta-igneous rocks including Amphibolites

Major element variations amongst the samples of meta-igneous rocks which have been studied are not significant. For example, the hornblende gneisses (average, 51.07% SiO₂ and range, 49.10 - 52.71%) as shown in Table 4.2A are typically high in TiO₂ (average, 1.14%; range, 0.41 - 2.12% and P₂O₅ (average, 0.16%; range, 0.07 - 0.29%), and locally extreme in composition. This has been said to be characteristic of the S.W. Highland metabasite suite (cf. Van De Kamp, 1970; Wilson & Leake, 1972). There is a wide range in the contents of FeO (average, 11.9%; range, 8.44 - 17.30%), and MgO (average, 5.5%; range, 4.19 - 8.68%), and a smaller range in CaO content (average, 8.72%; range, 7.77 - 9.89%). There is generally depletion in K₂O (average 0.44% and always 1%). The FeO_t/FeO_t + MgO values are high (average, 0.71) and this average is within the 0.41% - 0.94% range of tholeiites given by Rivalenti (1976). Comparison of these major element compositions (see Table 4.2A) for averages and ranges with those for basic Lewisian hornblende gneiss, given by Sheraton *et al.* (1973), and for average Archean tholeiite, Minnesota given by Arth & Hanson (1975) shows no significant differences. The data in Table 7.7 show that hornblende gneisses are depleted in K₂O and a consideration with the 'Enriched Archean Tholeiite' (EAT) composition of Condie (1976), (Table 7.7 column 14), suggests that the hornblende gneisses belong to this class.

Taking the rocks from both the Scourie and Foindle areas as a whole, compositions range from ultrabasic through to acid gneisses

and schists. Despite the fact that the rocks vary from ultrabasic to acid in composition, there is surprisingly little variation in $\text{FeO}_t/\text{FeO}_t + \text{MgO}$ ratio. A similar conclusion using the Fe/Mg ratio has been drawn for rocks in the Lewisian by other workers, e.g. Tarney et al. (1973).

Basic to ultrabasic rocks with $\text{CaO}/\text{Al}_2\text{O}_3 > 1$ have been described from the greenstone belts of South Africa by Viljoen & Viljoen (1969, a, b, c) who considered them to be peridotitic and basaltic komatiites, and from the greenstone belts of Australia (Williams, 1972), and Canada (Pyke et al. 1973). However, in rocks of the areas studied by the present author, the $\text{CaO}/\text{Al}_2\text{O}_3$ ratio is always less than 1, so that on the basis of this, it seems unlikely that komatiites are present. This conclusion is also favoured by the average MgO values (see Tables 4.2A & 4.2B) which are extremely low for komatiites.

The Na/K ratio is extremely variable and is highest in the hornblende gneisses and Quartz - feldspathic gneisses. The author supports the idea that the ratio should not be used to discriminate between meta-igneous and meta-sedimentary rocks, especially where secondary alteration like metasomatism can be established. Neither should the Na/K ratio be used as a tool to classify rock types in such circumstance. According to Rivalenti & Ross (1975), the low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio for Archean mafic suites should not be considered significant, for potassium has probably varied as a result of metamorphic alteration.

Rivalenti (1976) used $F = \text{FeO}_t/\text{FeO}_t + \text{MgO}$ as differentiation index for meta-volcanic amphibolites from South-West Greenland. In fig. 4.5, MgO , CaO , Al_2O_3 , and SiO_2 (all in weight percent) have been plotted against F for the hornblende gneisses (amphibolites). MgO and CaO slightly decrease while Al_2O_3 and SiO_2 remain almost constant with increasing F . Depletion of MgO could suggest an original fractionation trend dominated by olivine crystallization.

A slight decrease in CaO with fairly constant Al₂O₃, implies that olivine fractionation might have been accompanied by some fractionation of clino-pyroxene and plagioclase. Constant SiO₂ with increasing F, does not favour the possibility of an orthopyroxene fractionation. However, Rivalenti (op. cit) noted that in tholeiites, olivine fractionation can be accompanied by fractionation of some clino-pyroxene and plagioclase which can result in slight decrease in CaO and which keeps Al₂O₃ constant. Green & Ringwood (1967) interpreted such a feature as a low - pressure fractionation trend for both tholeiites and alkali basalts. Also, according to Osborn (1959), and Hamilton & Anderson (1967), the iron - enrichment trend (fig. 4.1) and the constancy of silica as differentiation proceeds, indicate that differentiation occurred under low or decreasing oxygen fugacity. Rocks with the chemical characteristics as these have been considered 'Primitive' by Engel et al. (1965), and Gale (1973), who suggested that they should represent direct melts of the mantle. Rivalenti (op. cit) also showed that if the differentiation index (F) values are between 0.52 and 0.84, the amphibolites were initially tholeiitic. The average F for the rocks being discussed is 0.71 with a range from 0.52 to 0.84 exactly (see Table 6.1). These figures, therefore, suggest that the amphibolites (or hornblende gneisses) were initially tholeiitic. A confirmation of this suggestion is provided in chapter 6.

4.3 Supracrustal rocks

Most of the rocks classified in the field as members of the Supracrustal group are intermediate (in terms of SiO₂) in composition, although a few are either basic or acid. Available major element data show that it is difficult, if not almost impossible, to draw a clear-cut boundary between meta-igneous rocks and the Supracrustals.

CIPW norms (averages and ranges) in Tables 4.3A and 4.3B, however, show that the quartz - rich rocks reclassified as metasediments (see Table 6.2) are essentially ~~corundum~~ normative. This suggests enrichment in alumina in the pre - metamorphic rocks. It can also imply sedimentary origin (see later chapters for evidences). Also, normative quartz value greater than 50% is unusual for meta-igneous rocks but is usually expected of highly siliceous sediments (e.g chert or sandstone (cf. Mason, 1966). Normative quartz values in Quartzitic gneisses range from 55.59% to 61.09% (see Table 4.3A). This is also reflected in Niggli si (average, 651.34; range, 524.26 - 711.96) for the same rock, type.

Niggli mg varies considerably in value but the values from rocks grouped as Supracrustals are not significantly different from those thought to be meta-igneous series. This feature merely reflects the potash metasomatism which has in part affected nearly all the rock groups, and the same effect can be seen in the triangular plots of the normative feldspar components, Or-Ab-An (fig. 4.2).

4.4 FMA

Low scatter linear trends are shown by the FMA diagram (fig. 4.1). Two trends - calc-alkaline and tholeiitic - are obvious. It must, however, be pointed out that the enrichment in alkalis for some rocks is interesting, and would suggest that 3 magmatic series (calc-alkali, alkali and tholeiitic) might have produced the meta-igneous rocks, by weathering of the latter, the supracrustal rocks studied in the Scourie - Foindle region. Most rocks (except the hornblende gneisses) are enriched in alkalis, but it must be emphasized again that this enrichment may not necessarily be a primary feature. A few rocks are enriched in iron, with the highest values in the hornblende

gneisses (average, 17.30% FeO), and Quartz - magnetite gneiss (16.28% FeO). The tholeiitic iron enrichment trend of these meta-igneous rocks suggests that they might not have originated from the same magma source as the calc-alkaline or alkali rocks. High MgO (wt. %) values are recorded only in the basic rocks.

4.5 Normative Or - Ab - An

The normative feldspar diagram (fig. 4.2) shows a wide scatter of data points with all rocks showing extremely low values in calcium - rich feldspar (see Tables 4.3A, 4.3B). High values in normative albite are characteristic of most rocks. Only a few samples are rich in potash feldspar, emphasizing the low Or content of the bulk of the rocks. However, the meta-igneous rocks and the Supracrustal rocks plot in regions **distinct** from each other. This discrimination is further discussed in Chapter 6.

4.6 K₂O - Na₂O - CaO

Fig. 4.3 shows variation in CaO, Na₂O, and K₂O abundances of the rocks, the distribution data points being similar to that in the normative feldspar diagram above. Wide scatter is a common feature, and is expected. But for the hornblende gneisses, most rocks plot at the centre. From the diagram, it cannot be said with certainty which of these elements are relatively enriched. It is likely that metasomatism gave rise to this complex situation.

4.7 K₂O - SiO₂

Figs. 4.4 (A & B) show wide variation of K₂O with SiO₂. However, the hornblende gneisses, are depleted in K⁺ (1%, see Tables 4.2A & fig. 4.4 (A)). For the other rock types, it can be said that there is a mixed fractionation of K₂O with increasing SiO₂. Such trends have been established in Assynt

but are less well marked in the Scottish Laxfordian and East Greenland gneisses (Sheraton et al. 1973). A general comparison of figures A and B, shows that rocks from Scourie have maximum K_2O of about 6% and a maximum SiO_2 of 75%. In Foindle ^{maximum} ~~minimum~~ K_2O value is about 8% with a maximum SiO_2 value of $\approx 80\%$. It seems, therefore, that retrogression added about (2% - 5%) K_2O on a regional scale, and caused fractionation of K_2O with increasing SiO_2 .

4.8 Oxidation ratio

The oxidation ratio has been calculated from the ratio (mols. $2Fe_2O_3 \times 100 / 2Fe_2O_3 + FeO$) of Chinner (1960). According to Elliot & Cowan (1966), there is a possibility that oxidation accompanies metamorphism. Eugster (1959) had earlier stated that higher degrees of metamorphism do not seem to produce any trends in the state of oxidation of mineral assemblages, and that extensive oxidation in nature is usually connected with large volumes of H_2O which are derived from an environment near the surface. Similarly, Chinner (1960) argued that, during metamorphism the pelitic gneisses of Glen Clova, Scotland, behaved as a system closed to oxygen, and he quoted an authority in favour of this view as a general truth (Elliot & Cowan, op. cit).

The oxidation ratios for all rock types are extreme in both areas studied. The highest values have been recorded in meta-igneous rocks, values up to 18.70 in the homogeneous basic gneiss, and 17.41 in the hornblende gneisses (amphibolites). The lowest ratios are for the supracrustal rocks (average 5.04; range 0.87 - 15.15), with the highest value (15.15) recorded from Quartz - magnetite gneiss. The high value of the oxidation ratio in this rock is fairly close to the range for the basic rocks, and can be interpreted to imply an association with the latter,

and if the oxidation ratio can be proved to be pre-metamorphic, it should help to establish the source of the pelitic rocks in the areas studied. Any classification based on use of the oxidation could, of course, be misleading because, as already mentioned, extensive oxidation is usually connected with movement of large volumes of H_2O . The average oxidation ratio for all the rocks in Scourie is increased by factor of 2 in the Foindle rocks (see Table 7.1). The increase is favoured by a greater abundance of hydrated minerals in Foindle (see preceding Chapter).

It has been noted that metamorphism was accompanied by intense deformation and most probably water was prevalent and aided the development of metamorphic textures. It is therefore, concluded that influx of water increased the oxidation ratios during the amphibolitization that followed granulite facies metamorphism. In Chapter 2, it has been shown that most of the shear zones mapped are within the homogeneous basic sheets (see Maps 1 & 2). The higher values of the oxidation ratio in such rocks can be interpreted to have resulted from

- (a) the presence of water which must have accumulated in tectonically deformed planes (e.g shear zones).

This interpretation is in agreement with that of Beach (1974)

- (b) the obvious iron enrichment character of these rocks and the Quartz - magnetite gneiss.

The relationship between the oxidation ratio and metamorphism, based on this study, is further discussed in Chapter 7.

4.9 Summary and Survey of interpretations

The first point to be established is that there do not appear to be significant major element differences, either

between Scourie - and Foindle rocks of the same type, or between rocks from both areas and similar rocks from other areas of the Lewisian Complex, or even from the whole of the North Atlantic Craton (see Tables 7.7 - 7.10). If, however, comparison is restricted to rocks from the two areas studied, then the Foindle rocks are more enriched in potash. Also, they have higher oxidation ratios, but the $\text{CaO}/\text{Al}_2\text{O}_3$ ratios are similar. On the basis of the available major element data, water enhanced textural changes during retrogression but the original rocks are yet to be established in later chapters. Classification of the rocks as shown in Tables 4.1, 4.2 (A & B), 4.3 (A & B) and Appendix IIB has been based partly on petrographic study. However, the classification has also been supported by considering the behaviour of certain geochemically immobile elements which might have remained behind in the rock system whilst others, mobile ones, were exchanged and entered the fluid during the processes named above. Which elements behave in a mobile or immobile fashion depends largely on the P & T conditions prevailing. For this reason, it is hardly possible to establish a sequence of geochemical mobility of the elements which would be equally valid for all P & T conditions. This is, because, in general, those components which are mobile are easily soluble in hydrothermal solutions, like Na^+ and K^+ . Al^{3+} can under most P & T conditions in the crust be regarded as rather immobile (Wedepohl et al. 1969; pp. 283). Korzhinsky (1955) thoroughly investigated this question of geochemical mobility and proposed the following general sequence, going from elemental oxides of high to those of low mobility:

H_2O , CO_2 , S, SO_3 , CL, K_2O , Na_2O , F, CaO, O_2 , Fe, MgO ,
 SiO_2 , P_2O_5 , Al_2O_3 , TiO_2 .

Many deviations can occur dependent on nature of the transporting

medium, the degree of oxidation, and the state of hydration of ions (Fersman, 1929; Barker, 1964).

Assuming that this sequence can be accepted as valid, even if as a generalised possibility, the author has used it to arrange grouping of individual supracrustal rocks based on concentration of immobile elemental oxides namely: TiO_2 , P_2O_5 , Al_2O_3 and MnO . Fortunately, the classification matched that based on petrographic consideration discussed in Chapter 3. There were a few anomalous cases but a combination of the attempt at geochemical classification with further petrographic study helped resolve them. A study of the behaviour of the refractory oxides (MgO , FeO , CaO) also helped in the rock classification.

Finally, it is necessary to mention here that the major element compositions have not been used to determine the nature of the original rock types. For the supracrustal rocks, they are merely suggestive. At this stage of this thesis, it does not seem unreasonable to suggest that the rocks studied are either meta-igneous or meta-sedimentary when their compositions are compared with those from similar types previously studied by other workers (see Tables 6.6 and 7.7 - 7.10). It also appears that the meta-igneous rocks were derived from three magma series: calc-alkaline, alkalic and tholeiitic (low - alkalic); and the supracrustal rocks were probably derived from the meta-igneous rocks by normal weathering and depositional processes.

TABLE 4.1. Summary of major element analyses for all rock types

ROCK TYPE	NUMBER OF ANALYSES
A. <u>META-IGNEOUS ROCKS</u>	
Ultramafic gneiss	1
Mafic gneiss	1
Hornblende gneiss	5
Quartz-feldspathic gneiss	6
B. <u>SUPRACRUSTAL ROCKS</u>	
Quartzitic gneiss	4
Feldspathic gneiss	1
Garnet granulite	2
Biotite-muscovite-garnet gneiss	8
Biotite-garnet gneiss	2
Biotite schist	2
Quartz-biotite schist	4
Quartz-biotite-garnet gneiss	12
Quartz-magnetite gneiss	1
Quartz-mica schist	2
Quartz-garnet-mica gneiss	2
Quartz-feldspar-garnet gneiss	2
Quartz-garnet-feldspar gneiss	1
TOTAL	56

TABLE 4.2A. Major Element Compositions (averages & ranges) for rocks in Foinde zone

	META-IGNEOUS ROCKS				SUPRACRUSTALS																
	Mafic gneiss	Hornblende gneiss (5)	Quartz feldspathic gneiss (5)		Quartzitic gneiss (4)	Feldspathic gneiss	Quartz-magnetite gneiss	Biotite-muscovite-garnet gneiss (8)		Biotite Schist (2)		Quartz-biotite schist (4)	Quartz-biotite-garnet gneiss (11)	Quartz-mica schist (2)		Quartz-garnet-mica gneiss (2)					
	Ave.	Range	Ave.	Range	Ave.	Range		Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range				
SiO ₂	52.84	51.07	49.10 - 52.71	72.86	70.23 - 77.40	80.85	78.94 - 81.76	66.82	56.89	60.84	58.40 - 61.95	55.93	54.98 - 56.88	74.22	70.55 - 75.07	67.05	63.83 - 69.67	74.94	73.47 - 76.41	77.34	76.57 - 78.11
TiO ₂	0.70	1.14	0.41 - 2.12	0.16	0.04 - 0.23	0.11	*	0.12	0.51	0.68	0.62 - 0.91	0.73	0.67 - 0.79	0.26	0.13 - 0.47	0.60	0.36 - 1.00	0.20	0.13 - 0.27	0.09	0.04 - 0.13
Al ₂ O ₃	15.98	14.77	12.79 - 16.05	13.58	11.37 - 15.32	9.80	9.14 - 10.04	18.14	12.23	17.09	16.07 - 19.53	15.84	15.03 - 16.64	12.08	9.21 - 15.20	15.69	14.76 - 16.33	12.92	12.23 - 13.61	11.85	10.68 - 13.02
Fe ₂ O ₃	1.72	2.88	1.05 - 4.08	0.18	0.01 - 0.38	0.04	0.01 - 0.08	0.14	3.23	0.48	0.28 - 0.76	0.45	0.21 - 0.68	0.16	0.05 - 0.27	0.17	0.04 - 0.52	0.07	0.06 - 0.07	0.06	0.02 - 0.11
FeO	6.72	11.69	8.44 - 17.30	1.95	0.89 - 4.49	1.38	0.50 - 1.15	0.60	16.28	5.38	4.72 - 6.08	8.79	7.68 - 9.90	2.63	1.54 - 5.29	3.70	1.86 - 6.10	1.77	1.54 - 2.00	0.95	1.44 - 1.46
MnO	0.17	0.22	0.18 - 0.26	0.11	0.02 - 0.40	0.11	0.03 - 0.28	0.11	0.18	0.10	0.06 - 0.17	0.20	0.13 - 0.26	0.06	0.03 - 0.12	0.07	0.03 - 0.12	0.04	0.03 - 0.05	0.02	0.01 - 0.03
MgO	4.11	5.57	4.19 - 8.68	0.91	0.50 - 1.70	0.49	0.21 - 0.88	0.53	3.80	2.94	2.60 - 3.58	5.24	5.10 - 5.38	1.46	1.13 - 2.19	1.83	0.73 - 2.53	0.92	0.72 - 1.12	0.24	0.02 - 0.45
CaO	11.00	8.72	7.77 - 9.89	2.69	1.03 - 3.49	1.89	1.17 - 2.82	1.97	1.77	4.59	3.76 - 5.50	4.76	3.48 - 6.04	2.13	1.34 - 2.90	3.85	1.62 - 6.65	1.93	1.23 - 2.63	0.47	0.08 - 0.85
Na ₂ O	2.18	2.81	1.69 - 3.30	4.30	2.29 - 5.73	1.60	1.33 - 1.78	4.44	0.10	3.62	2.24 - 4.55	1.54	1.11 - 1.96	2.50	1.48 - 3.28	3.77	2.90 - 4.73	3.55	2.84 - 4.26	1.07	1.56 - 0.58
K ₂ O	2.14	0.44	0.28 - 0.73	2.12	0.23 - 6.06	1.94	1.19 - 2.82	5.95	0.63	2.00	0.82 - 3.65	3.25	2.39 - 4.11	2.50	1.09 - 4.31	1.62	0.90 - 4.73	2.13	*	6.74	5.29 - 8.19
P ₂ O ₅	0.32	0.16	0.07 - 0.29	0.06	0.03 - 0.10	0.03	*	0.06	0.02	0.26	0.19 - 0.39	0.27	0.24 - 0.29	0.06	0.03 - 0.09	0.18	0.10 - 0.32	0.04	*	0.04	*
LOI	1.49	0.54	0.31 - 2.05	0.90	0.60 - 2.17	0.86	0.53 - 1.05	0.94	3.93	1.55	0.88 - 2.06	1.62	1.34 - 1.89	1.04	0.62 - 1.50	0.90	0.31 - 1.73	0.93	0.72 - 1.14	0.57	0.42 - 0.71
H ₂ O ⁻	0.06	0.07	*	0.06	0.04 - 0.11	0.05		0.03	0.03	0.11	0.09 - 0.13	0.13		0.08	0.05 - 0.10	0.08	0.04 - 0.11	0.14	0.08 - 0.19	0.03	*
Oxidation Ratio	18.70	17.41	10.07 - 19.94	9.04	8.07 - 14.87	2.28	0.89 - 3.47	17.36	15.15	6.96	4.80 - 11.47	4.11	2.40 - 15.82	5.80	3.00 - 7.84	3.86	1.00 - 7.60	3.22	3.05 - 3.39	9.00	1.22 - 18.37
FeO _T /FeO _T +MgO	0.66	0.71	0.52 - 0.84	0.61	0.31 - 0.74	0.73	0.70 - 0.76	0.58	0.83	0.66	0.60 - 0.71	0.63	0.59 - 0.67	0.63	0.58 - 0.72	0.62	0.06 - 0.85	0.60	0.50 - 0.69	0.69	0.60 - 0.77
CaO/Al ₂ O ₃	0.69	0.59	0.53 - 0.67	0.21	0.08 - 0.31	0.20	0.09 - 0.31	0.11	0.14	0.27	0.21 - 0.34	0.31	0.21 - 0.40	0.17	0.11 - 0.24	0.26	0.10 - 0.41	0.16	0.09 - 0.22	0.01	*
Na/K	0.90	6.13	3.16 - 7.70	5.80	0.34 - 16.11	0.81	0.56 - 1.22	0.67	0.14	2.12	1.06 - 4.04	0.50	0.24 - 0.75	1.22	0.45 - 2.73	3.62	0.99 - 17.81	1.28	0.77 - 1.78	0.16	0.06 - 0.26

* No significant change

Figures in brackets show no. of analyses

TABLE 4.2B Major Element compositions (averages & ranges) for rocks in Scourie zone

	META-IGNEOUS ROCKS		SUPRACRUSTALS							
	Ultra-mafic gneiss	Quartz feldspathic gneiss	Garnet granulite (2)	Biotite-garnet-gneiss (2)	Quartz biotite gneiss	Quartz garnet feldspar gneiss	Quartz feldspar-garnet gneiss (2)			
			Ave.	Range	Ave.	Range			Ave.	Range
SiO ₂	40.85	64.25	54.31	54.21-54.40	62.52	61.89-63.14	70.14	78.28	67.94	67.50-58.58
TiO ₂	2.23	0.61	1.15	1.13-1.17	0.72	0.68-0.75	0.31	0.32	0.41	0.36-0.47
Al ₂ O ₃	17.06	14.94	20.33	19.36-21.29	16.75	16.42-17.15	14.94	14.83	16.37	16.11-16.63
Fe ₂ O ₃	1.59	0.45	0.10	0.08-0.11	0.39	0.12-0.65	0.04	0.01	0.14	0.06-0.22
FeO	15.10	4.47	9.12	8.20-10.03	5.40	3.92-6.88	4.19	0.82	2.50	2.30-2.69
MnO	0.25	0.09	0.19	0.13-0.24	0.12	0.08-0.14	0.12	0.02	0.06	0.04-0.07
MgO	7.02	2.93	2.53	2.38-2.68	3.11	3.01-3.21	1.36	0.41	1.23	1.13-1.33
CaO	10.64	5.51	2.99	1.79-4.18	3.28	*	2.00	1.76	2.69	1.97-3.37
Na ₂ O	1.17	4.74	4.13	3.26-5.00	3.57	3.53-3.60	2.95	5.07	3.79	3.04-4.53
K ₂ O	1.04	0.74	2.61	2.29-2.92	2.00	1.12-2.87	2.85	1.37	3.36	1.29-5.43
P ₂ O ₅	0.83	0.12	0.10	0.05-0.14	0.10	0.07-0.13	0.04	0.04	0.08	0.04-0.12
LOI	0.00	1.00	0.89	0.67-1.11	0.67	0.39-0.95	0.45	0.44	0.54	0.24-0.84
H ₂ O ⁺	0.05	0.08	0.09		0.08	0.06-0.10	0.07	0.04	0.22	0.09-0.34
Oxidation Ratio	8.65	8.31	0.93	0.87-0.98	7.27	1.55-12.98	0.85	1.09	3.78	0.70-6.86
FeO _T /FeO _T +MgO	0.70	0.62	0.79	0.78-0.79	0.65	0.60-0.69	0.76	0.67	0.68	0.64-0.72
CaO/Al ₂ O ₃	0.62	0.37	0.15	0.08-0.22	0.20	0.19-0.20	0.13	0.12	0.14	0.07-0.20
Na/K	1.00	4.74	1.29	1.05-1.53	1.87	0.93-2.81	0.92	3.29	1.62	0.50-3.13

* No significant change

Figures in brackets show no. of analyses

TABLE 4.3A CIPW Norms and Niggli values (averages & ranges) for rock(s) Foindle zone

	META-IGNEOUS					SUPRACRUSTALS																
	Mafic gneiss	Hornblende gneiss (5)		Quartz-feldspathic gneiss (5)		Quartzitic gneiss (4)		Feldspathic gneiss	Quartz-magnetite gneiss	Biotite-muscovite-garnet gneiss (8)		Biotite schist (2)		Quartz-biotite schist (4)		Quartz-biotite garnet gneiss (11)		Quartz-mica schist (2)		Quartz-garnet-mica gneiss (2)		
CIPW Norms	Ave.	Range	Ave.	Range	Ave.	Range				Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.		
Qz	3.99	3.03	0.79-7.03	18.76-44.45	58.32	55.59-61.09	13.01	32.36	13.76	18.09	10.86	*	41.52	33.44-49.30	20.07-32.16	39.32	34.88-43.76	43.39	41.46-45.31			
Co				1.57	*	1.72	0.42-2.49	0.96	8.24	1.59	4.33	4.73	-	1.52	0.42-2.28	1.54-2.88	1.36	0.56-2.16	2.05	0.95-3.15		
Or	12.65	2.59	1.65-4.31	1.36-35.81	11.43	8.04-16.66	35.16	3.72	11.80	4.85-21.57	19.21	14.21-24.29	14.76	6.32-25.47	10.01	1.30-16.66	12.56	*	39.80	31.20-48.40		
Pl	45.94	50.14	40.79-55.21	24.23-59.59	22.67	19.33-26.81	46.95	9.43	52.68	35.06-60.15	33.25	24.76-41.74	31.37	19.72-41.55	48.30	40.57-61.27	39.38	36.87-41.89	11.10	5.04-17.16		
Ab	18.45	23.74	14.30-27.92	19.38-50.60	13.52	11.25-15.06	37.57	0.85	32.36	18.95-43.75	12.99	9.39-16.58	21.13	12.52-27.55	31.86	24.54-40.02	30.04	24.03-36.05	9.06	4.91-13.20		
An	27.50	26.41	24.03-28.30	4.85-14.70	9.15	4.27-13.79	9.38	8.85	20.32	16.11-23.29	20.26	15.37-25.15	10.19	6.45-13.80	16.45	6.86-23.95	9.34	5.84-12.84	2.05	0.14-3.96		
Hy	10.07	23.09	20.66-30.81	1.55-11.00	3.77	1.76-7.38	2.14	36.18	15.55	14.19-17.20	27.31	25.14-29.47	8.03	5.46-14.72	9.75	4.86-14.52	5.23	4.45-6.01	2.18	0.73-3.63		
Kt	2.49	4.18	4.06-6.96	0.01-0.55	0.05	0.01-0.12	0.20	4.68	0.70	0.42-1.10	0.64	0.30-0.99	0.22	0.07-0.39	0.25	0.06-0.75	0.10	*	0.09	0.03-0.14		
Il	1.33	2.17	0.78-4.03	0.08-0.44	0.21	*	0.21	0.87	1.17	0.20-1.73	1.39	1.27-1.60	0.49	0.25-0.89	1.14	0.68-1.90	0.38	0.25-0.51	0.17	0.08-0.25		
Ap	0.76	0.38	0.17-0.69	0.07-0.26	0.07	*	0.14	0.07	0.87	0.45-2.54	0.63	0.57-0.69	0.14	0.07-0.24	0.43	0.24-0.76	0.0	*	0.09	*		
Di	20.66	13.20	8.66-17.99	1.85-3.25	-	-	-	-	2.44	2.07-2.81	2.68	-	-	-	4.33	1.57-6.21	-	-	-	-		
Ol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Niggli values																						
al	24.83	21.01	17.85-23.18	5.47-47.81	46.39	39.96-51.87	48.01	22.91	34.70	32.11-37.49	27.72	26.47-28.97	39.58	30.82-44.85	38.66	31.76-45.50	43.70	*	49.79	54.90-		
fs	34.80	49.18	46.28-58.13	9.52-45.10	15.18	8.69-25.51	6.31	69.48	32.07	27.70-34.20	46.53	43.96-49.09	25.49	17.03-45.38	24.57	15.05-32.30	16.75	14.76-18.74	86.64	3.48-13.79		
c	31.13	22.54	19.72-24.51	6.55-25.35	15.74	0.55-24.72	9.48	16.92	16.92	14.87-19.98	15.18	11.02-19.34	12.54	8.78-17.47	16.79	8.63-26.90	12.14	7.22-17.05	3.56	0.61-6.50		
alk	9.19	7.26	4.30-8.49	9.19-36.12	22.70	15.60-30.90	36.20	1.59	16.42	15.05-19.94	10.58	*	22.47	14.74-29.85	19.95	13.76-30.37	27.42	24.75-30.08	38.03	34.82-41.23		
si	139.58	123.24	116.28-130.33	139.58-489.88	651.34	524.26-711.96	300.09	180.81	209.25	190.55-219.19	166.22	162.45-169.98	416.24	350.87-463.87	281.17	236.10-346.35	431.62	402.65-460.59	551.45	545.63-557.27		
k	0.39	0.10	0.07-0.16	0.04-0.64	0.41	0.32-0.61	0.47	0.81	0.27	0.12-0.52	0.58	0.45-0.71	0.39	0.18-0.56	0.22	0.03-0.38	0.29	0.25-0.33	0.80	0.69-0.90		
mg	0.46	0.40	0.25-0.62	0.38-0.50	0.37	0.32-0.42	0.56	0.26	0.47	0.42-0.54	0.51	0.46-0.55	0.51	0.41-0.55	0.45	0.24-0.51	0.47	*	0.21	0.06-0.35		
qs	+2.93	-5.79	(-0.93)-(-9.45)	+80.02-+199.96	+361.86-+496.52	+361.86-+496.52	+55.29	+174.47	+43.57	+36.29-+51.11	+23.90	+18.75-+29.05	+156.65-+269.61	+70.00-+101.39	+182.34-+261.60	+221.97	+261.60	+299.36	+280.71-+318.01			

* No significant change
Figures in brackets show no. of analyses.

TABLE 4.3B. CIPW Norms and Niggli values (averages & ranges) for rocks in Scourie zone

	META-IGNEOUS ROCKS		SUPRACRUSTALS							
	Ultra-mafic gneiss	Quartz-feld-spathic gneiss	Garnet granulite (2)		Biotite-garnet-gneiss (2)		Quartz-biotite-garnet gneiss	Quartz-garnet-feldspar gneiss	Quartz-garnet-feldspar gneiss (2)	
CIPW Norms			Ave.	Range	Ave.	Range			Ave.	Range
Qz		16.82	3.53	0.80-6.26	18.84	17.49-20.19	32.52	34.82	23.97	22.25-25.68
Co			5.51	4.25-6.77	3.04	1.74-4.33	3.46	1.90	2.70	1.75-1.94
Or	6.15	4.37	15.40	13.53-17.26	11.79	5.52-16.96	16.84	8.10	19.86	7.62-32.09
Pl	48.09	57.41	49.14	47.41-50.86	45.78	*	34.62	51.37	45.01	35.24-54.77
Ab	9.82	40.11	34.95	27.59-42.31	30.17	29.87-30.46	24.96	42.90	32.03	25.72-38.33
Hy	0.51	10.51	21.42	19.31-23.52	16.36	13.17-19.55	10.76	2.03	6.95	*
Mt	4.24	1.16	2.18	2.13-2.22	1.37	1.31-1.42	0.59	0.61	0.79	0.68-0.89
Ap	1.97	0.28	0.23	0.12-0.33	0.24	0.17-0.31	0.09	0.09	0.19	0.09-0.28
Di	7.59	7.64	-	-	-	-	-	-	-	-
Ol	26.97	-	-	-	-	-	-	-	-	-
Niggli values										
al	21.06	31.58	36.96	34.39-39.52	35.76	35.46-36.06	41.36	49.28	43.08	42.81-43.34
fm	51.32	30.57	35.75	33.31-38.19	34.36	31.01-37.70	26.60	7.45	18.18	17.60-18.76
o	23.88	21.18	9.77	6.04-13.50	12.72	12.33-13.10	10.07	10.63	12.75	9.52-15.97
alk	3.74	16.67	17.53	13.93-21.13	17.17	14.51-19.83	21.97	32.64	25.99	23.07-28.91
si	85.57	230.50	167.37	163.40-171.34	226.22	217.13-235.31	329.49	418.83	303.52	289.64-308.39
k	0.37	0.01	0.30	0.28-0.32	0.26	0.17-0.34	0.39	0.15	0.35	0.16-0.54
Mg	0.43	0.51	0.33	*	0.50	0.45-0.54	0.36	0.46	0.45	0.40-0.50
qs	-29.41	+63.83	-14.30	-13.19-+41.79	+57.54	+50.60-+59.08	+141.60	+188.27	+99.56	+92.75-+106.36

* No significant change

Figures in brackets show no. of analyses.

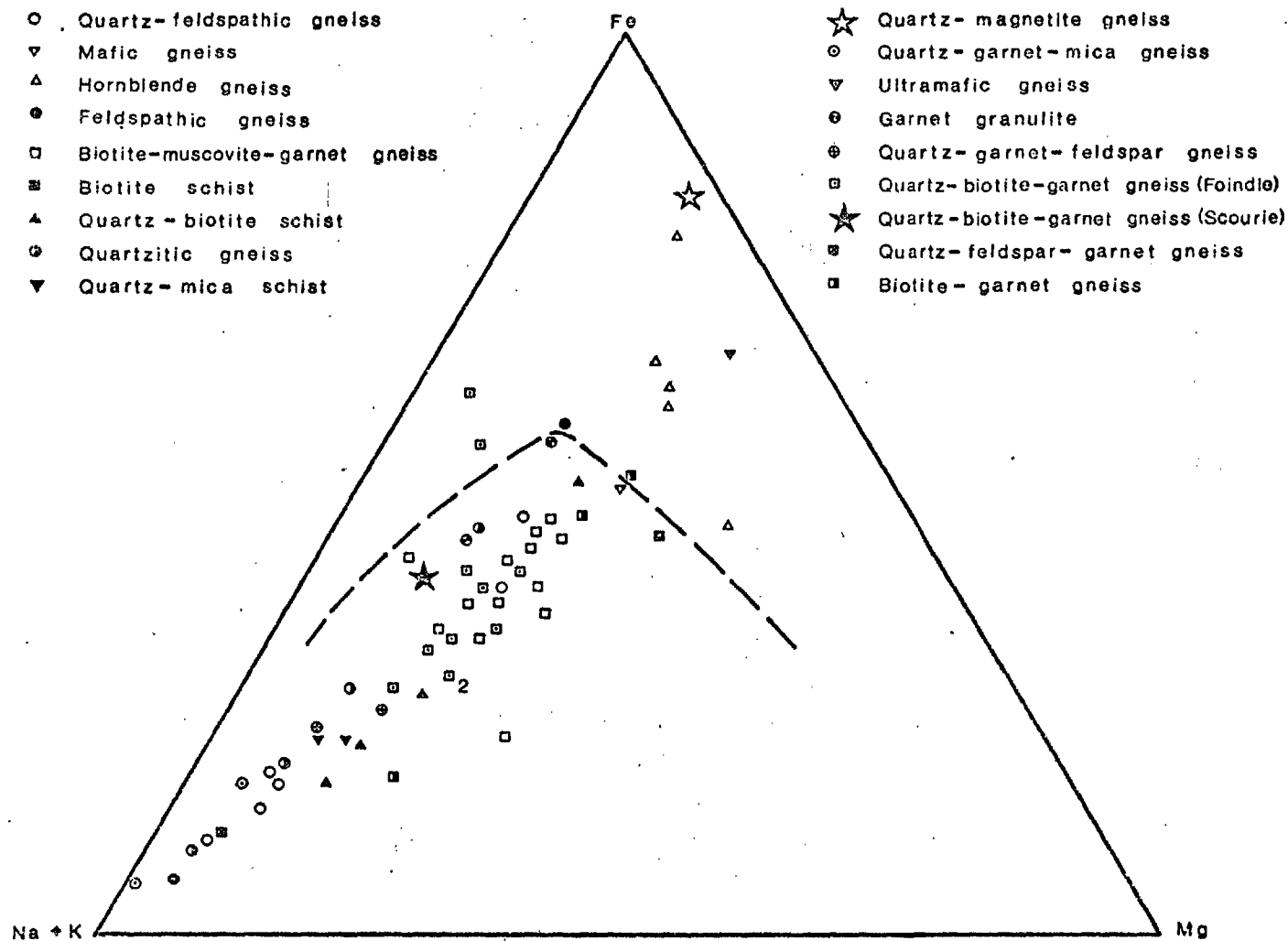


Fig. 4.1 FMA (atomic fractions) plots of the Foindlé - Scourie Supracrustal rocks, quartz-feldspathic, mafic and ultramafic gneisses. The dashed line is that suggested by Irving & Barager (1971) to separate tholeiitic (above) from calc-alkali (below) rock series.

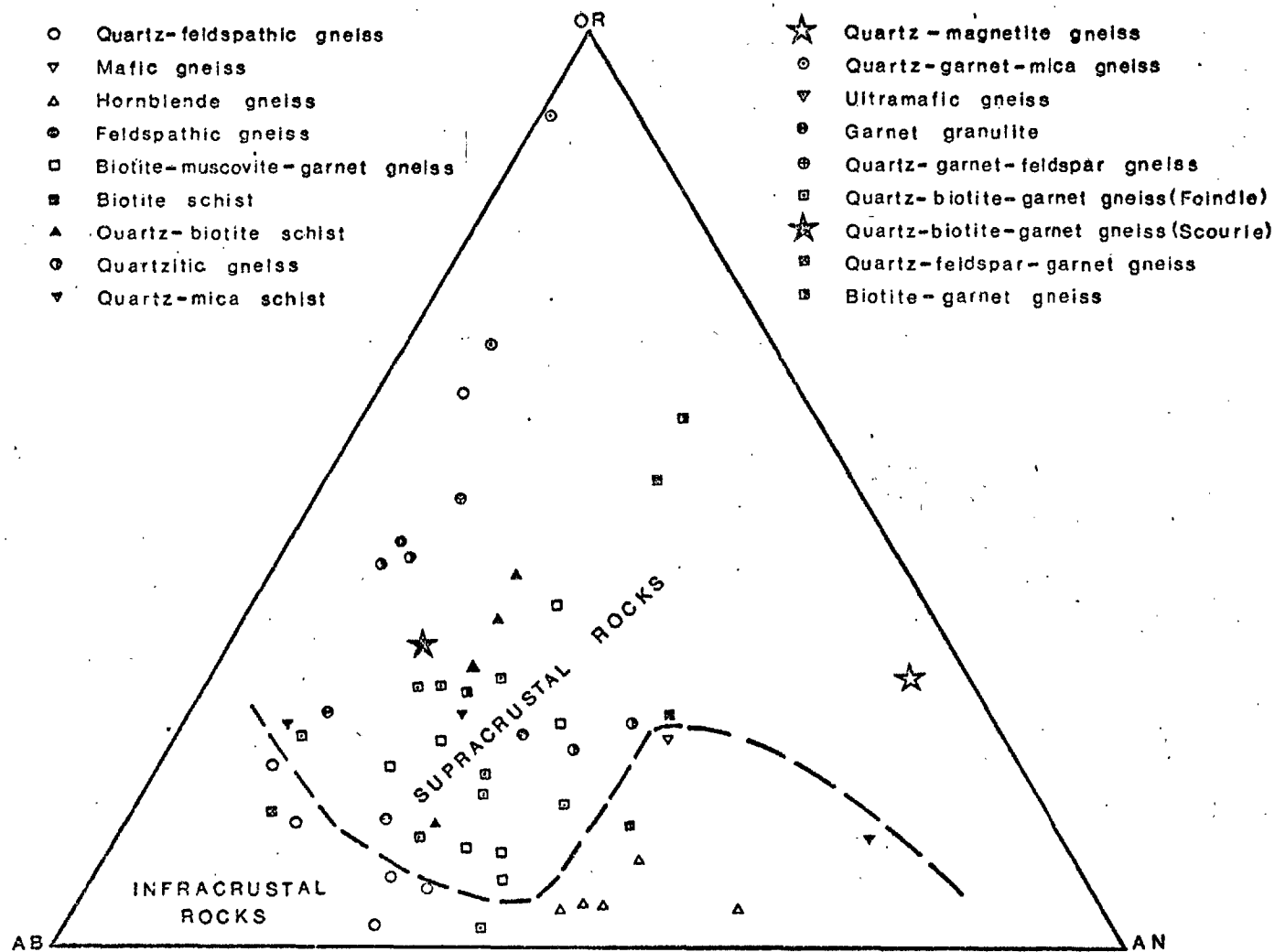


Fig. 4.2 Normative feldspar (Or - Ab - An) diagram for the rocks in Foindie and Scourie. Dashed line separates the two rock groups. The groups are based on field evidence (see Chapter 2)

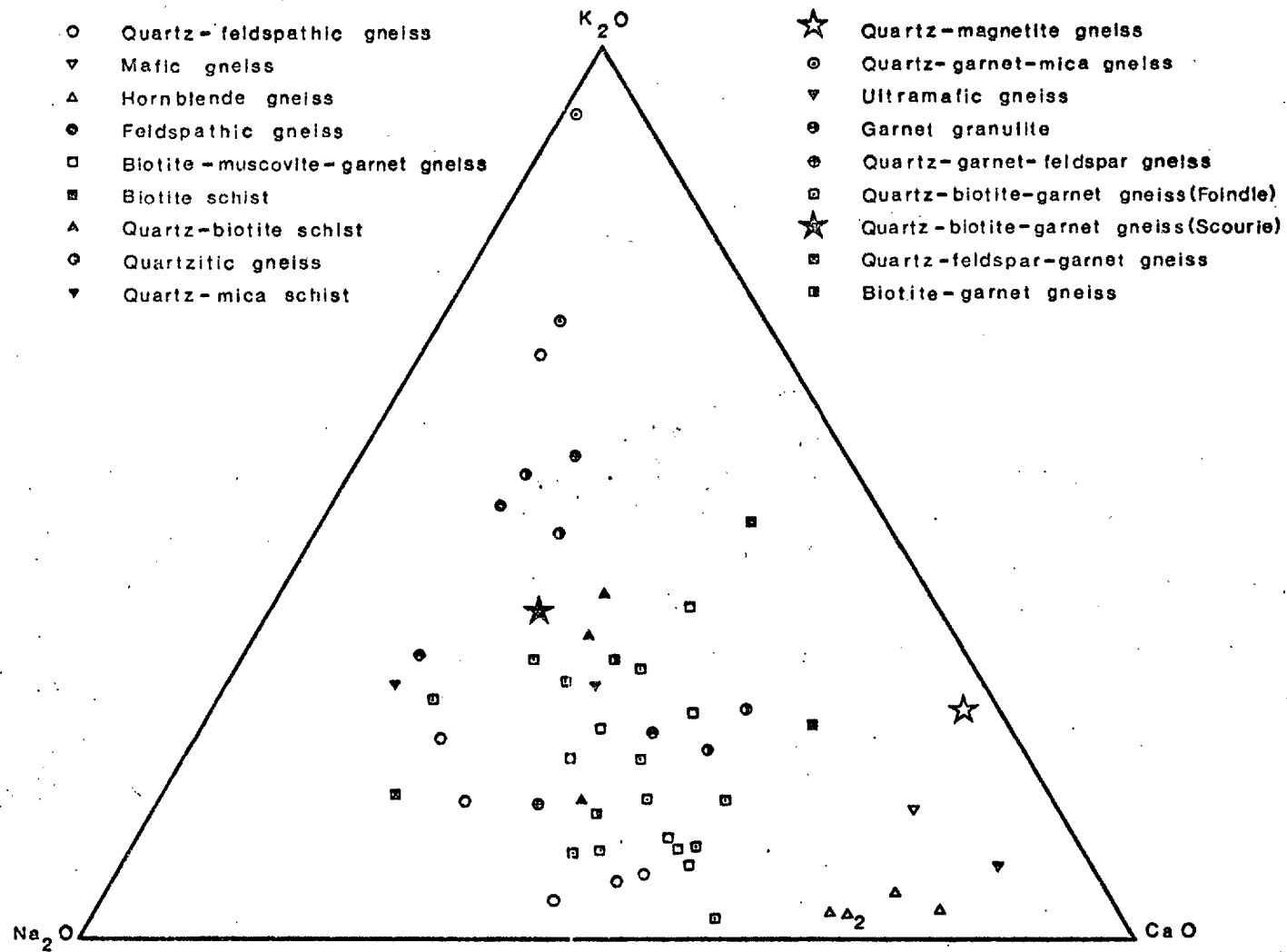


Fig. 4.3 $K_2O - Na_2O - CaO$ diagram showing major element abundances of the rocks in Foindie and Scourie.

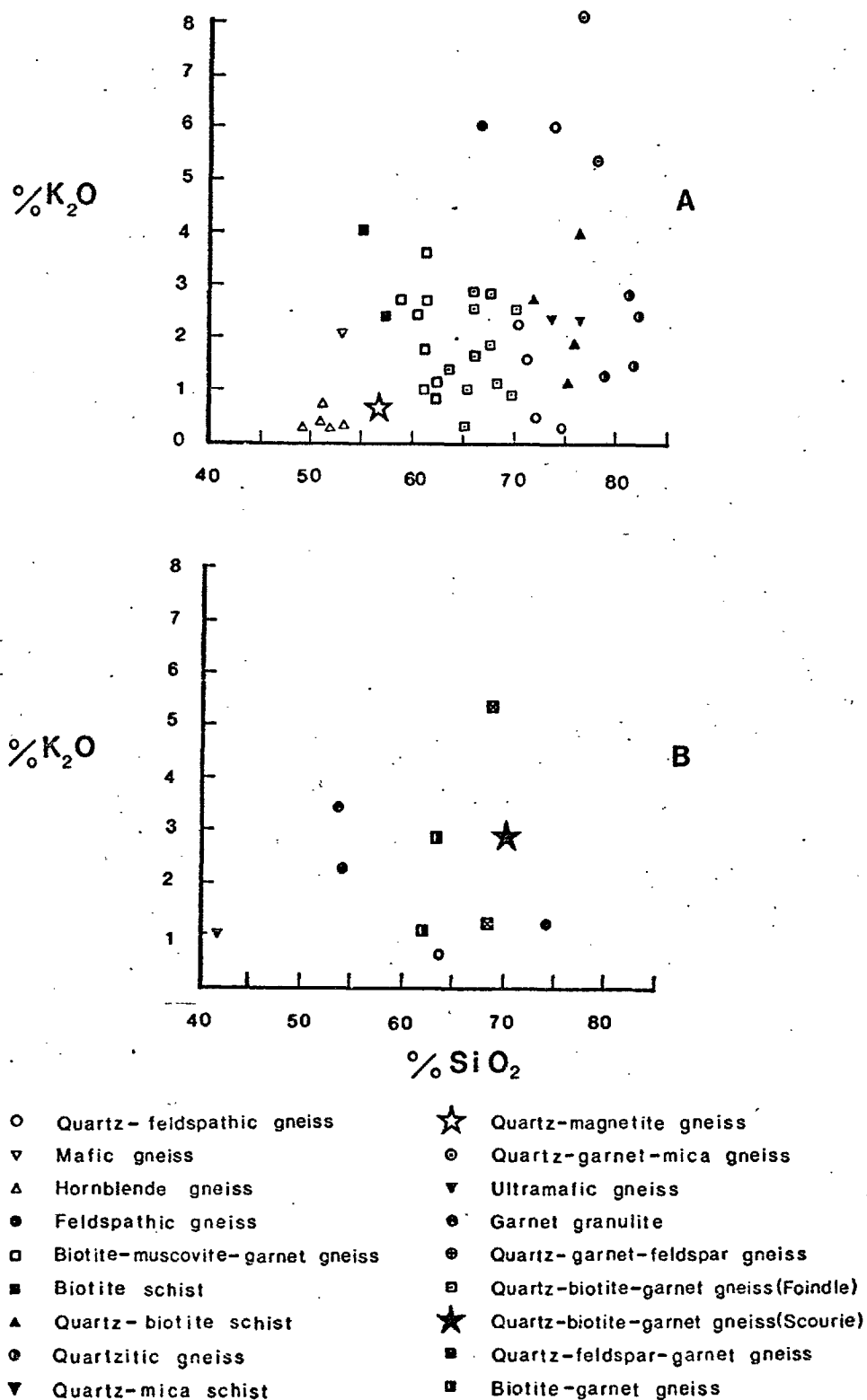


Fig. 4.4 K_2O vs SiO_2 plots for the Supracrustal rocks, quartz - feldspathic, mafic and ultramafic gneisses in Foindle and Scourie. A = Foindle assemblages, and B = Scourie assemblages.

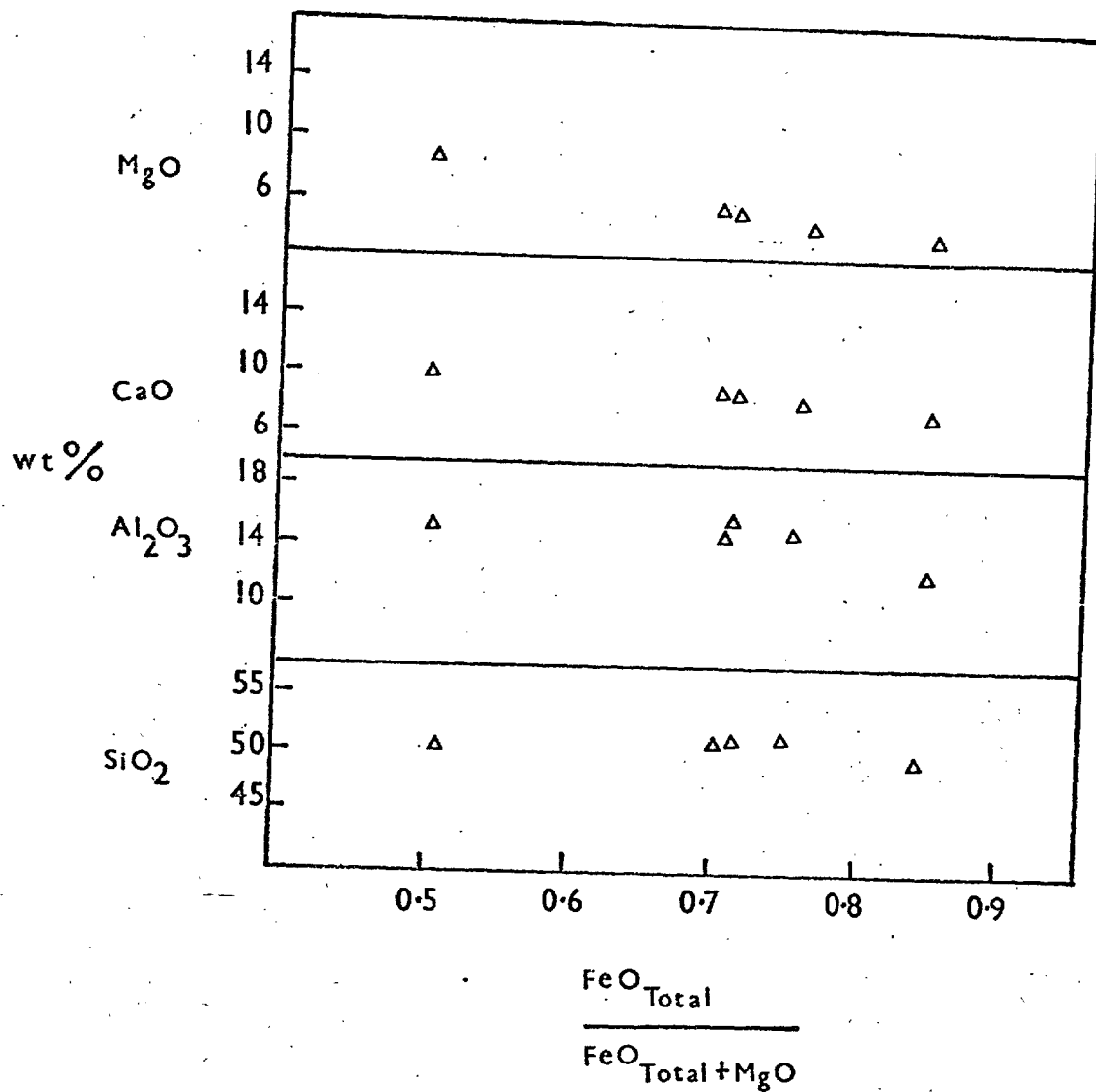


Fig. 4.5 Plot of MgO, CaO, Al₂O₃, SiO₂ (wt. %) vs Differentiation Index, $F = \text{FeO total} / (\text{FeO total} + \text{MgO})$ (after Rivalenti, 1976) for the Foindle Amphibolites

CHAPTER 5TRACE ELEMENT GEOCHEMISTRY5.1 General

The XRF trace element geochemistry is first discussed. The rare-earth element (REE) geochemistry is treated later in this chapter.

Some major elements (e.g. K, Ca, Si, Fe, Mn, Mg) are mentioned here because either they have been used to calculate elemental ratios or are useful in the discussions. A number of these ratios relate to the competition by minor elements for major element sites. Major and minor elements with similar ionic characters will show a change in ratio if a fractionation process, exploiting the slight differences in their physical or chemical properties, has taken place. The greater the similarity between the major and minor elements, the greater is the degree of fractionation required to affect the ratio that relates them.

Data in Table 7.1 show that for rocks from both areas studied, such trace element ratios as K/Rb, and Ba/Rb are high, while Rb/Sr and K/Ba are low. Such characteristics have also been noted by Bott et al. (1972) as typical of granulites. However, a comparison of data from both areas shows that the K/Rb ratio is reduced from the Scourie average of 700 to 560 in Foindle. The Ca/Y ratio is reduced also. All other ratios (K/Sr, K/Ba, and Ba/Sr) are increased.

XRF trace element data and REE data obtained by Neutron activation analysis are summarized in Table 5.1. Complete data for the major rock groups are presented in Appendix while the XRF trace element compositions (averages and ranges) are presented in Tables 5.2A & 5.2B. REE compositions (averages) for major rock groups thought to be genetically related, are shown in Table 5.4.

Table 5.1. Summary of whole-rock XRF trace element and REE analyses for all rock types

Rock Type	Number of Analyses
META-IGNEOUS ROCKS	
Ultramafic gneiss	1
Mafic gneiss	1
Hornblende gneiss	5
Quartz-feldspathic gneiss	6
SUPRACRUSTAL ROCKS	
Quartzitic gneiss	4
Feldspathic gneiss	1
Garnet granulite	2
Biotite-muscovite-garnet gneiss	8
Biotite-garnet gneiss	2
Biotite schist	2
Quartz-biotite schist	4
Quartz-biotite-garnet gneiss	12
Quartz-magnetite gneiss	1
Quartz-mica schist	2
Quartz-garnet-mica gneiss	2
Quartz-feldspar-garnet gneiss	2
Quartz-garnet-feldspar gneiss	1
T O T A L	56

Data from other areas used in comparison are shown in the tables in Chapter 7. The principal conclusion shown by the above is the over-all geochemical similarity of the rocks. In the description of the geochemistry of the various groups, emphasis will be placed on the points of divergence.

Broadly speaking, these analyses are substantially the same as the mean analyses for rocks from the Canadian Shield quoted by Fahrig & Eade (1968), and Shaw *et al.* 1967. The mean analysis of the South-Western Australian Shield given by Lambert and Heier (1968) is also similar. The only remarkable distinction is the higher potassium levels shown by these other rocks. Also useful for comparison are the means of quartz - feldspathic gneisses quoted by Poldervaart (1955), and those of similar Lewisian gneisses quoted by Ghaly (1966). Except for the lower potash and higher soda contents of most Scottish Lewisian rocks, these other compositions are comparable.

The author will examine results using methods devised to help understand origin and relationships of rocks series. Some of these methods were specifically designed to illuminate magmatic processes such as fractionation and would not necessarily have bearing on variation due to sedimentary processes. In order not to prejudge the issue, these plots are used, but their use does not imply that the author regards all the rocks discussed as meta-igneous.

5.1.1 K, Rb

Taylor (1965) stated that the normal value for the K/Rb ratio is between 150 and 300, and that values outside this range call for special explanation. However, he considered most of the exceptions to be below 150, and to be due to extreme fractionation. This conclusion was largely substantiated

by Shaw (1968), who performed covariance analysis on potassium and rubidium values from published data on igneous and quasi-igneous rocks. He showed that the ratio was not constant, and although it fell within Taylor's limit for potassium levels greater than 1%, it rose to 430 with values of K of 0.01%. Most recent work by Sighinolfi (1969) on amphibolites and granulite facies gneisses in the Alps has shown, by a similar procedure to Shaw, that enrichment of K relative to that at low potassium levels is even greater. It is therefore likely that high grade gneisses show a greater degree of Rb impoverishment than those samples used by Shaw.

Figs. 5.1 (A & B) for the rocks studied show wide scatter for the K vs Rb plot, but a trend of increasing K/Rb ratio with increasing K is evident in the two diagrams. Most rocks plot above the crustal average of 230 given by Taylor (1965). As mentioned earlier, the lower ratios are observed for the Foindle rocks. It is possible that this could be due to retrogression, which is thought to be more intense in Foindle (see Chapter 3).

5.1.2 K, Sr

Fig. 5.2 shows that there is no obvious positive correlation between K and Sr in the rocks analyzed. Most rocks plot below the 800 ppm Sr level. Whereas the K, Ba relationship (fig. 5.3) tends to emphasize differences between the groups the K, Sr distribution for all rocks shows remarkably little scatter. This indicates that strontium is probably occupying potassium sites. Taylor (1965) considers that this happens more readily than the entry of strontium into calcium sites. Thus, although the potassium - strontium relationship is very interesting, the K/Ba ratio is a better indicator of fractionation.

5.1.3 Ba

As already stated above, one particularly good test for fractionation in rocks is the Ba/Rb ratios. Although both Ba and Rb are able to occupy potassium sites in micas and feldspars, during fractionation rubidium tends to concentrate in these sites in the fractionating phase, and barium in the residual phase (Skinner, 1970). This is the result of the different size and charge of the two ions, and their behaviour is well documented for fractionation in igneous rocks (see e.g Taylor, 1965).

K/Ba ratio is preferred in this work because some of the rocks have initial K/Rb ratios which are widely divergent from the normal value of 200, and thus the Ba/Rb ratio gives anomalous values. The concentration of barium in potassium sites in the residual phase implies that the barium content would be expected to decrease, and the K/Ba ratio to increase, with an increase in potassium. Since these facts have been observed in South Harris migmatites by Skinner (1970) where fractionation was established, the K/Ba ratio is considered a suitable indicator. There is an increase in K/Ba with increasing potassium for many of the rocks although the degree of potassium enrichment varies considerably. The plot of K vs Ba (fig. 5.3) shows a fairly close correlation between Ba and K. There is certainly a wide scatter but individual rock types cannot be contoured due to the extreme variation in the two elements.

5.1.4 Ca, Sr

Strontium also shows an interesting correlation with calcium. This correlation is especially well marked in acid rocks, but it is not so prominent at higher calcium levels. This is readily explained by Taylor (1965), who noted that strontium much more readily enters calcium sites in plagioclase than in pyroxenes.

Table 5.2A XRF trace element compositions p.p.m. (averages & ranges) for rocks in Foindle zone

META-IGNEOUS ROCKS					S U P R A - C R U S T A L S																
Mafic gneiss	Hornblende gneiss (5)		Quartz-feldspathic gneiss (5)		Quartzitic gneiss (4)		Feldspathic gneiss	Quartz-magnetite gneiss	Biotite-muscovite-garnet (8) gneiss	Biotite schist (2)		Quartz-biotite schist (4)	Quartz-biotite garnet gneiss (11)		Quartz-mica schist (2)		Quartz-garnet mica-gneiss (2)				
	Ave.	Range	Ave.	Range	Ave.	Range			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range			
Cr	153	59	23-94	12	4-22	7	5-10	15	71	81	32-104	181	145-217	14	1-20	45	6-65	20	6-33	9	*
NI	67	26	16-34	8	4-11	9	6-11	7	15	40	25-61	64	46-83	14	4-11	24	6-58	10	7-13	5	4-6
Rb	23	3	41-7	39	2-84	43	33-50	60	8	38	16-86	39	42-112	38	21-49	30	3-65	67	43-90	116	107-124
Sr	346	194	109-240	273	99-631	89	64-119	631	3	476	410-555	385	187-582	302	108-444	424	254-761	241	111-373	75	39-110
Y	22	37	11-69	40	2-154	80	32-117	5	21	15	7-29	46	21-71	59	1-202	18	7-55	57	18-95	58	9-108
Zr	212	151	13-196	188	46-293	229	209-248	154	49	235	195-281	200	126-275	351	278-483	189	21-380	199	179-218	207	133-282
Ba	895	203	91-276	640	113-1249	903	640-1028	5465	84	842	40-1498	1134	1111-1158	1450	590-2972	736	65-2204	389	385-394	1023	793-1253
Th	1	1	1-3	5	1-11	10	4-14	3	6	1	1-2	7	2-12	2	1-3	6	3-9	8	1-15	6	1-11
Zn	89	134	57-188	50	15-138	402	20-959	14	103	34	84-256	209	172-246	58	44-79	86	15-182	33	30-35	49	14-84
Cu	8	7	1-13	13	4-23	9	6-18	5	2	34	5-69	49	25-73	11	9-13	48	5-213	7	4-11	5	4-7
V	178	236	229-318	16	6-24	6	4-7	15	103	103	35-143	154	131-176	27	4-44	72	20-107	17	4-30	4	3-5
K/Rb	791	2503	888-7653	517	237-822	379	226-513	822	665	464	319-616	389	304-473	525	422-737	554	253-988	304	196-412	480	408-552
K/Sr	52	23	13-57	63	10-181	259	178-460	78	1526	35	12-63	108	34-182	94	20-159	35	6-66	103	48-159	874	623-1124
K/Ba	20	25	9-67	25	13-40	18	10-23	9	21	19	13-21	24	18-30	17	8-26	23	11-38	45	45-46	55	*
Rb/Sr	0.07	0.02	*	0.13	0.01-0.28	0.51	0.4-0.80	0.10	2.29	0.08	0.03-0.18	0.34	0.08-0.60	0.17	0.05-0.30	0.07	0.01-0.18	0.47	0.12-0.81	2	1-3
Ba/Rb	40	250	39-167	28	10-61	22	13-31	91	11	24	17-36	18	10-27	35	18-61	29	12-69	7	4-9	9	7-10
Ba/Sr	3	3	1-8	2	1-5	11	9-14	9	25	2	1-3	4	2-6	4	1-7	2	1-5	2	1-4	16	11-20
Ca/Y	3600	7850	815-6429	4794	162-8190	235	72-412	3062	614	3802	1171-4552	1225	349-2102	10498	53-40000	3601	452-15500	341	199-484	60	57-63

* No significant change

Figures in brackets show no. of analyses.

Table 5.2B. XRF trace element compositions p.p.m. (averages & ranges) for rocks in Scourie zone.

	META-IGNEOUS ROCKS		SUPRACRUSTALS							
	Ultra-mafic gneiss	Quartz-feld-spathic gneiss	Garnet Granulite (2)		Biotite-garnet gneiss (2)		Quartz-biotite-garnet gneiss	Quartz-garnet-feld-spar gneiss	Quartz-feldspar-garnet gneiss (2)	
			Ave.	Range	Ave.	Range			Ave.	Range
Cr	44	93	303	201-405	154	15-294	47	17	45	44-46
Ni	31	28	185	70-303	65	14-116	12	7	18	10-26
Rb	45	-	37	34-39	12	9-15	73	10	57	13-102
Sr	3067	506	395	211-578	481	372-590	331	555	516	460-571
Y	235	7	31	17-46	12	1-22	71	3	13	3-23
Zr	178	24	206	176-237	153	71-235	367	307	319	16-622
Ba	402	426	891	425-1356	1466	353-2579	1034	3340	2177	976-3378
Th	9	3	15.40	*	5	*	8	3	4	3-5
Zn	1092	50	157	61-254	70	50-91	40	18	49	42-55
Cu	1019	14	178	71-286	34	14-54	7	4	8	*
V	936	81	262	256-268	102	49-155	62	30	58	*
K/Rb	191	-	578	854-601	1327	1066-1588	326	1163	635	448-822
K/Sr	3	12	83	33-113	33	25-40	72	21	59	19-99
K/Ba	21	14	22	14-30	18	9-26	23	3	12	11-12
Rb/Sr	0.02	-	0.13	0.06-0.19	0.03	*	0.22	0.02	0.12	0.02-0.22
Ba/Rb	9	-	25	11-39	106	41-172	14	341	54	33-75
Ba/Sr	0.13	0.84	2	*	3	1-4	3	6	5	2-7
Ca/Y	323	5549	702	655-750	12266	1081-23452	200	3701	4189	605-7773

* No significant change. Figures in brackets show no. of analyses.

Thus, when the majority of the calcium in the rock is contained in plagioclase, the strontium - calcium correlation is good, but as the proportion of mafic increases, this correlation is lost.

