Keele UNIVERSITY

A STUDY OF THE GRANITES AND ASSOCIATED LEWISIAN ROCKS OF LOCH LAXFORD, SUTHERLAND.

by

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ABSTRACT

The area studied, approximately 12 sq. km. in extent, lies at the landward end of Loch Laxford. Field mapping on a scale of about 1: 2,500 was followed by detailed petrographical, geochemical, and spectrochemical analyses.

The rock groups can be divided into 1. four groups of gneisses, namely the Claise Fearna, Badnabay, Weaver's Bay and Laxford Bay gneisses; 2. the Early Igneous Rocks, comprising metaperidotites, hornblendites, garnet-pyriclasites, amphibolites, plagioclasites, and metadiorites; 3. the Trondhjemitic Injection complex; and 4. the Granitic Injection complex.

It is concluded that two metamorphic episodes have affected the rocks thus: an Early granulite facies (= ?Scourian) metamorphism and a Later amphibolite facies (Laxfordian) metamorphism.

The gneisses are metasedimentary in origin, the parent rock being greywacke. The metagreywackes have suffered both metamorphisms and are now represented by trondhjemitic, quartz-dioritic, granodioritic, and granitic gneisses. They were intruded by those Early Igneous rocks that appear to form part of differentiating igneous series, that is, the metaperidotites, hornblendites, the metagabbro-anorthosite rocks, and the metadiorites. This igneous series has also suffered two metamorphisms. Certain amphibolites appear to be equivalent to the Scourie dyke swarm and are considered to be meta-tholeiites intruded after the granulite facies metamorphism but prior to the amphibolite facies metamorphism.

The Trondhjemitic Injection complex developed during the early part of the Laxfordian ~~complex~~ metamorphism and was accompanied by an extensive sodium metasomatism. Some trondhjemites are folded whereas others cut the Laxfordian foliation.

The Granitic Injection complex developed during the Laxfordian metamorphism and may have partly overlapped the Trondhjemitic Injection complex. The Injection complex proper (The Cnoc nan Cro group) has produced a series of microgranites, granites and

pegmatites intruded concordantly into the pre-existing rocks. Extensive potassium metasomatism, associated with the complex, has produced the Badnabay group - a series of microgranites, microsyenites, and other granitic rocks - and microgranite-trondhjemite bodies. The Laxford Quartzofeldspathites are granitic bodies developed locally by anatexis.

The Laxfordian phase of folding has produced NW-SE folds plunging SE and an associated axial plane foliation that dips to the SW. A late phase of E-W folding is also seen. NE-SW and WNW-ESE jointing, occasionally filled by pegmatitic material, represents the final phase of the Laxfordian metamorphism.

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I. INTRODUCTION

Geological background

In the Lewisian complex of the North West Highlands, three major zones were recognised and described by the Geological Survey (Peach and others, 1907, pp. 126-7 and pp. 172-190). These are (fig.1) (i) the northern zone, extending from Cape Wrath to a line between Tarbet and Ben Dreavie; (ii) the central zone, extending from this line to Loch Broom; and (iii) the southern zone, extending southwards from a line between Gruinard Bay and Loch na Sheallag, to include all remaining outcrops of Lewisian rocks. According to the Survey the northern zone consists of interbanded grey biotite-gneiss, hornblende-biotite-gneiss, hornblende-gneiss, and amphibolites, intruded by later granites and pegmatites, which are most abundant towards the southern margin. The central zone is typified by grey pyroxene-granulites and pyroxene-gneisses. The southern zone is similar to the northern zone except for the occurrence of metasediments in the Gairloch and Loch Maree districts, the occasional patch of pyroxene-granulites, and the absence of granites.

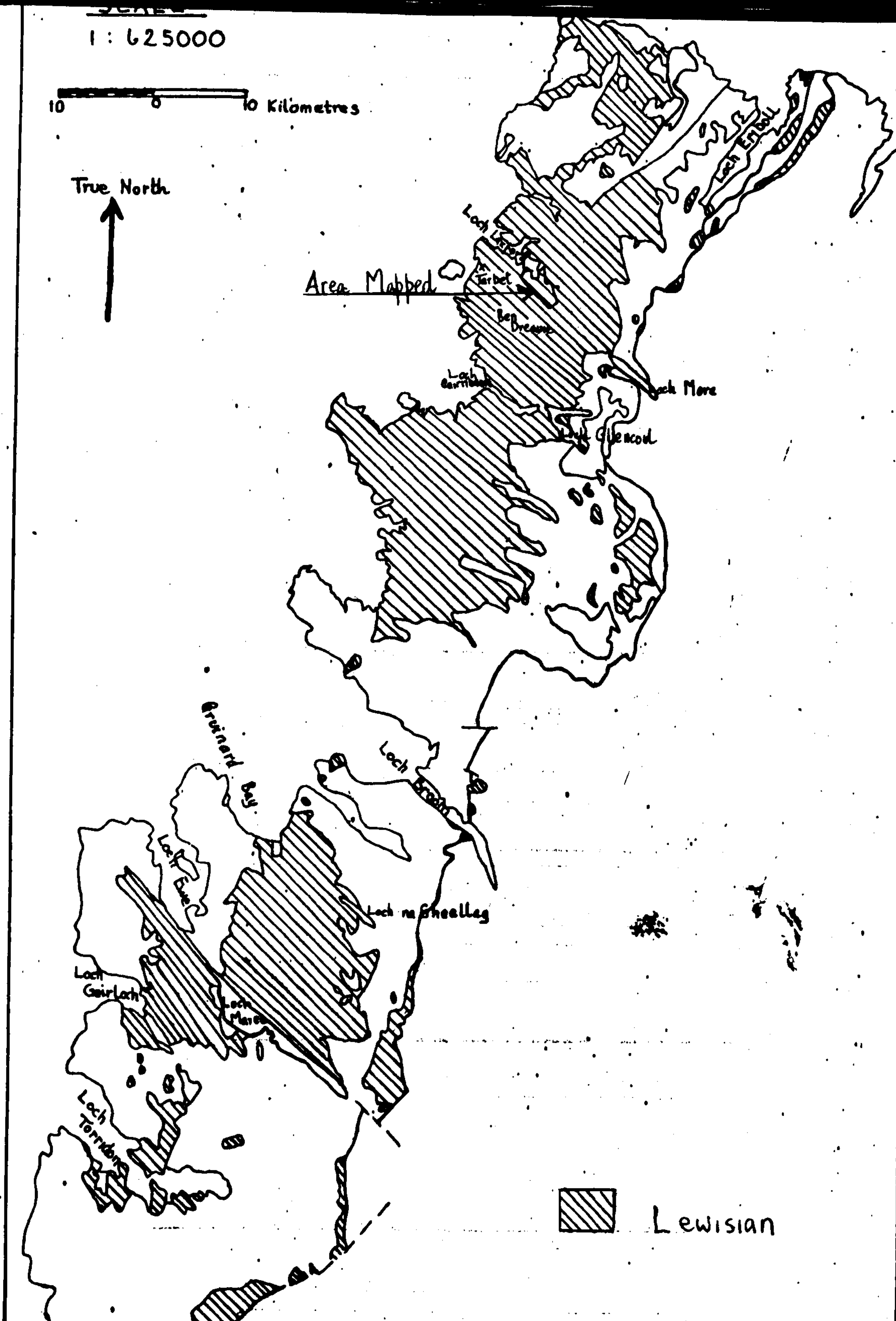


Fig. 1. Mainland Lewisian outcrop west of the Moine thrust in North-west Scotland.

These zones were confirmed by Sutton and Watson and used to define the Scourian and Laxfordian complexes (Sutton and Watson, 1951, p.292) the former occupying the central zone of the Geological Survey and the latter occupying the northern and southern zones. On the basis of the progressive metamorphism of a series of NW-SE trending dolerite dykes, Sutton and Watson (1951, p.295) separated the two metamorphic complexes in time as well as space, thus establishing a metamorphic history for the Lewisian, as follows:-

(1) An earlier metamorphism (Scourian) which gave rise to charnockitic gneisses in the north and hornblende - and biotite-gneisses in the south.

(2) The intrusion of a series of NW-SE trending dolerite dykes.

(3) A later metamorphism (Laxfordian) which resulted in the formation of hornblende - and biotite-gneisses in the north and south and the transformation of dolerites into amphibolites. In the north granites and pegmatites were associated with this metamorphism, while the central zone was unaffected by it.

This sequence of events has been partly confirmed by age determinations. A range of ages from 1900 million to 2460 million years has been obtained for pegmatites occuring in the Scourian (Giletti and others, 1961, p.241) while specimens from the Laxfordian yield a range of ages from 1160 million to 1620 million years. It has, therefore, been suggested that the Scourian metamorphism occurred at least 2,460 million years ago and the Laxfordian metamorphism occurred between 1,600 million and 1,500 million years ago (Giletti and others, 1961). More recent age-determinations have distinguished around Lochinver a further metamorphism (Inverian) of almandine-amphibolite facies occurring 2,200 million years ago (Evans & Lambert 1964).

The area between Loch Laxford and Loch Cairnbawn (fig 1) is further divided by Clough (in Peach and others, 1907, p.126) into three belts, thus:

(1) The southern belt, which belongs to the central zone (Scourian).

(2) The middle belt, part of the northern zone, where the hornblende and biotite gneisses are partly granulitic and are invaded by acid veins and cut by shear belts (Transitional).

(3) The northern belt, in which the hornblende and biotite gneisses are invaded by numerous sheets of granite and pegmatite and shear belts are absent (Laxfordian).

Watson (in Sutton and Watson, 1951) recognised a series of five zones on a structural and mineralogical basis, representing a gradual transition from Scourian rocks into Laxfordian rocks at the northern junction between the two complexes (map 1). These zones are

(1) The Scourie zone (part of Clough's southern belt) where the effects of the Scourian metamorphism are still dominant; this zone is cut by occasional Laxfordian shearbelts.

(2) The Claisfearn zone (equivalent to part of Clough's middle belt) where the acid charnockites have been completely metamorphosed. There is a constant NW-SE strike and shearbelts are more numerous.

(3) The Foindle zone (also equivalent to part of Clough's middle belt) which changes in character from the south-west to the north-east. Gradually the original banding is obscured and a new foliation of Laxfordian age is produced.

(4) The Badnabay zone, equivalent to part of Clough's northern belt, where the gneisses are plane-banded and intruded by numerous sheets of granite. The folds are plastic and the foliation parallel to their axial plane.

(5) The Laxford zone, also equivalent to part of Clough's northern belt, where an axial plane foliation is not developed, and the mineral banding appears to represent original Scourian banding. The gneisses exhibit plastic deformation.

The Scourie, Foindle and Badnabay zones represent "a progressive structural series whose evolution is controlled by the increasing mobility produced by metamorphism" (op.cit., p.279). Watson suggested that these three zones together with the Laxford zone show a sequence of changes indicating that granitisation advanced from the north-east and culminated in the development of numerous granites and pegmatites in the Badnabay and Laxford zones. A series of mineralogical transformations associated with the development of amphibolites from metadolerites suggested that the degree of alteration is a measure of the intensity of the Laxfordian metamorphism. In the Laxford and Badnabay zones metadolerites have been completely altered to amphibolites.

Nutter (1953), who carried out unpublished research on the trace elements of the granites and pegmatites of north-west Sutherland, reached only general conclusions: that the regional variation in the trace elements was consistent with Watson's hypothesis (op.cit.) that the Laxfordian metamorphism, accompanied by the intrusion of a series of NW-SE trending granite and pegmatite sheets, advanced from the north-east to a line one mile or so south-west of Laxford Bridge, and then receded to the north-east, and that the granites and pegmatites, although not all of the same age, were derived from a common source which was undergoing continuous differentation resulting in minor changes in the composition of the intruding material.

Hitchon (1960) who also investigated some of the Lewisian pegmatites, concluded that most of the pegmatites, which occur as a series of concordant sheets, are of magmatic origin. He also pointed out the close chemical similarity of the pegmatites to the rocks which they intrude.

Recently the hypotheses of Sutton and Watson (1951) that the Laxfordian rocks represent Scourian rocks transformed by the Laxfordian metamorphism and that there is only one swarm of dolerite dykes which are anorogenic and occur between the two metamorphisms, have been questioned by a number of workers. Bowes (1962a) suggested that, north of Scourie, the Laxfordian complex represents "folded and metamorphosed metasediments and metabasites", tectonically moved into its present position against the Scourian complex. However, detailed evidence in support of this suggestion is lacking. The use of the dykes in separating the two metamorphic complexes has suffered rather more criticism. Park (1961, 1964), Bowes (1962b)&Wright (1962) have all suggested that there is more than one series of dolerite dykes in the Lewisian, some of which are late Laxfordian in age. Tarney (1963) confirmed that the dykes are not all of the same age; he also confirmed that the dykes of Assynt were intruded at great depth under metamorphic conditions, as suggested by O'Hara (1962) for the Scourie dykes.

Bowes, Wright and Park (1964) have described a series of layered basic and ultrabasic intrusive rocks from the Lewisian between Loch Laxford and Loch Torridon. These rocks exhibit mineralogical banding and sedimentation features. One group has undergone granulite facies metamorphism (= Scourian); and second group has undergone a hydrous metamorphism (= Laxfordian); and a third group, which is later (post Laxfordian?) shows only uralitization of the pyroxenes.

Summary of the results of the present investigation

The area studied, approximately 12 sq. km. in extent, lies on both sides of Laxford Bay at the landward end of Loch Laxford (fig.1). The boundary is marked by a line joining the following landmarks (map 1): Badcall Quay, Loch na Fiacail, Laxford Bridge, Duchess' Pool, Cnoc Bad na h-Achlaise, Loch na Claise Fearna and Weaver's Bay. It lies entirely within the northern zone of the Geological Survey, that is within the Laxfordian as defined by Sutton and Watson (map 1). The south-western edge lies within Clough's middle belt (p.3), and within the Foindle zone as defined by Watson (p.4). The area also includes parts of Watson's Badnabay and Laxford zones. Part of the area lies within that mapped by Watson; the remainder has not been mapped since the Survey's work.

In many places the rocks are covered by a thin layer of drift, generally peat. However, exposures are on the whole excellent and many coastal sections yield complete exposure.

Previous discussions of the granitic rocks of the Laxford area (Peach and others, 1907) and (Watson, op.cit.) have shown that they exhibit considerable variation, for example Clough (op. cit., p.145) has described banded granites from several localities and Watson (op.cit.p.287) has stated that the granite sheets contain basic horizons; these writers have respectively ascribed a magmatic and

and metasomatic origin to the granites. It was, therefore, considered that a detailed study of the granites was required.

An area of small extent was chosen so that detailed mapping could be carried out. In order to establish the origin of the granitic rocks it was considered that a detailed knowledge of the other rock-types was required and therefore the mapping was primarily concerned with the position and relations of the various rock-types: the acid gneisses, the basic and ultrabasic rocks, the metadiorites, the trondhjemites and the granitic rocks; a detailed structural analysis was not attempted. The thesis is a study of these rock-types with particular emphasis on the origin of the granitic rocks and associated phenomena.

Field mapping was followed by detailed petrographical, geochemical and spectrochemical analyses of representative specimens and as a result four rock groups have been recognised thus:-

1. The Gneisses: Quartzose streaky or striped gneisses subdivided into the Claise Fearna, Badnabay, Weaver's Bay and Laxford Bay gneisses, each sub-group exhibiting distinguishing features (pp.67-8). Their geographical distribution is shown in map 1.

2. The Early Igneous Rocks: metaperidotites, hornblendites, garnet-pyriclasites, amphibolites, and metadiorites. The evidence suggests that many of these rock-types may represent the metamorphosed products of a series of related igneous rocks. The amphibolites that represent metatholeiites are probably equivalent, in part, to the Scourie dyke swarm.

3. The Trondhjemitic Injection Complex: trondhjemitic rocks. The injection of veins and sheets of trondhjemitic material was accompanied by widespread sodium metasomatism.

4. The Granitic Injection Complex: granitic and syenitic rocks. The Cnoc nan Cro group, composed of microgranites, granites, pegmatites, and migmatites forms the injection complex, sensu stricto, while the Badnabay group, composed of granitic, syenitic, and granodioritic types represents the products of potassium metasomatism related to the injection complex. The Rudha Ruadh and Loch na Seilge sheets (map 1) (pp.141-50) are prominent members of the latter group. The geographical distribution of these two groups can be seen in map 1. The NE-SW pegmatite dykes represent the final stage of magmatic activity. The Laxford Quartzofeldspathites are bodies that appear to have been formed by local anatexis during the development of the injection complex. Potassium metasomatism is associated with this complex.

The Laxfordian complex has suffered an earlier granulite facies (= Scourian?) and a later amphibolite facies (= Laxfordian) metamorphism. The injection complexes were associated with the later metamorphism.

Methods of Research

Field technique.

Mapping of the area was carried out using enlarged aerial photographs on a scale of approximately 25 inches to a mile. Data obtained in this way were later transferred to a 6 inches to a mile Ordnance Survey sheet.

While in the field an attempt was made to ascertain the mineralogical variation in the area by collecting specimens with one fairly flat surface at right angles to the foliation or as near to that as possible. This flat surface was dipped into hydrofluoric acid, care being taken to ensure that the entire surface was etched by the acid. After two minutes the specimen was removed and allowed to dry, when it was placed in a saturated solution of sodium cobaltinitrite for four minutes. The specimen was then removed and the excess sodium cobaltinitrite washed away. When the specimen was dry, quartz appeared glassy, plagioclase greyish white and potash felspar bright yellow; the mafics remained readily identifiable. A visual estimation of the amount of each mineral present was then made.

While field estimation of the amounts of the minerals present was of limited accuracy this technique proved extremely useful. Granitic rocks were quickly identified, trondhjemitic, tonalitic and potash feldspar-rich granodioritic gneisses were readily differentiated, and several other interesting features (described later) were discovered. This technique could be used with success in many migmatite areas, especially where potassium metasomatism is thought to have occurred.

Petrographic technique

A great many hand specimens were cut at right angles to the foliation and stained in the laboratory by the method just described. The smooth surface resulted in a better stain; textural relationships were more readily observed.

Numerous thin sections were examined in the conventional manner. To enable textural and mineral relationships to be carefully examined many of the thin sections were stained using either Chayes' sodium cobaltinitrite method for potash felspar (Chayes, 1952) or Bailey and Stevens' method which used sodium cobaltinitrite to stain potash felspar yellow and potassium rhodizonate to stain plagioclase pink (Bailey and Stevens, 1960). This staining also facilitated mineral identification during modal analysis.

The universal stage was used to determine the optic angle of pyroxenes and potash felspar (Winchell, 1937).

Modal analysis

The great majority of the specimens which were analysed chemically were also analysed modally using the Swift automatic point counter. Each analysis was made by identifying and counting the mineral on the cross-wire intersection, the point counter stage moving a distance of 0.3 mm in an east-west direction on each count. The east-west traverses were spaced 0.6 mm apart. In most cases between 2100 and 2500 points were counted usually over one thin section. The total area traversed was 400 sq. mm or more.

The IC number (Chayes, 1956, pp. 72-73) was determined for each thin section. This was never less than 70, except in the case of granites and pegmatites. In thin sections with IC numbers of seventy or greater Chayes established that the analytical error in point counting an area of 400 sq. mm is equal to or less than $\pm 2\%$. On the basis of a graph established by Barringer (1953) the maximum analytical error involved is $\pm 2\%$ (for 2,500 counts) which was the error for 50% of a mineral constituent; the analytical error decreased as the amount present increased or decreased from 50% (Table 1). If the amount present is 0.2% or less the analytical error is greater than or equal to the amount present, so that percentages of 0.2 or less, obtained from point countings, are meaningless. In the modal analyses which follow,

Amount present in per cent	Analytical error
0.05	± 0.10-0.09
0.10	± 0.14-0.13
0.20	± 0.20-0.18
0.50	± 0.31-0.28
1.00	± 0.45-0.40
5.00	± 1.00-0.90
10 and 90	± 1.40-1.25
15 and 85	± 1.65-1.45
20 and 80	± 1.80-1.60
25 and 75	± 1.90-1.75
30 and 70	± 2.00-1.80
35 and 65	± 2.10-1.90
40 and 60	± 2.15-1.95
50	± 2.25-2.00

Table 1. Errors in modal analysis using a point count of 2000 to 2500, based on a chart by Barringer(1953).

all mineral constituents that are present in a thin section (including those which may not have been point counted) but which account for 0.2% or less by volume of the rock, are designated as "trace". Table 1 should be referred to whenever a knowledge of the errors involved in any modal analysis is important.

Chemical analysis

After testing various methods of silicate analysis a scheme based primarily on the methods of Riley (1958a and 1958b) and Shapiro and Brannock (1956 and 1962) was evolved (Table 2).

TABLE 2.

OXIDE	METHOD	COMMENT
SiO_2	Riley (1958a)	Slightly modified see (1) below.
Al_2O_3	Riley (1958a) or Shapiro & Brannock (1962)	See (2) below.
Total iron as Fe_2O_3	Riley (1958a)	
FeO	Shapiro & Brannock (1956)	Slightly modified See (3) below.
MgO } CaO }	Riley (1958a)	See (4) below for removal of interfering ions.
Na_2O } K_2O }	Riley (1958a)	
TiO_2	Riley (1958a)	
P_2O_5	Riley (1958a)	
MnO	Riley (1958a)	
H_2O	Riley (1958b)	
CO_2	Riley (1958b)	

(1) Solution A was prepared following Riley (1958a) except that the acid used to neutralise the fused caustic cake, (25ml of 2.5N H_2SO_4) was replaced by 20ml 50 per cent HCl. Solution A is used to determine SiO_2 using Riley's molybdenum blue method (Riley, 1958a) and the change made in the preparation of Solution A required a slight adaptation to be made to the acid molybdate reagent which was, therefore, prepared as follows:-
8g ammonium molybdate A.R. were dissolved in 500ml water; 20ml concentrated HCl A.R. and 12.5ml N H_2SO_4 were added and the whole diluted to 1,000ml.

(2) Solution A was used also to determine Al_2O_3 using the Alizarin Red-S method of Shapiro and Brannock (1962). Al_2O_3 was also determined in Solution B using Riley's method (Riley, 1958a).

(3) The Shapiro and Brannock (1956) method for the determination of FeO was slightly modified as follows:-
After weighing 0.5000g of the rock powder into a platinum crucible 10ml 50 per cent H_2SO_4 and 5ml HF were added to the crucible. The contents were heated on a hot-plate for at least 25 minutes at a surface temperature of 200°C, to ensure that the contents had been boiling for at least 15 minutes. The rest of the method was unaltered.

(4) Before the chelatometric determination of CaO and MgO, iron and aluminium, which would otherwise have interfered considerably, had to be removed. This was done by precipitating them as hydroxides at pH 5., using a dilute solution of ammonium hydroxide. 100ml of Solution B, to which 50ml water was added, was used; after the hydroxides were precipitated the solution was made up to 250ml in a volumetric flask and was then filtered through Whatman's No.40 filter paper; the filtrate which had to be clear was then used for the determination of CaO and MgO.

Discussion of the methods of chemical analysis

To determine the precision of each method, replicate determinations of each oxide were made over a range of concentrations. The results are shown in Table 3. The precision of each method is not significantly different from that obtained by Mercy (1960) who states that the errors in his methods are "within the maximum limits of error for single determinations postulated in normal analytical practice" (Mercy, 1960, p.106). It is considered that the precision of the methods used to obtain the chemical analyses for the present research is quite satisfactory.

Only the determinations of CaO, MgO, Al_2O_3 and SiO_2 require further comment. Since MgO is determined by the subtraction of the CaO titre from the CaO and MgO titre its accurate determination depends on the accuracy of the CaO determination. In the CaO titration the end point, which is difficult to detect, must, therefore, be established with great care.

The alizarin Red S method for the determination of Al_2O_3 (Shapiro and Brannock, 1962) is not particularly satisfactory as the Al_2O_3 content must fall within a certain range. In addition the use of either G - 1 or National Bureau of Standards Felspar Number 99 as a standard introduces an additional variable. The use of a standard prepared from "Specpure" aluminium, as in

Oxide	Percentage concentration	Absolute error
SiO_2	70	0.3
	60	0.3
	50	0.3
Al_2O_3	20	0.15
	15	0.15
	10	0.15
Fe_2O_3	8	0.2
	5	0.1
	1	0.02
FeO	10	0.2
	5	0.1
	1	0.02
MgO	10	0.2
	5	0.2
	1	0.05
CaO	10	0.2
	5	0.2
	1	0.04
K_2O	10	0.15
	5	0.1
	1	0.03
Na_2O	10	0.15
	5	0.1
	1	0.03
TiO_2	2.5	0.02
	1.0	0.02
	0.1	0.005
P_2O_5	1.0	0.03
	0.1	0.01
	0.01	0.003
MnO	0.3	0.05
	0.1	0.02
	0.01	0.005
H_2O	5	0.15
	1.0	0.1
	0.1	0.05

Table 3. Precision of the various oxides over a range of concentrations.

Riley's method (Riley 1958a) is preferred. Although both methods have been used, it is considered that Riley's method is superior.

The errors involved in the determination of SiO_2 are large because of the high concentration of SiO_2 in the rock. Table 4 shows a series of duplicate determinations of SiO_2, the concentration from each fusion being determined four times spectrophotometrically (Riley, 1958a, p.416). Half of the SiO_2 concentrations quoted in the analyses are the average of two fusions. The duplicates quoted in Table 4 are a random selection and suggest that a high degree of precision can be obtained for SiO_2 if conditions throughout the determinations are constant.

The precision of each complete analysis was also tested by analysing G - 1 (a sample of Westerly granite, supplied by the United States Geological Survey) and S24 (a sample of a Loch Laxford microgranite) in replicate (Table 5). This was done during routine analysis when G-1 and S24, in duplicate, were used as controls in each batch of analyses. In addition several samples were analysed in duplicate (Table 6). The evidence from Tables 5 and 6 suggests that one analysis is sufficiently reliable for the only true check on the accuracy of any analysis is the final total which should approximate to 100 per cent. The limits of 99 per cent to 101 per cent set by the laboratories of the United

Rock No.	Analysis 1	Analysis 2	Mean	Deviation
L117	71.11	71.64	71.37	±0.28
L12	45.12	45.71	45.41	±0.30
L251	69.71	69.65	69.68	±0.03
L189	63.45	63.45	63.45	±0.00
L112	71.61	71.64	71.62	±0.02
L214a	67.35	67.30	67.32	±0.02
S9	61.60	62.01	61.81	±0.20
S29	70.50	69.90	70.20	±0.30
L78	72.40	72.13	72.26	±0.13
L126	69.26	69.26	69.26	±0.00
L83	67.81	67.61	67.71	±0.10

Table 4. Duplicate SiO_2 determinations with the mean and deviation in each case.

Oxide	1	2	3	4	5	6	Average
SiO_2	72.25	72.58	72.69	72.56	72.40	72.64	72.52
Al_2O_3	14.17	14.19	14.11	14.36	14.17	14.25	14.21
Fe_2O_3	0.88	0.87	0.93	0.93	0.90	0.90	0.90
FeO	0.94	0.95	0.93	0.93	0.93	0.93	0.93
MgO	0.38	0.40	0.42	0.39	0.38	0.42	0.40
CaO	1.40	1.35	1.36	1.34	1.35	1.37	1.36
Na_2O	3.50	3.38	3.40	3.32	3.30	3.32	3.37
K_2O	5.32	5.33	5.55	5.60	5.50	5.57	5.47
TiO_2	0.25	0.23	0.22	0.30	0.25	0.27	0.26
P_2O_5	0.08	0.07	0.08	0.07	0.09	0.09	0.08
MnO	0.03	0.03	0.03	0.02	0.03	0.03	0.03
H_2O^+	0.30	0.31	0.35	0.32	0.35	0.36	0.33
Total	99.50	99.69	100.13	100.14	99.65	100.15	99.86

(a) G-1 Standard deviation= 0.23

Oxide	1	2	3	4	5	6	Average
SiO_2	68.21	68.70	68.37	68.54	68.20	68.10	68.35
Al_2O_3	15.38	15.30	15.43	15.41	15.20	15.18	15.32
Fe_2O_3	0.98	1.09	1.03	1.04	0.96	0.98	1.01
FeO	1.09	1.00	1.02	1.05	1.09	1.10	1.06
MgO	0.84	0.88	1.05	0.86	0.92	0.95	0.90
CaO	2.28	2.14	2.26	2.20	2.20	2.24	2.22
Na_2O	4.01	4.34	3.98	4.20	4.10	4.10	4.12
K_2O	5.83	5.54	5.82	5.54	5.65	5.60	5.66
TiO_2	0.40	0.34	0.38	0.34	0.36	0.36	0.36
P_2O_5	0.21	0.21	0.22	0.21	0.21	0.22	0.21
MnO	0.04	0.03	0.04	0.04	0.04	0.04	0.04
H_2O	0.38	0.35	0.30	0.32	0.35	0.32	0.34
Total	99.65	99.92	99.90	99.75	99.28	99.19	99.59

(b) S24 Standard deviation= 0.21

Table 5. Replicate analyses of (a) G-1 and (b) S24

	[illegible]		[illegible]		[illegible]		[illegible]	
	1	2	1	2	1	2	1	2
SiO_2	72.40	72.63	69.26	69.26	72.60	72.60	69.90	70.04
Al_2O_3	14.78	14.79	16.10	16.18	14.77	14.65	14.60	14.46
Fe_2O_3	0.45	0.41	0.93	0.90	0.65	0.62	1.37	1.46
FeO	0.86	0.86	0.87	0.88	0.28	0.30	1.70	1.61
MgO	0.66	0.66	0.68	0.69	0.40	0.41	1.00	0.98
CaO	1.89	1.96	1.71	1.63	0.41	0.45	1.45	1.43
Na_2O	3.87	3.87	4.31	4.25	3.10	2.90	3.32	3.26
K_2O	4.27	4.30	5.09	5.02	8.00	8.00	5.62	5.72
TiO_2	0.18	0.14	0.44	0.43	0.02	0.02	0.32	0.31
P_2O_5	0.05	0.05	0.12	0.11	0.02	0.02	0.11	0.11
MnO	0.01	0.01	0.02	0.02	0.01	0.01	0.04	0.03
H_2O	0.15	0.20	0.66	0.60	0.20	0.15	0.34	0.30
Total	99.55	99.88	100.19	99.97	100.46	100.13	99.77	99.71

	L56		B47		L26		B346	
	1	2	1	2	1	2	1	2
SiO_2	59.32	59.38	45.50	45.57	57.14	57.64	51.13	51.00
Al_2O_3	13.15	13.23	25.38	25.19	19.64	19.84	10.81	11.10
Fe_2O_3	2.25	2.20	1.81	1.75	1.69	1.62	2.26	2.30
FeO	2.74	2.75	3.82	3.91	2.92	2.95	4.22	4.30
MgO	5.30	5.53	5.02	5.10	2.49	2.56	7.71	7.50
CaO	4.79	5.00	10.36	10.32	6.94	6.82	10.10	9.92
Na_2O	1.16	1.11	2.07	2.10	5.99	6.01	1.48	1.30
K_2O	7.65	7.35	2.57	2.55	1.00	0.93	7.05	6.85
TiO_2	1.25	1.21	0.31	0.35	0.46	0.51	1.94	1.90
P_2O_5	1.27	0.97	0.03	0.03	0.05	0.06	3.07	2.84
MnO	0.08	0.09	0.11	0.12	0.08	0.07	0.11	0.11
H_2O	1.10	1.17	2.63	2.50	0.66	0.58	0.87	0.81
Total	100.06	99.99	99.61	99.49	99.05	99.59	100.75	99.93

Table 6. Eight duplicate analyses, showing reasonable agreement.

States Geological Survey (Shapiro and Brannock, 1962), were used in the present research.

The accuracy of chemical analyses also depends on the choice and preparation of standards. This has already been mentioned in the determination of Al_2O_3 (pp. 17-8). All standards were prepared as suggested by Riley (1958a).

The optical densities of each standard were frequently checked against those recommended by Riley (1958a) and were in close agreement (Table 7). Thus, the table suggests that the standards have been correctly prepared. Standards used in the determination of Na_2O, K_2O, CaO, MgO and FeO could not be checked against those of Riley, but there is no reason to suspect that they were in error.

	1.	2.
SiO_2	0.745	0.743
Al_2O_3	0.394	0.392
Fe_2O_3	0.430	0.421
TiO_2	0.565	0.569
P_2O_5	0.386	0.383
MnO	0.265	0.272

Table 7. A comparison of the optical densities of Standard Solutions, determined by (1) Riley (1958) and (2) the writer. Fe_2O_3 includes FeO expressed as Fe_2O_3.

Collection and preparation of material for chemical and spectrographic analysis.

Specimens were collected during routine field mapping, and a detailed record was made of the locality and field relations of each. Grain size was the most important factor in deciding the weight or size of specimen required; in gneissic terrain the degree of streakiness or striping were also important. The following scheme, which is based on that suggested by Wager and Brown (Smales and Wager 1960, p. 6) was used:-

GRAIN SIZE	SAMPLE WEIGHT	FIELD DESCRIPTION
1 cm.	1,000 gm.	Full fist size
1cm. - 3cm.	2,000 gm.	Same weight as 4 lb. hammer.

Most of the specimens collected were of such a size that a chemical analysis would be possible. When a specimen was chosen for analysis it was washed, dried and either cut into slabs 3 mm thick or broken into pieces no larger than 1 cm. in size. From the slabs and pieces of material 150-300 gm. of the <1cm. size or 500 g. of the >1cm. size were taken, all weathered material being discarded. It was then crushed to about -16 mesh using a manually operated rock crusher similar to that described by Wager and Brown (in Smales and Wager 1960, fig.1). The -16 mesh material was crushed to -60 mesh using a mechanically driven roller crusher of the type described by Wager and

Brown (op. cit. fig III). After the -60 mesh material was carefully mixed and quartered, 25 - 30 g. were ground to -120 mesh in a mechanical agate mortar and pestle; the remaining material was stored for other purposes such as mineral separation. The -120 mesh powder was stored in a small glass bottle with a tightly fitting plastic stopper.

Before analysis, each rock powder was dried at 120°C for 2 hours, to drive off hygroscopic water.

Spectrographic techniques

The spectrographic determination of trace elements was carried out using a Hilger and Watts automatic, Littrow type optical spectrograph with interchangeable quartz and glass prisms. The optical system was as follows:-

At the slit:	a 30.2 cm focal length spherical lens which was incorporated in the step-sector.
12 cm from the slit:	a 30.2 cm focal length spherical lens.
27 cm from the slit:	a diaphragm with an aperture 5 mm wide.
41 cm from the slit:	a 6.4 cm focal length spherical lens.

The arc was situated 52 cm from the slit. The arc gap was 8 mm with the central two thirds of the arc being focussed onto the diaphragm. The camera slit width was set at 11 mm. To facilitate the preparation of working curves a seven-step rotating step sector was placed at the slit, thus varying the intensity along each spectral line. The ratio of the intensity of one step to that of the next step was 2 : 1. The voltage used was 250 volts D.C. on a clear circuit. Palladium was used as an internal standard over some wavelength ranges being introduced into the unknown powder by mixing the latter with a palladium-graphite mixture containing 1% of tetrammine - palladous nitrate. Electrodes were prepared as follows:-

1. Anodes were cut from Johnson Matthey graphite rods. Either J.M.2 or J.M.220 grade and cavities of various sizes were used as described below.

2. Cathodes with a tapered end were cut from J.M.1106 or J.M.1205 carbon rods.

The optical density (or intensity) of three steps on each analysis line was measured using a Joyce Loebl automatic recording micro densitometer.

Working curves were then prepared by plotting the following for a range of concentrations:-

a) Internal standard (constant concentration).

log. concentration of unknown ppm
vs

$$\log. \frac{\text{intensity of unknown}}{\text{intensity of standard}}$$

b) Internal standard (variable concentration)

$$\log. \frac{\text{concentration of unknown ppm}}{\text{concentration of standard \%}}$$

vs

$$\log. \frac{\text{intensity of unknown}}{\text{intensity of standard}}$$

The prism, the current, the wave length, the photographic plates, the plate processing, the shape of the anode and the internal standards varied from one wavelength range to another and the details are described below.

The standards used in the preparation of the working curves were G-1, W-1, a 1 : 1 mixture of G-1 and W-1, whose trace element contents are listed in Table 7a, and other suitable standards which were prepared

	G-1	W-1	G-1/W-1
Ba	1220	225	723
Co	2.2	38	20.1
Cr	22	120	71
Cu	13	110	62
F	730	200	465
Ga	18	16	17
La	150	30	90
Li	24	12	18
Ni	1.2	73	37.1
Rb	220	22	121
Sc	4	43	24
Sr	280	220	250
V	21	240	131
Zr	210	100	155

Table 7a. Trace element values of G-1, W-1, and a 1:1 mixture of G-1 and W-1, used in the preparation of working curves during routine spectrographic analysis.

by diluting a trace-element mixture containing all the important trace elements in pre-determined proportions, with L78, a rock powder from Loch Laxford. In the case of fluorine the standards were prepared by mixing a synthetic rock powder in various proportions with a fluorine mixture (powdered CaF_2).

The following methods were used to determine the trace element content of the rocks:-

1. Fluorine (F)

Glass optics; wavelength range: 4520 to 9000 A.U.

Current: 5 amps

Anode: 3.2 x 3.2 mm deep

Slit width: 0.02 mm.

Photographic plate: Ilford HP3

Developer: PQ Universal; strength 1+19; time 6 mins.

Stop bath: 3% acetic acid; time 6 mins.

Fixer: Kodafix, strength H3; time 6 mins.

Samples were mixed 1 : 1 specpure $CaCO_3$: 1 graphite and arced for 25 seconds.

Analysis line: CaF 5291 bandhead.

Internal standard line: CaO 5488 bandhead.

2. Alkalis (Li, Rb, Cs)

Glass optics; wavelength range: 4600 to 9600 A.U.

Current: 4.4 amps.

Anode: 2.4 x 2.5 mm deep

Slith width: 0.02 mm.

Photographic plate: Kodak I.R.E.R.

Developer: Kodak D.19b; strength 1+2; time 5½ min.

Stop bath: 3% acetic acid; time 30 seconds.

Fixer: Kodafix; strength 1+3; time 5½ minutes.

The samples were arced neat and the shutter opened immediately before the arc was struck. The burn continued until the end of the alkali distillation.

The spectral lines used were:-

Analysis lines: Li 6707, Rb 7800, Cs 8521.

Internal standard line: Na 5688

In practice Cesium was always below detection limits so that Cs 8521 was never used.

3. Sc, Cv, La, V, Ba, Sv

Glass optics; wavelength range: 3850 to 5480 A.U.

Current: 6.8 amps.

Anode: 3.2 x 4 mm deep or 2.5 x 5 mm deep.

Slit width: 0.01 mm.

Photographic plate: Ilford ordinary N30.

Developer: PQ universal; strength 1+19; time 3 mins.

Stop bath: 3% acetic acid; time 30 seconds.

Fixer: Kodafix; strength 1+3; time 5 minutes.

The samples were mixed with 2 parts of the graphite/Pd mixture. The shutter was opened immediately after the arc was struck and each sample burned for four minutes.

Spectral lines used were:-

Analysis lines: Sc4246, Cr 4254, La 4333, V 4379 Ba 4934.

Internal standard line: Pd 3958.64.

4. <u>Ga, Ni, Cu, Zr, Co</u>.

Quartz optics; wavelength range: 2470 to 3550 A.U.

All other conditions were the same as in the previous group, except that each sample was burned to completion and then for a further 10 seconds to obtain all the Zr excitation.

The spectral lines used were:-

Analysis lines: Ga 2944, Ni 3050.8, Cu 3274, Zr 3438, Co 3453.

Internal standard line: Pd 3258.8.

Discussion of the spectrographic results

In order to confirm the reliability of the methods used for trace element determinations a sample (L78) was analysed at the Department of Geology and Mineralogy, University of Oxford and the results obtained from each spectrograph were compared (Table 8). In general, the Keele determinations are lower than those from Oxford, although the order of magnitude is similar. It is suggested by G. M. Power that the differences may possibly be due to different methods of establishing working curves. There is no reason to suspect that the present set of trace element determinations is less reliable than those obtained from other laboratories. The relative deviation of each determination is shown in Table 9.

	Oxford	Keele
Ba	2420	2115
Co	3.6	2
Cr	56	35
Cu	40	35
Ga	15	15
Li	22	22
Ni	2.3	5
Rb	111	110
Sc	n,d.	2.8
Sr	400	363
V	32	23
Zr	102	89

Table 8. A comparison of the trace element values of L78, as determined by the Department of Geology and Mineralogy, University of Oxford and by the writer at the University of Keele. At Oxford all samples were mixed 1:2 with a 1% Pd/graphite mixture with the exception of samples burned to determine Rb,Na,Cu andGa, in which case the samples were burned unmixed. The Oxford results are the average of two determinations, except those of Cu,Ga and V, which are the average of four. The Keele results are the average for eight determinations. The trace elememt values are given in p.p.m..

Element	Relative deviation
Ba	12
Co	20
Cr	25
Cu	13
F	16
Ga	8
La	15
Li	5
Ni	14
Rb	12
Sc	14
Sr	15
V	9
Zr	18

Table 9. The relative deviation of each trace-element, determined by spectrographic analysis.

Presentation of results

Chemical analyses can be presented in a number of different ways. They are usually shown as weight percentages of the major oxides although in this form they are not easily compared. They are better compared if they are converted in the first instance into cation percentages recalculated to 100% together with the amount of O^{2-} that would combine with these 100 cations (Eskola 1954). From the cation percentages various values, including the catanorm, mesonorm and epinorm (Barth, 1959) and ratios can be calculated. Niggli numbers based on molecular proportions, can be used to obtain useful information (Niggli, 1954). In the calculation of Niggli numbers and cation percentages the equivalent molecular proportions and equivalent atomic proportions of the weight percentage of each oxide were obtained from tables drawn up by Burri (1959).

In the present research both the catanorm and the mesonorm were calculated, the former being equivalent to the molecular norm first suggested by Niggli (1936) and later modified by Barth (1952) and Eskola (1954). Hietanen (1962) compares the catanorm with the CIPW norm and finds that the respective values are closely similar so that it can be used in place of the CIPW and the values so obtained compared with the CIPW norm values in the literature. The mesonorm, however, is designed for rocks belonging to the mesozone, that is rocks of approximately amphibolite facies. Since the Laxfordian metamorphism is an amphibolite facies metamorphism (see pp. 275-6) the mesonorm is particularly suitable in the present research as it reflects the actual mineral composition of the rocks and can be directly compared with the mode. Niggli numbers are also used and are probably most useful in the study of amphibolites (Evans and Leake, 1960).

II. THE GNEISSES

The Laxfordian complex around Laxford Bay consists of interbanded grey biotite gneisses, hornblende-biotite gneisses, hornblende gneisses, and amphibolites, intruded by later "granites" and pegmatites (Peach and others, 1907, p. 1[illegible]7). Clough (op. cit.) sub-divided the gneisses into "granular" and "granulitic" types. In the field this sub-division is easily recognised although in current usage granular and granulitic are synonymous (see Holmes, 1921, pp. 381-382 ; Rice, 1953). It appears that the terms "granular" and "granulitic", as used by Clough, respectively refer to medium grained rocks with inequidimensional grains and fine grained rocks with equidimensional grains (see Peach and others, 1907, Plates XLII and XLIV). Watson (op.cit.) divided the Laxfordian complex into zones based on structural and mineralogical criteria. The three classifications are compared in Table 10.

Other gneisses are present in the Laxford area, for example the Cnoc nan Cro gneisses (p.96) but for reasons discussed later (p.197) they are considered to represent igneous rocks and are described in a separate chapter.

<table>
<tr><th>Classification of Geological Survey.</th><th>Classification of Watson.</th><th>Present classification.</th></tr>
<tr><td>granulitic gneisses</td><td>Foindle zone</td><td>Claise Fearna gneisses</td></tr>
<tr><td rowspan="3">granular gneisses</td><td rowspan="2">Badnabay zone</td><td>Badnabay gneisses</td></tr>
<tr><td>Weaver's Bay gneisses</td></tr>
<tr><td>Laxford zone</td><td>Laxford Bay gneisses</td></tr>
</table>

Table 10 A comparison of the classifications of the gneisses used by the Geological Survey (Peach et al.), Watson(1951), and the present writer.

The Claise Fearna Gneisses

This group of gneisses occurs at the north-east margin of Watson's Spindle zone (p.4) and at or near the junction between Clough's middle and northern belts (p.3), forming an extensive tract both along and across the strike. Traverses to the south-west show that similar gneisses crop out for a distance of at least 800 metres across the strike, although that part of the belt mapped in detail is little more than 100 metres wide. Along the strike the gneisses can be mapped as a continuous unit from north-west to south-east for a distance of about 5 km.

The gneisses have a well developed foliation which strikes NW-SE and dips steeply to the south-west, becoming vertical in some places, as for example in the crags just north of Loch na Claise Fearna. Folding is often seen (Plate 1), the foliation being parallel to the NW-SE axial plane of the folds which plunge to the south-east at angles varying from 5° to 35°. A lineation(Plate 2) which pitches to the south-east at angles commonly up to 35° and up to 70° in exceptional cases, is commonly seen.

Most of the gneisses have a flaggy appearance, reflecting their micaceous, granulitic nature and thus are equivalent to Clough's granulitic gneisses. Although never homogeneous, they do not exhibit striping to the same extent as the other groups of gneisses. More commonly they are streaky (plate 3) and often tend towards homogeneity, although many gneisses show well developed streaking and striping (plate 4). Streaking, 1 mm. or so thick, grades into striping several centimetres thick.

Distribution of the minerals

The amount of potash feldspar shows a noticeable variation. At the extreme south-west margin of the area potash feldspar never exceeds 10 per cent of the total rock volume and is often absent, with the gneisses trending towards a trondhjemitic composition. When present, potash feldspar is often distributed in alternating stripes of varying thickness. As the south-west margin of the Loch na Seilge sheet is approached, the volume of potash feldspar in the gneisses increases to as much as 30 per cent of the total rock volume, the yellow cobaltinitrite staining emphasising its streaky and striped distribution (plate 4).

The leucocratic lenses and stripes of the gneisses themselves contain variable amounts of potash feldspar, in some cases as much as 60% of the total rock volume and in one case 95% of the total. Within any one lens or stripe the potash feldspar often exhibits a streaky distribution (plate 4) while adjacent lenses and stripes often carry markedly different amounts. Although these leucocratic bodies generally contain more potash feldspar than the immediately adjacent 'normal' gneiss, the reverse has been observed in several instances.

The distribution of potash feldspar does not appear to be influenced by the amounts of the other minerals present in the gneisses, apart from the fact that the more mafic gneisses tend to contain smaller amounts than the less mafic gneisses. For example, although a difference of 10% in the mafics (5% and 15%) from one stripe to another is seen in one specimen the amount of potash feldspar is the same in both stripes.

Plagioclase is omnipresent, varying from 10% or less in some of the leucocratic stripes to more than 65% in the trondhjemitic gneisses. Typically it has a streaky distribution and appears to have an antipathetic relationship to potash feldspar.

Quartz is present in almost every specimen, usually forming between 5% and 35%. Thin streaks, 2 mm. or less thick and up to 3 cm. long, of this mineral are fairly common, several of these streaks being linked together by very thin streaks in some specimens.

Micaceous varieties of gneiss predominate although biotite is the only mica seen in the field. Hornblende and epidote are the other mafic minerals, occurring together with biotite in about one third of the gneisses. More than 50% of the remaining gneisses contain biotite with or without epidote, while the rest contain hornblende.

Usually the biotite gneisses have a maximum colour index of twenty whereas the hornblende gneisses have a maximum value of thirty.

Variations in the mafic mineral content produce the more obvious stripes in the gneisses. The variable distribution of quartz and the feldspars also produce stripes in the gneisses, although this is not readily apparent unless the gneisses are stained.

PLATE 1

Folds of Laxfordian age, folding an earlier foliation and striping. Claise Fearna gneisses.

PLATE 2

A lineation that pitches to the south-east, as seen in the Claise Fearna gneisses.

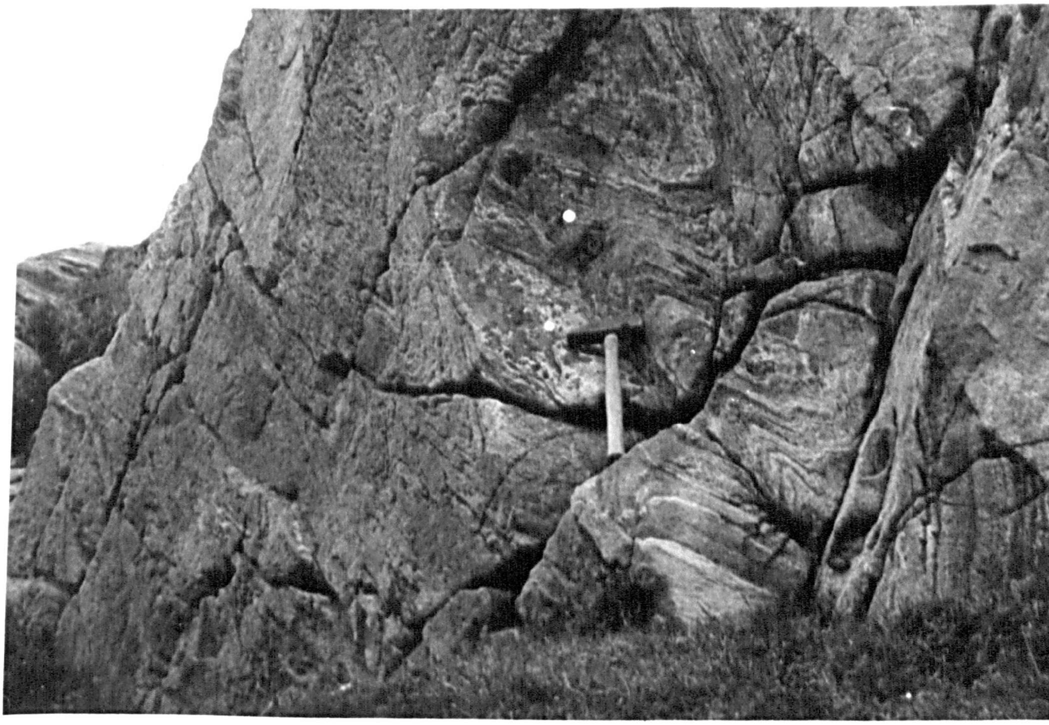


Plate I

Plate 2

PLATE 3

Flaggy, streaky Claise Fearna biotite-gneiss in which striping is absent.

PLATE 4

Claise Fearna hornblende-biotite-gneiss in which streaking and striping are well developed. The lowest stripe (1.5 c . thick is a leucocratic quartz-plagioclase (white) stripe with streaks of potash feldspar (grey).

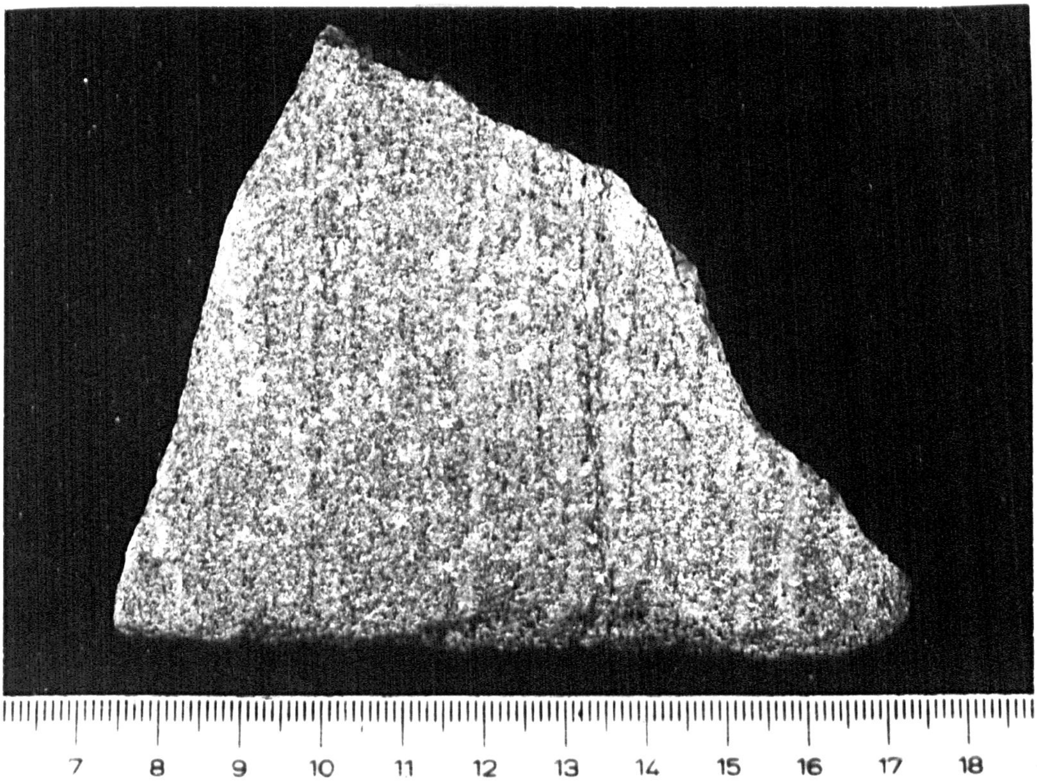


Plate 3

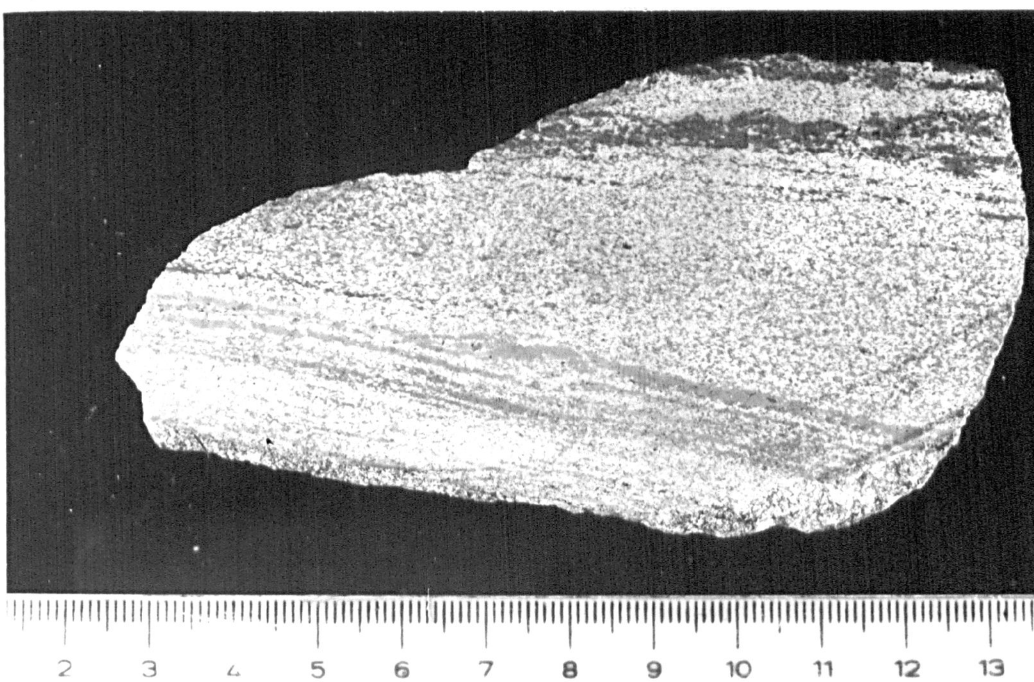


Plate 4

The Badnabay Gneisses

The Claise Fearna gneisses very rapidly grade into the underlying Badnabay gneisses which tend to be slightly coarserin grain. The transition, which has been described by Clough (1907, pp. 136-137) can be seen in several places to the west of the small glen which runs south-west from Badnabay, in addition to the locality described by Clough. To the east of this glen the south-west margin of the Loch na Seilge sheet (Map 1) obscures the junction.

The Badnabay gneisses are well exposed throughout the area, forming a series of ridges which mark the junction between the gneisses and the thicker sheets of microgranite. In general, they appear to be more resistant to weathering than the adjacent granitic rocks of the Badnabay group. Granitic material is commonly associated with the gneisses, and migmatites occur in many places although the granitic part of the migmatites often cannot be clearly distinguished from the gneisses. In contrast, microgranite and gneiss are easily distinguished in the Cnoc nan Cro migmatites (p. 132).

Foliation is well developed throughout the gneisses and can be recognised as a second foliation that is parallel to the axial plane of folds of an earlier foliation and banding (plate 5) (see Watson, 1951, p. 277). The foliation strikes NW-SE and dips steeply to the south-west at angles varying from 45° to 70°. The folds, usually isoclinal, plunge to the south-east at angles varying from 5° to 25°. A lineation can be observed to plunge in the same direction as the minor folds. The foliation is due to mineral orientation and to stripes or streaks of differing mineralogical composition. The lineation is due to a mineral orientation. This evidence contrasts with the statement of Watson (1951, p.279) that "there is no planar or linear orientation of the minerals" in the gneisses of the Badnabay zone. In some of the gneisses small relict fold closures, a few millimetres in size, of mafic minerals result in what has been termed a nebulitic gneiss (Sederholm,1926). The foliation is occasionally flexured, being rotated through as much as 90° with the angle of dip becoming vertical.

Distribution of the minerals

The gneisses are essentially hornblendic with well developed striping due to the distribution of the felsic and mafic components (plate 6). They form a somewhat monotonous series interlayered with numerous amphibolites. Hornblende-biotite gneisses are relatively common and biotite gneisses uncommon, although the latter predominate in some localities.

No systematic regional variation in the distribution of potash feldspar was observed. In many specimens adjacent grains of potash feldspar appear to be linked together by thin veins of the same mineral. Augen, which may be more than 1 cm. in size, occur rather sparsely. A few of the amphibolitic stripes contain potash feldspar. In some cases, where leucocratic stripes alternate with stripes containing 25 per cent or so of hornblende, no noticeable variation in the amount of potash feldspar can be detected from stripe to stripe and this evidence is considered to indicate that the distribution of potash feldspar is not due to metamorphic differentiation. Commonly, however, the leucocratic stripes contain more potash feldspar than the adjacent more mafic stripes, although the reverse has also been seen. Potash feldspar often exhibits a streaky distribution, some streaks containing up to 70 per cent of the mineral (plate 7). The total amount present in any specimen, however, rarely exceeds 25 per cent. As the amount of potash feldspar increases the gneisses change in character from trondhjemitic, through granodioritic, to granitic.

Plagioclase is present in all the gneisses, some containing as much as 70%. It is usually a milky white colour, while in a few specimens it exhibits a light blue schillerization. Streaks of plagioclase are a common feature of this group and the mineral itself appears to bear an antipathetic relationship to potash feldspar.

Quartz, which is present in amounts varying from 5% to 30%, often occurs as thin streaks or lenses.

Specimens of gneiss exhibiting folds, to which the main foliation is related, have been examined closely for evidence bearing on the mechanism of potassium metasomatism. Although there is no evidence suggesting that potash feldspar accumulated in fold closures, in specimen B96 from 750 metres south-south-east of Weaver's Bay potash feldspar is evenly distributed across a fold closure, irrespective of the mineral composition of the stripes and streaks which comprise the fold, possibly indicating a movement of potassium after the period of deformation. In another specimen from nearby (B373) a potash feldspar-rich stripe is flexured, but it is not clear whether the flexure has deformed or is associated with the main foliation.

Gneisses immediately adjacent to, or in contact with a micro-granite sheet are not enriched in potash feldspar relative to the gneisses further away, indicating that, if potassium metasomatism has occurred, the microgranite sheets were not the source. At one locality a potash feldspar-rich layer is flexured in the same manner as the adjacent layer rich in mafics, suggesting that if there has been a potassium metasomatism, it has been followed by a phase of deformation.

The mafic minerals include hornblende, biotite and epidote, the latter two being absent in many cases. Biotite rarely makes up more than 15% of the gneiss and epidote may reach 5% at most, whereas hornblende varies from almost zero to 95%, often forming streaks and clots in the gneisses. The more mafic layers of the gneisses most commonly occur in a series of alternations with the more felsic layers giving rise to the striped gneisses (plate 8). The mafic stripes vary in thickness from 1 mm. to several centimetres, and in some cases consist of a thin layer composed almost entirely of short stumpy hornblende grains.

PLATE 5

Folding of earlier striping and foliation. The second (Laxfordian) foliation is parallel to the earlier foliation where folding is isoclinal (bottom right) and produces a "Streaking-out" of the stripes at the fold noses (below hand lens). Badnabay gneisses.

PLATE 6

Typical striping of the Badnabay gneisses.

Plate 5

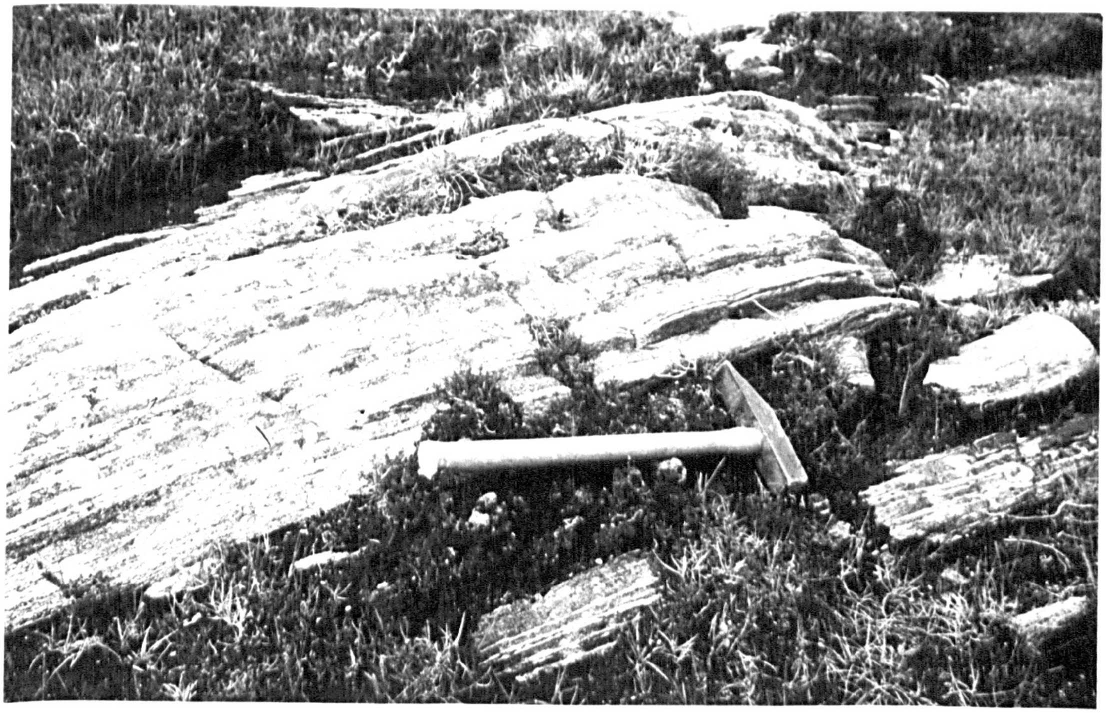


Plate 6

PLATE 7

Striped Badnabay gneiss in which streaks rich in potash feldspar (grey) are common. The streaks show a non-parallelism.

PLATE 8

A Badnabay gneiss in which mafic stripes are well-developed.

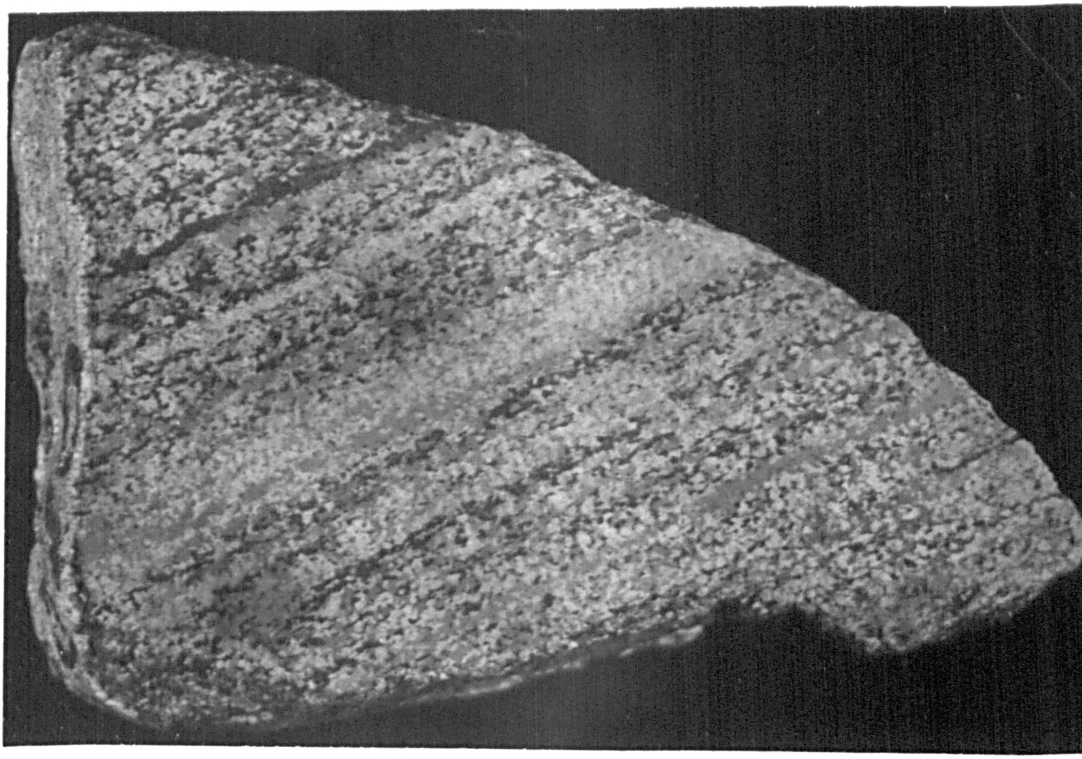


Plate 7

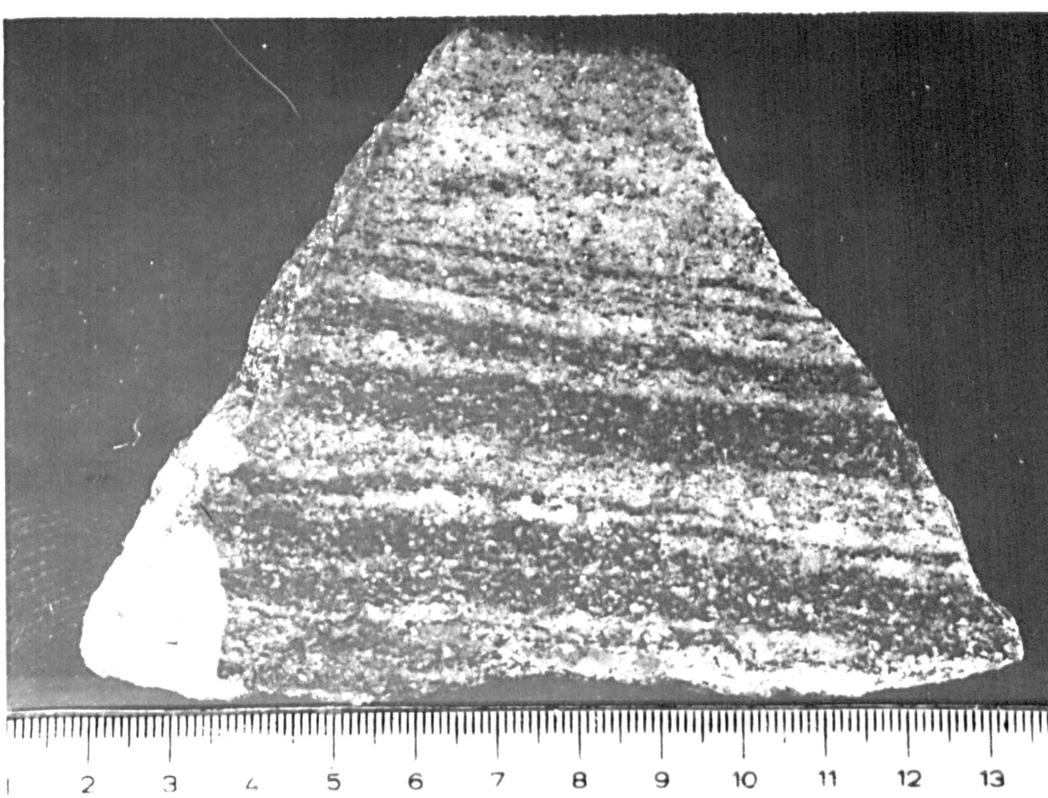


Plate 8

The Weaver's Bay Gneisses

The Weaver's Bay gneisses lie between the Rudha Ruadh granitic sheet and the Cnoc nan Cro gneisses. They are commonly interlayered with amphibolites, and with lenses and bands of the Cnoc nan Cro gneisses near the junction with that group. Together with the Cnoc nan Cro microgranites they form an extensive development of migmatites, which are described later (p. 132).

The gneisses have a well-developed foliation which strikes NW-SE and dips to the south-west at angles varying from 40° to 60°. The foliation is parallel to the axial plane of the folds that plunge to the south-east (Plate 9) and is occasionally flexured in a manner similar to that seen in the Badnabay gneisses (p. 36). On rare occasions a lineation is seen, but it is less frequently developed than in either the Claise Fearna or Badnabay gneisses. The foliation appears to be due to mineralogical streaking and striping (Plate 10). A mineral orientation has not been seen in the Weaver's Bay gneisses.

Distribution of minerals

The group consists essentially of hornblende-biotite-epidote gneisses, although occasionally hornblende or biotite gneisses occur. The gneisses are typically striped (Plate 10) and in many cases have a sugary granular texture.

As with the other groups of gneisses trondhjemitic, granodioritic, and tonalitic gneisses predominate; a few granitic gneisses also occur. Potash feldspar is usually subordinate to plagioclase, although some thin layers are enriched in potash feldspar. In general, it has a similar distribution to that seen in the other groups and occasionally forms augen. An important feature of the gneisses is the occurrence of thin ribs of quartzofeldspathic material, which vary in thickness from 2mm to 3cm (plate 11). In these ribs potash feldspar may be absent or present in varying amounts, plagioclase and quartz vary in amount, and the mafic minerals are sparse. The potash feldspar content could not be related to that of the host gneiss.

While no significant variation in the potash feldspar content of the gneisses could be established in stained specimens, it is clear that the microgranites, which not only form an essential part of the migmatites but also form thick homogeneous sheets, have not caused potassium metasomatism in the gneisses. Small inclusions or relics of gneiss within a microgranite do not appear to be enriched in potash feldspar relative to similar gneisses not enclosed by microgranite. This evidence, however, does not rule out the possibility of a general potassium metasomatism that may have originated from the same source as the microgranites.

Both plagioclase and quartz show similar features to those seen in the Badnabay gneisses; in addition, occasional porphyroblasts of plagioclase are seen (Plate 12).

In the majority of specimens, hornblende predominates slightly over biotite and epidote when the three mafic minerals occur together. It also predominates, to the exclusion of others, in many cases, in the mafic stripes that are amphibolitic in composition. However, many other gneisses contain only biotite and epidote.

A notable feature of the gneisses is the consistent presence of green epidote which is conspicuous in most gneisses by occurring in amounts that commonly exceed 5% of the total rock volume. Epidote, however, may be absent in the more mafic stripes. Variations in the proportions of the mafic and felsic mineral constituents from layer to layer produce the striped gneisses (Plate 12) that form the greater part of this group.

An exposure composed of alternations of quartzite and a flaggy, epidote-rich rock (Plate 13) represents one of the few examples of metasedimentary gneisses found in the area and can be seen 500 metres south of Cnoc nam Cro. Granular epidote is concentrated in layers.

Several small flakes of molybdenite are present in the gneisses near Weaver's Bay.

PLATE 9

Laxfordian folding in the Weaver's Bay gneisses.

PLATE 10.

Striping in the Weaver's Bay gneisses, emphasising the foliation.

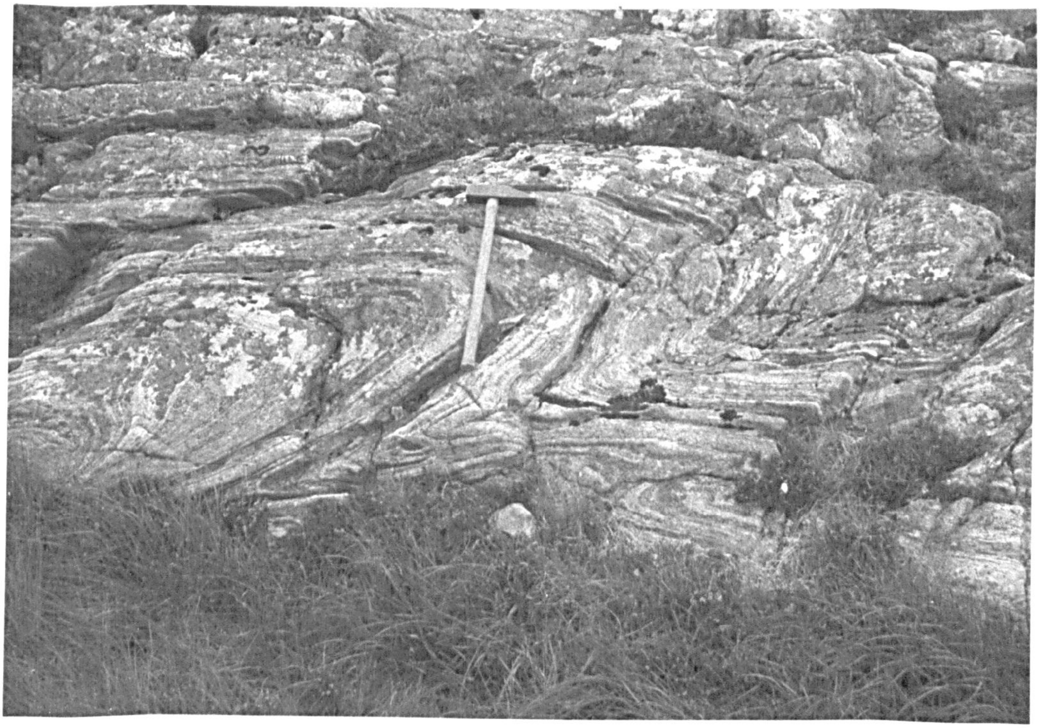


Plate 9

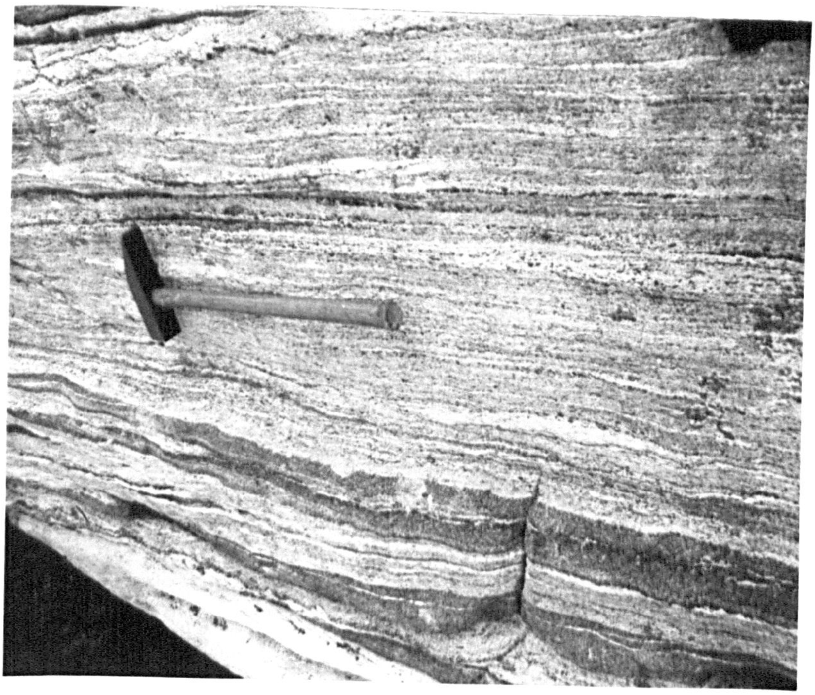


Plate 10

PLATE 11

Striped Weaver's Bay gneisses with two ribs of quartzo-feldspathic material, 1.5 mm and 2.5 mm thick.