5.1.5 Zn, V, Cr, Cu

Where silica is lower, the corresponding negatively correlated elements, Ti, Fe, Mn, Cr, Ni and Cu are higher. Eade et al. (1966) compared the amphibolite and granulite facies gneisses from New Quebec area of the Canadian Shield, and showed that the higher grade rocks were depleted in silicon and enriched in Al, Fe, Mg, Ca, and Ti. There is some evidence from this work, that elements such as calcium and iron are higher in Scourie where typical granulite facies rocks have been described. It has been observed in chapter two that in areas of inhomogeneous retrogression it is the basic (mafic) gneiss that are least affected. Notwithstanding this, it does seem that there may be some geological significance in these differences. It is also relevant to know that some rocks from Foindle have averages for these elements which compare closely with the Scourie ones (see Tables 5.2A & 5.2B). It is therefore possible that as the Foindle rocks are derived from granulites, they may have retained rather higher levels of Ca, Fe etc from the granulite metamorphic stage.

There is slight systematic decrease of vanadium as the compositions change from intermediate to acid, a characteristic feature of the calc-alkali and alkali rock series. This is also same for iron and magnesium. Vanadium exhibits considerable variation within the rock types. A close correlation exists between vanadium and iron, and vanadium and magnesium.

Due to extreme variations in Zn and Cu contents, and considering the processes that affected the rocks, their absolute

concentrations have not been compared with typical rocks from other areas. Cu particularly cannot be relied on to indicate degrees of fractionation as it is readily amenable to superficial processes, particularly weathering. Where there are high values, it is likely that these elements might have been concentrated in ferro-magnesian minerals (see correlation plots in chapter 6).

5.1.6 Zr

Zirconium is particularly distinctive in that it shows little correlation with any element, and occurs at a roughly constant level of around 200 ppm. It varies irregularly. Cha0 & Fleischer (1960) also noted that in igneous calc-alkaline to calcic suites of the orogenic belts, zirconium varies irregularly.

5.1.7 Th

Thorium values are generally low except in granitic rocks where values greater than 10 ppm have been obtained. Taylor (1965) gave a thorium value of 17 ppm for granite. For the rocks analysed by the author which are possibly metasedimentary, values are close to the average of 7 ppm in the Leverburgh metasediments of Tarney et al. (1972). The gneisses and schists, which are meta-pelites (see chapter 6), have values that are also close to the average value for such rocks of $Th = 12$ ppm given by Clark et al. (1966). Thorium with ionic radius of $1.02\text{\AA}$, is characterized by a tendency to become concentrated in residual magmas (Ringwood, 1955). It is unable to replace Ca^{2+} (ionic radius, $0.99\text{\AA}$) in silicate minerals because of difficulty in attaining electrostatic neutrality of the structure (Ringwood, op. cit.).

Thorium content has been used by Van De Kamp (1968) to distinguish between ortho- and para - amphibolites. The values obtained for the amphibolites from this study are within the range of the ortho-amphibolite of Van De Kamp (op. cit). The reader is referred to chapter 6 for more details.

5.1.8 Y

In the garnetiferous rocks, relatively high levels of yttrium have been observed (see tables 5.2A, 5.2B). A level of 19 ppm has been reported also in the metasediments of South Harris (Tarney et al., 1972; see Table 7.7 column 13). Most of the rock groups in Scourie and Foindle contain between 1 ppm and 201 ppm of yttrium.

There is not much information on the distribution of yttrium in high grade rocks. However, Lambert & Holland (1974) presented a survey of Y data to show its systematic behaviour in igneous, metamorphic and sedimentary rock series, due to its incorporation in a predictable and uniform manner in Ca - bearing minerals. Haskin et al. (1966) quote a mean crustal value for yttrium of around 30 ppm. This would seem to indicate extreme depletion in the average sedimentary rocks. However, analysis of the data shows that there is obvious variation of yttrium with other elements (e.g K, Rb, Th) which commonly show evidence of chemical mobility in the crust. Since it is not thought that there could be major errors in the present yttrium determinations, it is possible that Haskin's mean value for the continental crust is an over - estimate.

The high yttrium content in the metasedimentary rocks of the areas studied can fairly confidently be attributed to the presence of garnet, but it is interesting to consider how this higher concentration was brought about initially.

One possibility is that the occurrence of garnet is the result of a sedimentary origin for the gneisses and schists (see also Skinner, 1970). This idea has been supported by the higher yttrium values for the gneisses of Hess, which occur in association with distinctive metasédimentary rock types (see Watson, 1969), for supposed metasediments in Leverburgh belt (see Farney *et al.*, 1972). Respective values for these two groups are 15 and 19 ppm.

Ca and Y have similar chemical affinities, and yttrium is concentrated in such calcium rich minerals as pyroxene, apatite, and sphene. However, yttrium does not readily occupy calcium sites in plagioclase (see Wager & Mitchell, 1951). Thus Ca/Y ratio would be expected to increase more acid rocks as an increasing proportion of the calcium is found in the feldspar. Furthermore, Lambert & Holland (1974) showed that Hornblende, garnet, orthopyroxene, apatite, sphene, zircon and most K, Na rich minerals other than plagioclase have high yttrium for their Ca contents. They also showed that in sedimentary processes, Ca/Y ratio becomes lower in shales and sandstones, but higher in limestones, than their source while Ca/Y ratio falls as Ca falls in all igneous series for which Y data has been assembled. The author supports the view of the above workers that in sedimentary processes, Ca/Y ratio is lower in the derived shales and sandstones than in their source(s) (see Chapter 7), but on the basis of this study, he also favours the idea of Skinner (1970) that yttrium contents cannot be used to indicate a sedimentary origin. The use of yttrium as an indicator of the presence of garnet is preferred.

It is important to mention here that the striking quantities of garnets in these may not be easily attributed to the yttrium content. Some other source(s) must be found.

This is because garnet is necessarily not present because yttrium is present in the system. Also it has not been possible to distinguish between garnet - bearing and garnet - free rocks using variation diagrams such as Mg^{2+} - Fe^{2+} - Fe^{3+} triangular plot of Griffin & Heier (1969), ACF diagram, or yttrium content, or even Al^{3+}/Fe^{3+} ratio. This can be due to the problems of unrepresentative sampling since most of the garnet gneisses and schists are so heterogeneous that it is almost impossible to sample correctly.

In fig. 5.4(a), data from rocks in the two areas studied are compared with those in Lambert & Holland (1974). The Supracrustal rocks, possible metasediments, (see later in this chapter), plot in the same field as other Lewisian gneisses, and Ca/Y ratio decreases with increasing Y, Ca/Y ratio falls as Ca falls of Lambert & Holland (op. cit), as mentioned above. In fig. 5.4(b), the data for the hornblende gneisses (or amphibolites), are compared with similar rocks from other areas dealt with by Lambert & Holland (1974). The hornblende gneisses plot between 6000 and 1800 Ca/Y ratio and clearly define a trend oblique to the calc-alkaline trend of these workers as exemplified by the Supracrustal rocks. The trend shown by the hornblende gneisses therefore suggests a different origin from the other rock types. It can, however, be said that the hornblende gneisses (amphibolites) are not calc-alkali Archean basalts, neither are they mid - Atlantic type meta-basalts.

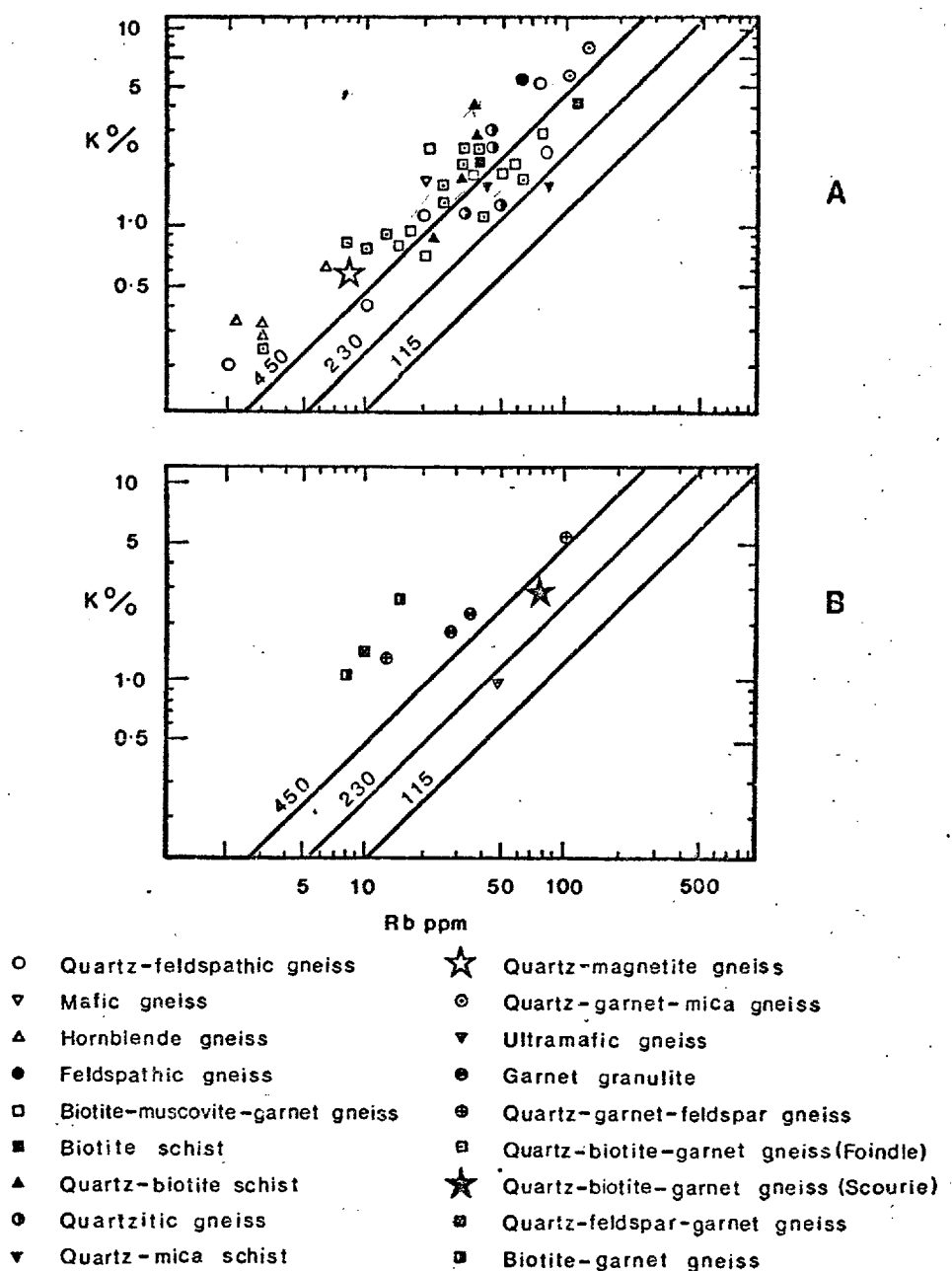
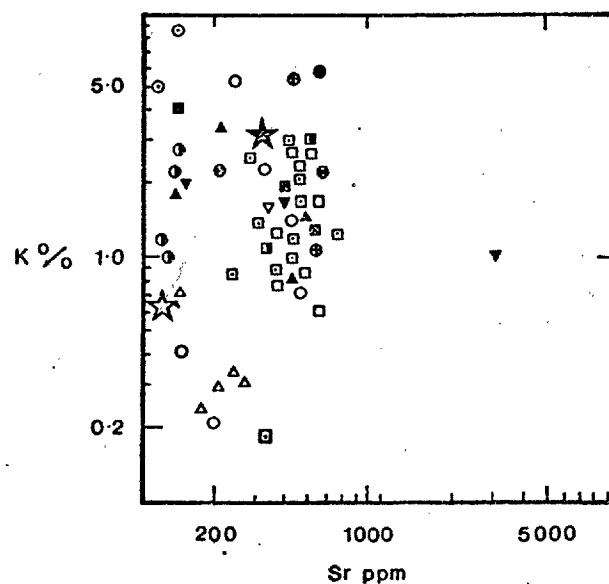
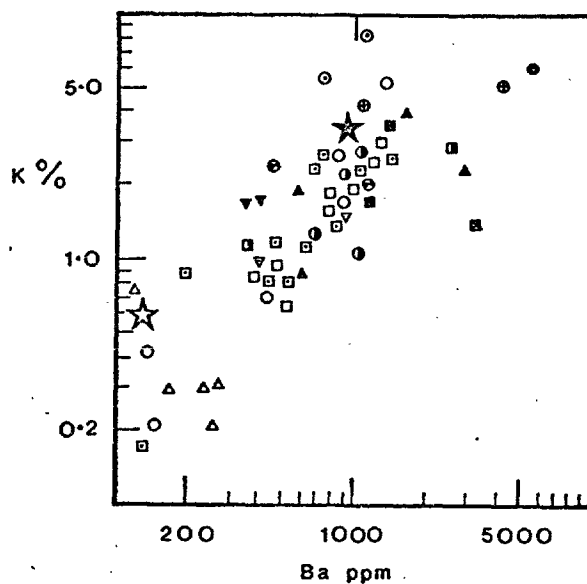


Fig. 5.1 Log plot of K(wt. %) vs Rb (ppm) (after Tarney et al., 1973) for the Supracrustal rocks, quartz - feldspathic, mafic and ultramafic gneisses in Foindle - Scourie region. A = Foindle assemblages and B = Scourie assemblages.



- | | |
|-----------------------------------|---|
| ○ Quartz-feldspathic gneiss | ☆ Quartz-magnetite gneiss |
| ▼ Mafic gneiss | ⊙ Quartz-garnet-mica gneiss |
| △ Hornblende gneiss | ▼ Ultramafic gneiss |
| ● Feldspathic gneiss | ⊕ Garnet granulite |
| □ Biotite-muscovite-garnet gneiss | ⊕ Quartz-garnet-feldspar gneiss |
| ■ Biotite schist | ⊕ Quartz-biotite-garnet gneiss(Foindie) |
| ▲ Quartz-biotite schist | ★ Quartz-biotite-garnet gneiss(Scourie) |
| ⊙ Quartzitic gneiss | ■ Quartz-feldspar-garnet gneiss |
| ▼ Quartz-mica schist | ■ Biotite-garnet gneiss |

Fig. 5.2 Log plot of K vs Sr for the Supracrustal rocks, quartz - feldspathic, mafic and ultramafic gneisses, Foindie - Scourie region.



- | | |
|-----------------------------------|---|
| ○ Quartz-feldspathic gneiss | ☆ Quartz-magnetite gneiss |
| ▼ Mafic gneiss | ⊙ Quartz-garnet-mica gneiss |
| ▲ Hornblende gneiss | ▽ Ultramafic gneiss |
| ● Feldspathic gneiss | ⊙ Garnet granulite |
| □ Biotite-muscovite-garnet gneiss | ⊕ Quartz-garnet feldspar gneiss |
| ■ Biotite schist | ⊞ Quartz-biotite-garnet gneiss(Foindie) |
| ▲ Quartz-biotite schist | ★ Quartz-biotite-garnet gneiss(Scourie) |
| ⊙ Quartzitic gneiss | ■ Quartz-feldspar-garnet gneiss |
| ▼ Quartz-mica schist | ■ Biotite-garnet gneiss |

Fig. 5.3 Log plot of K vs Ba for the rocks in Scourie and Foindie.

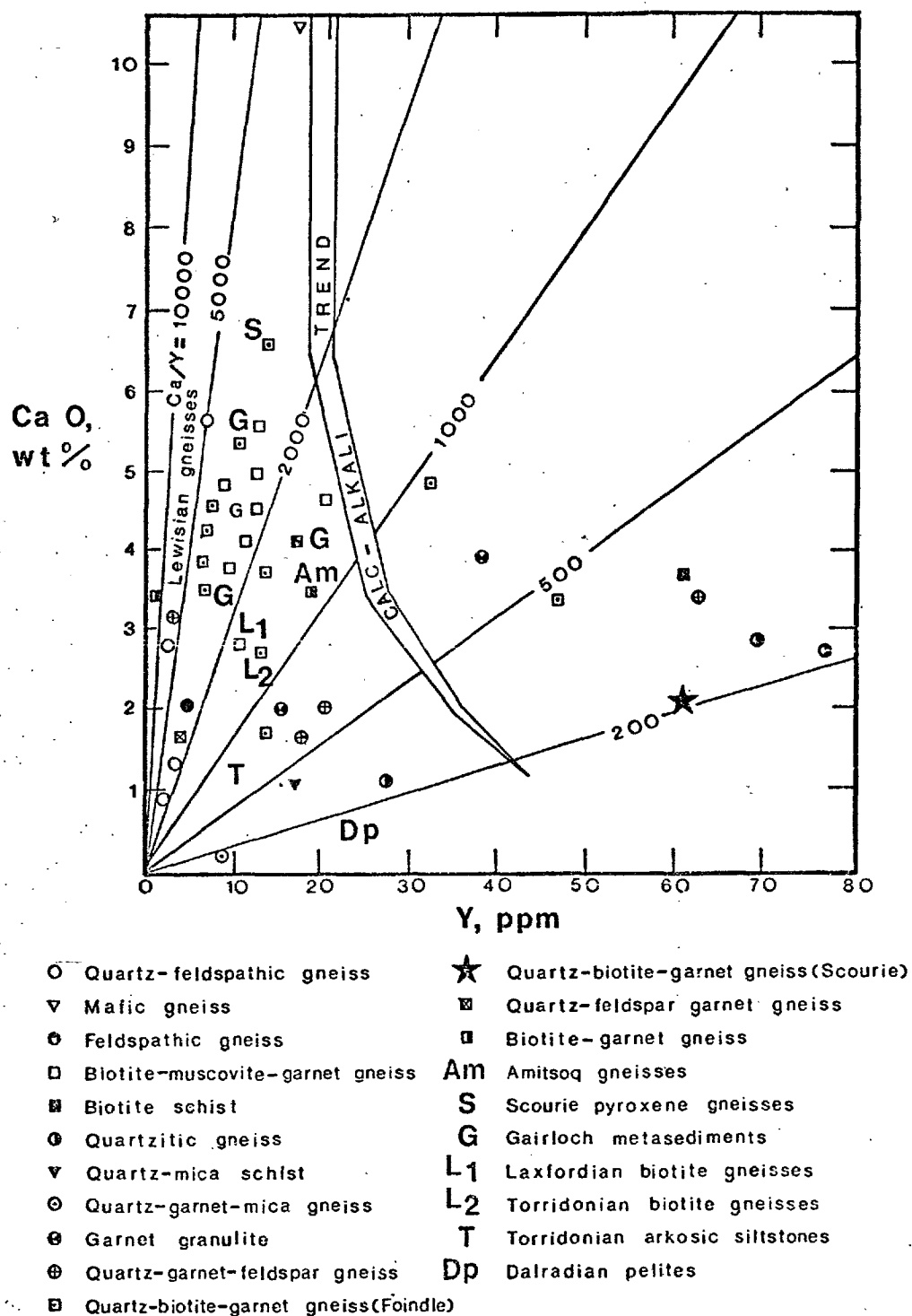
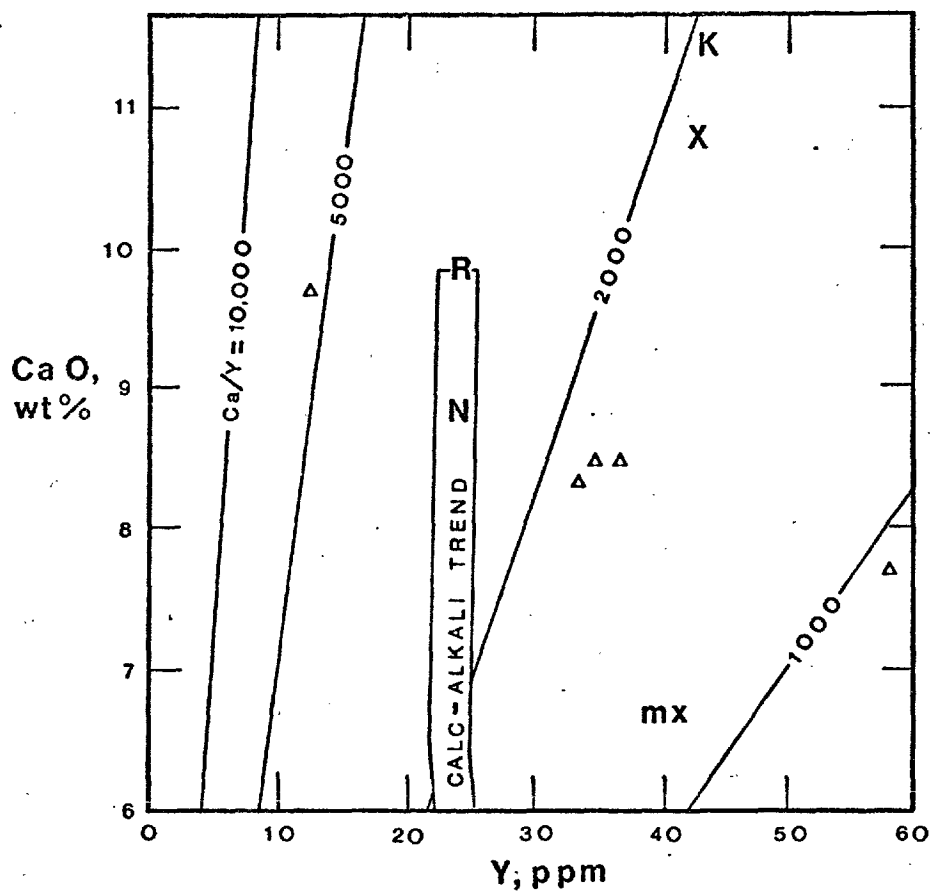


Fig. 5.4(a) CaO and Y contents of the Supracrustal rocks, quartz - feldspathic and mafic gneisses, Foindie - Scourie region compared with similar rocks from Greenland, Lewisian, Torridon and Gairloch of Scotland (after Lambert & Holland, 1974)



- R** Lewisian metadolerite
N Calc-alkali Archean basalt
Δ Amphibolite, Foindie
K Oceanic tholeiites
X Mid-Atlantic ridge metabasalts
mx Mid-Atlantic ridge metabasalt

Fig. 5.4(b) CaO and Y contents from the Foindie Amphibolites, Lewisian metadolerite, Mid - Atlantic ridge meta basalts (average), Oceanic tholeiites, Calc-alkali Archean basalts, Mid - Atlantic ridge meta basalt (after Lambert Holland, 1974).

5.2 Rare-earth elements (REE)

Few accurate data on REE concentrations in meta-sediments are available. The only widely accepted data are for a composite of metamorphosed NAS (North American Shales) and these have concentrations nearly identical to those of the NAS of Haskin *et al.* (1968), but anomalies exist. For example:

- (1) Meta-shales are europium enriched to 1.2 times the value for NAS. This can be due to metamorphism but the origin of the europium is not known and there is no evidence yet to show that a correlation exists between extent of metamorphism and extent of enrichment of europium.
- (2) Also, Yb^{3+} ($z = 70$) and Lu^{3+} ($z = 71$) are distinctly depleted in metamorphosed shales (Yb^{3+} , 3.10 - 2.71 ppm); Lu^{3+} (0.48 - 0.41 ppm) as compared with the NAS (Lu^{3+} by a factor of 0.83). No corresponding deficiencies in Yb^{3+} or Lu^{3+} have been found in the Precambrian sediments (Wilderman & Haskin, 1973).

The REE distributions in a series of progressively metamorphosed pelitic schists from N.W. Maine have been studied by Cullers *et al.* (1973) in order to see if there is any significant change in REE composition from the greenschist to amphibolite facies of regional metamorphism in rocks of rather restricted major element composition. Also Roaldset (1975) analyzed Precambrian rocks and their phyllosilicates, from Hømedal, Norway, which have been subjected to conditions characterizing the upper greenschist to lower amphibolite facies of Barrovian metamorphism (cf. Winkler, 1967).

More work has been done on the REE distributions in shales and greywackes than done on metamorphic rocks (Cullers *et al.* 1973). Composite samples have been analyzed for European

Shales (Haskin & Haskin, 1966; Haskin *et al.* 1968; Hermann, 1970), North American Shales (Haskin & Haskin, 1966; Haskin *et al.* 1968), and Russian shales (Balashov *et al.* 1964; Ronov *et al.* 1967). The absolute and relative contents of the REE in these composite samples are all quite similar and close to the average for igneous rocks in the continental crust (Hermann, 1970). Other results on individual samples of shales and greywackes have been published that are similar in relative and absolute REE content to the previous composites (Haskin *et al.*, 1966; Haskin & Gehl, 1962; Wilderman & Haskin, 1973; Wilderman & Condie, 1973).

For igneous rocks, especially basalts, much work has also been done. Those data which have been chosen for purposes of comparison in this thesis are mentioned as the need arises.

In this study 11 REE (see Appendix III) have been determined in 56 samples of rocks which are retrogressed granulites (see Table 5.1), and the data obtained are considered sufficient to determine the over-all distribution patterns in different rock types. Discussion is based on possible genetic classification of the rock types (see Appendix IIIC) in the region studied. The method is adopted in order to draw better comparisons with accepted major rock types used by many previous workers.

For determination of accuracy, BCR-1 and elemental standards were analyzed and the REE results for BCR-1 (Table 5.3) compare well with the results from Standard BCR-1 by other previous workers.

REE distribution patterns for all the major rock groups are shown in figs. 5.5 to 5.11. Appendix III shows all the available REE data. In Tables 5.4 and 5.5 are the data used for plotting all the REE diagrams.

5.2.1 Choice of chondrite - REE data

It is widely accepted that chondritic meteorites are the best available samples that represent the composition of the non-volatile elements of the earth as a whole, and they provide an excellent reference point for a study of chemical fractionation since they are generally considered the best available sources of undifferentiated matter (see Haskin & Gehl, 1962). Although Koljonen and Rosenberg (1974) chose REE data for Leedy (L6 chondrite) because Nakamura & Masuda (1973) reported that some fractionation of REE exists in the chondrites, the author along with many others still prefers to use the Haskin et al. (1966) values (see Table 5.3 column A). It must be pointed out that the choice of L6 chondrite by Koljonen & Rosenberg (1974) and Nakamura & Masuda (1973) was aimed at obtaining fine distribution patterns for their rocks. Furthermore Koljonen & Rosenberg (op. cit) in their study of REE in granitic rocks preferred plotting data on a decimal scale instead of a log scale. They, however, accept that concentrations in meteorites, peridotites and many sediments are better presented on a log scale. This method has been used in this study.

5.2.2 Normalization

The odd - even variation of REE concentrations in the rocks (which follows from the Oddo & Harkins' Rule) has been smoothened out by normalizing each REE concentration in the sample to some standard on an element by element basis (see also, Piper, 1974). The standards chosen are the chondrite of Haskin et al. (1966) & Gast et al. (1970), and the NASC of Haskin et al. (1966).

A procedure for interpretation of terrestrial rare-earth abundance patterns by Coryell et al. (1973) has been adopted in this study. According to these workers, normalization to

Table 5.3. Rare-earth element abundances (p.p.m)
in Chondrite, NASC, and BCR-1 standard

	A	B	C	D
La	0.30	32	29 ± 1	27.7
Ce	0.84	70	57 ± 2	49.6
Nd	0.58	31	33 ± 2	33.0
Sm	0.21	5.7	7.20 ± 0.2	7.3
Eu	0.074	1.24	2.10 ± 0.1	1.9
Gd	0.30	5.20	6.3 ± 0.3	5.9
Tb	0.049	0.85	0.82 ± 0.02	1.3
Ho	0.073	1.04	1.4 ± 0.02	0.9
Tm	0.033	0.50	0.53 ± 0.01	0.5
Yb	0.20	3.10	3.3 ± 0.1	3.3
Lu	0.031	0.48	0.57 ± 0.01	0.5

A = Average chondrite values from Haskin et al.
(1966) & Gast et al. (1970).

B = Average North American Shale Composite (NASC)
from Haskin et al. (1966).

C = Standard BCR-1 (Rey et al. (1970).

D = BCR-1 standard; this work.

Table 5.4. Rare-earth element data (p.p.m.) for the rocks in Scourie - Foindle region

	A	B	C	D	E	F	G	H
La	43.0	35.0	72.7	11.6	26.8	25.0	41.4	22.2
Ce	46.9	57.2	74.0	37.0	33.5	52.5	19.1	47.2
Nd	40.4	29.3	78.5	20.6	21.2	33.4	85.1	15.9
Sm	8.0	5.1	14.2	6.4	3.9	7.2	17.4	3.6
Eu	1.5	1.8	1.6	1.3	1.0	2.0	3.3	1.7
Gd	6.2	3.7	6.5	4.8	1.6	0.3	12.9	4.2
Tb	1.7	0.8	2.5	1.0	0.8	0.9	1.8	0.7
Hb	1.8	1.3	2.1	1.4	2.7	0.7	1.3	0.7
Tm	0.9	0.6	0.7	0.3	0.8	0.2	-	-
Yb	3.9	2.4	7.1	3.3	3.6	1.7	2.6	3.4
Lu	0.5	0.5	0.9	0.5	1.1	0.3	0.3	0.6
Σ REE	152.6	139.2	259.1	81.0	116.9	123.8	185.3	100.1
Y	35.1	26.4	79.3	37.2	33.4	22.0	235.0	-
Σ REE+Y	187.8	161.7	338.4	118.1	150.2	145.8	420.3	-
Eu/Eu*	0.7	-	0.5	0.5	-	0.7	0.6	1.6
La/Yb	10.8	14.3	11.7	3.8	62.5	15.3	16.3	6.4
La/Ce	1.0	0.6	1.0	0.4	0.9	0.5	2.2	0.5
$\frac{\Sigma \text{LREE}}{\Sigma \text{HREE}}$	11.7	25.9	14.7	6.6	20.5	30.7	8.7	9.3

Eu/Eu* = is europium enrichment factor

A = Average of 5 meta-pelites, Scourie - Foindle

B = Average of 34 mega-greywackes, Scourie - Foindle

C = Average of 4 meta-arkoses, Scourie - Foindle

D = Average of 5 Amphibolites, Foindle

E = Average of 6 Granitic gneisses, Scourie - Foindle

F = Basic gneiss, Foindle

G = Retrogressed Leuco-gabbro, Scourie

H = Meta-pelite?, Scourie More (Savage, pers. comm. 1977).

Table 5.5. Rare-earth element data (p.p.m.) for rocks used for comparison

	1	2	3	4	5	6	7	8	9	10	11	12	13
La	18	38.3	3.71	26	3 $\pm$ 1	0.31	0.42	34	28.4	61	44.33	8.2	26
Ce	46	77 28	9.55	53	31 $\pm$ 2	0.44	1.6	60	43.5	73.75	114.67	-	35
Nd	24	25.68	7 19	25.3	12.2 $\pm$ 0.5	0.49	0.93	28	18.2	75.5	43.67	7.7	24
Sm	6.5	4 96	2.34	4.2	2.24 $\pm$ 0.06	0.20	0.27	5.5	3.5	21.93	9.40	2.3	4.7
Eu	1.07	1.20	0.78	1.13	0.59 $\pm$ 0.02	0.059	0.082	0.96	1.0	9.1	1.91	0.38	1.0
Gd	64	4 27	3.03	3.75	2.1 $\pm$ 0.3	0 31	0.38	-	4.3	26.58	8.53	1.50	4.7
Tb	0.91	0.56	-	3.75	0.3 $\pm$ 0.01	0.051	0.069	0.65	1.15	3.55	1.34	0.29	0.52
Ho	1.21	-	-	0.60	0.4 $\pm$ 0.02	0.081	0.096	-	1.40	4.43	1.76	0.25	0.54
Tm	0.20	-	-	0.26	-	0.034	0.045	-	0.46	-	0.87	0.12	0.26
Yb	2.7	2.53	2.10	1.55	1.04 $\pm$ 0.02	0.27	0.31	1.33	3.55	18.68	5.38	0.96	1.63
Lu	0.66	0.26	-	0.26	0.155 $\pm$ 0.003	0.05	0.051	0.17	-	-	0.81	0.13	0.24

- 1 = European Shales (in Wilderman & Haskin, 1973)
- 2 = Granitic rocks, Finland (Koljonen & Rosenberg, 1974)
- 3 = Archean basalts, Ely Minnesota (Bor-ming Jahu et al. 1974)
- 4 = Wyoming greywackes, Wind River Mountains, Wyoming (Wilderman & Haskin, 1973).
- 5 = Moodie quartzites, Swaziland system (Wilderman & Haskin, 1973)
- 6 = Stillwater peridotite (Frey et al. 1971).
- 7 = Mathesa serpentinite (Frey, op.cit)
- 8 = Granitic pegmatite Siilinjara, Asikkala, Finland (Koljonen & Rosenberg, 1974)
- 9 = Rhyolitic volcanic rocks, Central North Island New Zealand (Ewart et al 1968).
- 10 = Precambrian granites, Numedal Norway (Elen Roaldset, 1975)
- 11 = Meta-greywackes, Couchiching formation, Rainy Lake Ontario (Wilderman & Haskin, 1973)
- 12 = Rib-Mountain quartzites, Wisconsin (Wilderman & Haskin, op. cit)
- 13 = Sebastian Sandstone, cretaceous, Oregon (Haskin et al. 1966).

chondrite compensates for element to element irregularities and reveals small relative abundance variations among neighbouring rare-earths as a result of natural processes.

For comparative purposes the REE abundances have been first normalized to Yb^{3+} and then to the average chondrite values given in Table 5.3. Also in fig. 5.11, the three major metasedimentary groups have been normalized to NASC (see also Table 5.3). The NASC data are thought to be a good approximation to average REE abundances in the continental crust (Haskin et al. 1968).

This method of normalization, instead of normalizing to chondrite only as done by many workers recently, is preferred because the plots obtained give better REE comparison diagrams for the rocks studied. This is because the REE vary systematically in their chemical properties and this method smoothes their variations in the rocks.

5.2.3 Plotting of REE data

Plotting of concentration ratios for any sample on log scale versus atomic number (z), has been adopted because it allows for direct comparison of its REE abundance pattern with that of another sample, regardless of absolute concentrations in the two rocks. By comparing the REE abundance patterns for samples of related origin it is possible to trace some of the steps in the geochemical evolution of the samples.

5.2.4 REE ratios

As shown in the REE data (see Appendix III, Table 5.4), rare-earth element ratios like $\Sigma \text{LREE} / \Sigma \text{HREE}$, La/Yb , La/Ce , and Eu/Eu^* have been used in this thesis. ΣLREE is the sum of light REE (La to Sm) while ΣHREE is the sum of heavy REE (Gd to Lu). Nane & Taylor (1976) used the ratio of the light REE to heavy

REE to divide Archean sediments into Archean and post-Archean. In this work, it is used in the same sense. However, the ratio can be used to estimate the degree of fractionation of light REE relative to heavy REE. The La/Yb ratio has been used also to estimate the degree of fractionation as did Frey *et al.* (1971), Nance & Taylor (1976). These ratios are mentioned as the need arises. Eu/Eu^* is the europium enrichment factor where Eu^* is the europium value relative to chondrite and Yb when there is no anomaly. The La/Ce ratio can be used to distinguish between meta-igneous and metasedimentary rocks (see next chapter for details).

5.2.5 Y & REE

Because yttrium and the REE behave so nearly alike chemically, the absolute concentration of yttrium has been added to the total REE (ΣREE) for each rock analysis. However, the bulk of the REE and yttrium is still present as trace quantities when compared with major elements.

5.2.6 Interpretations of REE data

Because of the extreme variation in the absolute concentration of REE in the rocks studied, interpretation has been possible only by describing the distribution patterns for rock groups and comparing them with similar types from other areas as done by previous workers. The extreme variation can perhaps be attributed to metamorphism, although there is not yet any widely accepted evidence for the effect of metamorphism on REE behaviour. However, the author believes that the over-all distribution patterns are not necessarily affected. Comparisons as noted above have favoured this view.

(1) Retrogressed Leuco - gabbro

One sample called the ultramafic gneiss (LNS 113) as a field name from Scourie was analyzed. Already, as reported in the chapter 2, the rock is highly retrogressed so that the original chemistry is masked by this alteration. In order to deduce the parent material, the REE pattern (fig. 5.5) is first compared with those from Ultramafic rocks by Frey et al. (1971). While the ultramafics of Frey et al. (op. cit) are highly depleted in REE and have flat patterns, this rock is characterized by a negative europium anomaly ($\text{Eu}/\text{Eu}^* = 0.62$), and a moderately high degree of fractionation ($\sum \text{LREE} / \sum \text{HREE} = 8.67$; $\text{La}/\text{Yb} = 16.25$). The petrographic study does not favour the metasedimentary origin implied by the La/Ce ratio of 2.16. In order to help in the interpretation, the REE pattern for LNS 113 was further compared with that for a mafic gneiss from Foindle. Apart from enrichment of neodymium (Nd) in the Ultramafic gneiss, the two patterns are fairly close. If the major element and other trace element data are compared with those for gabbro (see Table 7.10), it can be said that this rock is a retrogressed leuco - gabbro.

(2) Granitic gneiss

REE contents have been previously investigated in granitic rocks (see Gavrilova & Turanskaya, 1958; Balashov, 1963; Chase et al. 1963; Haskin et al. 1965; Towell et al. 1965; Taylor et al. 1968; Nagasawa, 1970; Nagasawa & Schnetzler, 1971), and high silica and alkalic volcanic rocks (see Ewart et al. 1968; Capaldi et al. 1972). According to Koljonen and Rosenberg (1974), the behaviour of REE in granitic rocks may be summarized as follows:-

- (a) During magmatic differentiation the content increases and in granites it is nearly three times that in

- (b) Light REE from La to Sm are enriched compared with heavy ones from Gd to Lu
- (c) Europium differs from the other REE in having the possible valency of +2 (ionic radius 1.09A) as well as +3. Under natural conditions, it may also partially separate from the other REE and be incorporated in place of Ca (ionic radius 0.99A) into common rock - forming minerals, especially plagioclase. It is also enriched in anorthosites and other Ca - rich magmatic differentiates and is depleted in granites
- (d) Ce may oxidize to Ce^{4+}

From fig. 5.6 there is no obvious europium anomaly. A high degree of fractionation is evident from the $LREE/HREE$ average value of 20.5; La/Yb average ratio of 62.5. Although the rhyolitic volcanic rocks of New Zealand (Table 5.5 column 9) are not lower in the total abundance than the average Scourie - Foindle granitic gneiss (Table 5.4 column E), they have a lower La/Yb ratio (7.97) and lower $\frac{\sum LREE}{\sum HREE}$ (1.79). Limited fractionation of the lighter REE has been noted in rhyolitic volcanic rocks by Ewart et al. (1968). It seems therefore that the quartz - feldspathic gneisses now re-classified as granitic gneisses are not of rhyolitic origin.

The La/Ce ratio is 0.9 but it cannot be used, in this case, to deduce the origin of these gneisses. The REE distribution patterns in fig. 5.9 showing rocks considered to be meta-greywackes are similar with those in fig. 5.6 and this could suggest that the meta-greywackes are derived from the granitic gneisses, and not from rhyolitic volcanics.

(3) Amphibolites

In fig. 5.7, the REE distribution pattern from an average

of 5 analyses from the Amphibolites of Foindle is compared with the equivalent pattern for average Archean basalt, Minnesota. There are many data on REE distribution patterns in basalts (e.g. Haskin et al., 1968), but the Minnesota basalt has been chosen because the rocks from Foindle are also Archean (see chapter 1). Wilderman & Haskin (1973) in their work on the rare-earth's in Precambrian sediments noted that except for Eu, the relative abundances of the REE at the earth's surface appear to have remained constant over the past 3 billion years. They, however, also noted that perhaps metamorphic processes could alter the **relative** Eu abundances. The diagrams in fig. 5.7 show that the Foindle amphibolites are enriched in Eu by a factor of 1.4 relative to the Minnesota basalt, although both are characterized by a negative europium anomaly ($\text{Eu}/\text{Eu}^* = 0.5$, Minnesota; $\text{Eu}/\text{Eu}^* 0.5$, Foindle). Also there is a flat pattern in Foindle amphibolites as is expected in Archean basalt such as the Minnesota type but displaced surely because of higher absolute concentrations (i.e. there is slight fractionation of lighter REE (average $\sum \text{LREE}/\sum \text{HREE} = 6.6$; average $\text{La}/\text{Yb} = 3.8$). Since the two distribution patterns are similar it can be said that the Amphibolites are comparable with Archean basalts. Frey et al. (1971) noted that the enrichment of basalts in the light REE is not solely a result of contamination by continental crust. They further noted that the enrichment in light REE characteristic of the crust appears to be a result of mantle processes that form crustal material. From the limited data available in this work, it is not possible to attribute the light REE enrichment in the Foindle amphibolites to any specific process.

Condie (1976) showed the existence of two major types of Archean tholeiites; depleted Archean tholeiite (DAT)

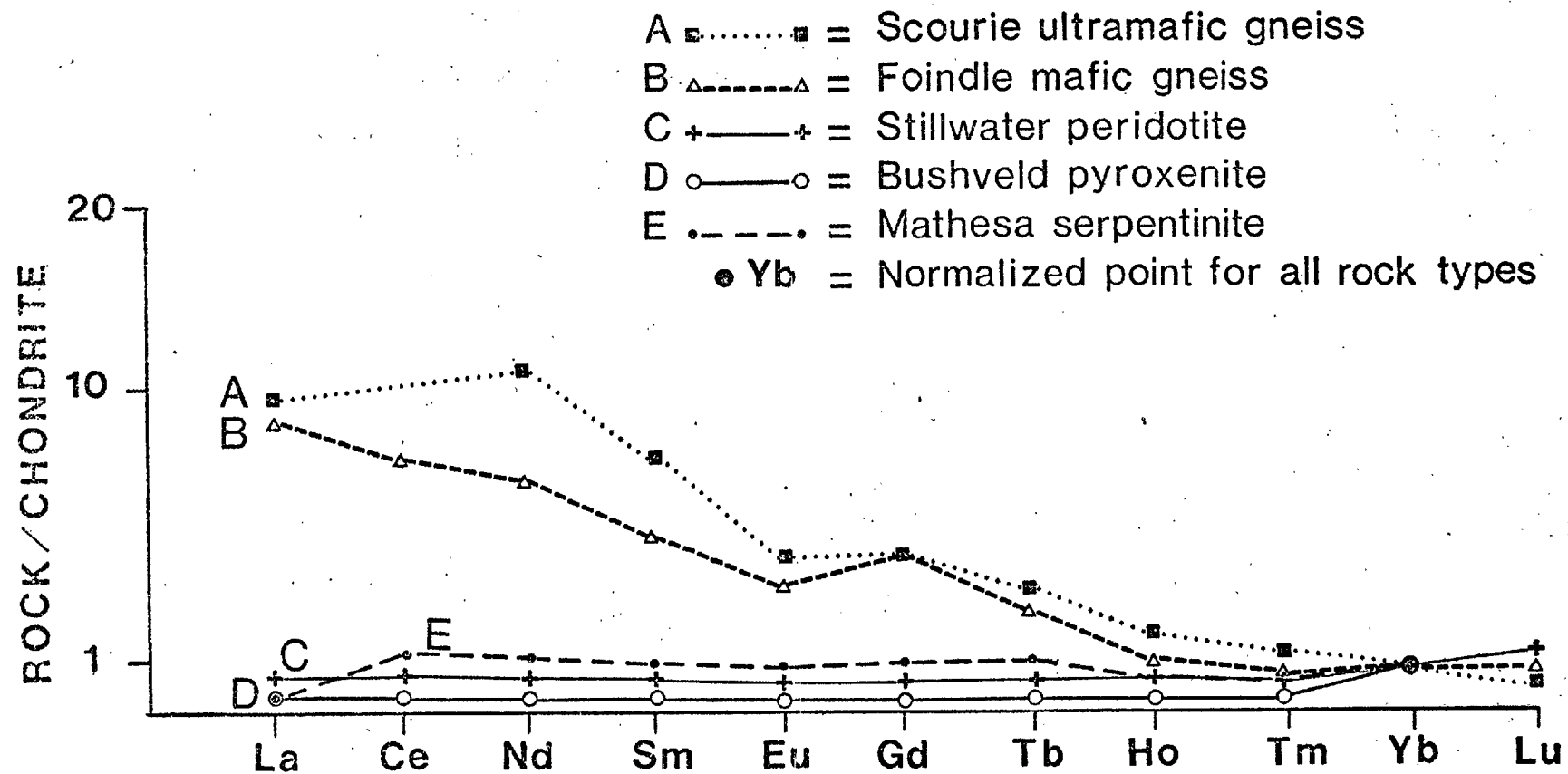


Fig. 5.5 Rare-earth comparison diagrams for the Scourie ultramafic gneiss (A); Foindie mafic gneiss (B); Stillwater peridotite (C); Bushveld pyroxenite (D); and Mathesa serpentinite (Frey et al., 1971).

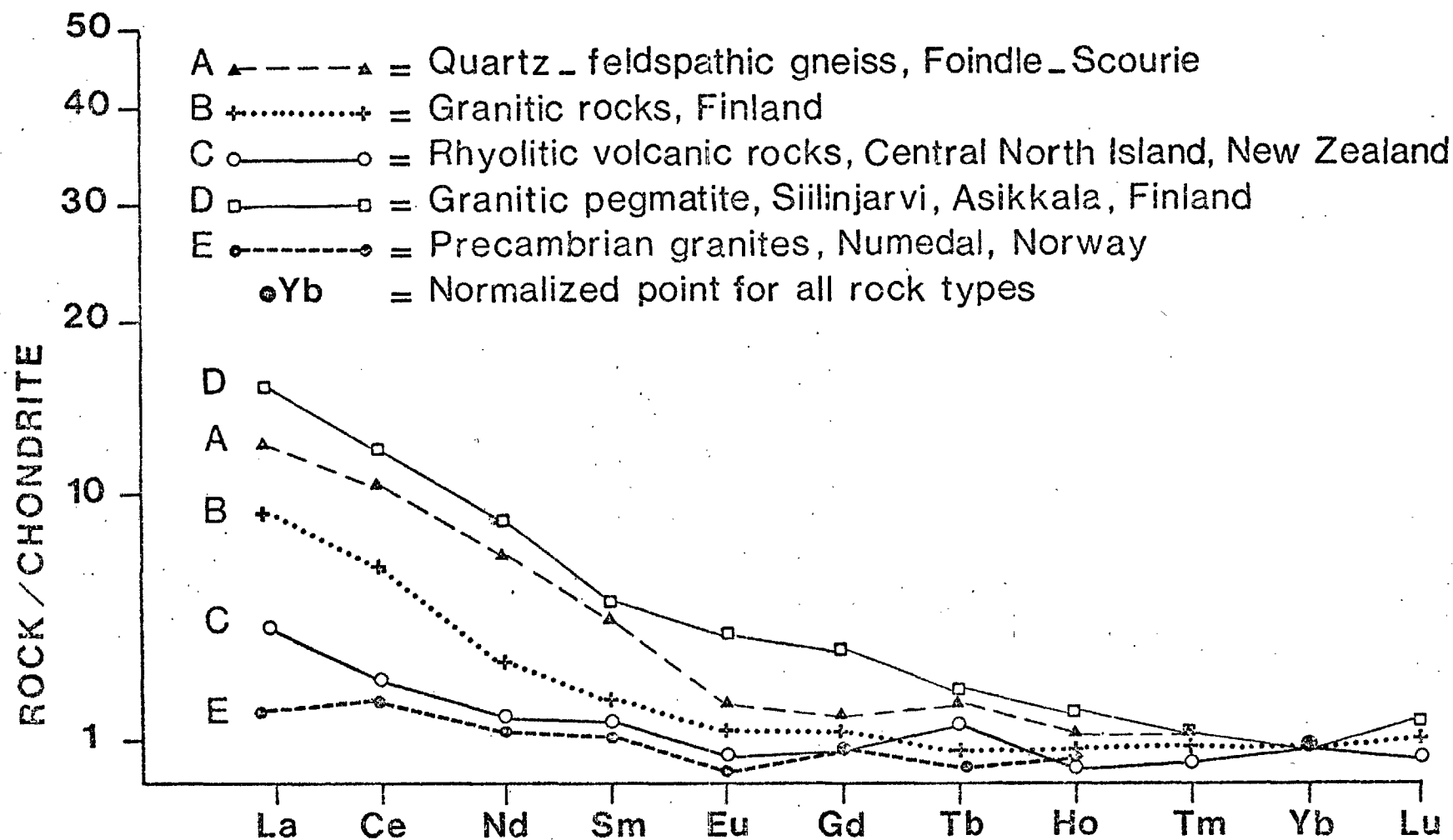


Fig. 5.6 Rare-earth comparison diagrams for the Foindle - Scourie Quartz - feldspathic (or granitic) gneiss (A); Granitic rocks, Finland (B) (Koljonen & Rosenberg, 1974); Rhyolitic volcanic rocks, Central North Island, New Zealand (C), (Ewart et al. 1968); Granitic pegmatite, Finland (D) (Koljonen & Rosenberg, 1974); and Pre cambrian granites, Numedal Norway (E) (Røedset, 1975).

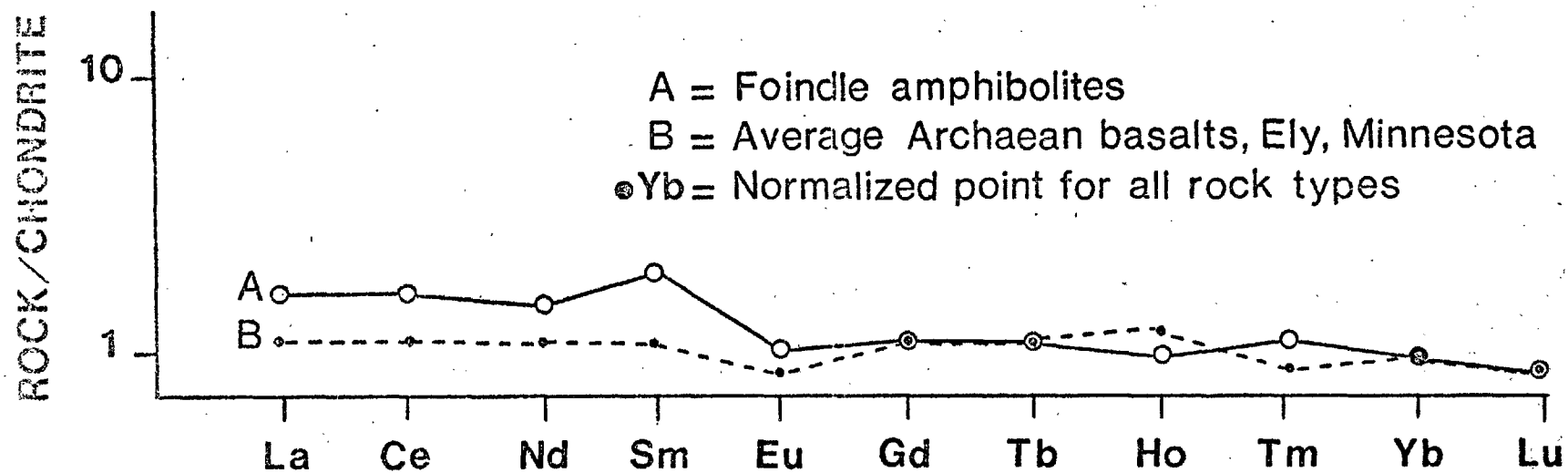


Fig. 5.7 Rare-earth comparison diagrams for Foindle Amphibolites (A), and Average Archean basalt (B), Ely, Minnesota (Bor - Ming et al., 1974).

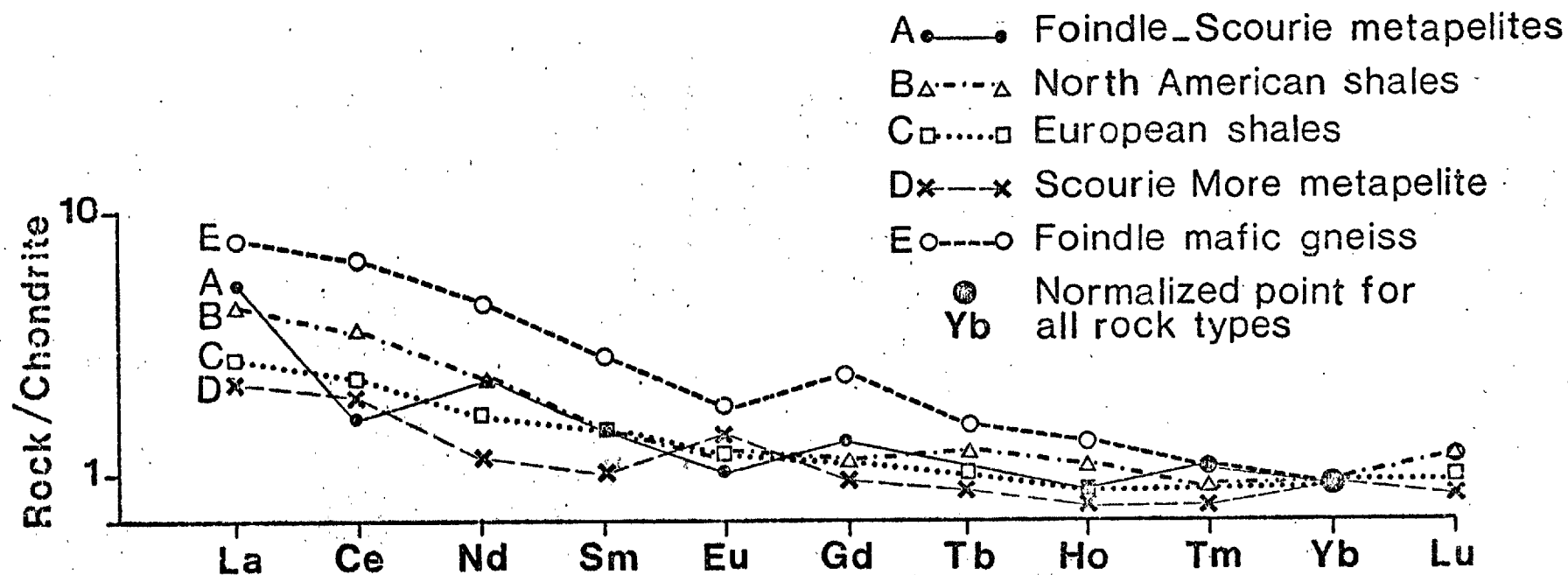


Fig. 5.8 Rare-earth comparison diagrams for Foindle - Scourie meta-pelites (A); Precambrian North American Shales (B); European Shales (C) (Haskin et al. 1968); and Scourie More meta-pelite? (D), (Savage, pers. comm. 1977); and Basic (or mafic) gneiss, Foindle (E).

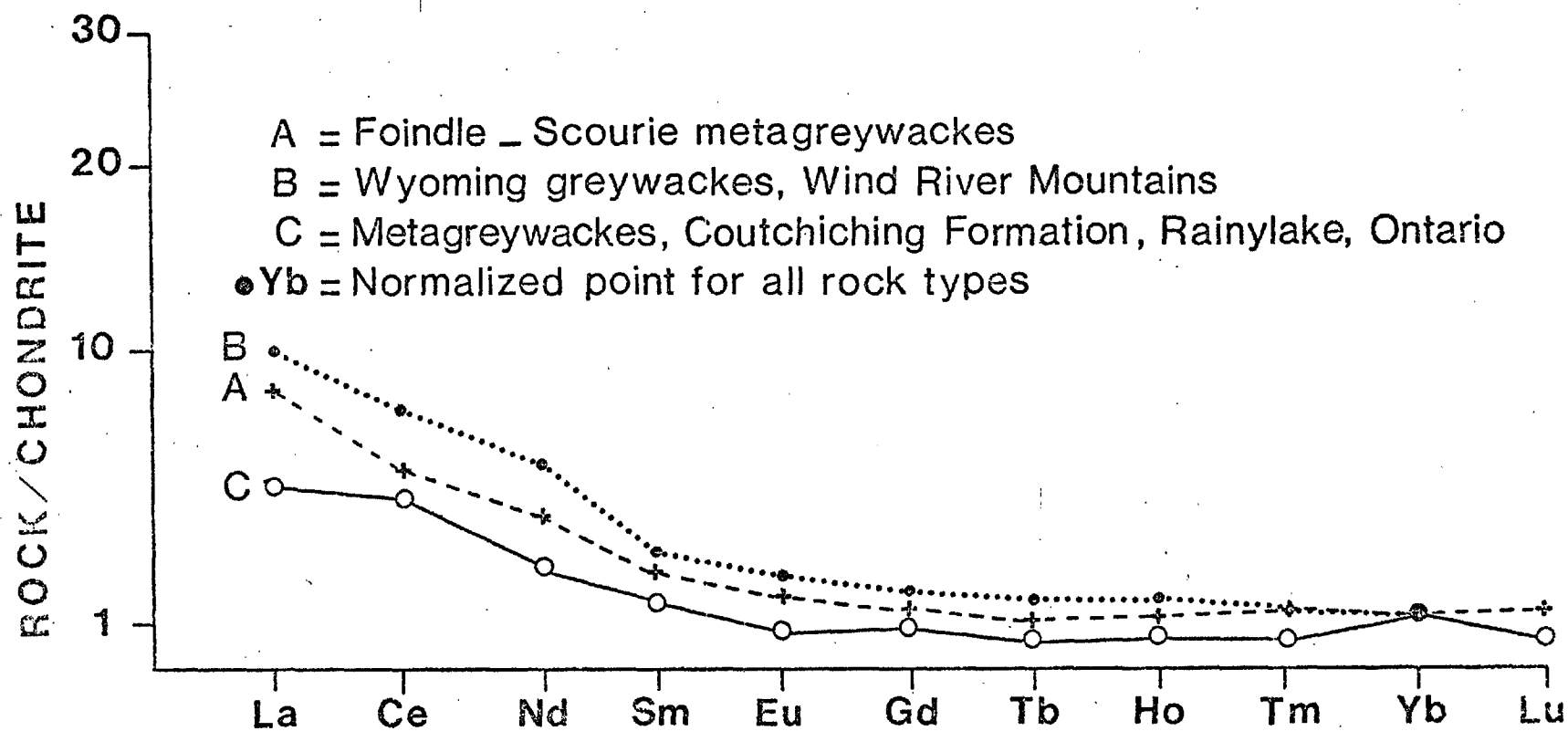


Fig. 5.9 Rare-earth comparison diagrams for the Foindle - Scourie meta-greywackes (A); Wyoming greywackes, Wind River Mountains (B), (Wilderman & Haskin, 1973); and Metagreywackes, Coutchiching Formation, Rainy Lake, Ontario (C) (Wilderman & Haskin, 1973).

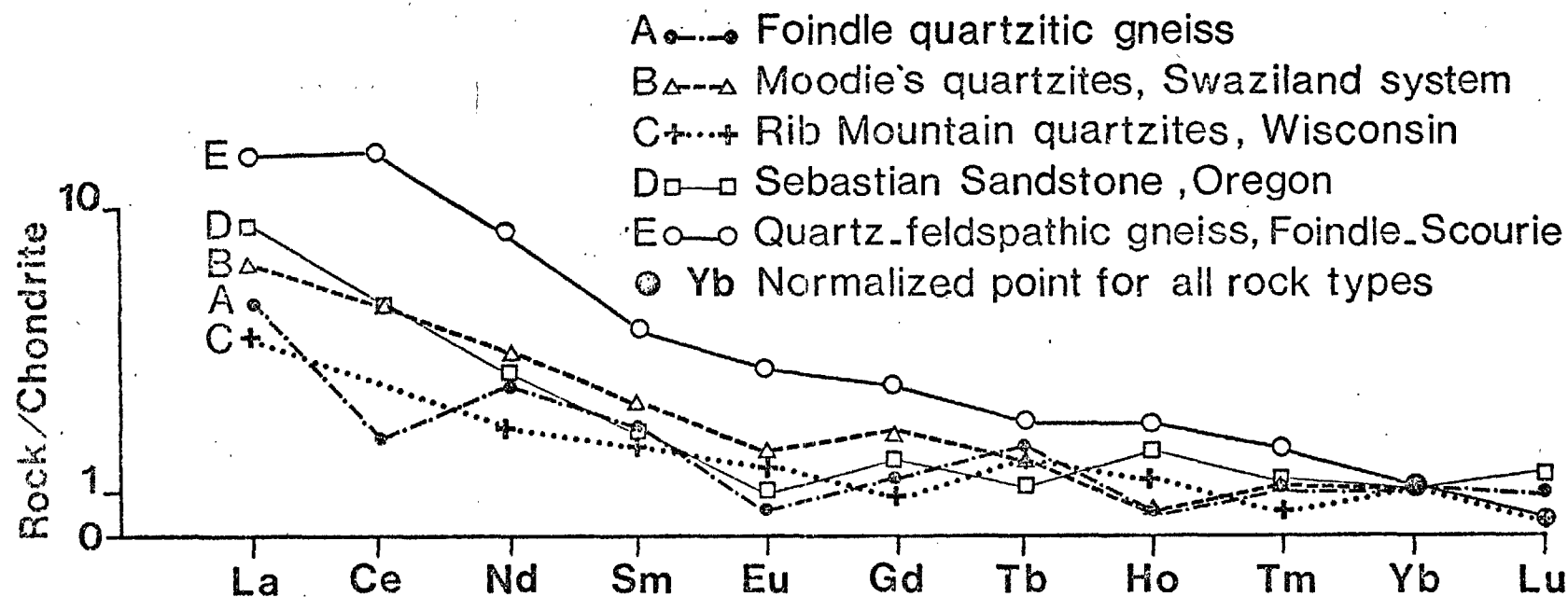


Fig. 5.10 Rare-earth comparison diagrams for Foindle quartzitic gneiss (or meta-arkose/impure quartzite) (A); Moodie's quartzites (B), Swaziland system, S. Africa; Rib - Mountain Quartzites (C), Wisconsin (Wilderman & Haskin, 1973); Sebastian Sandstone (D), Oregon (Haskin et al. 1966); and Quartz - feldspathic (or granitic) gneiss (E), Foindle - Scourie.

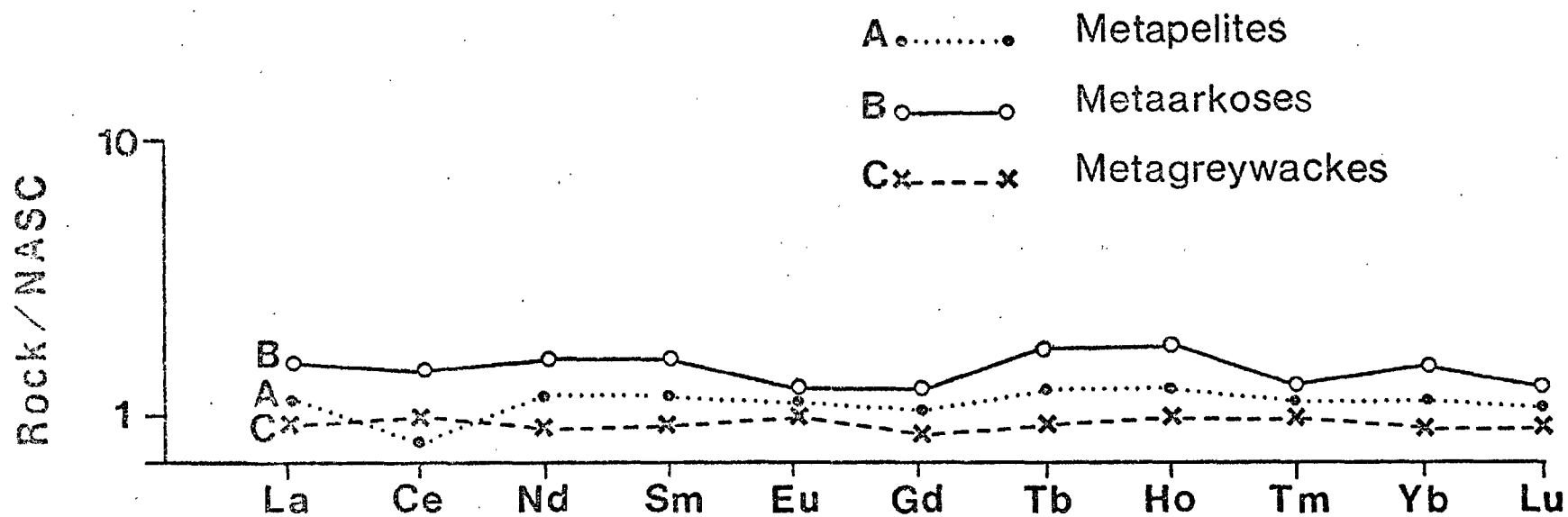


Fig. 5.11 Plots of Foindie - Scourie meta-pelites (A), meta-arkoses/impure quartzites (B), and meta-greywackes (C) normalized to the North American Shales Composite (NASC) of Haskin et al. (1966).

characterized by flat REE distribution (e.g. Minnesota type) and generally low LIL (large - ion - lithophile) element contents, and enriched Archean tholeiite (EAT) characterized by REE patterns some what enriched in light REE and LIL elements. The REE distribution pattern for Foindle amphibolites suggests that they may be of the EAT type.