PLATE 12

Porphyroblast of plagioclase around which a mafic stripe is flexured.

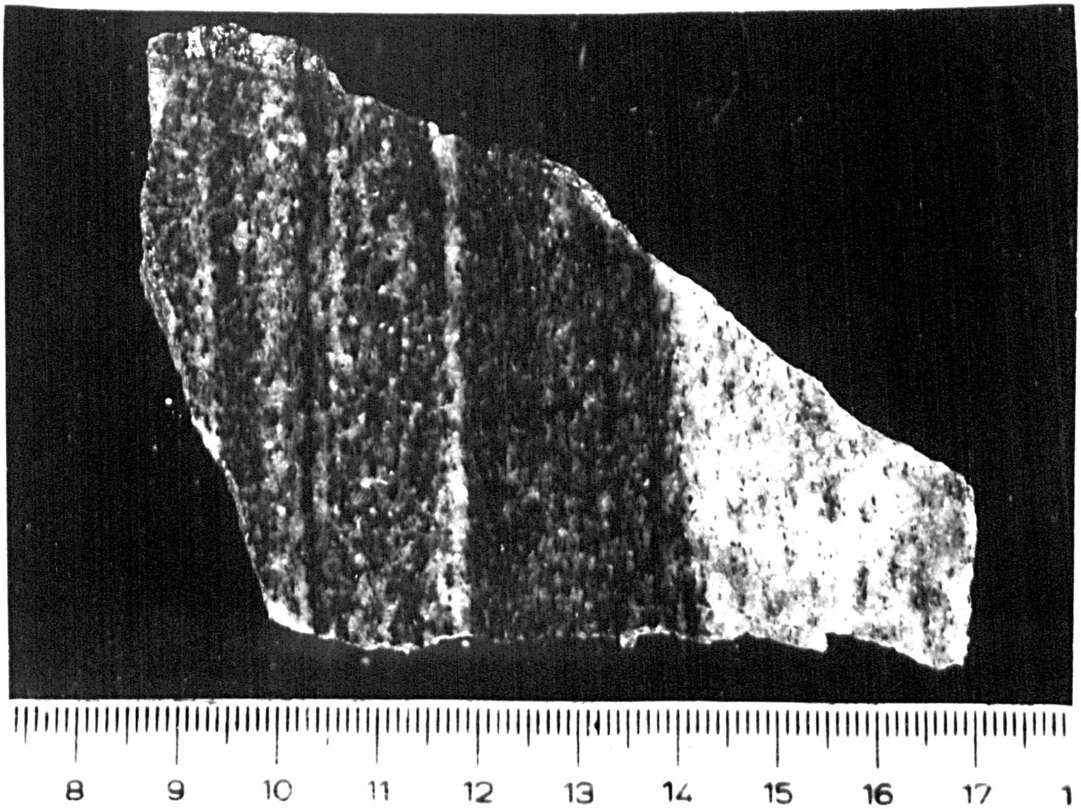


Plate II

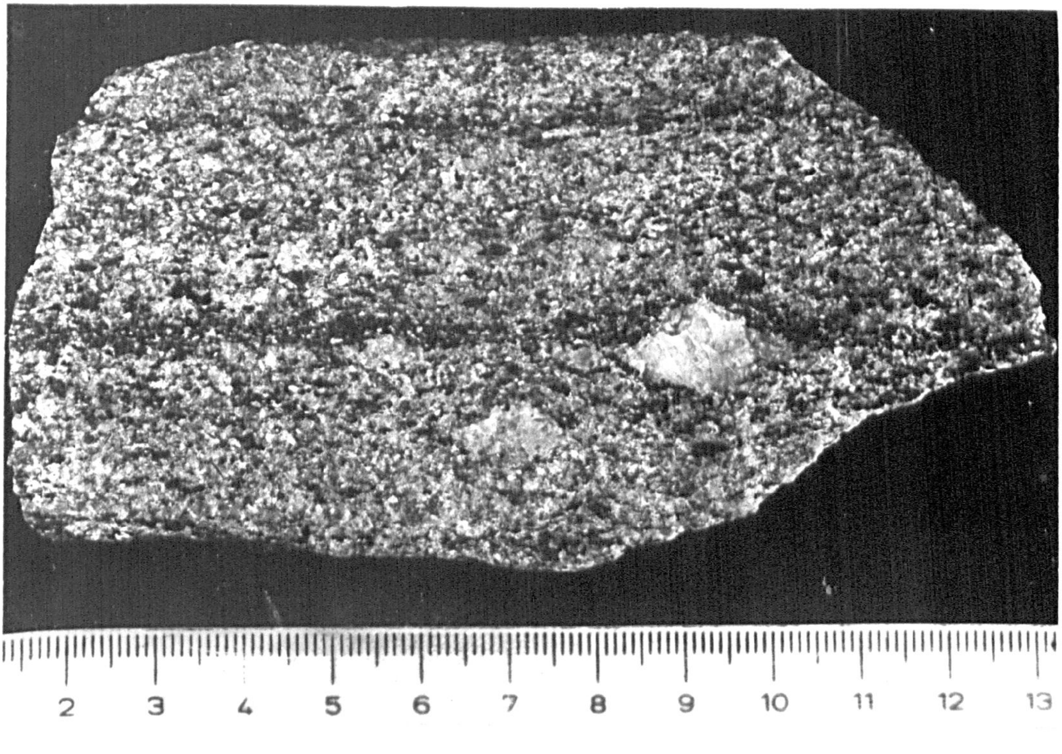


Plate I2

PLATE 13

A metasediment consisting of quartzite interlayered with epidote-plagioclase layers that are picked out by differential weathering.

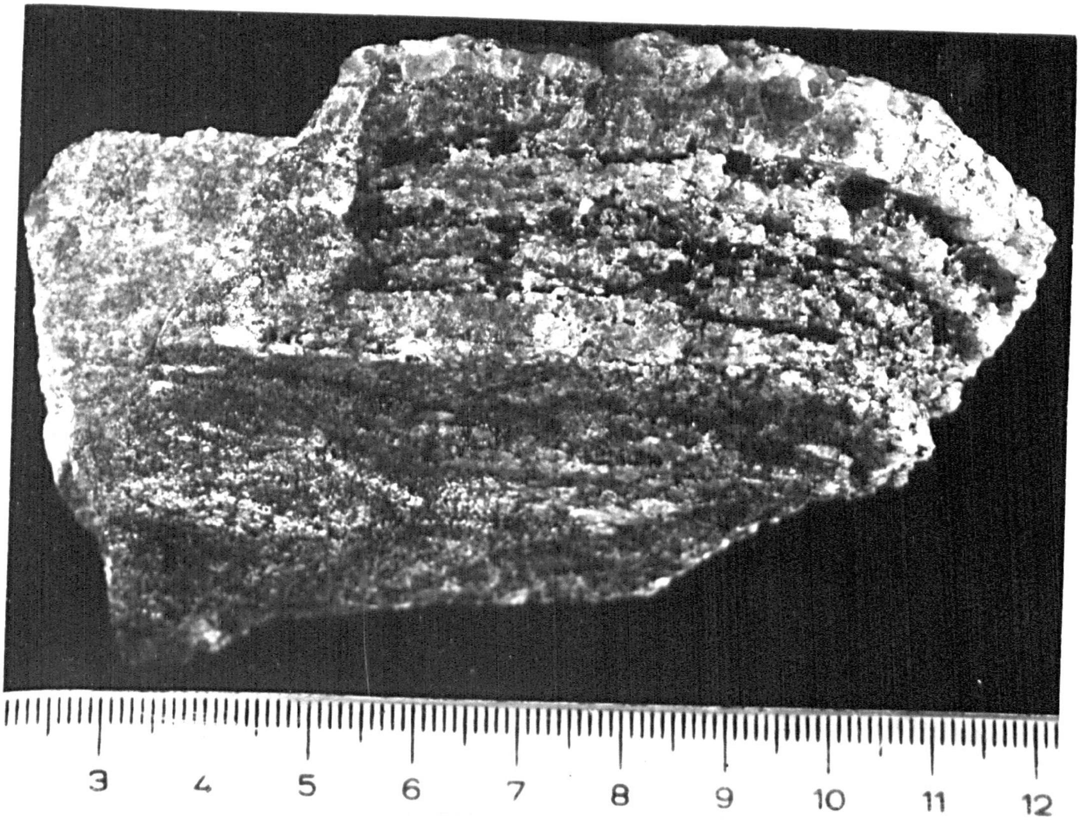


Plate I3

The Laxford Bay Gneisses

The differences between the gneisses on either side of the Cnoc nan Uro gneisses are imperceptible in the rocks immediately adjacent to that group, but become more apparent further away. The Weaver's Bay gneisses can thus be considered to grade into the Laxford Bay gneisses with the intervening Cnoc nan Uro gneisses making a convenient boundary. At first sight the Laxford Bay gneisses are much coarser grained than the Weaver's Bay gneisses, but this is principally due to the segregation of the mafic and felsic components into clots, patches, streaks and lenses, although there is also a slight increase in the grain-size. The group crops out on both sides of Laxford Bay and although a continuous section is not seen there is sufficient correlation between exposures to make it reasonably certain that the gneisses on both sides of the bay, which exhibit essentially the same features, form a single group.

The foliation of the Laxford Bay gneisses strikes NW-SE and usually dips to the south-west. South of Laxford Bay the angle of dip is 40° to 45° but further north it decreases and in several places the foliation dips to the north-east at 75° to 90°. There is no reason to suppose that this foliation differs from that in the gneisses further south (contrast Watson, op.cit., p.279).

Small contortions, plunging to the south-east at a few degrees, are commonly seen (Plate 14) and appear to represent a more plastic style of folding than appears in the other groups of gneisses.

Striped gneisses are rather less common than streaky, segregated gneisses (Plate 15).

Distribution of minerals

Felsic streaks, often granitic, are an essential feature of these gneisses and felsic stripes are present in many localities. Potash feldspar is almost always concentrated in the felsic rather than the mafic streaks, a feature brought out by the yellow cobaltinitrite stain (Plate 16). A high proportion of potash feldspar is also often contained in the leucocratic stripes of the striped gneisses, although there are cases where this mineral is more or less evenly distributed throughout a specimen of striped gneiss. It appears that segregation and streaking out of the mineral components into pods and lenses is accompanied in the leucocratic lenses by an increase in the volume of potash feldspar which eventually becomes the dominant mineral constituent in many of these lenses. When the granitic streak forms an essential part of the gneiss the grain-size of the specimen does not vary. There are also many lenticles and stripes of coarser-grained granitic material in which the otash feldspar has the same pink colour as this mineral in the pegmatites which are extensively developed in this group of gneisses. (Plate 17)

Other felsic streaks contain only quartz and plagioclase, which are also present in all the gneisses. Quartz commonly occurs in amounts varying from 20% to 35%, although it occurs only as an accessory in the mafic streaks and stripes, while the plagioclase content varies from 35% to 60%.

Hornblende occurs as the sole mafic mineral usually only in the mafic stripes. Otherwise it occurs with biotite and epidote, commonly both, the three minerals forming clots and other types of segregation. Biotite and epidote occur together in most gneisses and usually the former mineral predominates, in some cases to the exclusion of the latter.

Epidote occurs alone in a 20 cm. thick band of gneiss which crops out at the roadside just north of Laxford Bay. Within this band which is composed essential of quartz and plagioclase, granular epidote and abundant magnetite are concentrated in thin layers possibly reflecting original sedimentary layering.

PLATE 14

Small-scale folding in the Laxford Bay gneisses.

PLATE 15

Streaking in the Laxford Bay gneisses.

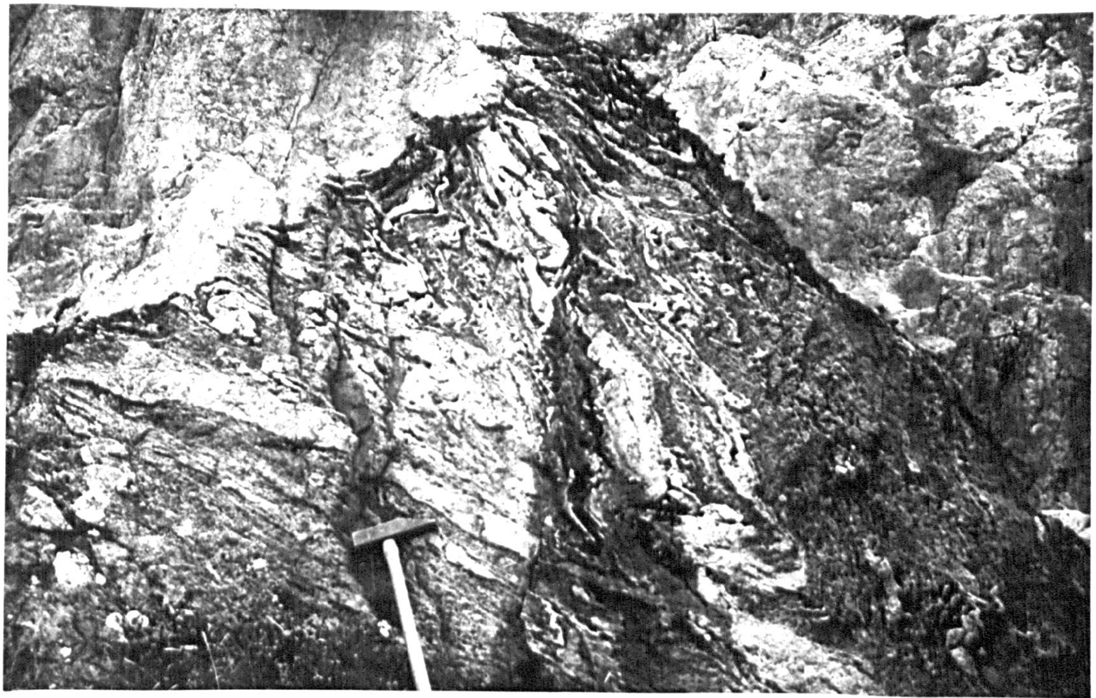


Plate I4

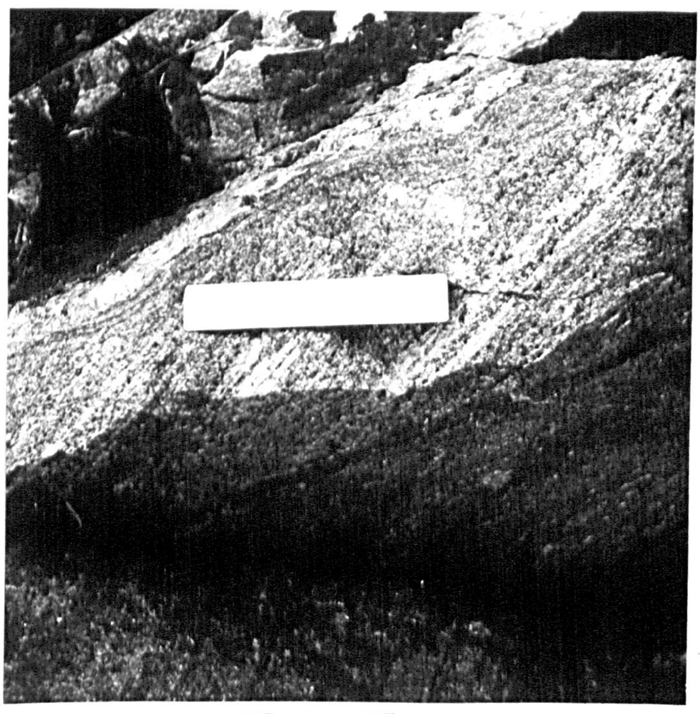


Plate I5

PLATE 16

Prominence of potash feldspar is shown by the grey colour in the felsic streaks.

PLATE 17

Pegmatitic potash feldspar (grey) penetrates the Laxford Bay gneisses. Two thirds of the narrow part of the specimen is composed of potash feldspar.

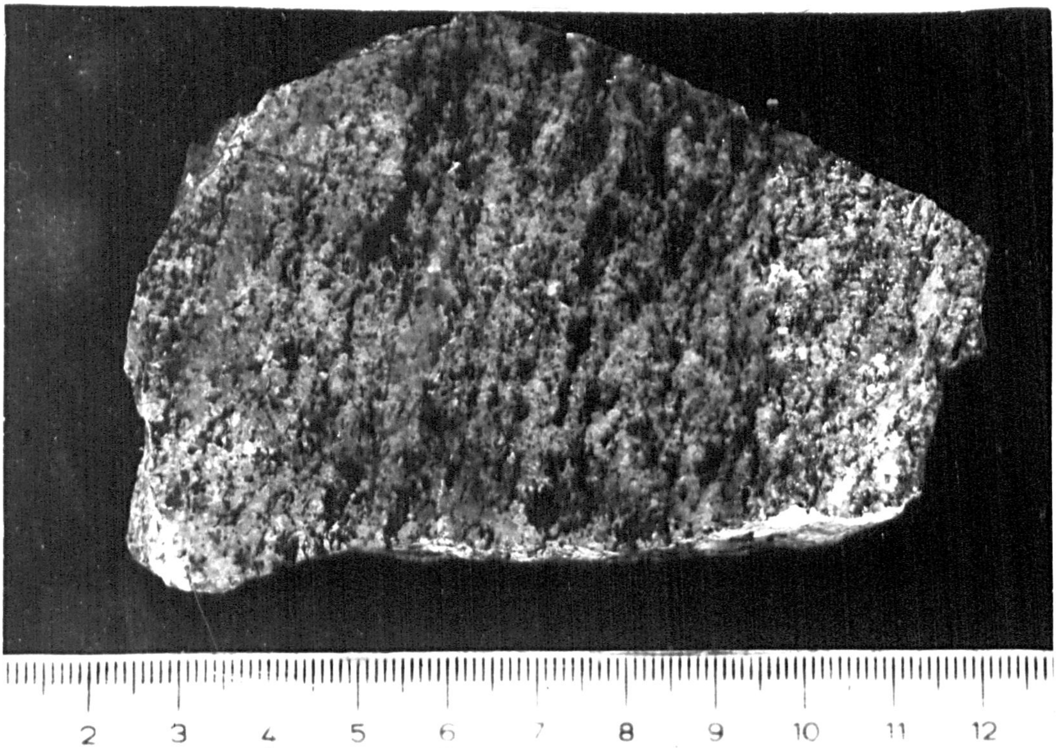


Plate I6

Plate I7

Metamorphic Segregation in the Gneiss Groups

The effects of metamorphic segregation are prevalent in all groups except the Claise Fearna gneisses. Mafic pods and lenses are the end products of this phenomenon and are best developed in the Laxford Bay gneisses in which they occur in great profusion at certain localities. For example, 300 metre ENE of Badcall Quay, they form 50% of a foliation surface exposure. The mafic pods, which reach a size of 30 cm., are predominantly composed of either hornblende or hornblende and pyroxene with an outer shell of hornblende (Plate 18). They usually form a sharp contact with the gneisses, but are occasionally either rimmed by or intermixed with quartzo-feldspathic material (Plate 19), features that may represent intermediate stages in the development of the mafic pods. The development of small irregular bodies of quartzo-feldspathic material, which usually contain variable amounts of mafic minerals, particularly hornblende, may be complementary to this process. Both the mafic pods and the quartzo feldspathic bodies are coarser in grain than the gneisses in which they occur.

Another manifestation of metamorphic segregation is the small both felsic and mafic clots and lenses less than 5 mm. in size, that are commonly seen in the Laxford Bay gneisses and to a lesser extent in the Weaver's Bay gneisses (pp.44-5 and pp.40-2). These small-scale segregations may represent the earliest stages in the formation of the larger mafic pods and quartzo-feldspathic bodies.

The striped gneisses are considered to be due to metamorphic segregation (differentiation) probably emphasising original compositional differences (cf. Deitrich, 1963). The striping shows all gradations from streaks and lenses, a few millimetres thick, consisting of quartz, biotite or hornblende to thick stripes with a highly variable mineral composition.

PLATE 18

An ultrmafic pod consisting of a core of hornblende and pyroxene with a rim of hornblende

PLATE 19

Pod of hornblende with a rim of quartzo-feldspathic material. To the right of the pod quartz, feldspar and hornblende are mixed more intimately.

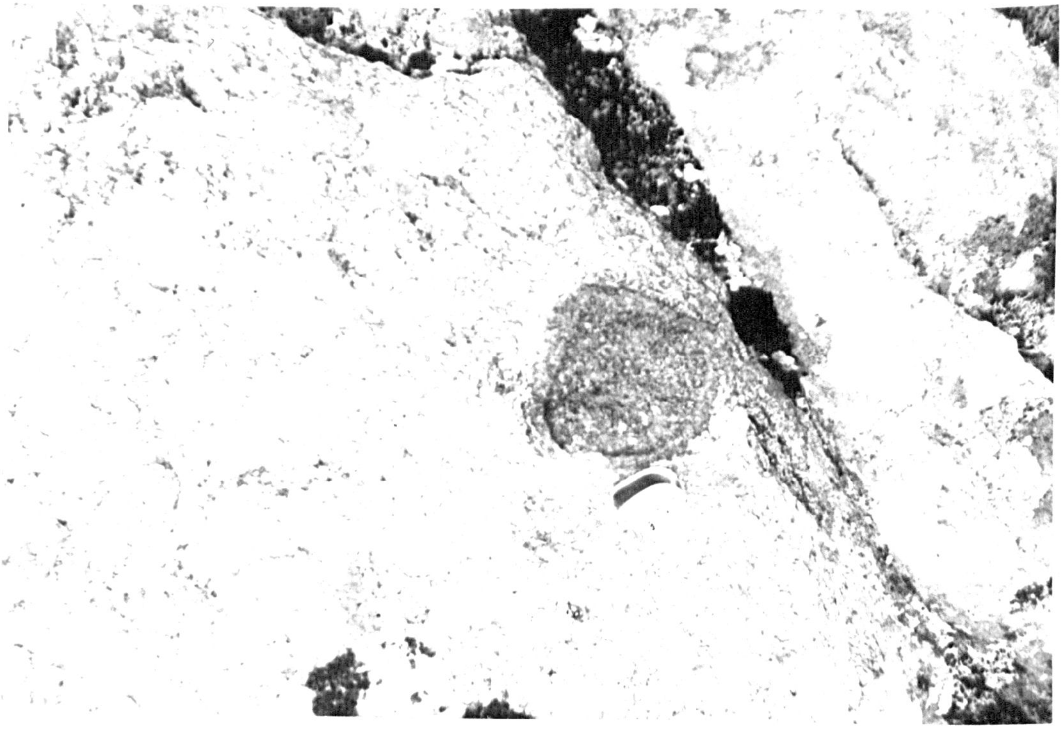


Plate I8

Plate I9

Microscopic Petrography of the Gneisses

The mineral constituents are essentially the same in each group of gneisses, but certain variations in the proportions of the mafic minerals distinguish one group from another (Table 11). Quartz, plagioclase, microcline, hornblende, biotite and epidote are the major mineral constituents and sphene, apatite, allanite, calcite, muscovite and opaque ores are the minor constituents. The main differences between the groups of gneisses are (i) the proportions of the mafic mineral constituents and (ii) the grain-size and textural relations of these minerals. Thus, the Claise Fearna gneisses are fine-grained, the Badnabay gneisses fine to medium-grained, the Weaver's Bay gneisses medium-grained and the Laxford Bay gneisses medium-grained (Table 12).

The range of mineral compositions, expressed in volume percentages, for the various groups of gneisses is shown in Table 13, the distribution of these minerals being summarised in Table 11.

Quartz shows a wide range of values, but it exceeds 25% in only two specimens (S.64 and L.22). Plagioclase also varies considerably, but there is no significant variation in the amount present in the different groups, as is the case with quartz. Microcline, similarly, does not vary markedly from group to group, although

DISTRIBUTION OF MINERALS IN THE GROUPS OF GNEISSES

	Claise Fearna	Badnabay	Weaver's Bay	Laxford Bay
Q	VC	VC	VC	VC
P	VC	VC	VC	VC
M	FC	FC	FC	FC
H	U	C	FC	FC
B	C	FC	C	C
E	C	U	FC	C
Musc.	r	a	r	r
Ores	u	u	u	u
Ap.	c	c	c	c
Sp.	c	c	c	fc
All.	c	u	fc	fc
Calc.	a	a	a	fc
Chl.	r	fc	r	r

VC — very common
C — common
FC — fairly common
U — uncommon
r — rare
a — absent

CAPITAL LETTERS — MAJOR CONSTITUENTS.
SMALL LETTERS — MINOR CONSTITUENTS.

Table 11 Mineralogical variations in the gneiss groups.

		Claise Fearna	Badnabay	Weaver's Bay	Laxford Bay
Q	R	0.05-0.7	0.05-1.5	0.06-1.8	0.06-3.0
	A	0.5	0.8	1.0	1.3
P	R	0.2-1.1	0.1-1.5	0.6-1.6	0.4-2.0
	A	0.7	0.9	1.1	1.3
M	R	0.06-3.0	0.1-1.0	0.1-1.2	0.1-1.2
	A	0.3	0.6	0.8	0.9
H	R	0.05-0.8	0.1-1.5	0.2-1.4	0.1-1.5
	A	0.5	0.6	0.6	0.7
B	R	0.05-0.8	0.1-1.4	0.3-1.3	0.3-1.4
	A	0.6	0.9	1.0	1.0
E	R	0.03-0.5	0.03-0.8	0.1-1.5	0.2-2.0
	A	0.3	0.5	0.7	0.8

Table 12. Variations in the grain-size of the gneisses.
Q=Quartz; P=Plagioclase; M=Microcline;
H=Hornblende; B=Biotite; E=Epidote.
R=Range of sizes.
A=Average or most common size.
In the case of biotite length of flake was measured.

there is a tendency for the Claise Fearna gneisses to be more trondhjemitic than the other gneisses while examination of the stained hand specimens suggests that potash feldspar tends to be more common in the Weaver's Bay and Laxford Bay gneisses than in the other groups. Hornblende and biotite show the variation previously described from field evidence, biotite predominating in the Claise Fearna and Laxford Bay gneisses, hornblende in the Badnabay gneisses, and both minerals occurring in approximately equal proportions in the Weaver's Bay gneisses. The distribution of epidote can also be related to the groups of gneisses: the mineral occurs in large amounts in the Claise Fearna gneisses, is virtually an accessory mineral only in the Badnabay gneisses, and gradually increases in amount towards the north-east, reaching its maximum in the Laxford Bay gneisses. Of the accessory minerals calcite is present only in the Laxford Bay gneisses and muscovite in all groups except the Badnabay gneisses; the others show no significant variation.

The textures and mineral relationships of the gneisses vary from group to group and appear to fall into a pattern that indicates an increase in the degree of recrystallization towards the north-east (cf. Watson op.cit). The texture of the gneisses is granoblastic but in the Weaver's Bay and Laxford Bay gneisses it is also partly crystalloblastic. An approximately equigranular texture, composed of polygonal grains of quartz and feldspar, is seen in many of the Claise Fearna gneisses (fig.2a), but, towards the north-east, the gneisses of each successive group become increasingly inequigranular (fig.2b).

The following petrographic description has been generalised to avoid repetition and is applicable to all groups of gneisses unless otherwise stated.

Quartz, showing a considerable range of grain-sizes (Table 12), exhibits undulose extinction in all but the smallest grains. It occurs in the following habits:-

1. Very small rounded or sub-rounded grains occur either within feldspar and hornblende or at the margins of these and other minerals.

2. Granular mosaics, the grains forming a roughly straight edged polygonal pattern, typically occur in the Claise Fearna gneisses but are absent in the other groups.

3. Irregularly shaped grains or patches composed of several grains are very common except in many of the Claise Fearna gneisses. They may be either interstitial or bulbous, lobate and usually convex towards the other minerals (fig.2c). Occasionally the grains and patches

are elongated into folia several millimetres in length and may enclose small grains of plagioclase and hornblende and flakes of biotite.

Quartz grain boundaries may be either smooth or sutured, mortar structure being present in some cases. Boundaries with the other minerals are usually smooth but occasionally quartz forms a serrated margin with plagioclase (fig2d) a feature particularly prominent in the Weaver's Bay gneisses from the island in Traigh Bad na Baighe and also seen in the Badnabay gneisses. Occasionally small inclusions of quartz in plagioclase have similar serrated margins. This feature is present at plagioclase-quartz contacts only when the twin lamellae are in contact with the quartz grain. The serrations are usually related to the twin lamellae, with one set of lamellae projecting into the quartz and the alternate set penetrated by that mineral. Occasionally those which project into the quartz have a clear, recrystallised, more sodic tip (fig.2e).

Plagioclase, whose composition usually varies only from An_{25}, to An_{29} irrespective of the mineralogical composition of the gneiss, does not show any variation in anorthite content from one group of gneisses to another. Zoning is never seen and twinned and untwinned feldspar occur in approximately equal amounts. Twinning is usually on the albite law with tapering, slightly curved lamellae being particularly prominent. Much of the plagioclase is fresh. Alteration, when present, is either patchy or confined to alternate lamellae, the products being either sericite or an unidentifiable dust. Plagioclase is usually granoblastic, but in the north-easterly-occurring gneisses it may be crystalloblastic. Two generations of plagioclase are present in some of the Badnabay gneisses, the later generation being slightly more sodic than the earlier one (fig. 2i). In these and other gneisses alteration sometimes occurs along a direction which is at a distinct angle to the albite twin lamellae. A clear, recrystallised rim, often more sodic than the core may form on plagioclase when this mineral is in contact with microcline (fig.2g) and occasionally with biotite (fig. 2h). Myrmekite may also be present at plagioclase/microcline contacts. Sodic rims occur in three ways: (1) as untwinned rims (2) as rims twinned in the same way as the plagioclase core and (3) as rims in which the twinning is reversed. In case (2) the sodic rim is only slightly more sodic than the core, the An content being greater than An_{20}. In case (3) the composition of the sodic rim is less than An_{20}, as indicated by the reversed twinning and is commonly around An_5. In the Weaver's Bay gneisses streaks more sodic than the host plagioclase can be observed to pass from one grain to another, occurring as a train of bubbles when a quartz grain intervenes (fig. 2i). In one of the Weaver's Bay gneisses streaks, which broaden at the edge of the grain, rather like the albite of flame perthite, occur at an angle to the twin lamellae of plagioclase and are slightly more sodic than the host (fig. 2j).

Microcline commonly exhibits well developed grid-twinning or, less commonly, wavy, slightly undulose twinning. Potash feldspar is only rarely untwinned but, following Tuttle & Bowen (1958, p.98), it is considered that this variety is also microcline. It is notable that a much higher percentage of microcline grains in the gneisses than in the granitic rocks exhibit grid-twinning, for example, in a 2 mm thick layer composed almost entirely of microcline every grain shows perfect grid-twinning. Microcline is present in varying amounts, the grain size increasing as the amount present increases; only rarely is it completely absent except in the Claise Fearna gneisses near the south-west edge of the area. It is commonly interstitial (fig. 3a) and often penetrates between or into other mineral grains (fig. 3b) particularly when present in small amounts. Microcline may envelop quartz and plagioclase grains (fig. 3c) and occasionally the latter appear to be slightly rotated parts of larger grains (fig. 3d). Microscopically visible perthite is rather uncommon in the microcline of the gneisses but when present it is of the flame perthite variety, the flames being composed of albite. Occasionally the albitic material that forms on plagioclase at plagioclase/microcline contacts appears to penetrate the grains of microcline, resulting in flame perthite (fig.3e). However, microcline with flakes of albite that have no obvious genetic relationship to plagioclase are common. In some cases the flames broaden towards a contact with biotite (fig.3f) and in other cases albite appears to form an independent phase (figs. 3g). Some large grains of microcline exhibit bulbous, convex relations towards plagioclase (fig. 3h) and occasionally short tongues penetrate that mineral.

Hornblende shows the least variation in grain-size (see table 12). It exhibits a crystalloblastic to granoblastic habit, the former being more common in this mineral than in the felsic minerals. Two varieties with the following pleochroic schemes are present in all groups of gneisses:-

	X	Y	Z
1.	pale green	green	dark green
2.	pale yellow-green	olive green	dark bluish green

The dark green variety is the more common and often the only one present in a thin-section. Hornblende is almost invariably fresh and the only alteration is a change from the usual strong pleochroic colours to very pale colours seen at a contact with biotite (plate 20). Small relics of hornblende are often enclosed by biotite at such contacts. In many of the more mafic bands, hornblende is associated with numerous oval granules of sphene. When it occurs in association with biotite and epidote both these minerals often cut completely across it. On rare occasions small grains of hornblende in optical continuity are enclosed by epidote. Concave relationships are usually shown towards plagioclase, quartz and microcline, hornblende remaining stable in all cases.

Biotite varies in length of flake not only from group to group (Table 12), but also within groups; for example in the Claise Fearna gneisses, the length increases from a maximum of 0.6 mm. in the gneisses of the extreme south-west to 0.8 mm. in the gneisses at the junction between the Claise Fearna and Badnabay groups, the increase being accompanied by an increase in the grain-size variation within specimens. There is a general increase in the length of the biotite flake from the Claise Fearna gneisses to the Laxford Bay gneisses. Three varieties of biotite occur with the following pleochroic schemes:-

	X	Y,Z
1.	straw	dark brown
2.	pale greenish brown	dark greenish brown
3.	pale reddish brown	dark reddish brown

According to Hayama (1959) colour differences in biotite are due to variations in composition. He concludes that the TiO_2 content and the ratio Fe_2O_3: Fe_2O_3 + FeO have the most important influence on colour: high TiO_2 content produces a reddish brown colour, high ferric to total iron a green colour, and a combination of these factors a brown colour. It should be noted that it is the relative proportions of these two factors that determine the colour. The greenish-brown variety is the most common in the gneisses throughout the area whereas reddish-brown biotite has not been seen in the Laxford Bay gneisses and is rather uncommon in the other groups. In most of the gneisses the biotite flakes are aligned in one plane although a haphazard arrangement is seen where hornblende is in close association and occasionally some individual flakes lie at right angles to the usual direction. They often have ragged ends and in all groups other than the Badnabay gneisses small flakes of white mica may be present at the ends. The flakes often terminate against epidote and are occasionally completely cut through by that mineral. In one case a small grain of epidote partly surrounded by biotite produces a pleochroic halo in the latter. The felsic minerals are often convex towards the ends of the flakes and usually moulded on to the sides. In a few thin-sections biotite and quartz form a symplectitic intergrowth, particularly when adjacent epidote forms a similar intergrowth. Biotite may be altered to chlorite and small scale puckering is occasionally seen.

Epidote is common in every group except the Badnabay gneisses, in which it is only occasionally prominent. It is either very pale-green and non-pleochroic or yellow and faintly pleochroic and occurs as prismatic and rhomboidal grains, as granular aggregates, or as irregular grains. It usually displays second order interference colours, although in some thin-sections from the Claise Fearna gneisses the interference colours are middle first order, suggesting a deficiency in ferric iron (Deer et al, 1963a, p.202) that can be correlated with a relatively low Fe_2O_3: $FeO+Fe_2O_3$ ratio in the reddish brown biotite of the same rock. The maximum angle of extinction ($z\wedge C$) is 25°. Epidote often forms a symplectitic intergrowth with quartz, particularly when it abuts against feldspar (which may be penetrated by the symplectite) and in some Laxford Bay gneisses the intergrowth fringes normal epidote (Plate 21). Epidote often partly or completely rims allanite and occasionally the opaque ores. The only mineral not cut by epidote is quartz which may display margins convex towards epidote.

Augite occurs only in the core of certain mafic pods within the gneisses. It is a pale-green non-pleochroic variety identical to that present in the amphibolites (p. 33). It may enclose small grains of hornblende but is rarely enclosed by that mineral.

The accessory minerals are allanite, apatite, calcite, chlorite, muscovite, opaque ores and sphene, their distribution being shown in Table 11 . Allanite, which is present in most of the gneisses, varies in size from 0.1 mm. to 0.6mm. and is often rimmed by epidote. Apatite, often associated with the mafic minerals, varies in size from 0.1 mm. to 1 mm. and occurs as oval or rounded grains that are apparently most abundant when large amounts of microcline are present in proximity to the mafic minerals. Calcite occurs either as an interstitial mineral or within plagioclase. Muscovite most commonly occurs as minute flakes of white mica fringing biotite, but in a few of the Claise Fearna and Weavers Bay gneisses it occurs as fairly large flakes that occasionally form a vermicular intergrowth with quartz. Sphene, a common accessory, occurs as oval granules that reach a size of 0.6 mm. and are commonly associated with the more mafic parts of a gneiss. The ore minerals are pyrite, magnetite and haematite occurring either alone or together in a complex series of associations:

Pyrite may be rimmed by either haematite or magnetite, each of which may be rimmed by the others or may occasionally vein and penetrate pyrite and one another in an intimate manner. Chlorite occurs as a rare late replacement.