(4) Meta-pelites

The REE distribution patterns for the average of 5 meta-pelites from Scourie and Foindle, the Precambrian North American Shale, European Shales, and the Scourie More meta-pelite are shown in fig. 5.8. But for the -ve Ce anomaly in the meta-pelites from Scourie and Foindle, all the distribution patterns are similar. The -ve cerium is attributed to the high factor of 4.4 for chondrite when the cerium concentration is normalized to that of ytterbium. The average concentration for La, Ce, Nd in the meta-pelites are very close (40 - 47 ppm) so that the effect of the chondrite factor (4.4) will be most pronounced in the normalization of cerium (sample) to cerium (chondrite) and it will result in the -ve Ce anomaly. These meta-pelites have a negative europium anomaly ($\text{Eu}/\text{Eu}^* = 0.67$) while the Scourie More meta-pelite has a positive europium anomaly ($\text{Eu}/\text{Eu}^* = 1.6$). The author thinks that the +ve europium anomaly in the Scourie More meta-pelite may possibly be due to local accumulation of feldspar during sedimentation or even metamorphism. It however implies Eu^{2+} was more stable than Eu^{3+} and that conditions were reducing during of the processes.

All the rocks show very similar degrees of fractionation. The degree of fractionation of light REE to HASC ($\text{La}/\text{Yb} = 10.32$) is quite close to that of the Scourie - Foindle meta-pelites ($\text{La}/\text{Yb} = 10.8$; $\{\text{LREE}\}/\{\text{HREE}\} = 11.7$). However, the average Yb

in these metapelites is 3.9 ppm which is very close to 3.10 ppm in the NASC. The slight increase in the La/Yb ratio in the meta-pelites is due to the greater abundance of lanthanum (average, 43.0 ppm in Foindle - Scourie meta-pelites; 32 ppm in the NASC). The average La/Ce ratio of 1.0 confirms a sedimentary origin. E (fig. 5.8) is the distribution pattern for Basic gneiss, Foindle. It compares well with the other patterns but it is more enriched in REE (absolute concentrations).

(5) Meta-greywackes

34 analyses (see Appendix IIIC) of intermediate and acid rocks in the Foindle and Scourie areas, which after comparison with typical greywacke composition of Condie (1967) and Pettijohn et al. (1973) have been averaged and plotted in fig. 5.9. The REE distribution pattern obtained is compared with Wyoming greywackes, and Meta-greywackes of Coutchiching formation. The three patterns are very close. This implies possible sedimentary origin for the Foindle and Scourie rocks. They are characterized by a high degree of fractionation (average La/Yb = 14.3; $\Sigma \text{LREE} / \Sigma \text{HREE} = 25.9$). The average La/Ce ratio is 0.6 and this also suggests sedimentary origin.

(6) Meta-arkoses/Impure Quartzites

The high SiO₂ values (average 80.85%) for the quartzitic gneisses (see Table 4.2A) suggests that these rocks could have been cherts or meta-arkoses or feldspathic sandstones prior to metamorphism under granulite facies conditions. In fig. 5.10, the distribution pattern from average quartzitic gneisses, now referred to as meta-arkoses/impure quartzites (see next chapter for more details) in Foindle, is compared with those from rocks of that class from other areas analyzed by previous

workers. But for the -ve cerium anomaly, the pattern from these rocks matches quite closely those for quartzites or sandstones from other areas. It has earlier been stated that Ce^{3+} may oxidize to Ce^{4+} . It is therefore possible that this oxidation, which is possible in granitic rocks (see Koljnen & Rosenberg, 1974), resulted in this anomaly, provided that the granites are perhaps the source of the meta-arkoses/impure quartzites. A negative europium anomaly is obvious ($Eu/Eu^* = 0.5$). The moderately high degree of fractionation of light REE relative to heavy REE is deduced from average $La/Yb = 11.7$ and average $\Sigma LREE/\Sigma HREE = 14.7$.

In order to consider further a possible source of the meta-arkoses/impure quartzites, the average granitic gneiss from Foindle is plotted in comparison. Again, with the exception of the -ve cerium anomaly, their distribution patterns are similar. However, there is no obvious negative europium anomaly in the granitic gneiss, as already mentioned earlier, and positive cerium anomaly can be said to exist for same rock. Table 5.4 column C shows that the average concentration for La, Ce, Nd are very close (72.7, 74.0, 73.5 ppm respectively) so that the -ve cerium anomaly is probably a result of normalization procedure. This case has earlier been noted in the meta-pelites. It therefore does not seem that the -ve cerium anomaly is due to its oxidation to Ce^{4+} . If the granitic gneisses are the source of the meta-arkose/impure quartzites and their distribution pattern does not show this anomalous feature, then the -ve cerium anomaly may be either due to metasomatism or normalization effect.

The La/Ce ratio is always 0.8 and this again suggests a sedimentary origin.

5.2.7 Summary of REE geochemistry

Compared with the North American Shales Composite (NASC) of Haskin *et al.* (1966), the meta-arkoses/impure quartzites are enriched in REE, the meta-pelites are normal, while the meta-greywackes are depleted in Light REE (see fig. 5.11). The degree of enrichment increases from meta-greywackes (by a factor of 0.92) through meta-pelites (by a factor of 1.01), to meta-arkoses/impure quartzites (by a factor of 1.72). It is possible that the depletion in Light REE for the meta-greywackes was due to the processes of initial melting of the mantle material that gave rise to the mafic magmas. The factor of 1.01 for the meta-pelites shows that there is no over-all enrichment in them relative to the NASC. This supports the view of many previous workers that REE distribution is not affected by metamorphism.

Relative to chondrite, all rocks are enriched in REE with the degree of enrichment increasing from Amphibolites (factor of 30.10), through granitic gneisses (factor of 43.44), Basic gneiss (factor of 51.8), meta-pelites (factor of 56.71), Retrogressed - leuco gabbro (factor of 68.88) to meta-arkoses/impure quartzites (factor of 96.32). This enrichment is expected of crustal rocks.

Generally, the rocks studied have rare-earth patterns characterized by

- (a) Light rare-earth element enrichment
- (b) Slight europium anomaly or in most cases, europium depletion. These features are also characteristic of Post - Archean sedimentary rocks (see Nance & Taylor, 1976 pp. 227). The +ve europium anomaly in the Scourie More meta-pelite is attributed to local accumulation of feldspar or even suggests the rock is Archean if the views of Nance & Taylor

(op.cit) are accepted.

(c) Varying degrees of heavy rare-earth element depletion.

It can be tentatively concluded that the REE distribution patterns have provided a reliable means distinguishing between sedimentary and magmatic origins for the rocks studied. Other parameters that can help in this discrimination are treated in the next chapter.

Beacause of the extreme variation of REE contents, the $\Sigma\text{LREE}/\Sigma\text{HREE}$ ratio may be preferred to the La/Yb ratio as a means of estimating the degree of fractionation in the various rocks. If one accepts the use of the ratio, as in Nance & Taylor (1976), then the rocks studied are the boundary between Archean and Post-- Archean in age.

The data obtained and summarized in Appendix III show that the content and distribution of the REE in the Foindle and Scourie rocks, might have been influenced by various geological features, such as primary compositions of the rock, mineralogical and geochemical changes during metamorphism and, possibly, leaching and adsorption processes during weathering. Occurrences of high REE content in the rocks indicate that the REE are concentrated in minerals like amphibole, epidote, garnet, apatite, or sphene. The REE data also support the view of Roaldset (1975) that there could have been the possibility of an extensive adsorption of REE ions on micaceous minerals during metamorphism and weathering processes.

CHAPTER 6

RECLASSIFICATION OF THE ROCK TYPES ON BASIS
OF OVER-ALL GEOCHEMISTRY

6.1 Introduction

So far it has been shown that the rocks studied are of igneous or sedimentary origin. For the meta-igneous rocks, classification into groups is not difficult, but for the metasedimentary rocks, this is not the case because, as already reported in chapter 2, these rocks are more heterogeneous and they have been more affected by the secondary alteration, metamorphism and weathering.

REE distribution patterns have been used in the preceding chapter to confirm the original nature of the rocks in Foinde and Scourie. In this chapter, other chemical parameters will be used to support the conclusions drawn from the REE geochemistry.

The discriminating diagrams or functions which have been used by various previous workers to distinguish rocks of either magmatic or sedimentary origin, and have been found useful in this study, are listed below:-

(A) Niggli values

ti - (al-alk)	(figs. 6.1A & 6.2A)
ti - mg	(figs. 6.1B & 6.2B)
Zr - (al-alk)	(figs. 6.3A & 6.4A)
(al-alk) - mg	(figs. 6.5A & 6.6A)
Ni - mg	(figs. 6.5B, 6.6B, 6.7B)
Cr - mg	(figs. 6.5C, 6.6C, 6.7A)
mg - c	(fig. 6.8)
al - si	(fig. 6.9A)
fm - si	(fig. 6.9B)
(al-alk) - c	(fig. 6.9C)
Cr - TiO ₂	(fig. 6.10A)
Ni - TiO ₂	(fig. 6.10B)

(B) Triangular diagrams

Normative	Qtz - Ab - Or	(fig. 6.11)
Normative	Or - Ab - An	(fig. 6.12)
	MgO - CaO - Al ₂ O ₃	(fig. 6.13)

(C) Major element compositions & Normative Corundum

- (1) Normative corundum, C (C 5%; C 10%, C 50%)
- (2) MgO CaO; K₂O Na₂O
- (3) MgO vs SiO₂
CaO vs SiO₂ fig. 6.14

(D) Discriminant functions

(E) Trace Elements

Also, it has been shown by the FMA diagram (fig. 4.1) in chapter 4 that rocks in the Poindale - Scourie areas may represent three initial magmatic series - calc-alkaline, alkaline and tholeiitic. The following diagrams have further been used to distinguish between them. Greater emphasis is laid on meta-igneous (chiefly, the Amphibolites)

Ti (10^{-2}) - Zr - Sr (0.5)	(fig. 6.15)
Ti (10^{-2}) - Zr - Y (x3)	(fig. 6.16)
TiO ₂ - K ₂ O - P ₂ O ₅	(fig. 6.17)
Ti (ppm) - Zr (ppm)	(fig. 6.18)
Na ₂ O + K ₂ O - SiO ₂	(fig. 6.19)
Yb (ppm) - MgO (wt.%)	(fig. 6.20)
Cen/Ybn - Yb	(fig. 6.21)

In the rest of the chapter, an attempt will be made to summarize the use of the above named variation diagrams and parameters to either distinguish between ortho - and para-

gneisses or calc-alkaline series from tholeiitic suites.

6.2 Migali values etc.

A persistent problem in basement complexes and migmatitic terrains is to distinguish magmatic quartz - feldspathic gneisses of granitic composition from those formed by recrystallization or metasomatism of pelite, semi-pelite or arkose. Generally very uniform gneiss bodies were probably igneous originally, but layered gneisses could reflect original sedimentary variations in an arkosic rock, metamorphic differentiation in a metamorphosed magmatic or sedimentary rock, or metamorphosed sediments injected by intrusive igneous layers. Sometimes, the field evidence may be diagnostic (Van De Kamp *et al.* 1976). Kroner (1971) and Schwarcz (1969) described acid metasedimentary rocks with interlayered mica schist that were originally shale and proposed that normally in sandstone deposits, sands have intercalated shales or siltstones and this assemblage when metamorphosed yields acid gneisses interlayered with garnet - bearing bands or bands with other typical pelite minerals which meta-igneous rocks would generally lack. Van De Kamp *et al.* (1976), however, stated that feldspathization of alumina - rich pelitic layers is common in migmatitic complexes and then reliance may have to be on chemical 'finger prints' of the original material.

Normative quartz is lower in meta-igneous rocks, than in meta-arkoses. Although the mobility of quartz in metamorphic and migmatitic rocks can make some changes in the proportion of quartz, siliceous sediments generally preserve their identity up to the highest grades of metamorphism below partial melting (Van De Kamp *et al.*; *op. cit.*).

Therefore, apart from any field evidence, possible chemical means must be found to identify the origin of the quartz - feldspathic gneisses (mainly Supracrustals) in the areas studied.

Two methods have been found useful in this study, namely:-

- (a) to identify any characteristic abundance patterns or chemical curiosities that indicate sedimentary or igneous rocks especially any that are unlikely to be significantly changed by metamorphism, and
- (b) to apply characteristic trends of chemical variation, especially trends based on immobile elements (e.g. not alkali), markedly distinct from the variation pattern found in magmatic granites

Figs. 6.1 to 6.10 are variation diagrams sometimes used to discriminate ortho-gneisses and para-gneisses. The use of trace element abundances or ratios is discussed in section 6.6.

Ti is particularly associated with clay minerals and micas, and shows marked positive correlation with al-alk in fig. 6.2A for the metasediments and a fairly negative correlation in fig. 6.1A (meta-igneous rocks). Van De Kamp *et al.* (1976, pp. 206) state that although Al, Na, and K all enter both feldspars and sheet silicates, Ti enters sheet silicates in substantial amounts but hardly at all into feldspars so that a characteristic feature of most sediments that contain detrital micas and clay minerals is a marked positive correlation of Ti and al-alk.

There is no significant relationship between Niggli mg and ti (fig. 6.1B or fig. 6.2B), especially for the granitic gneiss, or Ni or Cr (figs. 6.6B, 6.6C). A positive correlation, expected in basic igneous rocks, is shown in the Niggli mg vs Ni or Cr plots (figs. 6.5B & 6.5C) for the meta-igneous rocks.

The al-alk vs mg plot (fig. 6.5A) shows positive correlation for the meta-igneous rocks, and negative correlation for the metasediments (fig. 6.6A). The negative correlation of al-alk with Niggli mg, considering the higher Ni, Cr, Zn, or Ti in meta-pelites which have on the average, a lower mg than the

meta-arkoses, meta-greywackes, indicates that Fe, Mg, Ni, Cr, Zn and Ti were not added in basic rock detritus (which would give higher Ni with higher mg and lower al-alk). Van De Kamp et al. (1976) state that these elements may be within the clay minerals and were probably removed from suspension or solution by the clay - minerals, although their ultimate source was dissolved basic igneous rock.

A positive correlation in the Zn - mg plot in fig. 6.4B, especially for the meta-igneous is interesting. Since Zinc is dominantly carried in clay minerals, the values in meta-pelites are consistently higher than most of the meta-arkoses or meta-greywackes. The meta-igneous rocks show a negative correlation (fig. 6.3B).

The Zr vs al-alk plots (fig. 6.3A) for meta-igneous rocks show no significant relationship but in the equivalent diagram (fig. 6.4A) the metasediments, especially the meta-arkoses, show a negative correlation. Although Zr may be present in clay minerals (cf. Nicolls & Loring, 1962), it can also be present in major amounts in other phases, especially detrital zircon.

The Leake (1964, fig. 1) diagram has been modified slightly in fig. 6.8, which is the Niggli mg - c for the Supracrustal rocks (A) and meta-igneous rocks (B) in Foindie and Scourie. The amphibolites (hornblende gneisses) follow the igneous trend in fig. 6.8B. The quartzo - feldspathic gneisses fairly follow a trend which can be said to be igneous. In fig. 6.8A, the Supracrustal rocks all plot between typical pelite and sine pelite field and igneous trend boundary, and follow the sedimentary trend. These rocks also plot in the fields of shales, Wyoming and Vosges greywackes of Satyanarayana et al. (1974). It must, however, be said that the plot of mg against c can suffer from the limitation than igneous series may only

be truly identified if an extreme range of mg values is available because of the possible overlap of the two trends. In most studies of amphibolites, including this work (see also Leake, 1964; Gomes *et al.* 1964; Park, 1966; Elliot & Cowan, 1966), the range of composition found has been such that this plot can be ambiguous.

Amphibolites may be either para - or ortho-gneisses and figs. 6.9, B, C are plots of Niggli values after Evans & Leake (1960) and Leake (1964) used to classify the Foindle amphibolites. Para-amphibolite (calc-silicate rock) of Chowdhary *et al.* (1971) and ortho-amphibolite (Dash, 1967) have been shown in comparison. The Karoo dolerite is also shown. Clearly the amphibolites from Foindle follow the Karoo dolerite trend and plot in the ortho-amphibolite area of Dash (*op. cit.*). A metasomatic or sedimentary origin is therefore unlikely for these rocks.

Leake (1964) used some chemical variation trends as a basis for distinguishing between ortho - and para-amphibolites. Some of the most useful plots were Cr against Niggli mg or TiO_2 (wt. %) and Ni against Niggli mg or TiO_2 (wt. %). Also Power & Park (1969) used chemical evidence based on variation of Cr, Ni, TiO_2 and Niggli mg (cf. Leake, 1964) to suggest an igneous origin for Gairloch basites. Figs. 6.7 & 6.10 are Cr and Ni vs Niggli mg and Cr & Ni vs TiO_2 respectively for the Foindle amphibolites. Comparison is also drawn between the two amphibolite groups from the Lewisian. Fig. 6.7 shows an expected positive trend while in fig. 6.10 a negative trend is obvious also. These trends are similar to those from the Gairloch amphibolites. All are distinct trends expected from basic igneous rocks.

6.3 Triangular diagrams

The use of ACF, AQP, normative Qtz - Or - Ab or normative

Or - Ab - An diagrams in distinguishing between ortho - and para-gneisses is well known and needs no description here.

Fig. 6.11 and fig. 6.12 are normative Qtz - Or - Ab (for supposed granitic system only) and normative Or - Ab - An diagrams respectively for rocks in both areas studied. The ortho - and para-gneisses are clearly separated by dashed lines. The para-gneisses scatter very widely and show no tendency to cluster near a minimum melting position in fig. 6.11.

Leyreloup et al. (1977) used the MgO - CaO - Al₂O₃ diagram (fig. 6.13) to distinguish between metasedimentary and meta-igneous rocks from the French Massif Central. Here, it is used in the same sense. Clearly the field of magmatic rocks is quite different from that of the metasedimentary rocks. The metasedimentary rocks plot close to Al₂O₃ apex as is expected. The amphibolites plot in the basalt field (shaded area) of Leyreloup et al. (op. cit). It can be said that the diagram is reliable for discriminating ortho-amphibolites and meta-pelites, or retrogressed Leuco - gabbro and meta-pelites. For intermediate and acid rocks, the diagram cannot be used with certainty. There is clearly an overlap between granitic rocks, and meta-arkoses. It seems the diagram is controlled by silica and alumina. Therefore, since during retrogression, Al₂O₃ decreases with increasing SiO₂, and vice versa, this diagram may be unreliable for intermediate and acid rocks. MgO and CaO being oxides of refractory elements are relatively unaffected by metamorphic processes.

6.4 Major element compositions & Normative Corundum & Quartz

Dietrich (1960) used the Na/K ratio to distinguish between ortho - and para-gneisses. As already mentioned earlier (Chapter 4), the Na/K ratio cannot be used to discriminate

metasedimentary and meta-igneous rocks in the present situation. Normative corundum is useful but not conclusive. As seen in Table 6.2, the average normative corundum values for the metasedimentary rocks range from 1.72% in the meta-arkoses to 6.00% in meta-pelites. The average normative corundum value of 1.57% in granitic gneisses is attributed to possible leaching of soda which might have occurred during the process of retrogression or weathering and led to excess alumina and silica. Corundum and quartz would then be released and therefore appear in the norms of the granitic rocks. None of the other meta-igneous rock types are corundum normative.

As metamorphism in the region has resulted in partial or complete recrystallization of the original rocks, chemical criteria (Mason, 1966), summarized below, may be used to establish the sedimentary origin of metamorphosed rocks:-

- (a) excess alumina, which appears as C (corundum) when the norm is calculated.
 - C > 5% - sedimentary origin is suspected
 - C > 10% - sedimentary origin is almost certain
- (b) $K_2O > Na_2O$ and $MgO > CaO$ - characteristic of argillaceous rocks especially those containing appreciable amounts of illite and montmorillonite.
- (c) very high SiO_2 (wt. %) content i.e about 80% SiO_2 or 50% normative Quartz (Q) for sandstone or cherty rocks especially.

Normative corundum values for the metasedimentary rocks in the region under discussion range from 0.16% in meta-greywackes to a value of 8.2% in meta-pelites. It can best be said that their sedimentary origin is suspected if Mason's (op. cit) criterion (a) is valid. In criterion (b), $K_2O > Na_2O$ cannot be applied as already mentioned. Also $MgO > CaO$ must be used

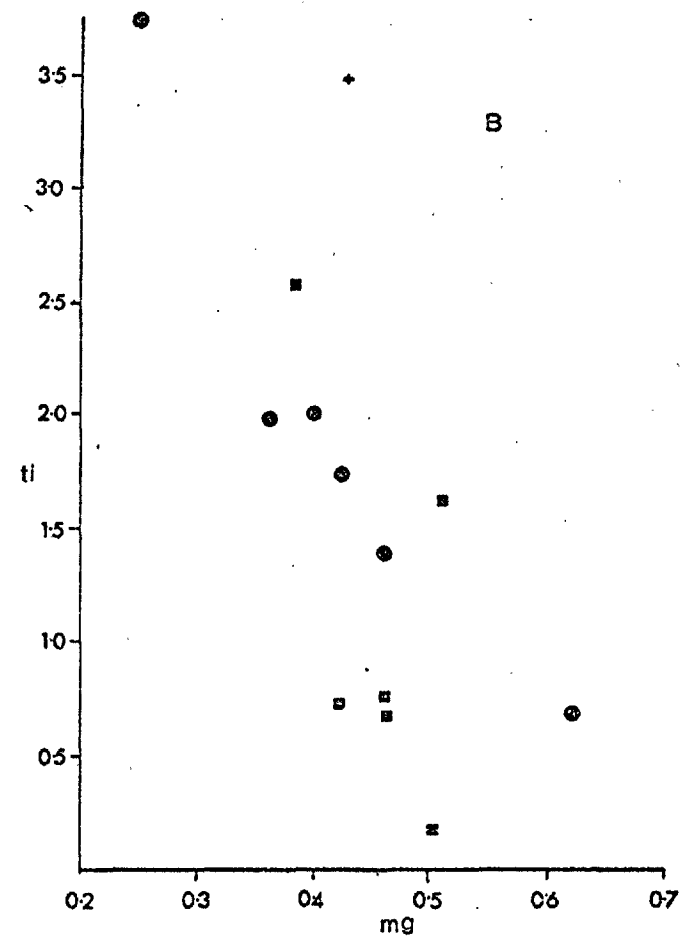
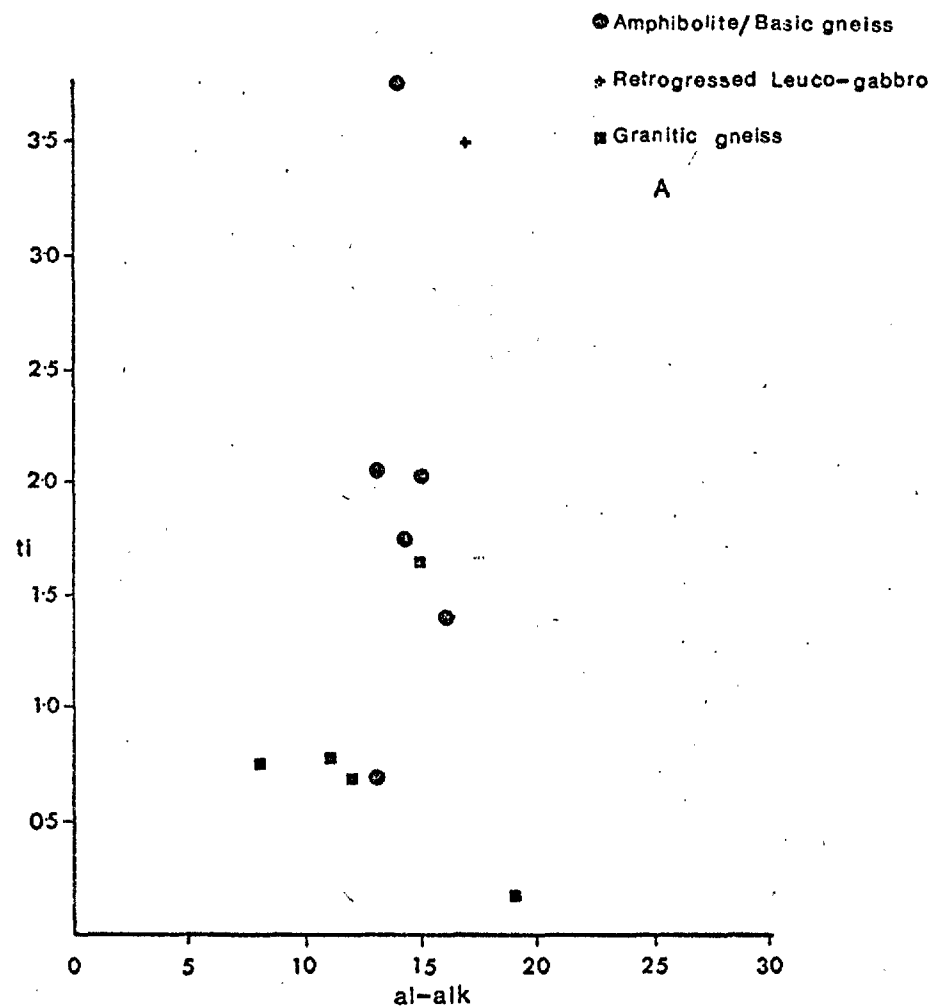


Fig. 6.1 Niggli ti vs (al-alk) and Niggli (ti vs mg) plots for the meta-igneous rocks.

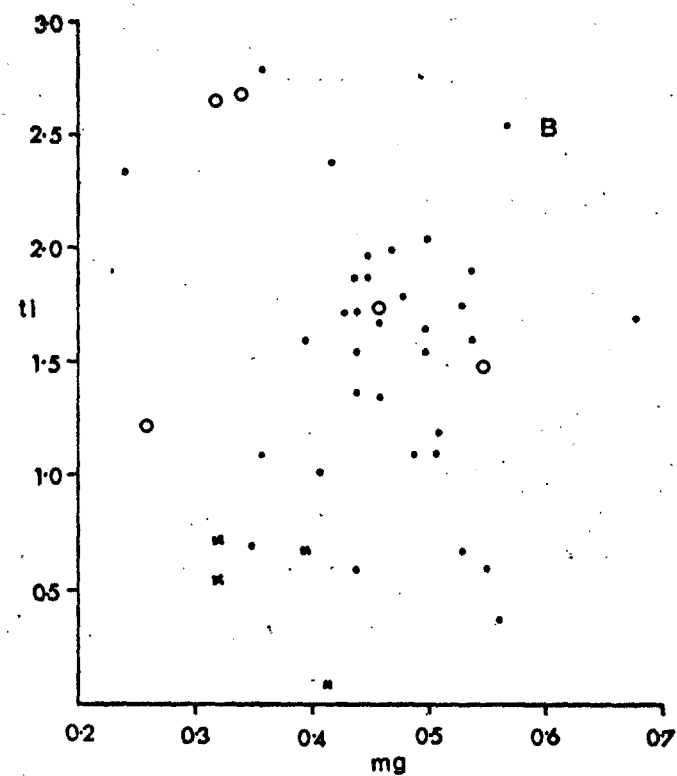
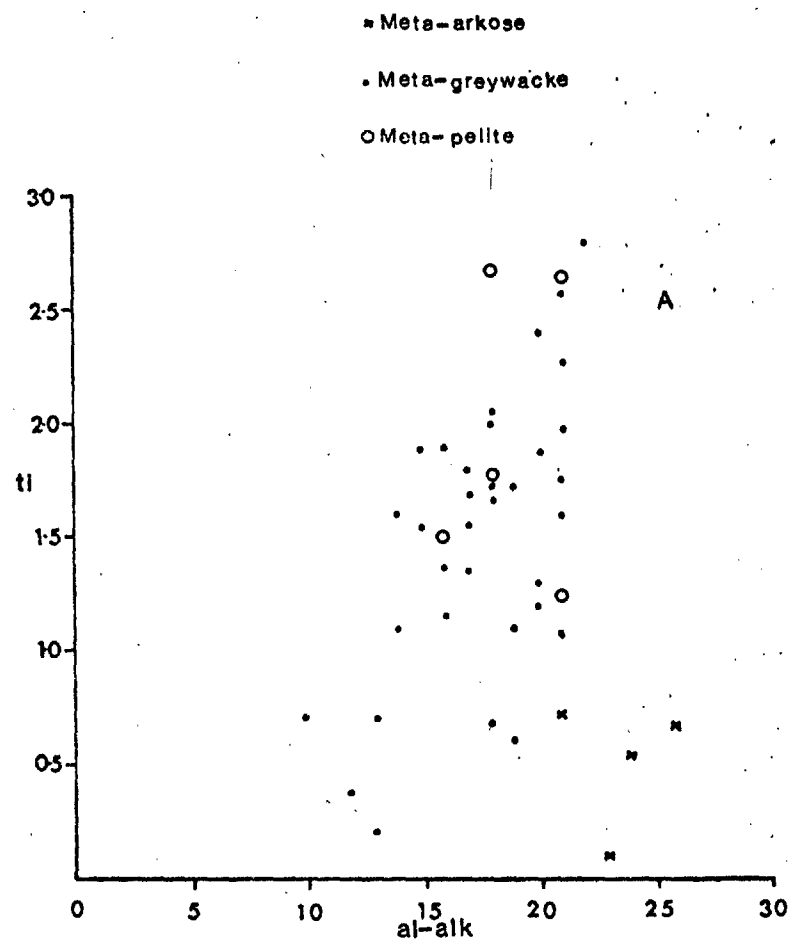


Fig. 6.2. Niggli ti vs $(al-alk)$, and Niggli (ti vs mg) plots for the meta-sedimentary rocks.

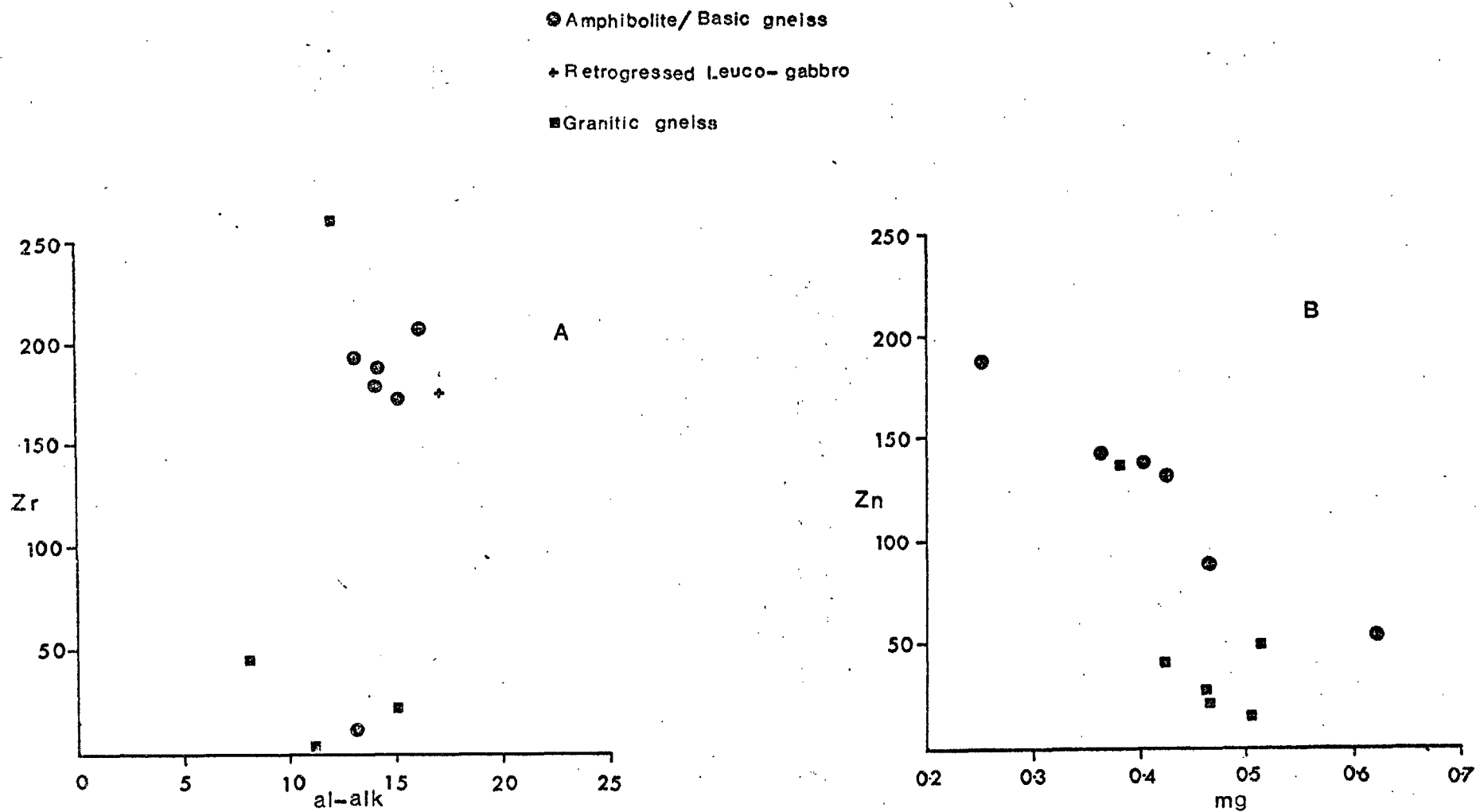


Fig. 6.3 Zr vs Niggli (al-alk) and Zn vs Niggli mg plots for the meta-igneous rocks.

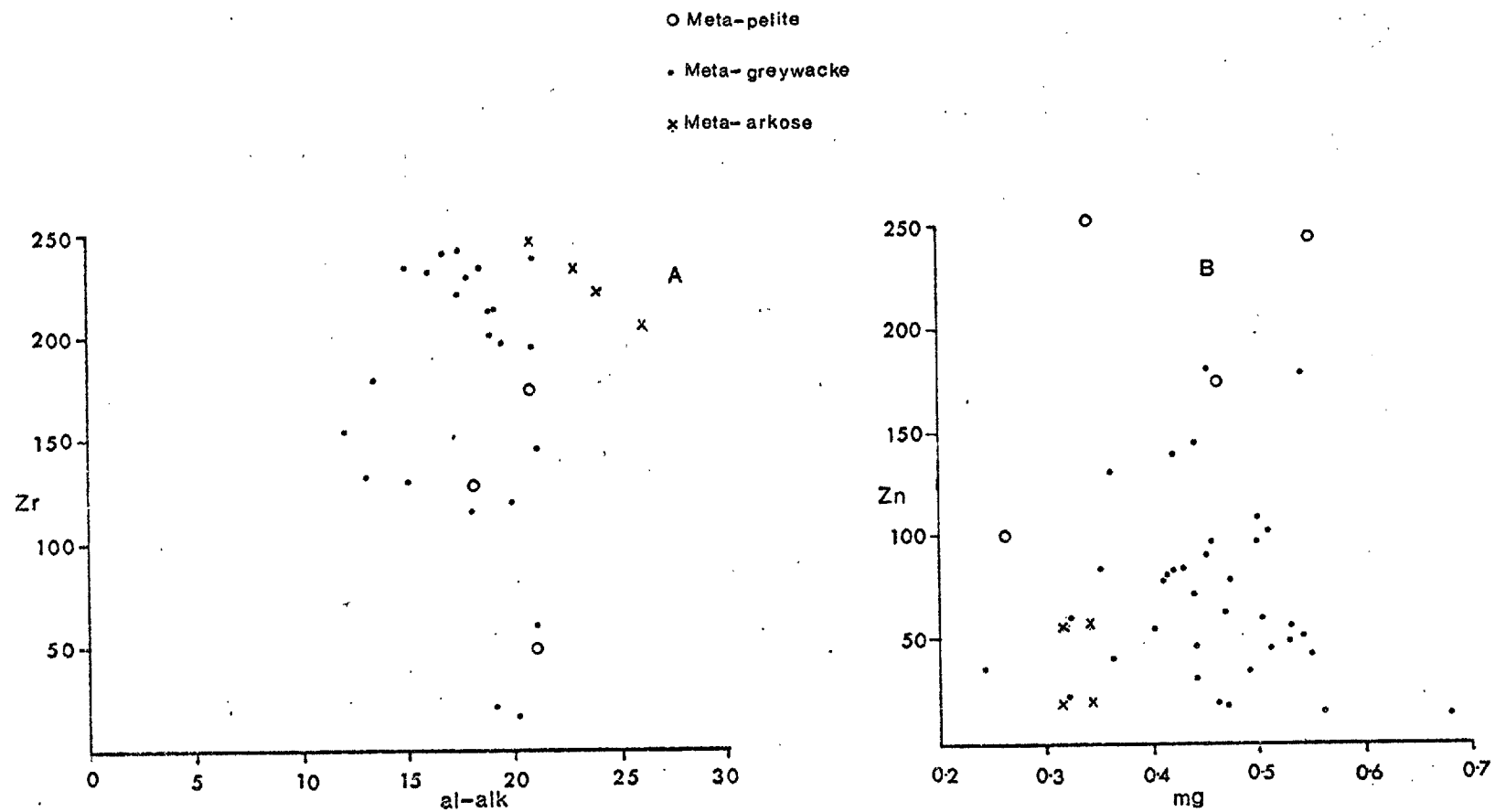


Fig. 6.4 Zr vs Niggli (al-alk) and Zn vs Niggli mg plots for the metasedimentary rocks.

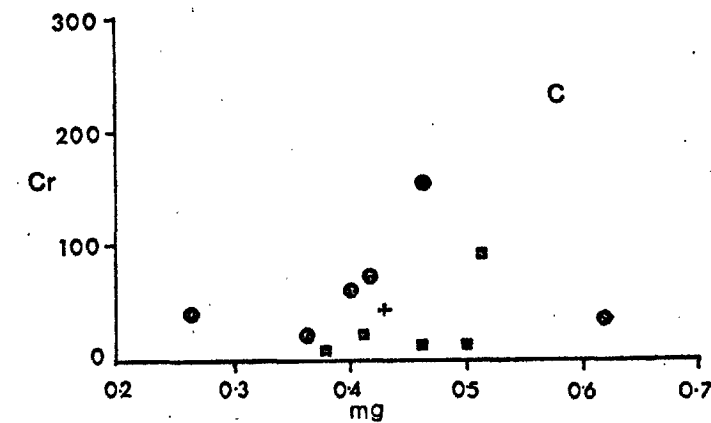
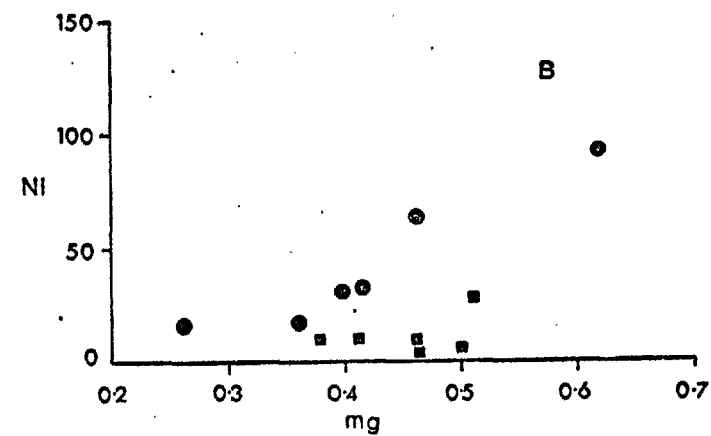
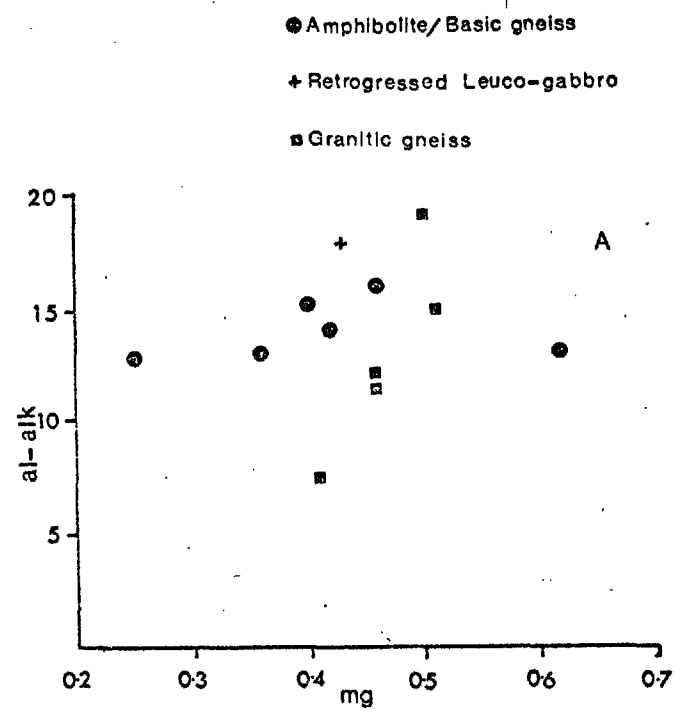


Fig. 6.5 Niggli (al-alk) vs mg, Ni vs mg, and Cr vs mg diagrams for the meta-igneous rocks.

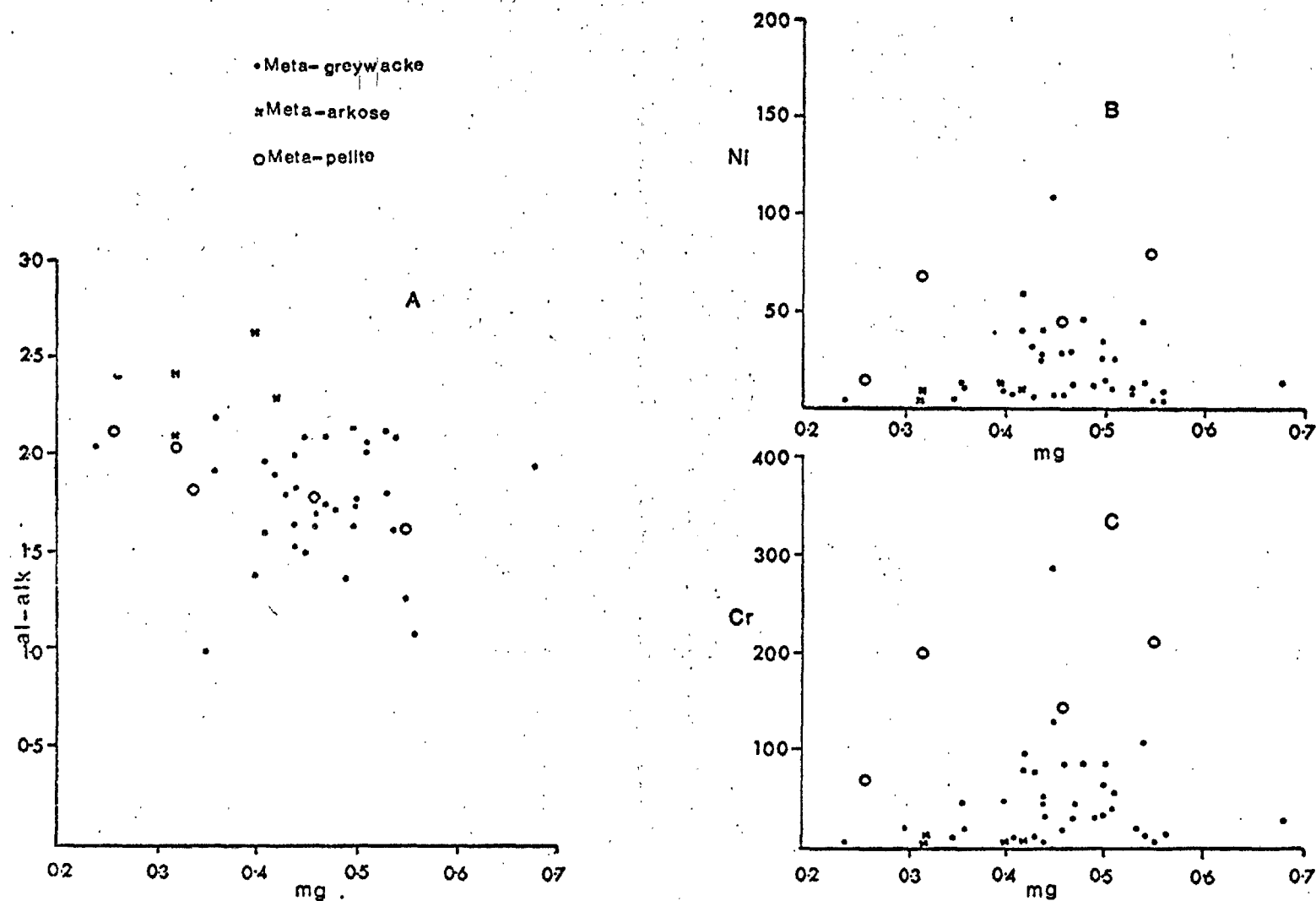


Fig. 6.6 Ni:li (al-alk) vs mg, Ni vs mg, and Cr vs mg diagrams for the meta-sedimentary rocks.

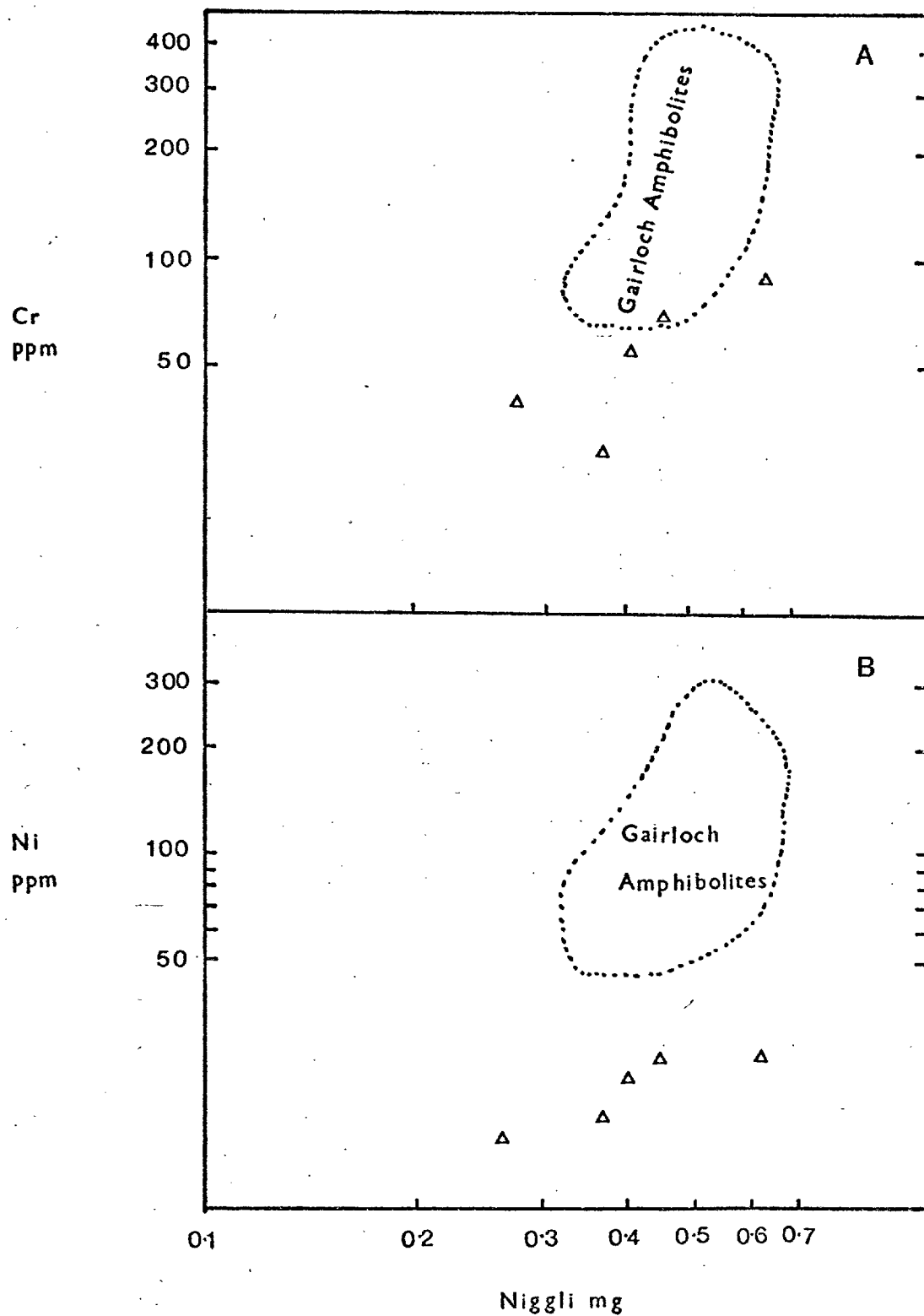
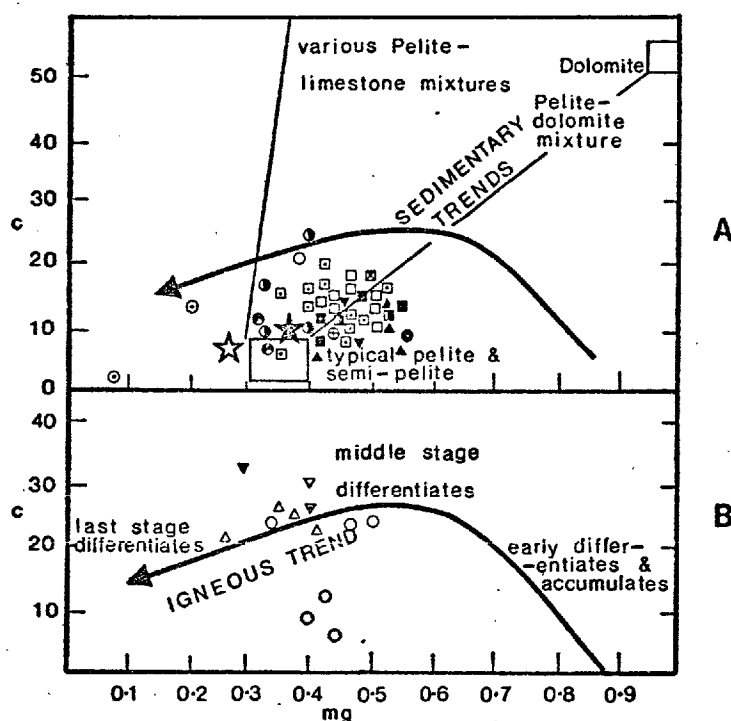
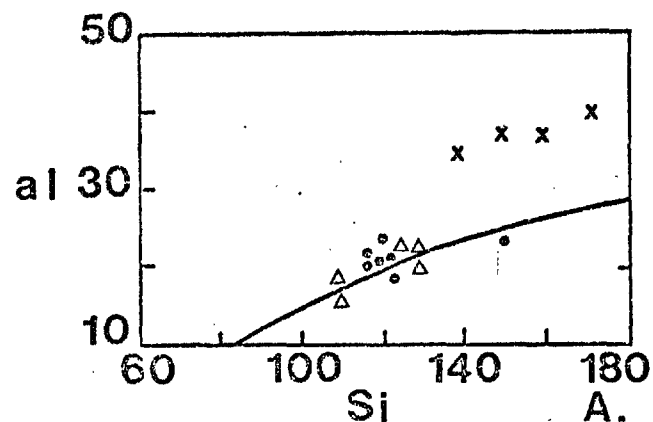


Fig. 6.7 Log - plots of Chromium and Nickel against Niggli mg (after Leake, 1964). Poindie amphibolites are compared with Gairloch, Ross-shire amphibolites of Power & Park (1969).



- | | |
|-----------------------------------|--|
| ○ Quartz-feldspathic gneiss | ☆ Quartz-magnetite gneiss |
| ▼ Mafic gneiss | ⊙ Quartz-garnet-mica gneiss |
| ▲ Hornblende gneiss | ▼ Ultramafic gneiss |
| ● Feldspathic gneiss | ⊙ Garnet granulite |
| □ Biotite-muscovite garnet gneiss | ⊙ Quartz-garnet-feldspar gneiss |
| ■ Biotite schist | ⊙ Quartz-biotite-garnet gneiss (Foindle) |
| ▲ Quartz-biotite schist | ★ Quartz-biotite-garnet gneiss (Scourie) |
| ⊙ Quartzitic gneiss | ⊙ Quartz-feldspar-garnet gneiss |
| ▼ Quartz-mica schist | ■ Biotite-garnet gneiss |

Fig. 6.8 Niggli mg-c plot slightly modified from Leake (1964, fig. 1) for the Foindle - Scourie Supracrustal rocks, quartz - feldspathic, mafic and ultramafic gneisses. A = Supracrustal rocks and B = meta-igneous rocks.



/ Karroo Dolerite trend

x Calc-silicate

(Chowdhary et al. 1971)

• Amphibolite; Strath Dionard-Rhiconich (Dash 1967)

△ Amphibolite; Foindle

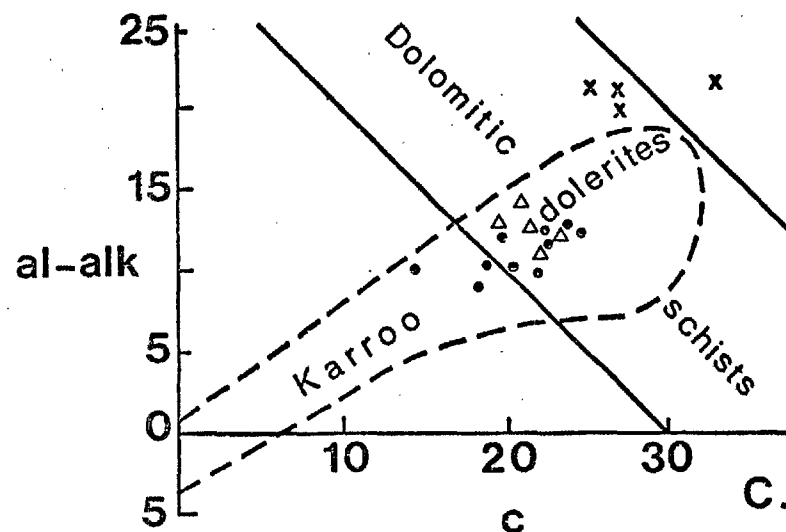
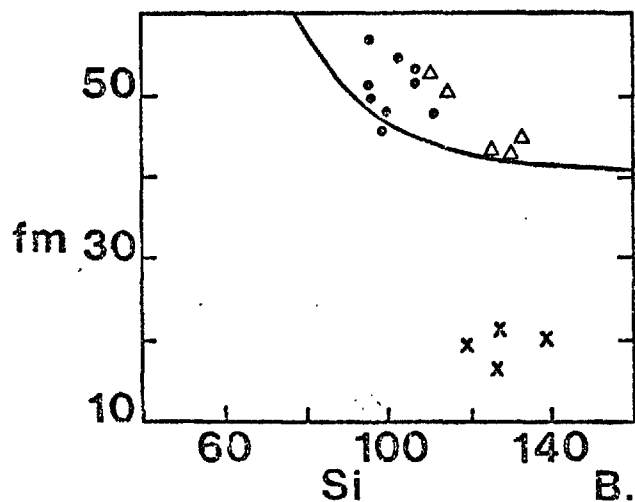


Fig. 6.9 Plots of Niggli values for Foindle Amphibolites, calc-silicates rock (Chowdhary et al., 1971) and Amphibolites, Strath - Dionard, Rhinconich (Dash, 1967) after Evans & Leake (1960) and Leake (1964).

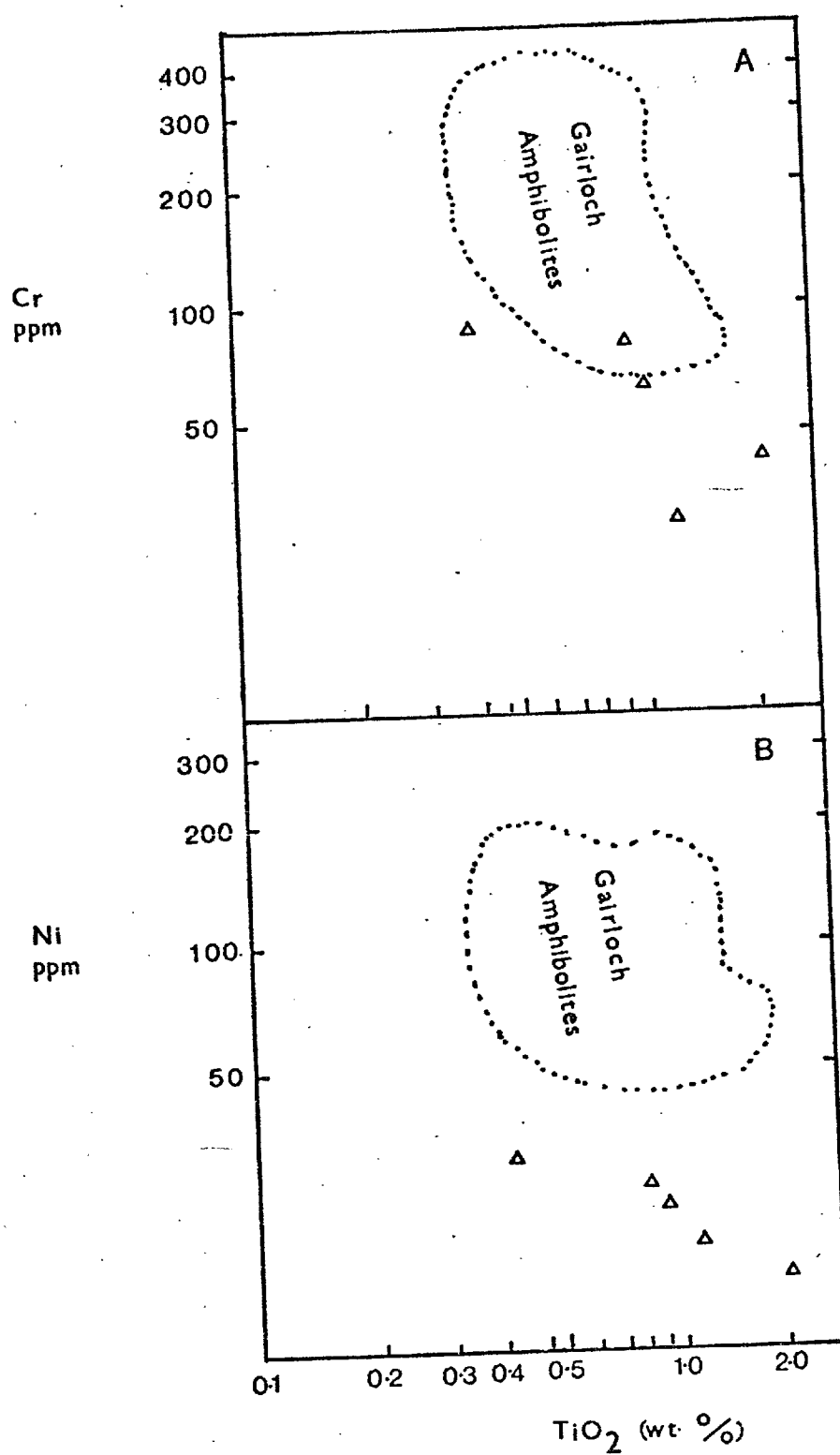


Fig. 6.10 Log - plots of Chromium and Nickel against Titanium oxide (after Leake, 1964). Foindle amphibolites are compared with Gairloch, Ross-shire amphibolites of Power & Park (1969).

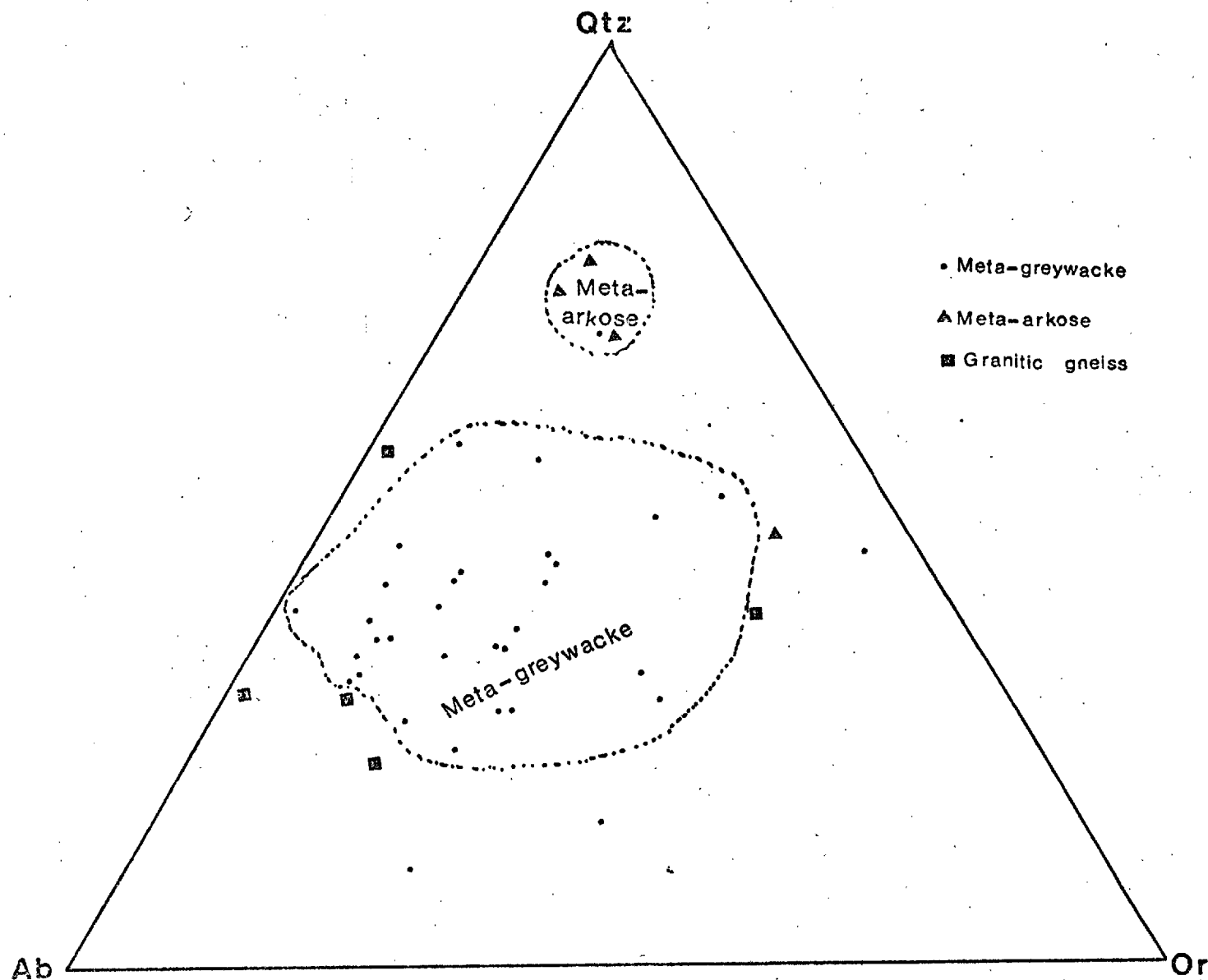


Fig. 6.11 Normative Qtz - Ab - Or plot for showing discrimination of metasediments and meta-igneous (granitic) rock.

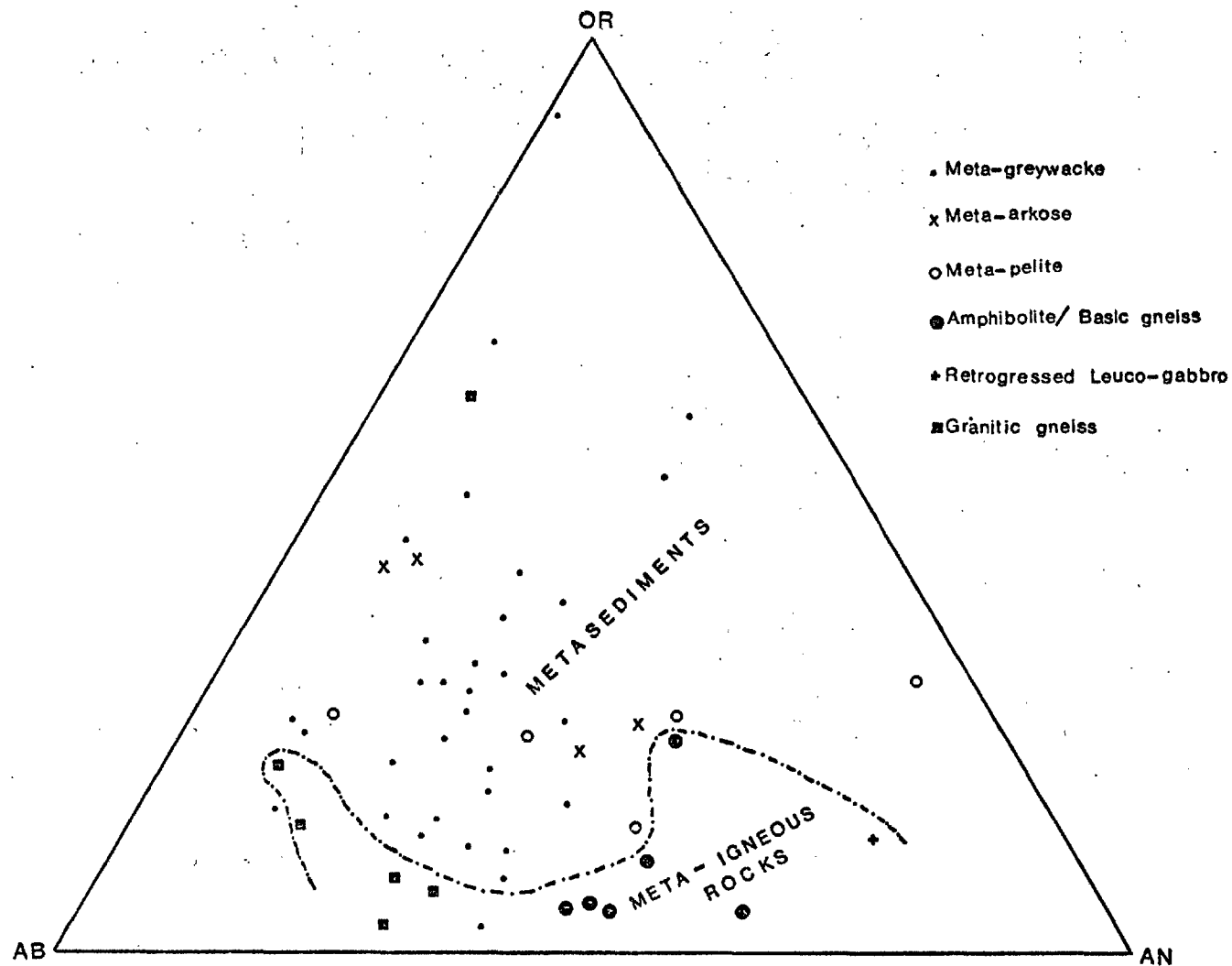


Fig. 6.12 Normative Or - Ab - An plots showing distinction between metasediments and meta-igneous rocks. Dashed and dotted line separates the two rock groups.