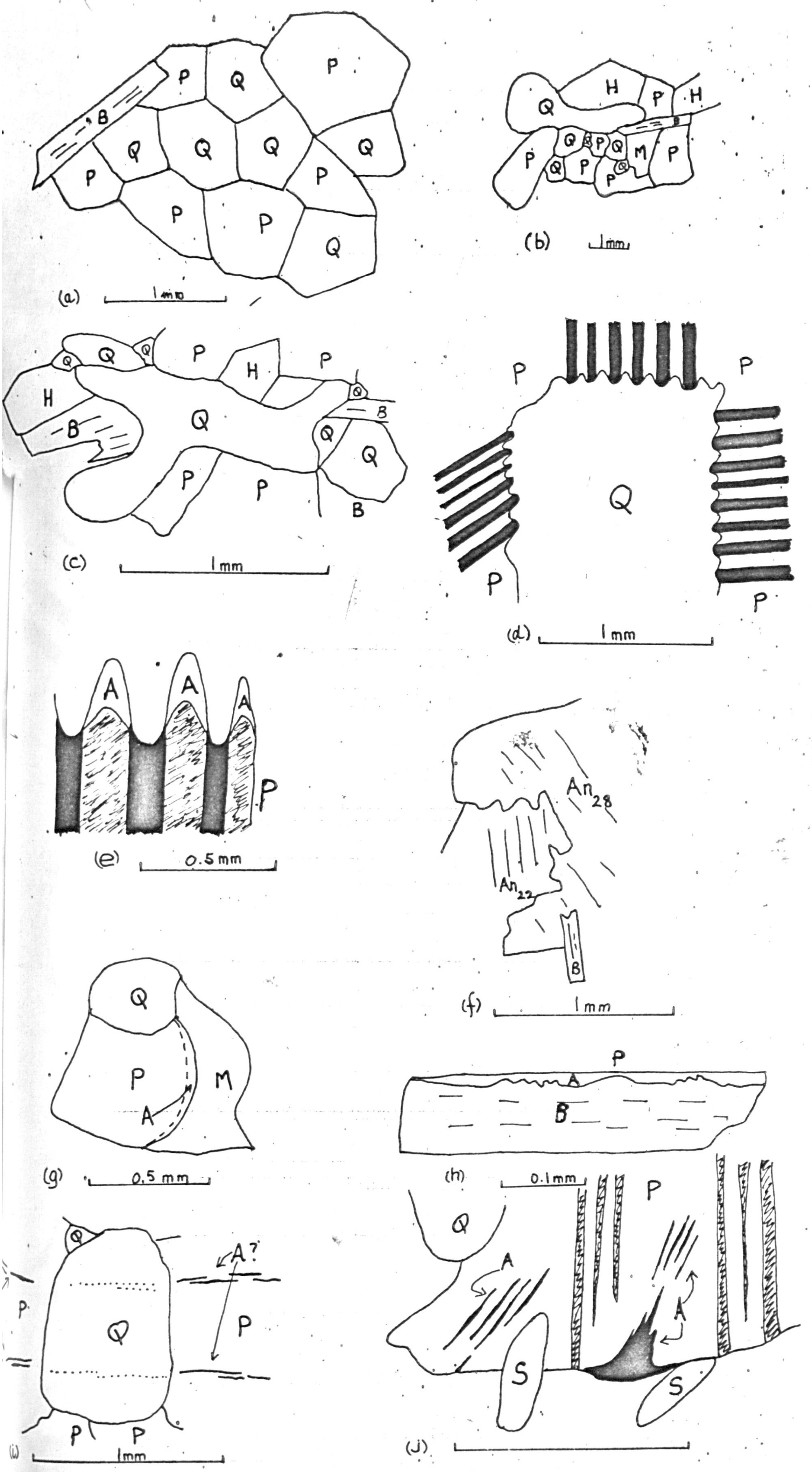


Fig 2 Mineralogical relationships in the gneisses

Fig. 3 Mineralogical relationships in the gneisses

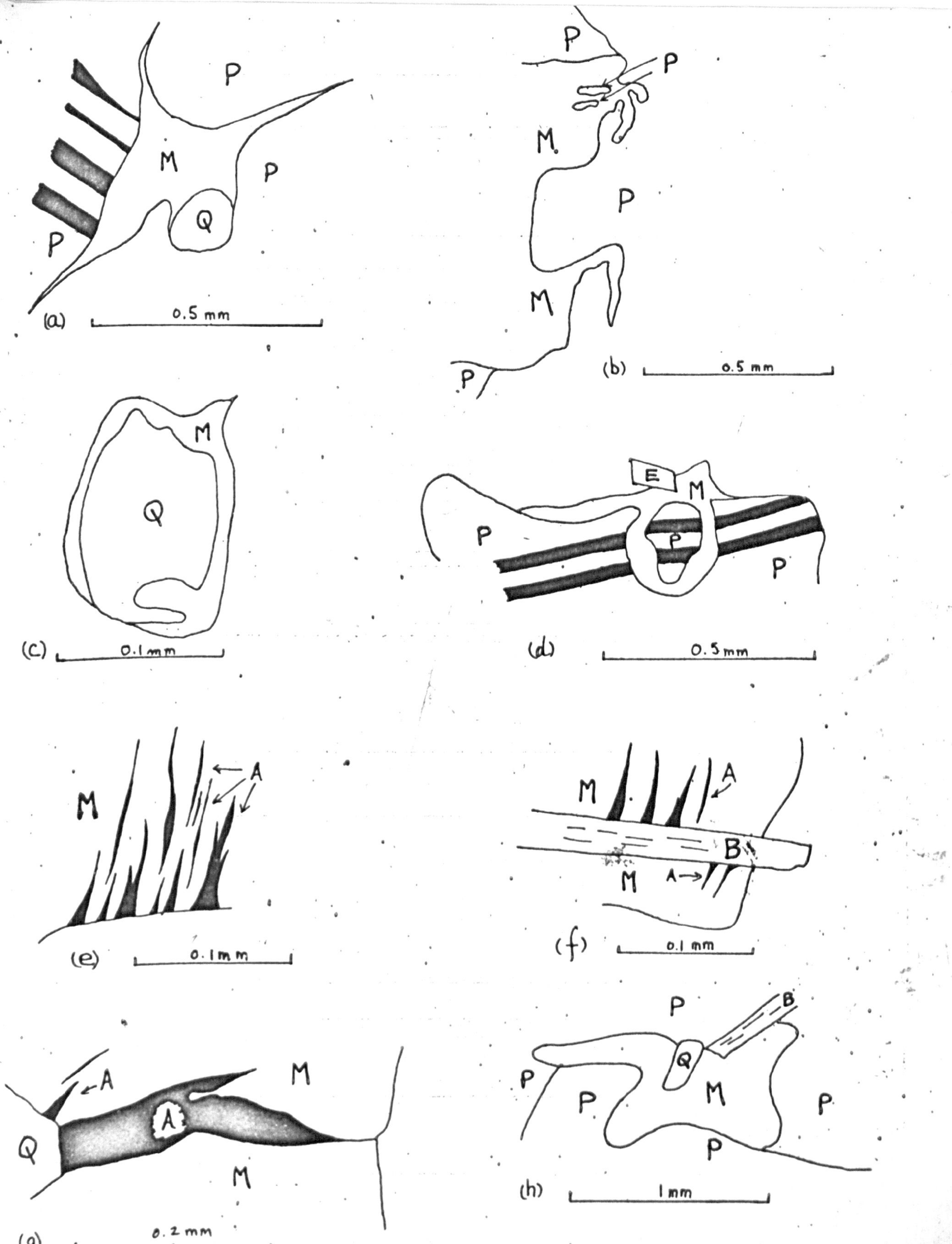


Fig. 3 Mineralogical relationships in the gneisses

Plate 20

Hornblende (partly bleached) in contact with biotite. X 100 Crossed nicols . Laxford Bay gneisses.

Plate 21

Epidote fringed by a quartz-epidote symplectite. X 100 Crossed nicols. Laxford Bay gneisses.

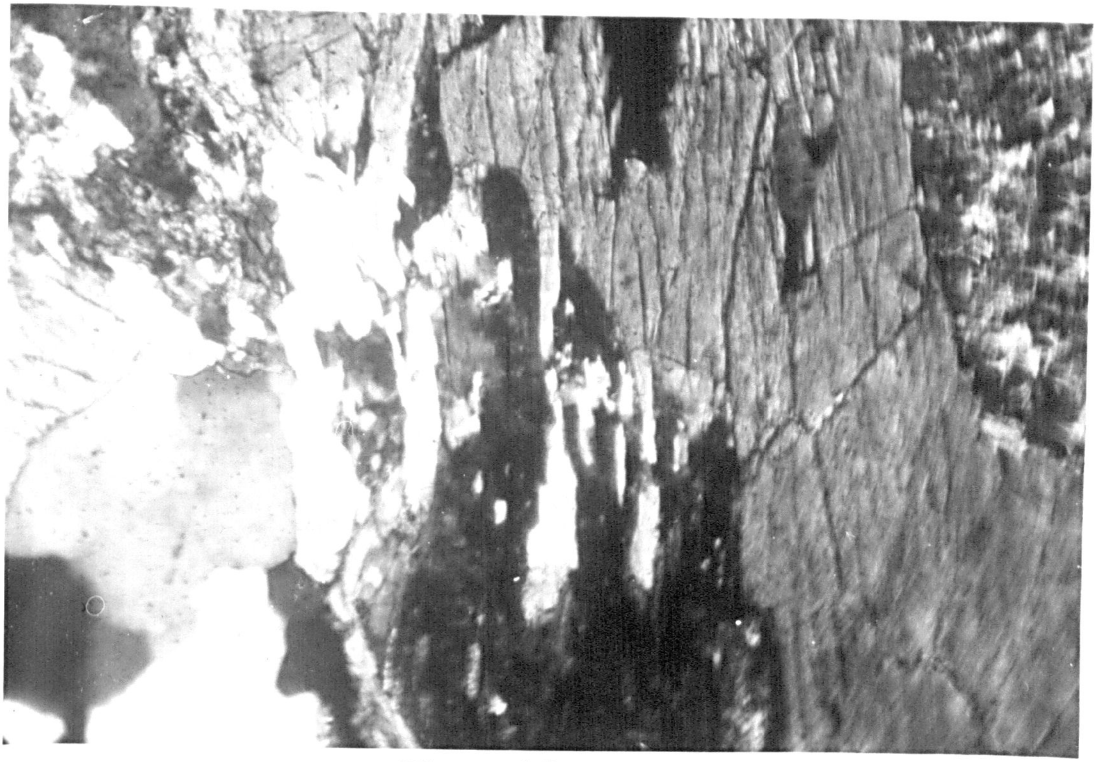


Plate 20

Plate 21

The Geochemistry

Published work on the geochemistry of the gneisses of the Laxfordian complex is confined to one analysis of the major oxides (Peach et al.,1907 - see Table 13, no.19) and an average of four trace element analyses (Hitchon, 1960 - see Table 13, no.20). In the present study 17 gneisses and one hornblendic pod have been analysed for their major oxides and of these 7 have been analysed also for trace elements and all for the alkali elements Li, Rb, and Cs by the methods described in Chapter I, to which reference should be made for the analytical details and errors (pp. 14-27).

Major Oxides

The chemical analyses, in weight per cent, of 18 Laxfordian gneisses, together with cation percentages, Niggli numbers and mesonorms are shown in Table 13. As might be expected from any series of gneisses, the analyses can be arranged to show a trend of increasing acidity. All the analysed gneisses are trondhjemitic, granodioritic, or quartz-dioritic with soda predominating over potash. With one exception (S14) the ratio lime:potash is greater than 1. The gneiss groups appear indistinguishable at first sight but the ratios $K^{+}:Na^{+}$ and $K^{+}:Si^{4+}$ suggest certain distinguishing features.

The consistent predominance of soda over potash in the gneisses contrasts with the one published chemical analysis of a biotite gneiss from near Durness (Peach et al, 1907 - see Table 13), in which potash predominates over soda. In this rock the $K^+:Na^+$ ratio, which is greater than 2, is greater than the $K^+:Na^+$ ratio of most of the Cnoc nan Cro granitic rocks (see pp.166). The relatively high potash value can be explained by the presence of considerable amounts of biotite (see mesonorm in Table 13, no.19) but the low soda content is more difficult to explain. The normative plagioclase contains 64 per cent of the anorthite molecule, whereas according to the petrographic description, the plagioclase is oligoclase. This analysis is, therefore, considered to be of doubtful quality, thus affecting the validity of parts of Watson's discussion of the chemical changes during the Laxfordian metamorphism (Sutton & Watson, 1951, pp. 290 - 291). Watson uses this analysis to support the suggestion that the total feldspar of the acid Laxfordian is not much greater than that of the acid Scourian. Comparing the analysis with one of an acid charnockite - a quartz-pyroxene gneiss (Table 13) - it is concluded that, relative to the Scourian, soda and lime have migrated out of the acid rocks and that microcline has replaced plagioclase during the Laxfordian metamorphism. The analyses quoted here show that this conclusion cannot be supported.

A close similarity exists between the Laxfordian gneisses and the gneisses from other areas of Pre-Cambrian basement, for example, the Svecofennides of Finland and the Pre Cambrian of West Africa. Table 13 compares the geochemistry of the Laxfordian gneisses with some synkinematic gneisses of West Africa (Marmo, 1962b), and Finland (Simonen 1960).

Gneisses of this kind may be either magmatic (Eskola, 1932, 1960) or metamorphic-metasomatic (Read, 1957; Marmo, 1962a) in origin. Trends obtained from chemical analyses may be useful in determining the origin of a series of gneisses (see Howie, 1955) and a number of diagrams of variations in ratios (Figs. 4-7) prepared from the analyses of the Laxfordian gneisses, are now discussed.

(1) <u>The ratio Na:K</u>

In all cases the ratio Na:K is greater than 2:1 and in most cases it is greater than 4:1. A plot of Na against K (fig. 4b) for the Laxfordian gneisses shows a wide scatter of points. A statistical analysis shows that the correlation coefficient between Na and K is + 0.031, a very low degree of positive correlation, suggesting that as Na increases K tends also to increase. However, the correlation coefficient is so close to zero that there is practically no linear agreement between Na and K. At the same time it is significant that the ratio Na:K is less than 5.5:1 for the Weaver's Bay and Laxford Bay gneisses, with the exception of L135a (the flaggy quartzite) and greater than 5.5:1 for the Claise Fearna and Badnabay gneisses, with the exception of 514. In addition, despite the evidence of a positive correlation coefficient, the lower Na:K ratios appear, in some cases, to be due to a combination of decreasing Na and increasing K; for example in L41 (Table 13, No.12) the values of Na and K are respectively lower and higher than in most of the gneisses and appears to suggest an antipathetic relationship.

(2) <u>The ratio $Mg:Fe^2 + Fe^3$</u>

A plot of Mg against $F^2 + Fe^3$ shows that there is a systematic variation in the relative proportions of these elements (Fig. 4a). The correlation coefficient for this ratio is + 0.84, a high degree of positive correlation indicating that as Mg increases so does $Fe^2 + Fe^3$ both increasing by approximately the same amount. Variations in the $Mg:Fe^2 + Fe^3$ ratio of 0.75:1 to 2:1 are not geographically significant, that is there is no apparent systematic change in the ratio from one group of gneisses to another.

(3) <u>The relative proportions of $Na+K:Fe^2+Fe^3:Mg$</u>

As expected from the previous ratio, there is a systematic, approximately linear variation in the relative proportions of these elements. (Fig. 5b). As Na+K increases Fe^{2}+ Fe^{3} and Mg decrease. These proportions reflect the variations in the feldspathic constituents and the ferromagnesian constituents, which are considered to be due, at least in part, to metamorphic segregation. There is no systematic variation from one group of gneisses to another.

(4) <u>The Niggli numbers</u>

The Niggli numbers **k**, al, fm, **c**, alk and **ti** have been plotted against si (fig. 6). The values al, k and alk all increase as si increases, whereas fm decreases, ti tends to decrease, and **c** shows a scatter of points which indicate neither an increase nor a decrease. al increases and fm decreases at approximately the same rate.

(5) <u>The Na and K: Si ratios</u>

The plot of Na against Si shows a scatter of points (fig. 7) and there is no significant increase or decrease in Na as Si increases. The plot of K against Si shows two significant trends as Si increases (fig. 7). Above Si values of 63% K values shows a divergence, one set of values increasing as Si increases and one set decreasing, indicating that as the gneisses become more acid they tend to form different types. The trend towards higher values of K appears to be associated with the Weaver's Bay and Laxford Bay gneisses and towards lower values of K with the Claise Fearna and Badnabay gneisses.

(6) The Quartz-albite-orthoclase diagram

The system quartz-albite-orthoclase-water, which has been studied experimentally by Tuttle & Bowen (1958) is discussed on p. 169. Two plots of normative quartz, albite and orthoclase, one recalculated from the catanorm and the other from the mesonorm, have been made for the Laxfordian gneisses. The field of the gneisses lies beyond the ternary eutectic at 4000kg/cm^2 water vapour pressure, suggesting that, unless very high water vapour pressures are invoked the origin of the Laxfordian gneisses cannot be explained by extrapolation from the quartz-albite-orthoclase diagram of Tuttle & Bowen (1958). (fig.8a).

(7) The orthoclase-albite-anorthite diagram

Two plots of normative orthoclase, albite and anorthite one recalculated from the catanorm and one recalculated from the mesonorm, have been made on the Or-Ab-An diagram for the Laxfordian gneisses. Those plotted from the mesonorm are moved towards the Ab apex with respect to to those plotted from the catanorm (fig. 8b). The plots are rather scattered indicating that there is no systematic variation between Ca, Na and K. as can also be seen in figure 5a.

Trace elements

The trace element concentration in gneisses from each of the groups and the alkali elements Li, Rb, and Cs for all the analysed specimens have been determined (Table 13). Cs was not detected in any specimen and, therefore, if this element is present its concentration is less than 5 ppm. Concentrations of Rb have been recalculated to cation ppm. and the resulting values plotted against the cation percentages of K (fig.9). The ratio Rb:K shows an approximately linear trend.

Ba is the only trace element that shows a notable variation in concentration from group to group.

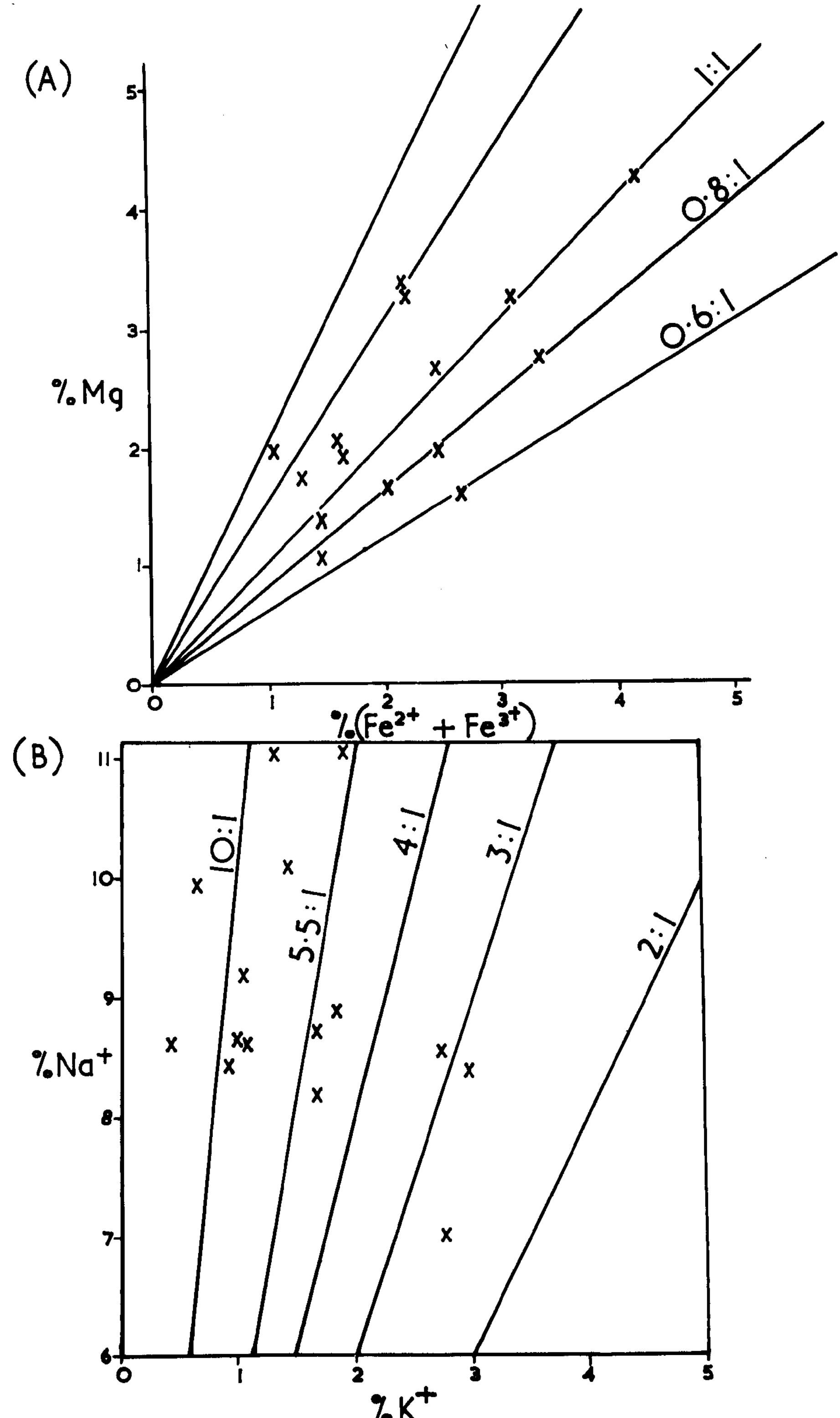


Figure 4 Plots of (a) %Mg against %(Fe^2+Fe^3)
(b) %Na against %K

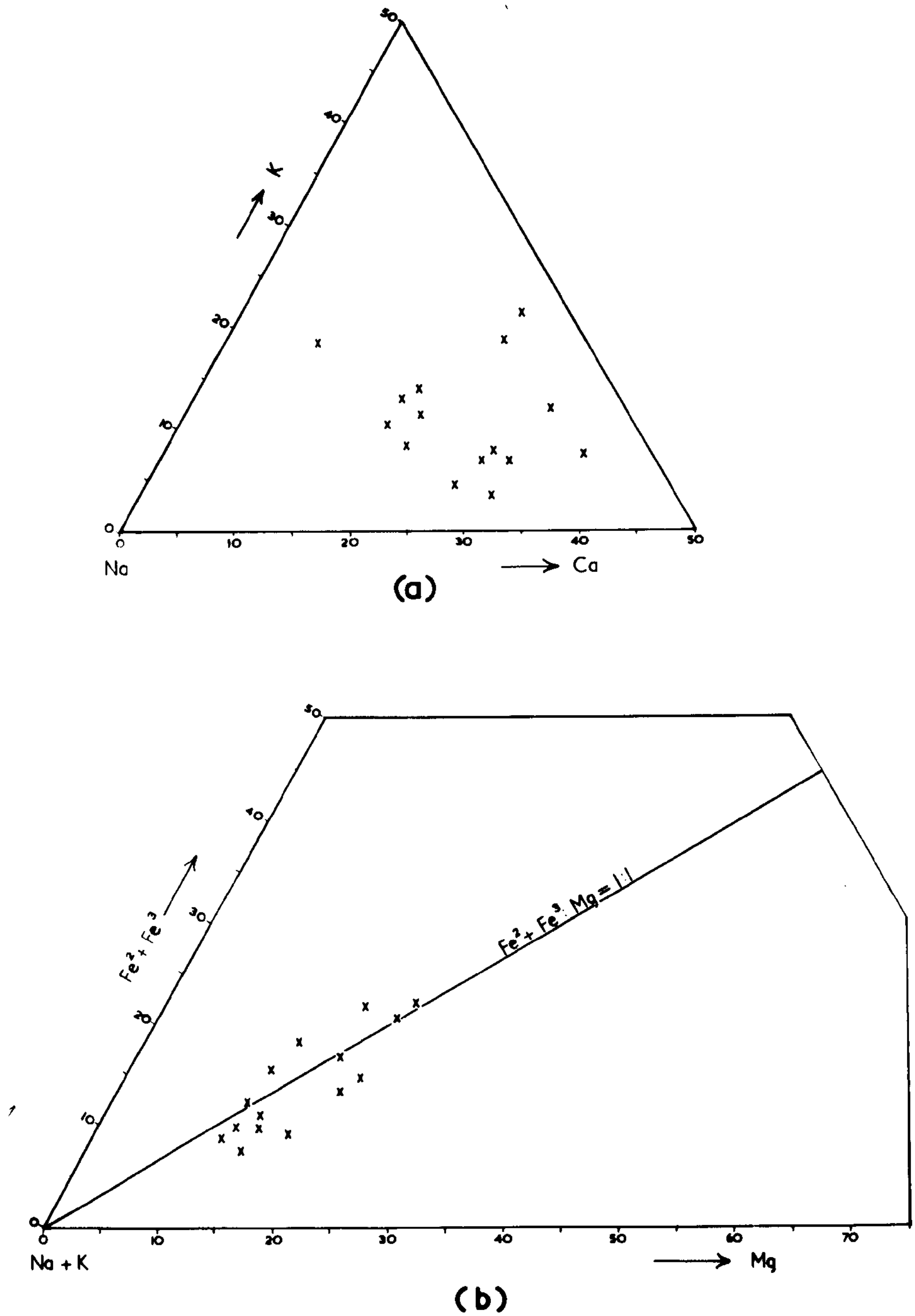


Figure 5 Triangular variation diagrams of
(a) Na, K, and Ca.
(b) Na+K, $Fe^{2}+Fe^{3}$, and Mg.

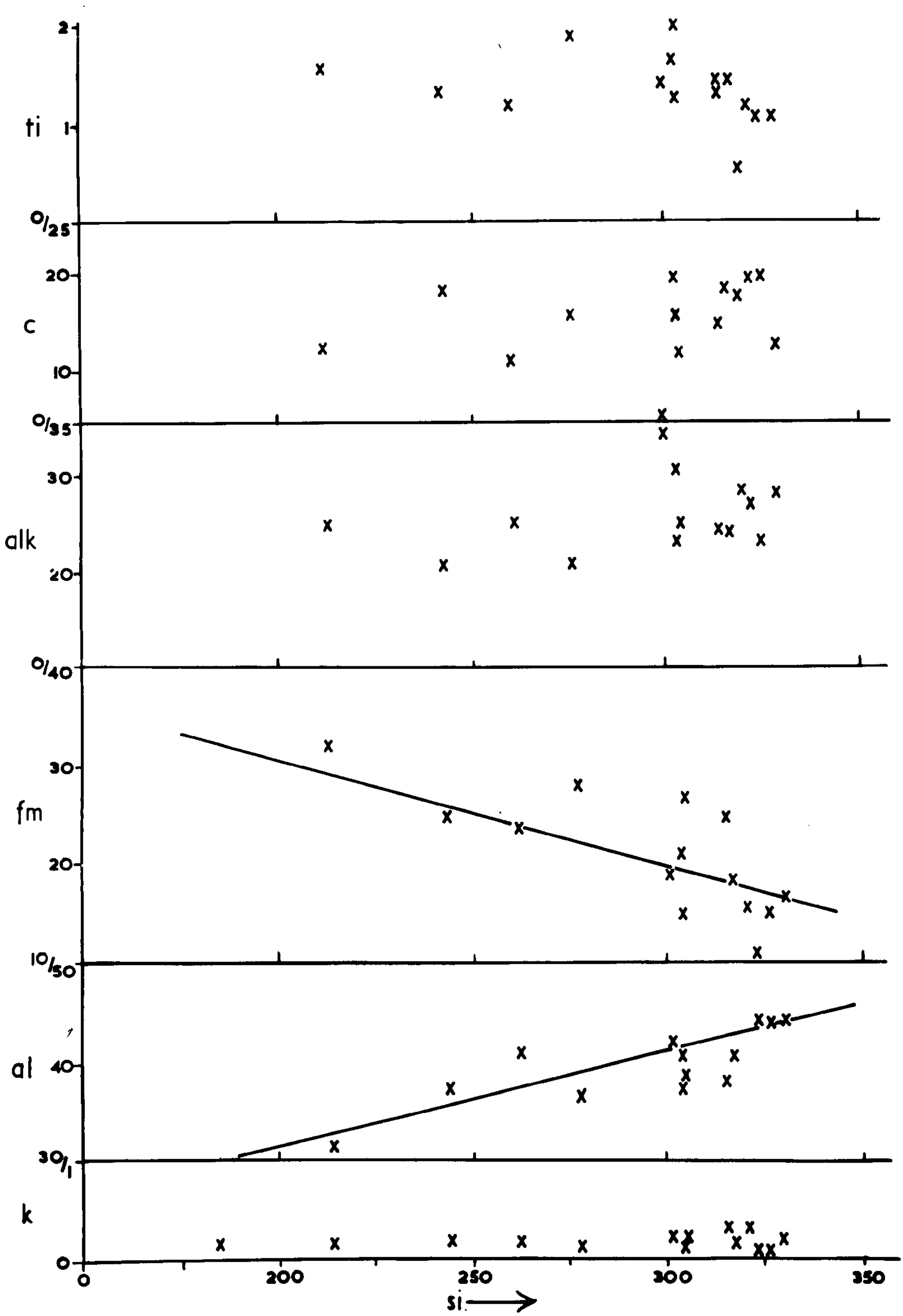


Figure 6 Plots of Niggli Numbers.

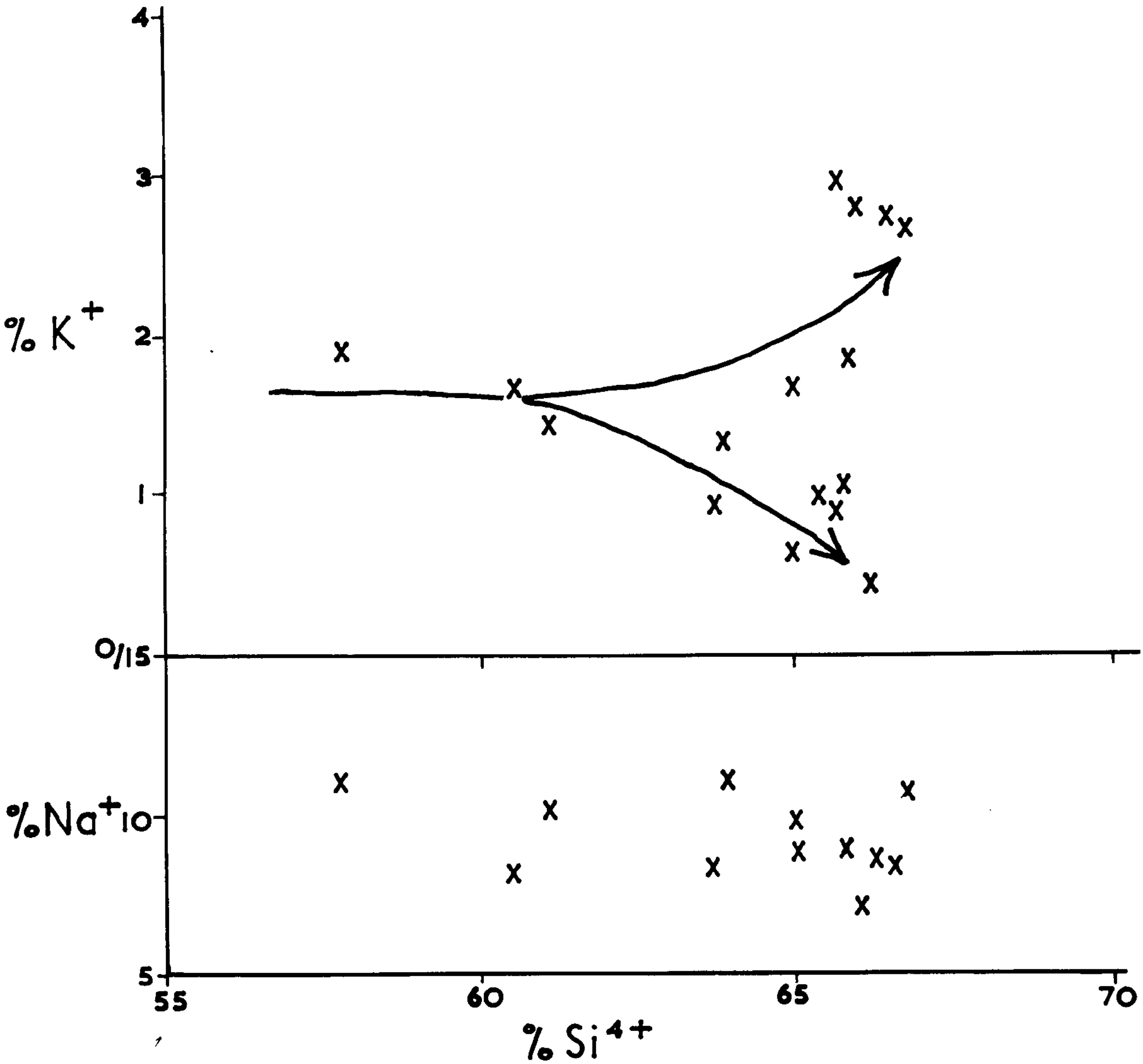


Figure 7   Plots of %Si against %Na and %K.

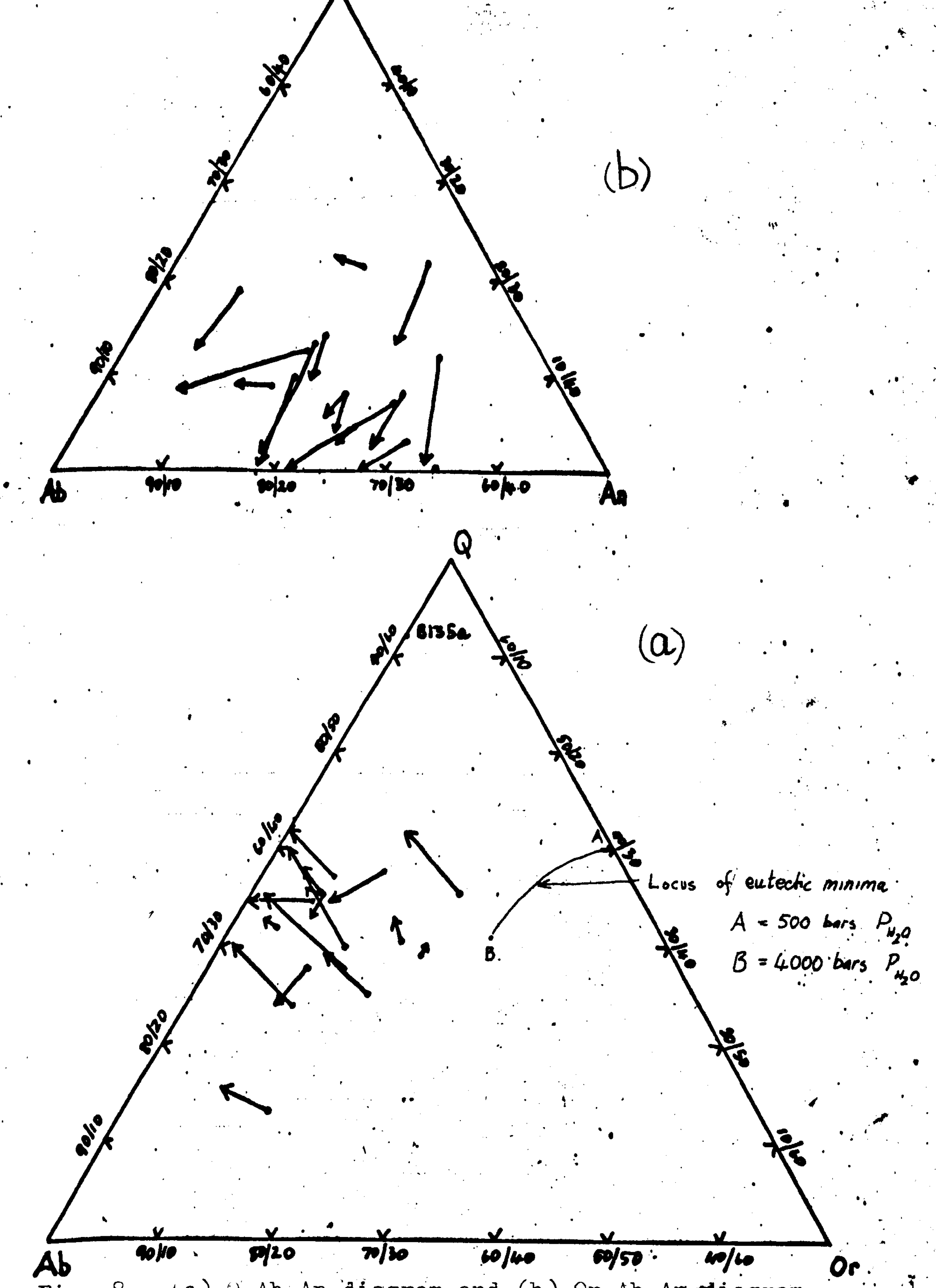


Fig. 8 (a) Q-Ab-An diagram and (b) Or-Ab-An diagram

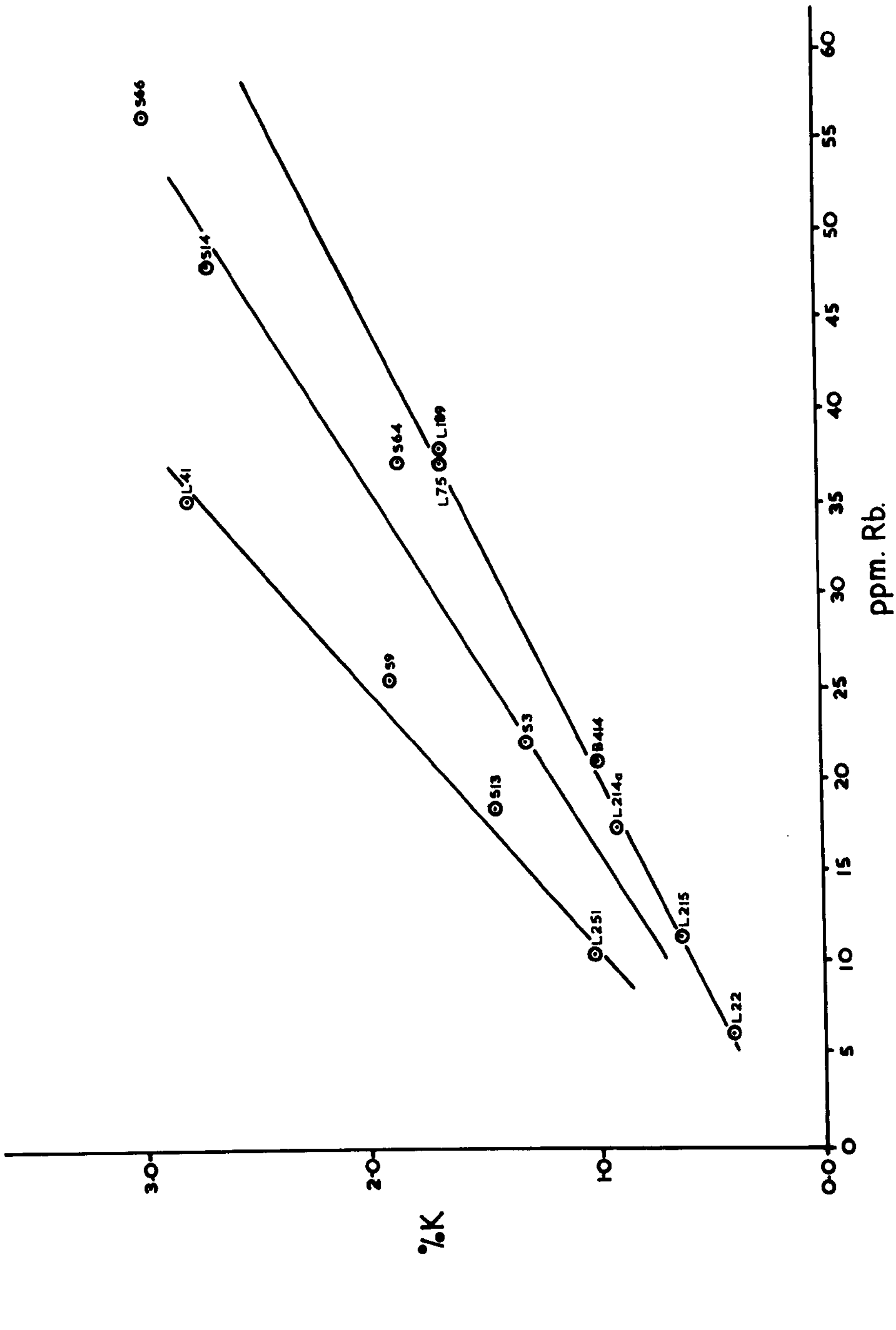


Fig.9 Plot of Rb against K

Distinguishing features of the gneiss group

The evidence so far offered shows that the four groups of gneisses can be distinguished from one another on structural, mineralogical, petrographical and geochemical grounds.

In the field the following criteria are important:

1. Biotite predominates in the Claise Fearna and Laxford Bay gneisses, and hornblende in the Badnabay gneisses, whereas hornblende and biotite occur in approximately equal proportions in the Weaver's Bay gneisses.

2. Striped gneisses are well developed in the Badnabay gneisses, the striping being progressively replaced by a streaky and lens shaped segregation in the Weaver's Bay and Laxford Bay gneisses. Streaky, sub-homogeneous gneisses are common in the Claise Fearna group.

3. The Claise Fearna gneisses are fine-grained and equigranular while inequigranularity and a sugary texture appear in the Badnabay gneisses and increase in the Weaver's Bay and Laxford Bay gneisses.

4. Folding, axial plane foliation and lineation are commonly seen in the Claise Fearna and Badnabay gneisses, but are less common in the Weaver's Bay gneisses. Foliation showing small scale puckering is present in the Laxford Bay gneisses while lineation is not prominent.

5. Epidote occurs in large amounts in the Claise Fearna gneisses, is virtually an accessory mineral only in the Badnabay gneisses and gradually increases in amount towards the north-east, reaching its maximum in the Laxford Bay gneisses.

Other criteria depend on thin-section analysis:

1. A gradual increase in grain-size in the gneisses is observed to occur towards the north-east.

2. Of the accessory minerals calcite is present only in the Laxford Bay gneisses, while muscovite is absent only in the Badnabay gneisses.

Geochemical criteria can also be used to distinguish between certain groups thus:

1. The Weaver's Bay and Laxford Bay gneisses can be distinguished from the Claise Fearna and Badnabay gneisses on the basis of the $Na^{+}:K^{+}$ ratio. In the former groups the ratio is usually less than 5.5:1 while in the latter groups it is greater than this value.

Although there are several ways in which the groups of gneisses can be distinguished, only a combination of features can be used to classify a gneiss sample. The Na:K ratio must be used carefully, for obviously the ratio in granitic gneisses of the Badnabay and Claise Fearna gneisses will be less than 5.5:1.

Metamorphic Facies

Sensitive mineral indicators, which would have given a precise indication of the metamorphic facies, are absent in the gneisses of the Laxford area. However, the wide distribution of the following conditions suggest that the acid gneisses belong to the epidote-amphibolite facies as defined by Ramberg (1952) (=staurolite-quartz subfacies of the almandine amphibolite facies of Fyfe, Turner and Verhoogen (1958)).

1. Plagioclase is rarely more calcic than An_{30}.
2. Epidote, very common in the gneisses, appears as a stable mineral in the presence of sodic plagioclase.

Watson, following Teall's petrographic description of the Lewisian rocks (in Peach et al., 1907) states that both basic and acid Laxfordian gneisses contain a green, non-pleochroic augite which has grown at the expense of hornblende (op.cit., 1951). In the present investigation a detailed petrographic study has shown that a pale green pyroxene occurs only in ultramafic pods and balls associated with the gneisses or, more rarely, in thin layers of gneiss rich in ferromagnesian minerals which are interlayered with the acid gneisses. This suggests that higher facies conditions existed at an earlier stage of the metamorphism. It is considered that this facies was the amphibolite facies as defined by Ramberg (1952) and that the stable epidote-sodic plagioclase association present in the acid gneisses represents a decrease in the metamorphic grade not reflected in a few ultramafic pods, balls and stripes, except on the rims.

It may be significant to note that in the amphibolites and the Northwest Adirondack Mountains, New York, a green clinopyroxene appears at about 540°C (Engel & Engel, 1962a).

Table 13

Chemical composition expressed as weight %, cation percentages, mesonorms, Niggli numbers, modes, trace element values, and catanorms are listed in order.

	1	2	3	4	5	6	7	8
	B137	L22	L251	S3	S9	S13	S14	L214a
SiO_2	71.80	70.53	69.71	70.17	62.56	66.14	70.28	67.85
Al_2O_3	15.69	15.89	15.02	15.70	15.45	17.35	15.09	14.97
Fe_2O_3	0.89	0.90	1.39	0.77	2.17	1.54	0.58	1.76
FeO	1.10	1.12	1.37	1.07	3.57	1.49	1.60	2.46
MgO	0.7[illegible]	1.00	1.17	1.29	3.07	2.39	1.45	2.30
CaO	3.03	3.96	3.72	3.30	3.3[illegible]	2.59	1.16	3.58
Na_2O	5.12	4.76	4.69	6.27	6.20	5.65	5.90	4.63
K_2O	0.88	0.36	0.89	1.15	1.62	1.21	2.26	0.77
TiO_2	0.29	0.26	0.38	0.57	0.57	0.37	0.30	0.53
P_2O_5	0.05	0.05	0.13	0.07	0.11	0.13	0.10	0.10
MnO	0.03	0.03	0.04	0.04	0.12	0.04	0.03	0.07
H_2O	0.82	0.55	0.56	0.56	0.74	0.63	1.25	0.55
Total	100.48	99.39	99.07	100.96	99.54	99.53	100.00	99.57
Si^{4+}	66.75	66.25	65.82	63.97	57.82	61.12	66.82	63.69
Al^{3+}	17.17	17.59	16.67	16.89	16.82	18.86	16.47	16.54
Fe^{3+}	0.63	0.62	1.01	0.53	1.51	1.07	0.41	1.25
Fe^{2+}	0.84	0.87	1.06	0.81	2.76	1.15	1.23	1.93
Mg^{2+}	1.08	1.41	1.65	1.74	4.23	3.30	2.00	3.21
Ca^{2+}	3.03	3.98	3.76	3.29	3.34	2.55	1.15	3.59
Na^{+}	9.19	[illegible]	8.59	11.07	11.10	10.12	10.58	8.41
K^{+}	1.05	0.41	1.06	1.31	1.91	1.45	2.68	0.92
Ti^{4+}	0.21	0.20	0.27	0.40	0.41	0.27	0.22	0.36
P^{5+}	0.04	0.03	0.09	0.04	0.07	0.09	0.05	0.06
Mn^{2+}	0.02	0.02	0.02	0.02	0.07	0.02	0.02	0.04

	9	10	11	12	13	14	15	16	17	18
	L215	B414	S30	L41	L135a	S64	S66	L75	L189	UB12
SiO_2	70.62	69.11	70.29	70.29	65.30	70.55	71.50	69.52	64.75	47.97
Al_2O_3	16.26	14.32	15.15	14.07	15.89	15.88	14.86	14.69	16.71	10.10
Fe_2O_3	0.54	1.20	0.92	1.00	2.80	1.04	0.40	0.95	1.77	5.02
FeO	1.03	2.12	1.34	2.25	0.80	1.55	1.08	2.10	2.74	10.24
MgO	0.64	1.36	1.43	1.88	1.10	0.95	1.41	2.35	1.95	12.50
CaO	3.96	4.13	2.67	3.11	11.07	2.49	3.63	2.39	4.49	10.22
Na_2O	5.57	4.71	4.91	3.84	2.02	4.94	4.70	4.81	4.52	1.11
K_2O	0.56	0.83	2.30	2.32	n.d.	1.56	2.54	1.38	1.38	0.77
TiO_2	0.29	0.61	0.34	0.35	0.42	0.26	0.14	0.36	0.49	0.66
P_2O_5	0.05	0.10	0.09	0.05	0.10	0.20	0.06	0.16	0.24	0.01
MnO	0.03	0.04	0.02	0.04	0.04	0.04	0.02	0.02	0.08	0.32
H_2O	0.30	0.51	0.60	0.40	1.15	0.54	0.30	0.53	0.62	1.54
Total	99.85	99.04	100.06	99.60	100.69	100.00	100.64	99.26	99.74	100.46
Si^{4+}	65.03	65.43	66.61	66.04	62.36	65.67	65.79	65.06	60.56	45.44
Al^{3+}	17.66	15.99	16.67	15.60	17.87	17.42	16.10	16.17	18.44	11.26
Fe^{3+}	0.38	0.85	0.64	0.73	2.06	0.75	0.28	0.67	1.25	3.59
Fe^{2+}	0.79	1.67	1.03	1.78	0.64	1.20	0.82	1.63	2.15	8.09
Mg^{2+}	0.87	1.92	1.99	2.63	1.58	1.31	1.94	3.26	2.73	17.57
Ca^{2+}	3.90	4.18	1.87	3.12	11.37	2.52	3.57	2.41	4.48	10.36
Na^{+}	9.95	8.66	8.55	7.01	3.71	8.90	8.40	8.73	8.18	2.03
K^{+}	0.65	0.99	2.75	2.79	n.d.	1.85	2.97	1.66	1.67	0.93
Ti^{4+}	0.22	0.35	0.26	0.25	0.31	0.20	0.09	0.26	0.33	0.47
P^{5+}	0.03	0.06	0.05	0.03	0.08	0.16	0.03	0.13	0.18	0.01
Mn^{2+}	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.04	0.25

	19	20	21	22	23	24	25	26	27	28
	NHW1	H1	NHW2	OH1	OH2	OH3	F1	M1	S1	S2
SiO_2	66.76	-	60.39	67.68	75.56	67.82	64.7	70.7	65.92	68.20
Al_2O_3	14.38	-	16.14	16.82	14.83	15.04	14.8	15.3	16.16	16.22
Fe_2O_3	2.04	-	3.56	1.01	0.22	1.25	1.5	0.9	1.17	0.48
FeO	3.75	-	3.88	1.93	n.d.	2.94	3.9	1.7	2.64	2.94
MgO	2.71	-	3.43	1.18	nil	1.25	2.2	1.0	2.19	1.17
CaO	4.62	-	6.36	5.02	2.59	4.96	3.1	2.7	4.22	3.37
Na_2O	1.44	-	3.75	4.53	5.78	3.99	3.1	5.1	4.87	4.54
K_2O	3.33	-	0.87	0.80	0.36	1.87	1.9	1.5	1.65	1.65
TiO_2	n.d.	-	n.d.	0.55	0.66	0.57	0.5	0.2	0.35	0.50
P_2O_5	n.d.	-	n.d.	0.17	0.05	0.23	0.2	0.2	0.06	0.83
MnO	0.14	-	0.86	0.03	nil	0.04	0.2	0.05	0.06	0.04
H_2O	0.49	-	0.91	0.57	0.11	0.31	2.4	0.6	0.93	0.68
Total	99.66		100.15	100.29	100.16	100.27	98.4	99.95	100.22	100.02

Table 13 Complete data on the gneisses.

Analyses 1-3 : Claise Fearna gneisses

Analyses 4-10: Badnabay gneisses

Analyses 11-13: Weaver's Bay gneisses

Analyses 14-17: Laxford Bay gneisses

Analysis 18 : Hornblendic pod in the Laxford Bay gneisses

Analysis 19 : Biotite gneiss, Durness. (Peach et al. 1907)

Analysis 20 : Average of 4 Laxfordian gneisses. (Hitchon,1960)

Analysis 21 : Quartz-pyroxene gneiss, Scourie. (Peach et al., op.cit.)

Analyses 22-24 : Scourian gneisses. (O'Hara,personal com.)

Analysis 25 : Average greywacke (Pettijohn,1957).

Analysis 26 : Average synkinematic gneiss, Seirra Leone (Marmo,1962b).

Analyses 27-28 : Gneisses from the Svecofennides of Finland(Simenon,1960).

III. THE EARLY IGNEOUS ROCKS

In the Laxford area Clough (op.cit.) distinguished three types of metamorphosed igneous rock from the gneisses of the Fundamental Complex, namely ultrabasic, basic and granitic and further differentiated between "early basics" and "late basics". Watson (op.cit.) also recognised these three types, in some cases equating the basic rocks (amphibolites) with metadolerites. However, she concluded that "the granite gneisses...represent the most strongly metasomatised parts of the complex" (Watson, op.cit., p.287).

The present study has shown that the following igneous rock-types (now mostly metamorphosed) can be recognised:-

1. Peridotites - now metaperidotites (cf. Bowes et.al.1964).
2. Pyroxenites and/or hornblendites - now hornblendites.
3. Gabbros - now amphibolites and garnet-pyriclasites (cf Berthelsen, 1960).
4. Tholeiites- now amphibolites.
5. Anorthosites - now plagioclasites (see Berthelsen,1960).
6. Diorites - now metadiorites.
7. Trondhjemites - now foliated trondhjemites.
8. Microgranites - now foliated microgranites.
9. Coarse-grained trondhjemites.
10. Granites and pegmatites.

In the Laxford area these rocks show the following relations to the gneisses and to one another:-

1. Metaperidotites and hornblendites occur as small isolated masses, often in proximity to either amphibolites or garnet pyriclasites. They do not appear to be cut by acid veins and their relations to the gneisses could not be well established.

2. Garnet-pyriclasites are usually flanked by, or form the core of, amphibolites.

3. Plagioclasites are interlayered with amphibolites and the gneisses, all three having a common foliation and fold pattern.

4. Metadiorites occur as concordant layers within, and have the same foliation as, the gneisses.

5. Garnet-pyriclasites, amphibolites, plagioclasites and metadiorites are cut or invaded by trondhjemitic and granitic material.

6. Foliated trondhjemites and coarse-grained trondhjemites cut most of the other rock-types of the Laxford area, apart from the ultrabasic and granitic types. They form veins, pods and irregular bodies, some of which cut folds of the main set while others are folded or contorted. Foliation is often parallel to the edges of each sheet or vein.

7. Granitic material has invaded or potassium metasomatism has affected all rock-types except the ultrabasics. There is no evidence of any igneous activity post-dating the

granitic rocks. Foliation is usually parallel to the margins of each granitic sheet.

The above mentioned relationships show that the metaperidotites, hornblendites, garnet-pyriclasites, amphibolites, plagioclasites and metadiorites were intruded as igneous rocks prior to the metamorphism that produced the present mineralogical and chemical composition and geometry of these rocks, that is the Laxfordian metamorphism. Watson (op.cit.) and Peach et. al. (1907) reach the same conclusions for the amphibolites and ultrabasic rocks. The trondhjemitic and granitic material was intruded during or after the main phase of folding associated with the Laxfordian metamorphism.

Thus the early igneous rocks are considered to be those meta-igneous rocks that are earlier (= older) than the granitoid rocks.

The Metaperidotites

The metaperidotites occur at various localities throughout the area. They are fine to medium-grained black or greenish black rocks that often contain numerous minute white flecks. They show two retrogressive trends yielding hydrous mineral assemblages: (1) a slightly micaceous variety grading into a highly micaceous variety in which numerous streaks and relict patches of metaperidotite are set in a mass of olive-green and golden coloured mica, all gradations being seen in a body that crops out 400 metres south-west of Laxford Bridge, (2) a tremolite-bearing variety grading into a coarse-grained tremolite-actinolite variety which consists of a mass of haphazardly orientated pale-green actinolite prisms that reach a size of 2 cm., interlocked with a felt of tremolite. Lowes, Wright & Park(1964) suggest that tremolite has developed where the metaperidotites have been involved in steep zones of movement. Watson (op.cit) lists biotite and actinolite as the typical minerals of these rocks south of Laxford Bridge with hornblende and biotite to the north, but the present research could not confirm this conclusion.

300 metres east of the northern end of Loch na Claise Fearna a banded metaperidotite occurs (Plate 22); the banding, which is also described by Teall (op.cit.), is similar to that described by Lowes, Wright and Park (1964) from layered metaperidotites of other localities in the

North-West Highlands, although sedimentation features such as current bedding are not present (cf. Bowes, Wright & Park, op.cit. p. 159). The banding is vertical at an angle of a few degrees to the foliation of the adjacent gneisses.

<u>PLATE 22</u>

Banding in a metaperidotite (300 metres east of the northern end of Loch na Claise Fearna).

Plate 22

Microscopic petrography

The least altered metaperidotites have a metamorphic fabric consisting of poikiloblasts and recrystallised granular aggregates of orthopyroxene, with lesser amounts of olivine set in an acicular felt of tremolite. The highly altered varieties also have a metamorphic fabric consisting of variable amounts of tremolite, olivine, chlorite, phlogopite and actinolite.

Olivine, which makes up as much as 25% of the metaperidotite, varies in size from 0.5 mm. to 3 mm. It is always serpentinized along irregular cracks, large amounts of iron are being associated with the pale-green serpentine. In some of the micaceous metaperidotites serpentinization is complete and both phlogopite and tremolite can be seen within and penetrating relict grains of olivine.

Hypersthene, which sometimes accounts for 40% of the metaperidotite, occurs only in certain layers. It forms sub-rounded recrystallised grains, 0.4 mm. to 1mm. in size, and poikiloblastic plates, 1 mm. to 2 mm., that enclose flakes of chlorite and grains of olivine but, in many cases, are penetrated by chlorite.

Tremolite and actinolite apparently exhibit a complete gradation of one into the other, in some cases forming 95% of the altered metaperidotite. In thin section most of the fibres or prisms are colourless, although in hand-specimen pale green varieties are as common as white or grey varieties. In the tremolite-actinolite rocks most of the large prisms are actinolitic in appearance. Tremolite occurs as clusters of radiating fibres and as an acicular felt between the clusters. When tremolite occurs in large amounts relict textures are obscured and the mineral may be accompanied by an abundant scattering of iron ore. In the tremolite-actinolite rocks the large prisms of actinolite and tremolite are set in a felt of fibrous tremolite.

Phlogopite occurs in the micaceous metaperidotites where it forms as much as 30% of the rock. It occurs as stumpy flakes - in many cases as broad as they are long - which vary in length from 0.2 mm. to 2 mm. The flakes either are colourless and non-pleochroic or exhibit a colourless to light-brown pleochroism, with an interference figure that is more nearly uniaxial than that of biotite. Phlogopite has not been described previously from the Laxford area, although it has been described from other metaperidotites further south (Bowes, Wright & Park, 1964). It is often quite cloudy and may contain streaks of iron ore. Rarely, parallel layers of chlorite occur within a flake of phlogopite, but it is not clear whether this is a replacement phenomenon. The phlogopite flakes occasionally exhibit small flexures.

Chlorite, which forms up to 10% of the metaperidotite, occurs in two varieties. When present in the tremolite-bearing metaperidotites chlorite occurs as stout flakes, varying from 0.5 mm. to 1.2 mm. in length, and exhibits an anomalous first order brown colour, polysynthetic twinning and a very small 2V. The flakes usually contain streaks of iron ore aligned parallel to the polysynthetic twinning. This variety is also present in the micaceous metaperidotites, together with a pale green, pleochroic variety that exhibits the anomalous blue penninitic colour and is associated with phlogopite. In the least altered metaperidotites the first variety appears to replace hypersthene.

Accessory minerals are sparse except for opaque ores that occur in considerable amounts in some varieties.

The Hornblendites

In general, hornblendites that may represent metamorphosed igneous rocks are rather sparsely developed. Several bodies that do not exceed a size of 2 metres by 4 metres crop out on the headland near Weaver's Bay where they consist of stout, stumpy hornblende that reaches 2 cm. in length, occasional flakes of biotite and small amounts of actinolite. 300 metres east of the northern end of Loch na Claise Fearna a granular hornblendite occurs near a banded metaperidotite, a garnet-pyriclasite and an amphibolite. These four rock-types are not in contact with one another, but their close association in the field suggests a genetic relationship.

The hornblendites are partly or almost completely altered to biotite when they are involved in zones of movement, occurring as highly contorted veins and lenses that are finally broken up into a series of pods.

Microscopic petrography

Hornblende occurs as interlocking stumpy prisms or as granular aggregates, having an average grain size of 0.8 mm., with interstitial quartz. It occasionally contains streaks of iron ore aligned parallel to a cleavage direction and in some cases it is penetrated by flakes of biotite.

The accessory minerals include actinolite, biotite and quartz.

The Amphibolites and Garnet-pyriclasites

The term "amphibolite" is used to describe high-grade metamorphic rocks with widely differing proportions of hornblende and plagioclase. Cannon (1963) suggests that amphibolite should be defined as "a rock containing hornblende as the dominant mafic mineral normally exceeding 50% of the total mineral content", and this definition is used in the present work. The total mafic mineral content must always exceed 50%. Cannon also suggests that the modal percentages of quartz and plagioclase should not differ from one another by more than 10%, but in most of the amphibolites in the Laxford area quartz is subordinate to plagioclase and differs from it by more than 10% as is the case in other parts of the world (for example, see Evans & Leake, 1960; Engel & Engel, 1962a).

"Pyriclasite" is used by Berthelsen (1960, p.20) to describe rocks composed of clino-and ortho-pyroxene and plagioclase and is considered to be the granulite facies equivalent of amphibolite. "Clino-pyriclasite" is used when clino-pyroxene predominates and ortho-pyroxene is almost excluded (Berthelsen, 1960, p.21).

(a) The Amphibolites

Amphibolites in the Laxford area occur as concordant layers or bands in the gneisses and have a variably developed foliation which is parallel with the foliation of the gneisses. The only major exceptions occur in the extreme south-west of the area and north of Laxford Bay where amphibolites can be seen cutting across the foliation of the gneisses. From a point 50 metres east of the northern end of Loch na Claise Fearna an amphibolite can be traced to the south-east cutting across the foliation of the gneisses at an angle of a few degrees; at the south-western edge of the area it swings into a south-south-easterly direction cutting across the foliation of the gneisses at an angle of 35°. The second example, which has been described by Watson (1951) can be seen 100 metres north-east of Badcall Quay, where a cliff face provides a section in which two amphibolites are clearly observed to cut across the foliation of the gneisses (see fig. 9 in Sutton & Watson, 1951). On the cliff-top these same amphibolites can be seen tonguing into the gneisses. When they are traced eastwards the amphibolites become concordant with the foliation of the gneisses within a very short distance. Other small discordances, in which amphibolite either cuts the foliation of the gneisses or occurs as tongues infolded with the gneisses, can be seen at several localities, for example along the margin of the thick amphibolite east of Weaver's Bay.

The amphibolite layers vary in thickness from a few millimetres to around 15 metres. In the field the amphibolites that are less than 15 cm. thick have not been mapped as individual units, but as either part of the striped gneisses, when the felsic layer contains more than 10% quartz, or part of the striped amphibolites, when the felsic layer contains less than 10% quartz. All the amphibolites occur as lenticular bodies and can rarely be traced along the strike for more than 100 metres, although an amphibolite, which crops out immediately north-east of the Rudha Ruadh sheet, can be traced from north-west to south-east for a distance of 1 km. or more as a series of lenses that on occasions occur en echelon.

The amphibolites are medium grained, dark coloured rocks and usually have a speckled, granular appearance, the weathered surface having a very conspicuous coating of greyish-white lichen. The poorly to well-developed foliation, which is emphasised in some cases by felsic and hornblendic streaks is present in all but a few of the more massive amphibolites. The felsic and hornblendic streaks also emphasise the small scale folding that is present in many of the amphibolites. The fold axes strike NW-SE and the folds plunge to the south-east at angles varying from 10° to 30°. In some cases, the foliation is turned through 90°, becoming vertical in attitude, and then swings back to its original NW-SE trend.

There is little variation in the essential mineral content of the amphibolites. Hornblende, which varies from 50% to 85% by volume, and plagioclase, which varies from 20% to 40%, are the dominant mineral constituents. Small amounts of a dull green pyroxene and quartz may be present and yellowish-green epidote, resinous white or grey scapolite and deep-red garnet, which is usually rimmed by plagioclase, are locally abundant. None of the mineral constituents shows a preferential geographical distribution (contrast Watson (op.cit) who states that pyroxene is absent from amphibolites that crop out south-west of a NW-SE line drawn through Loch Laxford). Magnetite is locally quite abundant; for example, an amphibolite occurring 500 metres north-east of Garbh Eilean contains more than 5% of magnetite. Small amounts of potash feldspar are present in a few amphibolites; its presence can only be detected in a hand specimen by staining and may not be detected in a thin section of the same specimen. Biotite, which is present in small amounts in some amphibolites, is the dominant mafic mineral in several amphibolites that crop out to the south-west of the Loch na Seilge granitic sheet. These rocks which weather to a brown colour and in which the biotite shows numerous small crenulations, are not amphibolites by definition, but since they appear to represent a retrogressive alteration of amphibolites they are classified with the amphibolites and termed biotite-amphibolites.

The amphibolites usually appear homogeneous when viewed from a distance, but closer examination reveals numerous streaks, often only 2 mm. or so in length, of hornblende and plagioclase, or, on rare occasions, quartz. Small clots of plagioclase, usually with a core of epidote granules occur in some amphibolites, although not in those to the south-west of the Loch na Seilge sheet. The clots vary in size, reaching a maximum of 3 cm, and all but the smallest are lens-shaped (augen). The augen, which appear to increase in size to the north-east, may be confined to certain layers within an amphibolite or be fairly evenly distributed throughout. A few amphibolites have streaky patches, finely speckled in appearance, and composed of hornblende and plagioclase, that may represent patches that have either resisted segregation or have recrystallised during shearing (Plate 23).

A few amphibolites, particularly those associated with the Cnoc nan Cro gneisses (plagioclasites) are massive and unfoliated. In these, hornblende occurs as stumpy interlocking grains which reach a size of 4 mm., a dull-green pyroxene may be present, and plagioclase and/or scapolite occur.

Striped amphibolites (Plate 24) composed essentially of amphibolite and plagioclasite, are present at several localities.

PLATE 23

Amphibolite with irregular speckled patches and streaks of hornblende and plagioclase emphasised by staining.

PLATE 24

Striped amphibolite.

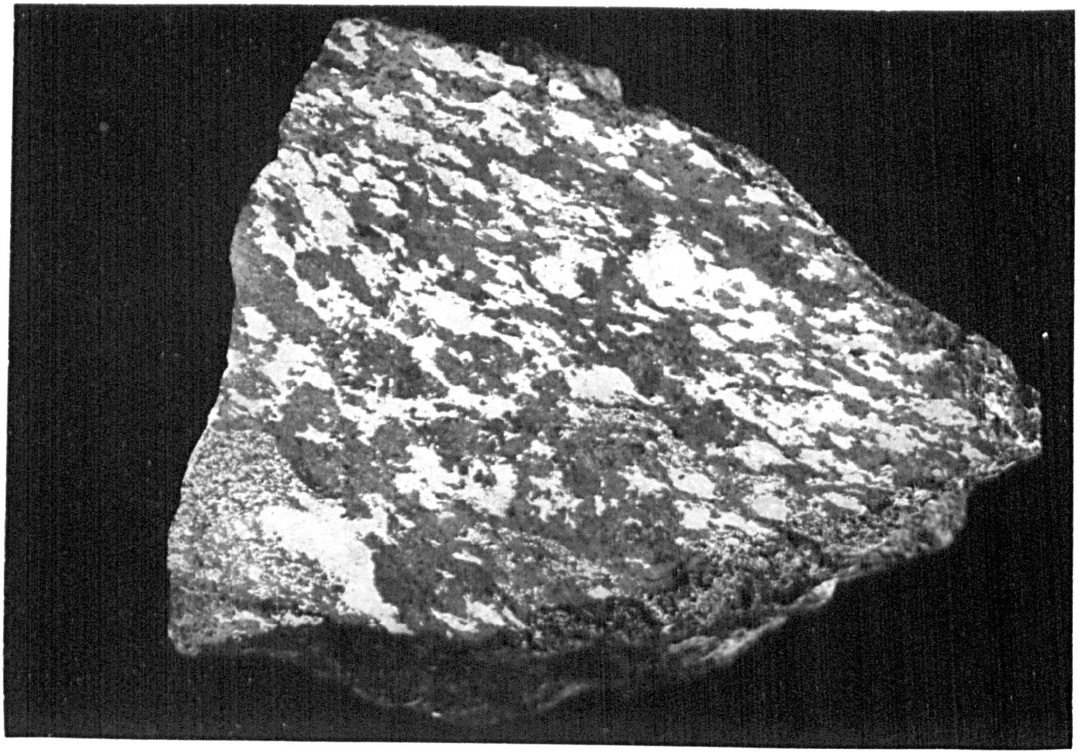


Plate 23

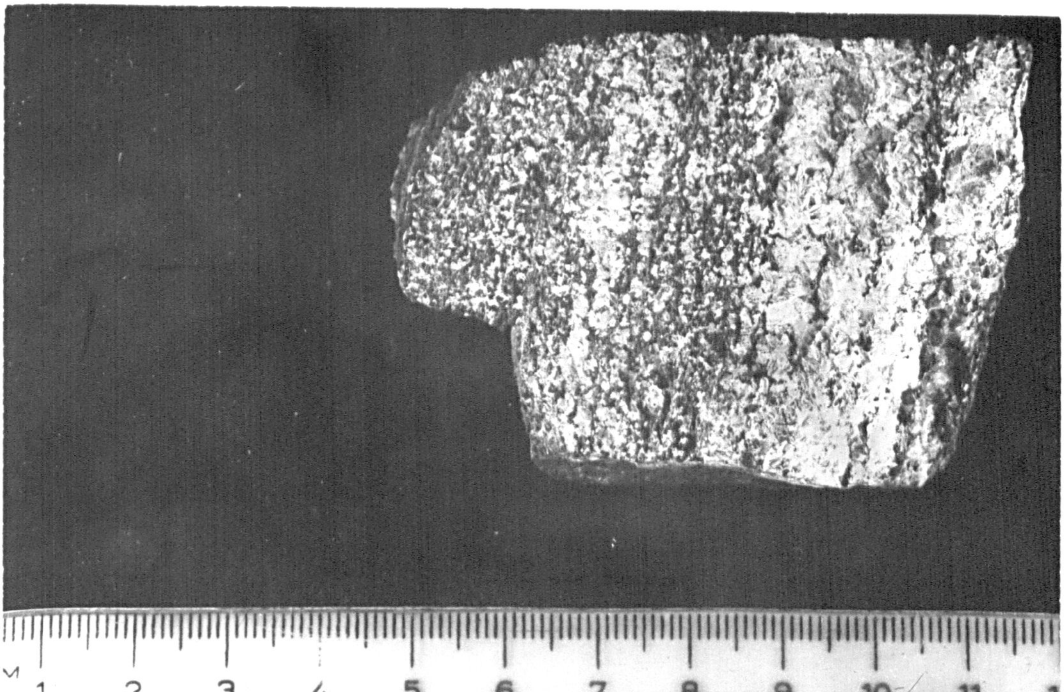


Plate 24

Microscopic petrography of the amphibolites.

Most of the amphibolites exhibit a granoblastic texture, although some of the more massive varieties tend to be crystalloblastic. The average grain-size of an amphibolite is about 1 mm., with the exceptions of the amphibolites that occur to the south-west of the Loch na Seilge sheet, in which the grain-size is about 0.8 mm., and the massive unfoliated amphibolites whose grain size varies from 1.5 mm. to 3 mm.

Hornblende and plagioclase are the dominant mineral constituents and pyroxene, epidote, biotite, garnet, scapolite, sphene, apatite, microcline, quartz and iron ore occur in varying amounts. Table 14 shows the variation in the proportions of the mineral constituents of the amphibolites.

Hornblende typically occurs as short stumpy grains which vary in size from 0.05 mm. to 3 mm., a maximum size that is only seen in the more massive amphibolites; in most amphibolites grain-sizes from 0.5 mm. to 1.5 mm. predominate. Usually some of the grains are idioblastic, particularly in the more massive amphibolites. The mineral exhibits two pleochroic schemes as follows:-

	X	Y	Z
1.	Straw Yellow	Olive Green	Dark Green
2.	Yellowish green	green	bluish green.

The dark green variety is the more common.

Small rounded grains of quartz and small flakes of biotite are occasionally enclosed by hornblende, but more often hornblende is cut or penetrated by long narrow flakes of biotite. In some amphibolites hornblende is closely associated with epidote and when these minerals are in contact the pleochroic colours of hornblende may be:-

X	Y	Z
Colourless	Yellowish Green	Pale Green

This "bleaching" does not occur in more than a few cases. Hornblende is usually fresh, but it may be altered to chlorite.

<u>Plagioclase</u> varies in composition from oligoclase (An_{25}) to labradorite (An_{53}), the more calcic varieties being found in the amphibolites which occur to the south-west of the Loch na Seilge granitic sheet; there is an abrupt transition between the latter and the oligoclase-andesine varieties north-east of the granitic sheet. Plagioclase may be fresh, partly altered or highly altered, the alteration products being either dusty unidentifiable material or sericite. The plagioclase grains, which vary in size from 0.3 mm. to 1.2 mm., may be twinned or untwinned; the latter tends to predominate, especially in the less calcic plagioclase. Cloudy, highly altered plagioclase forms the outer rim of the augen that are present in many amphibolites and, together with epidote, forms the core of the augen.

Pyroxene is present in amphibolites from various parts of the area from the extreme south-west to near the north-east boundary. It is pale green in colour and slightly pleochroic, with a 2V which varies from 59° to 61° and an extinction angle (Z^c) which varies from 46° to 50°. These optical properties, which are similar in all amphibolites, indicate that the pyroxene is augite. The augite occurs as smaller grains than hornblende, varying in size from 0.1 mm. to 0.6 mm. It encloses small grains of hornblende, occasionally occurring as large poikiloblastic plates, but is rarely itself enclosed by hornblende. In some augite grains orientated remnants of hornblende are present, suggesting that augite replaces hornblende. In one thin section these minerals occur as alternating lamellae that are aligned parallel to the b-axis, each set of lamellae being in optical continuity. These intergrowths, the grain in which they occur reaching a size of 3 mm., appear to represent replacement of hornblende by augite rather than augite by hornblende, since small separate grains of hornblende occur in the augite part of the intergrowth. There is no indication that any of the pyroxene is of igneous derivation.

Biotite is usually an accessory mineral and is absent in many cases. In some amphibolites, however, it predominates over hornblende. The flakes vary in size from 0.3 mm. to 3 mm. Two varieties of biotite are present, exhibiting pleochoism as follows:-

1. Yellow to dark green.

2. Light brown to very dark brown.

Many of the flakes have thin opaque streaks of what appears to be haematite. The flakes, which are occasionally altered to chlorite, are flexured in many cases. From the relationships with hornblende previously described biotite is clearly later than hornblende and, in turn, is cut by epidote.