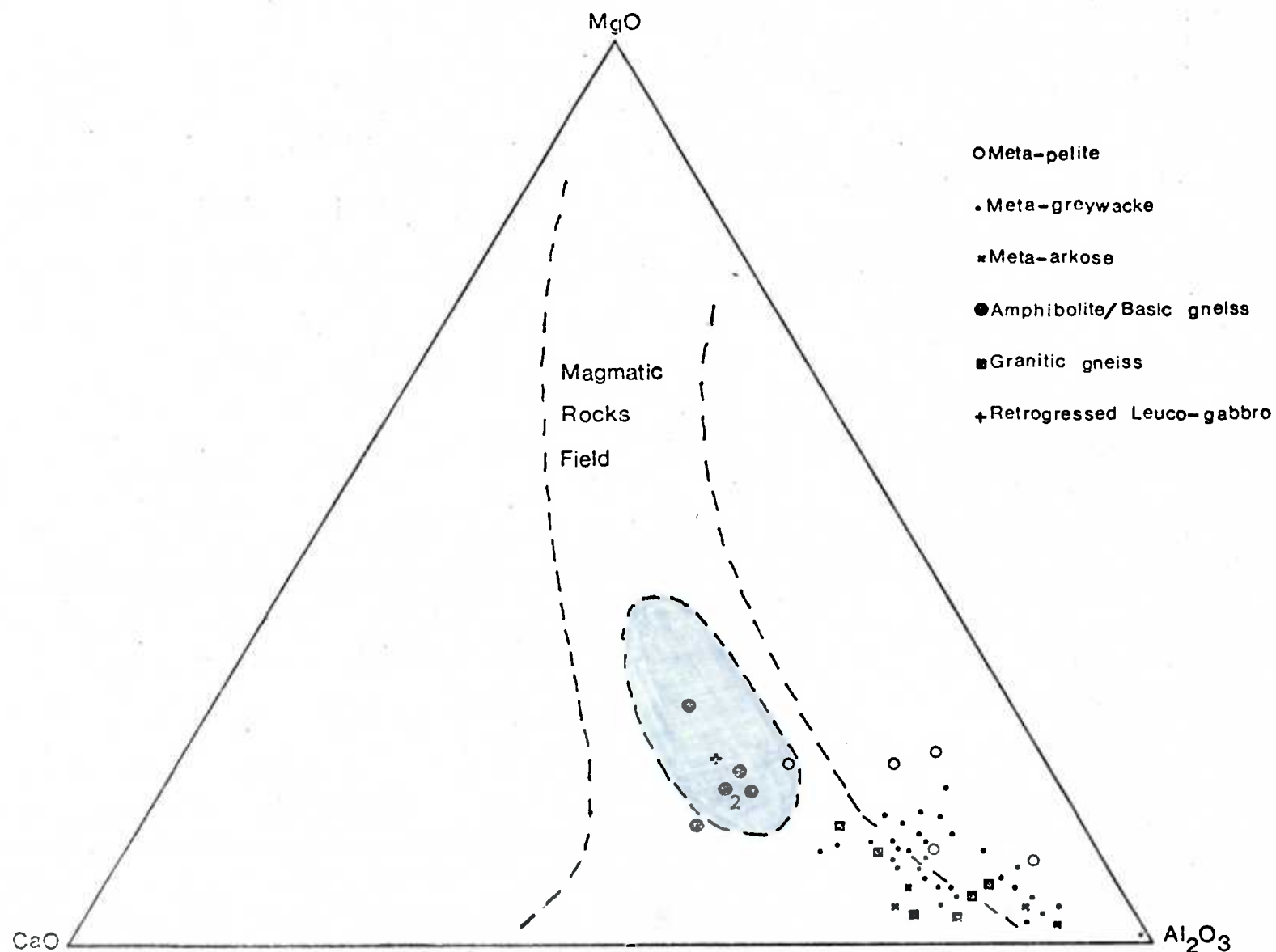


Fig. 6.13 MgO - CaO - Al₂O₃ diagram to distinguish between metasediments and meta-igneous rocks. The coloured area delineates the basalt field after Leyre loup et al. (1977).

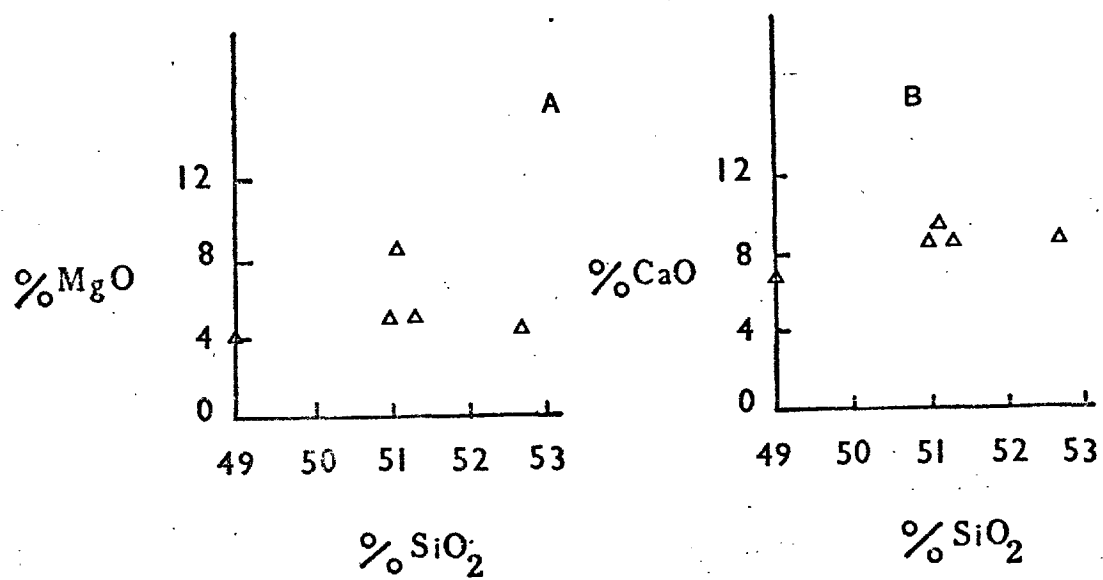


Fig. 6.14 Plots of MgO and CaO vs SiO_2 for the Foindle Amphibolites.

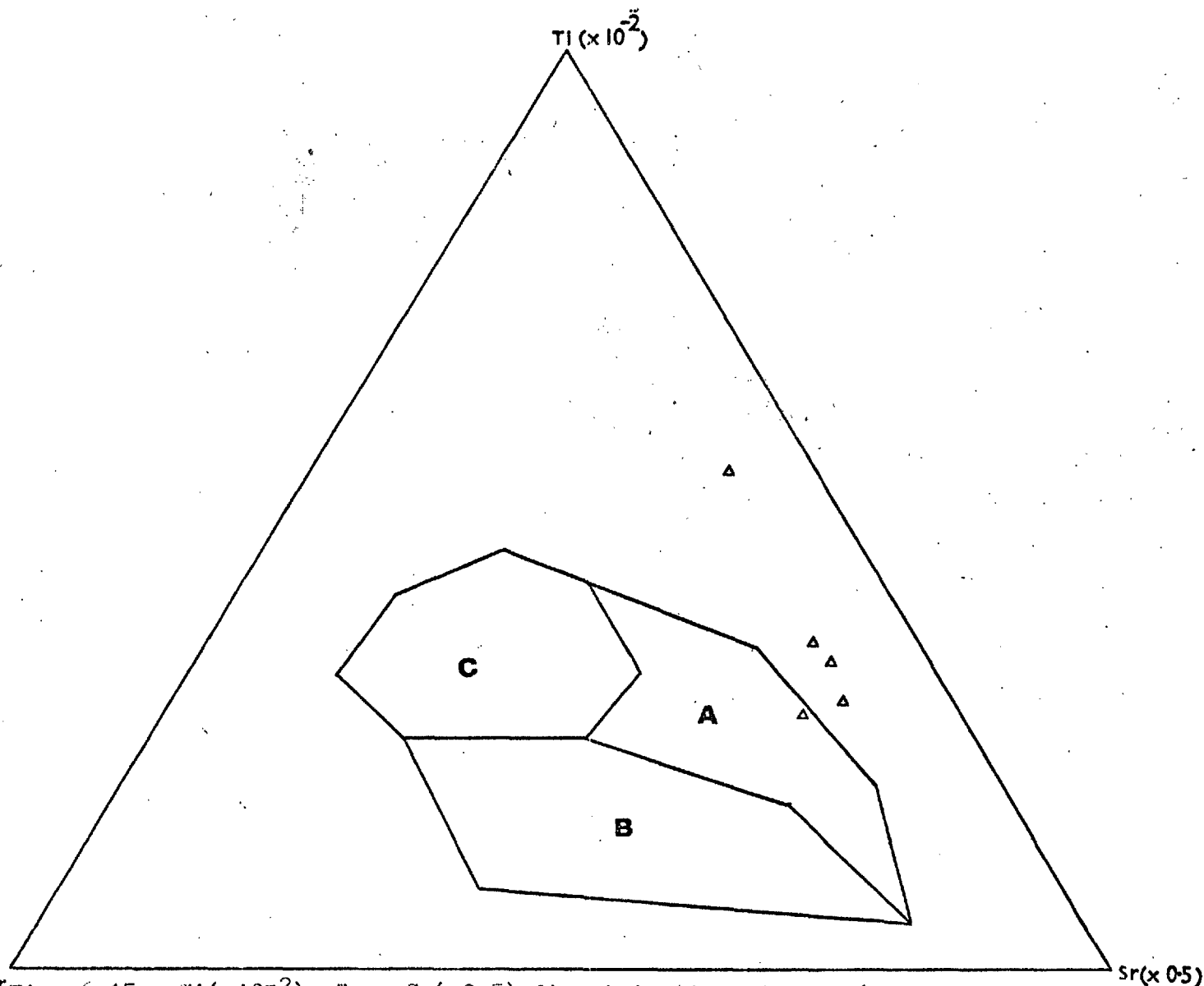


Fig. 6.15 $Ti(x10^{-2}) - Zr - Sr(x0.5)$ discrimination diagram (after Pearce and Cann, 1973) for the Poindie amphibolites. A = Low-K tholeiites, B = Calc-alkali basalts and C = Ocean floor basalts.

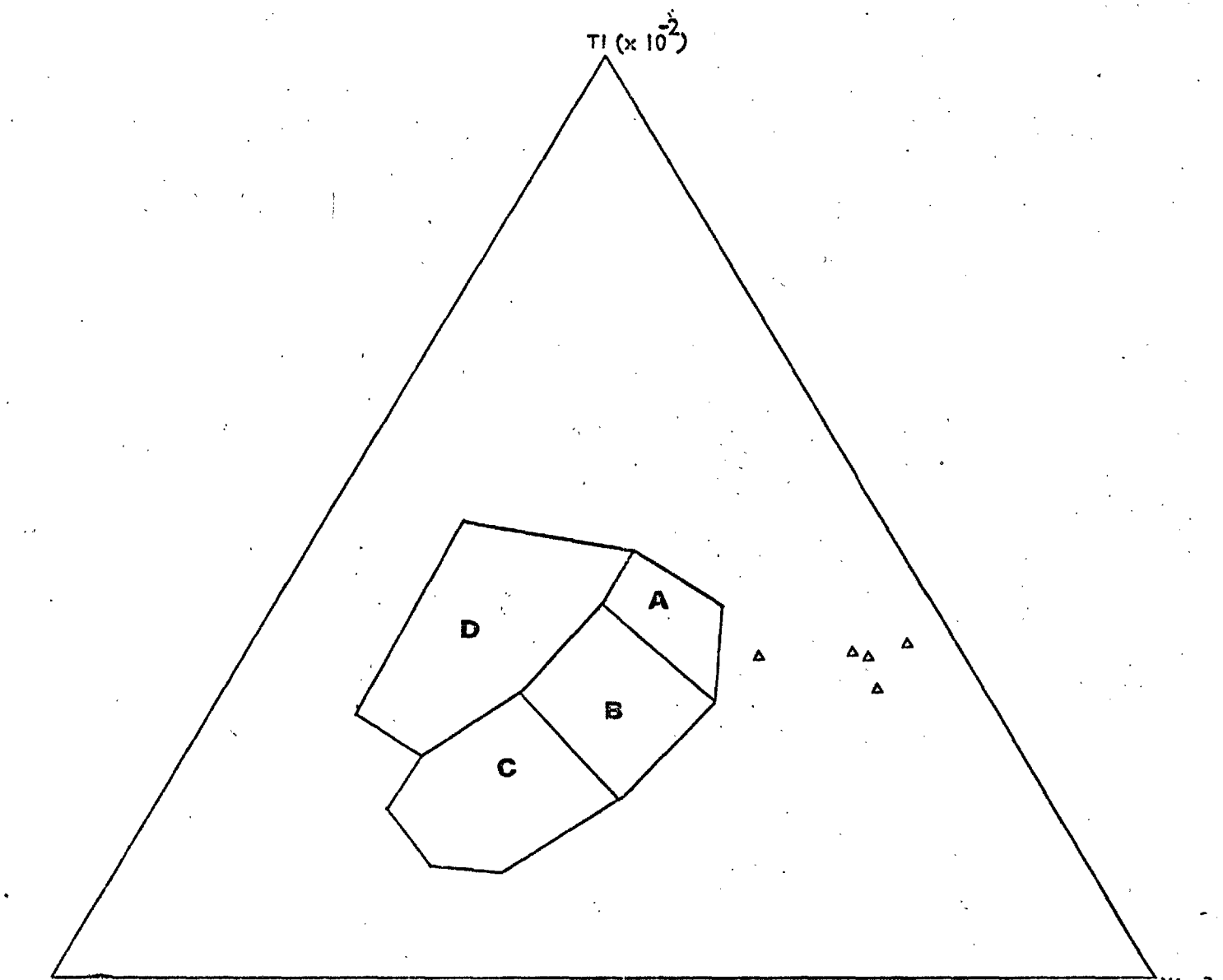


Fig. 6.16 Ti($\times 10^{-2}$) - Zr - Y ($\times 3$) diagram (after Pearce & Cann, 1973) for Foindie amphibolites. B = Ocean floor basalts; A & B = Low-K tholeiites, C & B = Calc-alkali basalts; and D = With plate basalts.

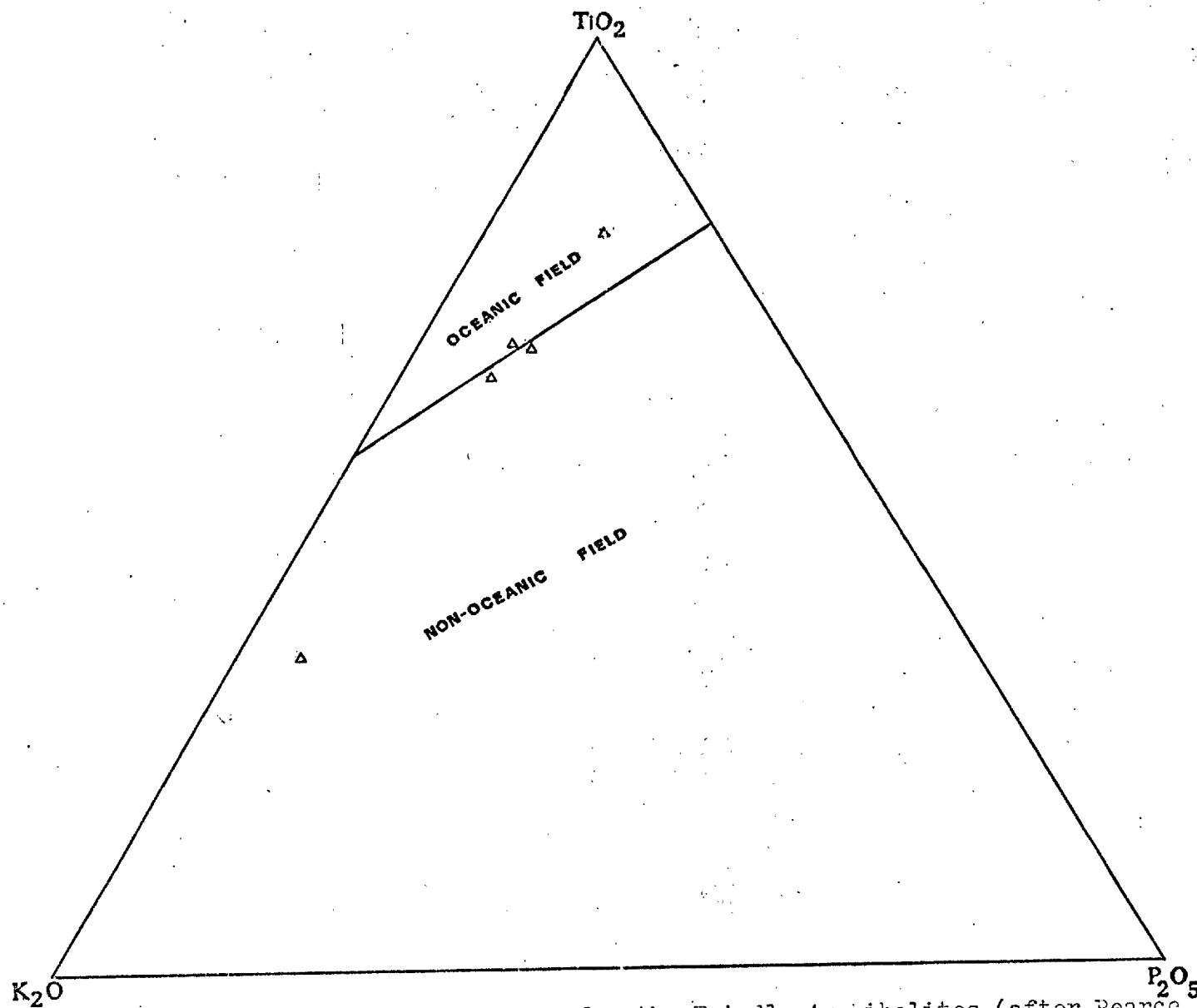


Fig. 6.17 TiO_2 - P_2O_5 - K_2O diagram for the Poindie Amphibolites (after Pearce et al., 1975).

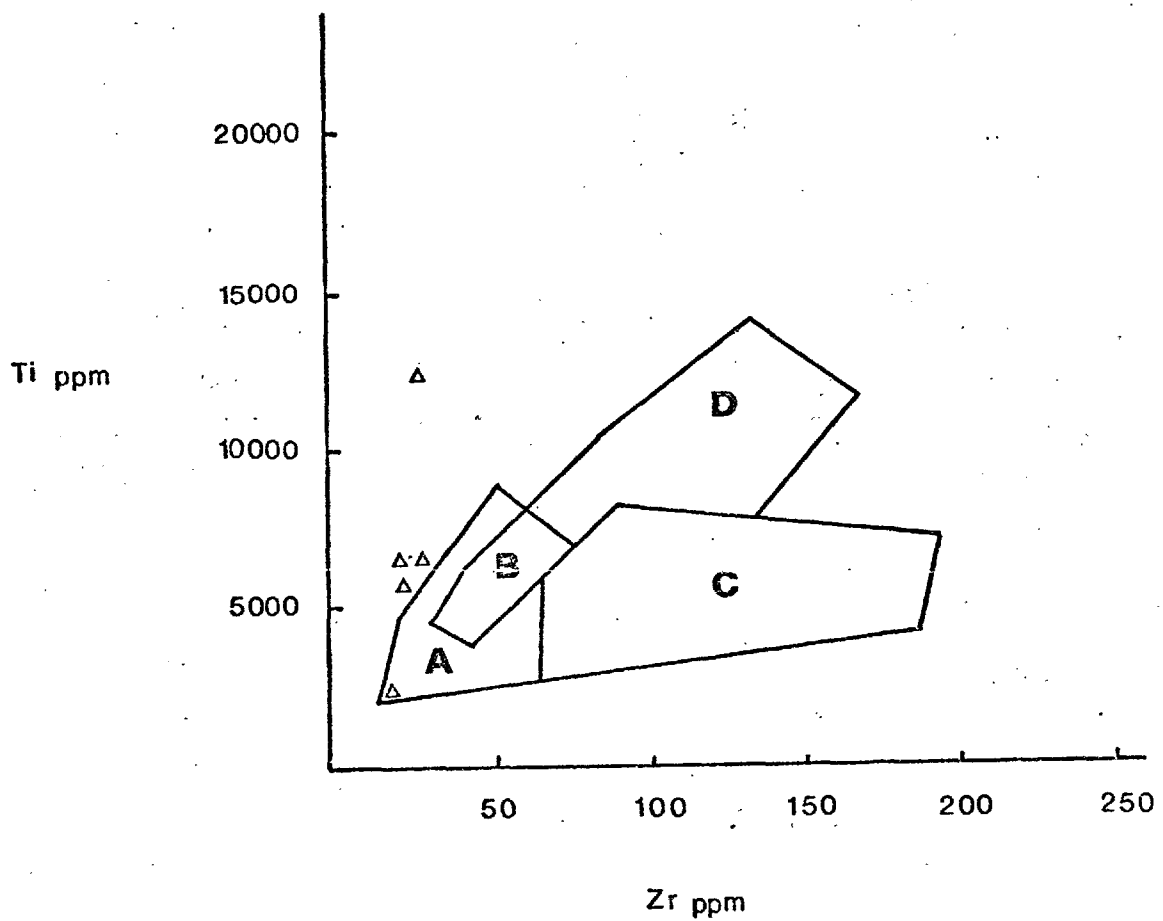


Fig. 6.18 Ti(ppm) vs Zr (ppm) discrimination diagram
(after Pearce & Can, 1973) for the Foindle
Amphibolites.

A & B = Low - K tholeiites

C & B = Calc-alkali basalts

D & B = Ocean floor basalts

with extreme caution knowing fully well that basic and ultrabasic rocks have high MgO that most times are greater than their CaO. Criterion (c) is the most reliable and should be, because highly siliceous rocks tend to resist any secondary alteration like metamorphism. Normative Quartz values suggest a sandstone or chert origin for the Quartzitic gneisses (now meta-arkoses/impure quartzites). REE data (chapter 5) suggest sandstone origin.

The fairly positive trends in MgO vs SiO₂ or CaO vs SiO₂ plots in fig. 6.14 (A & B) for the amphibolites are characteristic of Precambrian meta-igneous bodies. The trend in the amphibolites may be due to changes in the activities of Fe and Si (α_{FeO} , α_{SiO_2}).

Elliot & Cowan (1966) divided the Holleinden amphibolites into two groups on the basis of texture. One group is massive and coarse grained while the other is schistose. They established that the massive group has a significantly lower oxidation ratio (cf. Chinner, 1960) than the schistose group, and by comparison with the oxidation ratios of other groups of intrusive and extrusive rocks, concluded that the schistose amphibolites represented extrusive, and the massive amphibolites intrusive rocks respectively. Although the Foindle amphibolites are essentially schistose in texture, it is unlikely that variations in the oxidation ratio in these amphibolites at least, could be correlated with the mode of origin of the rocks, since it could be due to differences in their subsequent history as already suggested in chapter 4.

6.5 Discriminant functions

The origin of amphibolites is one of the most controversial and fascinating problems in metamorphic petrology. In spite of the fact that a large number of researchers have investigated these

controversial rock types, the net result does not appear to be very different from the views of Yoder (Wilcox & Poldervaart, 1958, p. 1324) that under equilibrium conditions ortho - and para-amphibolites would be indistinguishable if held at same temperature and pressure. Most investigators have recognised, at least in principle, three processes by which rocks of amphibolite composition and mineralogy might be produced i.e (1) meta-igneous, (2) meta-sedimentary, and (3) metasomatic (Orville, 1969). The field observations show the ubiquitous nature of the amphibolites in metamorphic terraines (e.g region under discussion) therefore require complete understanding of their origin to interpret the geologic history of the rocks with which they are associated. Major element composition of the amphibolites is not enough to distinguish between para - and ortho-amphibolites. Shaw & Kudo's (1965) discriminant functions have been tested for the purpose of splitting the the amphibolites into ortho - and para - groups. The trace element functions (X_1 & X_2) of these authors are not useful because Co and Sc, the most important elements in these discriminant functions were not determined in this project. The probability of mis classification is 5.7% in the major element discriminant function X_3 ($X_3 = 7.071 \log \text{TiO}_2 + 1.91 \log \text{Al}_2\text{O}_3 - 3.291 \log \text{Fe}_2\text{O}_3 + 8.48 \log \text{FeO} + 297 \log \text{MnO} + 4.81 \log \text{MgO} + 7.81 \log \text{CaO} + 3.92 \log \text{P}_2\text{O}_5 + 0.15 \log (\text{O}_2 - 15.08)$) and this method has been adopted in the test. According to Shaw & Kudo (op. cit) the most effective oxides for discrimination are TiO_2 , FeO , and P_2O_5 (oxides of comparatively immobile elements). CO_2 was not determined and as its amount is expected to be very small, it is omitted from the calculation of X_3 . The values of X_3 obtained are shown below:-

Sample No	X_3 value
30	+ 0.32

31	- 0.56
32	+ 0.185
34	+ 4.0139
56	+ 1.961

But for a negligible negative X_3 value in one sample, X_3 shows definite positive values that implies the samples are ortho-amphibolites. This suggests that their compositions are of basic igneous type. This view is in support of the findings from figs. 6.8 and 6.9. It must, however, be mentioned that any rock unit made up chiefly of hornblende, with a subordinate amount of plagioclase, whatever its origin may be, will approximate to a basaltic composition. The compositional field for the two - phase assemblage, hornblende - plagioclase, closely 'mimics' the composition field of basic igneous rocks (Orville, 1969). Metasediments have basaltic source rocks will give the same end composition and therefore, may not be very clearly differentiated from the basic rocks on basis of chemical composition alone. Evans & Leake (1960) believe that the Ni, Co and Cr contents of the para-amphibolites are lower than for the ortho-amphibolites. The negative X_3 discriminant value in sample 31 implies sedimentary origin (cf. Shaw & Kudo, 1965). Its Ni and Cr values are higher than the other amphibolites which have been regarded as ortho-amphibolites above. If the view of Evans & Leake (1960) is accepted, this rock is not a para-amphibolite. It is, however, possible that the predominance of basic rocks rich in these elements in the source area of the sediments can give rise to para-amphibolites.

In order to further distinguish between possible ortho - and para-gneisses, analyses from all rocks were plotted against the modified Larsen Index ($Si/3 + K - Ca - Mg$ wt. %) of Shaw (1972). Super position of the igneous and sedimentary rock

composition fields yielded numerous diagrams (not shown in this thesis) that suggest that the Larsen Index is not for rocks from the Scourie - Foindle region. The same problem has also been encountered using the author's DF discriminant function ($DF = 10.44 - 0.21 \text{ SiO}_2 - 0.32 \text{ Fe}_2\text{O}_3 \text{ (total iron)} - 0.98 \text{ MgO} + 0.55 (\text{CaO} + 1.46 \text{ Na}_2\text{O} + 0.54 \text{ K}_2\text{O})$). This is attributed to the effects of metasomatism on initial composition of the rocks.

6.6 Trace element abundances and ratios

Thorium abundances may distinguish between amphibolites derived from pelites and those from basic igneous rocks.

Thorium abundances after Clark et al. (1966) and Van De Kamp (1968) are summarized below:-

	Mean Th (ppm)	Range
Basic igneous rocks	2.7	0.1 - 10
'Common shales'	12	2 - 47
Carbonates	1.7	0.1 - 7.0
Ortho-amphibolites	2.7	2 - 10
Para-amphibolites	4.50	2 - 8

The data from Foindle amphibolites (Table 6.4) are not close to the mean or within the range for para-amphibolites of Clarke et al. (1966) and Van De Kamp (1968). The 0.5 ppm for the basic gneiss and 9.30 ppm for the retrogressed Leuco - gabbro are within the values for basic igneous rocks of these authors, although there is a slight bit of overlap on their data. The meta-pelite averages and ranges from this study are also within their limits for common shales.

Ba is less abundant on the average, in the amphibolites than in the other rock types (see Table 6.4). The metasediments have a wide range of values. This kind of variation in pelites has also been reported by Shaw (1956), Spencer (1966). The mean Ba

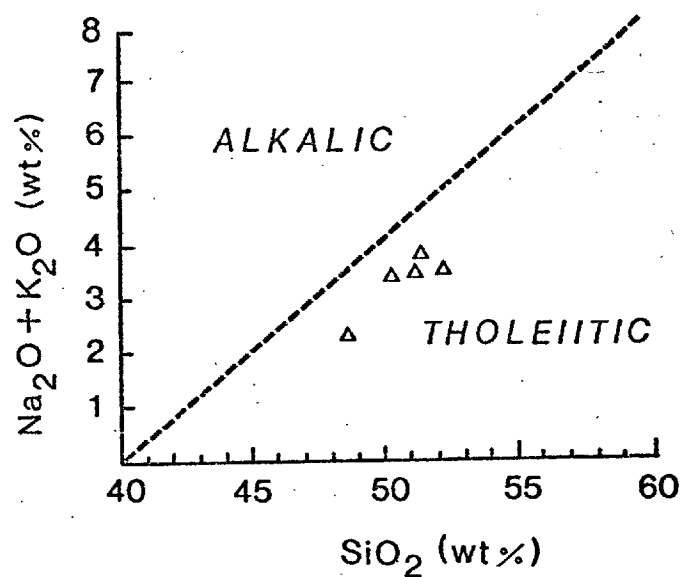


Fig. 6.19 Plot of the Foindle Amphibolites on the Na₂O + K₂O vs SiO₂ diagram of MacDonald & Katsura (1964).

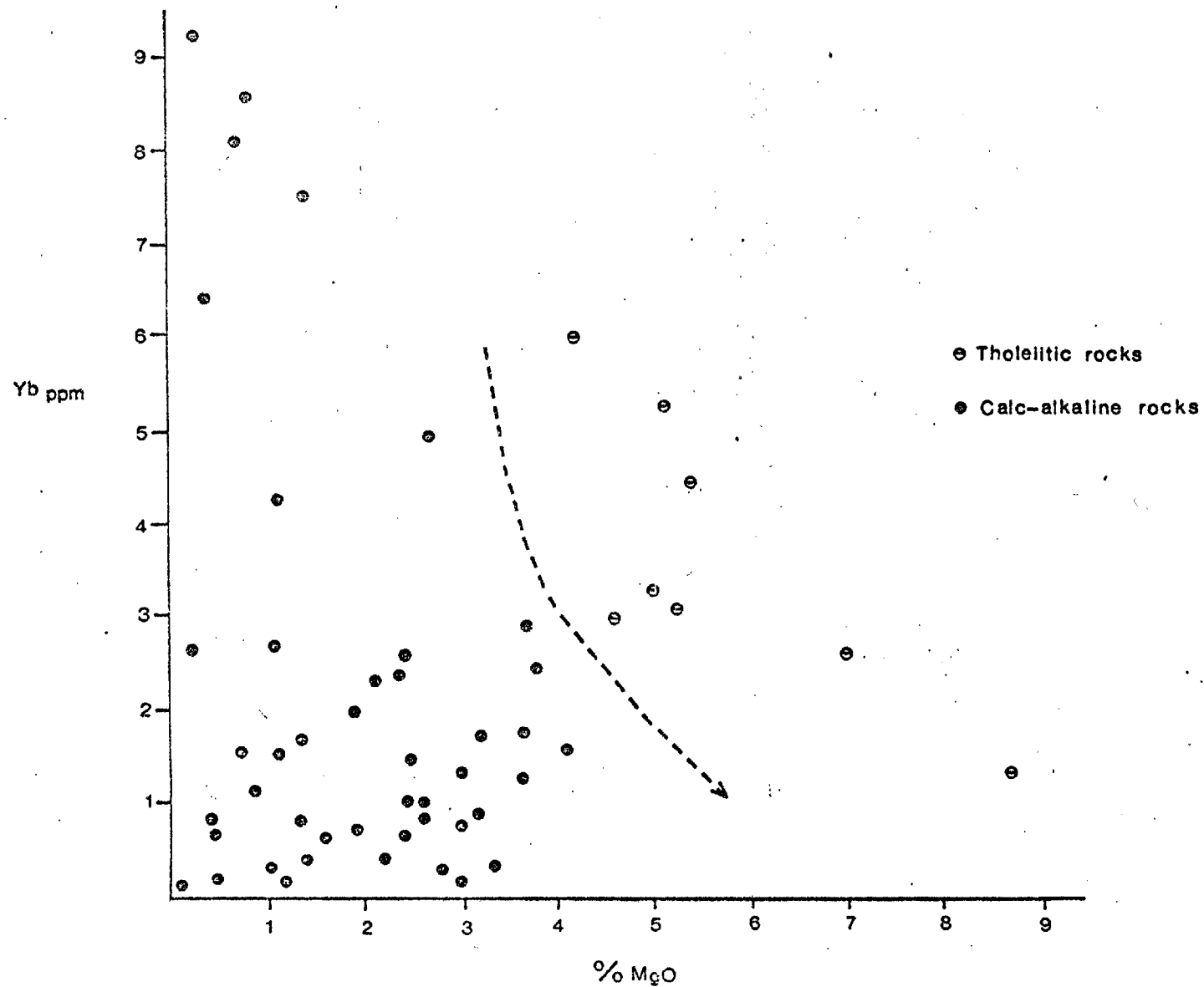


Fig 6.20 Yb vs MgO diagram to distinguish between calc-alkaline and Tholeiitic rocks. The dashed line separates the two magma types

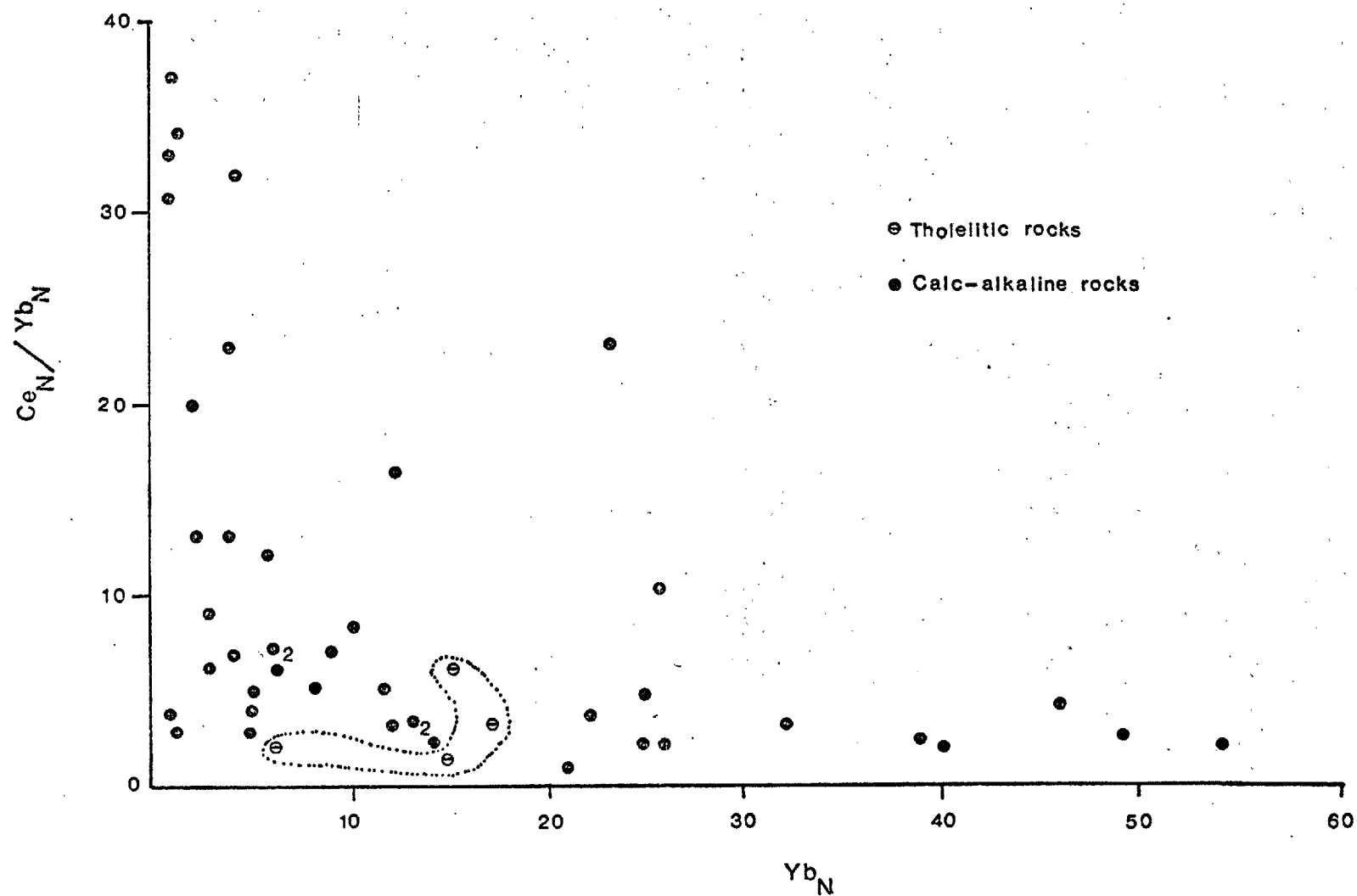


Fig. 6.21 Ce_N/Yb_N vs Yb_N diagram to distinguish between calc-alkaline and tholeiitic rocks.

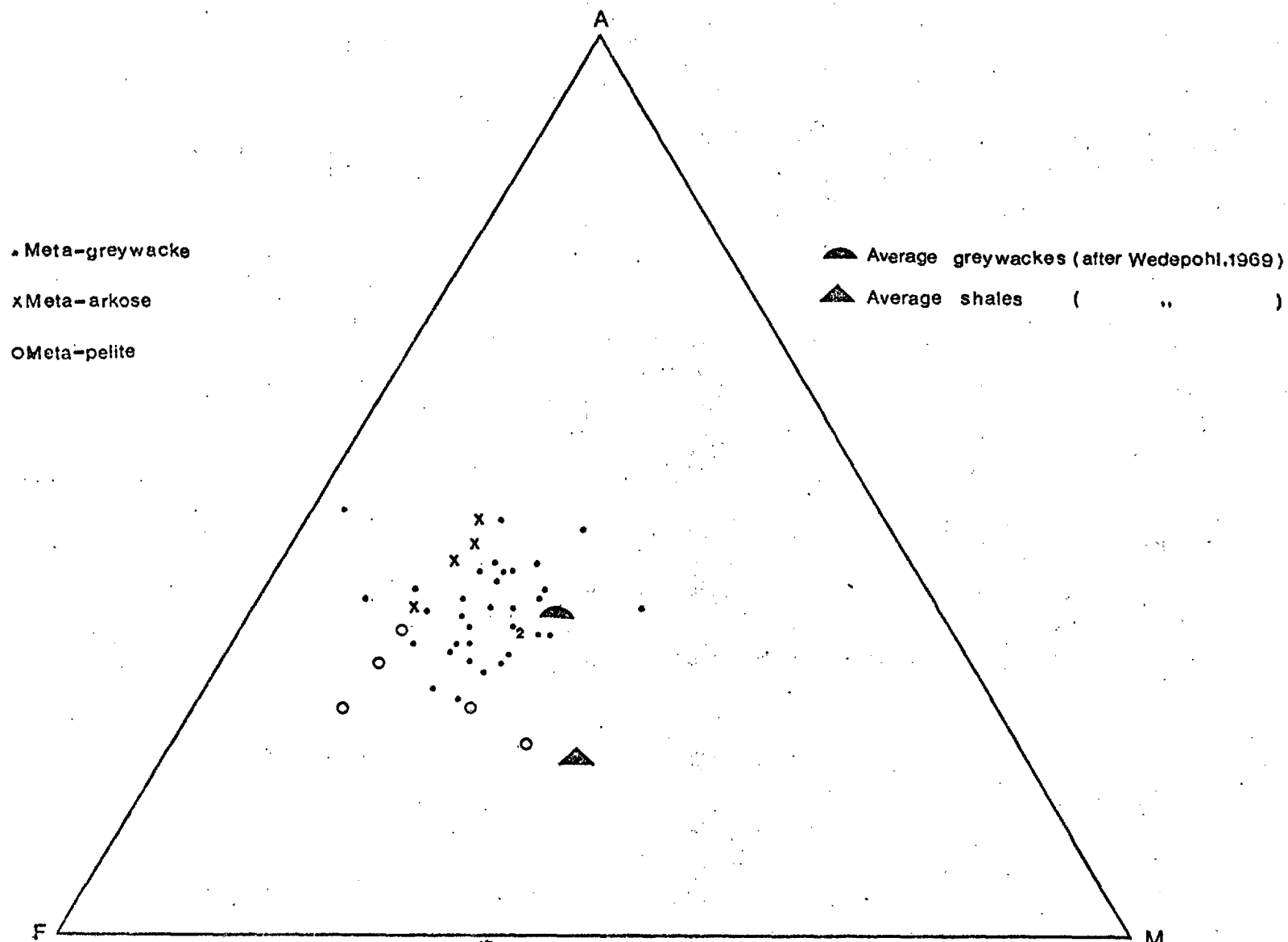


Fig. 6.22 AFM plots (after Blümel & Schreyer, 1977) showing compositions for meta-greywacke, metapelite, and meta-arkose. For comparison average greywacke and shale (Wedepohl, 1969) are plotted also.

content in pelites (700 ppm, Taylor 1965), is much higher than in the amphibolites (average, 203 ppm) probably as a result of the covariance of Ba and K (cf. Gunn, 1965). It would seem that Ba does not help to solve the amphibolite problem.

Cr and Ni have mean abundances and ranges shown in Table 6.4 for all rock types. Those for amphibolites, basic gneiss, and retrogressed leuco - gabbro are in the range for basic igneous rocks, especially the higher values. These, considered with the Niggli mg values that are quite close to those from meta-pelites, could suggest that the meta-pelites were derived from the basic igneous materials.

Vanadium has approximately similar distribution in amphibolites, basic gneiss, retrogressed Leuco - gabbro and meta-pelites. The means and ranges as shown in Table 6.4 are typical of basic igneous rocks. The meta-pelites (average, 187 ppm) contain considerably more Vanadium than the mean of 130 ppm for shales (Taylor, 1965). The shales analyzed by Spencer (1966) contain upto 887 ppm V and in those rocks V values covering most of the range of amphibolite values. Therefore, vanadium is not a certain indicator of sedimentary origin.

Zinc is distributed rather similarly in basic igneous rocks, shales, intermediate and acid rocks. For the amphibolites, this similarity means that Zn content is of little value in determining their possible origin. However, it is possible that zinc may have been added to the rocks metasomatically.

Copper is not useful as an identifier of origins, as it has wide, over-lapping ranges of abundance in meta-pelites, basic, intermediate and acid igneous rocks.

Yttrium is similar to Copper as an identifier. No systematic variation of zinc, copper, vanadium or yttrium with any other variables can be established. Zirconium values (i.e. for amphibolites, meta-pelites, basic gneiss) are typical of those found in basic igneous rocks and pelites and hence are also not useful indicators of origin.

Rb/Sr ratios can be useful indicators of rock origins as inferred from the data of Faure & Hurley (1963). Basic igneous rocks generally have ratios well below 0.15 and the ratios in shales are about 0.5 or higher (average meta-pelites, 0.64). The amphibolites have an average Rb/Sr ratio of 0.02 with a range (0.01 to 0.06). The ratio for the basic gneiss is 0.07. Para-amphibolites should have higher Rb/Sr ratios than these (cf. Van De Kamp, 1968). Even the K - rich amphibolite (LNB 56) has Rb/Sr ratio of 0.06 that is still low. The majority of the values are quite low and are similar to basic igneous rock values. Higher ratios are recorded in the metasediments (see Table 6.4).

Plots K against Rb are also useful in determining the identity of the parent rocks of amphibolites. Fig. 7.2 shows that most of the amphibolites are of igneous origin and have the same trend as oceanic tholeiite. The K - rich amphibolite (LNB 56; $K_2O = 0.73\%$) plots near the pelite area, owing to the well known covariance of Rb and K.

The data on the abundances of rare-earth elements (REE) presented by Haskin et al. (1966) indicate that certain of these elements might be useful in determining the parentage of metamorphic rocks. For amphibolites, where it is desired to separate those derived from basic igneous rocks from those derived from pelitic rocks, the ratio of La to Ce is useful. La/Ce ratio is generally above 0.4 for sedimentary rocks and

below 0.4 for basic igneous rocks. Mixtures of pelite and carbonate that might produce amphibolite would generally have La/Ce ratio over 0.4 (Van De Kamp, 1968). The La/Ce ratios (average & range) for all rocks analyzed are shown in Table 6.5. The values for amphibolite and basic gneiss are within the values expected for basic igneous rocks. Higher ratios are common with the metasediments (much > 0.40), with highest values in the meta-arkose. One problem of interest is the average value of 0.9 for the granitic gneiss. It would seem that the La/Ce ratio does not help to distinguish granitic gneiss from the meta-arkose.

6.7 Discrimination of magma types

REE geochemistry shows that the Foindle amphibolites were basalts prior to metamorphism at granulite facies and then retrogression that followed later. In order to establish the type of basalt, Pearce & Cann (1973) diagrams (figs. 6.15, 6.16, 6.18) have been plotted. These authors used such diagrams to discriminate the tectonic setting of basic volcanic rocks using trace element analyses. 3 groups of basalts were established by them namely; ocean floor basalts, low - K tholeiites, and calc-alkali basalts. All diagrams show that the amphibolites plot close to, but not in the low-K tholeiites field. It is likely that this is due to the effects of metasomatism. In the light of the present data, these diagrams must be used with caution since they have not helped to establish the type of basalt. The authors themselves accept that they do not yet stand the test for use in Precambrian volcanics, and therefore must be used with great caution. Pearce et al. (1975) also used the TiO_2 - K_2O - P_2O_5 diagram (fig. 6.17) to distinguish between oceanic and

Table 6.1 Major element compositions (averages and ranges) for rocks (re-classified) in Foinzie and Scourie

	META-IGNEOUS ROCKS						META-SEDIMENTARY ROCKS					
	Retro- gressed Leuco- gabbro	Basic gneiss	Amphibolite	Granitic gneiss			Meta-pelite	Meta- greywacke	Meta- arkose			
			(5)	(6)			(5)	(34)	(4)			
			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
SiO ₂	40.85	52.84	51.07	49.10- 52.71	71.42	64.25- 77.49	55.47	54.21- 56.89	67.69	60.19- 78.28	80.85	78.94- 81.76
TiO ₂	2.23	0.70	1.14	0.41- 2.12	0.24	0.04- 0.61	0.65	0.51- 1.17	0.50	0.12- 0.76	0.11	*
Al ₂ O ₃	17.06	15.98	14.77	12.79- 16.05	13.81	11.37- 15.32	16.91	12.23- 21.29	15.33	9.21- 19.53	9.80	9.14- 10.04
Fe ₂ O ₃	1.59	1.72	2.88	1.05- 4.08	0.23	0.01- 0.45	0.86	0.08- 3.23	0.23	0.01- 0.76	0.04	0.01- 0.08
FeO	15.10	6.72	11.69	8.44- 17.30	2.37	0.77- 4.49	10.42	7.68- 16.28	3.62	0.44- 6.88	1.38	0.50- 1.15
MnO	0.25	0.17	0.22	0.18- 0.26	0.11	0.01- 0.40	0.19	0.13- 0.26	0.07	0.01- 0.17	0.11	0.03- 0.28
MgO	7.02	4.11	5.57	4.19- 8.68	1.25	0.44- 2.93	3.87	2.68- 5.38	1.84	0.02- 3.58	0.49	0.21- 0.88
CaO	10.64	11.00	8.72	7.77- 9.89	3.16	1.03- 5.51	3.45	1.77- 6.04	3.29	0.08- 5.31	1.89	1.17- 2.82
Na ₂ O	1.16	2.18	2.81	1.69- 3.30	4.38	2.29- 5.98	2.29	0.10- 5.00	3.41	0.58- 4.55	1.60	1.33- 1.78
K ₂ O	1.04	2.14	0.44	0.28- 0.73	1.89	0.23- 6.06	2.47	0.63- 4.11	2.52	0.22- 8.19	1.94	1.19- 2.82
P ₂ O ₅	0.83	0.32	0.16	0.07- 0.29	0.07	0.03- 0.12	0.15	0.02- 0.29	0.15	0.03- 0.39	0.03	*
LOI	0.00	1.49	0.54	-0.30- 2.05	0.92	0.52- 2.17	1.79	0.67- 3.93	0.95	0.24- 2.06	0.86	0.53- 1.05
H ₂ O	0.05	0.06	0.07	*	0.07	0.04- 0.11	0.08	0.03- 0.13	0.09	0.02- 0.34	0.05	*
Oxidation Ratio	8.65	18.70	17.41	10.07- 19.94	8.92	1.15- 14.87	5.04	0.87- 15.15	5.32	0.70- 18.37	2.28	0.89- 3.47
FeO _T /FeO _T +MgO	0.70	0.66	0.71	0.52- 0.84	0.61	0.31- 0.74	0.73	0.59- 0.83	0.65	0.46- 0.85	0.73	0.70- 0.76
CaO/Al ₂ O ₃	0.62	0.69	0.59	0.53- 0.67	0.23	0.08- 0.37	0.21	0.08- 0.40	0.21	0.01- 0.41	0.20	0.09- 0.31
Na/K	1.00	0.90	6.13	3.16- 7.70	5.62	0.34- 16.11	0.72	0.14- 1.53	2.32	0.06- 17.81	0.81	0.56- 1.22

* No significant change. Figures in brackets show no. of analyses

Table 6.2. CIPW Norms (averages and ranges) for rocks re-classified in Foindle and Scourie

	META-IGNEOUS ROCKS						META - SEDIMENTARY ROCKS					
	Retro- gressed Leuco- gabbro	Basic gneiss	Amphibolite (5)	Granitic gneiss (6)			Meta-pelite (5)		Meta-greywacke (34)	Meta-arkose (4)		
			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
Qz	-	2.99	3.03	0.79- 7.03	29.25	16.82- 44.45	12.23	0.80- 32.36	26.39	4.53- 49.30	58.32	55.59- 61.09
Co	-	-	-	-	1.57	*	6.00	4.25- 8.24	1.91	0.16- 4.33	1.72	0.42- 4.29
Or	6.15	12.65	2.59	1.65- 4.31	11.18	1.36- 35.81	14.88	3.72- 24.29	14.20	1.30- 48.40	11.43	8.04- 16.66
Pl	48.09	45.94	50.14	40.79- 55.21	48.76	24.23- 59.59	34.84	9.43- 50.86	44.01	17.16- 60.15	22.67	19.49- 26.81
Ab	9.82	18.45	23.74	14.30- 27.95	37.02	19.38- 50.60	19.34	0.85- 42.31	29.27	4.91 43.75	13.52	11.25 15.06
An	38.27	27.50	26.41	24.02- 28.38	11.74	4.85- 17.30	15.49	8.55- 25.15	14.72	0.14- 23.95	9.15	4.27- 13.79
Hy	0.51	10.07	23.09	18.09- 30.81	5.64	2.52 11.00	26.72	19.31- 29.47	10.10	0.73- 17.20	3.77	1.76- 7.38
Mt	2.31	2.49	4.18	1.52 6.96	0.33	0.01 0.65	1.25	0.12 4.68	0.33	0.06- 1.10	0.05	0.01- 0.12
Il	4.24	1.33	2.17	0.08- 4.03	0.45	0.97- 1.16	1.62	0.12- 2.22	0.91	0.08- 1.90	0.21	*
Ap	1.97	0.76	0.38	0.17- 0.69	0.16	0.17- 0.28	0.36	0.17- 0.69	0.41	0.07- 2.54	0.07	*
Di	7.59	20.66	13.20	8.66- 17.99	3.48	2.14- 7.64	2.68	*	3.58	1.57 6.21	-	-
Ol	26.97	-	-	-	-	-	-	-	-	-	-	-

* No significant change. Figures in brackets show no. of analyses.

Table 6.3. Niggli values (averages and ranges) for rocks (re-classified) in Foindle and Scourie

	META-IGNEOUS ROCKS						META-SEDIMENTARY ROCKS					
	Retro- gressed Leuco- gabbro	Basic gneiss	Amphibolite		Granitic gneiss		Meta-pelite		Meta-greywacke		Meta-arkose	
			(5)		(6)		(5)		(34)		(4)	
			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
al	21.06	24.88	21.01	17.85- 23.18	32.13	5.47- 47.81	30.45	22.91- 39.52	38.34	31.76- 54.67	46.39	39.96- 51.87
fm	51.32	34.80	49.18	46.28- 58.13	20.44	8.03- 30.57	46.81	33.31- 69.48	24.27	3.48- 45.38	15.18	8.69- 25.51
c	23.88	31.13	22.54	19.22- 24.51	17.03	6.55- 25.35	11.19	6.03- 19.34	14.20	0.61- 26.90	15.74	8.55- 24.72
a/k	3.74	9.19	7.26	4.30- 8.49	27.44	16.67- 36.12	11.56	1.59- 21.13	22.02	13.76- 41.23	22.70	15.60- 30.90
si	85.57	139.58	123.24	116.28- 130.33	377.73	230.50- 489.88	169.60	162.45- 180.81	298.81	190.55- 545.63	651.34	524.26- 711.96
k	0.37	0.39	0.10	0.07- 0.16	0.19	0.01- 0.64	0.51	0.32- 0.81	0.31	0.03- 0.54	0.41	0.32- 0.51
mg	0.43	0.46	0.41	0.25- 0.62	0.45	0.38- 0.51	0.39	0.26- 0.55	0.45	0.06- 0.68	0.37	0.32- 0.42
qz	-29.41	+ 2.83	-5.79	(-0.93)- (-9.45)	+177.28	+63.83- +349.38	+30.07	(-13.19)- +74.47	+115.53	(+10.80)- +318.01	+460.57	+361.86 +496.52

Figures in brackets show no. of analyses.

Table 6.4. XRF trace element compositions, p.p.m. (averages and ranges) for rocks (re-classified) in Foindle and Scourie

	META-IGNEOUS ROCKS						META-SEDIMENTARY ROCKS					
	Retro- gressed leuco- gabbro	Basic gneiss	Amphibolite (5)	Granitic gneiss (6)			Meta-pelite (5)	Meta-greywackes (34)	Meta-arkose (4)			
			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
Cr	44	152	59	23- 94	25	4- 93	208	71- 405	51	1- 294	7	5- 10
Ni	313	67	26	15- 34	11	4- 28	103	15- 300	26	4- 116	10	6- 11
Rb	45	23	3	1- 7	39	2- 84	47	8- 112	42	3- 124	43	33- 50
Sr	3067	346	194	109- 240	312	99- 506	313	3- 582	407	39- 761	89	64- 119
Y	235	22	37	11- 69	34	2- 154	35	21- 71	27	1- 202	80	32- 117
Zr	178	212	151	13- 196	139	71- 294	173	49- 275	234	21- 622	229	209- 248
Ba	9	1	1	91- 3	5	113- 11	9	84- 15	4	65- 15	902	640- 1028
Th	9	2	1	1- 3	5	2- 11	9	2- 15	4	1- 15	10	4- 14
Zn	1092	89	134	57- 188	50	15- 138	167	61- 254	80	14- 256	402	20- 959
Cu	1020	8	6	1- 13	13	4- 23	91	2- 286	29	4- 213	10	6- 18
V	936	178	236	220- 318	27	6- 81	187	103- 285	65	3- 155	6	4- 7
K/Rb	191	791	2503	888- 7653	517	237- 789	519	304- 665	580	196- 1588	379	226- 513
K/Sr	2.6	52	23	13- 57	54	10- 181	378	33- 1526	99	6- 1124	259	178- 460
K/Ba	21.4	20	25	9- 67	23	13- 40	22	14- 30	23	3- 55	18	10- 23
Rh/Sr	0.02	0.07	0.02	0.01- 0.06	0.13	0.05- 0.28	0.64	0.06- 2.3	0.22	0.01- 2.80	0.50	0.40- 0.80
Ba/Rb	8.9	40	250	39- 167	27	10- 61	20	10- 39	43	4- 341	22	13- 31
Ba/Sr	0.13	2.6	2.5	0.7- 8.2	1.9	0.7- 5.0	7.4	1.9- 24.7	3	1- 11	11	9- 14
Ca/Y	323	3600	2849	815- 6429	4945	162- 8190	894	348- 2102	4208	53- 40000	235	72- 412

Figures in brackets show no. of analyses

Table 6.5. REE compositions, p.p.m. (averages and ranges) for rocks (re-classified) in Foinde and Scourie

	META-IGNEOUS ROCKS						META - SEDIMENTARY ROCKS					
	Retro- gressed- Leuco gabbro	Basic gneiss	Amphibolite		Granitic gneiss		Meta-pelite		Meta-greywacke		Meta-arkose	
			(5)		(6)		(5)		(34)		(4)	
			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
La	41.4	25.0	11.6	10.2- 16.8	26.8	4.3- 61.7	43.0	21.2- 68.5	35.0	17.5- 61.6	72.7	49.7- 110.6
Ce	19.1	52.5	37.0	12.7- 79.6	28.5	3.6- 46.9	46.9	34.5- 67.	57.2	10.3- 166.5	74.0	38.8- 96.3
Nd	85.1	33.4	20.6	8.2- 37.4	21.2	1.2- 60.3	40.4	17.2- 68.8	29.3	1.7- 74.5	78.5	5.2- 124.2
Sm	17.4	7.2	6.4	4.5- 9.2	3.9	0.3- 13.1	8.0	3.6- 12.1	5.1	0.5- 13.8	14.2	5.2- 22.4
Eu	3.3	2.0	1.3	0.4- 1.6	1.0	*	1.5	0.8- 2.0	1.8	0.9- 8.4	1.6	1.3- 1.9
Gd	12.9	0.3	4.9	2.6- 7.8	1.6	0.3- 3.7	6.2	2.9- 9.7	3.7	0.4- 18.3	6.5	2.7- 13.4
Tb	1.8	0.9	1.0	0.4- 1.7	0.8	0.1- 3.3	1.7	0.5- 2.4	0.8	0.1- 2.9	2.5	0.6- 4.0
Ho	1.9	0.7	1.4	0.7- 2.9	2.7	0.4- 4.9	1.8	1.3- 2.4	1.3	0.2- 4.5	2.1	0.6- 3.2
Tm	-	0.2	0.3	0.1- 0.5	0.8	0.2- 2.1	0.9	0.3- 2.0	0.6	0.1- 2.9	0.7	0.0- 2.2
Yb	2.6	1.7	3.3	1.3- 6.0	3.6	0.2- 13.4	2.9	2.4- 4.9	2.4	0.1- 22.5	7.1	2.6- 10.8
Lu	0.3	0.3	0.3	0.1- 0.7	1.1	0.2- 2.0	0.3	0.3- 0.7	0.5	0.1- 3.2	0.9	0.4- 1.5
ΣREE	185.3	123.8	81.0	40.8- 131.7	116.9	53.3- 229.9	152.6	84.4- 198.7	139.2	38.0- 232.7	259.1	138.6- 376.2
Y	235.	22	37.2	10.9- 48.6	33.4	2.1- 152.5	35.1	17.2- 71.4	26.4	42.6- 107.2	79.3	170.6- 116.8
ΣREE+Y	420.3	145.8	118.1	51.7- 167.8	150.2	55.4- 382.4	187.8	101.6- 264.8	161.7	42.6- 439.9	338.4	170.6- 493.0
La/Yb	16.3	15.3	3.8	2.8- 5.0	62.5	4.7- 127.2	10.8	8.7- 13.9	14.3	0.7- 433.5	11.7	8.0- 18.8
LREE	163.1	116.0	68.5	35.3- 119.3	100.6	47.7- 202.1	138.3	76.6- 181.7	128.2	30.1- 266.4	239.3	129.7- 353.4
HREE	18.8	3.9	11.2	5.1- 19.1	9.5	1.9- 25.6	12.7	6.41- 21.4	8.2	2.0- 36.5	18.2	7.0- 28.5
LREE/ HREE	8.7	30.7	6.6	3.4- 11.2	20.5	7.9- 49.4	11.7	8.2- 18.6	25.9	1.0- 112.4	14.7	7.7- 18.5
Eu/Eu*	0.6	0.7	0.50	-	-	2.	0.7	-	-	-	0.5	-
La/Ce	2.2	0.5	0.4	0.2- 0.5	0.9	0.4- 1.2	1.0	0.6- 1.6	0.61	0.2- 1.7	1.0	0.8- 1.3

* No significant change

Figures in brackets show no. of analyses.

Table 6.6. Average chemical compositions of selected sedimentary and igneous rocks for comparison.

	A	B	C	D	E	F
SiO ₂	78.70	70.00	66.70	58.90	89.90	50.83
TiO ₂	0.25	0.25	0.60	0.78	0.20	2.03
Al ₂ O ₃	4.80	8.20	13.50	16.70	3.70	14.07
Fe ₂ O ₃	1.10	2.50	1.60	2.80	2.30	2.88
FeO	0.30	1.50	3.50	3.70	n.d.	9.00
MnO	0.03	0.06	0.10	0.09	0.10	0.18
MgO	1.20	1.90	2.10	2.60	0.50	6.34
CaO	5.50	4.30	2.50	2.20	0.30	10.42
Na ₂ O	0.45	0.58	2.90	1.60	0.70	2.23
K ₂ O	1.30	2.10	2.00	3.60	0.70	0.82
H ₂ O+	1.30	3.00	2.40	5.00	1.20	0.91
P ₂ O ₅	0.08	0.10	0.20	0.16	0.90	0.23

A = Sandstones; average of 253 by Clarke (1924)

B = Sandstones, from platforms; average of 3700 by Vinogradov & Ronov (1956)

C = Greywackes, average of 61 determinations by Pettijohn (1957)

D = Shales from platforms; average of 6800 by Vinogradov & Ronov (1956)

E = Cherts; average of 10 by Cressman (1962)

F = Tholeiitic basalts; average of 137 (after Nockolds, 1954).

n.d. = Not determined

non-oceanic basalts. Although they state that majority of analyses of Archean meta-basalts from Precambrian Shield areas should fall within the oceanic basalt field, the plots of the Foindele amphibolites do not show this. Potash metasomatism established in chapters 4 & 7, must have given rise to this. The diagram must therefore be used with great caution in such a situation.

The total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) vs SiO_2 diagram of MacDonald & Katsura (1964) shown in fig. 6.19 clearly favour tholeiitic type for the amphibolites from Foindele. This is agreement with the FMA diagram (fig. 4.1) and the K - Rb plot (fig. 7.2). Also the average amphibolite (see Table 6.1) compares well with the average of 137 tholeiitic basalts (after Nockolds, 1954) in Table 6.6 column F.

The author supports the view of Robinson & Leake (1975) that AFM ($A = \text{Na}_2\text{O} + \text{K}_2\text{O}$, $F = \text{total iron as FeO}$, $M = \text{MgO}$) diagrams should not be used to deduce origin of highly metamorphosed gneisses and quartz - feldspathic rocks that might be meta-arkoses, meta-granites or meta-volcanic rocks. In this thesis, FMA diagram (fig. 4.1) is used purely to establish three magma suites for the rocks studied (see chapter 4). Sedimentary rock series when plotted on AFM diagrams partly mimic trends generally considered characteristic of igneous variation, especially the calc-alkaline trend. Although the scatter in sedimentary rock plots is generally greater than that given by igneous rocks this is not necessarily so, for calc-alkaline suites often show considerable scatter.

Hawkesworth & O'Nions (1977), in their study of some Archean volcanic rocks from South Africa used Ce/Ybn vs Ybn and Yb ppm vs % MgO diagrams to distinguish between calc-alkaline and Tholeiitic suites. In fig. 6.20 the two magma suites are

clearly separated by the dashed line. This distinction has also been done with the FMA diagram in fig. 4.1. Fig. 6.21 is the Cen/Ybn vs Ybn diagram of these authors tested with the Poindie - Scourie rocks. On this diagram, the tholeiitic rocks exhibit a flat-lying positive correlation, while the calc-alkaline rocks display a steep - negative trend. The same features were obtained for the South African rocks of Hawkesworth & O'nions (op. cit).