Epidote is absent from most amphibolites and, when present, appears to be one of the last formed minerals. It occurs as irregular or idioblastic, rhomboidal and prismatic grains which vary in size from 0.1 mm. to 0.8 mm. It also occurs as numerous small grains or granules, varying in size from 0.03 mm. to 0.6 mm., in the augen previously described (p. 87). These grains or granules, which are scattered throughout each augen, sometimes have a core with a higher birefringence than the rim. The difference in birefringence suggests that there is a decrease in the ferric iron content from the core outwards. Most of the epidote throughout the area is colourless or faintly green, but occasionally a pale yellow pleochroic variety is present.

Garnet, although locally abundant, is sparsely developed. The grains, the larger of which are usually shattered, vary in size from 0.07 mm. to 1 cm., and have a tendency to roundness. Usually garnet is completely separated from the other mafic minerals by a rim of altered, cloudy plagioclase. Although inclusions are generally few in number, pyroxene, hornblende and plagioclase have been noted and trains of minute unidentifiable grains are seen in some of the larger grains.

Scapolite occurs in amphibolites from the northern slopes of Cnoc nan Cro, at the roadside near Duchess's Pool, and 500 metres south of Weaver's Bay. In one specimen 90% of the felsic minerals consist of scapolite. Grains are usually large (a size of 1 mm. or more is common) and fresh, but sometimes they are highly altered, muscovite being the most common alteration product. A few metres south of Laxford Bridge scapolite occurs in a vein which cuts an amphibolite composed of hornblende and highly sericitized plagioclase. In this vein it is associated with a mineral whose optical properties suggest prehnite.

Of the accessory minerals, sphene and iron ore are always present except in certain of the scapolite-bearing amphibolites. The iron ores include magnetite, which predominates, pyrite, which may be rimmed by magnetite, haematite, or both, and haematite. Sphene forms small oval granules, often less than 1 mm., that occur as isolated grains, in clusters, or in trains that are aligned roughly parallel to the foliation. Sometimes larger grains occur, but they never exhibit the typical wedge shape of sphene. Apatite usually occurs as rounded or sub-rounded grains that range up to 0.5 mm. in size, but occasionally as abundant minute idioblastic grains, either prismatic or hexagonal. Quartz occurs as small interstitial grains, no larger than 0.5 mm. Microcline also occurs as small sparse interstitial grains.

(b) The Garnet-pyriclasites

In the Laxford area, pyriclasites always contain considerable amounts of garnet and are, therefore, termed garnet-pyriclasites. Usually clinopyroxene predominates, but for the sake of concision, the prefix "clino" is omitted from the rock-name (contrast Berthelsen, op.cit.)

Garnet-pyriclasites occur at several localities, either flanked or completely enclosed by amphibolite, as, for example, 500 metres south-east of Loch Bad ant-Seabhaig. The largest garnet-pyriclasite mass measures 3 metres by 5 metres and, like the other bodies, is lenticular in shape. The bodies are massive and devoid of any planar structure; they consist of deep-red fractured garnet, which may reach a size of 2 cm., and pyroxene with varying amounts of plagioclase which often forms rims round garnet.

Microscopic petrography of the garnet-pyriclasites.

Garnet, pyroxene and plagioclase occur in varying proportions and have an irregular distribution. In most thin-sections the texture is partly crystalloblastic partly granoblastic and there is a gradation from fine-grained into coarse-grained parts.

Garnet which forms porphyroblasts 2mm to 2cm in size, occurs in clusters, each garnet having a rim of sericitized plagioclase. It often has numerous inclusions of diopside and plagioclase, particularly the latter. The smaller garnets are sub-rounded, but the larger ones are irregularly shaped and extensively fractured.

Diopside, which forms approximately 45% of the rock, occurs as fairly large grains that reach a size of 1.5 mm. It may contain thin lamellae of hypersthene, aligned parallel to (100) and it is sometimes fringed by uralitic amphibole.

Hypersthene, which forms between 5% and 15% of the rock, usually occurs as aggregates of small grains that are normally less than 0.5 mm. in size. It is slightly pleochroic as follows:-

X	Y	Z
Orange-brown	Colourless	Very pale green

It may be partly or completely altered to uralitic amphibole or pale yellowish green chlorite.

Plagioclase, occurring as grains usually less than 0.5 mm. in size, is labradorite and ranges in composition from An_{52} to An_{64}. Grains are fresh and usually twinned on the albite, carlsbad-albite or pericline law.

Accessory minerals are pale-green serpentine, usually found in veins, olive to deep-green spinel and small amounts of iron ore, either ilmenite or pyrite.

The geochemistry of the amphibolites and garnet-pyriclasites.

Six amphibolites have been analysed and their chemical composition in weight percentages are listed in Table 14 together with trace-element content, norms, modes and Niggli numbers.

The amphibolites may be classified on the basis of their normative mineral assemblages. According to the scheme of Yoder & Tilley (1962) three are quartz-tholeiites, one an olivine tholeiite and two alkali-basalts.

Evans & Leake (1960) use Niggli numbers to establish trends in the striped amphibolites of Connemara, Ireland. In the present research fm, al, c, alk and mg are plotted against si and, in all cases except mg against si, the analysed amphibolites fall within the Karroo dolerite field (fig. 11). Results are similar when al-alk against c is plotted (fig. 12). The trend of plots of the analysed amphibolites on a 100 mg , c and al-alk triangular diagram (fig. 13) approximates closely to the trend suggested by Leake (1963) for differentiation of basic igneous rocks.

The chemical compositions and catanorms of L12 and B412 are similar to those of the metagabbros of the Outer Hebrides (Table 14) while L50, L77 and B355 are similar to the Scourie dykes of the mainland (Table 14). Comparison of the trace-element content between L50 and the "type" Scourie dyke (Table 14) strengthens the similarity observed in the major elements, but no such similarity exists between L12 and B412 and the metagabbros of the **Outer** Hebrides in trace-element amounts (Table 14).

Trace-element amounts can be used to distinguish the tholeiitic from the remaining types of amphibolites (Table 14). Thus, Ba, Cu, Sc and V are lower and Cr and Ni higher by significant proportions in L50 than in L12, L15 and B412. Cu and V increase and Cu and Ni decrease systematically as Mg decreases this trend being from alkali-basaltic, through olivine-tholeiitic, to oversaturated tholeiitic types.

	1	2	3	4	5	6	7	8	9	10
	L50	I77	B355	L15	L12	B412	A4	A5	A6	A7
SiO_2	49.38	49.26	50.50	47.75	45.91	46.39	44.06	48.4	46.54	48.9
Al_2O_3	12.14	12.70	12.90	14.74	15.68	14.59	13.15	13.4	15.13	12.6
Fe_2O_3	5.67	7.06	3.73	3.52	4.36	1.57	2.67	3.1	2.04	4.5
FeO	12.06	9.17	10.62	9.12	7.78	6.49	13.48	13.2	10.64	10.9
MgO	[illegible]	5.94	5.33	[illegible]	9.33	12.46	10.31	5.3	8.73	6.4
CaO	7.67	[illegible]	10.42	10.47	12.38	[illegible]	13.31	9.7	12.50	9.7
Na_2O	[illegible]	2.44	2.52	[illegible]	2.46	2.17	1.02	2.4	1.37	2.5
K_2O	0.78	0.93	0.65	0.99	0.38	1.25	0.30	0.7	0.54	0.6
TiO_2	2.54	1.47	1.25	[illegible]	[illegible]	[illegible]	[illegible].82	2.6	0.89	1.9
P_2O_5	0.35	0.67	0.10	0.02	0.02	0.02	-	0.2	0.09	0.2
MnO	0.26	0.24	0.24	0.32	0.24	0.13	0.28	0.2	0.30	0.2
H_2O^+	[illegible]	0.47	1.23	1.77	1.83	1.68	0.92	0.7	0.31	1.2
H_2O^-	-	-	-	-	-	-	0.07	-	0.85	-
CO_2	-	-	-	-	-	-	-	-	-	-
	99.34	99.56	99.99	100.66	100.93	99.37	100.39	99.9	99.93	99.6

	1	2	3	4	5	6	7	8
Si^{4+}	48.02	47.25	48.59	44.94	43.29	42.97	-	-
Al^{3+}	13.88	14.35	14.53	16.35	17.43	15.90	-	-
Fe^{3+}	4.12	5.10	2.69	2.49	3.08	1.06	-	-
Fe^{2+}	9.79	7.37	8.50	7.20	6.15	5.00	-	-
Mg^{2+}	8.43	9.93	8.40	13.60	13.12	17.2[illegible]	-	-
Ca^{2+}	7.98	9.06	10.75	10.55	11.38	12.18	-	-
Na^+	4.46	4.53	4.66	3.02	4.49	3.90	-	-
K^+	0.96	1.13	0.75	1.18	0.43	1.47	-	-
Ti^{4+}	1.88	1.03	0.90	0.45	0.42	0.22	-	-
P^{5+}	0.30	0.04	0.06	0.01	0.01	0.01	-	-
Mn^{2+}	0.20	0.21	0.17	0.25	0.20	0.09	-	-

Table 14 Complete data on the amphibolites.

Niggli numbers, mesonorms, modes, trace element values, and catanorms are listed in order on the following pages.

Analyses 1-3 : Metatholeiites

Analyses 4-6 : Metagabbros

Analysis 7 : Metagabbro, South Harris (Dearnley, 1963).

Analysis 8 : Average of two type Scourie dykes, Scourie (O'Hara, 1961a).

Analysis 9 : Average of two garnetiferous basic gneisses (garnet-pyriclasites), Scourie (O'Hara, 1961b).

Analysis 10 : Average of 34 Scourie dykes (Burns, 1958).

	1	2	3	4	5	6
	I50	I77	B355	I15	I12	B412
si	119	115	121	101	96	94
al	17.3	17.3	18.2	18.4	19.3	17.2
fm	44.3	54.1	48.5	51.8	50.1	50.6
c	19.8	21.7	26.6	25.8	25.2	26.4
alk	6.7	6.9	6.7	4.8	5.4	5.8
ti	4.6	2.6	2.2	1.0	0.9	0.4
p	0.4	0.1	0.14	0.05	0.05	0.03
k	0.17	0.21	0.14	0.29	0.09	0.28
mg	0.37	0.44	0.43	0.58	0.58	0.74

Qtz	6.41	3.48	2.25	-	-	-
Or	-	4.82	3.75	-	2.15	-
Ab	22.30	21.65	23.30	14.40	15.95	-
An	5.00	3.65	5.40	10.70	12.45	-
Ho	46.05	53.22	52.20	59.03	52.27	-
Bi	7.68	1.33	-	9.66	-	-
Di	-	-	7.20	-	0.90	-
Bk	-	-	-	1.12	10.40	-
Mt	6.18	7.65	4.04	3.74	4.62	-
Sph	5.58	3.09	2.70	1.35	1.26	-
Ap	0.80	0.11	0.16	0.03	0.03	-

Quartz	3.6	3.3	2.0	-	-	-
Plagioclase	30.1	31.2	30.1	23.4	27.5	19.5
Hornblende	59.7	63.8	57.2	67.0	64.4	58.0
Augite	-	-	-	6.0	6.7	2.0
Biotite	3.1	0.3	-	-	-	-
Epidote	-	0.3	trace	3.1	0.8	-
Iron ore	3.2	trace	0.6	0.4	trace	-
Scapolite	-	-	-	-	-	19.3
Sphene	-	1.4	trace	trace	0.5	trace
Apatite	trace	-	-	-	trace	-
Garnet	-	-	8.5	-	-	-

	1	2	3	4	5	6	7	8
	L50	L77	B355	L15	L12	B412	A4	A5
Ba	448	-	-	142	75	167	35	190
Co	2[illegible].5	-	-	42	34.8	13.5	30	45
Cr	79	-	-	440	255	705	150	100
Cu	91	-	-	27.8	28	17.3	-	-
Ga	18	-	-	15.2	16.6	15.6	1	17
Li	15	-	-	19	20	20	30	4
Ni	52	-	-	185	183	168	40	62
Rb	50	-	-	62	54	40	-	28
Sc	44	-	-	30	23	21.5	50	50
Sr	212	-	-	222	152	278	45	116
V	275	-	-	194	153	116	600	410
Yt	-	-	-	-	-	-	-	55
Zr	90	-	-	62	28.6	50	4	180

Qtz	5.55	2.94	2.33	-	-	-	-	0.48
Or	4.80	5.65	3.75	5.90	2.15	7.35	1.67	4.06
Ab	22.30	22.65	23.30	15.10	21.40	7.53	7.86	20.02
An	21.15	21.73	22.80	30.38	31.30	26.32	30.30	23.87
Ne	-	-	-	-	0.63	7.19	-	-
Di	13.00	18.84	24.36	17.88	20.40	27.60	29.46	19.40
Hy	22.50	18.44	17.46	15.32	-	-	-	21.34
Ol	-	-	-	10.83	18.69	21.96	24.09	-
Mt	6.18	7.65	4.04	3.74	4.62	1.59	3.94	4.44
Il	3.72	2.06	1.80	0.90	0.84	0.44	1.52	4.93
Ap	0.80	0.11	0.16	0.03	0.03	0.03	-	0.36

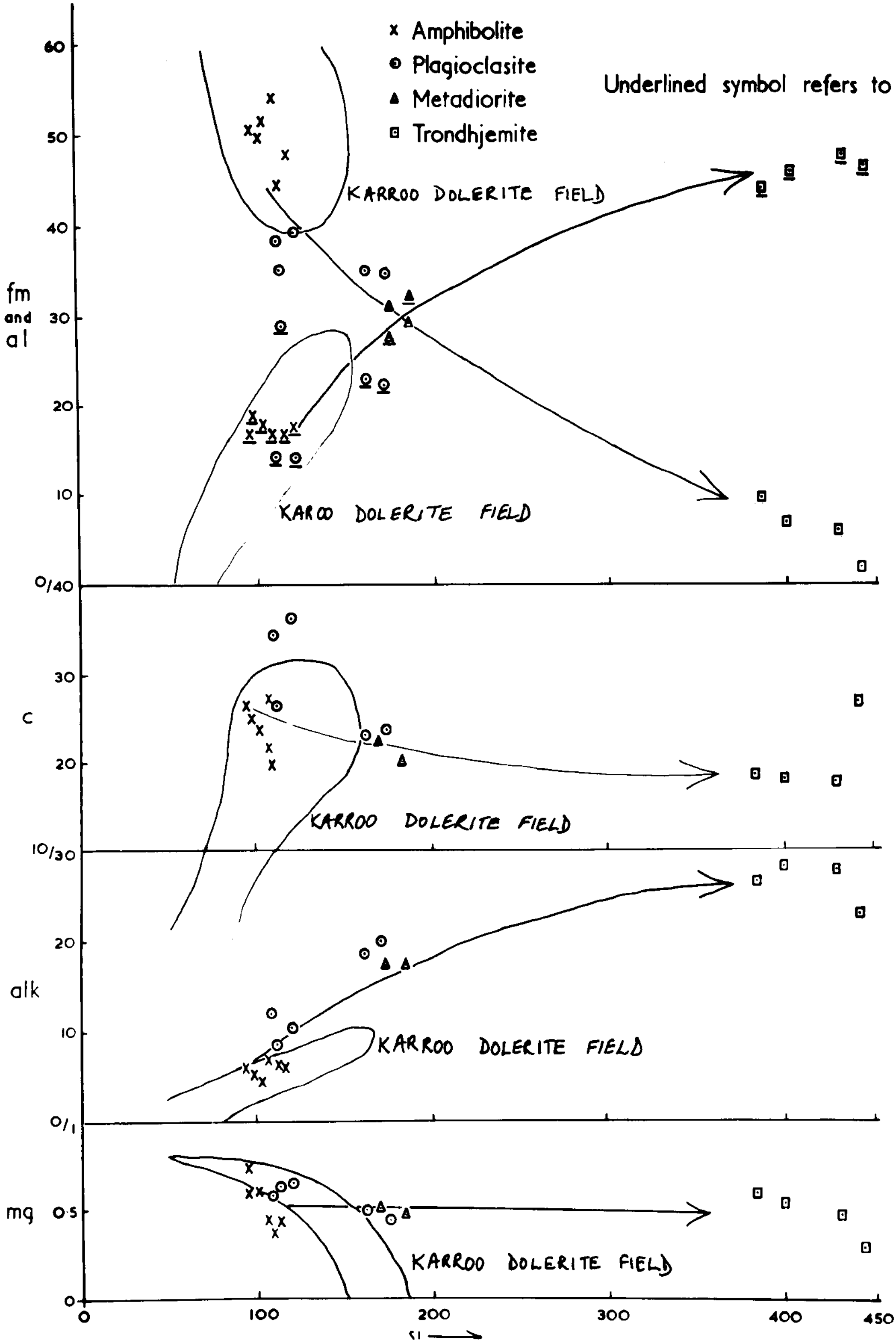


Figure 11 Plots of Niggli numbers : si against fm, al, c, alk, and mg

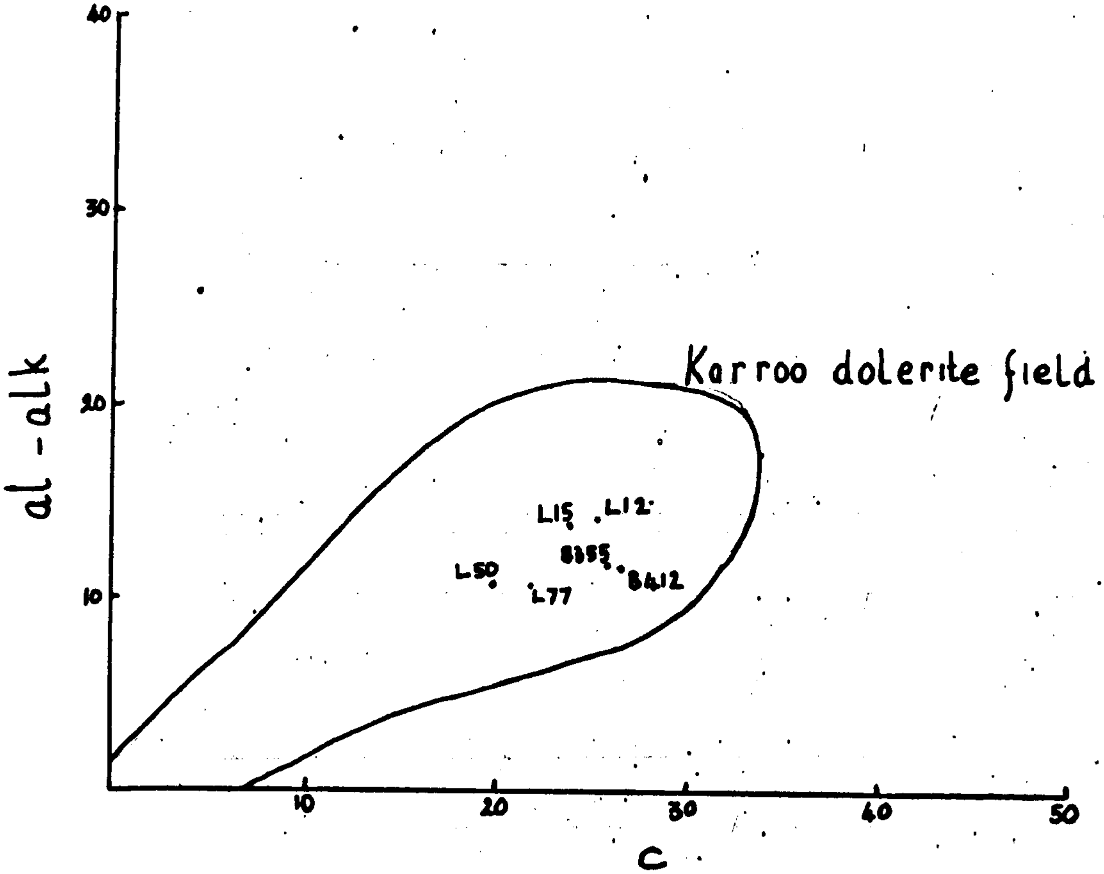


Fig.12 Plots of al-alk against c for the amphibolites.

The Plagioclasites

The term "plagioclasite" is used by Berthelsen (1960) to define "basic" rocks that are very rich in plagioclase. In the Laxford area the silica content of certain plagioclasites lies outside the accepted range for basic igneous rocks (Turner & Verhoogen, 1951) but since free quartz is sparse or absent these rocks can be described as basic on the basis of their mineralogy.

For the sake of convenience all plagioclasites in the area are described here although, as discussed later, some of these are probably not igneous in origin.

Plagioclasites occur individually, or interbanded and interstriped with amphibolites. As with the amphibolites (see p. 83) an arbitrary value of 15 cm. was chosen as the thickness above which the plagioclasites were mapped as individual bands and below which they were mapped as an integral part of the striped gneisses, the striped amphibolites, or the striped plagioclasites. Plagioclasites are extensively developed on the northern slopes of Cnoc an Cro (see below) where a total thickness of 30 metres is rarely exceeded.

Plagioclasites grade into amphibolites by an increase in hornblende, which is the most common mafic mineral. When the modal hornblende content lies between 15% and 50% the term hornblende-plagioclasite is used. In the plagioclasites, sensu lato, the mafic minerals are either distributed homogeneously throughout a specimen or occur as segregated clots and streaks. The other mafic minerals are biotite and epidote, both of which usually occur in small amounts, and in one case garnet which, together with biotite, forms 40% by volume of a biotite-garnet-plagioclasite that crops out in the crags a few metres west of Laxford Bridge.

As the term implies, plagioclase is the dominant mineral, forming as much as 95% by volume of the plagioclasite. Quartz and potash feldspar may be also present, but usually occur in small amounts.

500 metres south of Weaver's Bay an apparent gradation from amphibolite into plagioclasite can be seen. Adjacent to the amphibolite the hornblende-plagioclasite contains approximately 35% hornblende and 65% plagioclase and over a distance of 60 cm. the hornblende content decreases gradually to less than 15%, plagioclase increasing antipathetically.

A rude foliation can be seen in the plagioclasites when the mafic minerals are present in sufficient amounts. It is parallel to the foliation of the adjacent rocks. Small relict fold closures are occasionally preserved.

The Cnoc nan Cro gneisses

These gneisses, extending continuously across the area in a belt that reaches a maximum thickness of 30 metres on the northern slopes of Cnoc nan Cro, are easily recognised by their white or grey weathering which superficially resembles the weathering of carbonate rocks. They are composed of plagioclasites and striped plagioclasites (Plate 25) and are interbanded with amphibolites. When fresh the leucocratic stripes and layers are grey-green to sea-green in colour and the mafic stripes are dark-green or black. Differential erosion emphasises the striping (Plate 26). The gneisses tend to break up into slabs, the parting occurring either along a micaceous layer or at the junction of felsic and mafic layers.

The gneisses have a well developed foliation that is parallel to that of the adjacent Weaver's Bay and Laxford Bay gneisses. Small folds, often isoclinal, are common and usually plunge to the south-east at angles of up to 30°.

Similar gneisses are present outside the 30 metres thick belt, but only fairly close to the belt, where they are either interlayered with the other gneisses or occur as relics in the Cnoc nan Cro microgranites.

Plagioclase and scapolite are virtually the only felsic minerals present in the gneisses since neither potash feldspar nor quartz has been recorded. Scapolite is recognised by its grey or very pale colour and its slightly transparent, vitreous or resinous appearance. The yellow coloured scapolite mentioned by Watson (1949)

PLATE 25

Mineralogical variations in a striped plagioclasite from the Cnoc nan Cro gneisses. Natural size.

PLATE 26

Striping in the Cnoc nan Cro gneisses. A fold closure can be seen.

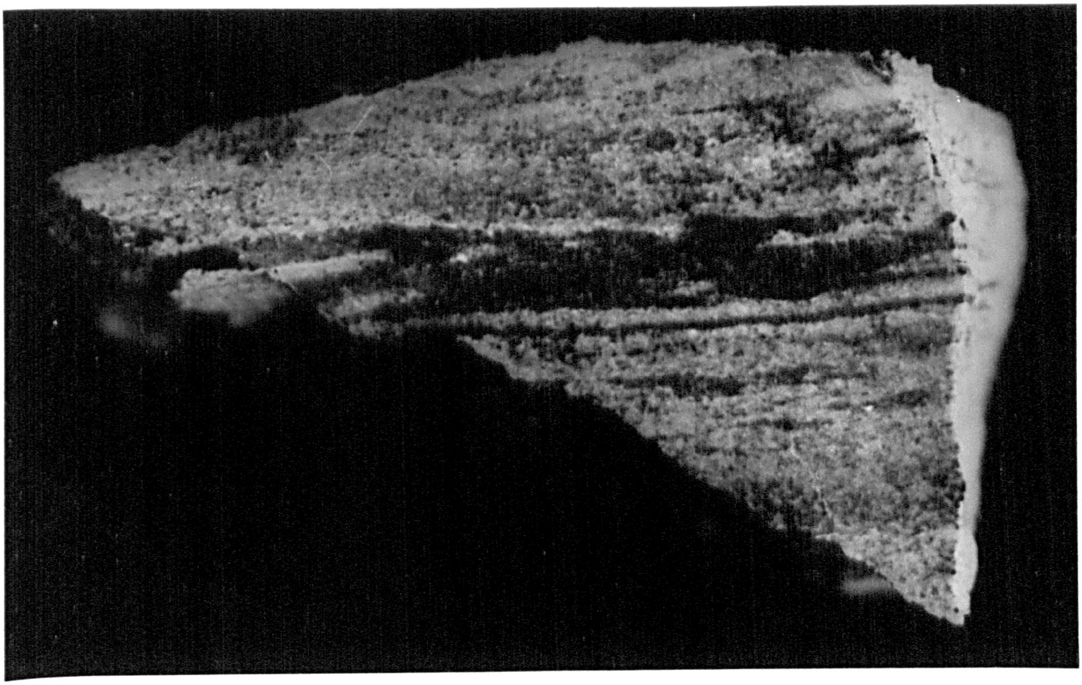


Plate 25

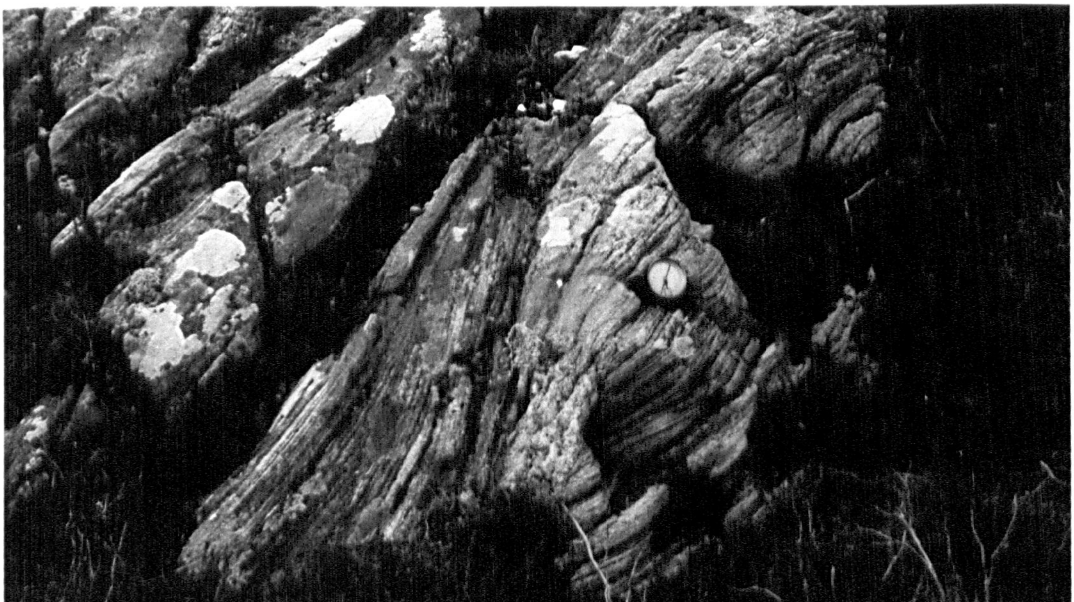


Plate 26

seems to be relatively sparsely developed. A large amount of the felsic material occurs as relatively soft, opaque spots that are apparently highly altered.

The mafic minerals include epidote, which varies in colour from green to yellowish orange, hornblende and biotite, each of which may occur in large amounts. All gradations from plagioclasite layers composed entirely of felsic minerals to layers composed entirely of mafic minerals can be seen. Muscovite is prominent in many layers.

Microscopic petrography

While the Cnoc nan Cro gneisses form a distinctive group in the field, they exhibit mineral relationships in thin-section similar to those of the other plagioclasites, although the highly altered nature of many of the gneisses tends to obscure their texture. A crystalloblastic texture is usual, although a few plagioclasites have a granoblastic texture. The variation in mineral constituents can be seen from the table of modal analyses (Table 16). Plagioclase, scapolite, hornblende, biotite garnet and epidote may occur in large amounts, while muscovite, clinozoisite, calcite, chlorite, sphene, apatite, allanite, tremolite, quartz, microcline and iron ore form the accessory minerals.

Plagioclase, the dominant mineral in these rocks, varies in grain-size from 0.1 mm. to 2 mm., grains of 1 mm. to 1.5 mm. predominating. The composition ranges from An_{25} to An_{38} (oligoclase-andesine), tending to be a little more calcic than in the adjacent gneisses. In contrast to the plagioclase of the gneisses the majority of the grains are twinned either on the albite or pericline law and the twin lamellae are few in number, quite thick, and rather irregularly spaced in any grain. The broad lamellae are constant in thickness along their length in contrast with the narrow tapering closely spaced twin lamellae that are also present and indicate secondary glide twinning (Vance, 1961). On the rare occasions when plagioclase is in contact with microcline, it may have a clear albitic rim. Fresh plagioclase is very common, but many grains have suffered some dusty or sericitic alteration which, in some cases, affects complete grains. In the early stages of sericitization small flakes of white mica, usually with a common alignment within a plagioclase grain, occur as individuals or in clusters. The amount of sericite may increase until the original grain has been entirely replaced by that mineral. Subsequent recrystallization of the sericite results in the formation of muscovite. Small patches of sericite give rise to small flakes of muscovite and in the final stage muscovite has more or less replaced the original grain, the original outline still being preserved. Another type of alteration is a saussuritization in which plagioclase has been replaced to a variable extent by sericite, clinozoisite and small amounts of calcite. There is no evidence that plagioclase has been replaced by scapolite, even when the two minerals are in contact.

Scapolite, usually forms grains of 0.5 mm to 1.5 mm in size, most of the fresh grains having smooth margins. It is often partly altered to sericite and sometimes completely to muscovite which may be accompanied by a colourless mineral with first order interference colours. Scapolite occasionally contains small grains of hornblende.

Hornblende, together with the other ferromagnesian minerals, occurs as dots, patches and streaks. Both blue-green and dark green varieties occur. It occurs as short, stumpy grains which vary in size from 0.1 mm. to 0.8 mm. and as large poikiloblastic plates that reach a size of 5 mm. and enclose plagioclase, biotite and epidote. Rarely small rounded grains of quartz are enclosed by the stumpy grains of hornblende, which are cut and penetrated by rhomboidal or prismatic epidote and flakes of biotite. Hornblende is occasionally altered to scapolite.

Epidote occurs as either idioblastic grains that are prismatic and rhomboidal in shape or irregularly shaped grains that may form a symplectitic intergrowth with quartz. It varies in grain-size from 0.05 mm. to 0.8 mm., and is usually colourless or pale green in colour. In the Cnoc nan Cro gneisses it is often the only mafic mineral present in the leucocratic layers and is commonly found in the more mafic layers. Birefringence and pleochroism vary from one specimen to another and often within one specimen. A strongly pleochroic yellow epidote is common in some layers. Some varieties exhibit anomalous blue first order colours, suggesting a fairly low iron content (Deer et.al., 1962 (a)); most, however, have middle 2nd order interference colours typical of epidote with moderate amounts of iron. Rarely, one grain may be composed of both pleochroic yellow epidote and non-pleochroic colourless epidote, the one grading into the other.

Biotite occurs in three varieties with the following pleochroic schemes:-

1. Light brown to brown.
2. Light greenish brown to dark greenish brown.
3. Light reddish brown to dark reddish brown.

The mineral, although it is usually dispersed throughout a specimen, may either be concentrated in certain layers or occur as clusters of haphazardly orientated flakes.

It commonly occurs as long thin flakes which vary from 0.4 mm. to 1.5 mm. in size. It is occasionally altered to chlorite or muscovite and may be cut by epidote. The flakes are sometimes flexured and in one case form an isoclinal fold.

The accessory minerals include sphene, apatite, muscovite iron ores, garnet, augite, quartz, chlorite, tremolite, calcite, allanite, and microcline, the last eight minerals being absent from many plagioclasites. Iron ore comprises magnetite and pyrite. Sphene is invariably present, occurring as small isolated granules or in clusters, usually associated with the mafic minerals. Apatite occurs as small sub-rounded grains and tremolite and chlorite as accessories only in the biotite-garnet-plagioclasite. Chlorite flakes are pale-green in colour and pleochroic and range up to 2 mm. in size, being found as layers within biotite flakes; its general mode of occurrence suggests that chlorite is secondary after biotite. Garnet, seen in only one plagioclasite, occurs as sub-rounded, oval or irregularly shaped grains varying from 0.3 mm. to 2 mm. in size. The larger grains contain inclusions of plagioclase, green chlorite and biotite and all grains have irregular cracks. Pale-green augite is present in a few specimens.

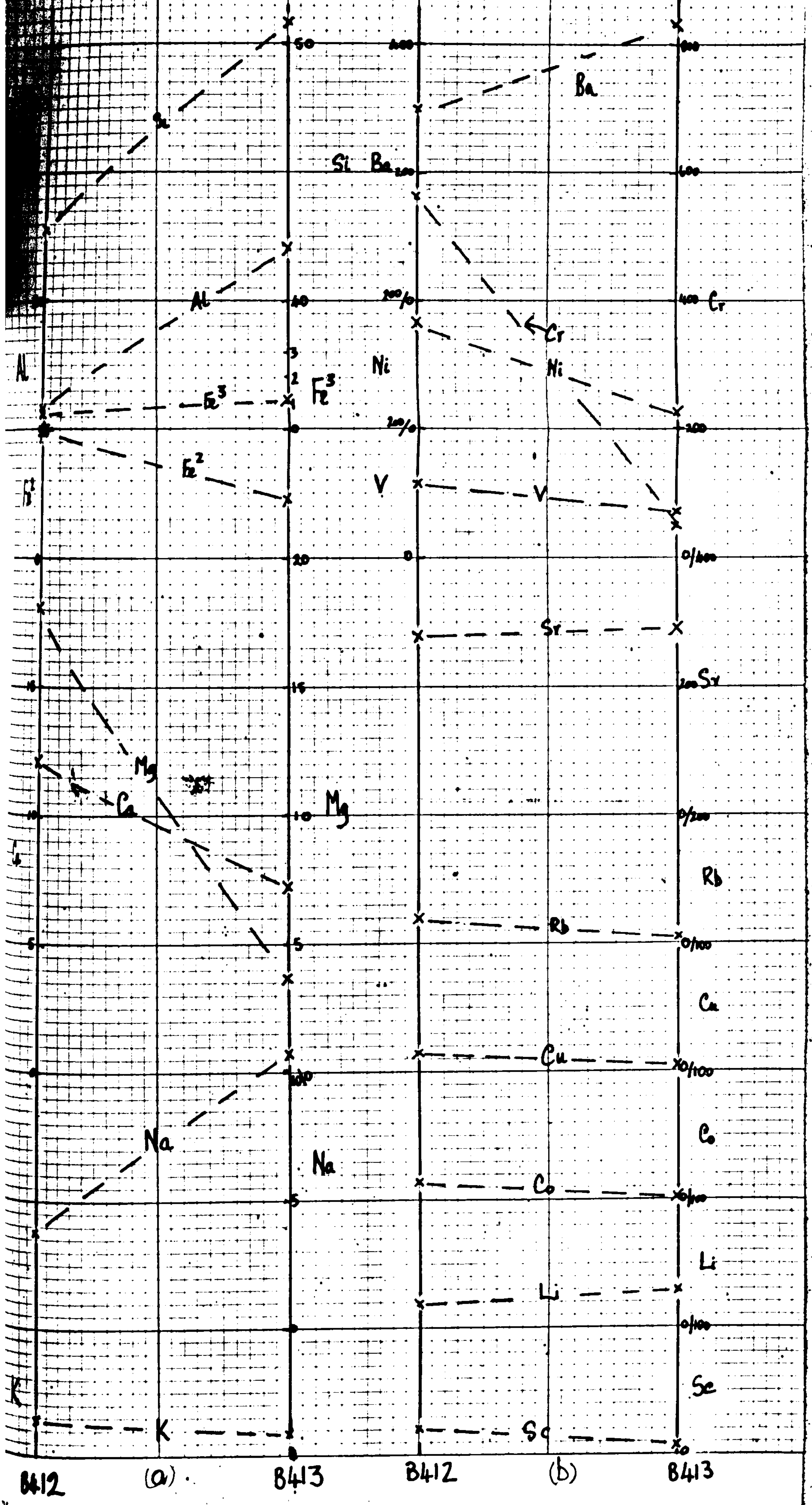


Fig. 14 (a) major and (b) trace element comparison bet[illegible] an amphibolite (B41[illegible]) and a pla[illegible]ioclasite ([illegible]).

The Geochemistry of the Plagioclasites

Five plagioclasites have been analysed (Table 16). Three (B.47, L.231 and K1) resemble in some respects an anorthosite from South Harris (Table 16) and two resemble anorthosite from Southern Norway (Table 16). All plagioclasites contain more FeO and MgO than is present in a pure anorthosite (cf. anorthosite from South Harris - Table 16). The high values of potash in L.231 and K1 can be correlated with the large amounts of muscovite in these specimens.

On the triangular diagram of Niggli numbers 100 mg. c and (al-alk), the plots of the analyses lie close to one another (fig.13) but fall far from the trend line of the Karoo dolerites (Leake, 1964).

One amphibolite (B412) abuts against one of the plagioclasites (B413) and cation percentages of each have been plotted (fig.14a). From B412 to B413 Si, Al and Na increase and Ca and Fe^2 decrease by similar proportions; Mg decreases markedly while K and Fe^3 show little variation.

Plots of trace element contents (fig.14b) of B412 and B413 indicate that only Ba shows a marked increase in the plagioclasite, while Li and Sr increase slightly. Apart from Ga which remains constant, the remaining elements decrease, particularly Cr, Ni and V (fig.14b). The high Ba and Rb values of B47 (647 ppm and 324 ppm respectively) and L231 (795 ppm and 320 ppm respectively) are worthy of note and can be related to the high potash content of these plagioclasites (Table 16).

Table 16

Complete data on the plagioclasites.

Chemical composition, cation percentage, Niggli numbers, mesonorm, mode, trace element values, and catanorm are listed in order on the following pages.

Analyses 1-5 : Plagioclasites from the Laxford area

Analysis 6 : Anorthosite, South Harris (Dearnley, 1963).

Analysis 7 : Anorthosite, Southern Norway (Barth, 1936).

	1	2	3	4	5	6	7
	[illegible]26	B47	B41[illegible]	1231	X1	P1	[illegible]2
SiO_2	57.14	45.50	55.[illegible]0	47.15	44.48	55.[illegible]0	54.[illegible]
Al_2O_3	19.[illegible]4	25.38	20.[illegible]1	26.35	27.09	28.08	25.2
Fe_2O_3	1.59	1.81	1.79	1.05	1.53	0.31	1.1
FeO	2.[illegible]	3.42	3.07	1.36	1.30	0.[illegible]2	[illegible].1
MgO	[illegible].49	5.02	2.[illegible]7	2.37	[illegible].34	-	1.0
CaO	6.94	10.56	7.31	13.25	13.31	11.64	6.7
Na_2O	5.99	2.07	6.[illegible]1	1.91	2.75	3.88	5.4
K_2O	1.[illegible]0	2.57	0.83	3.36	3.6[illegible]	[illegible].62	0.7
TiO_2	0.46	0.31	0.30	0.09	0.20	-	1.3
P_2O_5	0.05	0.03	0.19	0.04	0.03	-	0.1
MnO	0.08	0.11	0.08	0.11	0.06	-	-
H_2O^+	0.66	2.63	0.95	3.67	3.92	0.30	-
H_2O^-	-	-	-	-	-	0.10	-
CO_2	-	-	-	0.14	0.19	-	-
	99.06	99.61	99.51	100.85	101.15	99.45	100.4
Si^{4+}	52.67	42.88	50.85	44.52	41.66	-	-
Al^{3+}	21.12	2[illegible].16	22.11	29.23	29.89	-	-
Fe^{3+}	1.19	1.28	1.23	0.74	1.08	-	-
Fe^{2+}	2.26	3.[illegible]1	2.38	1.05	1.24	-	-
Mg^{2+}	3.45	7.04	3.68	3.[illegible]5	[illegible].29	-	-
Ca^{2+}	6.92	10.45	7.23	13.59	13.31	-	-
Na^+	10.82	3.80	10.79	3.51	5.00	-	-
K^+	1.18	3.08	0.93	4.03	4.29	-	-
Ti^{4+}	0.[illegible]2	0.22	[illegible].56	0.06	0.14	-	-
P^{5+}	0.03	0.02	0.15	0.03	0.04	-	-
Mn^{2+}	0.04	0.06	0.04	0.09	0.[illegible]6	-	-

	1	2	3	4	5
	I[illegible]	B47	E413	I231	X1
si	173	109	161	120	108
al	34.6	35.8	35.1	39.5	38.7
fm	22.8	28.9	23.3	14.1	14.6
c	22.8	26.6	23.0	36.2	34.6
alk	19.8	8.8	18.6	10.0	12.0
ti	1.1	0.6	1.8	0.15	0.37
p	0.1	-	0.2	0.04	0.05
k	1.0	0.45	0.08	0.53	0.47
mg	0.50	0.62	0.50	0.64	0.58
Qtz	-	-	-	-	-
Or	5.90	10.15	4.10	-	-
Ab	54.10	19.00	53.95	-	-
An	15.00	20.00	19.60	-	-
Ho	22.18	39.28	17.14	-	-
Bi	-	8.40	1.28	-	-
Mt	1.78	1.92	1.85	-	-
Sph	0.96	0.66	1.68	-	-
Ap	0.08	0.03	0.40	-	-
Quartz	trace	-	-	-	-
Plagioclase	84.9	80.0	71.2	-	-
Microcline	0.4	2.0	-	-	-
Scapolite	-	-	-	x	x
Muscovite	-	-	-	x	x
Hornblende	11.6	9.8	18.2	-	-
Biotite	0.6	5.7	7.2	x	x
Epidote	2.0	2.0	3.8	x	x
Iron ore	-	trace	trace	-	-
Sphene	0.4	0.6	-	-	-
Apatite	0.3	-	trace	trace	-
Chlorite	trace	-	-	-	-

	1	2	3	4	5	6
	126	B47	B413	1231	X1	F1
Ba	-	647	410	[illegible]95	-	90
Co	-	< 2	< 2	-	-	(10)
Cr	-	42	27	71	-	(30)
Cu	-	5.6	3.7	-	-	-
Ga	-	15.7	15.7	-	-	20
Li	-	30	31	37	-	(10)
Ni	-	100	24	-	-	50
Rb	-	324	16	320	-	-
Sc	-	18.7	7.8	9.7	-	-
Sr	-	225	239	218	-	350
V	-	88	67	[illegible]3	-	30
Zr	-	23	45	-	-	(30)
Qtz	0.30	-	-	-	-	3.84
Or	5.90	15.40	4.90	20.15	5.30	3.34
Ab	54.10	10.80	53.95	1.78	-	33.01
An	22.80	52.25	25.85	54.25	51.50	57.35
Ne	-	4.92	-	9.46	15.00	-
Leu	-	-	-	-	12.92	-
Di	9.64	-	7.24	9.96	11.76	-
Hy	4.86	-	1.63	-	-	-
Ol	-	13.89	4.59	1.53	1.59	-
Mt	1.78	1.92	1.85	1.11	1.62	0.46
Ap	0.08	0.05	0.40	0.08	0.11	-
Hae	-	-	-	-	-	0.98

The Metadiorites.

A series of homogeneous metadiorites containing accessory quartz crop out to the north-east of the Rudha Ruadh sheet, being particularly well developed on the headland round from Weaver's Bay where they occur as concordant bands several metres thick. They can be distinguished from the gneisses, in which they occur, by (1) the absence of striping (2) a sugary granular texture rather similar to that of the amphibolites and (3) a speckled appearance.

The foliation of the metadiorites is parallel to that of the adjacent gneisses, but is poorly developed because of the homogeneous nature of the rocks. Occasional mafic and felsic streaks and concordant stripes of quartzo-feldspathic material emphasise the foliation (Plate 27).

The metadiorites contain 50% to 60% plagioclase, 30% to 40% mafic minerals and less than 10% quartz. Hornblende, which usually predominates, biotite and epidote occur together in most specimens. Potash feldspar is sparse or absent. Concordant stripes, varying in thickness from 2 mm. to 1 cm. and composed of quartz and plagioclase with occasional potash feldspar and biotite are an essential feature of the group.

Metadiorites are sometimes cut or enclosed by microgranite.

PLATE 27

A homogeneous speckled metadiorite with a concordant stripe of quartzo-feldspathic material.

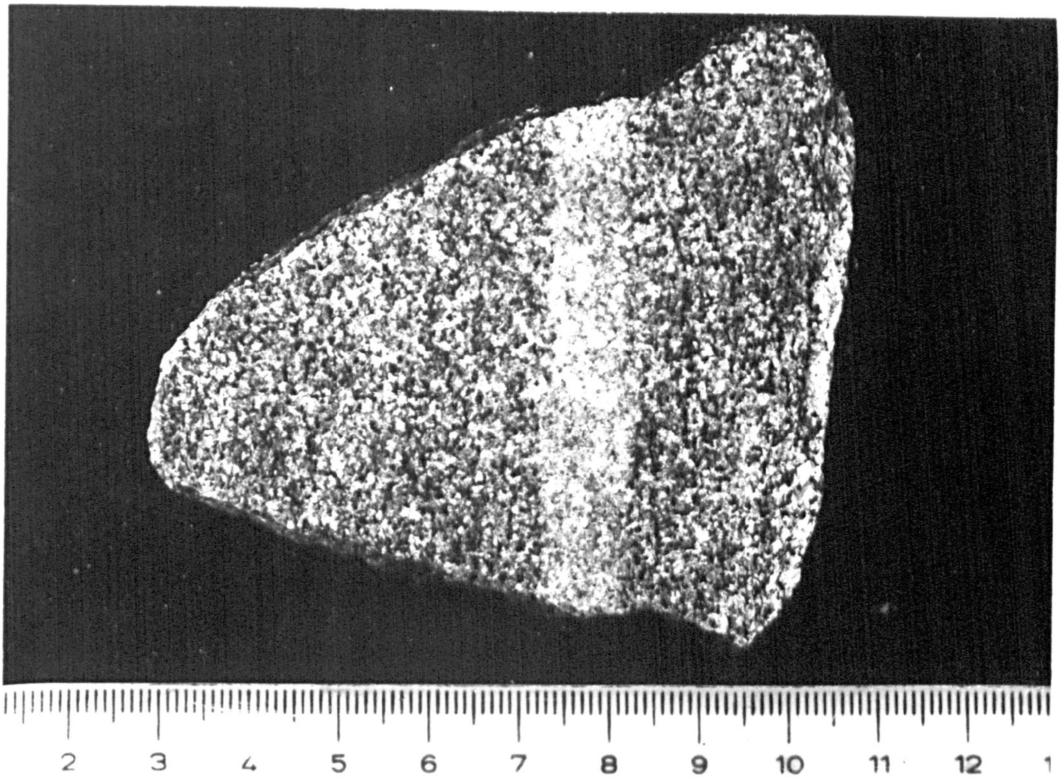


Plate 27

Microscopic petrogrpahy

The metadiorites are medium-grained and granoblastic, composed of plagioclase, quartz, microcline, hornblende, biotite and epidote with minor amounts of apatite, sphene, allanite and iron ore. They are mineralogically very similar to the tonalites of zone IV on South Harris (Dearnley, 1963, p.268). (Table 17).

Quartz, present in amounts that do not exceed 10%, is usually granoblastic to interstitial in habit, rarely exceeding 0.5 mm. in size. A few rounded grains occur within plagioclase. Quartz invariably exhibits undulose extinction.

Plagioclase, varying in size from 0.4 mm. to 2 mm. is oligoclase (An_{27} - An_{30}) in composition. The grains are predominantly untwinned and have suffered a variable degree of alteration. In one thin-section several cracks and cleavage planes are filled with minute muscovite flakes and occasionally biotite.

Microcline occasionally occurs as interstitial grains.

Hornblende, which occurs in every specimen, forms grains that average 0.8 mm. in size, having the following pleochroic scheme:-

X	Y	Z
Light yellow-brown	Green	Darkish green with bluish tinge .

It is occasionally very pale in colour when associated with epidote and biotite, both of which are commonly seen to cut across hornblende.

Epidote, a common constituent, occurs as rhomboidal or irregularly shaped grains, varying in size from 0.1 mm. to 1.1 mm. It often forms symplectitic intergrowths with quartz and cuts across biotite flakes.

Biotite occurs as two varieties with the following pleochroic schemes:-

	X	Y, Z
1.	Straw	Dark Brown
2.	Pale reddish brown	Dark reddish brown.

Many of the flakes are aligned in one direction, but when biotite occurs in association with hornblende and epidote the three minerals exhibit a haphazard arrangement. In some cases biotite occurs as very narrow flakes in cracks in plagioclase.

The accessory minerals include apatite, allanite, sphene and opaque ores. Apatite is particularly prominent, occurring as oval or rounded grains that reach a size of 1 mm. Allanite is rare and may be fringed by epidote. Sphene, also very common, occurs as small oval grains that reach a size of 0.5 mm. Opaque ores are rather uncommon.

The Geochemistry of the Metadiorites

The chemical composition of the metadiorites is closely similar to that of the tonalites of South Harris (Table 17), particularly when soda and potash are added together. Soda is higher and potash lower in the Laxford metadiorites than in the South Harris tonalites (Table 17). This similarity is accentuated by the close agreement between the trace element content of each (Table 17).

The chemical analyses, when plotted on the Fe^2+Fe^3, Na+K and Mg triangular diagram, fall close to the linear trend line for the gneisses (fig. 15a). Similarly, plots of Na^+ against K^+ fall within the field of the gneisses, the ratio Na:K being greater than 7:1. The tie-line between the two plots suggests that as Na decreases K increases. The South Harris tonalite also falls close to this line (fig.15b).

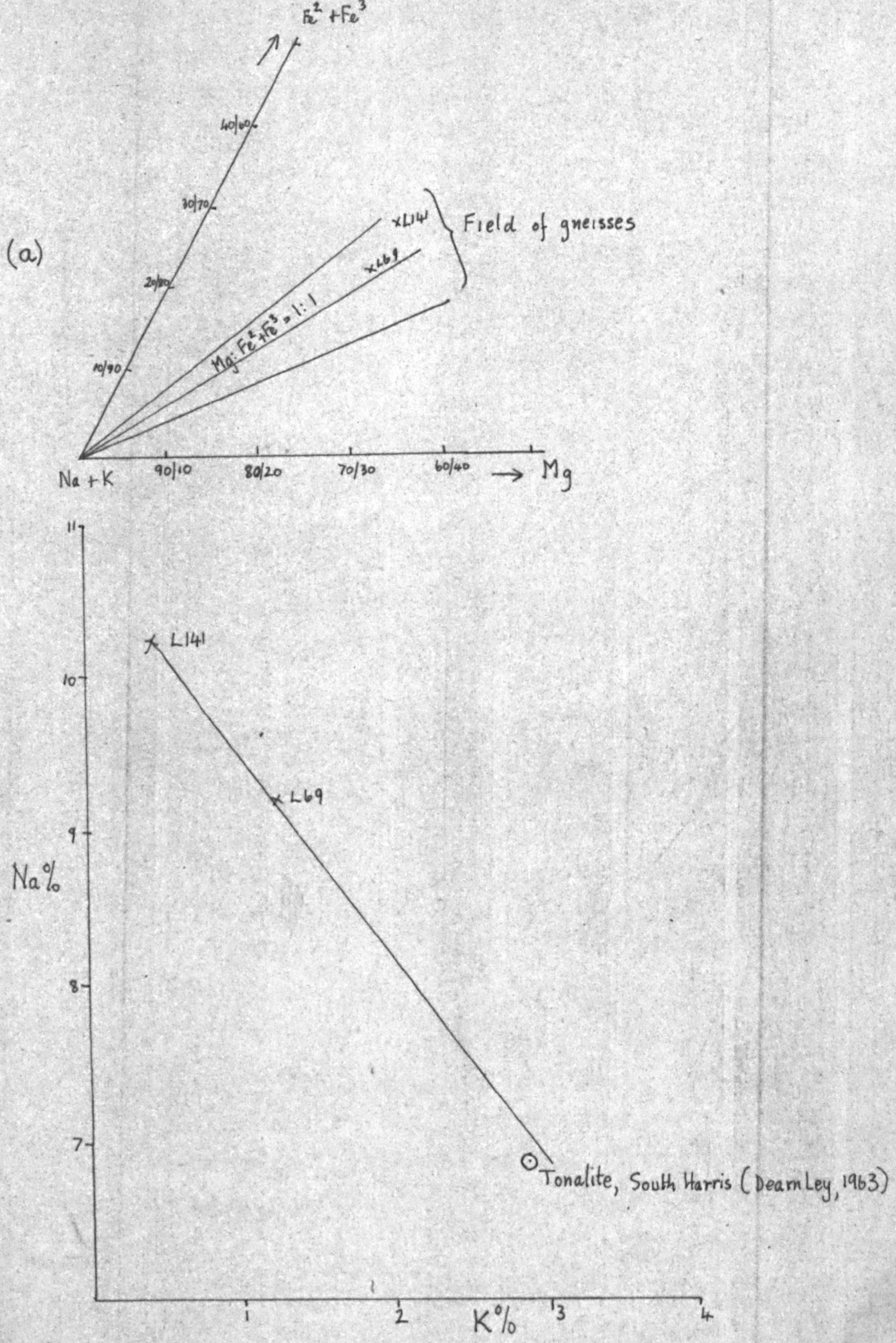


Fig.15 (a) and (b). See text p.107 for explanation.

	1 L69	2 L141	3 M1
SiO_2	59.07	57.50	56.13
Al_2O_3	17.70	15.68	17.17
Fe_2O_3	2.19	3.95	2.97
FeO	3.74	4.68	4.98
MgO	3.03	3.16	3.95
CaO	6.03	7.26	6.35
Na_2O	5.12	5.86	3.74
K_2O	1.07	0.38	2.41
TiO_2	0.60	0.70	0.83
P_2O_5	0.33	0.30	0.17
MnO	0.09	0.11	0.10
H_2O^+	0.68	1.00	1.09
H_2O^-	-	-	0.08
	99.65	100.58	99.92

	1 L69	2 L141	3 M1
Ba	355	-	600
Co	<2	-	<3
Cr	29	-	<30
Cu	4.9	-	-
F	1100	-	-
Ga	15.8	-	4
Li	30	-	$\ll 30$
Ni	11.8	-	2
Rb	23	-	-
Sc	21.5	-	3
Sr	395	-	600
V	91	-	40
Zr	125	-	65

	1 L69	2 L141	3 M1
Si^{4+}	54.80	53.43	-
Al^{3+}	19.34	17.14	-
Fe^{3+}	1.55	2.73	-
Fe^{2+}	2.92	3.62	-
Mg^{2+}	4.17	4.41	-
Ca^{2+}	6.00	7.23	-
Na^+	9.23	10.22	-
K^+	1.25	0.44	-
Ti^{4+}	0.44	0.49	-
P^{5+}	0.25	0.23	-
Mn^{2+}	0.05	0.06	-

	1 L69	2 L141	3 M1
Qtz	7.42	5.37	5.10
Or	6.25	2.20	14.46
Ab	46.15	51.10	31.44
An	22.15	15.45	23.07
Di	4.64	15.08	6.31
Hy	9.52	4.90	12.26
Mt	2.33	4.10	4.41
Il	0.88	0.98	1.52
Ap	0.66	0.62	0.34

Table 17. Metadiorites: Chemical analyses expressed as weight and cation percentages, trace element values and catanorm. Modes, mesonorms and Niggli numbers are listed on following page. M1: Tonalite, South Harris. (Dearnley, 1963.)

	1	2	3
	I69	I141	M1
si	185	173	-
al	32.7	27.9	-
fm	29.3	31.4	-
c	20.2	23.6	-
alk	17.7	17.3	-
ti	1.5	1.6	-
p	0.43	0.38	-
k	0.12	0.04	-
mg	0.48	0.46	-
Qtz	10.47	4.65	-
Or	0.45	2.20	-
Ab	46.15	51.10	-
An	18.55	10.20	-
Di	-	7.66	-
Hb	9.36	18.00	-
Bi	9.28	-	-
Mt	2.33	4.11	-
Sph	1.32	1.47	-
Ap	0.66	0.63	-
Quartz	9.6	3.2	8.1
Plagioclase	62.4	59.3	41.6
Microcline	0.4	1.0	
Hornblende	16.2	21.2	28.2
Biotite	8.7	2.5	11.6
Epidote	1.9	2.1	-
Iron ore	trace	trace	1.0
Sphene	0.4	0.4	0.3
Apatite	0.4	0.3	0.7
Allanite	trace	trace	-
Scapolite	-	-	8.5

The Metamorphic Facies

Mineral assemblages of three metamorphic facies can be recognised in the early igneous rocks. An orthopyroxene-olivine-tremolite assemblage is present in metaperidotites near the south-western egde of the area while a plagioclase-orthopyroxene-diopside-garnet-(spinel) assemblage is present in all garnet-pyriclasites that have been examined. Neither of these assemblages exhibits the textural relations of igneous rocks and both can, therefore, be considered to indicate the occurrence of a granulite-facies metamorphism, as defined by Ramberg (1952), at some stage during the metamorphic history of the early igneous rocks. An upper amphibolite facies metamorphism is suggested by the presence of a pale green, non-pleochroic clinopyroxene in addition to the common green amphibole in many of the amphibolites (cf. Engel & Engel, 1962c). This mineral is not igneous in origin (cf. Watson, op.cit.). Most amphibolites contain the typical amphibolite facies assemblage of plagioclase and hornblende (Ramberg, 1952), but the stable assemblage of plagioclase and epidote in the metadiorites indicates a lower or epidote amphibolite facies (Ramberg, 1952) and probably indicates that the more acidic rocks are more susceptible to metamorphic change.

IV. THE GRANITOID ROCKS

"Granitoid rock" is used for the whole class of quartz-feldspar rocks of granitoid texture. The term is thus equivalent to the terms granite and granitic rock used by many writers (for example, Sutton & Watson 1962). Granitoid rock is strictly a non-compositional and non-genetic term.

In the Laxford area the granitoid rocks can be divided into two groups: (1) the sodic varieties, typified by the trondhjemites and (2) the potassic varieties, typified by the microgranites. There is a sharp distinction between the sodic varieties in which potash feldspar is absent and the potassic varieties in which potash feldspar makes up at least 30% of the rock. Rock-types, intermediate in amounts of potash feldspar are few in number and appear to represent sodic varieties modified by potassium metasomatism.

The potassic varieties are described under the heading "granitic rocks and allied types", "granitic" being used to describe rocks in which potash feldspar comprises at least 50% of the feldspar component.

The granitoid rocks are distinguished from the other meta-igneous rocks because (1) they are quite different in composition and (2) they often display discordant relations to those rocks and/or the Laxfordian foliation, (see Chapter III). At this stage a genetic distinction is not made.

The Sodic Varieties

Sodic (trondhjemitic) granitoid rocks occur throughout the Laxford area. They are either fine to medium grained (a grain-size of 1 mm. is most common) or coarse-grained and pegmatitic. For convenience the former are termed trondhjemites and both the latter varieties are termed pegmatitic trondhjemites.

For reasons given in Chapter III the trondhjemites are considered to be the older of the granitoid rock groups, probably developing in the early stages of the Laxfordian metamorphism. Many have been modified by a later potassium metasomatism associated with the intrusion and development of the potassic varieties (≡ granitic rocks).

The pegmatitic trondhjemites form concordant sheets, irregular patches of various sizes, or small lenticular bodies. There is no clear association between the pegmatitic trondhjemites and the trondhjemites as is seen, for example, in the Cnoc nan Cro group of granitic rocks (pp.130-1). The pegmatitic trondhjemites are composed of quartz and plagioclase with small amounts of biotite, chlorite and epidote. They are occasionally folded (Plate 28).

The trondhjemites can be divided into (1) a folded or contorted variety and (2) an undeformed variety. The folded trondhjemites often occur in amphibolites as highly contorted veins (Plate 29) in which the contortions are small-scale folds that have the same geometry as the folds in the adjacent gneisses and the contortions are, therefore, interpreted as deformational features rather than ptygmatic structures. These veins contain contorted wisps of biotite, but more often that mineral is disseminated throughout the rock (Plate 30). Some trondhjemites are infolded with the gneisses. Some folded trondhjemites in the amphibolites are associated with lenses and pods of trondhjemite containing small amounts of hornblende (fig.16c). Such features have been considered to represent metamprphic segregation (for example, Ramberg, 1956).

The undeformed trondhjemites occur as either concordant or discordant veins, the latter variety predominating (fig. 16b). They are often foliated parallel to their margins which may have a thin layer of biotite when the vein cuts an amphibolite. When present in the Cnoc nan Uro gneisses the trondhjemites may be a metre or so thick, sometimes stopping abruptly and sometimes breaking up into tongues that penetrate along the foliation (fig. 16a).

Many of the trondhjemites that occur in amphibolites appear to have reacted with the host rock, converting hornblende into biotite. They usually occur as slightly discordant veins or pods, the margins of which consist almost entirely of biotite or biotite and hornblende (Plate 31). Within any vein the mafic minerals, usually biotite but sometimes hornblende, or both minerals, occur as wisps or streaks, often several centimetres long and usually contorted, that decrease in volume away from the margins of the vein. Some trondhjemitic material has intimately penetrated the amphibolites in an agmatitic manner (Plate 32). However, trondhjemites most commonly occur in the amphibolites as narrow veins that cut those bodies in several directions.

Most of the trondhjemites are composed of quartz, feldspar and biotite although hornblende occurs in some of the lenticular and reaction bodies. Plagioclase predominates and is often, or always, if all the potash feldspar is accounted for by potassium metasomatism, the only feldspar. Quartz occurs up to a maximum of 40% by volume, but, although many of the trondhjemites contain between 25% and 30%, amounts of 5% and 10% are not uncommon. In a few veins quartz is absent and plagioclase forms 95% by volume of the rock. It may be that those plagioclase veins are the end-members of a series of trondhjemites showing increasing plagioclase content, with quartz-rich varieties grading into plagioclase-rich varieties.

In one vein, molybdenite, occurring as radiating flakes, forms 5% by volume of the trondhjemite. Nutter (1953) also describes molybdenite from quartzose veins, 800 metres south-west of Badnabay.

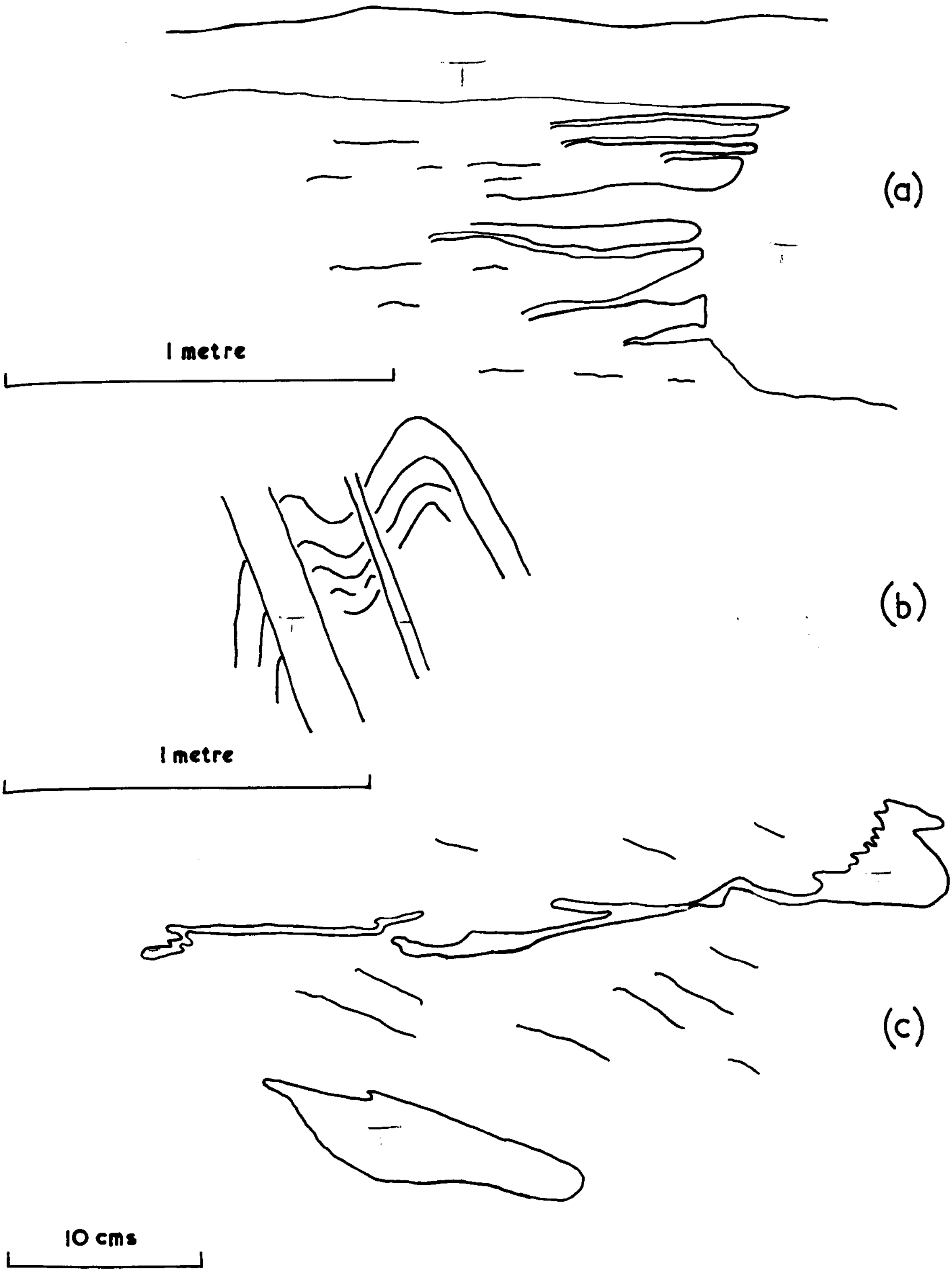


Fig. 16 see text, p112

PLATE 28

Folded trondhjemite (to the right of the hammer) with thin veins of trondhjemite (to the left of the hammer); Laxford Bay.

PLATE 29

Small scale folds of Laxfordian age in trondhjemites; near north end of Loch na Claise Fearna.

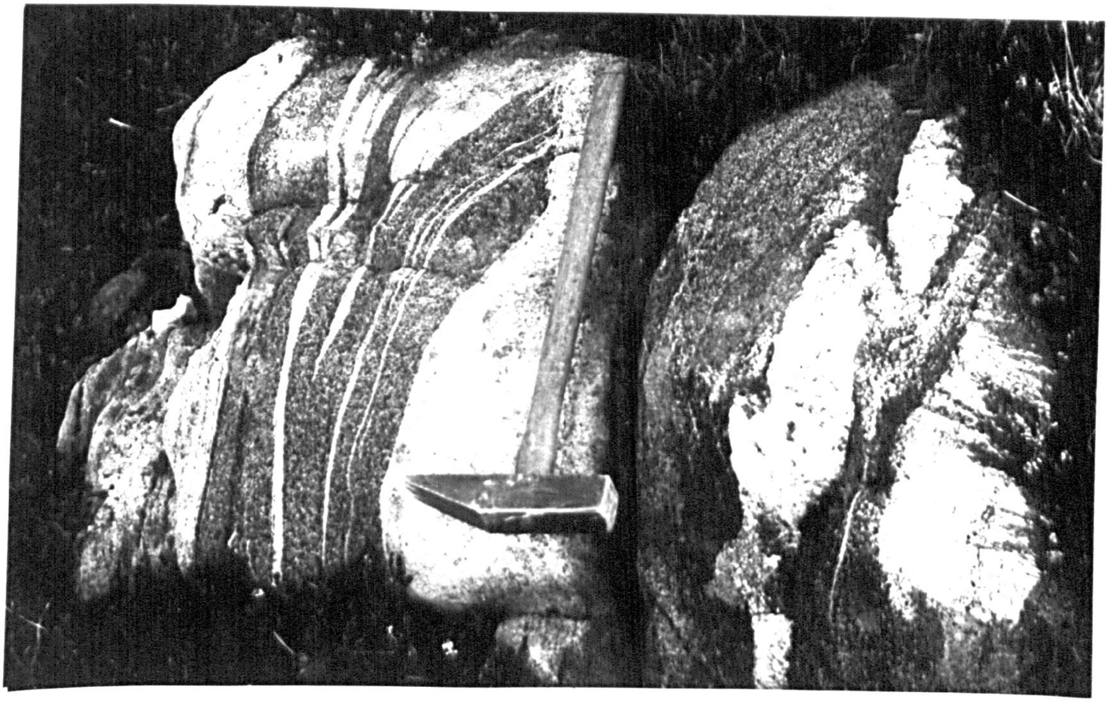


Plate 28

Plate 29

PLATE 30

Trondhjemite in which biotite is distributed evenly throughout the specimen. Arrow shows small crenulations in thin wisps of biotite flakes; near north end of Loch na Claise Fearna.

PLATE 31

Amphibolite with concordant and discordant rims and lenses of trondhjemite that contain numerous wisps and streaks of biotite. The pod at the bottom right of the photograph is almost completely surrounded by a rim of biotite; 300 metres south of Weaver's Bay.

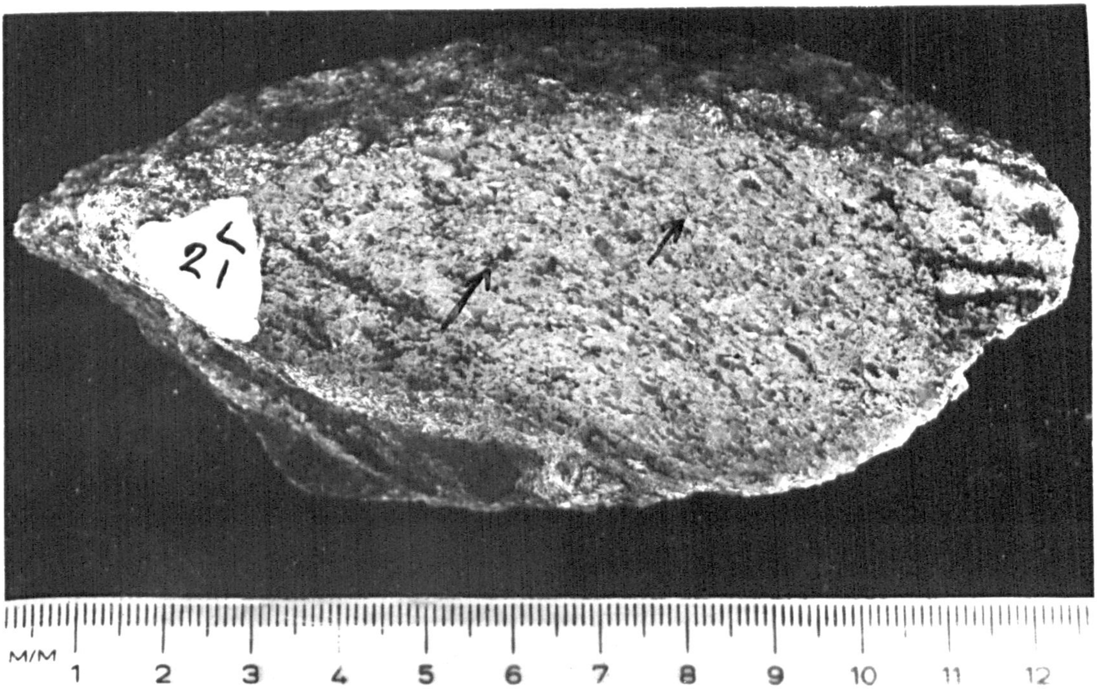


Plate 30

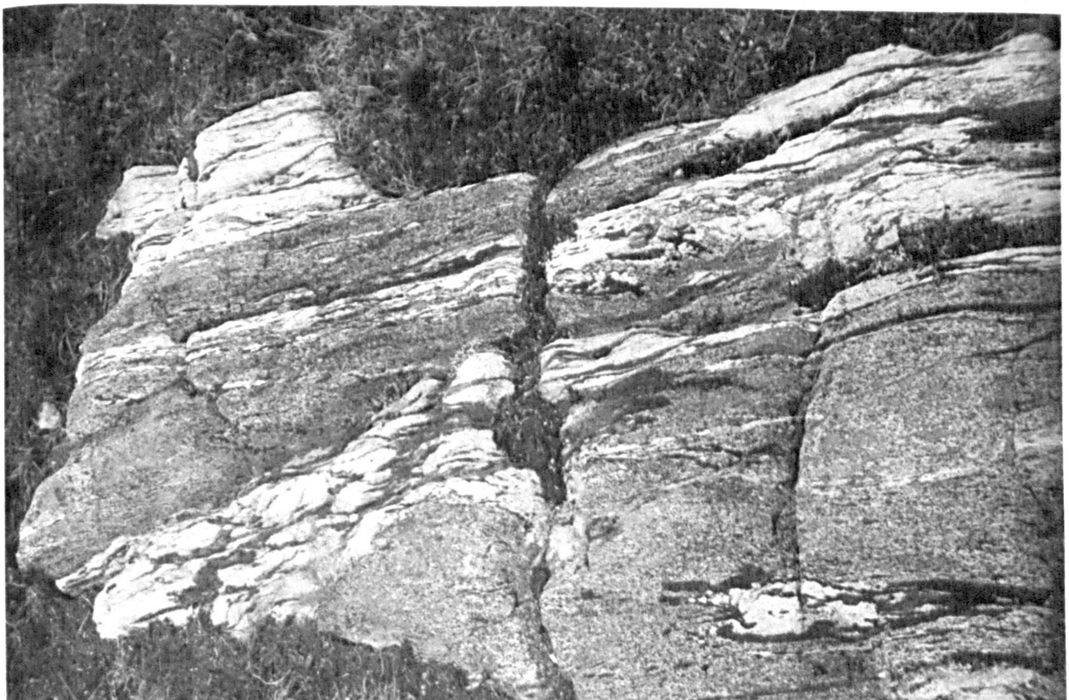


Plate 31

PLATE 32

An agmatitic association of trondhmemite and amphibolite, near Loch Bad an t-Seabhaig.