6.8 Summary

Use of different chemical parameters and variation diagrams confirms that in Scourie and Poindie, the rocks studied are of meta-igneous and meta-sedimentary type, in support of the findings from the REE geochemistry discussed in the preceding Chapter. Neither the chemical parameters or the variation diagrams, however, give unambiguous evidence as to the precise type of igneous or metasedimentary parent for the rocks studied.

Blümel & Schreyer (1977) used AFM ($A = 100 (Al_2O_3 - K_2O - Na_2O - CaO) / (Al_2O_3 - K_2O - Na_2O - CaO + FeO + MgO)$, $M = 100 MgO / (MgO + FeO)$, $F = 100 - M$) diagram to show the positions for the average greywackes and average shales (after Wedepohl, 1969). Fig. 6.22 is the same diagram used to show fields of the Scourie - Poindie metasediments. The rocks which have been re-classified as meta-greywackes or meta-pelites (based on REE data discussed in chapter 5 and after comparison with rocks in Table 6.6 and Tables 7.7 to 7.10) plot very close to the average greywackes and average shales of Wedepohl (op. cit), although they cluster near the AF axis. The shift to the AF axis is likely to be a metasomatic effect. If these rocks are now accepted to be metasediments of meta-pelite, meta-greywacke, and meta-arkose types, their chemical data for different

groups are shown in the Appendices IIC and IIIC. All the averages and ranges for chemical data are shown in Tables 6.1 to 6.5. Maps 3 & 4 (pocket of thesis) are the lithological maps of Scourie and Foindle areas respectively based on this re-classification.

GENERAL DISCUSSION OF GENESIS AND
METAMORPHISM

7.1 Introduction

It should now be clear that many of the Supracrustals, other than the amphibolites, are metasediments. If this is the case, then the rocks studied in the region comprise a metasedimentary and a meta-igneous (basic to acid in composition) series. Chemical and petrographic evidence combined with field relations indicate that these formerly granulite facies rocks have been regionally retrogressed. In this chapter, other chemical evidence (apart from REE) will be used to discuss the source of the metasediments, and the retrograde metamorphism that affected all rocks from both areas studied. Later a summary of chronological events in the region based on field relations and geochemistry will be given. Suggestions resulting from this study are also given at the end of the chapter.

7.2 Problem of migmatization

The K-Rb data do not permit an unequivocal choice between anatectic melting and metamorphic differentiation as a mechanism of origin of the migmatitic gneisses (Davies, 1974) regarded as 'Banded acid gneisses in this study. Available data do not enable the author to establish these gneisses as genuine migmatites. In the case of metamorphic differentiation, the observed distribution of K and Rb could have arisen directly by diffusion of these ions into their preferred mineralogical environments, K being relatively concentrated in the feldspathic portions and Rb in their biotite portions. White (1966) has

argued for metamorphic differentiation in the case of migmatites from the Palmer region, South Australia, on the basis of the distribution of K, Rb and Ba. The data from this study are not sufficient to take sides. The entire issue is even further complicated by the intensive deformation that occurred in the region studied. Hence, it is difficult to attribute the inter-banding in some acid gneisses to anatexing melting, metamorphic differentiation or deformation.

7.3 Genesis

The presence of Supracrustal (metasedimentary or meta volcanic) horizons in granulite terrains is not uncommon. This might suggest burial to great depths with prograde metamorphism of the whole complex to granulite facies (Tarney & Windley, 1977). Many such supracrustal horizons are tectonic intercalations (McGregor, 1973). These views cannot be disputed on the basis of this study. However, in this section of the chapter an attempt is made to favour derivation from an igneous source, perhaps intrusive rocks for the sediments.

The association of volcanics and carbonates in assemblages formed 1200 - 1300 m.y ago (Silver & Lumbers, 1965) provides an example of widespread extrusive igneous activity at the same time as limestones were being deposited. Certain areas of south-west Pacific Ocean (e.g Truk) may provide modern examples of a similar environment. Van De Kamp (1976) suggested that the depositional environment of the pre-metamorphic rocks may have been a submarine shelf - area in which limestone was deposited. He further stated that volcanics occurred at the same time and formed extrusive tuff deposits interbedded with the limestone.

Davies (1974) recognized calc-silicate gneiss in the

area east of Foindle. Barcoah (1970) also reported the same rock type to the south-east of Scourie. If these identifications are accepted, it is then worth considering the possibility that some of the Supracrustal rocks could be derived from volcanic rocks, since the common association of possible volcanics and carbonates, as mentioned above, is indicated. Unfortunately, no calc-silicate rocks have been recognized in the region studied. Sutton & Watson (1951) and Beach (1974), however, recognized such rocks in the eastern part of Foindle. Although REE abundances can be affected by secondary processes (metamorphic or sedimentary), the values from the Supracrustal rocks (excepting the amphibolites) are high when compared with what are expected from volcanics, and are close to values from sediments. Also, their rare-earth distribution patterns indicate that their progenitors are probably igneous rocks similar in composition with the associated intrusives studied.

Chowdhary (1971) in his study of zircon populations in Lewisian quartzites, gneiss and granite, north of Loch Laxford, noted that

- (1) in intrusive granitic rocks, the majority of the zircons are normally in the form of euhedral grains (Poldervaart, 1956 pp. 532)
- (2) in many sedimentary rocks, the majority of zircons will be rounded with elongation maxima at less than 2 (Poldervaart, 1950; pp. 574; 1955, pp. 433), and
- (3) zircon, being one of the most refractory minerals, will not readily recrystallize during metamorphism (Poldervaart, 1950).

As already noted in the conclusions from the petrographic study (Chapter 3, section 3.4 (e), the occurrence of zircon as an accessory mineral in the Supracrustal rocks is interesting,

and deserves some mention. Zircon crystals are rounded and elongated, a form which suggests sedimentary origin (cf. Chowdhary, 1971). The rounding could have resulted either from regrowth of sedimentary grains during metamorphism (cf. Dalziel, 1963) or rounding of euhedral zircons by metamorphic processes (Kalsbeck & Zwart, 1967). A study of zircon populations in these rocks would help to make a choice. This has not been done in this study, and therefore it is impossible to account for this. The elongate (i.e. overgrowths and outgrowths of Poldervaart & Eckelmann, 1955) zircon crystals could be due to recrystallization.

Zircon crystals have been observed in sandstones by Poldervaart (1955), and in Rona quartzites in the Inner Hebrides by Bowes et al. (1976). Barooah (1970) also reported zircon as one of the accessory minerals in his study of south-east Scourie. Zircon crystals have not been recognized in the quartzitic gneisses examined in this study. Derivation from either chert or sandstone cannot easily be established. This has been discussed in Chapter 6.

Origin of zircon is of significance in a consideration of the age of the Supracrustal rocks (now metasediments). Bowes et al. (1976) concluded from their study of Archean quartzite, Rona, Inner Hebrides as follows:-

- (a) there was crustal material in existence in the Scottish region before the development of the Lewisian Complex, and
- (b) some of this material was at the surface and subject to erosion at the time of the development of at least some of the crust - building pile that immediately preceded the Scourian episode. Data from the present work tend to favour the existence of the Supracrustal

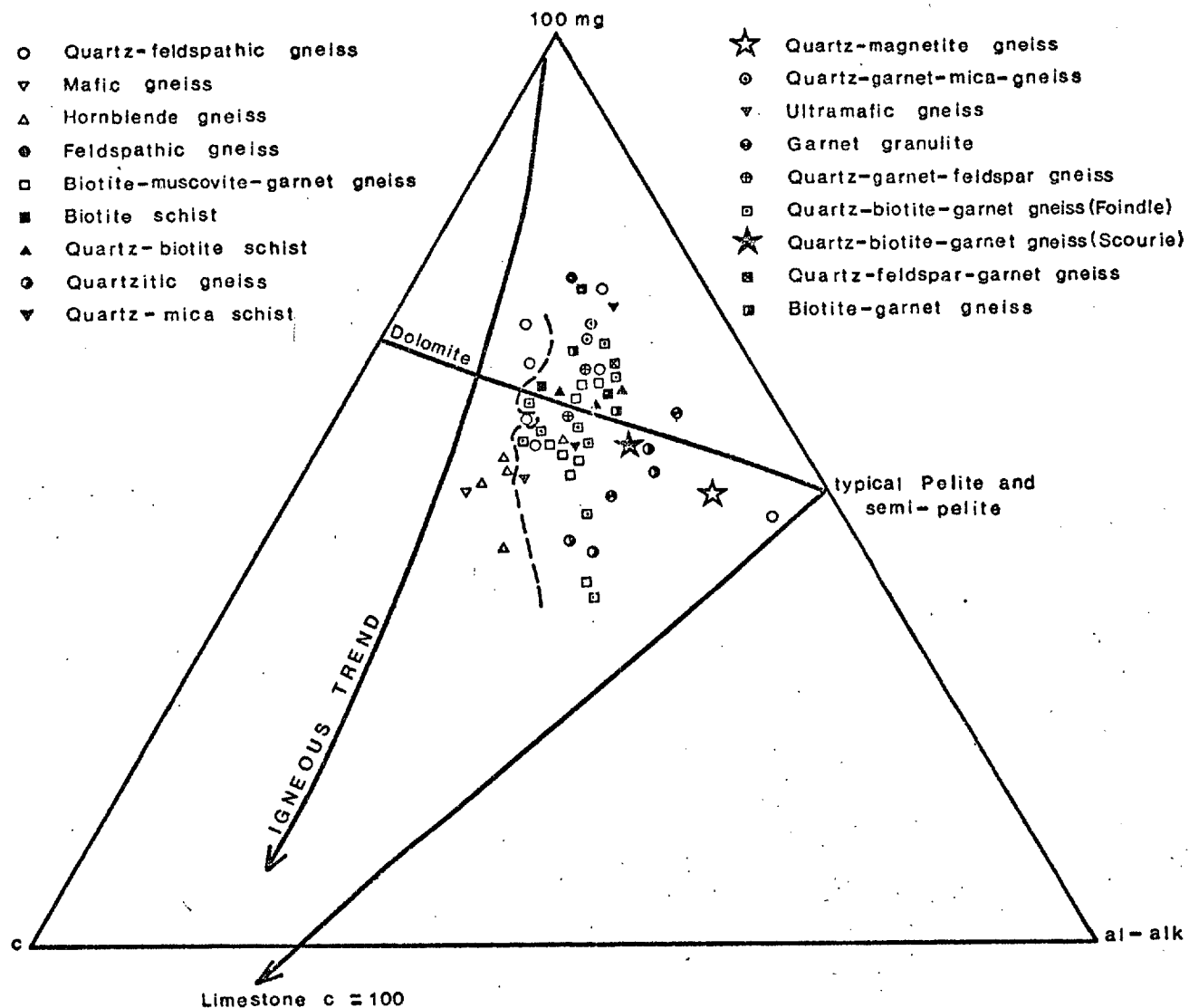


Fig. 7.1 Plot for Nigli 100 mg -(al-alk) - C = 100 (after Leake, 1964) for the Foindie - Scourie Supracrustal rocks, quartz - Feldspathic, mafic and ultramafic gneisses. Dashed Line separates ortho-gneisses from para - gneisses.

rocks prior to the development of intrusive igneous series. It is often said that granulite facies rocks are dominantly of igneous derivation (e.g. Kylesku group south of Scourie; see Bowes et al. 1971; Sheraton, 1969). It, therefore, seems that the Supracrustal rocks are granulite facies rocks derived from essentially igneous materials.

There is no Na^+ enrichment such as is commonly seen in rocks like greywackes from volcanics. Enrichment of Na^+ by alteration is commonly observed in volcanic sediments of this type (cf. Pettijohn et al. 1973). Meta-greywackes are the most abundant sedimentary rock in the region and deserve some mention. Furthermore, trace element distributions in Archean greywackes are better known than in other sediments (Condie, 1976, pp. 401). Detailed studies of greywacke provenance have been made in Wyoming (Condie, 1967; Wilderman & Condie, 1973), and of the Fig Tree Group in the Barberton belt of South Africa (Condie et al. 1970; Wilderman & Condie, 1973). Condie (1976) used the chondrite - normalized trace element concentrations for Wyoming greywacke to discuss their possible source. He listed three possible sources namely:-

- (a) granitic - gneiss terrain, by weathering and erosion
- (b) volcanic terrain, and
- (c) mixed volcanic and granitic terrain.

The REE patterns discussed in chapter 5 suggest that the meta-greywackes were probably derived from granitic gneiss. This is in support of alternative (a) above which has been shown by Condie (1976) to dominate in some areas like Wyoming.

Lambert & Holland (1974) showed that in sedimentary processes, the Ca/Y ratio becomes lower in shales and sandstones than in their source rocks. Below is a summary of the average

Ca/Y ratios for all rocks studied:-

Meta-pelite	893.81
Meta-greywacke	4208.00
Basic gneiss	3600.00
Meta-arkose	235.11
Amphibolite	2849.84
Granitic gneiss	4944.64

In this thesis, it has been emphasized that the metasediments were derived from igneous rock parents, probably chemically similar to the igneous sheets associated with metasediments in the region studied - the meta-pelites from basic bodies, and the meta-greywackes and meta-arkoses from granitic gneisses. The above data also favour this view and therefore sedimentary processes are a likely mechanism. The 100 mg - c - (al-alk) diagram in fig. 7.1 illustrates the igneous trend of the Karoo dolerite and the trends to be expected for pelite - carbonate mixtures, from Leake (1964). The meta-igneous rocks all follow the igneous trend. The metasediments also plot in the same field as the greywackes of Satyanarayana et al. (1974) i.e between igneous and sedimentary fields. This means that both igneous and sedimentary materials have been mixed. But for a few overlapping cases, especially in the quartz - feldspathic gneisses, the metasedimentary rocks plot to the right of the associated igneous series. The diagram, however, suffers one ambiguity. It does not clearly show the source of the sediments. It, however, shows that the present rocks have resulted from mixing of pelite and semi-pelite, and basic igneous material. It however, clearly shows that the amphibolites are a meta-basic rock. Since no para-amphibolites have been recognized in this region (see other chemical evidences in chapters 5 & 6), metasediments earlier than these basic igneous rocks are doubtful.

It is commonly suggested in studies of amphibolites that mixtures of dolomite and shale, metamorphosed and decarbonated, might produce amphibolites with virtually the same composition as basic igneous rocks (Van De Kamp, 1968). Some of the difficulties involved in producing amphibolites from such mixtures are mentioned by Evans & Leake (1960), who emphasized that these mixtures would not have the same composition as basic igneous rocks. For example, Al and K would be too high, Na would be too low.

The amphibolites from this study have been shown to be of igneous origin although the precise type of basic rock is difficult to establish. Are they basalt tuffs? Engel & Engel (1962, pp. 76) with reference to the origin of amphibolites stated that it is unreasonable to postulate that the thin seemingly accordant amphibolites are mafic tuffs, as is so frequently suggested in the literature.

Norrin (1940) gave detailed descriptions of three tuff layers in the Eocene of Denmark. Two layers are basic and the third is acidic in composition. These tuffs serve as marker horizons in the area. They are of the order of 10 - 50 cms thick and occur over an area at least 50 km across interlayered with clays and carbonates.

Mason (1949) and Schofield (1951) have given descriptions of basaltic tuffs in the Oligocene of New Zealand. Snively & Wager (1964) have shown that basic tuffs are widespread in western Oregon and Washington. Some are thin bedded and occur with greywackes. Stark & Hay (1963) described the volcanic rocks of Truk and mentioned the occurrence of basic tuffs. Some of the tuffs may be interbedded with limestones in the area. Reynolds (1916) described basalt tuffs in the Carboniferous limestones of Somerset. These are of fairly widespread

distribution in West Somerset. Buddington & Chapin (1929) and Brew & Muffer (1965) described Triassic basalt tuffs from Alaska. These occur with limestone and clastic sediments.

The above summary shows that basalt tuffs, although not common, are found in metamorphosed rocks of various types. There is therefore a likelihood that such rocks can exist in Precambrian sediments (such as those in the Foindle - Scourie region) which are now retrogressed granulite facies metamorphic rocks.

Fig. 7.2 is the K vs Rb plot for all the main rock groups. Two main trends are observed - main trend (M.T) and oceanic trend (O.T) of Payne & Shaw (1967). Because of retrogression, the abundances in K-Rb pairs of the intermediate and acid rocks do not plot below the meta-pelites as should be the case (cf Van De Kamp, 1968 pp. 1351). All rocks, except the amphibolites, follow the main trend. The amphibolites clearly follow the oceanic trend. Van De Kamp (op. cit; fig. 9) note that the ortho-amphibolites occurring within metasediments in the Haliburton - Madoc area, south-eastern Ontario follow the oceanic - tholeiitic trend. Hence, the occurrence of amphibolites/ meta-basalts within metasediments is not peculiar to the Foindle - Scourie region. Available data from this study do not permit a convincing evidence to be shown in order to classify the amphibolites as basic tuffs as against metabasalts.

7.4 Metamorphism

During metamorphism, the chemical compositions of all but high grade metamorphic rocks are often more or less constant except for loss of volatiles, particularly water and CO₂. This has been demonstrated by serial analyses of rocks from low to high grade, for example, Shaw's (1956) study of the Littleton

Table 7.1. Summary of Elemental and Oxidation ratios for all rock types

Ratio	Mean value SCOURIE (n=10)	Mean value FOINDLE (n=46)
Oxidation Ratio	4.42	9.31
Na/K	2.10	1.57
K/Rb	700	560
K/Sr	33	263
K/Ba	15	25
Rb/Sr	0.08	0.53
Ba/Rb	94	25
Ba/Sr	3	7
Ca/Y	3847	2635

n = no. of samples analysed

Table 7.2. Mineralogy and Metamorphism in the Supracrustal rocks in Scourie and Foindle

AREA	ROCK TYPE	LOCALITY ZONE	INDEX MINERALS	BARROVIAN ZONE CLASSIFICATION
SCOURIE	Schists	LOCHAN	Hornblende	
	&	GREIGE	Andesine (An40)	
	Gneisses	'MHAIL	Garnet Biotite Quartz Sillimanite Rutile	Sillimanite
FOINDLE	Mainly	LOCH	Hornblende	
	Schists	NAM	Plagioclase Biotite	Garnet/ Biotite
		BRAC	Garnet Epidote Quartz	
	Mainly	LOCH NA	Biotite	
	Schists	'HARIGH	Muscovite Chlorite	Biotite
		GLAISE	Quartz	

INCREASING AMPHIBOLIZATION
↓

LOCHAN CREIGE 'MHAIL - Loch North of Scourie Bay
 LOCH NAM BRAC - Loch between Foindle and Tarbet Road
 LOCH NA 'HARIGH GLAISE - Loch along Foindle/Fanagmore Road

pelites, by comparing the compositions of unmetamorphosed sediments and igneous rocks with their metamorphosed equivalents. Thus, excluding migmatites, it is generally thought that the non-volatile composition of metamorphic rocks is largely controlled by, and reflects, processes that took place in forming the original sedimentary or igneous rock. Leake (1972) recognized the modifying influence of metasomatism, which he considered on the whole, to be an external influence, which might introduce certain elements, remove elements, or commonly carry out both addition and compensatory removal at the same time.

This account presupposes that the chemical composition of some metamorphic rocks is modified and controlled by the stable mineralogy, unwanted elements being held or increased by subtraction from the intergranular fluid. Leake (op. cit) also pointed out that the compositions of some metamorphic rocks are partly mineralogically controlled, not as a result of metasomatism externally activated but as a result of internal metamorphic reactions i.e mineral instabilities and stabilities, which themselves aid the metasomatism.

It is generally agreed that the metasomatic removal of water and CO_2 from metamorphic rocks is largely controlled by dehydration and decarbonation of hydrous minerals and carbonates, while metasomatic hydration is largely directed by the formation of stable hydrous minerals in place of anhydrous or less hydrous minerals. It can, therefore, be said that a significant control over the water or even CO_2 contents of a metamorphic rock is the stable mineralogy and not only the original composition of the rock. It is, therefore, possible that the presence of certain dominant minerals may prevent the crystallization of minor minerals, even though these minerals

would be within their pressure - temperature stability fields, and thus provoke the metasomatic removal of elements which would have formed the minor minerals.

Few unaltered granulite facies rocks were found in the two areas studied (see Tables 3.2 & 3.3). Most rocks are retrogressed granulites, deformed at least twice. As a result, discussion on the metamorphic history is mainly on rocks of slightly lower temperature grade than the higher temperature granulites still preserved south of the region. Therefore, the extent of amphibolitization is discussed by comparing mean major element, mean trace element, and mean REE values for major rock units, based on the re-classification in Chapter 6, found in Scourie (less amphibolitized) with similar ones in Foindle (more amphibolitized) see Tables 7.3, 7.4, and 7.5). The best estimate of Scourie granulite assemblage (Holland & Lambert, 1975; Table 7.8 column F) has been used to show the extent of limited amphibolitization in the Scourie rocks. Comparison of the data in Table 7.3 with the above shows that amphibolitization in Scourie was characterized by minor potash feldspathization (higher K_2O , higher SiO_2).

On the basis of mineralogical assemblages shown in Table 7.2, two zones probably representing upper amphibolite to lower granulite facies conditions, (Engel & Engel, 1962) can be said to exist in Foindle and Scourie respectively.

Green & Ringwood (1967) subdivided granulites into three groups with the following mineral assemblages:-

- (1) lower pressure, characterized by olivine + plagioclase with cordierite and andalusite
- (2) medium pressure, typified by the assemblage; .
plagioclase + hypersthene + clino-pyroxene + quartz.
Kyanite and sillimanite are characteristic but the

plagioclase - olivine pair is unstable.

- (3) high pressure, with garnet + clino-pyroxene + hypersthene + plagioclase.

Clifford (1974) pointed out that almost all African granulites contain the association: plagioclase + hypersthene + clino-pyroxene + garnet + quartz in rocks of appropriate composition and that they formed under medium pressure metamorphic conditions. In metamorphosed pelites, the $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ ratio of the bulk composition determines the mineral assemblage and the maximum pressure range of cordierite + garnet assemblages (Hensen & Green, 1970; Currie, 1971). If the above ratio is less than 0.8 to 0.9, these assemblages may occur in medium high pressure (i.e. probably lower pressure than that for typical granulites and Clifford (1974) noted that many African and Madagascan granulites and gneisses do have ratios in the range 0.3 to 0.7. Neither cordierite nor andalusite has been observed in the rocks studied. The low pressure granulites of Green & Ringwood (1967) are unlikely. The $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ ratios for the meta-pelites studied in the region range from 0.65 to 0.85 and would suggest the rocks are medium high pressure granulites (group (2) of Green & Ringwood, op. cit). Also, Tarney & Windley (1977) conclude that the geothermal gradient in lower levels of the crust in early Precambrian times was predominantly of an intermediate type indicative of medium pressure metamorphism. The temperature cannot be estimated on the basis of this study. It, however, seems that it was too high for cordierite to be stable, as it could not be detected in the rocks studied. Higher temperature aluminosilicates (kyanite and sillimanite) have been recognized in a few samples, mainly the garnet granulites (or meta-pelites).

It has already been mentioned that there are very few rocks

with primary granulite facies characteristics in the region studied. Therefore, discussion has been mainly on geochemical changes produced during retrogressive metamorphism. This does not preclude a brief mention of some granulite facies problems, particularly K-Rb distributions, since a few granulite facies minerals (the Pyroxene particularly), have been observed in some rocks in Scourie (see chapter 3, Tables 3.2 & 3.3).

Examination of Tables 7.1 to 7.5 shows that there are significant differences in composition between slightly retrogressed granulite facies rocks in Scourie and their pervasively retrogressed equivalents in Foindle. Apparently, the noticeable changes during retrogression include

- (a) an increase in K content in the granitic rocks and meta-pelites. (potash feldspathization of Mehnert, 1969; pp. 284). This is reflected in lower Na/K ratio in Foindle (see Table 7.1). For the meta-greywackes, there is not much change. Little difference has also been noted in K - content of granulite and amphibolite facies intermediate to acid gneisses in Coll and Tiree of the Lewisian by Drury (1974)
- (b) a decrease in Ca in the granitic gneiss but an increase in the metasediments.
- (c) an increase in Rb for the metasediments. A comparison is not possible for the granitic gneiss from this study
- (d) a marked decrease in Sr concentration in all rocks
- (e) an increase in Ba content in the granitic gneiss and a decrease for the metasediments.

To access these changes more objectively, it is necessary to consider various parameters which are sensitive to geochemical fractionation processes. The ones chosen are K/Rb, Rb/Sr, K/Ba,

and Ba/Rb. Their importance in following igneous fractionation patterns is well known (cf. Taylor, 1965), and they have recently gained prominence in geochemical studies of basement metamorphic complexes (e.g. Lambert & Heier, 1968; Spighinolfi, 1971; Drury, 1974). Bivariate diagrams for K/Rb and K/Ba have been discussed in Chapter 5. Considering the above named four ratios, higher values of K-Rb, K-Sr, Ba-Rb are evident. Other ratios are low (see Table 7.1). Such features are not uncommon in granulite facies rocks. However, comparing values from both areas studied, the K/Rb ratio is reduced from a mean value of 700 in Scourie to 560 in Foindale. Other ratios, except Ba/Rb, are increased. This is attributed to influx of Rb in the fluid phase, thereby reducing the K/Rb ratio. Taylor (1965) notes also that a highly fractionated fluid is expected to have a low K/Rb ratio and high Rb/Sr ratio. The mean value quoted above in Foindale rocks is comparable to the K/Rb ratios for Precambrian terrains (cf. Lewis & Spooner, 1973).

This geochemical evidence suggests, in general, that the incoming fluid must have been enriched in K and Rb and capable of removing Ca, P, Sr, and Ba during the retrogression. Which elements leave or enter a migrating phase of this sort would depend upon the proportions of individual elements able to be stabilized in the minerals being formed under a particular physical regime, and on individual concentration gradients across the fluid/mineral interface (Drury, 1974). Considering micas, for example, and the minerals contributing to their formation during retrogression, such as feldspars and pyroxene, Rb^+ ($1.47\text{\AA}$) enters K^+ ($1.33\text{\AA}$) sites of 12-fold co-ordination in larger ionic radius, and it is therefore enriched in micas. Sr^{2+} ($1.12\text{\AA}$) on the other hand has a smaller ionic radius than K^+ ($1.33\text{\AA}$) and is precluded from substitution in micas. Therefore,

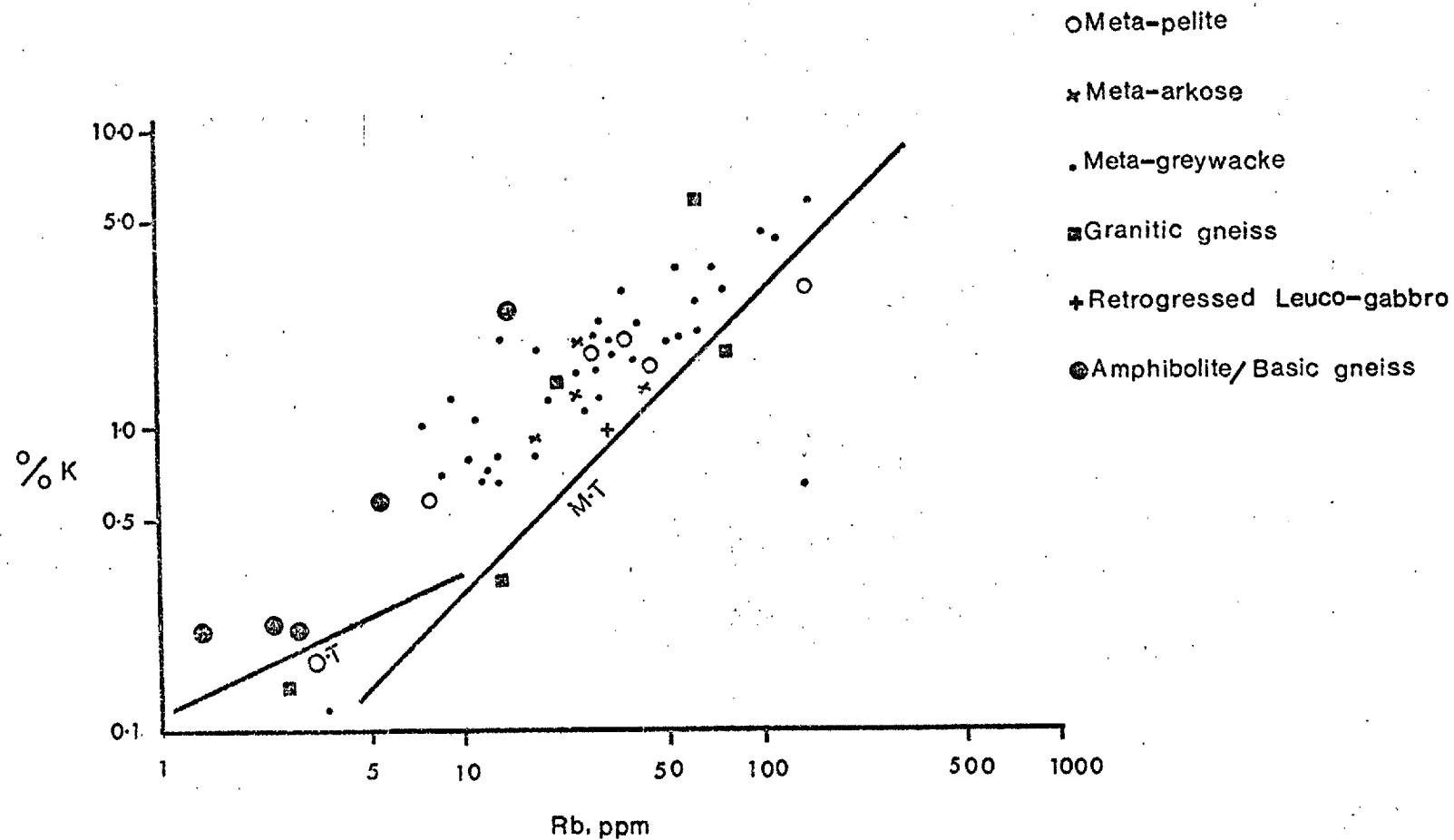


Fig. 7.2 K-Rb plot for the analyzed rocks. The main trend (M.T) and Oceanic Tholeiitic trend (O.T) of Payne & Shaw (1967) are shown. Note that most of the amphibolites (ortho-) follow the oceanic tholeiitic trend.

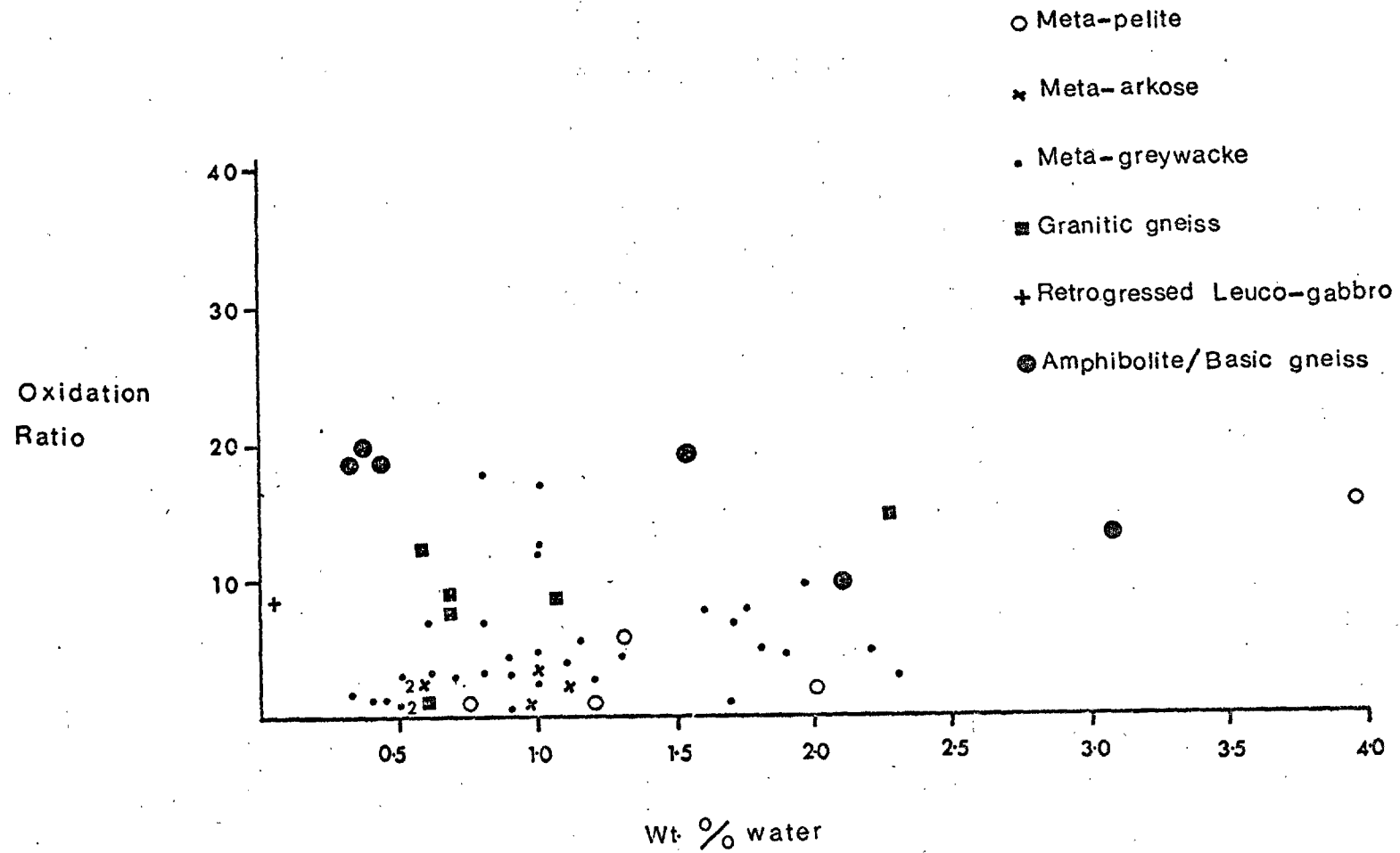


Fig. 7.3 Diagram showing the variation of Oxidation ratio (of Chinner, 1960) with water content in all rock types.

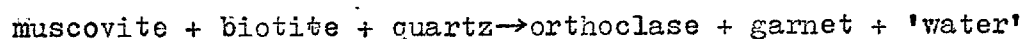
where mica is growing due to retrogression, it will be enrichment in Rb and it will be unable to retain its previous complement of Sr, if in contact with an Rb - rich fluid phase. Hence, its Rb/Sr ratio will increase.

An external source region for a migrating and chemically active hydrous fluid which has caused geochemical and other changes during retrogressive metamorphism must either be in the process of dehydration or contain an abundance of hydrous fluids. In the latter case it could be a large body of granitic magma. This, however, seems unlikely because there is no evidence for any large diapiric granitic intrusion, as in other cratonic terrains, either in the region studied or anywhere in the Lewisian Complex. A dehydrating source region seems more likely. Volatiles containing incompatible elements such as K, Rb and Th could be driven upwards from such a source as intergranular aqueous fluids. Such a possible source region might have consisted of sediments younger than the intrusive bodies which had in some way been downwarped into acid/or overthrust by the older high grade rocks. This sort of situations has been suggested for the major structural, petrographic and geochemical boundary (Ben Stack Line) of Beach & Fyfe (1972). Some part of the region studied, especially the Foindle area, is probably within the Ben Stack Line. The chemically active fluid which has caused geochemical and other changes during retrogression could be due to large of amounts of water moving along shear zones.(Beach, 1974) or coming from the lower crust or upper mantle.

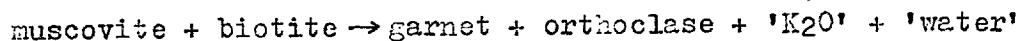
Although the rocks studied are within the Amphibolitised belt of the Lewisian mainland, some granulite facies mineral assemblages have been recognized in a few samples from Scourie (see Chapter 3). A brief mention is now made on the distribution

of K and Rb in the granulites. Many workers have drawn attention to the low Rb content and high K/Rb ratios of the granulite facies rocks (Lambert & Heier, 1968; Heier & Thoresen, 1971; Sighinolfi, 1971; Green et al., 1970; Farney et al., 1972; Drury, 1973; Lewis & Spooner, 1973; Sheraton et al., 1973; Field & Clough, 1976; Kalsbeek, 1976), with the implication that the lower crust is deficient in Rb relative to the upper crust. There is no general agreement as to the cause(s) of the relative Rb depletion in granulites.

One mechanism which could account for the relative depletion of Rb in the granulites facies rocks could be the appearance and growth of almandine garnet, possibly at the expense of biotite. Based on available data, an exact reaction cannot be formulated but a reasonable possibility might be:



This reaction taking place in the presence of an intergranular fluid phase containing alkalis, would produce a decrease in K/Rb ratio in the fluid. This is in consequence of the fact that both micas concentrate Rb relative to K - feldspar, so that as the reaction proceeds to the right with increasing temperature, the fluid phase would become enriched in Rb relative to K. If the fluid were subsequently expelled, the net result would be an increase in the K/Rb ratio of the residual gneiss. The fact that garnet is more abundant in the Scourie rocks than muscovite in the later lower grade equivalents in Foinde suggests that another possible reaction could be:



Since this leads to release of K in excess of available alumina, a net loss of K would be expected along with the increase in the K/Rb ratio. Such observations have been reported by Engel & Engel (1962) who noted a depletion in K₂O along with H₂O and some SiO₂ in the para-gneiss with increasing metamorphic grade.

This is further supported by lower oxidation ratios, water, K_2O and SiO_2 in the metasediments from Scourie (see Tables 7.1 & 7.3). In the light of the available evidence from this study, these reactions though possible, are difficult to validate.

Another explanation for the increased K/Rb ratio in granulite facies rocks is anatectic melting and subsequent upward migration of the melt. Lambert & Heier (1968) suggest that this is the major mechanism responsible for the increase in K/Rb ratio and depletion of granitophile elements which they observe in the high pressure granulite facies rocks of the Australian Shield. This, however, cannot be the explanation based on available data from this work, because much would depend on the nature of fractionation of K and Rb between biotite and melt. If Rb is relatively concentrated in the melt, formation and removal of an anatectic liquid would raise the K/Rb ratio in the residual gneiss, while Rb concentration in the biotite would on the other hand produce a reduction in the K/Rb ratio. Any work to determine the distribution coefficients for K and Rb between biotite and granitic liquid may clarify this point.

It is therefore reasonable to conclude as follows:-

- (1) the fractionation of K and Rb probably occurred during the retrogression that followed the Scourian granulite facies metamorphism.
- (2) K/Rb ratios in Scourie rocks are significantly higher than these in Foindle. This is attributed to a regional depletion K which must have taken place during the granulite facies metamorphism that occurred before the retrogression. Therefore, K/Rb variations in the rocks studied or even in Precambrian granulites (Tarney & Windley, 1977) are not primary igneous trends. The cause of this Rb depletion is an open debate. Because high K/Rb ratios tend to correlate with low K,

Table 7.3. Average major element compositions for meta-greywacke, meta-pelite, and granitic gneiss

Wt.%	META-GREYWACKE		META-PELITE		GRANITIC GNEISS	
	SCOURIE (7)	FOINDLE(27)	SCOURIE (2)	FOINDLE (3)	SCOURIE (1)	FOINDLE (5)
SiO ₂	68.97	67.36	54.31	56.25	64.25	72.86
TiO ₂	0.45	0.51	1.15	0.66	0.61	0.16
Al ₂ O ₃	15.67	15.23	20.33	14.63	14.94	13.58
Fe ₂ O ₃	0.17	0.25	0.10	1.37	0.45	0.18
FeO	3.26	3.72	9.12	11.29	4.47	2.85
MnO	0.07	0.07	0.19	0.19	0.09	0.11
MgO	1.65	1.89	2.53	4.76	2.93	0.91
CaO	2.41	3.52	2.99	3.76	5.51	2.69
Na ₂ O	3.85	3.30	4.13	1.06	4.74	4.30
K ₂ O	2.44	2.40	2.61	3.17	0.74	2.12
P ₂ O ₅	0.07	0.17	0.10	0.18	0.12	0.06
LOI	0.64	1.03	0.89	2.39	1.00	0.90
H ₂ O	0.13	0.08	0.09	0.08	0.08	0.06
Oxidation Ratio	3.87	5.69	0.93	7.79	8.31	9.04
Na/K	1.91	2.42	1.29	0.38	4.74	5.88

Figures in brackets are no. of determinations

Table 7.4. Average XRF trace element composition for meta-greywacke, meta-pelite, and granitic gneiss

p.p.m	META-GREYWACKE		META-PELITE		GRANITIC GNEISS	
	SCOURIE (7)	FOINDLE(27)	SCOURIE (2)	FOINDLE(3)	SCOURIE (1)	FOINDLE (5)
Gr	71	46	303	144	93	12
Ni	28	23	185	48	28	8
Rb	38	43	37	54	-	39
Sr	465	395	395	258	506	273
Y	20	46	31	38	7	40
Zr	257	228	207	150	24	168
Ba	171	1053	891	784	426	640
Th	4	5	15	6	3	5
Zn	47	88	157	174	50	50
Cu	15	32	178	33	14	13
V	63	65	262	137	81	16

Figures in brackets are no. of determinations.

Table 7.5. Average REE compositions for meta-greywacke, meta-pelite, and granitic gneiss

p.p.m.	META-GREYWACKE		META-PELITE		GRANITIC GNEISS	
	SCOURIE (7)	FOINDLE(27)	SCOURIE (2)	FOINDLE (3)	SCOURIE (1)	FOINDLE (5)
La	35.5(7)	33.5(27)	44.9(2)	41.7(3)	15.8	29.0(5)
Ce	47.9(7)	62.0(27)	40.3(2)	51.3(3)	42.2	31.8(5)
Nd	17.9(7)	33.4(26)	34.6(2)	44.3(3)	21.0	21.2(5)
Sm	2.8(7)	5.7(27)	6.1(2)	9.3(3)	3.7	3.9(5)
Eu	1.5(7)	1.8(27)	1.7(2)	1.4(3)	1.1	1.0(5)
Gd	1.4(6)	4.3(24)	6.3(2)	6.2(2)	3.7	1.0(4)
Tb	0.6(7)	0.8(26)	1.2(2)	2.0(3)	0.4	0.9(5)
Ho	1.0(4)	1.0(23)	2.4(1)	1.4(2)	0.4	3.8(2)
Tm	0.7(5)	0.6(12)	1.2(2)	0.6(2)	-	0.8(3)
Yb	2.1(7)	2.5(27)	3.7(2)	4.0(3)	0.8	4.6(3)
La	0.4(5)	0.5(20)	0.4(2)	0.6(3)	0.2	2.0(1)
Σ REE	101.8(7)	147.7(26)	141.6(2)	159.9(3)	89.2	126.1(3)
Ce/La	1.4(7)	1.9(27)	0.9(2)	1.2(3)	2.7(1)	1.1(5)

Figures in brackets are no. of determinations.

and especially with low Rb, it is reasonable to assume that the mechanism responsible is loss of K and Rb, but with preferential loss of the larger Rb ion relative to K. This could be accomplished

- (a) during anatexis where granulites represent some form of residuum (Pyfe, 1973; Kalsbeek, 1976), or
- (b) during expulsion of hydrous fluids when anhydrous high pressure mineral assemblages are developed (Lambert & Heier, 1968; Heier, 1973) or
- (c) due to more extensive leaching by metasomatic fluids at or near granulite facies (Tarney et al. 1972; Drury, 1973; Sheraton et al. 1973; Field & Clough, 1976).

Y values differ widely amongst all rocks studied. However, greater abundance is observed in Foindle rocks (see Table 7.4).

Two reasons can account for this, namely:-

- (a) the greater proportion of garnetiferous rocks in Foindle, and
- (b) as Y shows systematic coherence with Ca, especially for igneous rocks (cf. Lambert & Holland, 1973, 1974), other Ca minerals e.g. Hornblende, apatite, can carry yttrium. These minerals are more abundant in Foindle rocks.

It would seem that retrogression has altered the Ca/Y ratios in the region. Table 7.1 shows that the ratio is reduced from a mean value of 3847 in Scourie to 2635 in Foindle rocks. This view does not therefore favour the idea of Lambert & Holland (op. cit) that metamorphic processes do not seem to alter inherited Ca/Y ratios.

Table 7.5 shows that the REE are more abundant in Foindle rocks than in those from Scourie. Petrographic study in chapter 3, suggests that this is due to a greater proportion of possible REE bearing minerals (garnet, amphibole, epidote, apatite, sphene) in the Foindle rocks. Also, lower Ce/La ratios than the value of 2.0 recorded for high grade members of

the Coll/Tiree Complex (Drury, 1974) are observed in almost all the rocks studied. It is possible that these patterns are due to the effects of a fluid enriched in K, Ba and the rare-earths. Hence, in a highly fractionated fluid, the larger La ions will be enriched relative to Ce ions, and the fluid can impart an abnormally low Ce/La ratio to the rocks it affects.

Roaldset (1975) showed that the distribution of REE can be influenced by such geochemical factors as the mineralogical and geochemical changes during metamorphism. He also stated that during metamorphism and weathering processes, REE may be strongly accumulated by surface adsorption on phyllosilicates (the micas). Data from this study indicate that there is the possibility of an extensive adsorption of REE ions on micaceous minerals either by metamorphism or weathering. However, whatever the process that might have operated it does not seem to have changed the over-all rare-earth element distribution pattern of any particular rock group studied.

The Supracrustal rocks in this region are essentially quartz - plagioclase - muscovite - biotite - garnet - kyanite - iron oxide mineral gneisses with a range in the oxidation ratio. Most of these are found intimately interbedded. Increasing oxidation ratios in these rocks are accompanied by increasing amounts of muscovite and iron-oxides as exemplified in Foindle. Chinner (1960) stated that the confinement of rocks of varying oxidation ratio to well-defined sedimentary bands suggests that the differences in oxygen content are of pre-metamorphic diagenetic origin. He also further supported this view by showing a correlation between oxidation ratio and both the manganese and total iron contents of the rocks. His conclusion is in harmony with recent suggestions that during regional metamorphism rocks in general behave as narrowly defined

units 'closed' to oxygen, the oxygen partial pressure in each unit being determined by the mineral assemblage, and hence the original oxygen content, rather than being externally imposed. It may be possible that the differences in oxygen content (especially in pelitic rocks than can be said to be similar to those from Glen Clova that Chinner (1960) based his conclusion), are of pre-metamorphic or diagenetic origin but this is not supported by lack of correlation between oxidation ratio and both manganese and total iron contents of the rocks studied. Furthermore, these rocks have been shown to contain hydrated mineral assemblages, so that it has not been possible to establish that at least some of the oxygen content might not have been externally imposed. Chinner (op. cit), however, emphasizes that partial oxygen pressures and oxygen contents can be dependent variables, and hence it could equally well be assumed that the varying partial pressures in a vapour phase imposed from outside generated the composition of the minerals, thus producing the varying oxygen contents of the various rock layers. This is essentially the situation realized in the experimental work of Eugster (1959) on the system annite - phlogopitic water, in which biotites are synthesized at partial pressures of oxygen imposed by an external 'buffer' redox pair. In a natural system thus 'open' to oxygen, as probable in the region studied, varying oxygen contents between rock layers would have to be regarded as being of metamorphic (i.e. metasomatic) origin. In such a system, the oxidation ratio is expected to increase with increasing water content as exemplified in fig. 7.3 where the metasediments show this clearly. The rocks in Scourie - Foindle region are also extremely veined by quartz - feldspathic segregations and injections, which imply, however, the existence of a certain degree of metasomatic activity

during the metamorphism.

In summary, rocks in both areas are amphibolitized granulites involving the hydration of essentially anhydrous mineral assemblages. It can therefore be supposed that a thermodynamically open system (retrogressive process) was dominant, in support of Beach (1974). Metasomatism was on a relatively large scale and could be classed as infiltration metasomatism of (Korzhinskii, 1970). The greater enrichment of potassium etc., in the rocks from Foindle suggests that retrogression was more intense there than in Scourie.

7.5 Summary of chronological events

Lack of para-amphibolites in this region is interesting. Table 7.6 is a summary of chronological events in both areas based strictly on field and chemical evidences resulting from this study. According to Read & Watson (1975) the only Lewisian rocks which could represent a post-Scourian cover - succession are those of Loch Maree Group which form a number of narrow belts sandwiched between masses of regenerated gneiss. This series is made up of thin psammites, pelites, graphitic schists, marbles and calc-schists alternating with thick sheets of basic rocks, all showing a metamorphic imprint of low amphibolite or albite-epidote amphibolite facies. The exact age and metamorphic grade cannot be estimated from the available data in this study. These data, however, tend to show that the Supracrustal rocks or metasediments in Scourie - Foindle region were derived from intrusive igneous rocks that are probably similar in composition with the intrusive sheets analyzed. If the 'loose' term 'Scourian' denotes pre-dyke episode, then the rocks in this region are Scourian in age (possibly early Scourian), hence the view of Read & Watson (op. cit) above is also favoured by this work.

Table 7.6. Chronological events in the Scourie-Foindle region

6. Deformation and regional retrogressive metamorphism at slightly low temperature and medium high pressure
5. Intrusion of Scourie dykes (dolerite)
4. Scourian metamorphism, deformation and migmatization
3. Intrusion of basic, ultrabasic and acid sheets
2. Sedimentation (i.e, deposition of Supracrustals)
1. Igneous activity ?

Table 7.7. Average chemical compositions from rocks used for comparison and discussions in this Chapter

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	52.22	50.20	51.01	57.60	49.90	79.20	59.52	64.40	63.20	67.02	50.50	49.80	67.36	49.70	64.93
TiO ₂	0.78	1.38	1.25	1.00	1.51	0.23	0.70	0.62	0.50	0.38	1.26	1.89	0.64	1.00	0.52
Al ₂ O ₃	13.85	13.70	12.45	15.40	17.20	11.10	17.20	15.50	15.30	15.61	13.30	12.70	14.61	14.90	14.63
Fe ₂ O ₃	5.55		3.39	1.82	2.00	0.52		6.54	0.99	1.89	14.30*	16.50*	2.45	2.60	1.36
FeO	4.97	13.70*	6.57	5.96	6.9	0.9	6.80*		4.26	1.05			3.31	8.80	2.75
MnO	0.16	0.22	0.13	0.15	0.17		0.16		0.07	0.04	0.22	0.24	0.06		0.07
MgO	7.26	6.65	10.02	3.75	7.20	0.36	3.42	3.12	3.42	1.46	7.20	6.10	2.86	6.30	2.24
CaO	8.76	8.33	9.13	5.64	11.80	2.16	7.03	2.22	2.76	3.42	9.90	10.20	3.20	9.40	4.12
Na ₂ O	3.09	2.76	2.15	3.70	2.70	3.40	3.68	3.74	3.51	4.97	2.50	2.20	2.52	2.10	3.46
K ₂ O	0.61	0.29	1.35	0.84	0.16	1.58	1.60	2.44	2.09	1.13	0.90	0.40	2.75	0.32	3.10
P ₂ O ₅	0.13	0.14	0.43	0.22	0.12		0.28		0.11	0.15			0.13		0.15
Cr	2.63		3.63	1.03	2.97	4	56			26			1.20	1.75	99
Ni	1.34		1.81	63	97	1	18			40			36	1.00	23
Rb	6	5	35		1.1	15	31	88	58	15			59	10	1.18
Sr	3.92	1.50	10.40	2.63	1.36	90	3.85	4.24	4.57	6.15			4.05	1.65	3.40
Y	18		13	14	43	23	21			3			19	13	
Zr	1.10		1.76	1.60	95	1.25	1.10			2.78			2.88	1.00	4.00
Ba	4.55	70	12.10	2.48	10.5	1.75	2.70		5.06	9.84			11.00	90	10.70
Th	2		5		0.14	1.6	0.70			1.15			7		
Cu															1.10
Zn															1.00
V															
K/Rb	8.30	4.81	3.00		10.50	8.70	4.30	2.20	2.99	6.25			3.87	3.50	2.20
Rb/Sr	0.016	0.033	0.033		0.008	0.17	0.08	0.207	0.127	0.024			0.015	0.06+	0.35
Ba/Rb	75	14	33		10	11	8.7		9.80	65.6			19	9.00+	9
Ba/Sr	1.20	0.45	1.20	0.70	0.08	1.90	0.70		1.20	1.60			2.7	0.55	3.10
K/Sr+	12.92	16.05	10.77	26.51	9.76	145.71	34.49	46.76	37.96	15.23			58	16.10+	75
K/Ba+	11.13	34.39	9.26	28.11	126.48	74.94	49.19		30.65	9.53			20.7	28	24

+ Calculated from data

* Total iron as Fe₂O₃

1. Average of 11 analyses of Basic Hornblende gneisses, Lewisian by Sheraton et al (1973)
2. Average of Archean Tholeiites, Minnesota (Arth & Hanson, 1975)
3. Average of 15 Basic granulites (Wright et al. 1973)
4. Average of 232 Archean Andesites, Canadian Shield (Baragar & Goodwin, 1969)
5. Ocean ridge basalt
6. Island Arch Dacite (values from Jakes & White, 1972)
7. Mean Circum-Pacific andesite (Taylor, 1969)
8. Average of 23 Precambrian greywackes, Wyoming (Conbie, 1967)
9. Early Precambrian greywacke, Minnesota (Arth & Hanson, 1975)
10. Average of Retrogressed Granulite facies grey gneisses, Assnt by Sheraton et al (1973)
11. Average of metadolerites and metabasites in the Lewisian (Holland & Lambert, 1973)
12. Average of metadolerite in Scourie assemblage (Holland & Lambert, op cit)
13. Average of 21 metasedimentary gneisses from Leverburgh belt, S. Harris (Tarney et al. 1972)
14. Average Enriched Archean Tholeiite (EAT) (Condie, 1976)
15. Average composition of the Precambrian Shield (Shaw et al. 1967).

Table 7.8. Average granulites from type localities

	A	B	C	D	E	F	
SiO ₂	60.60	64.00	60.70	64.56	61.22	61.50	+ calculated from data
TiO ₂	0.90	0.54	0.95	0.47	0.54	0.56	* Total iron as Fe ₂ O ₃
Al ₂ O ₃	15.40	16.80	15.83	15.74	15.64	15.50	A Average of Musgrave Range granulites (23 analyses) (Lambert & Heier, 1968)
Fe ₂ O ₃	7.20*	1.50	1.7;	2.53	3.07	6.20*	
FeO		3.50	5.50	2.00	3.57		
MnO	0.20	0.07	0.11	0.06	0.08	0.10	B Average of New Quebec granulites (Eade & Fahrig, 1971)
MgO	3.90	2.20	3.02	2.23	3.36	3.50	
CaO	5.70	3.70	5.28	4.50	5.57	5.90	C Average of Brazillian granulites (62 analyses) (Spighinolfi, 1971)
Na ₂ O	2.80	4.10	3.55	4.60	4.42	4.00	
K ₂ O	2.80	2.60	2.28	1.15	1.03	1.00	D Average for Assynt gneisses (154 analyses) (Sheraton et al. 1973)
P ₂ O ₅	0.20	0.19		0.16	0.18		
H ₂ O+					1.43		E Average for Drumbeg gneisses (254 analyses) (Sheraton et al. op cit)
V							
Cr		88	71	48	88		F 'Best estimate' of Scourie granulite assemblage (Holland & Lambert, 1975).
Ni		22		37	58		
Cu							
Zu							
Rb	70		46	13	11		
Sr	3.40	4.10	5.43	5.65	5.69		
Ba	10.90	7.70	12.17	7.79	7.57		
Th	2.10			1.0	1.0		
Zr	3.10		2.22	1.97	2.02		
Rb/Sr+	0.21		0.09	0.02	0.02		
K/Sr+	63.47	52.63	34.85	16.89	15.02		
K/Ba+	19.80	28.03	15.55	12.25	11.29		
Ba/Rb+	15.57		26.46	59.92	68.82		
Ba/Sr+	3.21	1.88	2.24	1.38	1.33		
K/Rb+	308.29		411.39	734.23	777.18		

Table 7.9. Average grey gneisses from Scotland and Greenland

	A	B	C	D	E	
SiO ₂	69.20	66.70	67.60	67.17	68.15	+ Calculated from data
TiO ₂	0.34	0.34	0.33	0.31	0.39	* Total iron as Fe ₂ O ₃
Al ₂ O ₃	15.90	16.04	15.19	15.79	16.32	A Average of 268 Lewisian grey gneisses, Laxford assemblage (Holland & Lambert, 1973)
Fe ₂ O ₃	3.40*	1.94	1.75	1.68	3.60*	
FeO		1.47	1.28	1.41		
MnO	0.06	0.04	0.05	0.04	0.03	B Average of 39 Lewisian grey gneisses, North of Laxford bridge (Sheraton et al. 1973)
MgO	1.50	1.44	1.28	1.09	1.00	
CaO	3.20	3.18	3.22	3.54	3.98	C Average of 22 Lewisian grey gneisses, Harris and Lewis, Outer Hebrides (Sheraton et al., op cit)
Na ₂ O	4.20	4.90	4.15	4.74	4.45	
K ₂ O	2.30	2.09	2.58	2.10	2.07	D Average of 41 grey gneisses, Angmagsslik, East Greenland (Sheraton, et al., 1973)
P ₂ O ₅		0.14	0.11	0.12	0.20	
Cr		32	30	23	21	E Average of 21 grey gneisses, Fiskenaesset, West Greenland (Tarney, Cheesman & Windley, unpublished data).
Ni		20	18	13	13	
Rb		74	77	44	60	
Sr		580	475	580	460	
Y		7	6	8	17	
Zr		193	182	207	215	
Ba		713	840	1040	673	
Th		11	8	10	4	
K/Rb		234	278	396	625	
Rb/Sr		0.127	0.162	0.076	0.130	
Ba/Rb		9.60	10.90	23.60	11.20	
Ba/Sr		1.20	1.80	1.80	1.50	
K/Sr+		29.91	45.08	30.05	37.35	

Table 7.10. Average chemical compositions of selected gabbroic rocks

	A	B	
SiO ₂	48.01	43.08	
TiO ₂	1.51	0.86	
Al ₂ O ₃	19.11	16.69	* = other constituents including P ₂ O ₅
Fe ₂ O ₃	1.20	4.47	n.d. = not determined
FeO	8.44	9.32	
MnO	n.d	0.21	
MgO	7.72	9.36	A Olivine - gabbro, chilled marginal
CaO	10.33	14.67	facies, Skaergaard, E. Greenland
Na ₂ O	2.34	1.00	(Anal. W.A. Dear), Skaergaard Mem.,
K ₂ O	0.17	0.15	Q.J.G. Soc., 102 (1947 pp. 47)
P ₂ O ₅	0.82*	-	

Trace elements in parts per million

Cr	354	
Ni	88	B Average of 37 analyses of Ultramafic
Sr	40	and mafic gabbros from the gabbroic
		rim of the Anorthosite Complex,
		S. Harris (Witty, 1975).

CIPW Norms

Qz	-
Cu	-
Or	0.88
Ab	9.82
An	40.61
Di	26.09
Hy	-
Ol	16.72
Mt	6.48
Il	1.63

When compared with the entire area of the Lewisian Complex, this region is extremely small, but it certainly throws some light onto the problems of interpretation of the geology of the Complex. Rocks from the region have chemical compositions which are remarkably close to those from other areas of the Lewisian Complex, or even the North Atlantic Craton (see Tables 7.7 - 7.10). This thesis therefore, cannot be concluded without making some suggestions for future workers in the region, near this region, or even within the entire Lewisian Complex. These suggestions are drawn from the outcome of this study. They are:-

(1) The rocks in both areas studied have been compared with similar types in Scourie (typical of granulite facies) and North of Loch Laxford (typical amphibolite facies). Comparison of chemical data with those from North of Loch Laxford shows that Foindle is probably within the amphibolite facies zone, therefore the extent and position of the Ben Stack Line is questionable. The Line could include the Foindle - Panagmore area, i.e it should be further south than its present position. As already mentioned in chapter 1, the two areas where the best examples of the Supracrustal rocks outcrop, were selected and studied for the purposes of this project. Although dykes cross-cut the country - gneisses, the author favours the idea of Beach et al. (1974) that the exact extent of the Ben Stack Line remains a problem and therefore should not be used to separate rocks representing the two facies of metamorphism.

(2) Metasediments have been reported recently from many parts of the Lewisian Complex of the N.W. Highlands of Scotland and could be the oldest rocks in the complex. The rocks have now been recorded in 3 belts - southern, central, and northern, as well as from the Lewisian masses occurring as Caledonian thrust

slices and from the Inner and Outer Hebrides (see Bowes, 1968; Coward *et al.*, 1969; Hopgood, 1965; Tarney *et al.*, 1972), and many others as summarized in Chapter 1. It has been said by many previous workers that the occurrence of metasediments is of significance in interpreting Lewisian history. The author, therefore, joins Chowdhary *et al.* (1971) in suggesting that reliable criteria for stratigraphic correlation are now needed. This can be attempted by confirming the proposed sedimentary origin for the Supracrustal rocks wherever they have been found in the Lewisian Complex by REE or Oxygen isotope studies. REE data can be obtained by any of the available techniques e.g. neutron activation as done in this study or isotope dilution. Using mass spectrometry, (precision better than ± 0.1 per mil in most laboratories (Epstein & Taylor, 1967)), oxygen isotope data can be obtained to investigate the genesis and history of metasediments and other meta-igneous rock types. The $^{18}\text{O}/^{16}\text{O}$ ratios of metamorphic rocks and minerals in some cases reflect the grade of metamorphism (Epstein & Taylor, *op. cit.*). The difference in these values between coexisting minerals commonly appears to be only temperature dependent and may therefore be useful as a geothermometer. It may also be possible to obtain information about the degree of oxygen communication between the rocks and their environment during metamorphism. Confirmation of metasedimentary origin for the Supracrustal rocks can then be followed up by radiometric dating to ascertain their age(s). Stratigraphic correlation can then be done.

(3) Shear zones have been recorded by Beach (1971) on the basis of structural and photo - geologic evidence. Gravity anomalies can help in detecting shear movements when favourable structural conditions exist. As a follow-up of Beach's work, gravity survey of the Scourie - Laxford region, and other areas

in the Lewisian Complex, paying particular attention to responses from shear zones and faults, combined with aeromagnetic data from I.G.S one inch survey, could show that these shear zones are probably related to the interaction between the African and North American plates or European and North American plates during the opening of the Atlantic in the Proterozoic times. Shear zones in north Egypt interpreted from gravity data have been shown in Riad (1977) to be related to the interaction between European and African plates. The geophysical studies can be backed up by detailed geochemical work on these shear zones in order to understand more of their history.

(4) Reliable P & T conditions for retrogression that occurred in the region studied are difficult on the basis of available chemical data. However, the occurrence of sillimanite and kyanite in some of the meta-pelites suggests a temperature of about 600°C and a pressure of about 5 - 8 Kb. Kyanite schists formed at temperatures of 510 - 580°C must have crystallized at pressures of at least 4 - 6 Kb (Newton, 1966) or 10 - 12 Kb (Bell, 1963), depending on whose kyanite - sillimanite transition data are more accurate. Available data do not permit reliable P & T values, but if medium high pressure as suggested on the basis of the $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ ratio, seems reasonable, then Newton's (op. cit) pressure range seems more appropriate to the retrogressive metamorphism that occurred in the region studied, although Bell's values cannot be rejected outright.

CONCLUSIONS

The Supracrustal rocks and the associated igneous bodies between Scourie and Foindle occupy north-easterly and north-westerly trending zones respectively. They are brown-weathering rocks, that look distinctly different from the intrusive igneous sheets (ultramafic to acid). Rocks in the region studied have been affected by regional retrogression after granulite facies metamorphism and deformed at least twice. Effects of retrogression and deformation are more pronounced in Foindle than in Scourie. It is suggested that this retrogression probably increased the abundance of hornblende. First phase of the deformation (F_1) led to the development of synclines and anticlines in both areas. The second phase (F_2) was accompanied by the development of shear zones, lineations, minor folds, joints, boudins and faults. In Scourie, axial trace of F_1 folds strike north-east (same strike as the Scourian foliations). Steeper foliations are common in Foindle area and strike north-west. Axial trace of F_1 folds also strike north-west in Foindle.

Petrographic studies show that a few granulite facies minerals (e.g. the pyroxenes) or textures are still found in some Scourie rocks. However, unaltered pyroxenes were not found; i.e. they were observed replaced either partially or in most areas completely by hornblende (as in Foindle). The Supracrustal rocks are essentially quartz - feldspathic gneisses characterized by the assemblage: quartz + biotite + feldspars + garnet $\pm$ muscovite $\pm$ sillimanite $\pm$ hornblende $\pm$ kyanite $\pm$ zircon $\pm$ rutile. In the meta-igneous rocks, typical assemblage is: hornblende $\pm$ quartz + feldspars $\pm$ garnet $\pm$ biotite. Granular texture is typical of Scourie rocks, while the rocks from Foindle are essentially schistose. This is attributed to the intensive deformation that is more pronounced in Foindle.

Major element data do not provide reliable criteria for distinguishing between metasediments and meta-igneous rocks. However, the data show that 3 magma types appear to have been available for injection into the crust during the evolution of the rocks studied in the region. These are calc-alkalic, alkalic and tholeiitic (low in alkalis). Such magmatic associations today are typical of the volcanic cycle in island arc regions, and the question which now arouses interest is whether or not these rocks investigated originated in an analogous environment.

Generally the rocks studied have rare-earth patterns characterized by

- (a) light rare-earth element enrichment
- (b) slight europium anomaly or in most cases europium depletion
- (c) varying degrees of heavy rare-earth element depletion.

REE distribution patterns have provided a reliable means of confirming the sedimentary origin of the Supracrustal rocks (excepting the amphibolites) and distinguishing between sedimentary and magmatic origins for the rocks studied in Foindle and Scourie. Some of the other chemical parameters as discussed in chapter 6 provide ambiguous discrimination criteria. Occurrences of high REE content in the rocks indicate that the REE are concentrated in minerals like amphibole, epidote, garnet, apatite, or sphene. Also, the REE data tend to show that there could have been the possibility of an extensive adsorption of REE ions on micaceous minerals during metamorphism and weathering processes. Therefore, REE abundances are affected by metamorphism, but the over-all normalized distribution patterns seem to remain relatively unchanged.

The lithologies of these rocks (supracrustals) are closely comparable to those of the Supracrustal assemblage of the Outer Isles described by Coward *et al.* (1969), Watson & Lisle (1973), Moorbath *et al.* (1975), Dickinson (1974) or of the Scourie - Laxford region described by Davies (1974). However, no calc-silicate gneiss or marble has been recognized amongst the rocks studied in this project. The geochemical data also do not differ remarkably from those accepted metasediments from the Leverburgh belt presented in Tarney *et al.* (1972).

The Supracrustal rocks are therefore, metasediments (meta-pelite, meta-greywacke, and meta-arkose) while the amphibolites (ortho-) are meta-basites of low - alkali tholeiitic type. Although the metasediments could be detrital sediments (formed by the weathering and erosion of older rocks) or derived from fragmental volcanic material (pyroclastic), this work does not favour volcanic origin. Available data tend to suggest that the metasediments studied were derived from older igneous rocks, chemically comparable with the intrusive igneous bodies analyzed, by sedimentary processes. This, perhaps, happened in early Scourian or pre - Scourian.

High grade metamorphism produced scapolite, clino-pyroxene, ortho-pyroxene etc. assemblages, and also oxidation of the rocks. Accompanying this was loss of water. During later retrogression and deformation, addition of potassium, water and hydrous mineral phases was enormous at Poindie and Scourie. The classification of the rocks as retrograde metamorphosed rocks (or retrogressed granulites) is mostly based on field association and mineral petrographic features. This classification seems correct and is supported by chemical data. On the basis of available chemical data it is difficult to state reliable P & T conditions for the retrogression. However, the occurrence of sillimanite

and kyanite in some of the meta-pelites suggests a temperature of about 600°C and a pressure of about 5 - 8 Kb.

REFERENCES

- ABBEY, S., 1973. Studies in 'Standard samples' of silicate rocks and minerals. Geol. Surv. Canada, paper 73, 25
- ARTH, J.G., & HANSON, G.N., 1975. Geochemistry and origin of the early Precambrian crust of north eastern Minnesota, Geochim. et Cosmochim. Acta, 39, 325 - 362
- BAILEY, E.B., 1951. Scourie dykes and Laxfordian metamorphism. Geol. Mag. Lxxxv111, No.3
- BALASHOV, Yu. A., 1963. Regularities in the distribution of the rare-earths in the Earth's crust. Geochemistry, 2, 107 - 124
- BALASHOV, Yu.A., RONOY, A.B., MIGDISOV, H.A., & TURANSKAYA, N.V., 1964. The effect of climate and facies environment on the fractionation of the rare earths during sedimentation. Geochem. Intern., 5, 951 - 969
- BARAGAR, W.R.A., & GOODWIN, A.M., 1969. Andesites and Archean volcanism of the Canadian Shield. In McBirney (ed.), Proc. Andesite conf. (1968). Oregon State, Dept. Geology & Mineral Industries Bull, 65, 121 - 142
- BARKER, F., 1964. Reaction between mafic magmas and pelitic schist, Cortlandt, New York. Am. J. Sc., 282, 614 - 634
- BAROOSH, B.C., 1970. Significance of calc-silicate rocks and meta-arkose in the Lewisian Complex, South-east of Scourie. Scott. J. Geol., 6, 221 - 225
- BEACH, A., 1971. The relationship between metamorphic reactions and tectonic structure at Scourie, Sutherland: a study of regeneration. Ph.D Thesis, University of London, Imperial College.

- BEACH, A., 1973. The mineralogy of high temperature shear zones at Scourie, N.W. Scotland. *J. Petrol.*, 14, 23 - 248
- BEACH, A., 1974a. The measurement and significance of displacements on Laxfordian shear zones, north-west Scotland. *Proc. Geol. Ass. Lond.*, 85(1), 13 - 21
- BEACH, A., 1974b. Amphibolitization of Scourian granulites. *Scott. J. Geol.*, 10 (1), 35 - 43
- BEACH, A., COWARD, M.P., & GRAHAM, R.H., 1974. An interpretation of the structural evolution of the Laxford front north-west Scotland. *Scott. J. Geol.*, 2, 297 - 308
- BEACH, A., & FYFE, W.S., 1972. Fluid transport and shear zones at Scourie, Sutherland; Evidence of Overthrusting? *Contr. Mineral. Petrol.*, 36, 175 - 180
- BECKMANN, G., 1976. A paleomagnetic study of part of the Lewisian Complex, north-west Scotland. *Jl. Geol. Lond.*, 132, 45 - 49
- BELL, P.M., 1963. Aluminium silicate system; Experimental deformation of the triple point. *Science*, 139, 1055 - 1056
- BLÜMEL, P., & SCHREYER, W., 1977. Phase relations in pelitic and psammitic gneisses of the sillimanite - potash feldspar and cordierite - potash feldspar zones in the Moldanubicum of the Lan - Bodenmais area, Bavaria. *Jl. Petrol.*, 18(3), 431 - 459
- BOR-MING, J., CHI-YU, S., & MURTHY, V.R., 1974. Trace element geochemistry of Archean volcanic rocks. *Geochim. et Cosmochim. Acta*, 38, 611 - 627
- BOTT, M.H.P., HOLLAND, J.G., STORRY, P.G., & WATTS, A.B., 1972. Geophysical evidence concerning the structure of the Lewisian of Sutherland, N.W. Scotland. *Jl. Geol. Soc. Lond.*, 128, 559 - 612

- BOWDIDGE, C.R., 1969. Petrological studies of Lewisian Basic and Ultrabasic rocks near Scourie, Sutherland Ph.D Thesis, University of Glasgow.
- BOWES, D.R., 1968. An orogenic interpretation of the Lewisian of Scotland. Rept. Int. Geol. Congr. xx111 session, Progue 4, 225 - 236
- BOWES, D.R., BAROOAH, B.C., & KHOURY, J.G., 1971. Original nature of Archean rocks of north-west Scotland. Geol. Soc. Aust. Spec. Publ. 3
- BOWES, D.R., & BATTACHARJEE, C.C., 1967. The metamorphic and migmatitic history of the Lewisian rocks north-west of Loch Tollie, Ross-shire, Scotland. Krystalini kam, 5, 7 - 60
- BOWES, D.R., & GHALY, T.S., 1964. Age relations of Lewisian basic rocks, south of Gairloch, Ross-shire. Geol. Mag., 101, 150 - 160
- BOWES, D.R., HOPGOOD, A.M., & PIDGEON, R.T., 1976. Source of ages of zircon in the Archean quartzite, Rona, Inner Hebrides, Scotland. Geol. Mag., 113 (6), 545 - 552
- BOWES, D.R., & KHOURY, S.G., 1965. Successive periods of basic dyke emplacement in the Lewisian Complex, south of Scourie, Sutherland. Scott. J.G. Geol., 1, 295 - 299
- BREW, D.A., & MUFFER, L.J.P., 1965. Upper Triassic undevitrified volcanic glass from Hound Island, Keku strait, south eastern Alaska. U.S. Geol. Surv. Profess. Paper, 525-c, 38 - 43
- BRIDGEWATER, D., WATSON, J., & WINDLEY, B.F., 1973. The Archean craton of the North Atlantic region. Phil. Trans. Roy. Soc. Land., A273, 493 - 519
- BROWN, G.C., & FYFE, W.S., 1972. The transition from metamorphism to melting: status of the granulite and eclogite facies. xxiv Int. geol. Congr. 2, 27-34

- BUDDINGTON, A.F., & CHAPIN, T., 1929. Geology and mineral deposits of south-eastern Alaska, U.S. Geol. Surv. Bull., 800, 398
- BURNS, D.J., 1966. Chemical and mineralogical changes associated with the Laxfordian metamorphism of dolerite dykes in the Scourie - Loch Laxford area, Sutherland, Scotland. Geol. Mag. 103, 19 - 35
- CAPALDI, G., GASPARINI, P., MOAURO, A., SALVIA, E., & TRAVAGLIONE, O., 1972. Rare-earth abundances in the alkaline volcanic rocks from Campania, south Italy. Earth Planet. Sci. Lett. 17, 247 - 257
- CHAO, E.C.T., & FLEISHER, M., 1960. Abundance of Zirconium in igneous rocks. Rep. Int. Geol. Congr. XXI Session (Norden) 1, 106 - 131
- CHASE, J.W., WINCHESTER, J.W.M & CORYELL, C.D., 1963. Lanthanum, europium and dysprosium distributions in igneous rocks and minerals. J. Geophys. Res., 68, 567 - 575
- CHINNER, G.A., 1960. Pelitic gneisses with varying ferrous/ferric ratios from Glen Clora, Angus, Scotland. Jl. Petrol., 1(2), 178 - 217
- CHOWDHARY, P.K., 1971. Zircon Populations in Lewisian quartzite, gneiss and granite north of Loch Laxford, Sutherland. Geol. Mag. 108(3), 255 - 262
- CHOWDHARY, P.K., DASH, B., & FINDLAY, D., 1971. Metasediments in the Rhinconich group of the Lewisian between Loch Laxford and Durness, Sutherland. Scot. J. Geol., 7, 1 - 9
- CLARK, F.W., 1924. Data of geochemistry. 5th ed. U.S. Geol. Surv. Bull., 770
- CLARK, S.P., PETERMAN, Z.E., & HEIER, K., 1966. Abundances of uranium, thorium, and potassium, in Handbook of physical constants. Geol. Surv. Am - Mem. 97
- CLIFFORD, T.N., 1974. Review of African granulites and related rocks. Spec. Pap. Geol. Soc. Am. 156, 49

- CLOUGH, 1910. In the geology of Glenelg, Lochalsh and S.E. Skye. Mem. Geol. Surv. Scotland, No. 71
- CONDIE, K.C., 1967. Geochemistry of early Precambrian greywackes from Wyoming. *Geochim. et Cosmochim. Acta*, 31, 2135 - 2149
- CONDIE, K.C., 1976. Trace element geochemistry of Archean Greenstone Belts. *Earth Science Reviews*, 12, 393 - 417
- CONDIE, K.C., MACKE, J.E., & REIMER, T.O., 1970. Petrology and geochemistry of early Precambrian greywackes from the Fig Tree Group, South Africa. *Geol. Soc. An. Bull.* 81, 2759 - 2776
- CORYELL, C.D., CHASE, J.W., & WINCHESTER, J.W., 1963. A Procedure for geochemical interpretation of Terrestrial rare-earth abundance patterns. *J. Geophys. Res.*, 68 (2), 559 - 566
- COWARD, M.P., 1969. The structural and metamorphic geology of South Uist, Outer Hebrides. Ph.D Thesis, University of London, Imperial College.
- COWARD, M.P., FRANCIS, P.J., GRAHAM, R.H., MYERS, J.S., & WATSON, J., 1969. Remnants of an early metasedimentary assemblages in the Lewisian complex of the Outer Hebrides. *Proc. Geol. Assoc. Lond.*, 80, 387 - 408
- COWARD, M.P., FRANCIS, P.J., GRAHAM, R.H., & WATSON, J., 1970. Large scale Laxfordian structures of the Outer Hebrides in relation to those of Scottish mainland. *Tectonophys.*, 10, 425 - 435
- GRESSMAN, E.R., 1962. Non detrital siliceous sediments Chapt T in M. Fleischer(ed.), *Data of Geochemistry*. U.S. Geol. Surv. Profess. Papers, 440 - T
- CULLERS, R.L., MEDARIS, L.G., & HASKIN, L.A., 1973. Experimental studies of the distribution of rare-earths as trace elements among silicate minerals and Liquids and water: *Geochim. et Cosmochim. Acta.*, 37, 1499 - 1512

- CURRIE, K.L., 1971. The relation 3 cordierite = 2 garnet + 4 sillimanite + 5 quartz as geological thermometer in the Opinicon Lake region, Ontario. *Contrib. Mineral. Petrol.*, 33, 215 - 226
- DALZIEL, I.W.D., 1963. Zircons from the granitic gneiss of Western Ardgour, Argyll; their bearing on its origin. *Trans. Edinb. geol. Soc.*, 19, 349 - 362
- DASH, B., 1967. The geology of the Lewisian rocks between Strath Dionard and Rhiconich, Sutherland, Scotland. Ph.D Thesis, Glasgow University
- DAVIDSON, C.F., 1943. The Archean rocks of the Rodil District, South Harris, Outer Hebrides. *Trans. Roy. Soc. Edin.* 61, 71 - 112
- DAVIES, F.B., 1974. The evolution of two assemblages of metamorphosed supracrustal and intrusive rocks in the Lewisian Complex. Ph.D Thesis, University of London, Imperial College.
- DAVIES, F.B., 1976. Early Scourian structures in the Scourie - Laxford region and their bearing on the evolution of the Laxford front. *Jl. Geol. Soc. Lond.*, 132, 543 - 554
- DAVIES, F.B., & WATSON, J.V., 1977. Early basic bodies in the type Laxfordian complex, N.W. Scotland and their bearing on its origin. *Jl. Geol. Soc. Lond.*, 133, 123 - 131
- DEARNLEY, R., 1959. Metamorphic petrology and history of the Lewisian rocks of South Harris, Outer Hebrides. Ph.D Thesis, University of Leeds.
- DEARNLEY, R., 1962. An outline of the Lewisian Complex of the Outer Hebrides in relation to that of the Scottish mainland. *Q. Jl. Geol. Soc. Lond.*, 118, 143 - 176
- DEARNLEY, R., 1963. The Lewisian Complex of South Harris. *Q. Jl. Geol. Soc. Lond.* 119, 243 - 312

- DICKINSON, B.B., 1974. The metamorphic evolution of the Leverburgh Supracrustal belt, South Harris, with special reference to textural variations, Ph.D Thesis, University of London, Imperial College.
- DIEBTRICH, R.V., 1960. Banded gneisses. P. Petrol. 1, 99 - 118
- DRURY, S.A., 1973. The geochemistry of Precambrian granulite facies rocks from the Lewisian Complex of Tiree, Inner Hebrides, Scotland. Chem. Geol., 11, 167 - 188
- DRURY, S.A., 1974. Chemical changes during retrogressive metamorphism of Lewisian granulite facies rocks from Collie & Tiree, Scott. J. Geol. 10(3), 237 - 256
- EADE, K.E., & FAHRIG, W.F., 1971. Geochemical evolutionary trends of continental plates - a preliminary Study of the Canadian Shield, Geol. Surv. Can. Bull., 179, 51
- EADE, K.E., FAHRIG, W.F., & MAXWELL, J.A., 1966. Composition of crystalline shield rocks and fractionating effects of regional metamorphism. Nature, 211, 1245 - 1249
- ELLIOT, R.B., & COWAN, D.R., 1966. The petrochemistry of the amphibolites of the Holleindalen Greenstone Group, Jotunheimen, Norway. Norsk Geologisk Tidsskrift 46(3), 309 - 325
- ENGEL, A.E.J., & ENGEL, C.G., 1962. Progressive metamorphism of amphibolite, north-west Adirondacks, New York in Petrologic studies (Buddington volume). Geol. Soc. Amer., 37 - 82
- ENGEL, A.E.J., ENGEL, C.G., & HAVENS, R.G., 1965. Chemical characteristics of Oceanic basalts and the Upper Mantle. Bull. Geol. Soc. Am. 76, 719 - 734
- EPSTEIN, S., & TAYLOR, JR. H.P., 1967. Variations of O^{18}/O^{16} in Minerals and Rocks. In Researches in geochemistry, - vol. 2 Philip H. Abelson (ed.), 29 - 62, John Wiley & Sons, Inc.
- EUGSTER, H.P., 1959. Reduction and Oxidation in metamorphism. In Researches in Geochemistry, 397 - 426, Wiley, New York

- EVANS, B.W., & LEAKE, B.E., 1960. The composition and origin of the striped amphibolites of Connemara, Ireland. *Jl. Petrol.*, 1, 337 - 363
- EVANS, C.R., 1963. The geology of the Lochinver district, Sutherland. D. Phil. Thesis, University of Oxford.
- EVANS, C.R., 1964. Geochronology of the Lewisian basement near Lochinver, Sutherland. (abs.). *Advant. Sci. Lond.* 20, 446
- EVANS, C.R., 1965. Geochronology of the Lewisian near Lochinver, Sutherland. *Nature, London*, 207, 54 - 55
- EVANS, C.R., & LAMBERT, R.St.J., 1974. The Lewisian of Lochinver, the type area for the Inverian metamorphism. *Jl. Geol. Soc. Lond.*, 130, 125 - 150
- EVANS, C.R., & TARNEY, J., 1964. Isotopic ages of Assynt dykes, *Nature, Lond.*, 204, 638 - 641
- EWART, A., TAYLOR, S.R., & CAPP, A.C., 1968. Trace & Minor element geochemistry of the Rhyolitic volcanic rocks, Central North Island, New Zealand. *Contrib. Mineral. & Petrol.*, 18, 76 - 104
- FAHRIG, W.F., & EADE, K.E., 1968. Chemical evolution of the Canadian Shield. *Can. Jl. Earth Sci.*, 5, 1247 - 1252
- FAURE, G., & HURLEY, P.M., 1963. The isotopic composition of strontium in oceanic and continental basalts: application to the origin of igneous rocks. *Jour. Petrol.*, vol. 4 31 - 50
- FERSMAN, A., 1929. Geochemische Migration der Elemente. *Abhandl. Prakt. Geol.* 18, 1 - 116; 19, 1 - 36
- FIELD, D., & CLOUGH, P.W.L., 1976. K/Rb ratios and metasomatism in metabasites from a Precambrian amphibolite - granulite transition zone. *Jl. Geol. Soc. Lond.*, 132, 277 - 288
- FLANAGAN, F.J., 1973. values for international geochemical reference samples. *Geochim-et Cosmochim. Acta*, 37, 1189 - 1200
- FLEISCHER, H., & ALTSCHULER, Z.S., 1969. The relationship of the rare-earth composition of minerals to geological environment. *Geochim. et Cosmochim. Acta*.

- FREY, F.A., HASKIN, L.A., & HASKIN, M.A., 1971. Rare-earth element abundances in some ultramafic rocks. *Jl. Geophys. Res.*, 76 (8), 2057 - 2070
- FYFE, W.S., 1973. The granulite facies, partial melting and the Archean crust. *Phil. Trans. Roy. Soc. Lond.* 273A, 457 - 462
- FYFE, W.S., TURNER, F.J., & VERHOOGEN, J., 1958. Metamorphic reactions and metamorphic facies. *Geol. Soc. Am. Mem.* 73
- GALE, G.H., 1973. Palaeozoic basaltic Komatiite and ocean floor type basalts from north eastern New foundland. *Earth Planet. Sci. Lett.*, 18, 22 - 28
- GARRILOVA, L.K., & TURANSKAYA, R.V., 1958. Distribution of rare-earths in rock forming and accessory minerals of certain granites. *Geochemistry*, 2, 163 - 170
- GAST, P.W., HUBBARD, N.J., & WISEMAN, H., 1970. Chemical composition and petrogenesis of basalts from Tranquility Base. *Proc. Apollo 11 Lunar Sci. Conf.* Levinson, A.A. (ed) vol. 2, 1143 - 1163, Pergamon.
- GHALY, T.S., 1966. The Lewisian geology of the area between Loch Sheidaig and Loch Braigh Horrisdale, Gairloch, Ross-shire. *Scott. J. Geol.*, 2, 282 - 305
- GILLETI, B.J., MOORBATH, S., & LAMBERT, R.St.J., 1961. A geochronological study of the metamorphic complexes of the Scottish highlands. *Q. Jl. Geol. Soc. Lond.*, 117, 233 - 272
- GOMES, C.de.B., SANTINI, P., & SATURA, C.V., 1964. Petrochemistry of a Precambrian amphibolite from the Jarague area, Sau Paulo, Brazil. *J. Geol.*, 72, 664 - 680
- GORDON, G.E., RANDLE, K., GOLES, G.G., CORLISS, J.B., BEESON, M.H., & OXLEY, S.S., 1968. Instrumental activation of standard rocks with high-resolution X-ray detectors.

- GRAHAM, R.H., 1969. A structural analysis of Lewisian rocks in parts of North Uist and South Harris, Outer Hebrides. Ph.D Thesis, University of London, Imperial College
- GREEN, T.H., BRUNFELT, A.O., & HEIER, K.S., 1970. Rare-earth element distribution and K/Rb ratios in granulite, mangerites and Anorthosites, Lofoten - Vesteraalen, Norway. Geochim-et Cosmochim - Acta, 36, 241 - 257
- GREEN, D.H., & RINGWOOD, A.E., 1967a. The genesis of basaltic a magmas. Contrib. Min. Petrol., 15, 103 - 190
- GREEN, D.H., & RINGWOOD, A.E., 1967b. An experimental investigation of the gabbro to eclogite transformation and its petrological implications. Geochim. et Cosmochim. Acta, 31, 767 - 833
- GRIFFIN, W.L., & HEIER, K.S., 1969. Paragenesis of garnet in granulite facies rocks, Lofoten - Vesteraalen, Norway. Contrib. Mineral. Petrol., 23, 89 - 116
- GUNN, B.M., 1965. K/Rb and K/Ba ratios in Antarctic and New Zealand tholeiitic and alkali basalts. J. Geophys. Res. 70, 6241 - 6247
- HAMILTON, D.L., & ANDERSON, G.M., 1967. Effects of water and oxygen pressures on the crystallization of basaltic magmas. In Hess, H.H., & Poldervaart, A., (eds.), Basalts - The Poldervaart Treatise on rocks of basaltic composition. Wiley, Vol.1, 445 - 482
- HARKER, A., 1939. Metamorphism. 2nd edition. London.
- HASKIN, L.A., FREY, F.A., SCHMITT, R.A., & SMITH, R.H., 1965. Meteoritic, Solar, and Terrestrial rare-earth distributions. General Atomic division of General dynamics, GA - 6900, San Diego.
- HASKIN, L.A., FREY, F.A., SCHMITT, R.A., & SMITH, R.H., 1966.

Meteoritic, Solar and Terristial rare-earth distributions. Physics and Chemistry of the Earth, 1, 167 - 330

HASKIN, L.A., & GEHL, M.A., 1962. The rare-earth distribution in sediments. Jl. Geophys. Res., 67, No.6, 2537 - 2541

HASKIN, M.A., & HASKIN, L.A., 1966. Rare-earths in European shales: A Redetermination. Science, 154, No.3748, 507 - 509

HASKIN, L.A., HASKIN, M.A., FREY, F.A., & WILDERMAN, T.R., 1968. Relative and abosolute terrestrial abundances of the rare-earths. In Origin and Distribution of the Elements - (editor, L.H. Ahrens), Pergamon, 889 - 912

HASKIN, L.A., WILDERMAN, T.R., FREY, F.A., COLLINS, K.A., KEEDY, C.R., & HASKIN, M.A., 1966. Rare-earths in sediments. J. Geophys. Res., 71 (24), 6091 - 6105

HASKIN, L.A., WILDERMAN, T.R., & HASKIN, M.A., 1968. An accurate procedure for the Determination of the Rare-earth by Neutron Activation. J. Radioanal. Chem., 1, 337 - 348

HAWKESWORTH, C.J., & O'NIONS, R.K., 1977. The Petrogenesis of some Archean volcanic rocks from Southern Africa. Jl. Petrol., 18, 487 - 520

HEIER, K.S., 1973. Geochemistry of granulite facies rocks and problems of their origin. Phil. Trans. Roy. Soc. Lond. 273A, 429 - 442

HEIR, K.S., & THORESSEN, K., 1971. Geochemistry of high grade metamorphic rocks, Lofoten - Vesteralen, North Norway. Geochim. et Cosmochim. Acta, 35, 89 - 99

HENSEN, B.J., & GREEN, D.H., 1970. Experimental data on coexisting cordierite and garnet under high grade metamorphic conditions. Earth & Planet. Interiors, 3, 431 - 440

- HERMANN, A.G., 1970. Yttrium and lanthanides. In Handbook of geochemistry. 39, Wedepohl, K.H. (ed.), Springer-Verlag
- HOLLAND, J.G., 1966. Geochemical studies in the Lewisian. University of Oxford, D.Phil thesis
- HOLLAND, J.G., LAMBERT, R.St.J., 1969. Structural regimes and metamorphic facies. Tectono physics, 7, 197 - 217
- HOLLAND, J.G., & LAMBERT, R.St.J., 1973. Comparative major element geochemistry of the Lewisian of the mainland of Scotland. In Early Precambrian of Scotland and Related Rocks of Greenland. Park, R.G., & Tarney, J. (eds), University of Keele; Staffordshire.
- HOLLAND, J.G., & LAMBERT, R.St. J., 1975. The chemistry and origin of the Lewisian gneisses of the Scottish mainland: The Scourie & Inver assemblages and sub-crustal accretion. Precambrian Research, 2, 161 - 188
- HOPGOOD, A.M., 1965. Structure and tectonic history of Lewisian gneiss, Isle of Barra. University of St. Andrews Ph.D Thesis
- IRVINE, T.N., & BARAGER, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Can, J. Earth. Sci. 8, 523 - 548
- JAKES, P., & WHITE, A.J.R., 1972. Major and trace element abundances in volcanic rocks of orogenic areas. Bull. Geol. Soc. Am., 83, 29 - 40
- JEHU, T.J., & CRAIG, R.M., 1927. Geology of the Outer Hebrides - Part 4, South Harris. Trans. Roy. Soc. Edin., 35, 457 - 488
- KALSBECK, F., 1976. Metamorphism of Archean rocks of West Greenland. 225 - 235. In the Early History of the Earth, Windley, B.F (ed.). John Wiley

- KALSBECK, F., & ZWART, H.J., 1967. Zircons from some gneisses and granites in the Central and Eastern Pyrenees. *Geologie. Minjub.*, 46, 1 - 10
- KERR, P.F., 1959. *Optical Mineralogy*. McGraw-Hill, London
- KOLJONEN, T., & ROSENBERG, R.J., 1974. Rare-earth elements in granitic rocks. *Lithos.* 7, 249 - 261
- KORZHINSKY, D.S., 1955. *Outline of metasomatic processes*. 2nd ed. Moskwa. Akad.
- KORZHINSKY, D.S., 1970. *Theory of metasomatic zoning*. Translated Jean Angrell, Oxford.
- KRONER, A., 1971. The origin of the southern Namagualanc Gneiss Complex, South Africa, in the light of geochemical data - *Lithos.*, 4, 325 - 344
- LAMBERT, I.B., & HEIER, K.S., 1968. Geochemical investigations of deep-seated rocks in Australian Shield. *Lithos.*, 1, 30 - 53
- LAMBERT, R.St.J., & HOLLAND, J.G., 1973. Ca/Y ratios as petrogenetic indicators. *Trans. Ame. Geophysical Union* 54 (1), p.1225. (Abs.) DSDP Conference on igneous and metamorphic rocks.
- LAMBERT R.St.J., HOLLAND, J.G., 1974. Yttrium geochemistry applied to petrogenesis utilizing calcium - yttrium relationships in minerals and rocks. *Geochim. et Cosmochim. Acta*, 38, 1393 - 1414
- LEAKE, B.E., 1964. Chemical distinction of ortho- and para-amphibolites *J. Petrol.*, 5, 238 - 254
- LEAKE, B.E., 1972. The mineralogical modification of the chemistry of metamorphic rocks. *Geol. Mag.*, 109 (4), 331 - 337
- LEWIS, J.D., & SPOONER, C.M., 1973. K/Rb ratios in Precambrian granulite terranes. *Geochim. et Cosmochim. Acta*, 37, 1111 - 1118

- LEYRELOUP, A., DUPUY, C., & ANDRIAMBOLOLONA, R., 1977. Chemical composition and consequences of the evolution of the French Massif Central Precambrian crust. *Contrib. Mineral. Petrol.* 62, 283 - 300
- LISLE, R.J., 1974. The application of methods of structural analysis to the study of the basement complex of north-west Lewis. Ph.D thesis, University of London, Imperial College.
- MacCULLOCH, 1819. A description of the Western Isles of Scotland. 3 vols. London.
- MacDONALD, G.A., & KATSURA, T., 1964. Chemical composition of Hawaiian lavas. *J. Petrol.*, 5, 82 - 133
- MASON, B., 1966. Principles of Geochemistry. 3rd edition, John Wiley & Sons
- MASON, B.H., 1949. The geology of the Mandamus-Pahau district, North Canterbury. *Trans. Proc. Roy. Soc. New Zealand*, 77, 403 - 428
- MCGREGOR, V.R., 1973. The early Precambrian gneisses of Godthaab district, west Greenland. *Phil. Trans. Roy. Soc. Lond.* 273A, 343 - 358
- MEHNERT, K.R., 1969. Allochemical series of metamorphism (metasomatism). In *Handbook of Geochemistry*. Wedepohl, K.H. (ed.), vol.1, 282 - 286. Springer-Verlag
- MOORBATH, S., O'NIONS, R.K., & PANKHURST, R.J., 1975. The evolution of early Precambrian crustal rocks at Isua, West Greenland - geochemical and isotopic evidence. *Earth Planet Sci. Lett.*, 27, 229 - 239
- MOORBATH, S., WELKE, H., & GALE, N.H., 1969. The significance of lead isotope studies in ancient high grade metamorphic basement complexes, as exemplified by the rocks of north-west Scotland. *Earth Planet. Sci. Lett.*, 6, 245 - 256

- MOORE, J.G., 1966. Rate of palagonitization of submarine basalt adjacent in Hawaii. U.S. Geol. Surv. Profess. Paper 550-D, 163 - 171
- MUECKE, G., 1969. The petrochemistry of the Scourie granulites. D. Phil. thesis, Oxford University
- MYERS, J.S., 1968. The tectonic and metamorphic history of the Lewisian migmatite complex of Western Harris, Outer Hebrides, Scotland. Ph.D thesis, University of London, Imperial College
- MYERS, J.S. 1970. Gneiss types and their significance in the repeatedly deformed and metamorphosed Lewisian Complex of Western Harris, Outer Hebrides. Scott. J. Geol., 6, 186 - 199
- MYERS, J.S., 1971. The late Laxfordian granite - migmatite complex of Western Harris, Outer Hebrides. Scott. J. Geol., 7, 254 - 284
- NAGASAWA, H., 1970. Rare-earth concentrations in zircons and apatites and their host dacites and granites. Earth Planet. Sci. Lett., 9, 359 - 364
- NAGASAWA, H., & SCHNETZLER, C.C., 1971. Partitioning of rare-earth, alkali and alkaline earth elements between phenocrysts and acidic igneous magma. Geochim. et Cosmochim. Acta, 35, 953 - 968
- NAKAMURA, N., & MASUDA, A., 1973. Chondrites with peculiar rare-earth patterns. Earth. Planet. Sci. Lett., 19, 429 - 437
- NANCE, W.B., & TAYLOR, S.R., 1976. Rare-earth element patterns and crustal evolution - 1. Australian post-Archean sedimentary rocks. Geochim. et. Cosmochim. Acta, 40, 1539 - 1551
- NEWTON, R.C., 1966. Kyanite - sillimanite equilibrium at 750 C. Science, 151, 1222 - 1225

- NICHOLLS, E.D., & LORINC, D.H., 1962. The geochemistry of some British Carboniferous sediments. *Geochim. et Cosmochim. Acta*, 26, 187 - 223
- NOCKOLDS, S.R., 1954. Average chemical compositions of some igneous rocks. *Geol. Soc. Ame. Bull.*, 65, 1007 - 1032
- NORIN, R., 1940. Problems concernign the volcanic ash layers of the lower Tertiary of Denmark. *Geol. Foren. Stockholm. Forh.*, 62, 31 - 44
- O'HARA, M.J., 1961a. Petrology of the Scourie dyke, Sutherland. *Mineral. Mag.*, 32, 845 - 865
- O'HARA, M.J., 1961b. Zoned ultrabasic and basic gneiss masses in the early Lewisian metamorphic complex at Scourie. *J. Petrol.*, 2, 248 - 276
- ORVILLE, P.M., 1969. A model for metamorphic differentiation origin of thin layered amphibolites. *Am. Jour. Sci.*, 267, 64 - 86
- OSBORN, E.F., 1959. Role of oxygen pressure in the crystallization and differentiation of basaltic magma. *Amer. J. Sci.* 257, 609 - 647
- PARK, R.G., 1964. The structural history of the Lewisian rocks of Gairloch, Western Ross, Scotland. *Q. Jl. Geol. Soc., Lond.*, 120, 397 - 433
- PARK, R.G., 1966. Nature and origin of Lewisian basic rocks of Gairloch, Ross-shire. *Scott. J. Geol.*, 2, 179 - 199
- PARK, R.G., 1970. Observations on Lewisian chronology. *Scott. J. Geol.* 6, 379 - 399
- PAYNE, J.G., & SHAW, D.M., 1967. K-Rb relations in the Blue Mountain nepheline syenite. *Earth. Planet. Sci. Lett.* 2, 289 - 291

- PEACH, B.N., HORNE, J., GUNN, W., CLOUGH, C.T., & HINXMAN, B.A., 1907. The geological structure of the north-west highlands of Scotland (with petrological notes by J.J.H. Teall). Mem. Geol. Surv. Scotland
- PEARCE, J.A., & CANN, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth Planet. Sci. Lett., 19, 290 - 300
- PEARCE, J.A., GORMAN, B.E., & BIRKETT, T.C., 1975. The TiO_2 - K_2O - P_2O_5 diagram - a method of discriminating between oceanic and non-oceanic basalts. Earth Planet. Sci. Lett., 24, 419 - 426
- PETTIJOHN, F.J., 1957. Sedimentary rocks, 2nd edition, New York, Harper & Brothers.
- PETTIJOHN, F.J., POTTER, P.E., & SIEVER, R., 1973. Sand and Sandstone. Springer-Verlag
- PIPER, D.Z., 1974. Rare-earth elements in the sedimentary cycle: a summary. Chem. Geol., 14, 285 - 304
- POLDERVAART, A., 1950. Statistical studies of zircon as a natural criterion in granitization. Nature Lond., 165, 574 - 575
- POLDERVAART, A., 1955a. Chemistry of the earth's crust, 119 - 144, in Poldervaart, A. (ed.). The crust of the Earth, Geol. Soc. Amer. Spec. Paper, 62
- POLDERVAART, A., 1955b. Zircons in rocks - 1. Sedimentary rocks. Am. J. Sci., 253, 433 - 461
- POLDERVAART, A., 1956. Zircons in rocks - 2. Igneous rocks. Am. Sci., 254, 521 - 544
- POLDERVAART, A., & ECKELMANN, F.D., 1955. Growth phenomena in zircon of autochthonous granites. Bull. Geol. Soc. Am. 66, 947
- POWER, G.M., & PARK, R.G., 1969. A chemical study of five amphibolite

bodies from the Lewisian of Garloch, Ross-shire.
 Scott. J. Geol., 50 (1), 26-41

- PYKE, D.R., NALDRETT, A.J., & ECKSTRAND, O.R., 1973. Archean ultramafic flows in Munro Township, Ontario. Bull. Geol. Soc. Am., 84, 955 - 970
- READ H.H., & WATSON, J., 1975. Introduction to Geology vol.2, Part 1. Early stages of Earth. History, Macmillan.
- REY, P., WAKITA, H., & SCHEMITT, R.A., 1970. Radiochemical neutron activation analysis of Indium, cadmium, Yttrium, and the 14 rare-earth elements in rocks. Anal. Chim. Acta, 51, 163 - 178
- REYNOLDS, S.H., 1916. Further work on the igneous rocks associated with the Carboniferous Limestone of the Bristol District. Q. Jl. Geol. Soc. Lond., 72, 23 - 42
- RIAD, S., 1977. Shear zones in North Egypt interpreted from Gravity data. Geophysics, 42, No.6, 1207 - 1214
- RINGWOOD, A.E., 1955. The principles governing trace element behaviour during magmatic crystallization. Pt 2. The role of complex formation. Geochim. et Cosmochim. Acta, 7, 242 - 254
- RIVALENTI, G., 1976. Geochemistry of meta volcanic amphibolites from South west Greenland. 213 - 223. In the Early History of the Earth. B.F. Windley (ed.), John Wiley & Sons.
- RIVALENTI, G., & ROSSI, A., 1975. Geochemistry of Precambrian amphibolites in the area near Fiskenaesset, South West Greenland. Bull. Soc. Geol. Int. (unpublished)
- ROALDSET, E., 1975. Rare-earth element distributions in some Precambrian rocks and their phyllosilicates, Numedal, Norway. Geochim. et Cosmochim. Acta., 39, 455 - 469
- ROBINSON, D., & LEAKE, B.E., 1975. Sedimentary and igneous trends in

- RONOV, A.B., BALASHOV, Y.A., & MIGDISOV, A.A., 1967. Geochemistry of the rare-earths in the sedimentary cycle. *Geochem. Int.* 4, 1 - 17
- SATYANARAYANA, S.M., HAQVI, V., DIVAKARA, R., & HUSSAIN, S.M., 1974. Geochemistry of Archean amphibolites from Karnataka state, Peninsular India. *Chem. Geol.*, 14, 305 - 315
- SCHOFIELD, J.C., 1951. Distribution of Lower Oligocene volcanics in New Zealand. *New Zealand J. Sci. Tech. Sec. B.*, 33, 201 - 217
- SCHWARCZ, H.P., 1969. Pre-cretaceous sedimentation and metamorphism in the Winchester area, Northern Peninsular Ranges, California. *Geol. Soc. Amer. Spec. Paper*, 100, 63
- SHAW, D.M., 1956. Trace elements in pelitic rocks, Part 3. *Geol. Soc. Amer. Bull.*, 67, 919 - 934
- SHAW, D.M., 1968. A review of K-Rb fractionation trends by covariance analysis. *Geochim. et Cosmochim. Acta*, 2, 573 - 603
- SHAW, D.M., 1972. The origin of the Apsley Gneiss, Ontario, Can. *J. Earth. Sci.*, 9, 18 - 35
- SHAW, D.M., & KUDO, A.M., 1965. A test of the discriminant function in the Amphibolite problem. *Min. Mag.*, 34, 423 - 435
- SHAW, D.M., REILLY, G.A., MUYSSON, J.R., PATTENDEN, G.E., & CAMPBELL, F.E., 1967. An estimate of the chemical composition of the Canadian Precambrian Shield. *Can. J. Earth. Sci.*, 5, 829 - 853
- SHERATON, J.W., 1969. The Lewisian geology of the Drumbeg area, N.W. Highlands of Scotland. Ph.D Thesis, University of Birmingham.

- SHERATON, J.W., 1970. The origin of the Lewisian of N.W. Scotland with particular reference to the Drumbeg area, Sutherland. *Earth Planet. Sci. Lett.*, 8, 301 - 310
- SHERATON, J.W., SKINNER, A.C., & TARNEY, J., 1973. The geochemistry of the Scourian gneisses of the Assynt district. In *Early Precambrian of Scotland and related rocks of Greenland*. R.G. Park, & J. Tarney (eds.), University of Keele, 13 - 30
- SIGHINOLFI, G.P., 1969. K-Rb ratio in high grade metamorphism: A confirmation of hypothesis of a continental crustal evolution. *Contr. Miner. Petrol.*, 21, 346 - 356
- SIGHINOLFI, G.P., 1971. Investigations into deep crustal levels: Fractionating effects and geochemical trends related to high - grade metamorphism. *Geochim. et Cosmochim. Acta*, 35, 1005 - 1021
- SILVER, L.T., & LUMBERS, S.B., 1965. Geochronologic studies in the Bancroft - Madoc area of the Greenville Province, Ontario, Canada (Abstr.), *Geol. Soc. Am. Spec. Paper*, 87, 157
- SKINNER, A.C., 1970. Geochemical studies on the Lewisian of N.W. Scotland and comparable rocks of East Greenland. Ph.D Thesis, University of Birmingham
- SNAVELY, P.D., & WAGER, H.C., 1964. Geologic sketch of North western Oregon, U.S. *Geol. Surv. Bull.* 1181-M, 17
- SPENCER, D.W., 1966. Factors affecting element distributions in a silurian graptolite band. *Chem. Geol.*, 1, 221 - 249
- SPRY, A., 1974. *Metamorphic textures*. Pergamon
- STARK, J.T., & HAY, R.L., 1963. Geology and petrography of volcanic rocks of the Truk Islands, East Caroline

Islands, U.S. Geol. Surv. Profess. Paper, 49, 41

SUTTON, J., & WATSON, J., 1951. The Pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the North-west Highlands, and its bearing on the chronological classification of the Lewisian.

Jl. Geol. Soc. Lond., 106, 241 - 307

SUTTON, J., & WATSON, J., 1961. Further observations in the margin of the Laxfordian Complex of the Lewisian near Laxford, Sutherland. Trans. Roy. Soc. Edin. Vol. Lxv, No.5, 89 - 106

TARNEY, J., 1963. Assynt dykes and their metamorphism. Nature, Lond. 199, 672 - 674

TARNEY, J., SKINNER, A.C., & SHERATON, J.W., 1972. A geochemical comparison of major Archean gneiss units from N.W. Scotland and E. Greenland. Proc. 24th Intl. Geol. Congr. Montreal. 1, 162 - 174

TARNEY, J., & WINDLEY, B.F., 1977. Chemistry, thermal gradients and evolution of the lower continental crust. Jl. Geol. Soc. Lond., 134, 153 - 172

- TAYLOR, S.R., 1965. The application of trace element data to problems in geology. *Phys. Chem. Earth*, 6, 133 - 213
- TAYLOR, S.R., 1969. Trace element chemistry of andesites and associated calc-alkaline rocks. *Bull. Dept. Geol. Min. Resources, State of Oregon*, 65, 43 - 53
- TAYLOR, S.R., EWART, A., & CAPP, A.C., 1968. Leuco-granites and rhyolites: Trace element evidence for fractional crystallization and partial melting. *Lithos.*, 1, 179 - 186
- TEALL, J.J.H., 1885. Metamorphism of dolerite into hornblende schist. *Q.J.G.S.*, LI, 132
- TOWELL, D.G., WINCHESTER, J.W., & SPIRIN, R.V., 1965. Rare-earth distributions in some rocks and associated minerals of the batholith of southern California. *J. Geophys. Res.*, 70, 3485 - 3496
- VAN DE KAMP, P.C., 1968. Geochemistry and origin of metasediments in the Haliburton-Madoc area, south-eastern Ontario. *Can. J. Earth. Sci.* 5 (6), 1337 - 1372
- VAN DE KAMP, P.C., 1970. Green beds of the Scottish Dalradian series: Geochemistry, origin, and metamorphism of mafic sediments. *Jl. Geol.*, 78, 281 - 303
- VAN DE KAMP, P.C., LEAKE, B.E., & SENIOR, A., 1976. The petrography and geochemistry of some Californian arkoses, with application of identifying gneisses of metasedimentary origin. *Jl. Geol.*, 84, 195 - 212

- VILJOEN, M.J., & VILJOEN, R.P., 1969a. An introduction to the geology of the Barberton granite - greenstone terrain. Geol. Soc. South Africa. Sp. Publ. 2, 9 - 28
- VILJOEN, M.J., & VILJOEN, R.P., 1969b. The geology and geochemistry of the lower ultramafic unit of the Onverwacht Group and a proposed new class of igneous rocks. Geol. Soc. South Africa Sp. Publ., 2, 55 - 85
- VILJOEN, M.J., & VILJOEN, R.P., 1969c. The geochemical evolution of the granitic rocks of the Barberton region. Geol. Soc. South Africa Sp. Publ., 2, 189 - 219
- VINOGRADOV, T.W., & RONO, A.B., 1956. Composition of the sedimentary rocks of the Russian platform in relation to the history of its tectonic movements. Geochemistry (U.S.S.R). English Translated, 6, 533
- WAGER, L.R., & MITCHELL, R.L., 1951. The distribution of trace elements during strong fractionation of basic magma - a further study of the Skae gaard intrusion, East Greenland. Geochim. et Cosmochim. Acta, 1, 129 - 208
- WATSON, J., 1949. The geology of the Lewisian of the Scourie area. Ph.D Thesis, University of London, Imperial College.
- WATSON, J., 1965. LEWISIAN. In Craig, G.Y (ed.). The Geology of Scotland, Oliver & Boyd, Edinburgh, 49 - 77
- WATSON, J., 1969. The Precambrian gneiss complex of Ness, Lewisian relation to the effects of Laxfordian regeneration. Scott. J. Geol., 5, 269 - 285
- WATSON, J., & LISLE, R.J., 1973. The Pre-Laxfordian Complex of the Outer Hebrides. In early Precambrian of Scotland and related rocks of Greenland. Park, R.G., & Tarney, J., (eds.), University of Keele.

- WEDEPOHL, K.H., 1969. Composition and abundance of common sedimentary rocks. In Wedepohl, K.H. (ed.), Hand book of Geochemistry, 1, Springer-Verlag
- WESTBROOK, G.K., 1972. Structures and metamorphism of the Lewisian of East Tiree, Inner Hebrides. *Scott. J. Geol.*, 8, 13 - 30
- WHITE, A.J.R., 1966. Genesis of migmatites from the Palmer Region of South Australia. *Chem. Geol.*, 1, 165 - 200
- WHITTEN, D.G.A., & BROOKS, J.R.V., 1972. The Penguin Dictionary of Geology. Penguin.
- WILCOX, R.E., & POLDERVAART, A., 1958. Meta-dolerite dike swarm in Baskersille - Roam Mountain area, North Carolina. *Geol. Soc. Am. Bull.*, 69, 1323 - 1368
- WILDERMAN, T.R., & CONDIE, K.C., 1973. Rare-earths in Archean greywackes from Wyoming and from the Fig Tree Group, South Africa. *Geochim. et Cosmochim. Acta*, 37, 439 - 453
- WILDERMAN, T.R., & HASKIN, L.A., 1973. Rare-earths in Precambrian sediments. *Geochim. et Cosmochim. Acta*, 37, 419 - 438
- WILLIAMS, D.A.C., 1972. Archean ultramafic, mafic, and associated rocks, Mt. Monger, Western Australia. *J. Geol. Soc. Australia*, 19, 163 - 188
- WILSON, J.R., & LEAKE, B.E., 1972. The petrochemistry of the epidiorites of the Tayvallich peninsula, North Knapdale, Argyllshire. *Scott. J. Geol.*, 8, 215 - 252
- WINKLER, H.G.F., 1967. Petrogenesis of Metamorphic rocks. 2nd edition. Springer-Verlag. Berlin.
- WITTY, G.J., 1975. The geochemistry of the Roneval Anorthosite, South Harris, Scotland. Ph.D thesis, University of London, Imperial College.

WRIGHT, A.E., TARNEY, J., PALMER, K.F., MOORLOCK, B.S.P., &

SKINNER, A.C., 1973. The geology of the
Angmagssalik area, East Greenland and possible
relationships with the Lewisian of Scotland: In
Early Precambrian of Scotland and related rocks
of Greenland, Park, R.G., & Tarney, J., (eds.),
University of Keele, Staffordshire.

ABBREVIATIONS.General

REE	Rare - earth element
secs	Seconds
μ g	micrograms
Cm	centimetre
m	metre
Km	kilometre
My	million years
Ma	million years ago

Sampling

LNB	Loch Nam Brac
LNS	Loch North of Scourie

Petrography

opx	Orthopyroxene
plag	Plagioclase
biot	Biotite
qtz	Quartz
ap	Apatite
epid	Epidote
zir	Zircon
rut	Rutile
hbl	Hornblende
cal	Calcite
haem	Haematite
il	Ilmenite
ky	Kyanite
cor	Corundum
mus	Muscovite

sph Sphene

str Staurolite

chl Chlorite

trem Tremolite

gar Garnet

Anth Anthophyllite

Kfsp Potash feldspar

pyx Pyroxene

Other symbols or abbreviations used in this thesis are conventional.

ANALYTICAL METHODS & DATA

Chemical data presented in this thesis have been determined using 3 methods:

- (a) Wet chemical techniques for Na_2O and FeO
- (b) X-ray fluorescence techniques with Philips 1212 automatic spectrometer for major element oxides (SiO_2 , TiO_2 , Fe_2O_3 , MnO , MgO , CaO , K_2O , P_2O_5) as wt. %, and trace element (Cr, Ni, Cu, Zn, Zr, Rb, Sr, Th, Y, Ba, V) compositions in parts per million.
- (c) Instrumental neutron activation analysis (INAA) technique for the Rare-earth element (La, Ce, Nd, Sm, Eu, Gd, Tb, Ho, Tm, Yb, Lu) compositions in parts per million also.

Only what are considered to be vital points used in obtaining results are mentioned here. Details of sample preparation and analytical procedures for XRF and Wet Chemical techniques are available in the Department of Geology, Royal School of Mines. Procedure for the use of a nuclear reactor in the INAA are available at the University of London Reactor Centre, Ascot.

(a) Wet Chemical Analysis

All analyses were done using ignited rock powder. As a prerequisite for the XRF machine run, Na_2O and FeO determinations were made using flame photometry and titration with potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) solution respectively. Results for standards used to determine accuracy are represented in Table A.1 (1 & 2).

(b) X-ray fluorescence Analysis

The XRF technique is based on the Calibration method and relationship between the count rate in counts per second and the concentration of the element. All samples analysed were ignited rock powder. For major element analyses, fused glass beads were ground down to approximately 200 mesh in 'Tema' mill, mixed with

polyvinyl alcohol solution, and then pressed into discs ready for running on the machine. For trace element analyses, ignited rock powder mixed with polyvinyl alcohol (PVA) solution was pressed into a disc with baric acid backing. Raw count data on both types of disc were processed using the College computers to obtain major and trace elements compositions.

Computer programs used in processing all XRF data are as follows:

Major element determination - 'START', 'PJKE', 'MW'

Trace element determination - 'BTRANS', 'NUTRACE'.

Program 'AGNORM' produced the CIPW Norms. Niggli values were determined with the University of London Computer Centre (ULCC) program 'BEDNORM'.

Calibration Line data for the major element chemical data for the samples shown in Appendix B and Appendix C are given in Appendix A (Tables A.2 to A.10). These are used to check the accuracy of the data used in this work. For purposes of precision, standards were run in duplicate (hence, last digit of 3), or one standard was analysed twice (hence last digit of 1) or three times (last digit of 2 in the analytical number). For the same purpose, all samples were run in duplicate. Most major element compositions are therefore averages of duplicate results.

In most cases, there was obvious magnesium interference and this affected the results. Also for the same element, most standards did not calibrate well between ultrabasic and basic rocks. Hence, sometimes, SiO₂ calibration or magnesium calibration split was done during the data processing (e.g Tables A.7 (1) and A.7 (2)). As a result, better totals, better figures of merit, and most important, acceptable average absolute errors and average relative errors were obtained.

Also, in the major element analyses, some standards were run as unknown along with the rock samples. The results are presented with the equivalent recommended values in Tables A.11.

The quality of the trace element data can be assessed by an inspection of the Standard's data in Table A.12.

(c) INAA

Rare-earth element compositions were determined by instrumental neutron activation analyses using Gamma-ray spectroscopy. Approximately 0.1 gm of each rock powder (ground to 200 mesh) was sealed in a small polythene capsule. Each polythene core - tube containing a maximum of 11 of these capsules, was later sealed by soldering. The arrangement of the capsules in each core - tube was noted. The first and the last capsules in every core - tube contained an equivalent quantity (i.e 0.1 gm) of the elemental standard. The core - tubes were then irradiated and allowed to cool for a few days before counting was done. The irradiated capsules were brought out of the core - tubes and placed on an automatic sample changer and counting done through the link control system using the conditions summarized in Table A.1 (Appendix 3).

REE concentrations in ppm were calculated with the values for multi-elemental standards shown in Table A.2 (Appendix 3), using the following formula :-

$$\text{Results (ppm)} = \frac{\text{Sample integral counts}}{\text{Elemental Standard equivalent counts for sample}} \times \frac{\text{wt. of elemental Standard (Hg)}}{\text{wt. of sample (gm)}}$$

where sample integral counts = integral counts for the sample given as printout for the region of interest set up in the control unit. These values are dependent on conditions in Table A.1 (Appendix 3).

wt. of sample = 0.1 gm approx. for the whole analysis.

In order to determine the elemental standard equivalent integral counts for the sample, the arrangement of the capsules containing the irradiated sample powders in the core - tubes must be known.

For example, the standard integral count, Std (1) can be calculated from

$$\text{Std (1)} = \frac{\text{st (1)} + \text{St (2)} - \text{St (1)}}{10}$$

when St (1) = integral counts for elemental standard in position 1 of a core tube

St (2) = integral counts for elemental standard in position 11 of the same core tube.

10 = total no. of spaces between one capsules and another in the core - tube.

The value of St (1) is now spread over the integral counts for samples contained in the capsule 2 to 9 of some core tube, in order to obtain the elemental standard equivalent integral counts for them. This is the correction due to flux variation. Since short counting times were used, decay correction was not essential.

For a check on accuracy, BCR - 1 standard was also analysed in duplicate as an unknown. No.6 of Table A.3 (Appendix 3) gives the average data for BCR - 1 obtained for this study compared with similar determinations by other previous workers. The REE data for rock samples studied are shown in Appendix 3 (B & C).

APPENDIX

II

XRF DATA

A - STANDARDS'

DATA

Table A.1 standard Na_2O & FeO values (Wet Chemical Analyses)

(1) <u>FeO</u>		
Standard	Recommended value (wt. %)	Value, this work (wt. %)
91 (Phonolite)	1.41	1.41
2003 (Gabbro)	7.23	7.01
2005 (Russian granite)	2.18	2.16
NIM-N (Norite)	7.49	7.49
NIM-D (Dunite)	14.62	14.60
(2) <u>Na₂O</u>		
Standard	Recommended value (wt. %)	Value, this work (wt. %)
91 (Phonolite)	7.28	7.24
NIM-G (Granite)	3.36	3.37

Table A.2 SiO₂ Calibration Line - All concentration data on volatile free (Ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error percent	Corrected c.p.s.
9460	NIM-D	38.57	38.57	-0.00	-0.00	4948.6
9463	NIM-D	38.57	38.57	-0.05	-0.13	4955.2
9410	NIM-P	50.86	50.73	-0.13	0.25	6509.3
9413	NIM-P	50.86	50.75	0.11	0.22	6511.4
9430	NIM-N	52.48	52.99	-0.50	-0.96	6798.5
9433	NIM-N	52.48	52.91	-0.43	-0.82	6789.1
9440	NIM-L	53.98	52.93	1.05	1.95	6790.8
9443	NIM-L	53.98	52.99	0.98	1.82	6799.4
9270	BCR	54.84	54.92	-0.07	-0.13	7045.8
9273	BCR	54.84	55.10	-0.26	-0.48	7069.9
9470	PCC	44.03	43.44	0.59	1.34	5574.1
9473	PCC	44.03	43.84	0.19	0.43	5625.4
9290	DTS	40.65	40.44	0.21	0.53	5188.6
9293	DTS	40.65	40.75	-0.09	-0.23	5228.2
9260	W-1	52.66	52.99	-0.334	-0.64	6799.1
9261	W-1	52.66	53.20	-0.54	-1.03	6825.7
9250	AGV	60.16	60.63	-0.47	-0.77	7778.7
9253	AGV	60.16	60.41	-0.25	-0.41	7750.9
9450	NIM-S	63.68	64.44	-0.76	-1.20	8267.9
9453	NIM-S	63.52	64.52	-0.85	-1.33	8278.3
9240	GSP	68.01	68.37	-0.36	-0.52	8771.7
9243	GSP	68.01	68.20	-0.19	-0.27	8749.8
9210	G-2	69.68	69.56	0.12	0.17	8924.6
9213	G-2	69.68	69.86	-0.18	-0.26	8963.0
9200	G-1	72.94	72.31	0.64	0.88	9276.8
9201	G-1	72.44	73.18	-0.23	-0.32	9388.8
9420	NIM-G	75.99	75.23	0.77	1.01	9651.7
9423	NIM-G	75.99	75.31	0.69	0.90	9662.2

Figure of merit = 0.69
 Average Absolute error = 0.395
 Average Relative error = 0.63
 Slope of Calibration Line = 0.77942 E-02

Table A.3 TiO₂ Calibration Line - All concentration data on volatile free (Ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	0.02	0.02	-0.00	-3.23	77.8
9463	NIM-D	0.02	0.02	-0.00	-3.32	77.9
9410	NIM-P	0.20	0.19	-0.01	5.08	711.9
9413	NIM-P	0.20	0.19	0.01	4.65	715.1
9430	NIM-N	0.20	0.19	0.01	2.94	727.9
9433	NIM-N	0.20	0.19	0.01	4.24	718.2
9440	NIM-L	0.50	0.50	0.01	1.33	1866.7
9443	NIM-L	0.50	0.50	0.01	1.31	1867.1
9270	BCR	2.22	2.23	-0.01	-0.28	8389.9
9273	BCR	2.22	2.23	-0.01	-0.44	8403.7
9470	PCC	0.01	0.01	0.00	0.03	37.7
9473	PCC	0.01	0.01	-0.00	-1.31	38.2
9290	DTS	0.01	0.01	0.00	15.29	31.9
9293	DTS	0.01	0.01	0.00	10.24	33.8
9260	W-1	1.07	1.08	-0.01	-0.71	4057.6
9261	W-1	1.07	1.08	-0.01	-0.88	4064.1
9250	AGV	1.06	1.06	0.00	0.15	3981.2
9253	AGV	1.06	1.05	0.01	0.44	3969.7
9450	NIM-S	0.05	0.05	0.01	1.83	185.0
9453	NIM-S	0.05	0.05	0.00	5.13	178.8
9240	GSP	0.67	0.66	0.01	1.85	2467.2
9243	GSP	0.67	0.66	0.01	0.95	2489.8
9210	G-2	0.50	0.49	0.02	3.37	1835.4
9213	G-2	0.50	0.48	0.02	4.83	1807.6
9200	G-1	0.26	0.26	0.00	0.93	974.5
9201	G-1	0.26	0.26	0.00	0.49	978.8
9420	NIM-G	0.09	0.09	-0.00	-4.82	355.5
9423	NIM-G	0.09	0.09	-0.00	-3.76	351.9

Figure of merit = 1.20

Average Absolute error = 0.006

Average Relative error = 3.00

Slope of Calibration Line = 0.2653 E-03

Table A.4 Al_2O_3 Calibration Line - All concentration data on volatile free (Ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	0.26	0.38	-0.12	-47.63	41.5
9463	NIM-D	0.26	0.38	-0.13	-49.41	42.0
9410	NIM-P	4.24	4.19	0.05	1.17	458.2
9413	NIM-P	4.24	4.18	0.07	1.62	456.1
9430	NIM-N	16.42	16.23	0.19	1.15	1773.0
9433	NIM-N	16.42	16.34	0.07	0.45	1785.0
9440	NIM-L	13.91	13.70	0.21	1.50	1497.0
9443	NIM-L	13.91	13.82	0.09	0.66	1509.7
9270	BCR	13.68	13.58	0.09	0.68	1484.1
9273	BCR	13.68	13.71	-0.03	-0.23	1497.8
9470	PCC	0.76	0.74	0.03	3.29	80.6
9473	PCC	0.76	0.74	0.03	3.33	80.6
9290	DTS	0.29	0.26	0.03	10.96	28.2
9293	DTS	0.29	0.29	0.00	0.16	31.6
9260	W-1	14.85	15.01	-0.16	-1.07	1640.0
9261	W-1	14.85	15.12	-0.27	-1.81	1651.9
9250	AGV	17.35	17.26	0.09	0.52	1885.4
9253	AGV	17.35	17.37	-0.02	-0.12	1897.5
9450	NIM-S	17.20	17.31	-0.12	-0.68	1891.6
9453	NIM-S	17.20	17.49	-0.30	-1.73	1911.2
9240	GSP	15.35	14.99	0.36	2.35	1637.4
9243	GSP	15.35	15.18	0.17	1.09	1658.5
9210	G-2	15.46	15.36	0.10	0.66	1677.6
9213	G-2	15.46	15.36	-0.00	-0.02	1689.1
9200	G-1	14.10	14.31	-0.21	-1.50	1563.4
9201	G-1	14.10	14.43	-0.33	-2.36	1576.8
9420	NIM-G	12.17	12.12	0.05	0.41	1324.3
9223	NIM-G	12.17	12.18	-0.01	-0.09	1331.0

Figure of merit = 1.07

Average Absolute Error = 0.12

Average Relative Error = 4.88

Slope of Calibration Line = 0.9153 E-02

Table A.5 Fe_2O_3 Calibration Line - All concentration data on volatile free (Ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	17.03	17.18	-0.15	-0.88	23373.9
9463	NIM-D	17.03	17.30	-0.26	-1.53	23525.4
9410	NIM-P	12.81	12.43	0.38	2.99	16906.1
9413	NIM-P	12.81	12.47	0.34	2.68	16961.0
9430	NIM-N	8.98	8.98	-0.00	-0.03	12215.5
9433	NIM-N	8.98	9.13	-0.15	-1.69	12418.5
9440	NIM-L	10.21	10.19	0.01	0.11	13866.0
9443	NIM-L	10.21	10.23	-0.02	-0.19	13908.1
9270	BCR	13.54	13.44	0.18	1.34	18280.2
9273	BCR	13.54	13.58	0.04	0.29	18473.4
9470	PCC	8.68	8.80	-0.11	-1.31	11966.0
9473	PCC	8.68	8.81	-0.14	-1.56	11994.7
9290	DTS	8.65	8.79	-0.15	-1.69	11958.4
9293	DTS	8.65	8.90	-0.25	-2.93	12104.2
9260	W-1	11.18	11.08	0.10	0.89	15069.4
9261	W-1	11.18	11.23	-0.06	-0.49	15279.7
9250	AGV	6.90	6.83	0.07	1.07	9283.6
9253	AGV	6.90	6.86	0.04	0.51	9336.7
9450	NIM-S	1.44	1.44	0.00	0.01	1962.7
9453	NIM-S	1.44	1.43	0.02	1.06	1942.0
9240	GSP	4.38	4.32	0.06	1.45	5872.7
9243	GSP	4.38	4.32	0.06	1.45	5873.8
9210	G-2	2.69	2.69	0.00	0.15	3655.1
9213	G-2	2.69	2.68	0.01	0.54	3640.7
9200	G-1	1.95	1.96	-0.01	-0.39	2661.4
9201	G-1	1.95	1.96	-0.01	-0.29	2658.8
9420	NIM-G	1.97	1.98	-0.12	-0.78	2697.7
9423	NIM-G	1.97	1.99	0.02	-1.23	2709.9

Figure of merit = 1.21

Average Absolute Error = 0.10

Average Relative Error = 1.05

Slope of Calibration Line = 0.7352 E-03

Table A.6 MnO Calibration Line - All concentration data on volatile free (ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	0.21	0.22	-0.02	- 7.86	1483.3
9463	NIM-D	0.21	0.23	0.02	- 9.61	1507.3
9410	NIM-P	0.22	0.24	-0.02	-10.47	1599.5
9413	NIM-P	0.22	0.24	0.02	- 9.32	1582.8
9430	NIM-N	0.18	0.19	-0.01	- 4.75	1239.7
9433	NIM-N	0.18	0.19	-0.01	- 5.39	1247.3
9440	NIM-L	0.78	0.76	0.02	3.12	4689.5
9443	NIM-L	0.78	0.77	0.01	1.81	5057.0
9270	BCR	0.19	0.19	-0.00	- 0.01	1256.4
9273	BCR	0.19	0.19	0.00	- 0.57	1263.4
9470	PCC	0.13	0.13	-0.01	- 5.06	868.2
9473	PCC	0.13	0.13	-0.01	- 5.10	868.6
9290	DTS	0.11	0.13	-0.02	-19.37	868.1
9293	DTS	0.11	0.13	-0.02	-18.00	858.1
9260	W-1	0.17	0.18	-0.01	- 5.08	1181.0
9261	W-1	0.17	0.18	-0.01	- 5.42	1184.9
9250	AGV	0.10	0.10	-0.00	- 0.98	674.3
9253	AGV	0.10	0.10	-0.00	- 2.66	685.5
9450	NIM-S	0.01	0.01	-0.00	- 2.70	67.9
9453	NIM-S	0.01	0.01	0.00	0.09	66.1
9240	GSP	0.04	0.04	-0.00	- 8.40	286.7
9243	GSP	0.04	0.04	-0.00	-11.10	293.8
9210	G-2	0.04	0.04	0.00	10.43	236.9
9213	G-2	0.04	0.04	0.00	10.21	237.5
9200	G-1	0.03	0.03	0.00	1.72	194.9
9201	G-1	0.03	0.03	0.00	2.12	194.1
9420	NIM-G	0.02	0.02	0.00	5.21	125.3
9423	NIM-G	0.02	0.02	0.00	4.46	126.3

Figure of merit = 5.23

Average Absolute Error = 0.008

Average Relative Error = 6.11

Slope of Calibration Line = 0.1513 E-03

Table A.7 (1) MgO Calibration Line - All concentration data on volatile free (ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9430	NIM-N	7.54	7.34	0.19	2.55	126.0
9433	NIM-N	7.54	7.48	0.06	0.88	128.2
9270	BCR	3.49	3.62	-0.14	- 3.96	62.2
9273	BCR	3.49	3.59	0.10	2.86	61.6
9260	W-1	6.62	6.48	0.14	2.14	111.2
9261	W-1	6.62	6.48	-0.14	- 2.09	116.0
9250	AGV	1.56	1.64	-0.08	- 5.09	28.1
9253	AGV	1.56	1.67	0.11	- 6.85	28.6
9450	NIM-S	0.48	0.74	-0.26	-53.68	12.7
9453	NIM-S	0.48	0.53	-0.53	- 9.28	9.0
9240	GSP	0.97	1.16	-0.19	-19.71	19.9
9243	GSP	0.97	1.24	-0.27	-28.18	21.3
9210	G-2	0.78	0.85	0.08	-10.01	14.6
9213	G-2	0.78	0.84	0.07	- 8.82	14.5
9200	G-1	0.38	0.53	-0.15	-39.86	9.2
9201	G-1	0.38	0.48	-0.09	-24.34	8.1
9420	NIM-G	0.05	0.06	-0.01	-13.92	1.0
9423	NIM-G	0.05	0.03	0.02	40.15	0.5

Table A.7 (2) MgO Calibration Line - All concentration data on volatile free (ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9410	NIM-P	25.12	24.73	0.402	-1.60	231.3
9412	NIM-P	25.12	25.55	-0.429	-1.71	239.1
9462	NIM-D	43.09	43.09	-0.003	-0.01	403.2
9470	PCC	45.48	45.67	-0.19	-0.41	427.3
9472	PCC	45.48	45.91	-0.44	-0.96	429.6
9290	DTS	49.70	48.72	0.99	1.98	455.8
9293	DTS	49.70	50.04	-0.33	-0.67	468.2

Figure of merit = 0.98

Average Absolute Error = 0.397

Average Relative Error = 1.05

Slope of Calibration Line = 0.1069 E+00

Table A.8 CaO Calibration Line - All concentration data on volatile free (ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	0.26	0.30	-0.04	-14.98	311.4
9463	NIM-D	0.26	0.30	-0.04	-16.51	315.6
9410	NIM-P	2.65	2.63	0.03	1.01	2767.6
9413	NIM-P	2.65	2.62	0.03	1.24	2761.4
9430	NIM-N	11.43	11.51	-0.07	-0.63	12126.1
9433	NIM-N	11.43	11.50	-0.06	-0.55	12115.9
9440	NIM-L	3.27	3.24	0.03	0.94	3414.0
9443	NIM-L	3.27	3.23	0.04	1.15	3406.6
9270	BCR	6.98	7.02	-0.04	-0.55	7395.7
9273	BCR	6.98	6.99	-0.01	-0.15	7366.2
9470	PCC	0.55	0.59	-0.03	-6.05	619.2
9473	PCC	0.55	0.59	-0.04	-7.00	624.7
9290	DTS	0.15	0.15	0.00	0.07	158.0
9293	DTS	0.15	0.15	0.00	0.12	157.9
9260	W-1	10.97	10.94	0.02	0.21	11533.2
9261	W-1	10.97	10.93	0.03	0.30	11522.9
9250	AGV	5.04	4.98	0.06	1.24	5242.8
9253	AGV	5.04	4.98	0.06	1.12	5248.8
9450	NIM-S	0.68	0.73	-0.05	-7.49	771.4
9453	NIM-S	0.68	0.74	-0.06	-8.42	778.1
9240	GSP	2.04	2.01	0.03	1.45	2119.7
9243	GSP	2.04	2.02	0.02	0.92	2131.2
9210	G-2	1.99	1.94	0.05	2.59	2047.0
9213	G-2	1.99	1.94	0.06	2.83	2042.0
9200	G-1	1.40	1.35	0.04	3.09	1425.7
9201	G-1	1.40	1.36	0.04	2.84	1429.4
9420	NIM-G	0.77	0.79	-0.01	-1.69	828.4
9423	NIM-G	0.77	0.79	-0.01	-1.76	829.0

Figure of merit = 1.05

Average Absolute Error = 0.36

Average Relative Error = 3.10

Slope of Calibration Line = 0.9489 E-03

Table A.9 K₂O Calibration Line -- All concentration data on volatile free (ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	0.02	0.02	-0.00	-14.86	31.9
9463	NIM-D	0.02	0.02	0.00	0.08	27.7
9410	NIM-P	0.09	0.09	0.00	0.55	122.8
9413	NIM-P	0.09	0.09	-0.00	- 1.35	125.1
9430	NIM-N	0.25	0.21	0.04	14.71	294.6
9433	NIM-N	0.25	0.22	0.03	13.79	297.8
9440	NIM-L	5.66	5.54	0.12	2.15	6858.3
9443	NIM-L	5.66	5.58	0.10	1.79	6883.1
9270	BCR	1.68	1.75	-0.07	- 3.89	2421.0
9273	BCR	1.68	1.74	-0.06	- 3.83	2419.7
9260	W-1	0.64	0.66	-0.02	- 3.60	918.3
9261	W-1	0.64	0.66	-0.03	- 4.26	924.1
9250	AGV	2.95	3.02	-0.07	- 2.35	4191.0
9253	AGV	2.95	3.03	0.07	- 2.49	4197.1
9450	NIM-S	15.43	15.40	0.03	0.22	21361.5
9453	NIM-S	15.43	15.46	-0.03	- 0.18	21447.6
9240	GSP	5.59	5.64	-0.05	- 0.84	7816.7
9243	GSP	5.59	5.63	-0.04	- 0.78	7811.8
9210	G-2	4.55	4.56	-0.01	- 0.14	6323.6
9213	G-2	4.55	4.58	-0.03	- 0.56	6350.1
9200	G-1	5.50	5.60	-0.09	- 1.68	7761.6
9201	G-1	5.50	5.60	-0.10	- 1.80	7771.0
9420	NIM-G	5.06	5.07	-0.02	- 0.30	7037.1
9423	NIM-G	5.06	5.08	-0.02	- 0.33	7039.5

Figure of merit = 1.30

Average Absolute Error = 0.05

Average Relative Error = 3.34

Slope of Calibration Line = 0.7209 E-03

Table A.10 P₃ 05 Calibration Line - All concentration data on volatile free (ignited) Basis.

Analytical No.	Standard	Std. Conc.	Calc. Conc.	Abs. Error	Rel. Error Percent	Corrected C.P.S.
9460	NIM-D	0.03	0.01	0.02	73.96	3.1
9463	NIM-D	0.03	0.00	0.03	85.82	1.7
9410	NIM-P	0.02	0.02	-0.00	-11.10	8.9
9413	NIM-P	0.02	0.03	-0.00	-34.76	10.8
9430	NIM-N	0.04	0.04	0.00	- 9.55	14.4
9433	NIM-N	0.04	0.04	-0.00	- 3.80	16.6
9440	NIM-L	0.07	0.07	-0.00	- 3.17	29.6
9443	NIM-L	0.07	0.08	-0.00	- 5.20	30.2
9270	BCR	0.33	0.37	-0.04	-10.89	146.0
9273	BCR	0.33	0.36	-0.03	- 8.01	142.2
9260	W-1	0.14	0.16	-0.02	-15.41	64.5
9261	W-1	0.14	0.16	0.02	-16.93	65.3
9250	AGV	0.50	0.48	0.02	4.54	192.0
9253	AGV	0.50	0.49	0.02	3.46	194.2
9450	NIM-S	0.14	0.14	0.00	1.38	55.1
9453	NIM-S	0.14	0.14	0.00	2.41	54.5
9240	GSP	0.28	0.28	0.00	0.23	112.7
9243	GSP	0.28	0.28	0.01	2.47	110.1
9210	G-2	0.14	0.14	0.00	0.95	55.7
9213	G-2	0.14	0.14	0.00	2.39	54.9
9200	G-1	0.09	0.09	-0.00	- 0.02	35.9
9201	G-1	0.09	0.07	0.02	26.09	26.5
9420	NIM-G	0.02	0.02	-0.00	- 0.33	8.0
9423	NIM-G	0.02	0.02	0.00	1.96	7.8

Figure of merit = 7.13

Average Absolute Error = 0.01

Average Relative Error = 13.53

Slope of Calibration Line = 0.2506 E-02

Table A.11 Major element composition for AGV, ECR, G-1.

	A G V		B C R		G - 1	
wt. %	Recommended value	Value, This work	Recommended value	Value, This work	Recommended value	Value, This work
Si 02	60.16	60.87	54.84	54.45	72.94	72.11
Ti 02	1.06	1.07	2.22	2.25	0.26	0.26
Al 03	17.35	17.52	13.68	13.49	14.10	14.17
Fe 03*	6.90	6.93	13.62	13.60	1.95	1.93
Mn 0	0.10	0.10	0.19	0.19	0.03	0.03
MgO	1.56	1.92	3.49	3.70	0.38	0.43
CaO	5.03	5.02	6.98	7.02	1.40	1.34
Na 20	4.34	4.34	3.29	3.29	3.33	3.33
K2O	2.95	3.05	1.68	1.76	5.50	5.57
P2 05	0.50	0.49	0.33	0.37	0.09	0.09

* total iron as Fe₂ O₃.

Table A.12 XRF STANDARD TRACE ELEMENT DATA (ppm)

Standard	Cr	Mn	Cu	Zn	Zr	Rb	Sr	Th	Y	Ba	V	Line
W-1	114	76	110	86	105	21	190	2	25	160	265	1
	120	78	110	86	105	21	190	2	25	160	240	2
	130	75	115	83	86,95	21	191	4	25	151	266	3
	123	73	118	81	95	22	189	1	25	157	270	4
BCR	18	16	18	120	191	47	331	6	37	677	400	1
	16	13	19	120	186	46	331	6	46	682	411	2
	16	13	20	118	184	47	331	5		714	405	3
	16	15	21	120	186	48	336	6	36	672	404	4
AGV	12	19	60	85	227	68	662	6	21	1218	126	1
	13	17	64	85	222	68	665	6	26	1210	126	2
	15	19	55	84	239	70	657	7	21	1174	122	3
	12	17	56	83	215	70	670	6	25	1241	126	4
GSP	13	13	34	99	506	257	236	104	31	1314	53	1
	13	-	35	99	506	253	233	104	32	1314	50	2
	15	-	33	105	501	259	237	-	32	1346	54	3
	12	11	36	99	512	256	236	75	32	1347	56	4
G-1	20	1	13	45	211	221	251	50	13	1205	17	1
	20	-	13	45	211	221	251	-	13	1205	17	2
	31	-	13	49	215	219	252	-	14	1001, 1012	21	3
	33	22	15	50	218	216	257	45	15	985	19	4
G-2	7	5	12	86	302	169	432	24	12	18831	36	1
	9	-	11	86	302	171	483	24	12	1863	34	2
	15	-	17	92	306	-	479	25	12	1842	44	3
	9	4	16	87	313	167	478	21	13	1884	40	4
PGC	2864	2454	12	38	-	-	-	-	-	-	31	1
	3158	2638	12	38	-	-	-	-	-	-	33	2
	2731	-	12	47	-	-	-	-	-	-	30	3
	2964	2667	11	46	0	0	0	3	0	0	31	4
DTS	4008	2274	7	45	-	1	-	-	-	2	10	1
	4388	2441	7	45	-	1	-	-	-	2	13	2
	3719	-	2	48	-	1	-	-	-	290	9	3
	3731	2564	7	47	0	0	0	0	0	0	8	4
NIM-N	40	78	13	80	25	-	-	-	7	90	225	1
	34	120	13	85	25	-	-	-	7	110	220	2
	124	113	18	62	41	-	-	-	8	88	174	3
	138	109	17	56	37	4	268	-	7	90	168	4
KIM-P	-	470	17	100	20	-	-	-	-	56	224	1
	-	568	14	100	20	-	-	-	-	48	249	2
	-	600	22	109	9	-	-	-	-	7	218	3
	-	603	17	103	16	4	36	1	2	14	218	4
NIM-S	13	8	23	21	30	-	-	-	5	-	-	1
	12	8	19	20	30	-	-	-	5	-	-	2
	14	5	24	16	9	-	-	-	6	-	-	3
	16	4	25	14	23	-	62	0	2	2514	9	4
NIM-L	21	11	15	320	-	183	-	71	31	451	78	1
	15	10	15	287	-	205	-	72	30	461	81	2
	6	3	12	433	-	190	-	-	17	402	70	3
	7	4	16	426	0	197	1167	51	22	396	71	4
NIM-G	12	11	15	60	-	275	-	62	100	180	2	1
	15	-	13	60	-	341	-	57	100	211	2	2
	13	-	14	51	-	337	-	60	176	147	7	3
	17	4	12	49	-	330	7	59	127	118	1	4
NIM-D	2830	2105	8	90	-	-	-	-	-	-	65	1
	2786	2263	10	90	-	-	-	-	-	-	42	2
	2843	-	7	91	-	-	-	-	-	-	33	3
	2810	2221	8	85	0.0	1.0	3	1	0	0	35	4

Line 1 = values of
Flanagan (1973)

Line 2 = values of
Abbey (1973)

Line 3 = values of
R. Parker (unpublished).

Line 4 = values from
this work.

B - SAMPLES' DATA.

Classification based on Mineralogy

SAMPLE NO.	QUARTZ - FELDSPATHIC GNEISS					MAFIC GNEISS	FELDSPATHIC GNEISS
	LNB 40	LNB 41	LNB 54	LNB 61	LNB 83	LNB 57	LNB 74
SiO ₂	77.40	72.25	70.76	73.64	70.23	52.84	66.82
TiO ₂	0.04	0.15	0.22	0.16	0.23	0.70	0.12
Al ₂ O ₃	12.43	11.37	15.12	13.67	15.32	15.98	18.14
Fe ₂ O ₃	0.01	0.38	0.16	0.14	0.21	1.72	0.14
FeO	0.77	4.49	1.64	0.89	1.97	6.72	0.60
MnO	0.02	0.09	0.03	0.01	0.40	0.17	0.11
MgO	0.44	1.70	0.87	0.50	1.04	4.11	0.53
CaO	3.45	3.49	2.96	1.03	2.52	11.00	1.97
Na ₂ O	4.13	3.38	5.73	2.29	5.98	2.18	4.44
K ₂ O	0.23	0.43	1.50	6.06	2.39	2.14	5.95
P ₂ O ₅	0.03	0.03	0.08	0.04	0.10	0.32	0.06
LOI	0.60	2.17	0.63	0.52	0.60	1.49	0.94
H ₂ O	0.04	0.11	0.05	0.05	0.07	0.06	0.03
TOTAL	99.72	100.54	99.74	99.01	100.68	99.42	99.78
Oxidation Ratio	1.15	14.87	8.07	12.34	8.76	18.70	17.36
FeO _T /FeO _T + MgO	0.64	0.74	0.67	0.67	0.31	0.66	0.58
CaO/Al ₂ O ₃	0.28	0.31	0.20	0.08	0.16	0.69	0.11
Na /K	16.11	6.94	3.39	0.34	2.22	0.9	0.67
	CIPW		NORMS				
Qz	44.45	37.99	23.77	33.71	18.76	3.99	13.01
Co	-	-	-	1.57	-	-	0.96
Or	1.36	2.54	8.86	35.81	14.12	12.65	35.16
Pl	49.65	43.18	59.59	24.23	58.50	45.94	46.95
Ab	34.95	28.60	48.49	19.38	50.60	18.45	37.57
An	14.70	14.58	11.11	4.85	7.90	27.50	9.38
Hy	1.55	11.00	3.47	2.52	4.76	10.07	2.14
Mt	0.01	0.55	0.23	0.20	0.31	2.49	0.20
Il	0.08	0.28	0.42	0.30	0.44	1.33	0.21
Ap	0.07	0.07	0.19	0.09	0.26	0.76	0.14
Di	1.85	2.14	2.54	-	3.25	20.66	-

	LNB 40	LNB 41	LNB 54	LNB 61	LNB 83	LNB 57	LNB 74
	<u>Trace Elements in parts per million</u>						
Cr	13.00	5.20	14.00	4.30	22.00	152.30	14.70
Ni	5.70	11.30	8.60	4.30	8.20	66.60	7.20
Rb	2.40	9.90	22.20	78.70	84.00	22.50	60.10
Sr	195.60	98.80	430.20	277.70	363.90	345.50	631.40
Y	-	153.70	2.90	2.10	2.20	22.00	4.60
Zr	-	293.30	71.20	260.40	45.90	212.40	154.40
Ba	145.10	113.10	857.30	1248.50	834.90	895.00	5464.50
Th	2.00	11.10	2.30	6.80	3.00	0.50	3.40
Zn	14.90	137.90	27.40	25.30	46.10	88.50	14.40
Cu	5.90	3.70	22.80	15.10	18.70	7.90	5.10
V	13.50	5.50	24.20	14.00	22.40	177.80	15.40
K/Rb	789.00	363.00	559.00	639.00	237.00	791.00	822.00
K/Sr	10.00	37.00	29.00	181.13	55.57	51.52	78.28
K/Ba	13.00	31.49	14.48	40.29	23.78	19.89	9.05
Rb/Sr	0.01	0.10	0.05	0.28	0.23	0.07	0.10
Ba/Rb	60.50	11.42	38.62	15.86	9.94	39.78	90.92
Ba/Sr	0.74	1.14	1.99	4.50	2.29	2.59	8.65
Ca/Y	-	162.40	7298.00	2523.81	8190.00	3600.00	3062.00
	<u>NIGGLI VALUES</u>						
al	44.40	5.47	41.62	47.81	39.69	24.88	48.01
fm	8.03	45.10	13.15	9.52	16.24	34.80	6.31
c	22.41	25.35	14.81	6.55	11.87	31.13	9.48
alk	25.16	24.08	30.42	36.12	32.19	9.19	36.20
si	469.57	489.88	330.54	437.09	308.78	139.58	300.09
k	0.04	0.08	0.15	0.64	0.21	0.39	0.47
mg	0.50	0.38	0.46	0.46	0.42	0.46	0.56
qz	+268.93	+349.38	+108.87	+192.62	+80.02	+2.83	+ 55.29

SAMPLE NO.	BIOTITE SCHIST			QUARTZ - BIOTITE SCHIST		
	LNB 9	LNB 37	LNB 19	LNB 24	LNB 25	LNB 94
SiO ₂	56.88	54.98	75.87	70.55	74.99	75.48
TiO ₂	0.67	0.79	0.13	0.47	0.16	0.27
Al ₂ O ₃	15.03	16.64	11.87	15.20	12.03	9.21
Fe ₂ O ₃	0.21	0.68	0.05	0.12	0.18	0.27
FeO	7.68	9.90	1.54	1.80	1.90	5.29
MnO	0.13	0.26	0.04	0.03	0.04	0.12
MgO	5.38	5.10	1.13	1.21	1.32	2.19
CaO	6.04	3.48	1.34	2.79	2.90	1.48
Na ₂ O	1.96	1.11	2.20	3.05	3.28	1.48
K ₂ O	2.39	4.11	4.31	2.79	1.09	1.82
P ₂ O ₅	0.24	0.29	0.03	0.08	0.09	0.03
LOI	1.89	1.34	0.98	1.06	1.50	0.62
H ₂ O	0.13	-	0.05	0.10	0.09	0.05
TOTAL	98.63	99.87	99.54	99.25	99.55	99.00
Oxidation Ratio	2.40	5.82	3.00	5.65	7.84	3.15
FeOt/FeOt + MgO	0.59	0.67	0.58	0.61	0.61	0.72
CaO/Al ₂ O ₃	0.40	0.21	0.11	0.18	0.24	0.16
Na/K	0.75	0.24	0.45	0.97	2.73	0.73
CIPW NORMS						
Qz	10.80	10.92	40.90	33.44	42.45	49.30
Co	-	4.73	1.22	2.28	0.42	2.17
Or	14.12	24.29	25.47	16.49	6.32	10.75
Pl	41.74	24.76	25.07	39.13	41.55	19.72
Ab	16.58	9.39	18.62	25.81	27.55	12.52
An	25.15	15.37	6.45	13.32	13.80	7.20
Hy	25.14	29.47	5.46	5.50	6.44	14.72
Mt	0.30	0.99	0.07	0.17	0.26	0.39
Il	1.27	1.50	0.25	0.89	0.30	0.51
Ap	0.57	0.69	0.07	0.19	0.21	0.07
Di	2.68	-	-	-	-	-

	LNB 9	LNB 37	LNB 19	LNB 24	LNB 25	LNB 94
	<u>Trace Elements in parts per million</u>					
Cr	216.70	145.00	1.00	20.10	20.10	13.30
Ni	82.50	46.30	3.60	11.40	8.20	8.60
Rb	41.90	112.40	48.60	48.70	21.10	32.80
Sr	582.10	187.40	224.70	432.50	444.10	107.90
Y	20.70	71.40	18.40	0.50	14.20	201.90
Zr	274.90	125.90	364.20	279.40	277.60	483.40
Ba	1110.50	1157.50	1629.80	2971.70	609.90	589.60
Th	1.50	11.80	-	0.20	-	3.00
Zn	245.90	172.40	43.90	49.50	58.30	78.90
Cu	73.40	24.50	8.90	12.80	12.00	11.80
V	130.50	176.40	4.10	44.20	33.50	25.30
K/Rb	473.00	304.00	737.00	476.00	422.00	464.00
K/Sr	34.01	182.00	159.32	53.64	20.04	141.00
K/Ba	17.83	29.50	21.48	7.81	14.59	25.57
Rb/Sr	0.08	0.60	0.11	0.05	0.22	0.30
Ba/Rb	26.50	10.30	33.53	61.02	28.91	17.98
Ba/Sr	1.91	6.18	7.25	1.31	1.37	5.46
Ca/Y	2101.45	348.50	521.74	40000.00	1415.49	52.77
	<u>NIGGLI VALUES</u>					
al	26.47	28.97	42.77	44.85	39.86	30.82
fm	43.96	49.09	18.61	17.03	20.95	45.38
c	19.34	11.02	8.78	14.83	17.47	9.06
alk	10.23	10.92	29.85	23.56	21.72	14.74
si	169.98	162.45	463.87	350.87	421.66	428.56
k	0.45	0.71	0.56	0.38	0.18	0.45
mg	0.55	0.46	0.55	0.53	0.53	0.41
qz	+29.05	+18.75	+244.48	+156.65	+234.80	+269.61

HORNBLLENDE GNEISS					
SAMPLE NO.	LNB 30	LNB 31	LNB 32	LNB 34	LNB 56
SiO ₂	51.18	51.30	52.71	49.10	51.05
TiO ₂	1.10	0.95	1.11	2.12	0.41
Al ₂ O ₃	16.05	15.65	14.61	12.79	14.79
Fe ₂ O ₃	2.80	2.75	3.00	4.80	1.05
FeO	10.80	10.40	11.50	17.30	8.44
MnO	0.25	0.20	0.19	0.26	0.18
MgO	5.06	5.30	4.61	4.19	8.68
CaO	8.51	8.60	8.87	7.77	9.89
Na ₂ O	3.17	3.30	3.28	1.69	2.59
K ₂ O	0.40	0.40	0.38	0.28	0.73
P ₂ O ₅	0.14	0.13	0.16	0.29	0.07
LOI	0.37	0.33	0.28	0.31	2.05
H ₂ O	0.07	0.07	0.06	0.06	0.10
TOTAL	99.90	99.33	100.76	100.34	100.07
Oxidation Ratio	18.88	19.17	18.97	19.94	10.07
FeO _T /FeO _T + MgO	0.72	0.71	0.75	0.84	0.52
CaO/Al ₂ O ₃	0.53	0.55	0.61	0.61	0.67
Na/K	7.07	7.36	7.77	5.38	3.16
		<u>CIPW</u>	<u>NORMS</u>		
Qz	1.26	0.79	3.03	7.03	-
Co	-	-	-	-	-
Or	2.36	2.36	2.25	1.65	4.31
Pl	55.21	54.50	51.77	40.79	48.44
Ab	26.82	27.92	27.75	14.30	21.92
An	28.30	26.57	24.02	26.49	26.57
Hy	23.28	22.51	20.66	30.81	18.07
Mt	4.06	3.99	4.35	6.96	1.52
Il	2.09	1.84	2.11	4.03	0.78
Ap	0.33	0.31	0.38	0.69	0.17
Di	10.78	12.68	15.89	8.66	17.99

	LNB 30	LNB 31	LNB 32	LNB 34	LNB 56
	<u>Trace Elements in parts per million</u>				
Cr	57.30	71.30	23.40	48.90	94.30
Ni	29.80	33.40	18.20	16.40	34.40
Rb	3.40	1.60	3.40	0.30	6.80
Sr	237.20	240.30	208.80	175.20	108.50
Y	35.60	36.10	34.60	68.60	10.90
Zr	174.90	177.20	194.50	196.20	13.30
Ba	276.10	266.40	134.00	246.80	90.90
Th	0.10	1.80	0.90	-	2.80
Zn	139.30	135.40	147.90	187.80	57.10
Cu	2.00	-	10.50	1.30	12.70
V	230.10	219.80	237.40	317.70	186.10
K/Rb	971.00	2063.00	941.00	7653.00	888.00
K/Sr	13.91	13.73	15.32	13.13	57.00
K/Ba	11.95	12.39	23.88	9.32	67.11
Rb/Sr	0.01	0.01	0.02	0.02	0.06
Ba/Rb	81.21	166.50	39.42	822.67	142.08
Ba/Sr	1.16	1.10	0.65	1.41	8.24
Ca/Y	1721.91	1714.68	1846.82	814.89	6429.00
	<u>NIGGLI VALUES</u>				
al	23.18	22.59	21.29	17.85	20.16
fm	46.31	46.28	46.75	58.13	48.44
c	22.35	22.64	23.50	19.72	24.51
alk	8.16	8.49	8.46	4.30	6.88
si	125.45	126.05	130.33	116.28	118.10
k	0.08	0.07	0.07	0.10	0.16
mg	0.40	0.42	0.36	0.25	0.62
qz	-7.18	-7.90	-3.51	-0.93	-9.45

BIOTITE - MUSCOVITE - GARNET GNEISS								
SAMPLE NO.	LNB 7	LNB 8	LNB 12	LNB 16	LNB 22	LNB 33	LNB 35	LNB 36
SiO ₂	60.19	61.15	60.78	61.27	58.49	61.70	61.95	61.15
TiO ₂	0.71	0.62	0.91	0.63	0.63	0.66	0.65	0.66
Al ₂ O ₃	17.06	17.87	17.18	16.16	19.53	16.07	16.08	16.76
Fe ₂ O ₃	0.65	0.29	0.45	0.30	0.28	0.76	0.76	0.37
FeO	5.45	5.11	5.36	5.34	4.72	5.48	5.48	6.08
MnO	0.17	0.09	0.12	0.08	0.06	0.08	0.08	0.09
MgO	3.26	3.58	2.41	3.20	2.88	3.00	2.60	2.60
CaO	4.24	3.76	4.76	4.30	4.26	5.50	4.95	4.96
Na ₂ O	3.57	2.24	3.11	3.79	4.55	4.04	3.86	3.83
K ₂ O	2.35	3.65	2.63	1.79	2.68	0.82	1.01	1.04
P ₂ O ₅	0.19	0.39	0.28	0.23	0.33	0.23	0.22	0.24
LOI	1.84	1.80	1.60	2.06	0.89	0.88	1.65	1.70
H ₂ O	0.13	0.09	0.11	0.17	0.10	0.11	0.10	0.12
TOTAL	99.22	100.69	99.71	99.32	99.64	99.33	99.39	99.60
Oxidation Ratio	9.67	4.84	7.01	4.80	5.05	11.57	7.57	5.18
FeO _t /FeO _t + MgO	0.65	0.60	0.71	0.64	0.63	0.67	0.70	0.71
CaO/Al ₂ O ₃	0.25	0.21	0.28	0.27	0.22	0.34	0.31	0.30
Na/K	1.35	0.55	1.06	1.73	1.52	4.04	3.40	3.28
		CIPW	NORMS					
Qz	4.53	18.09	15.89	15.09	5.86	16.12	17.95	16.54
Co	-	4.33	1.23	0.72	2.19	-	0.16	0.89
Or	13.87	21.57	15.54	10.58	15.84	4.85	5.97	6.15
Pl	60.15	35.06	48.10	51.90	57.48	57.48	55.78	55.45
Ab	43.75	18.95	26.32	32.07	38.50	34.19	32.66	32.41
An	16.40	16.11	21.79	19.83	18.98	23.29	23.12	23.04
Hy	15.34	17.20	14.19	16.64	14.68	14.94	14.99	16.41
Mt	0.94	0.42	0.65	0.43	0.41	1.10	1.10	0.54
Il	1.35	1.18	1.73	1.20	0.20	1.25	1.23	1.25
Ap	0.45	0.92	0.66	0.54	0.78	2.54	0.52	0.57
Di	2.81	-	-	-	-	2.07	-	-

	LNB 7	LNB 8	LNB 12	LNB 16	LNB 22	LNB 33	LNB 35	LNB 36
	<u>Trace Elements in parts per million.</u>							
Cr	86.60	104.30	98.50	85.30	31.60	86.00	79.70	75.30
Ni	47.90	45.90	60.90	35.60	24.90	27.90	41.50	35.60
Rb	37.50	85.70	49.10	24.20	55.40	21.30	15.90	16.30
Sr	554.60	478.40	448.80	409.90	483.70	546.00	419.00	468.10
Y	6.70	14.90	29.30	14.90	9.00	16.50	13.10	13.50
Ba	963.50	1498.40	856.50	852.10	1210.00	508.00	401.40	437.90
Th	-	2.10	1.50	0.40	-	-	1.20	0.10
Zn	256.30	179.20	143.30	110.10	98.30	98.10	84.30	84.90
Cu	14.70	4.50	53.80	22.60	24.40	33.90	69.10	50.60
V	110.00	131.80	142.90	100.40	35.10	100.10	103.60	96.10
K/Rb	520.00	354.00	444.00	616.00	401.00	319.00	528.00	528.00
K/Sr	35.16	63.34	48.57	36.35	45.90	12.45	20.05	18.37
K/Ba	20.23	20.22	25.45	17.28	18.35	13.39	20.95	19.64
Rb/Sr	0.07	0.18	0.11	0.06	0.11	0.04	0.04	0.03
Ba/Rb	25.70	17.48	17.44	35.62	21.84	23.85	25.35	26.87
Ba/Sr	1.74	3.12	1.91	2.10	2.50	0.93	0.96	0.94
Ca/Y	4552.24	1818.79	1170.65	2080.54	3411.11	2400.00	2717.56	2644.44
	<u>NIGGLI VALUES</u>							
al	33.96	36.36	36.51	33.44	37.49	32.11	33.53	34.20
fm	33.95	34.20	29.95	33.46	27.70	32.87	32.19	32.25
c	15.34	13.91	17.94	16.18	14.87	19.98	18.76	18.40
alk	16.75	15.54	16.50	16.91	19.94	15.05	15.52	15.15
si	203.30	211.13	213.78	215.17	190.55	209.18	219.19	211.73
k	0.30	0.52	0.36	0.24	0.28	0.12	0.15	0.15
Mg	0.48	0.54	0.42	0.50	0.50	0.46	0.43	0.42
qz	+36.29	+48.99	+47.76	+47.52	+10.80	+48.97	+57.11	+51.12

QUARTZITIC GNEISS

SAMPLE NO.	LNB 38	LNB 39	LNB 44	LNB 50
SiO ₂	78.94	81.76	81.50	81.21
TiO ₂	0.11	0.11	0.11	0.11
Al ₂ O ₃	10.21	9.82	9.14	10.04
Fe ₂ O ₃	0.08	0.01	0.03	0.02
FeO	2.87	1.00	1.15	0.50
MnO	0.10	0.03	0.02	0.28
MgO	0.88	0.43	0.44	0.21
CaO	2.66	1.17	2.82	0.90
Na ₂ O	1.64	1.64	1.33	1.78
K ₂ O	1.19	2.37	1.36	2.82
P ₂ O ₅	0.04	0.03	0.03	0.03
LOI	0.53	0.91	1.05	0.95
H ₂ O	0.05	0.05	0.05	0.07
TOTAL	99.58	99.43	99.18	99.00
Oxidation Ratio	2.45	0.89	2.29	3.47
Fe _{0t} /Fe _{0t} + MgO	0.76	0.70	0.73	0.71
CaO/Al ₂ O ₃	0.26	0.12	0.31	0.09
Na/K	1.22	0.61	0.87	0.56
		<u>CIPW</u>	<u>NORMS</u>	
Qz	55.59	59.25	61.09	57.34
Co	1.48	2.49	0.42	2.49
Or	7.03	14.00	8.04	16.66
Pl	26.81	19.49	25.05	19.33
Ab	13.88	13.88	11.25	15.06
An	12.93	5.61	13.79	4.27
Hy	7.38	2.90	3.04	1.76
Mt	0.12	0.01	0.04	0.03
Il	0.21	0.21	0.21	0.21
Ap	0.09	0.07	0.07	0.07
Di	-	-	-	-

	LNB 38	LNB 39	LNB 44	LNB 50
<u>Trace Elements in parts per million.</u>				
Cr	5.00	7.20	5.20	9.80
Ni	6.00	10.90	11.30	6.80
Rb	32.50	41.60	50.20	45.70
Sr	74.30	98.40	63.70	118.50
Y	90.40	116.80	78.70	32.00
Zr	222.40	235.30	208.90	248.40
Ba	1019.10	923.20	640.30	1027.70
Th	13.80	11.40	12.20	4.00
Zn	61.80	958.70	567.60	20.10
Cu	7.30	17.50	5.60	7.20
V	6.40	3.60	5.60	6.20
K/Rb	304.00	472.00	226.00	513.00
K/Sr	460.00	200.00	178.00	197.00
K/Ba	9.65	21.28	17.59	22.76
Rb/Sr	0.44	0.42	0.79	0.40
Ba/Rb	31.36	22.19	12.75	22.49
Ba/Sr	13.72	9.38	10.05	8.67
Ca/Y	411.50	71.62	256.20	201.10
<u>NIGGLI VALUES</u>				
al	39.96	49.64	44.07	51.87
fm	25.51	12.97	13.56	8.69
c	18.93	10.76	24.72	8.55
alk	15.60	26.63	17.65	30.90
si	524.26	702.03	667.11	711.96
k	0.32	0.42	0.40	0.51
mg	0.34	0.42	0.40	0.32
qz	+361.86	+495.51	+496.52	+488.37

	QUARTZ-MICA SCHIST		QUARTZ- MAGNETITE- GNEISS	QUARTZ - MICA	GARNET- GNEISS
SAMPLE NO.	LNB 43	LNB 76	LNB 90	LNB 42	LNB 49
SiO ₂	76.41	73.47	56.89	78.11	76.57
TiO ₂	0.13	0.27	0.51	0.13	0.04
Al ₂ O ₃	12.23	13.61	12.23	10.68	13.02
Fe ₂ O ₃	0.06	0.07	3.23	0.02	0.11
FeO	1.54	2.00	16.28	1.46	0.44
MnO	0.05	0.03	0.18	0.03	0.01
MgO	0.72	1.12	3.80	0.45	0.02
CaO	2.63	1.23	1.77	0.85	0.08
Na ₂ O	2.84	4.26	0.10	1.56	0.58
K ₂ O	2.12	2.13	0.63	5.29	8.19
P ₂ O ₅	0.04	0.04	0.02	0.04	0.04
IOI	0.72	1.14	3.93	0.42	0.71
H ₂ O	0.08	0.19	0.03	0.03	0.02
TOTAL	99.75	99.56	99.68	99.21	99.88
Oxidation Ratio	3.39	3.05	15.15	1.22	18.37
FeO _T /FeO _T + MgO	0.69	0.50	0.83	0.77	0.60
CaO/Al ₂ O ₃	0.22	0.09	0.14	0.01	0.01
Na/K	0.77	1.78	0.14	0.26	0.06
	CIPW		NORMS		
Qz	43.76	34.88	32.36	45.31	41.46
Co	0.56	2.16	8.24	0.95	3.15
Or	12.53	12.59	3.72	31.20	48.40
Pl	36.87	41.89	9.43	17.16	5.06
Ab	24.03	36.05	0.85	13.20	4.91
An	12.84	5.84	8.85	3.96	0.14
Hy	4.45	6.01	36.18	3.63	0.73
Mt	0.09	0.10	4.68	0.03	0.14
Il	0.25	0.51	0.97	0.25	0.08
Ap	0.09	0.09	0.07	0.09	0.09
Di	-	-	-	-	-

	LNB 43	LNB 76	LNB 90	LNB 42	LNB 49
	<u>Trace Elements in parts per million.</u>				
Cr	6.30	32.60	70.90	9.00	7.90
Ni	7.20	12.90	15.30	5.50	4.30
Rb	90.10	43.00	7.80	107.20	124.30
Sr	110.60	372.90	3.40	39.00	110.00
Y	94.60	18.40	20.60	107.50	9.10
Zr	217.80	179.10	49.20	282.00	132.50
Ba	393.70	384.90	83.90	793.40	1252.70
Th	14.90	1.20	5.60	10.50	1.20
Zn	29.9	35.20	103.40	84.10	13.50
Cu	4.10	10.70	1.70	3.70	6.60
V	4.30	29.80	103.00	4.90	3.30
K/Rb	196.00	412.00	665.00	408.00	552.00
K/Sr	159.00	47.47	1526.00	1124.30	623.00
K/Ba	44.72	45.99	20.60	55.27	54.27
Rb/Sr	0.81	0.12	2.29	2.80	1.13
Ba/Rb	4.37	8.95	10.76	7.40	10.08
Ba/Sr	3.56	1.03	24.68	20.34	11.39
Ca/Y	198.70	483.70	614.34	56.50	62.86
	<u>NIGGLI VALUES</u>				
al	43.44	43.95	22.91	44.90	54.67
fm	14.76	18.74	69.48	13.79	3.48
c	17.05	7.22	6.03	6.50	0.61
alk	24.75	30.08	1.59	34.82	41.23
si	460.59	402.65	180.81	557.27	545.63
k	0.33	0.25	0.81	0.69	0.90
mg	0.44	0.49	0.26	0.35	0.06
qz	+261.60	+182.34	+ 74.47	+318.01	+280.71

QUARTZ - BIOTITE - GARNET GNEISS											
SAMPLE NO.	LNB 6	LNB 10	LNB 15	LNB 17	LNB 21	LNB 26	LNB 62	LNB 63	LNB 81	LNB 87	LNB 95
S102	69.45	67.57	68.43	64.66	66.87	66.28	67.02	63.83	66.09	67.65	69.67
TiO2	0.65	0.60	0.43	0.56	0.46	0.36	0.62	1.00	0.68	0.76	0.50
Al2O3	14.92	15.69	14.85	14.76	16.27	16.32	15.74	16.33	16.25	15.97	15.53
Fe2O3	0.14	0.14	0.18	0.27	0.04	0.04	0.12	0.52	0.20	0.09	0.17
FeO	3.92	3.97	3.43	5.29	2.01	3.60	3.76	6.10	4.14	2.62	1.86
MnO	0.10	0.05	0.05	0.09	0.03	0.07	0.05	0.12	0.07	0.05	0.04
MgO	0.73	0.81	1.60	2.53	2.43	2.17	1.94	2.08	2.50	1.38	0.94
CaO	3.46	3.84	4.17	5.31	6.65	4.05	2.34	4.57	2.79	3.50	1.62
Na2O	3.95	3.46	4.39	4.01	4.41	3.57	3.52	2.90	3.48	2.99	4.73
K2O	0.90	1.74	1.01	1.00	0.22	1.61	2.82	1.40	2.73	2.81	2.39
P2O5	0.16	0.25	0.15	0.12	0.21	0.17	0.10	0.21	0.14	0.32	0.18
LOI	0.41	0.62	0.87	0.68	0.31	1.57	0.79	0.72	1.06	1.11	1.73
H2O	0.09	0.07	0.07	0.11	0.04	0.11	0.10	0.07	0.05	0.05	0.10
TOTAL	99.31	99.81	99.63	99.39	99.95	99.92	98.92	99.85	100.17	99.59	99.64
Oxidation Ratio	3.11	3.07	4.50	4.38	1.76	1.00	2.78	7.11	4.17	3.00	7.60
FeO _t /FeO _t + MgO	0.85	0.69	0.69	0.69	0.46	0.62	0.67	0.76	0.63	0.06	0.68
CaO/Al2O3	0.23	0.24	0.28	0.36	0.41	0.25	0.15	0.28	0.17	0.22	0.10
Na/K	3.91	1.78	3.87	3.58	17.81	1.97	1.11	1.85	1.14	0.99	1.77
		CIPW	NORMS								
Qz	32.16	27.71	26.02	20.07	23.41	25.14	25.45	25.05	23.16	29.22	27.50
Co	1.54	1.73	-	-	-	1.74	2.88	2.24	2.83	2.41	2.65
Or	5.32	10.28	5.97	5.97	1.30	9.51	16.66	8.27	16.13	16.61	14.12
Pl	49.54	46.69	54.98	53.25	61.27	49.19	40.74	45.84	42.37	40.57	46.88
Ab	33.42	29.28	37.15	33.93	37.32	30.21	29.79	24.54	29.45	25.30	40.02
Hy	8.01	10.78	8.73	12.42	6.00	11.52	10.71	14.52	12.67	7.01	4.86
Mt	0.20	0.21	0.26	0.39	0.06	0.06	0.17	0.75	0.29	0.13	0.25
Il	1.23	0.74	0.82	1.06	0.87	0.68	1.18	1.90	1.29	1.44	0.95
Ap	0.38	0.59	0.36	0.28	0.50	0.40	0.24	0.50	0.33	0.76	0.43
Di	-	-	1.57	5.22	6.21	-	-	-	-	-	-

	LNB 6	LNB 10	LNB 15	LNB 17	LNB 21	LNB 26	LNB 62	LNB 63	LNB 81	LNB 87	LNB 95
	<u>Trace Elements in parts per million.</u>										
Cr	5.90	47.70	30.80	49.50	24.50	52.10	45.60	22.60	64.80	27.00	125.60
Ni	5.80	40.00	26.90	24.90	16.60	10.30	30.30	11.80	29.90	12.00	58.40
Rb	14.30	34.10	10.80	8.40	3.20	23.30	65.00	45.80	46.40	32.10	48.20
Sr	253.60	329.50	462.40	378.10	334.00	425.30	393.50	761.30	344.30	477.50	509.10
Y	54.70	18.40	7.40	13.30	15.10	6.30	10.90	34.50	11.60	6.50	13.40
Zr	146.00	120.90	257.70	233.70	197.30	238.30	242.10	390.20	113.70	20.70	130.60
Ba	198.30	865.50	415.80	534.40	64.60	468.30	796.40	680.70	671.20	2204.60	1098.50
Th	3.00	-	-	-	8.70	-	7.50	7.60	5.50	3.50	7.00
Zn	38.80	146.40	48.60	74.30	14.50	106.50	67.00	132.50	61.20	72.60	181.80
Cu	8.90	52.20	43.30	24.40	6.00	4.60	75.49	24.90	213.30	8.90	62.20
V	30.20	78.20	58.50	95.20	20.40	57.70	73.80	93.10	90.20	91.70	106.60
K/Rb	532.00	422.00	778.00	988.00	563.00	575.00	360.00	253.00	447.00	728.00	449.00
K/Sr	30.00	47.30	18.17	21.95	5.39	31.51	59.47	15.24	65.78	49.00	43.00
K/Ba	37.85	16.64	20.20	15.53	27.86	28.61	29.38	17.04	33.73	10.57	18.03
Rb/Sr	0.06	0.10	0.02	0.02	0.01	0.06	0.17	0.06	0.13	0.07	0.10
Ra/Rb	13.87	25.38	38.50	63.62	20.19	20.10	12.25	14.86	14.47	68.67	22.74
Ba/Sr	0.78	2.63	0.90	1.41	0.19	1.10	2.02	0.89	1.95	4.62	2.16
Ca/Y	452.30	15500.00	4054.05	2872.18	3172.19	4634.92	1541.28	953.62	1720.00	3850.00	864.40
	<u>NIGGLI VALUES</u>										
al	40.97	38.54	37.16	31.76	36.20	38.81	40.05	35.75	38.18	42.37	45.50
fm	21.23	25.70	23.06	30.94	20.23	25.56	28.63	32.30	29.50	19.62	15.50
c	17.28	17.15	18.97	20.77	26.90	17.51	10.82	18.19	11.62	16.88	8.63
alk	20.52	18.61	20.81	16.52	16.67	18.11	22.50	13.76	20.40	21.12	30.37
si	323.64	281.66	290.57	236.10	252.47	267.49	289.35	237.12	263.53	304.59	346.35
K	0.13	0.25	0.13	0.14	0.03	0.23	0.35	0.24	0.34	0.38	0.25
mg	0.24	0.44	0.44	0.44	0.68	0.51	0.47	0.36	0.50	0.47	0.45
qz	+141.56	+707.23	+107.35	+70.00	+85.78	+95.04	+99.36	+82.08	+81.95	+120.11	+124.85

	ULTRAMAFIC GNEISS	GARNET GRANULITE	QUARTZ - GARNET - FELDSPAR GNEISS	QUARTZ - BIOTITE - GARNET GNEISS	QUARTZ-FELDSPAR - GARNET GNEISS	BIOTITE-GARNET GNEISS	QUARTZ - FELDSPATHIC GNEISS			
SAMPLE NO.	LNS 113	LNS 104	LNS 112	LNS 111	LNS 108	LNS 101	LNS 110	LNS 99	LNS 114	LNS 115
SiO ₂	40.85	54.21	54.40	78.28	70.14	67.50	68.38	63.14	61.89	64.25
TiO ₂	2.23	1.17	1.13	0.32	0.31	0.36	0.47	0.68	0.75	0.61
Al ₂ O ₃	17.06	19.36	21.29	14.83	14.94	16.63	16.11	16.42	17.15	14.94
Fe ₂ O ₃	1.59	0.11	0.08	0.01	0.04	0.06	0.22	0.65	0.12	0.45
FeO	15.10	10.03	0.20	0.82	4.19	2.30	2.69	3.69	6.88	4.47
MnO	0.25	0.24	0.13	0.02	0.12	0.04	0.07	0.08	0.14	0.09
MgO	7.02	2.68	2.38	0.41	1.36	1.33	1.13	3.01	3.21	2.93
CaO	10.64	4.18	1.79	1.76	2.00	3.37	1.97	3.28	3.28	5.51
Na ₂ O	1.16	3.26	5.00	5.07	2.95	4.53	3.04	3.60	3.53	4.74
K ₂ O	1.04	2.29	2.92	1.37	2.85	1.29	5.43	2.87	1.12	0.74
P ₂ O ₅	0.83	0.14	0.05	0.04	0.04	0.12	0.04	0.13	0.07	0.12
LOI	0.00	0.67	1.11	0.44	0.45	0.84	0.24	0.95	0.39	1.00
H ₂ O	0.05	0.08	0.09	0.04	0.07	0.09	0.34	0.10	0.06	0.08
TOTAL	99.50	99.49	99.48	99.50	99.92	99.72	100.40	99.68	99.33	99.92
Oxidation Ratio	8.65	0.98	0.87	1.09	0.85	0.70	6.86	12.98	1.55	8.31
FeO ^t /FeO ^t +MgO	0.70	0.79	0.78	0.67	0.76	0.64	0.72	0.60	0.69	0.62
CaO/Al ₂ O ₃	0.62	0.22	0.08	0.12	0.13	0.20	0.07	0.20	0.19	0.37
Na/K	1.00	1.05	1.53	3.29	0.92	3.13	0.50	0.93	2.81	4.74
			CIPW	NORMS						
Qz	-	6.26	0.80	34.82	32.52	25.68	22.25	17.49	20.19	16.82
Co	-	4.25	6.77	1.90	3.46	1.94	1.75	1.74	4.33	-
Or	6.15	13.53	17.26	8.10	16.84	7.62	32.09	16.96	6.62	4.37
Pl	48.09	47.41	50.86	51.37	34.62	54.77	35.24	45.88	45.68	57.41
Ab	9.82	27.59	42.31	42.90	24.96	38.33	25.72	30.46	29.87	40.11
An	38.27	19.82	8.55	8.47	9.66	15.93	9.51	15.42	15.81	17.30
Hy	0.51	23.52	19.31	2.03	10.76	6.97	6.93	13.17	19.55	10.51
Mt	2.31	0.16	0.12	0.01	0.06	0.09	0.32	0.94	0.17	0.65
Il	4.24	2.22	2.13	0.61	0.59	0.68	0.89	1.31	1.42	1.16
Ap	1.97	0.33	0.12	0.09	0.09	0.28	0.09	0.31	0.17	0.28
Di	7.59	-	-	-	-	-	-	-	-	7.64
Ol	26.97	-	-	-	-	-	-	-	-	-

	LNS 113	LNS 104	LNS 112	LNS 111	LNS 108	LNS 101	LNS 110	LNS 99	LNS 114	LNS 115
	<u>Trace Elements in parts per million.</u>									
Cr	44.00	200.60	405.40	17.30	47.30	43.70	46.10	14.60	293.70	93.10
Ni	313.00	70.50	300.10	7.10	11.90	25.50	9.70	14.10	115.50	27.60
Rb	45.30	34.40	39.30	9.80	72.60	13.00	101.70	15.00	8.70	-
Sr	3066.50	578.20	211.40	555.10	331.10	571.40	460.40	589.90	371.90	506.10
Y	235.40	45.60	17.20	3.40	71.20	3.10	23.30	1.00	21.90	7.10
Zr	177.70	176.30	236.90	306.70	367.20	16.30	662.40	235.50	70.90	23.60
Ba	402.10	1356.70	425.80	3340.40	1034.40	976.50	3378.60	2579.00	353.70	426.40
Th	19.30	15.40	-	2.80	8.40	3.20	5.30	4.40	5.00	3.10
Zn	1091.60	253.90	60.50	17.70	40.20	42.80	55.10	48.90	90.70	49.60
Cu	1019.50	71.20	285.50	4.30	6.70	8.80	17.80	13.80	54.40	14.20
V	935.90	256.10	268.00	30.40	61.70	58.10	57.90	48.50	154.60	81.40
K/Rb	191.00	554.00	601.00	1163.00	326.00	822.00	448.00	1588.00	1066.00	-
K/Sr	2.81	33.00	113.06	21.00	71.60	19.00	99.00	40.40	25.00	12.11
K/Ba	21.41	14.00	29.83	3.40	22.90	10.94	13.55	9.23	26.22	14.37
Rb/Sr	0.02	0.06	0.19	0.02	0.22	0.02	0.22	0.03	0.02	-
Ba/Rb	8.90	39.42	10.70	340.86	14.25	75.12	33.22	171.93	40.66	-
Ba/Sr	0.13	2.35	2.01	6.02	3.12	1.71	7.34	4.37	0.95	0.84
Ca/Y	323.20	654.76	750.00	3701.00	200.80	7773.00	604.50	23452.00	1080.70	5549.00
	<u>NIGGLI VALUES</u>									
al	21.06	34.39	39.52	49.28	41.36	43.34	42.81	36.06	35.46	31.58
fm	51.32	38.19	33.31	7.45	26.60	17.60	18.76	31.01	37.70	30.57
c	23.88	13.50	6.04	10.63	10.07	15.97	9.52	13.10	12.33	21.18
alk	3.74	13.93	21.13	32.64	21.97	23.07	28.91	19.83	14.51	16.67
si	85.57	163.40	171.34	418.83	329.49	298.64	308.39	285.31	217.13	230.50
k	0.37	0.32	0.28	0.15	0.39	0.16	0.54	0.34	0.17	0.01
mg	0.43	0.32	0.34	0.46	0.36	0.50	0.40	0.54	0.45	0.51
qz	-29.41	+41.79	-13.19	+188.27	+141.60	+106.36	+92.75	+56.00	+59.08	+63.83

C - SAMPLES' DATA

Classification based on over-all geochemistry or possible origin

SAMPLE NO.	AMPHIBOLITE					BASIC GNEISS	RETROGRESSED LEUCO- GABBRO
	LNB 30	LNB 31	LNB 32	LNB 34	LNB 56	LNB 57	LNS 113
SiO ₂	51.18	51.30	52.71	49.10	51.05	52.84	40.85
TiO ₂	1.10	0.95	1.11	2.12	0.41	0.70	2.23
Al ₂ O ₃	16.05	15.60	14.61	12.79	14.79	15.98	17.06
Fe ₂ O ₃	2.80	2.75	3.00	4.80	1.05	1.72	1.59
Feo	10.80	10.40	11.50	17.30	8.44	6.72	15.10
Mno	0.25	0.20	0.19	0.26	0.18	0.17	0.25
MgO	5.06	5.30	4.61	4.19	8.68	4.11	7.02
CaO	8.51	8.60	8.81	7.77	9.89	11.00	10.64
Na ₂ O	3.17	3.30	3.28	1.69	2.59	2.18	1.16
K ₂ O	0.40	0.40	0.38	0.28	0.73	2.14	1.04
P ₂ O ₅	0.14	0.13	0.16	0.29	0.07	0.32	0.83
LoI	0.37	0.33	0.28	-0.31	2.05	1.49	0.00
H ₂ O	0.07	0.07	0.06	0.06	0.10	0.06	0.05
TOTAL	99.90	99.33	100.76	100.94	100.07	99.42	99.50
Oxidation Ratio	18.88	19.17	18.97	19.94	10.07	18.70	8.65
FeO _T /FeO _T + MgO	0.72	0.71	0.75	0.84	0.52	0.66	0.70
CaO/Al ₂ O ₃	0.53	0.55	0.61	0.61	0.67	0.69	0.62
Na/K	7.07	7.36	7.70	5.38	3.16	0.90	1.00
	<u>CIPW NORMS</u>						
Qz	1.26	0.79	3.03	7.03	-	3.99	-
Co	-	-	-	-	-	-	-
Or	2.36	2.36	2.25	1.65	4.31	12.65	6.15
Pl	55.21	54.50	51.77	40.79	48.44	45.94	48.09
Ab	26.82	27.92	29.75	14.30	21.92	18.45	9.82
An	28.38	26.57	24.02	26.49	26.57	27.50	38.27
Hy	23.38	22.51	20.66	30.81	18.09	10.07	0.51
Mt	4.06	3.99	4.35	6.96	1.52	2.49	2.31
Il	2.09	1.84	2.11	4.03	0.78	1.33	4.24
Ap	0.33	0.31	0.38	0.69	0.17	0.76	1.97
Di	10.78	12.68	15.89	8.66	17.99	20.66	7.59
ol	-	-	-	-	-	-	26.97

	LNB 30	LNB 31	LNB 32	LNB 34	LNB 56	LNB 57	LNS 113
	<u>Trace Elements in parts per million.</u>						
Cr	57.30	71.30	23.40	48.90	94.30	152.30	44.00
Ni	29.80	33.40	18.20	16.40	34.40	66.60	313.10
Rb	3.40	1.60	3.40	0.30	6.80	22.50	45.30
Sr	237.20	240.30	208.80	175.20	108.50	345.50	3066.50
Y	35.60	36.10	34.60	68.60	10.90	22.00	235.40
Zr	174.90	177.20	194.50	196.20	13.30	212.40	177.70
Ba	276.10	266.40	134.00	246.80	90.90	895.00	402.10
Th	0.10	1.80	0.90	-	2.80	0.50	19.30
Zn	139.30	135.50	147.90	187.80	57.10	88.50	1091.60
Cu	2.00	-	10.50	1.30	12.70	7.90	1091.50
V	230.10	219.80	237.70	317.70	186.10	177.80	935.90
K/Rb	971.00	2063.00	941.00	7653.00	888.00	791.00	191.00
K/Sr	13.91	13.73	15.32	13.13	57.00	51.52	2.81
K/Ba	11.95	12.39	23.88	9.32	67.11	19.89	21.41
Rb/Sr	0.01	0.01	0.02	0.02	0.06	0.07	0.02
Ba/Rb	81.21	166.50	39.42	822.67	142.08	39.78	8.90
Ba/Sr	1.16	1.10	0.65	1.41	8.24	2.59	0.13
Ca/Y	1721.91	1714.68	1846.82	814.89	6429.00	3600.00	323.20
	<u>NIGGLI VALUES</u>						
al	23.18	22.59	21.29	17.85	20.16	24.88	21.06
fm	46.31	46.28	46.75	58.13	48.44	34.80	51.32
c	22.35	22.64	23.50	19.72	24.51	31.13	23.88
alk	8.16	8.49	8.46	4.30	6.88	9.19	3.74
si	125.45	126.05	130.33	116.28	118.10	139.58	85.57
k	0.08	0.07	0.07	0.10	0.16	0.39	0.37
mg	0.40	0.42	0.36	0.25	0.62	0.46	0.43
qz	-7.18	-7.90	-3.51	-0.93	-9.45	+2.83	-29.41

GRANITIC GNEISS						
SAMPLE NO.	LNB 40	LNB 41	LNB 54	LNB 61	LNB 83	LNB 115
SiO ₂	77.40	72.25	70.76	73.64	70.23	64.25
TiO ₂	0.04	0.15	0.22	0.16	0.23	0.61
Al ₂ O ₃	12.43	11.37	15.12	13.67	15.32	14.94
Fe ₂ O ₃	0.01	0.38	0.16	0.14	0.21	0.45
FeO	0.77	4.49	1.64	0.89	1.97	4.47
MnO	0.02	0.09	0.03	0.01	0.40	0.09
MgO	0.44	1.70	0.87	0.50	1.40	2.93
CaO	3.45	3.49	2.96	1.03	2.52	5.51
Na ₂ O	4.13	3.38	5.73	2.29	5.98	4.74
K ₂ O	0.23	0.43	1.50	6.06	2.39	0.74
P ₂ O ₅	0.03	0.03	0.08	0.04	0.10	0.12
LoI	0.60	2.17	0.63	0.52	0.60	1.00
H ₂ O	0.04	0.11	0.05	0.05	0.07	0.08
TOTAL	99.72	100.54	99.74	99.01	100.68	99.92
Oxidation Ratio	1.15	14.87	8.07	12.34	8.76	8.31
FeO _T /FeO _T + MgO	0.64	0.74	0.67	0.67	0.31	0.62
CaO/Al ₂ O ₃	0.28	0.31	0.20	0.08	0.16	0.37
Na/K	16.11	6.94	3.39	0.34	2.22	4.74
<u>CIPW NORMS</u>						
Qz	44.45	37.99	23.77	33.71	18.76	16.82
Co	-	-	-	1.57	-	-
Or	1.36	2.54	8.86	35.81	14.12	4.37
Pl	49.65	43.18	59.59	24.23	58.50	57.41
Ab	34.95	28.60	48.49	19.38	50.60	40.11
An	14.70	14.58	11.11	4.85	7.90	17.30
Hy	1.55	11.00	3.47	2.52	4.76	10.51
Mt	0.01	0.55	0.23	0.20	0.31	0.65
Il	0.08	0.28	0.42	0.30	0.44	1.16
Ap	0.07	0.07	0.19	0.09	0.26	0.28
Di	1.85	2.14	2.54	-	3.25	7.64

	LNB 40	LNB 41	LNB 54	LNB 61	LNB 83	LNS 115
	<u>Trace Elements in parts per million.</u>					
Cr	13.40	5.20	14.00	4.30	22.00	93.10
Ni	5.70	11.30	8.600	4.30	8.20	27.60
Rb	2.40	9.90	22.20	78.70	84.00	-
Sr	195.60	98.80	430.20	277.70	363.90	506.10
Y	-	153.70	2.90	2.10	2.20	7.10
Zr	-	293.30	71.20	260.40	45.90	23.60
Ba	145.10	113.10	857.30	1248.50	854.90	426.40
Th	2.00	11.10	2.30	6.80	3.00	3.10
Zn	14.90	137.90	27.40	25.30	46.10	49.60
Cu	5.90	3.70	22.80	15.10	18.70	14.20
V	13.50	5.50	24.20	14.00	22.40	81.40
K/Rb	789.00	363.00	559.00	639.00	237.00	-
K/Sr	10.00	37.00	29.00	181.13	55.57	12.11
K/Ba	13.05	31.49	14.48	40.29	23.78	14.37
Rb/Sr	0.01	0.10	0.05	0.28	0.23	-
Ba/Rb	60.50	11.42	38.62	15.86	9.94	-
Ba/Sr	0.74	1.14	1.99	4.50	2.29	0.84
Ca/Y	-	162.40	7298.00	3523.81	8190.00	5549.00
	<u>NIGGLI VALUES</u>					
al	44.40	5.47	41.62	47.81	39.69	31.58
fm	8.03	45.10	13.15	9.52	16.24	30.57
c	22.41	25.35	14.81	6.55	11.87	21.18
alk	25.16	24.08	30.42	36.12	32.19	16.67
si	469.57	489.88	330.54	437.09	308.78	230.50
k	0.04	0.08	0.15	0.64	0.21	0.01
mg	0.50	0.38	0.46	0.46	0.42	0.51
qz	+268.93	+349.38	+108.87	+192.62	+80.02	+63.83

META - PELITE

SAMPLE NO.	LNB 9	LNB 37	LNB 90	LNS 104	LNS 112
SiO ₂	56.88	54.98	56.89	54.21	54.40
TiO ₂	0.67	0.79	0.51	1.17	1.13
Al ₂ O ₃	15.03	16.64	12.23	19.36	21.29
Fe ₂ O ₃	0.21	0.68	3.23	0.11	0.08
FeO	7.68	9.90	16.28	10.03	8.20
MnO	0.13	0.26	0.18	0.24	0.12
MgO	5.38	5.10	3.80	2.68	2.38
CaO	6.04	3.48	1.77	4.18	1.79
Na ₂ O	1.96	1.11	0.10	3.26	5.00
K ₂ O	2.39	4.11	0.63	2.29	2.92
P ₂ O ₅	0.24	0.29	0.02	0.14	0.05
LoI	1.89	1.34	3.93	0.67	1.11
H ₂ O	0.13	-	0.03	0.08	0.09
TOTAL	98.63	99.87	99.68	99.49	99.48
Oxidation Ratio	2.40	5.82	15.15	0.98	0.87
FeO _T /FeO _T + MgO	0.59	0.67	0.83	0.79	0.78
CaO/Al ₂ O ₃	0.40	0.21	0.14	0.22	0.08
Na/K	0.75	0.24	0.14	1.05	1.53
<u>CIPW NORMS</u>					
Qz	10.80	10.92	32.36	6.26	0.80
Co	-	4.73	8.24	4.25	6.77
Or	14.12	24.29	3.72	13.53	17.26
Pl	41.74	24.76	9.43	47.41	50.86
Ab	16.58	9.39	0.85	27.59	42.31
An	25.15	15.37	8.58	19.82	8.55
Hy	25.14	29.47	36.18	23.52	19.31
Mt	0.30	0.99	4.68	0.16	0.12
Il	1.27	1.50	0.97	2.22	2.13
Ap	0.57	0.69	0.07	0.33	0.12
Di	2.68	-	-	-	-

	LNB 9	LNB 37	LNB 90	LNS 104	LNS 112
<u>Trace Elements in parts per million.</u>					
Cr	216.70	145.00	70.90	200.60	405.40
Ni	82.50	46.30	15.30	70.50	300.10
Rb	41.90	112.40	7.80	34.40	39.80
Sr	583.10	187.40	3.40	578.20	211.40
Y	20.70	71.40	20.60	45.60	17.20
Zr	274.90	125.90	49.20	176.30	236.90
Ba	1110.50	1157.50	83.90	1356.00	425.80
Th	1.50	11.80	5.60	15.40	-
Zn	245.90	172.40	103.40	253.90	60.50
Cu	73.40	24.50	1.70	71.20	285.50
V	130.50	176.40	103.00	256.10	268.00
K/Rb	473.00	304.00	665.00	554.00	601.00
K/Sr	34.01	182.00	1526.00	33.00	113.06
K/Ba	17.83	29.50	20.60	14.00	29.83
Rb/Sr	0.08	0.60	2.29	0.06	0.19
Ba/Rb	26.50	10.30	10.76	39.42	10.70
Ba/Sr	1.91	6.18	24.68	2.35	2.01
Ca/Y	2101.45	348.50	614.34	654.76	750.00
<u>NIGGLI VALUES</u>					
al	26.47	28.97	22.91	34.39	39.52
fm	43.96	49.09	69.48	38.19	33.31
c	19.34	11.02	6.03	13.50	6.04
alk	10.23	10.92	1.59	13.93	21.13
si	169.98	162.45	180.81	163.40	171.34
k	0.45	0.71	0.81	0.32	0.28
mg	0.55	0.46	0.26	0.32	0.34
qz	+29.05	+18.75	+74.47	+41.79	-13.19

META ARKOSE/IMPURE QUARTZITE ?

SAMPLE NO.	LNB 38	LNB 39	LNB 44	LNB 50
SiO ₂	78.94	81.76	81.50	81.21
TiO ₂	0.11	0.11	0.11	0.11
Al ₂ O ₃	10.21	9.81	9.14	10.04
Fe ₂ O ₃	0.08	0.01	0.03	0.02
FeO	2.87	1.00	1.15	0.50
MnO	0.10	0.03	0.02	0.28
MgO	0.88	0.43	0.44	0.21
CaO	2.66	1.17	2.82	0.90
Na ₂ O	1.64	1.64	1.33	1.78
K ₂ O	1.19	2.37	1.36	2.82
P ₂ O ₅	0.04	0.03	0.03	0.03
LoI	0.53	0.91	1.05	0.95
H ₂ O	0.05	0.05	0.05	0.07
TOTAL	99.58	99.43	99.18	99.00
Oxidation Ratio	2.45	0.89	2.29	3.47
FeO _T /FeO _T + MgO	0.76	0.70	0.73	0.71
CaO/Al ₂ O ₃	0.26	0.12	0.31	0.09
Na/K	1.22	0.61	0.87	0.56
	<u>CIPW NORMS</u>			
Qz	55.59	59.25	61.09	57.34
Co	1.48	2.49	0.42	2.49
Or	7.03	14.00	8.04	16.66
Pl	26.81	19.49	25.05	19.33
Ab	13.88	13.88	11.25	15.06
An	12.93	5.61	13.79	4.27
Hy	7.38	2.90	3.04	1.76
Mt	0.12	0.01	0.04	0.03
Il	0.21	0.21	0.21	0.21
Ap	0.09	0.07	0.07	0.07
Di	-	-	-	-

	LNB 38	LNB 39	LNB 44	LNB 50
	<u>Trace Elements in parts per million</u>			
Cr	5.00	7.20	5.20	9.80
Ni	6.00	10.90	11.30	6.80
Rb	32.50	41.60	50.20	45.70
Sr	74.30	98.40	63.70	118.50
Y	90.40	116.80	78.70	32.00
Zr	222.40	235.30	208.90	248.40
Ba	1019.10	923.20	640.30	1027.70
Th	13.80	11.40	12.20	4.00
Zn	61.80	958.70	567.60	20.10
Cu	7.30	17.50	5.60	7.20
V	6.40	3.60	5.60	6.20
K/Rb	304.00	472.00	226.00	513.00
K/Sr	460.00	200.00	178.00	197.00
K/Ba	9.65	21.28	17.59	22.76
Rb/Sr	0.44	0.42	0.79	0.40
Ba/Rb	31.36	22.19	12.75	22.49
Ba/Sr	13.72	9.38	10.05	8.67
Ca/Y	411.50	71.62	256.20	201.10
	<u>NIGGLI VALUES</u>			
al	39.96	49.64	44.07	51.87
fm	25.51	12.97	13.56	8.69
c	18.93	10.76	24.72	8.55
alk	15.60	26.63	17.65	30.90
si	524.26	702.03	667.11	711.96
k	0.32	0.42	0.40	0.51
mg	0.32	0.42	0.40	0.32
qz	+361.86	+495.51	+496.52	+488.37

META-GREYWACKE											
SAMPLE NO.	LNB 6	LNB 7	LNB 8	LNB 10	LNB 12	LNB 15	LNB 16	LNB 17	LNB 19	LNB 21	LNB 22
SiO ₂	69.45	60.19	61.15	67.57	60.78	68.43	61.27	64.66	75.87	66.87	58.49
TiO ₂	0.65	0.71	0.62	0.60	0.91	0.43	0.63	0.56	0.13	0.46	0.63
Al ₂ O ₃	14.92	17.06	17.87	15.69	17.18	14.85	16.16	14.76	11.87	16.27	19.53
Fe ₂ O ₃	0.14	0.65	0.29	0.14	0.45	0.18	0.30	0.27	0.05	0.04	0.28
FeO	3.92	5.45	5.11	3.97	5.36	3.43	5.34	5.29	1.54	2.01	4.72
MnO	0.10	0.17	0.09	0.05	0.12	0.05	0.08	0.09	0.04	0.03	0.06
MgO	0.73	3.26	3.58	1.81	2.41	1.60	3.20	2.53	1.13	2.43	2.88
CaO	3.46	4.24	3.76	3.84	4.76	4.17	4.30	5.31	1.34	6.65	4.26
Na ₂ O	3.95	3.57	2.24	3.46	3.11	4.39	3.79	4.01	2.20	4.41	4.55
K ₂ O	0.90	2.35	3.65	1.74	2.63	1.01	1.79	1.00	4.31	0.22	2.68
P ₂ O ₅	0.16	0.19	0.39	0.25	0.28	0.15	0.23	0.12	0.03	0.21	0.33
LoI	0.41	1.84	1.80	0.62	1.60	0.87	2.06	0.68	0.98	0.31	0.89
H ₂ O	0.09	0.13	0.09	0.07	0.11	0.07	0.17	0.11	0.05	0.04	0.10
TOTAL	99.31	99.22	100.69	99.81	99.71	99.63	99.32	99.39	99.54	99.95	99.64
Oxidation Ratio	3.11	9.67	4.84	3.07	7.01	4.50	4.80	4.38	3.00	1.76	5.05
Fe ₂ O ₃ /FeO + MgO	0.85	0.65	0.60	0.69	0.71	0.69	0.64	0.69	0.58	0.46	0.63
CaO/Al ₂ O ₃	0.23	0.25	0.21	0.24	0.28	0.28	0.27	0.36	0.11	0.41	0.22
Na/K	3.91	1.35	0.55	1.78	1.06	3.87	1.73	3.58	0.45	17.81	1.52
CIPW NORMS											
Qz	32.16	4.53	18.09	27.71	15.89	26.02	15.09	20.17	40.90	23.41	5.86
Co	1.54	-	4.33	1.73	1.23	-	0.72	-	1.22	-	2.19
Or	5.32	13.87	21.57	10.28	15.54	5.97	10.58	5.97	25.47	1.30	15.84
Pl	49.54	60.15	35.06	46.69	48.10	54.98	51.90	53.25	25.07	61.27	57.48
Ab	33.42	43.75	18.95	29.28	26.32	37.15	32.07	33.93	18.62	37.32	38.50
An	16.12	16.40	16.11	17.42	21.79	17.85	19.83	19.32	6.45	23.95	18.98
Hy	8.01	15.34	17.20	10.78	14.19	8.73	16.64	12.42	5.46	6.00	14.68
Mt	0.20	0.94	0.42	0.21	0.65	0.26	0.43	0.39	0.07	0.06	0.41
Il	1.23	1.35	1.18	1.14	1.73	0.82	1.20	1.06	0.25	0.87	0.20
Ap	0.38	0.45	0.92	0.59	0.66	0.36	0.54	0.28	0.07	0.50	0.78
Di	-	2.81	-	-	-	1.57	-	5.22	-	6.21	-

	META-GREYWACKS										
	LNB 6	LNB 7	LNB 8	LNB 10	LNB 12	LNB 15	LNB 16	LNB 17	LNB 19	LNB 21	LNB 22
Cr	5.90	86.60	104.30	47.70	98.50	30.80	85.30	49.50	1.00	24.50	31.60
Ni	5.80	47.90	45.70	40.00	60.90	26.90	35.60	24.90	3.60	16.60	24.90
Rb	14.30	37.50	85.70	34.10	49.10	10.80	24.20	8.40	48.60	3.20	35.40
Sr	253.60	554.60	479.40	329.50	448.80	462.40	409.90	378.10	224.70	334.00	483.70
Y	54.70	6.70	14.90	18.40	29.30	7.40	14.90	13.30	18.40	15.10	9.00
Zr	146.00	280.50	194.70	120.99	279.80	257.70	220.10	233.70	264.20	197.30	233.70
Pu	198.30	963.80	1498.40	865.50	415.80	862.10	534.40	1629.80	64.60	1210.00	2971.70
Th	3.00	-	2.10	-	1.50	-	0.40	-	-	8.70	-
Zn	38.80	256.30	179.20	146.40	143.30	48.60	110.10	74.30	43.90	14.50	98.30
Cu	8.90	14.70	4.50	52.20	53.80	43.30	22.60	24.40	8.90	6.00	24.40
V	30.20	110.00	131.80	78.20	142.90	58.50	100.40	95.20	4.10	20.40	35.10
K/Rb	532.00	520.00	354.00	422.00	444.00	778.40	616.00	988.00	737.00	563.00	401.00
K/Sr	30.00	35.16	63.34	47.30	48.57	18.17	36.35	21.95	159.32	15.39	45.90
K/Ba	37.85	20.23	20.22	26.64	25.45	20.20	17.28	15.53	21.48	27.36	18.35
Rb/Sr	0.06	0.07	0.18	0.10	0.11	0.02	0.06	0.02	0.11	0.01	0.11
Ba/Rb	13.87	25.70	17.48	25.38	17.44	38.50	35.62	63.62	33.53	20.19	21.84
Ba/Sr	0.78	1.74	3.12	2.63	1.91	0.90	2.10	1.41	7.25	0.19	2.50
Ca/Y	452.30	4552.24	1818.79	15500.00	1170.65	4054.05	2080.54	2872.18	521.74	3172.19	3411.11
al	40.97	33.96	36.36	38.54	36.51	37.16	33.44	31.76	42.77	36.20	37.49
fm	21.23	33.95	34.20	25.70	29.95	23.06	33.46	30.94	18.61	20.23	27.70
o	17.28	15.34	13.91	17.15	17.94	18.97	16.18	10.77	8.78	26.90	14.57
alk	20.52	16.75	15.54	18.61	16.50	20.81	16.91	16.52	29.85	16.67	19.94
si	323.64	203.30	211.13	281.66	213.78	290.57	215.17	236.10	463.87	252.47	190.55
K	0.13	0.30	0.52	0.25	0.36	0.13	0.24	0.14	0.56	0.03	0.28
my	0.24	0.48	0.54	0.44	0.42	0.44	0.50	0.44	0.55	0.68	0.50
qs	+141.56	+36.29	+48.49	+107.23	+47.76	+101.35	+47.52	+70.00	+244.48	+85.78	+10.80

META - GREYWACKE

SAMPLE NO.	LNB 24	LNB 25	LNB 26	LNB 33	LNB 35	LNB 36	LNB 42	LNB 43	LNB 49	LNB 62	LNB 63	LNB 74
SiO ₂	70.55	74.99	66.28	61.70	61.95	61.15	78.11	76.41	76.57	67.02	63.83	66.82
TiO ₂	0.47	0.16	0.36	0.66	0.65	0.66	0.13	0.13	0.04	0.62	1.00	0.12
Al ₂ O ₃	15.20	12.03	16.32	16.07	16.08	16.76	10.68	12.23	13.02	15.74	16.33	18.14
Fe ₂ O ₃	0.12	0.18	0.04	0.76	0.76	0.37	0.02	0.06	0.11	0.12	0.52	0.14
FeO	1.80	1.90	3.60	5.48	5.48	6.08	1.46	1.54	20.44	3.76	6.10	0.60
MnO	0.03	0.04	0.07	0.08	0.08	0.09	0.03	0.05	0.01	0.05	0.12	0.11
MgO	1.21	1.32	2.17	3.00	2.60	2.60	0.45	0.72	0.02	1.94	2.08	0.53
CaO	2.79	2.90	4.05	5.50	4.95	4.96	0.85	2.63	0.08	2.34	4.57	1.97
Na ₂ O	3.05	3.28	3.57	4.04	3.86	3.83	1.56	2.84	0.58	3.52	2.90	4.44
K ₂ O	2.79	1.09	1.61	0.82	1.01	1.04	5.29	2.12	8.19	1.82	1.40	5.95
P ₂ O ₅	0.08	0.09	0.17	0.23	0.22	0.24	0.04	0.04	0.04	0.10	0.21	0.06
LoI	1.06	1.50	1.57	0.88	1.65	1.70	0.42	0.72	0.71	0.79	0.72	0.94
H ₂ O	0.10	0.90	0.11	0.11	0.10	0.12	0.03	0.08	0.02	0.10	0.07	0.03
TOTAL	99.25	99.55	99.92	99.33	99.39	99.60	99.21	99.75	99.88	98.92	99.85	99.78
Oxidation Ratio	5.65	7.84	1.00	11.57	7.57	5.18	1.22	3.39	18.37	2.78	7.11	17.36
FeO _T /FeO _T + MgO	0.61	0.61	0.62	0.67	0.70	0.71	0.77	0.69	0.60	0.67	0.76	0.58
CaO/Al ₂ O ₃	0.18	0.24	0.25	0.34	0.31	0.30	0.01	0.22	0.01	0.15	0.28	0.11
Na/K	0.97	2.73	1.97	4.04	3.40	3.28	0.26	0.77	0.06	1.11	1.85	0.67
Qz	33.44	42.45	25.14	16.12	17.95	16.54	45.31	43.76	41.46	25.45	25.05	13.01
Co	2.28	0.42	1.74	-	0.16	0.89	0.95	0.56	3.15	2.88	2.24	0.96
Or	16.49	6.32	9.51	4.85	5.97	6.15	31.20	12.53	48.40	16.66	8.27	35.16
Pl	39.13	41.55	49.19	57.48	55.78	55.45	17.16	36.87	5.04	40.74	45.84	46.95
Ab	25.81	27.55	30.21	34.19	32.66	32.41	13.20	24.03	4.91	29.79	24.54	37.57
An	13.32	13.80	18.98	23.29	23.12	23.04	3.96	12.84	0.14	10.96	21.30	9.38
Hy	5.50	6.44	11.52	14.94	14.99	16.41	3.63	4.45	0.73	10.71	14.52	2.14
Ms	0.17	0.26	0.06	1.10	1.10	0.54	0.03	0.09	0.14	0.17	0.75	0.20
Il	0.89	0.30	0.68	1.25	1.23	1.25	0.25	0.25	0.08	1.18	1.90	0.21
Ap	0.19	0.21	0.40	2.54	0.52	0.57	0.09	0.09	0.09	0.24	0.50	0.14
Di	-	-	-	2.07	-	-	-	-	-	-	-	-

METAGREYWACKE

	LNB 24	LNB 25	LNB 26	LNB 33	LNB 35	LNB 36	LNB 42	LNB 43	LNB 49	LNB 62	LNB 63	LNB 74
	<u>Trace Elements in parts per million.</u>											
Cr	20.10	20.10	52.10	86.00	79.70	75.30	9.00	6.30	7.90	45.60	22.60	14.70
Ni	11.40	8.20	10.30	27.90	41.50	35.60	5.50	7.20	4.30	30.30	11.80	7.20
Rb	48.70	21.10	23.30	21.30	15.90	16.30	107.20	90.10	124.30	65.00	45.80	60.10
Sr	432.50	444.10	425.30	546.00	419.00	468.10	39.00	110.60	110.00	393.90	761.30	631.40
Y	0.50	14.20	6.30	16.50	13.10	13.50	107.50	94.60	9.10	10.90	34.50	4.60
Zr	279.40	277.60	238.30	241.50	202.60	229.40	282.00	217.80	132.50	242.10	380.20	154.40
Ba	2971.70	609.90	468.30	508.00	401.40	437.90	793.40	393.70	1252.70	796.40	680.70	5464.50
Th	0.20	-	-	-	1.20	0.10	10.50	14.90	1.20	7.50	7.60	3.40
Zn	49.50	58.30	106.50	98.10	84.30	84.90	84.10	29.90	13.50	67.00	132.50	14.40
Cu	12.80	12.00	4.60	33.90	69.10	50.60	3.70	4.10	6.60	75.49	24.90	5.10
V	44.20	33.50	57.70	100.10	103.60	96.10	4.90	4.30	3.30	73.80	93.10	15.40
K/Rb	476.00	422.00	575.00	319.00	528.00	528.00	408.00	196.00	552.00	360.00	253.00	822.00
K/Sr	53.64	20.04	31.51	12.45	20.05	18.37	1124.30	159.00	623.00	59.47	15.24	78.28
Y/Ba	7.81	14.59	28.61	13.39	20.95	19.64	55.27	44.72	54.27	29.38	17.04	9.05
Rb/Sr	0.05	0.22	0.06	0.04	0.04	0.09	2.80	0.81	1.13	0.17	0.06	0.10
Ba/Rb	61.02	28.91	20.10	23.85	25.35	26.87	7.40	4.37	10.08	12.25	14.86	90.92
Ba/Sr	1.31	1.37	11.39	0.93	0.96	0.94	20.34	3.56	1.10	2.02	0.89	8.65
Ca/Y	40000.00	1415.49	4636.92	2400.00	2717.56	2644.44	56.50	198.78	62.86	1541.28	953.62	3062.00
	<u>NIGGLI VALUES</u>											
al	44.85	39.86	38.81	32.11	33.53	34.20	44.90	43.44	54.67	40.05	35.75	48.01
fm	17.03	20.95	25.56	32.19	32.87	32.25	13.79	14.76	3.48	26.63	32.30	6.31
o	14.83	17.47	17.51	19.98	18.76	18.40	6.50	17.05	0.61	10.82	18.19	9.48
alk	23.56	21.72	18.11	15.05	15.52	15.15	34.82	24.75	41.23	22.50	13.76	36.20
sl	350.07	421.66	267.40	209.18	219.19	211.73	557.27	460.59	545.63	289.35	237.12	300.09
K	0.38	0.18	0.23	0.12	0.15	0.15	0.69	0.33	0.90	0.35	0.24	0.47
my	0.53	0.53	0.51	0.46	0.43	0.42	0.35	0.44	0.06	0.47	0.36	0.56
qs	+156.65	+234.80	+95.04	+48.97	+57.11	+51.12	+318.01	+261.60	+280.71	+99.36	+82.08	+55.29

META-GREYWACKE

SAMPLE NO.	LNB 76	LNB 81	LNB 87	LNB 94	LNB 95	LNB 99	LNS 101	LNS 108	LNS 110	LNS 111	LNS 114
SiO2	73.47	66.09	67.65	75.48	69.45	63.14	67.50	70.14	68.38	78.28	61.89
TiO2	0.27	0.68	0.76	0.27	0.65	0.68	0.36	0.31	0.47	0.32	0.75
Al2O3	13.61	16.25	15.97	9.21	14.92	16.42	16.63	14.94	16.11	14.83	17.15
Fe2O3	0.07	0.20	0.09	0.27	0.14	0.65	0.06	0.04	0.22	0.01	0.12
FeO	2.00	4.14	2.62	5.29	3.92	3.92	2.30	4.19	2.69	0.82	6.88
MnO	0.03	0.07	0.05	0.12	0.10	0.08	0.04	0.12	0.07	0.02	0.14
MgO	1.12	2.50	1.38	2.19	0.73	3.01	1.33	1.36	1.13	0.41	3.21
CaO	1.23	2.79	3.50	1.48	3.46	3.28	3.37	2.00	1.97	1.76	3.28
Na2O	4.26	3.48	2.99	1.48	3.95	3.60	4.53	2.95	3.04	5.07	3.53
K2O	2.13	2.73	2.81	1.82	0.90	2.87	1.29	2.85	5.43	1.37	1.12
P2O5	0.04	0.14	0.32	0.03	0.16	0.13	0.12	0.04	0.04	0.04	0.07
LoI	1.14	1.06	1.11	0.62	0.41	0.95	0.84	0.45	0.24	0.44	0.39
H2O	0.19	0.05	0.05	0.05	0.09	0.10	0.09	0.07	0.34	0.04	0.06
TOTAL	99.56	100.17	99.59	99.00	99.31	99.28	98.72	99.92	100.40	99.50	99.33
Oxidation Ratio	3.05	4.17	3.00	3.15	3.11	12.98	0.70	0.85	6.86	1.09	1.55
Fe2t/Fe2t + MgO	0.50	0.63	0.06	0.72	0.85	0.60	0.64	0.76	0.72	0.67	0.69
CaO/Al2O3	0.09	0.17	0.22	0.16	0.23	0.20	0.20	0.13	0.07	0.12	0.19
Na/K	1.78	1.14	0.99	0.73	3.91	0.93	3.13	0.92	0.50	3.29	2.81
Qz	34.88	23.16	29.22	49.30	32.16	17.49	25.68	32.52	22.25	34.82	20.19
Co	2.16	2.83	2.41	2.17	1.54	1.74	1.94	3.46	1.75	1.90	4.33
Or	12.59	16.13	16.61	10.75	5.32	16.96	7.62	16.84	32.09	8.10	6.62
Pl	41.89	42.37	40.57	19.72	49.54	45.88	54.77	34.62	35.24	51.37	45.68
Ab	36.05	29.45	25.30	12.52	33.42	30.46	38.33	24.96	25.72	42.90	29.87
An	5.84	12.93	15.27	7.20	16.12	15.42	15.93	9.66	9.51	8.47	15.81
Hy	6.01	12.67	7.01	14.72	8.01	13.17	6.97	10.76	6.93	2.03	19.55
Mt	0.10	0.29	0.13	0.39	0.20	0.94	0.09	0.06	0.32	0.01	0.17
Il	0.51	1.29	1.44	0.51	1.23	1.31	0.68	0.59	0.89	0.61	1.42
Ap	0.09	0.33	0.76	0.07	0.38	0.31	0.28	0.09	0.09	0.09	0.17
Di	-	-	-	-	-	-	-	-	-	-	-

	META-GREYWACKE										
	LNB 76	LNB 81	LNB 87	LNB 94	LNB 95	LNB 99	LNS 101	LNS 108	LNS 110	LNS 111	LNS 114
Cr	32.6	64.80	27.00	13.30	125.60	14.60	43.70	47.30	46.10	17.30	293.70
Mn	12.90	29.90	12.00	8.60	58.40	14.10	25.50	11.90	9.70	7.10	115.50
Rb	43.00	46.40	32.10	32.80	48.20	15.00	13.00	72.60	101.70	9.80	8.70
Sr	372.90	344.20	477.50	107.90	509.10	589.90	571.40	331.10	460.40	555.10	371.90
Y	18.40	11.60	6.50	201.90	13.40	1.00	3.10	71.20	23.30	3.40	21.90
Zr	179.10	113.70	20.70	483.40	130.60	235.50	16.30	367.20	622.40	306.70	70.90
Ba	384.90	671.20	2204.60	589.60	1098.50	2599.00	976.50	1034.40	3378.60	3340.40	353.70
Th	1.20	5.50	3.50	3.00	7.00	4.40	3.20	8.40	5.30	2.80	5.00
Zn	35.20	61.20	77.60	78.90	181.80	48.90	42.80	40.20	55.10	17.70	90.70
Cu	10.70	213.30	8.90	11.80	62.20	213.80	8.80	6.70	7.80	4.30	54.40
V	29.80	90.20	91.70	25.30	106.60	48.50	58.10	61.70	57.90	30.40	154.60
K/Rb	412.00	447.00	728.00	464.00	449.00	1588.40	822.00	326.00	448.00	1163.00	1066.00
K/Sr	47.47	65.78	49.00	141.00	43.00	40.40	19.00	71.60	99.00	21.00	25.00
K/Ba	45.99	33.73	10.57	25.57	18.03	9.23	10.94	22.90	13.35	3.40	26.22
Rb/Sr	0.12	0.13	0.07	0.30	0.10	0.03	0.02	0.22	0.22	0.02	0.02
Ba/Rb	8.95	14.47	68.67	17.98	22.79	1771.93	75.12	14.25	33.22	340.86	40.66
Ba/Sr	1.03	1.95	4.62	5.46	2.16	4.37	1.71	3.12	7.34	6.02	0.95
Ca/Y	483.70	1720.00	3850.00	52.77	864.40	23452.00	7773.00	200.80	604.50	3701.00	1080.70
al	43.95	33.18	42.37	30.82	45.50	36.06	43.34	41.36	42.81	49.28	35.46
fm	18.74	29.50	19.62	45.38	15.50	31.01	17.60	26.60	18.76	7.45	37.70
o	7.22	11.62	16.88	9.06	8.63	13.10	15.97	10.07	9.52	10.63	12.33
alk	30.08	20.40	21.12	14.74	30.37	19.83	23.07	21.97	28.91	32.64	14.51
si	402.65	263.53	304.59	428.56	346.35	236.31	298.64	329.49	308.39	418.83	217.13
K	0.25	0.34	0.38	0.45	0.25	0.34	0.16	0.39	0.54	0.15	0.17
my	0.43	0.50	0.47	0.41	0.45	0.54	0.50	0.36	0.40	0.46	0.45
qs	+182.34	+81.95	+120.11	+269.61	+124.85	+56.00	+106.36	+141.60	+92.75	+188.27	+59.08

APPENDIX

III

INAA

A - Analytical conditions & standards'

DATA

Table A.1 Nuclear data, detectors, and counting times for REE.

Nuclide	Half-life	Main energies (Kev); reactor Centre recommendation	Main energies (Kev) or peaks used	Detector used	Counting time (secs.)
¹⁴⁰ La	40.2 hrs	815.8, 1591.4	1595.0	Ge(Li)	600
¹⁴¹ Ce	33 days	145.4	145.60		
¹⁴⁷ Nd	11.1 days	91.4, 531.0	91.40		
¹⁵² Eu	12 days	121.8, 344.4	121.9		
¹⁵³ Sm	47 hrs	69.7, 103.2	103.1		
¹⁵³ Gd	242 days	97.4, 103.2	97.7		
¹⁶⁰ Tb	72.1 days	86.8, 298.5, 879.3	87.0		
¹⁶⁶ Ho	29.9 hrs	80.6	80.7		
¹⁶⁹ Yb	31.8 days	63.1, 109.8, 198.0	63.4		
¹⁷⁰ Tm	130 days	84.3	84.4		
¹⁷⁷ Lu	6.7 days	113.0, 208.4	208.4		

Germanium

6,000 - 10,800

Table A.2 Multi-elemental standards (μg per 0.09903 cm^3)

La 2.878

Ce 0.889

Nd 2.768

Sm 0.5932

Eu 0.1984

Gd 0.5983

Tb 0.0990

Ho 0.10184

Tm 0.08635

Yb 0.3961

Lu 0.06288

Table A.3. BCR-1 Analyses (values in p.p.m)

	La	Ce	Nd	Sm	Eu	Gd	Tb	Ho	Tm	Yb	Lu
1. Flanagan (1973)	26	53.9	29	6.6	1.94	6.6	1.0	1.2	0.6	3.36	0.55
2. University of London Reactor Centre	27 $\pm$ 1	44 $\pm$ 4	31 $\pm$ 3	7.2 $\pm$ 2	1.95 $\pm$ 0.05	5 $\pm$ 1	1.2 $\pm$ 0.1	1.4 $\pm$ 0.2	0.63 $\pm$ 0.06	3.6 $\pm$ 0.1	0.66 $\pm$ 0.03
3. Gordon et al (1968)	23 $\pm$ 2	46 $\pm$ 5	-	5.9 $\pm$ 0.05	1.95 $\pm$ 0.1	-	1.0 $\pm$ 0.1	-	0.6 $\pm$ 0.1	3.2 $\pm$ 0.4	0.60 $\pm$ 0.05
4. Rey et al. (1970)	29 $\pm$ 1	57 $\pm$ 2	33 $\pm$ 2	7.2 $\pm$ 0.2	2.1 $\pm$ 0.2	6.3 $\pm$ 0.3	0.82 $\pm$ 0.02	1.40 $\pm$ 0.02	0.53 $\pm$ 0.01	3.3 $\pm$ 0.10	0.57 $\pm$ 0.01
5. Haskin et al. (1968)	24-26	55-66	31	7.4- 7.5	1.93- 1.96	6.7- 8.1	1.8	1.22- 1.47	-	3.5	0.53
6. This work	27.65	49.57	33.00	7.29	1.90	5.90	1.34	0.94	0.51	3.32	0.54

B - SAMPLES' DATA

Classification based on Mineralogy.

SAMPLE NO.	QUARTZ - FELDSPATHIC GNEISS					MAFIC GNEISS	FELDSPATHIC GNEISS
	LNB 40	LNB 41	LNB 54	LNB 61	LNB 83	LNB 57	LNB 74
La	4.26	61.77	31.91	19.09	28.18	24.93	18.79
Ce	3.63	66.92	27.06	20.17	41.21	52.51	12.63
Nd	1.18	60.29	17.17	7.02	20.50	33.43	-
Sm	0.30	13.07	2.28	1.45	2.50	7.16	1.30
Eu	0.74	2.18	0.66	0.52	0.79	1.96	1.85
Gd	0.26	-	1.27	1.36	1.21	0.25	1.13
Tb	0.05	3.34	0.19	0.57	0.16	0.89	0.29
Ho	-	4.86	-	2.79	-	0.65	0.89
Tm	-	2.05	-	0.19	0.21	0.17	0.49
Yb	-	13.35	-	0.15	0.29	1.63	0.66
Lu	-	2.02	-	-	-	0.26	-
Σ REE	-	229.85	-	53.31	95.05	123.84	38.03
Y	-	152.50	2.90	2.10	2.20	22.00	4.06
Σ REE + Y	-	382.35	-	55.41	97.25	145.84	42.63
La/Yb	-	4.70	-	127.27	97.17	15.29	28.47
Σ LREE	-	202.05	78.42	47.73	92.39	118.03	32.72
Σ HREE	-	25.62	-	5.06	1.87	3.85	3.46
Σ LREE/ Σ HREE	-	7.89	-	9.43	49.41	30.66	9.46
La/Ce	1.17	0.94	1.18	0.95	0.68	0.47	1.48

SAMPLE NO.	BIOTITE SCHIST			QUARTZ BIOTITE SCHIST		
	LNB 9	LNB 37	LNB 19	LNB 24	LNB 25	LNB 94
La	37.67	61.41	17.53	22.14	20.40	15.76
Ce	67.00	39.50	10.31	19.73	34.78	5.94
Nd	35.87	68.77	1.71	5.73	13.35	7.14
Sm	7.74	12.08	0.54	1.34	2.04	2.88
Eu	1.36	1.86	1.45	2.34	2.07	1.05
Gd	6.50	-	1.40	1.47	1.66	1.89
Tb	1.38	2.35	0.27	-	0.27	2.48
Ho	1.34	1.55	1.24	1.76	0.13	1.30
Tm	0.54	-	0.78	-	0.17	-
Yb	4.36	5.17	4.25	0.12	1.66	22.50
Lu	0.67	0.71	0.73	-	0.29	3.17
Σ REE	164.45	193.35	40.21	54.63	76.82	70.59
Y	20.70	71.40	18.40	0.50	14.20	200.30
Σ REE + Y	185.15	264.75	58.61	55.13	91.02	270.89
La/Yb	8.70	11.88	4.12	184.50	12.29	0.70
Σ LREE	148.28	181.71	30.09	48.94	70.57	31.72
Σ HREE	14.81	9.78	8.67	3.35	4.18	31.34
Σ LREE/ Σ HREE	10.01	18.58	3.47	14.61	16.88	1.01
La/Ce	0.56	1.55	1.70	1.12	0.59	2.65

HORNBLLENDE GNEISS

SAMPLE NO.	LNB 30	LNB 31	LNB 32	LNB 34	LNB 56
La	11.00	13.81	10.21	16.83	6.35
Ce	33.92	79.57	21.71	-	12.71
Nd	18.82	20.50	17.75	37.44	8.23
Sm	4.86	5.41	4.51	9.17	8.00
Eu	1.40	1.38	1.45	1.61	0.41
Gd	4.29	5.08	4.46	7.83	2.56
Tb	0.95	0.94	0.87	1.65	0.44
Ho	0.74	1.05	1.42	2.90	0.80
Tm	0.47	0.14	0.40	-	-
Yb	3.34	3.00	2.95	6.00	1.26
Lu	0.52	0.46	0.49	0.72	0.07
Σ REE	80.31	131.72	66.22	85.76	40.83
Y	35.60	36.10	34.60	68.60	10.90
Σ REE + Y	115.91	167.82	100.82	154.36	51.73
La/Yb	3.29	4.60	3.46	2.81	5.04
Σ LREE	68.6	119.29	54.18	65.05	35.29
Σ HREE	10.31	10.67	10.59	19.10	5.13
Σ LREE/ Σ HREE	6.65	11.15	5.12	3.41	6.88
La/Ce	0.32	0.17	0.47	-	0.50

BIOTITE - MUSCOVITE - GARNET GNEISS.

SAMPLE NO.	LNB 7	LNB 8	LNB 12	LNB 16	LNB 22	LNB 33	LNB 35	LNB 36
La	31.75	40.38	44.55	35.43	41.29	31.93	30.51	31.00
Ce	125.86	33.06	36.73	89.00	36.40	69.04	21.81	118.04
Nd	23.25	43.41	49.32	33.27	45.87	30.32	22.76	31.51
Sm	3.76	7.44	9.14	5.73	7.56	5.37	5.31	5.34
Eu	1.91	1.61	1.34	0.91	1.54	8.43	1.56	1.85
Gd	2.44	4.77	6.03	4.38	6.05	4.48	5.14	4.84
Tb	0.30	0.81	0.88	0.55	0.48	0.54	0.59	0.42
Ho	0.17	-	1.36	-	0.69	0.43	-	0.43
Tm	-	0.82	-	-	-	0.05	-	-
Yb	0.26	1.21	2.52	0.89	0.25	1.29	1.00	0.84
Lu	0.06	0.29	0.17	0.21	-	0.18	0.13	0.11
Σ REE	186.00	133.80	152.04	170.37	140.13	151.98	98.81	194.38
Y	6.70	14.90	29.30	14.90	6.50	16.50	13.10	13.50
Σ REE + Y	192.70	148.70	181.34	185.27	146.63	168.48	111.91	207.88
La/Yb	122.12	33.37	17.68	39.81	165.16	24.75	30.57	36.90
Σ LREE	180.86	124.29	139.74	163.43	131.12	136.66	90.39	185.89
Σ HREE	3.23	7.90	10.96	6.03	7.47	6.89	6.86	6.64
Σ LREE/ Σ HREE	55.99	15.73	12.75	27.10	17.55	19.83	13.18	28.00
La/Ce	0.25	1.22	1.21	0.40	1.13	0.46	1.40	0.26

QUARTZITIC GNEISS

SAMPLE NO.	LNB 38	LNB 39	LNB 44	LNB 50
La	68.51	110.58	62.05	49.73
Ce	87.85	96.29	73.08	38.77
Nd	83.25	124.19	70.31	36.04
Sm	15.51	22.40	13.51	5.18
Eu	1.57	1.28	1.79	1.89
Gd	-	3.29	13.39	2.74
Tb	3.08	4.04	2.48	0.56
Ho	2.48	1.94	3.22	0.59
Tm	0.38	0.06	2.18	0.13
Yb	8.60	10.80	6.39	2.64
Lu	1.14	1.46	0.79	0.37
Σ REE	272.37	376.21	249.19	138.64
Y	90.20	116.80	78.10	32.00
Σ REE + Y	362.57	493.01	327.29	170.64
La/Yb	7.97	10.24	9.71	18.84
Σ LREE	255.12	353.38	218.95	129.72
Σ HREE	15.68	21.59	28.45	7.03
Σ LREE/ Σ HREE	16.27	16.37	7.70	18.45
La/Ce	0.78	1.15	0.85	1.28

SAMPLE NO.	QUARTZ MICA SCHIST		QUARTZ - MAGNETITE GNEISS	QUARTZ - GARNET - MICA GNEISS	
	LNB 43	LNB 76	LNB 90	LNB 42	LNB 49
La	53.10	28.16	26.00	61.01	13.94
Ce	61.10	23.15	47.51	152.29	14.18
Nd	56.78	17.02	28.10	67.01	5.85
Sm	12.17	2.61	8.03	13.79	0.85
Eu	1.21	0.99	0.82	2.18	2.23
Gd	12.26	-	5.82	18.34	0.43
Tb	2.70	0.39	2.15	2.91	0.24
Ho	4.52	0.80	-	3.24	0.41
Tm	2.89	-	0.56	1.23	0.20
Yb	8.08	1.46	2.42	9.27	0.96
Lu	0.99	-	0.41	1.47	0.10
Σ REE	215.80	74.58	121.92	332.74	39.39
Y	94.40	18.40	20.60	107.20	9.10
Σ REE + Y	310.20	92.98	142.52	439.94	48.49
La/Yb	6.57	19.29	10.74	6.58	14.52
Σ LREE	183.15	70.94	109.74	294.10	34.82
Σ HREE	31.44	2.65	11.36	36.46	2.34
Σ LREE/ Σ HREE	5.83	26.77	9.66	8.07	14.88
La/Ce	0.87	1.22	0.55	0.40	0.98

QUARTZ - BIOTITE - GARNET GNEISS

SAMPLE NO.

	LNB 6	LNB 10	LNB 15	LNB 17	LNB 21	LNB 26	LNB 62	LNB 63	LNB 81	LNB 87	LNB 95
La	47.22	35.22	23.37	-	27.64	36.81	91.94	41.61	46.61	39.70	54.26
Ce	37.66	67.46	17.38	12.54	23.79	150.27	182.87	166.50	35.98	31.67	106.93
Nd	47.62	33.45	18.57	22.15	36.22	25.42	35.68	43.77	42.91	36.85	79.51
Sm	8.88	5.00	3.08	4.22	6.54	3.56	5.90	8.27	6.51	5.14	12.20
Eu	1.73	1.57	1.10	1.18	1.02	1.13	1.37	1.72	1.35	1.78	2.20
Gd	1.94	4.53	2.32	5.64	-	2.67	-	-	3.21	3.28	2.42
Tb	0.84	0.44	0.37	0.50	0.99	0.30	1.06	1.31	0.83	0.26	1.17
Ho	1.58	0.70	0.37	-	0.80	0.36	0.50	0.87	2.04	0.34	-
Tm	0.30	0.19	-	-	-	-	-	0.01	-	-	0.16
Yb	1.46	1.95	0.62	1.01	0.63	0.38	0.67	2.31	1.39	0.36	1.06
Lu	0.25	0.37	0.05	-	-	0.12	0.14	0.41	-	-	0.18
ΣREE	149.49	150.88	67.43	-	97.63	221.01	270.13	266.78	140.83	119.38	260.11
Y	54.30	18.40	7.40	13.30	15.10	6.30	10.90	34.50	11.60	6.50	12.30
ΣREE + Y	203.79	169.28	74.83	-	112.73	227.31	281.03	301.28	152.43	125.88	272.41
La/Yb	32.34	18.06	37.69	-	43.87	96.87	62.60	18.01	33.53	110.28	51.19
ΣLREE	141.38	141.13	62.40	-	94.19	216.05	266.39	260.15	132.01	113.36	252.90
ΣHREE	6.38	8.18	3.93	-	-	3.83	2.37	4.91	7.47	4.24	4.99
ΣLREE/ΣHREE	22.16	17.25	15.88	-	-	56.41	112.40	52.98	17.67	26.74	50.68
La/Ce	1.25	0.52	1.35	-	1.16	0.24	0.23	0.25	1.30	1.25	0.51

SAMPLE NO.	ULTRAMAFIC GNEISS	GARNET GRANULITE		QUARTZ - GARNET - FELDSPAR GNEISS	QUARTZ - BIOTITE - GARNET GNEISS	QUARTZ - FELDSPAR - GARNET GNEISS	BIOTITE - GARNET GNEISS		QUARTZ - FELDSPATHIC GNEISS	
	LNS 113	LNS 104	LNS 112	LNS 111	LNS 108	LNS 101	LNS 110	LNS 99	LNS 114	LNS 115
La	41.43	68.49	21.24	37.14	42.14	42.73	36.10	27.95	28.39	15.75
Ce	19.14	46.13	34.52	23.13	63.93	24.33	26.85	60.23	49.87	42.17
Nd	85.14	52.06	17.22	4.96	28.57	21.40	5.77	24.18	23.28	20.97
Sm	17.43	8.63	3.59	1.01	5.17	2.83	1.30	2.59	4.18	3.74
Eu	3.33	2.01	1.44	2.00	1.51	1.65	1.79	1.35	1.48	1.11
Gd	12.93	9.65	2.90	0.44	3.41	0.98	0.50	1.43	1.84	3.72
Tb	1.75	1.87	0.52	0.14	1.86	0.32	0.44	0.15	0.75	0.43
Ho	1.28	2.42	-	0.41	-	0.26	-	-	2.66	0.39
Tm	-	1.95	0.34	0.86	1.45	-	0.72	0.32	0.14	-
Yb	2.55	4.94	2.40	0.77	7.50	0.76	2.73	0.11	1.65	0.76
Lu	0.31	0.53	0.25	0.04	1.26	-	0.35	0.01	0.36	0.17
Σ REE	185.29	198.68	84.42	70.90	157.39	88.60	68.40	138.04	114.60	89.21
Y	235.00	45.50	17.20	3.40	71.20	3.10	23.20	1.00	21.70	7.10
Σ REE + Y	420.29	244.18	101.62	74.30	228.59	91.70	91.60	139.04	136.30	96.31
La/Yb	16.25	13.86	8.85	48.23	5.70	47.40	10.24	433.45	17.21	20.72
Σ LREE	161.14	175.31	76.57	66.24	140.40	84.63	61.87	134.68	105.72	82.63
Σ HREE	18.82	21.36	6.41	2.66	15.48	2.32	4.74	2.01	7.40	5.47
Σ LREE/ Σ HREE	8.67	8.21	11.95	24.90	9.07	36.48	13.05	67.00	14.29	15.11
La/Ce	2.16	1.48	0.62	1.61	0.68	1.48	1.04	0.79	0.57	0.37

C - SAMPLES' DATA

Classification based on over - all geochemistry or possible origin

SAMPLE NO.	AMPHIBOLITE					BASIC GNEISS	RETROGRESSED LEUCO - GABBRO
	LNB 30	LNB 31	LNB 32	LNB 34	LNB 56	LNB 57	LNS 113
La	11.00	13.81	10.21	16.83	6.35	24.93	41.43
Ce	33.92	79.57	21.71	-	12.71	52.51	19.14
Nd	18.82	20.50	17.75	37.44	8.23	33.43	85.14
Sm	4.86	5.41	4.51	9.17	8.00	7.16	17.43
Eu	1.40	1.38	1.45	1.61	0.41	1.96	3.33
Gd	4.29	5.08	4.46	7.83	2.56	0.25	12.93
Tb	0.95	0.94	0.87	1.65	0.44	0.89	1.75
Ho	0.74	1.05	1.42	2.90	0.80	0.65	1.28
Tm	0.47	0.14	0.40	-	-	0.17	-
Yb	3.34	3.00	2.95	6.00	1.26	1.65	2.55
Lu	0.52	0.46	0.49	0.72	0.07	0.26	0.31
Σ REE	80.31	131.72	66.22	85.76	40.83	123.84	185.29
Y	35.60	36.10	34.60	68.60	10.9	22.00	235.00
Σ REE + Y	115.91	167.82	100.82	154.36	51.73	145.84	420.29
La/Yb	3.29	4.60	3.46	2.81	5.04	15.29	16.25
Σ LREE	68.6	119.29	54.18	65.05	35.29	118.03	163.14
Σ HREE	10.31	10.67	10.59	19.10	5.13	3.85	18.82
Σ LREE/ Σ HREE	6.65	11.15	5.12	3.41	6.88	30.66	8.67
La/Ce	0.32	0.17	0.47	-	0.50	0.47	2.16

GRANITIC GNEISS

SAMPLE NO.	LNB 40	LNB 41	LNB 54	LNB 61	LNB 83	LNS 115
La	4.26	61.71	31.91	19.09	28.18	15.75
Ce	3.63	66.92	27.06	20.17	41.21	42.17
Nd	1.18	60.29	17.17	7.02	20.50	20.97
Sm	0.30	13.07	2.28	1.45	2.50	3.74
Eu	0.74	2.18	0.66	0.52	0.79	1.11
Gd	0.26	-	1.27	1.36	1.21	3.72
Tb	0.05	3.34	0.19	0.57	0.16	0.43
Ho	-	4.86	-	2.79	-	0.39
Tm	-	2.05	-	0.19	0.21	-
Yb	-	13.35	-	0.15	0.29	0.76
Lu	-	2.02	-	-	-	0.17
Σ REE	-	229.85	-	53.31	95.05	89.21
Y	-	152.50	2.90	2.10	2.20	7.10
Σ REE + Y	-	382.35	-	55.41	97.25	96.31
La/Yb	-	4.70	-	127.27	97.17	20.72
Σ LREE	-	202.05	78.42	47.73	92.39	82.63
Σ HREE	-	25.62	-	5.06	1.87	5.47
Σ LREE/ Σ HREE	-	7.89	-	9.43	49.41	15.11
La/Ce	1.17	0.94	1.18	0.95	0.68	0.37

NETA - PELITE

SAMPLE NO.	LNB 9	LNB 37	LNB 90	LNS 104	LNS 112
La	37.67	61.41	26.00	68.49	21.24
Ce	67.00	39.50	47.51	46.13	34.52
Nd	35.87	68.77	28.10	52.06	17.22
Sm	7.74	12.08	8.03	8.63	3.59
Eu	1.36	1.86	0.82	2.01	1.44
Gd	6.50	-	5.82	9.65	2.90
Tb	1.38	2.35	2.15	1.87	0.52
Ho	1.34	1.55	-	2.42	-
Tm	0.54	-	0.56	1.95	0.34
Yb	4.38	5.17	2.42	4.94	2.40
Lu	0.67	0.71	0.41	0.53	0.25
Σ REE	164.45	193.35	121.92	198.68	84.42
Y	20.70	71.40	20.60	45.50	17.20
Σ REE + Y	185.15	264.75	142.52	244.18	101.62
La/Yb	8.70	11.80	10.74	13.86	8.85
Σ LREE	148.28	181.71	109.74	175.31	76.57
Σ HREE	14.81	9.78	11.36	21.36	6.41
Σ LREE/ Σ HREE	10.01	18.58	9.66	8.21	11.95
La/Ce	0.56	1.55	0.55	1.48	0.62

META - ARKOSE/IMPURE QUARTZITE

SAMPLE NO.	LNB 38	LNB 39	LNB 44	LNB 50
La	68.51	110.58	62.05	49.73
Ce	87.85	96.29	73.08	38.77
Nd	83.25	124.19	70.31	36.04
Sm	15.51	22.40	13.51	5.18
Eu	1.57	1.28	1.79	1.89
Gd	-	3.29	13.39	2.74
Tb	3.08	4.04	2.48	0.56
Ho	2.48	1.94	3.22	0.59
Tm	0.38	0.06	2.18	0.13
Yb	8.60	10.80	6.39	2.64
Lu	1.14	1.46	0.79	0.37
Σ REE	272.37	376.21	249.19	138.64
Y	90.20	116.80	78.10	32.00
Σ REE + Y	362.57	493.01	327.29	170.64
La/Yb	7.97	10.24	9.71	18.84
Σ LREE	255.12	353.38	218.95	129.72
Σ HREE	15.68	21.59	28.45	7.03
Σ LREE/Σ HREE	16.27	16.37	7.70	18.45
La/Ce	0.78	1.15	0.85	1.28

META-GREYWACKE											
SAMPLE NO.	LNB 6	LNB 7	LNB 8	LNB 10	LNB 12	LNB 15	LNB 16	LNB 17	LNB 19	LNB 21	LNB 22
La	47.22	31.75	40.38	35.22	44.55	23.37	35.43	-	17.53	27.64	41.29
Ce	37.66	125.86	33.06	67.46	36.73	17.38	89.00	12.54	10.31	23.79	36.40
Nd	47.62	23.25	43.41	33.45	49.32	18.57	33.27	22.15	1.72	36.22	45.87
Sm	8.80	3.76	7.44	5.00	9.14	3.08	5.73	4.22	0.54	6.54	7.56
Eu	1.73	1.91	1.61	1.57	1.34	1.10	0.91	1.18	1.45	1.02	1.54
Gd	1.94	2.44	4.77	4.53	6.03	2.32	4.38	5.64	1.40	-	6.05
Tb	0.85	0.30	0.81	0.44	0.88	0.37	0.55	0.50	0.27	0.99	0.48
Ho	1.58	0.17	-	0.70	1.36	0.57	-	-	1.24	0.80	0.69
Tm	0.30	-	0.82	0.19	-	-	-	-	0.78	-	-
Yb	1.46	0.26	1.21	1.95	2.52	0.62	0.89	1.01	4.25	0.63	0.25
Lu	0.25	0.06	0.29	0.37	0.17	0.05	0.21	-	0.73	-	-
ΣREE	149.49	186.00	133.80	150.88	152.04	67.43	170.37	-	40.21	97.63	140.13
Y	54.30	6.70	14.90	18.40	29.30	7.40	14.90	13.30	18.40	15.10	6.50
ΣREE + Y	203.79	192.70	148.70	169.28	181.34	74.83	185.27	-	58.61	112.73	146.63
La/Yb	23.34	122.12	33.37	18.06	17.68	37.69	39.81	-	4.12	43.87	165.16
ΣLREE	141.38	180.86	124.29	141.13	139.74	62.40	163.43	-	30.09	94.19	131.12
ΣHREE	6.38	3.23	7.90	8.18	10.96	3.93	6.03	-	8.67	-	7.47
ΣLREE/ΣHREE	22.16	55.99	15.73	17.25	12.75	15.88	27.10	-	3.47	-	17.55
La/ce	1.25	0.25	1.22	0.52	1.21	1.35	0.40	-	1.70	1.16	1.13

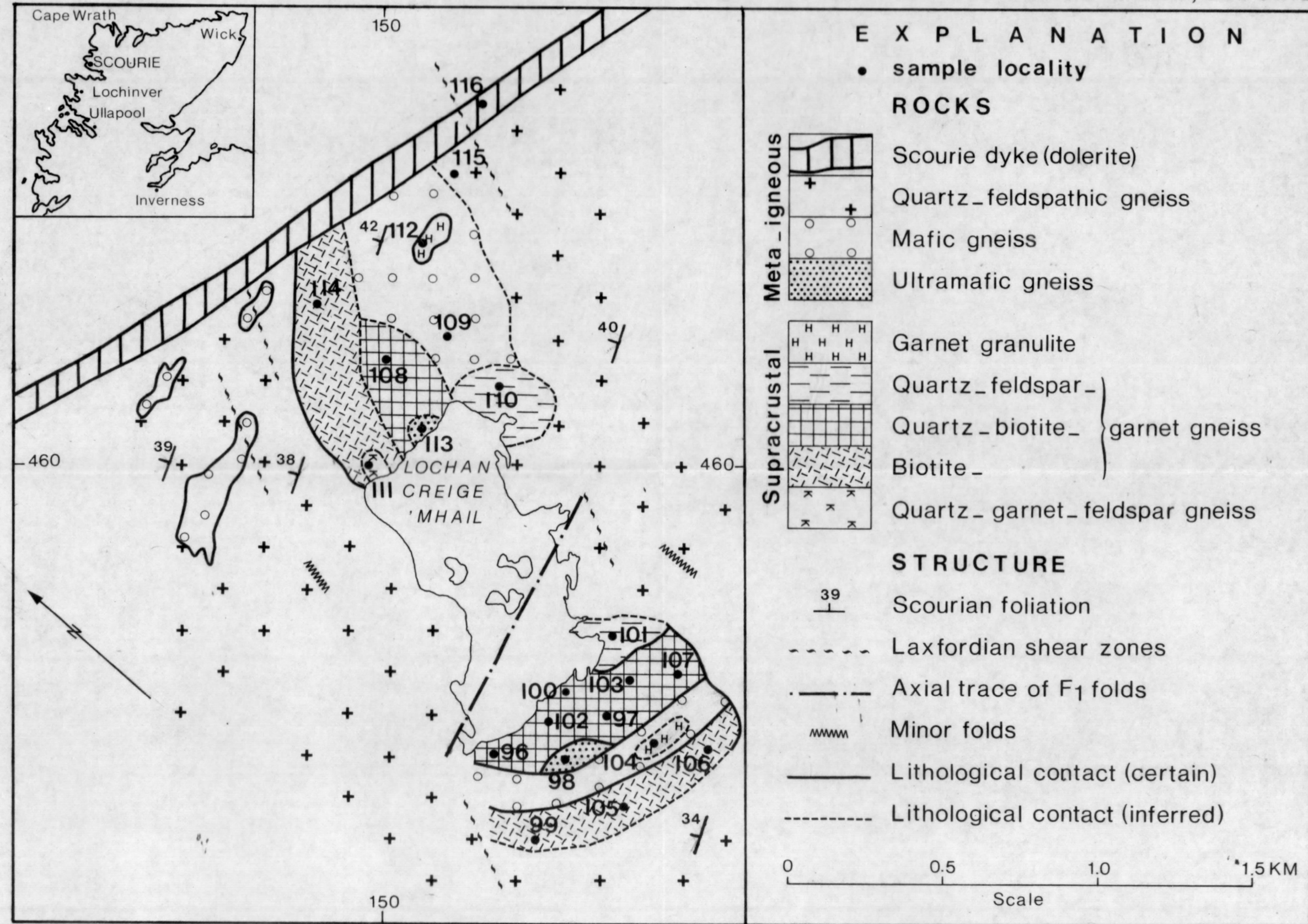
META - GREY WACKE

SAMPLE NO.	LNB 24	LNB 25	LNB 26	LNB 33	LNB 35	LNB 36	LNB 42	LNB 43	LNB 49	LNB 62	LNB 63	LNB 74
La	22.14	20.40	36.81	31.93	30.51	31.00	61.01	53.10	13.94	41.94	41.61	18.74
Ce	19.73	34.70	150.27	69.04	21.81	118.04	152.29	61.10	14.18	182.87	166.50	12.63
Nd	5.73	13.35	25.42	30.32	32.76	31.51	67.01	56.78	5.85	35.68	43.77	-
Sm	1.34	2.04	3.56	5.37	5.31	5.34	13.79	12.17	0.85	5.90	8.27	1.30
Eu	2.34	2.07	1.13	8.43	1.56	1.85	2.18	1.21	2.23	1.37	1.72	1.85
Gd	1.47	1.66	2.67	4.48	5.14	4.84	18.34	12.26	0.43	-	-	1.13
Tb	-	0.27	0.30	0.54	0.59	0.42	2.91	2.70	0.24	1.06	1.31	0.29
Ho	1.76	0.13	0.36	0.43	-	0.43	3.24	4.52	0.41	0.50	0.87	0.89
Tm	-	0.17	-	0.05	-	-	1.23	2.89	0.20	-	0.01	0.49
Yb	0.12	1.66	0.38	1.29	1.00	0.84	9.27	8.08	0.96	0.67	2.31	0.66
Lu	-	0.29	0.12	0.18	0.13	0.11	1.47	0.99	0.10	0.14	0.41	-
ΣREE	54.63	76.82	221.01	154.98	98.84	194.38	332.74	215.80	39.39	270.13	266.78	38.03
Y	0.50	14.20	6.30	16.50	13.10	13.50	107.20	94.40	9.10	10.90	34.50	4.06
ΣREE + Y	55.13	91.02	227.31	168.48	111.91	207.88	439.94	310.20	48.49	281.03	301.28	42.63
La/Yb	184.50	12.29	96.87	24.75	30.57	36.90	6.58	6.57	14.52	62.60	18.01	28.47
ΣLREE	48.94	70.57	216.05	136.66	90.39	185.89	294.10	183.15	34.82	266.39	260.15	32.72
ΣHREE	3.35	4.18	3.83	6.89	6.86	6.64	36.46	31.44	2.34	2.37	4.91	3.46
ΣLREE/ΣHREE	14.61	16.88	56.41	19.83	13.18	28.00	8.07	5.83	14.88	112.40	52.98	9.46
La/ce	1.12	0.59	0.24	0.46	0.40	0.26	0.40	0.87	0.98	0.23	0.25	1.48

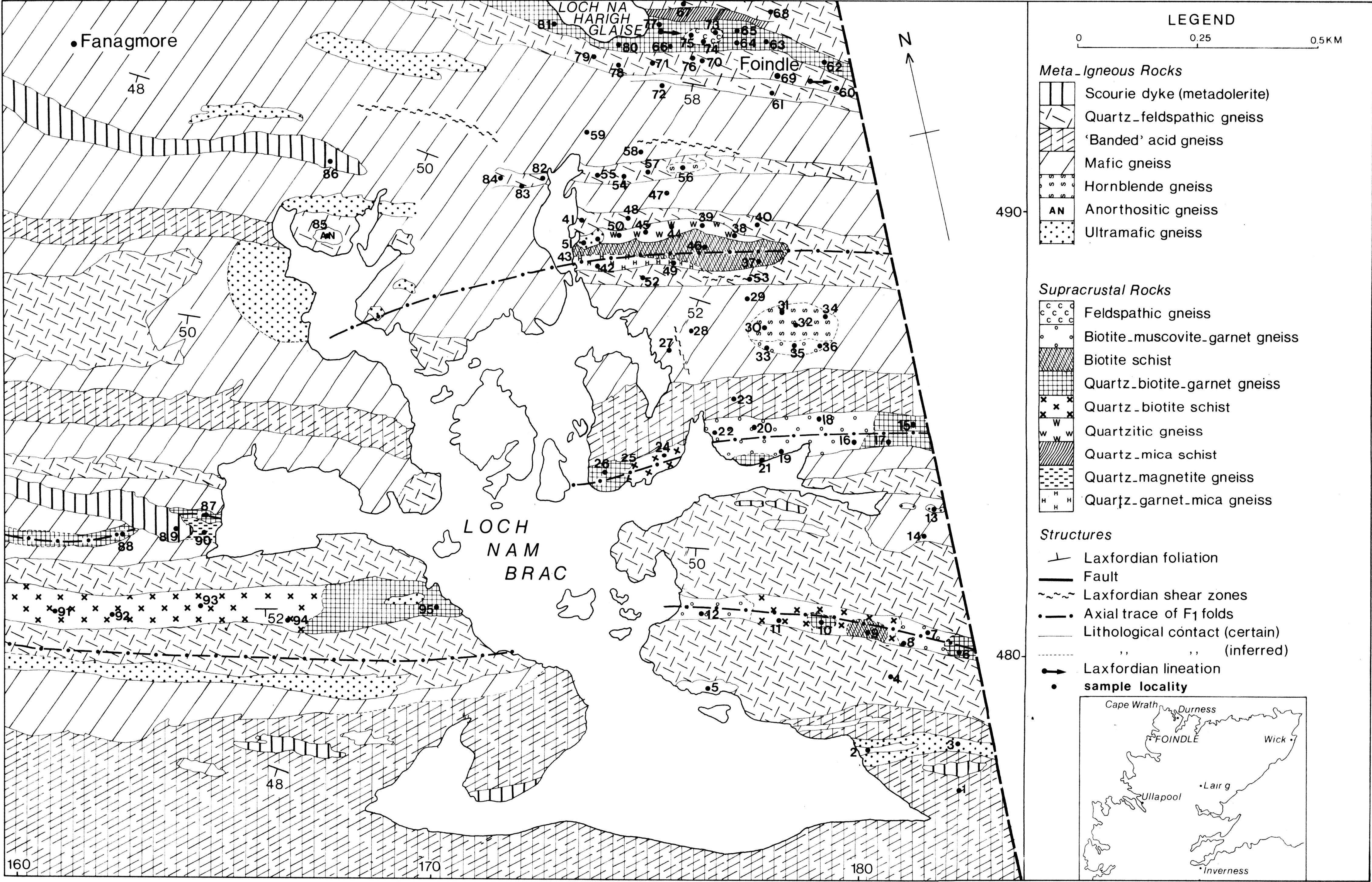
META-GREYWACKE

SAMPLE NO.	LNB 76	LNB 81	LNB 87	LNB 94	LNB 95	LNB 99	LNS 101	LNS 108	LNS 110	LNS 111	LNS 114
La	28.16	46.81	39.70	15.76	54.26	47.68	36.10	42.73	27.95	37.14	28.39
Ce	23.15	35.98	31.67	5.94	106.93	60.23	24.33	63.93	26.85	23.13	49.87
Nd	17.02	42.91	36.85	7.14	79.51	24.18	21.40	28.57	5.77	4.96	23.28
Sm	2.61	6.51	5.14	2.88	12.20	2.59	2.83	5.17	1.30	1.01	4.18
Eu	0.99	1.35	1.78	1.05	2.22	1.35	1.65	1.51	1.79	2.00	1.48
Gd	-	3.21	3.28	1.89	2.42	1.43	0.98	3.41	0.50	0.44	1.84
Tb	0.39	0.83	0.26	2.48	1.17	0.15	0.32	1.86	0.44	0.14	0.75
Ho	0.80	2.04	0.34	1.30	-	-	0.26	-	-	0.41	2.66
Tm	-	-	-	-	0.16	0.32	-	1.45	0.72	0.86	0.14
Yb	1.46	1.39	0.36	22.50	1.06	0.11	0.76	7.50	2.73	0.77	1.65
Lu	-	-	-	3.17	0.18	0.01	-	1.26	0.35	0.04	0.36
ΣREE	74.58	140.83	119.38	70.59	260.11	138.04	88.60	157.39	68.40	70.90	114.60
Y	18.40	11.60	6.50	200.30	12.30	1.00	3.10	71.20	23.20	3.40	21.70
ΣREE + Y	92.98	152.43	125.88	270.88	272.41	139.04	91.70	228.59	91.60	74.30	136.30
La/Yb	19.29	33.53	110.28	0.70	51.19	433.45	47.40	5.70	10.24	48.23	17.21
ΣLREE	70.94	132.01	113.36	31.72	252.90	134.68	84.63	140.40	61.87	66.24	105.72
ΣHREE	2.65	7.47	4.24	31.34	4.99	2.01	2.32	15.48	4.74	2.66	7.40
ΣLREE/ΣHREE	26.77	17.67	26.74	1.01	50.68	67.00	36.48	9.07	13.05	24.90	14.29
La/Ce	1.22	1.30	1.25	2.65	0.51	0.79	1.48	0.68	1.04	1.61	0.57

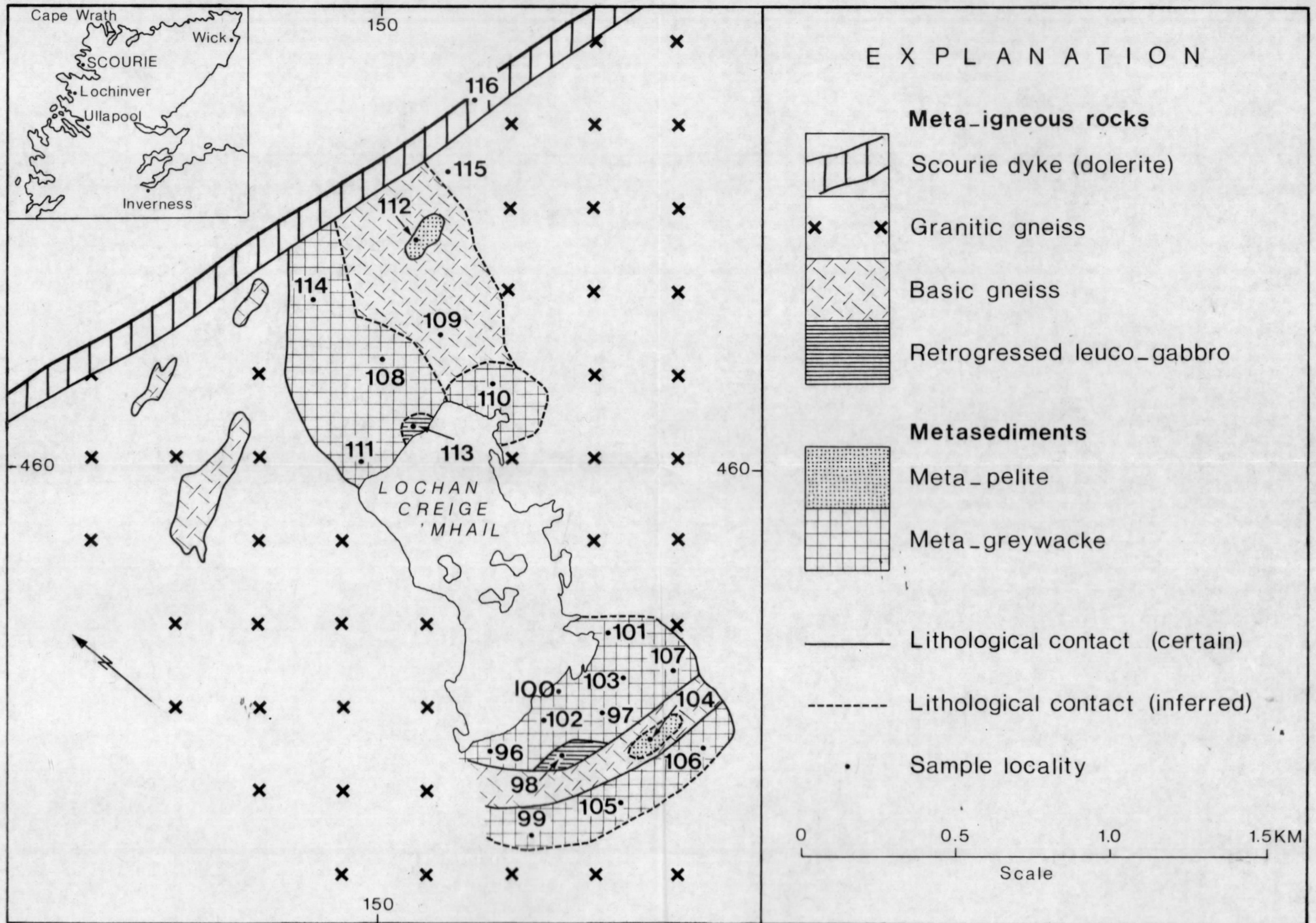
Map 1 - GEOLOGICAL MAP OF THE SUPRACRUSTAL BELT AROUND LOCHAN CREIGE 'MHAIL, SCOURIE



Map 2 - GEOLOGICAL MAP OF THE SUPRACRUSTAL BELT AROUND LOCH NAM BRAC, FOINDLE



Map 3 - LITHOLOGICAL MAP OF THE SUPRACRUSTAL BELT AROUND LOCHAN CREIGE 'MHAIL, SCOURIE



Map 4 - LITHOLOGICAL MAP OF THE SUPRACRUSTAL BELT AROUND LOCH NAM BRAC, FOINDLE