Plate 32

Microscopic petrography of the trondhjemitic rocks

The texture of the trondhjemites is granoblastic, although it has a tendency to be crystalloblastic, particularly in the coarse-grained and pegmatitic varieties. In the medium-grained trondhjemites the grain-size increases from 1 mm in the south-west of the area to around 1.5 mm in the north-east.

Quartz is usually present in amounts varying from 20% to 40%, but may be sparse or absent. In some of the veins and lenses it occurs as either rounded or sub-rounded grains set in a linked network of feldspar, particularly plagioclase, or very small rounded grains enclosed by a larger plagioclase grain. Some quartz always occurs as large grains, up to 1.5 mm in size, that are often bulbous and lobate. Undulose extinction is invariably present.

Plagioclase more than 50% of which is untwinned, is oligoclase in composition varying from An_{25} to An_{28}. Cloudy and sericitic alteration are patchily developed. A connected network of plagioclase is typical of the trondhjemites, isolated grains being rarely seen. Albite is also present in the coarse-grained and pegmatitic trondhjemites.

Biotite is the most common mafic mineral. It is usually brown or greenish brown in colour, occurring as small parallel or sub-parallel lathes, except in the "reaction" trondhjemites where it is either dark-brown or reddish-brown in colour and occurs as aggregates of flakes or individual flakes disseminated in a rough parallelism or sinuous pattern throughout a specimen. The latter variety of biotite often occurs in association with epidote in which cases biotite may form a symplectitic intergrowth with quartz. Biotite is occasionally altered to chlorite.

Hornblende is only present in the "reaction" trondhjemites and lenses within amphibolites. In these bodies it exhibits a pleochroism different from that of the amphibolites as follows:-

X	Y	Z
Straw yellow	Yellowish green	Emerald green

When present in the lenses, hornblende is identical to that present in the host amphibolite and is usually associated with a symplectitic intergrowth of epidote and quartz. In the "reaction" trondhjemites hornblende is associated with biotite and epidote, both of which cut across it.

Epidote is sparse or absent in the normal trondhjemites but fairly common in the "reaction"-trondhjemites. It often forms a symplectitic intergrowth with quartz and occasionally rims allanite.

The accessory minerals are sparse in the normal trondhjemite but quite common in the "reaction"-trondhjemite, particularly sphene, which fringes ilmenite. The accessories include apatite, usually occurring as sub-rounded grains; allanite, occurring as prisms; sphene, in oval grains; and opaque ore minerals. In one specimen, pyrite was seen to have a rim of haematite which in turn was completely rimmed by magnetite.

The geochemistry of the trondhjemitic rocks.

The chemical composition of the trondhjemites is similar to the type-specimen described by Goldschmidt (1916)(Table 18a) except that the former are richer in silica and poorer in alumina. While the analyses plot close to the (Na+K) apex of the (Fe^2+Fe^3), (Na+K), and Mg triangular diagram, one analysis (L11) does not fall close to the 1:1 line for Mg:Fe^2+Fe^3 (fig. 17).

Trace element values also suggest that L11 differs from the other trondhjemites: thus it contains more Cr, Cu, Ga, and Ni but less Ba, Li, Rb, Sc, and Sr (Table 18a).

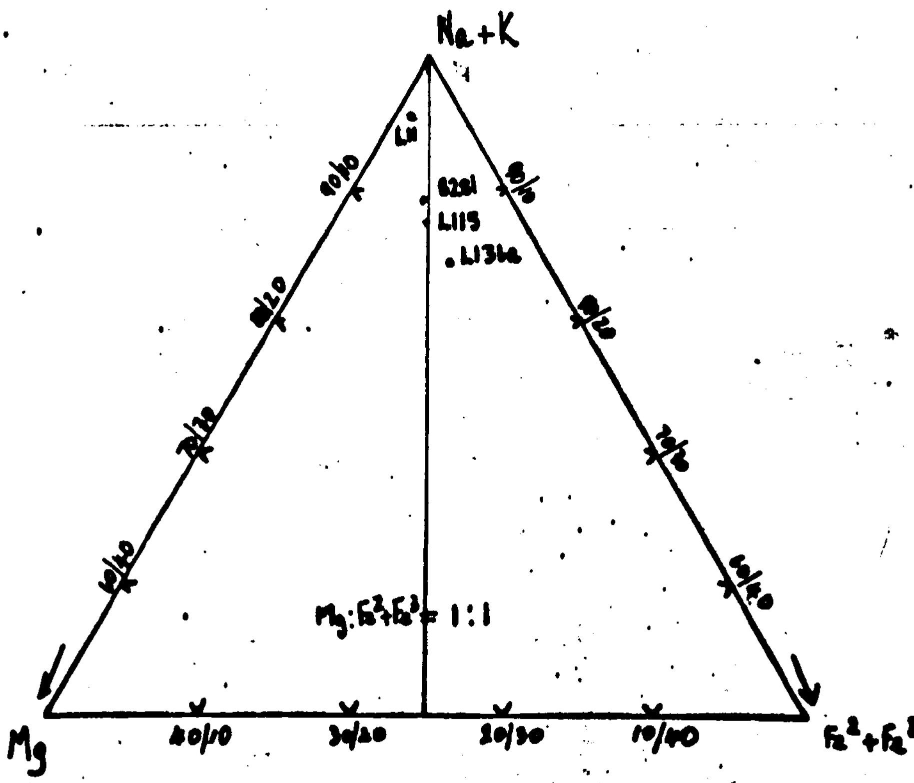


Fig.17 Triangular variation diagram Na+K, Mg, Fe^2+Fe^3.

	1	2	3	4	5
	I11	[illegible]261	[illegible]115	I136a	G1
SiO_2	7[illegible].7[illegible]	75.21	73.81	73.68	69.30
Al_2O_3	1[illegible].36	14.37	14.67	14.59	1[illegible].81
Fe_2O_3	0.16	0.20	0.31	0.37	0.28
FeO	0.15	0.59	0.65	0.60	1.26
MgO	0.08	0.36	0.48	0.75	1.08
CaO	4.46	2.95	3.10	3.35	3.34
Na_2O	3.73	4.63	4.95	4.82	6.00
K_2O	0.48	0.40	0.65	0.59	1.39
TiO_2	0.03	0.11	0.25	0.17	0.23
P_2O_5	trace	0.05	0.03	0.04	0.05
MnO	0.01	0.01	0.01	0.01	trace
H_2O	0.65	0.46	0.35	0.24	0.50
Total	99.15	99.34	99.26	99.21	100.22

Si^{4+}	7[illegible].24	70.98	6[illegible].90	69.10
Al^{3+}	15.35	15.97	16.09	16.10
Fe^{3+}	0.13	0.17	0.23	0.25
Fe^{2+}	0.1[illegible]	0.45	0.50	0.47
Mg^{2+}	0.09	0.50	0.67	1.04
Ca^{2+}	4.54	2.98	3.10	3.38
Na^{+}	[illegible].89	8.46	8.95	8.77
K^{+}	0.59	0.45	0.76	0.75
Ti^{4+}	0.02	0.06	0.19	0.15
P^{5+}	-	0.03	0.03	0.02
Mn^{2+}	0.01	0.01	0.01	0.01

Table 18a Trondhjemites

Chemical analyses , cation percentages, Niggli numbers, Mesonorms, modal analyses, Trace element values, and Catanorms are listed in order.

G1 Typical trondhjemite (Goldschmidt, 1916).

Others are from the Laxford area.

	1	2	3	4
	L11	B281	L115	L136a
si	444	431	400	385
al	47.1	48.4	46.6	44.9
fm	2.1	6.4	7.5	10.0
c	27.9	18.0	17.9	18.8
alk	22.9	27.1	28.1	26.4
ti	0.1	0.3	1.1	0.7
p	-	0.1	0.1	0.1
k	0.07	0.05	0.08	0.07
mg	0.27	0.47	0.52	0.59
Qtz	41.57	38.45	33.83	33.99
C	-	1.30	0.65	0.18
Or	2.95	0.82	2.02	1.42
Ab	34.45	42.30	44.80	43.85
An	19.67	14.35	14.30	16.00
Di	0.68	-	-	-
Hi	-	2.31	2.85	3.73
Mt	0.19	0.25	0.34	0.37
Sph	0.06	0.18	0.57	0.45
Ap	-	0.08	0.08	0.05
Quartz	43.9	37.5	31.5	31.8
Plagioclase	53.9	59.5	64.5	63.8
Microcline	-	-	-	-
Hornblende	1.7	-	-	-
Biotite	-	2.5	3.1	3.8
Epidote	0.3	0.3	0.3	0.3
Iron ore	trace	trace	trace	trace
Sphene	trace	trace	trace	trace
Apatite	-	trace	trace	trace
Allanite	-	trace	trace	-

	1	2	3	4
	L11	B231	L115	L136a
Ba	150	750	-	550
Co	2	11	-	2
Cr	22	16	-	8
Cu	17.3	8.1	-	11.4
Ga	17.3	14.2	-	1[illegible].1
Li	16	26	-	23
Ni	11	5	-	5
Rb	20	25	-	25
Sc	n.d.	2.8	-	6.6
Sr	193	303	-	300
V	17	17.5	-	22
Zr	56	81	-	111
Qtz	41.20	37.47	32.76	32.65
C	-	1.08	0.27	-
Or	2.95	2.25	3.80	3.75
Ab	34.45	4[illegible].30	44.80	43.85
An	15.67	14.65	15.25	16.45
Wo	1.18	-	-	0.12
En	0.18	1.00	1.34	2.08
Fs	0.10	0.64	0.42	0.42
Mt	0.19	0.25	0.34	0.37
Il	0.08	0.12	0.38	0.30
Ap	-	0.08	0.08	0.05

THE GRANITIC AND ALLIED ROCKS

Granitic and pegmatitic material is extremely abundant around Loch Laxford, as observed by Clough (op.cit., pp.120 - 123 and pp.143 - 148) and later by Watson (op.cit., pp. 286 - 288). North of Laxford Bridge granites and pegmatites predominate over micro-granites whereas to the south foliated microgranites, most of which are concordant sheets, predominate.

Foliation is universally present in the microgranites and is usually parallel to the margins of the sheets. This feature has led Clough (op.cit., p.120) and Watson (op.cit., p.287) to describe these rocks as "granite gneisses". Gneissosity is only seen occasionally and it is, therefore, proposed here to restrict the term "gneiss" to the more heterogeneous rocks and to use the term "foliated microgranite" for the group of rocks that are described in the following paragraph.

Quartz, plagioclase and potash feldspar are the dominant mineral constituents of the microgranites, a few of which fall marginally within the field of granodiorite, plagioclase being slightly more abundant than potash feldspar (Johannsen, 1932, p.144). However, as these microgranodiorites are so nearly identical in mineralogy, chemistry and field relationships with the microgranites they are grouped together. Plagioclase and potash feldspar usually occur in approximately equal proportions, but in a few microgranites potash feldspar is completely dominant over plagioclase. The grain-size is typically 1 mm. or so, hence the use of the prefix "micro", "foliated" being omitted for brevity. In this work, microgranite is equivalent to "granite" and "granite gneiss", as used by Clough (op.cit.) and Watson (op.cit.). In addition, both these writers use "pegmatite ribs" to describe the ribs of material that are present in the microgranites, of which many do not exceed 2 mm. in grain size and none 1 cm; these are here termed ribs of microgranite and granite.

The microgranites are particularly abundant immediately north-east and, to a lesser extent, immediately south-west of Badnabay. 800 metres south-west of Badnabay the proportion of microgranite decreases sharply and south-west of the Loch na Seilge sheet only an occasional microgranite sheet occurs (map 1). Similarly, to the north-east the proportion of microgranite decreases rapidly on crossing the belt of the Cnoc nan Cro gneisses. North-east of this group of gneisses, microgranites remain fairly abundant, although granite and pegmatite become dominant over microgranite.

The two thickest sheets, both more than 120 metres thick in places, have been named the Rudha Ruadh sill and Loch na Seilge sill respectively by the Geological Survey

(Peach and others, 1907), but it is proposed to use the term "sheet" in place of sill so as not to imply a necessarily magmatic origin. The Rudha Ruadh sheet stretches from near Loch Stack Lodge in the south-east through Traigh Bad na Baighe, to the promontory of Rudha Ruadh in the north-west. The Loch na Seilge sheet crops out on the north-east slopes of Ben Stack and continues north-westwards, passing the north-eastern edge of Loch na Seilge, to the south of Loch Bad ant-Seabhaig where it divides into several thinner sheets. These sheets gradually decrease in width north-westwards until, north-east of Loch na Claise Fearna, the Loch na Seilge sheet is represented by only a few thin sheets, with a maximum thickness of 1.5 metres.

Watson (1949) terms the microgranites of the Badnabay zone the "Rudha Ruadh granite gneisses" and bases her description of them on the Rudha Ruadh sheet, but many of the microgranites have a mineral composition that bears little resemblance to that of the Rudha Ruadh sheet.

In the field the microgranites can be divided into two groups which show differences in mineral composition, effects of weathering, field relationships with the gneisses and early igneous rocks, and, to some extent, location. The first group, termed the Badnabay microgranites, comprises the Rudha Ruadh sheet and most of the microgranites to the south-west, including the Loch na Seilge sheet (Map 1).

These microgranites contain hornblende or biotite or both; muscovite is never present. Generally they are less resistant to weathering than the adjacent gneisses and often form low-lying peaty ground; as a result they are poorly exposed. The second group, termed the Cnoc nan Cro microgranites, comprises a series of microgranite sheets that crop out to the north-east of the Rudha Ruadh sheet (Map 1). These microgranites contain muscovite as well as biotite, but hornblende has not been observed in any of them. They form massive, homogeneous sheets which crop out as hard, smooth, resistant knobs, standing out above the adjacent gneisses, with which they also form an extensive development of migmatites.

Numerous other rock-types are associated with each group and appear to be genetically related to them. Granites, pegmatites, migmatites, sheets of microsyenite and ribs of granodioritic rocks are associated with the Badnabay microgranites; each of these rock-types is preceded by "Badnabay" and collectively known as the Badnabay group. Similarly, the Cnoc nan Cro group comprises the Cnoc nan Cro microgranites and associated granites, pegmatites and migmatites.

The Laxford quartzofeldspathites, a small group of bulbous bodies composed essentially of quartz and feldspar, the microgranite/trondhjemite bodies and the

NE-SW pegmatites, a series of late, joint-filling pegmatites, are not included in either the Badnabay or Cnoc nan Cro groups and are described separately.

Potassium metasomatism commonly appears to be associated with the formation of the granitic rocks. In addition there are various features, such as the occurrence of microgranite within veins of trondhjemite, the origins of which may be ascribed to potassium metasomatism. Such phenomena are described in a subsequent section (pp.162-3).

THE CNOC NAN CRO GROUP

The Microgranites

The muscovite-biotite-micrograanites are extensively developed on the slopes of Cnoc nan Cro, whence they can be traced south-eastwards and north-westwards for a distance of at least 1500 metres to the edges of the area, the sheets generally trending NW-SE. As already stated (p.120) they are geographically separated from the Badnabay micrograanites for, with very few exceptions they crop out to the north-east of the Rudha Ruadh sheet. Two of these are found to the south-west of the Loch na Seilge sheet. Both are less than 3 metres thick, cut across the foliation and striping of the gneisses, and, since they either disappear under peat or end abruptly against the gneisses, are not obviously related to adjacent micrograanites.

Usually the thicker sheets are well defined and easily mapped over considerable distances. Contacts with the adjacent gneisses are often seen and are usually sharp, as seen in the crags near Laxford Bridge. Chilled margins are never seen, the grain size of each sheet remaining more or less constant from the upper to the lower margin. No evidence of potassium metasomatism has been observed at any of the contacts. Between the mappable sheets there is a considerable amount of similar micrograanite which occurs as thin sheets, veins and lenticular bodies, interlayered with the gneisses and forming migmatites in the original sense (Sederholm, 1923 and 1926) - see p.132.

The hard smooth resistant knolls formed by the micrograniтes tend to emphasise the homogeneous character of each sheet, although this homogeneity is interrupted by veins, ribs and patches of slightly coarser microgranite and granite and occasional relict fragments of gneiss.

While many of the microgranite sheets are broadly concordant with the foliation of the gneisses, discordant relations are frequently observed, being most obvious when a sheet furcates, in which case at least one of the branches is discordant (Plate 34). Furcation and discordance are features that indicate the intrusive nature and mobility of the Cnoc nan Cro microgranites.

A poorly developed foliation, which is produced by the alignment of biotite flakes and quartz lenses, is present in the microgranites, but is often difficult to detect. It is usually parallel to the margins of each sheet and therefore to the foliation in the gneisses; it strikes NW-SE and dips to the south-west at 40° to 50°. It is often emphasised by the presence of thin ribs of leucocratic material. The foliation flows round inclusions of gneiss. Flexures of the microgranite sheets and their foliation can be seen at several localities, such as the headland at Weaver's Bay. Typical Laxfordian folding has not been observed in the microgranites, but near Weaver's Bay several examples may be seen of microgranite penetrating along a limb and round the nose of an isoclinal fold in the gneisses. Usually the margins of each sheet are straight and parallel to one another, but occasionally one side of the sheet bulges into the gneisses with the foliation of the microgranite paralleling the bulge. Microgranite sheets may be flexured through 90°, in which case the foliation parallels the flexure and becomes vertical in attitude.

In hand-specimen the micrograntes vary in colour from grey to pale pink. The grain-size is about 1 mm; it is rarely greater, but lenses of quartz and potash feldspar occasionally give an impression of greater coarseness. The lenses rarely exceed 3 mm. Quartz, plagioclase and potash feldspar occur in approximately equal amounts, making up 90% by volume of the microgranite. In most of the micrograntes these three constituents are evenly distributed (Plate 35). Many grains and patches of potash feldspar are linked to one another by narrow necks of that mineral. In a few specimens lenses and pods rich in potash feldspar are seen. Quartz is often lenticular. The remaining essential mineral constituents are biotite and muscovite. The accessory minerals include epidote and iron ore, but the others cannot be distinguished in hand specimen.

In several instances the microgranites have been observed to cut across from hornblende-biotite gneiss to amphibolite with no detectable change in the mineral constituents. Muscovite is rarely present in the gneisses, while it is a common and essential constituent of the microgranites.

The "late foliated granites" of the Laxford zone (Watson, 1951, p.288) have the same mineral composition and texture as the Cnoc nan Cro microgranites and are considered also to fall in this group. They strike consistently NW-SE and dip to the south-west at about 45°, as do a great many of the other microgranites. They cut several of the pegmatites north of Laxford Bay, but other examples are seen in which these microgranites are cut by pegmatites.

The Cnoc nan Cro microgranites have suffered cataclastic deformation in a few cases (cf. Clough, 1907, p.152) as seen at the roadside 50 metres east of Laxford Bridge and 300 metres south-south-west of Badcall Quay. All gradations occur from microgranite with widely separated wisps of granulated material, through microgranite with closely spaced thin wisps of granulated material to almost completely mylonised microgranite. One partly mylonised microgranite which crops out 30 metres west of Laxford Bridge can be traced north-westwards for a distance of 500 metres. This granulation, which is occasionally seen in the granites and pegmatites, is confined to the granitic sheets and is not present in adjacent or other gneisses.

Small quartz veins occasionally cut the microgranites for example 100 metres east of Laxford Bridge, but are extremely sparsely developed.

Inclusions in the microgranites vary from small lenses (Plate 36) to remnants a few centimetres thick and over 50 metres in length. They are consistently elongated parallel to the foliation of the enclosing microgranites and therefore, in most cases, to that of the adjacent gneisses. There is no evidence of forceful intrusion in the form of either fragmented or deformed inclusions.

The granites

The Cnoc nan Cro sheets, while composed predominantly of homogeneous microgranite, usually contain a certain amount of coarser grained material, occurring as streaks, lenses, ribs, veins and patches.

1. Ribs of Granite

In a microgranite sheet, granites form concordant and discordant ribs (Plate 37) some of which appear to grade into microgranite (Plate 38). Some of the ribs are only slightly coarser-grained than the host microgranite, vary from about 2 mm. in thickness upwards and are parallel to the foliation of the microgranites (Plate 39). Together with the following type, these ribs of granite make up an average about 10% of a sheet.

2. Folded and irregular ribs and veins of granite

A number of ribs and veins are apparently folded (Plate 40) while others are offshoots from a large patch of granite. Age relations between concordant ribs and apparently folded veins are difficult to establish: in some cases the former cut the latter and in other cases the reverse is seen (Plate 41).

3. Nodes of granite

Granite ribs and veins occasionally bulge out at intervals along their length, forming a series of nodes (Plate 42) (cf. Watson, op.cit.).

4. Layers of granite

As its volume in a sheet increases, granite forms, first, patches and then concordant layers that enclose lenses of microgranite. Thus, in the field all gradations can be seen from microgranite with occasional lenses and patches of granite, through bodies in which both occur in approximately equal amounts to granite with occasional lenses and patches of microgranite. There is usually a sharp contact between both rock-types.

5. <u>Sheets and veins of granite</u>

Sheets and veins of granite are rather sparsely developed. However, many have been recorded (Plate 43).

The granites are composed of quartz, potash feldspar and plagioclase which most commonly occur in approximately equal amounts. These minerals are usually evenly distributed throughout a specimen, but in a few cases potash feldspar exhibits a streaky distribution (Plate 44). Biotite and muscovite can usually be distinguished. Accessories distinguished in the field include opaque ore, uraninite and allanite from which cracks radiate (Plate 45).

The Pegmatites

Pegmatites are very abundant north of Laxford Bay (Clough, op.cit., and Watson, op.cit.) and in this study are considered to form part of the injection complex for they are intimately associated with the granites and microgranites. According to Mitchon (1960) all the Laxfordian pegmatites are concordantly intruded into the gneisses and have sharp, slightly undulatory margins.

Pegmatites decrease in number in a south-westerly direction until south-west of a NW-SE line drawn through Cnoc nan Cro they are sparsely distributed. This decrease is accompanied by an increase in the number of sheets of microgranite and granite.

Pegmatites form concordant and discordant sheets or large irregular patches. They cut all rock-types including sheets of microgranite, but are themselves cut by thin microgranite sheets (cf. late foliated granites of Watson (op.cit.)). In addition, these rock-types intimately penetrate one another (Plate 46) and pegmatite occasionally grades into granite. Pegmatites may contain relics of gneiss, particularly when they form concordant sheets, and from some of the irregular patches the relics either can be traced into the adjacent gneisses or are more numerous at the margins.

The pegmatites consist essentially of quartz and dull-red to pink microcline that is sometimes perthitic, with lesser amounts of plagioclase and small amounts of muscovite and biotite. The predominance of microcline is confirmed by chemical analyses of the pegmatites and thus contrasts with the evidence of Watson (1951, p.288) that microcline and oligoclase occur in equal proportions. Quartz forms irregularly shaped interstitial patches while biotite occurs either as books up to 4 cm. in size or as dispersed flakes. Accessory minerals include epidote, allanite, uraninite and opaque ores. Allanite, which sometimes has a soft green or brown weathered outer layer, is a very common accessory and often produces radial cracks in the adjacent minerals. Uraninite, occurring as knobs up to 3 cm. in size, is locally abundant.

Contacts with amphibolites and gneisses rarely show evidence of a reaction between the pegmatite and host rocks. However, 200 metres ENE of Badcall Quay, books of biotite, up to 3 cm. in size, can be seen at the margin of an amphibolite in contact with pegmatite. Otherwise, there is little evidence of metasomatism even when pegmatite intimately penetrates the gneisses.

The pegmatites are not foliated perhaps because of the coarse grain-size. None of the larger pegmatites is folded but a few small bodies exhibit contortions similar to those of the gneisses. In a few cases the pegmatites form noded bodies and in one occurrence near Duchess's Pool the outer few centimetres is finer grained than the core.

The migmatites

Migmatites are extensively developed north-east of the Rudha Ruadh sheet where they form a prominent part of the rocks that lie between the sheets of microgranite. Essentially, the migmatites are composed of either Weaver's Bay or Laxford Bay gneisses intimately penetrated and veined by granitic material of the Cnoc nan Cro group. South-west of Laxford Bay the granitic part of the migmatites occurs as discrete veins and very thin sheets whereas to the north-east it usually occurs as streaks and pods that are more intimately associated with the gneisses (Plate 17). In the latter area the streaks and pods decrease in size until they cannot be recognised as an individual phase (Plate 16), except by virtue of the pink colour in the potash feldspar. In this case they would not be termed migmatites by Crowder (1959) who, in attempting to systematise the terminology, considers that a migmatite should be recognisable as composed of at least two rocks, one of which is granitoid, at a distance of a few paces from the exposure. While there is probably a genetic relationship between the thin granitic streaks and pods of the gneisses and the thicker granitic parts of the migmatites, the definition of Crowder, being similar to the original definition (Sederholm, 1926, pp.133-139) is adhered to in this study.

Plate 34

Bifurcation in a Cnoc nan Cro micrогranite sheet; Laxford Bridge.

Plate 35

Homogeneous Cnoc nan Cro microgranite. Quartz(pale grey), plagioclase(white) and microcline(dark grey) occur in approximately equal proportions; Cnoc nan Cro.

Plate 34

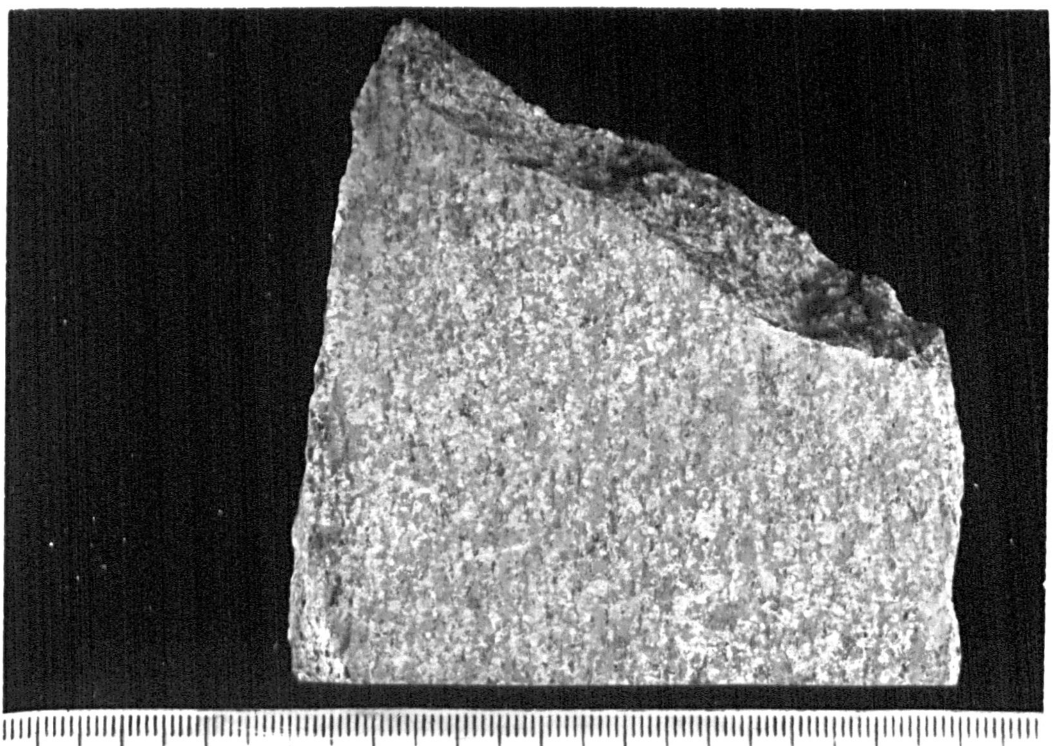


Plate 35

Plate 36

Small inclusions of gneiss aligned parallel to the foliation (poorly developed in this case) of the host microgranite; Cnoc nan Cro.

Plate 37

Thin concordant ribs of granitic material in microgranite; Weaver's Bay.

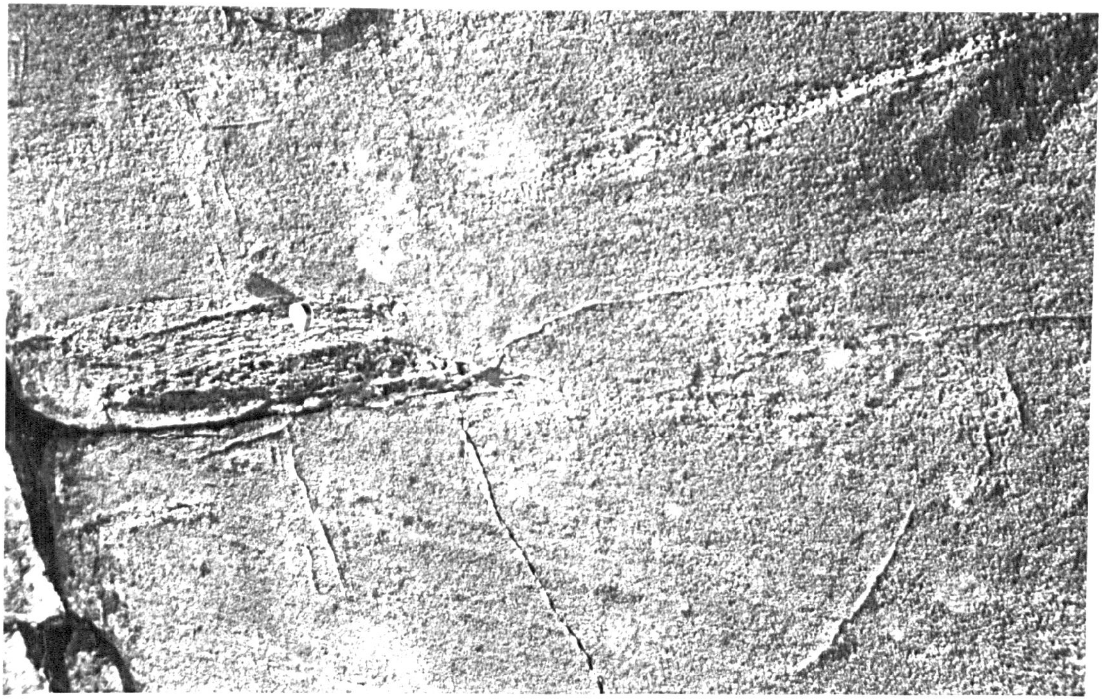


Plate 36

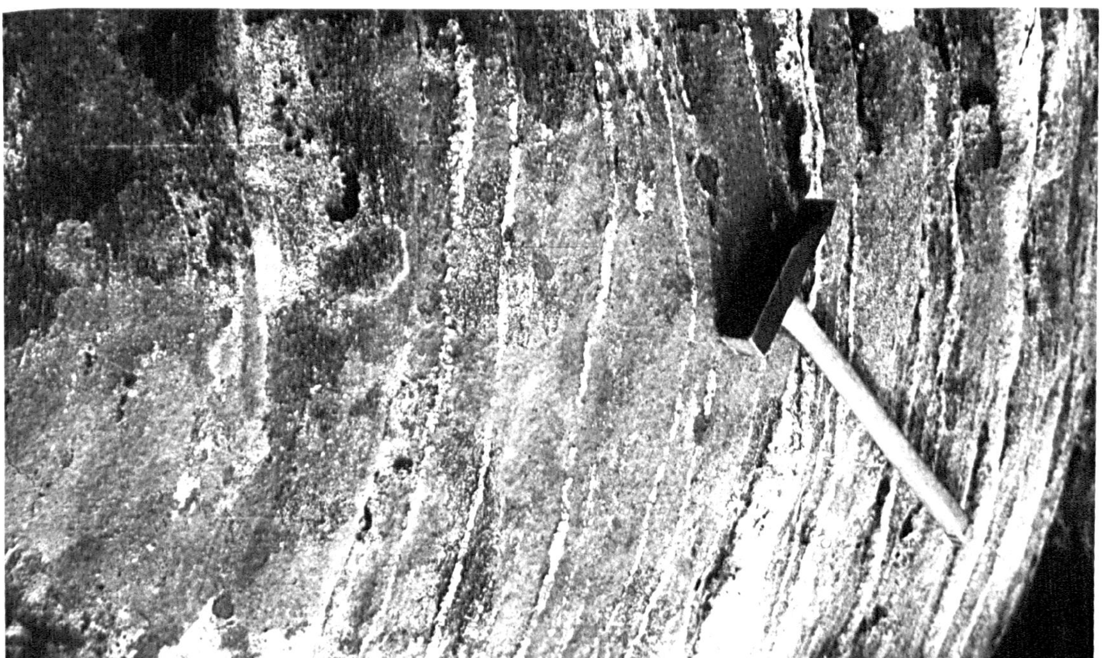


Plate 37

PLATE 38

A concordant rib of granite that grades into microgranite; Cnoc nan Cro.

PLATE 39

Ribs of granite that are concordant and vary in thickness; Laxford Bay (x1)

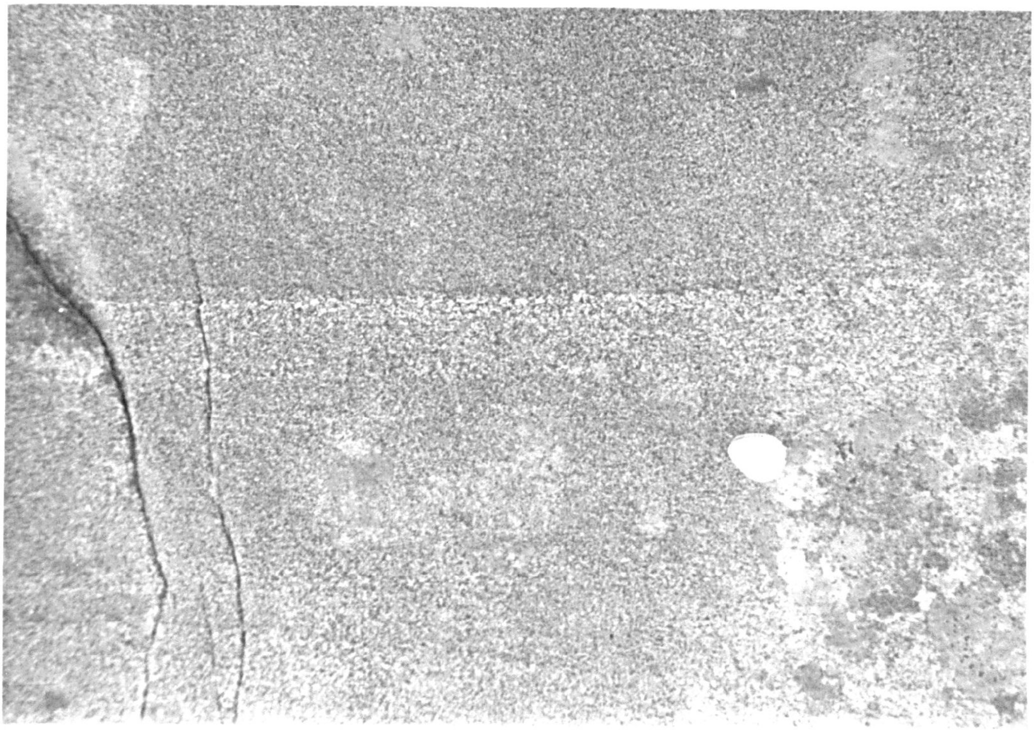


Plate 38

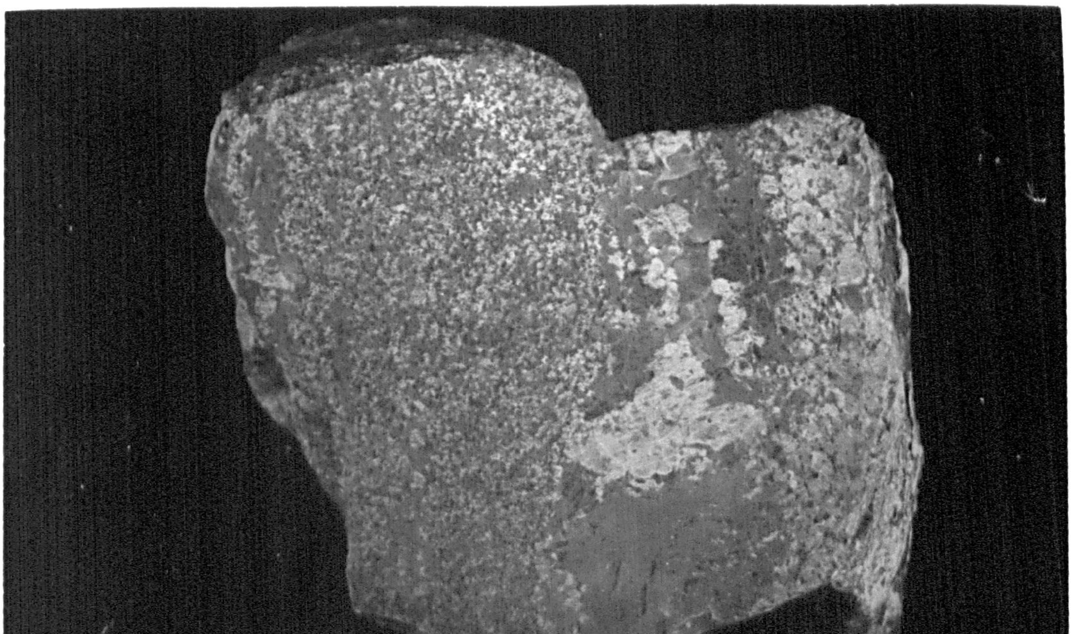


Plate 39

Plate 40

Veins of granite that appear to be folded; Cnoc nan Cro.

Plate 41

Veins projecting from a large patch of granite; they are cut by a folded vein (see overlay); Cnoc nan Cro.

Plate 40

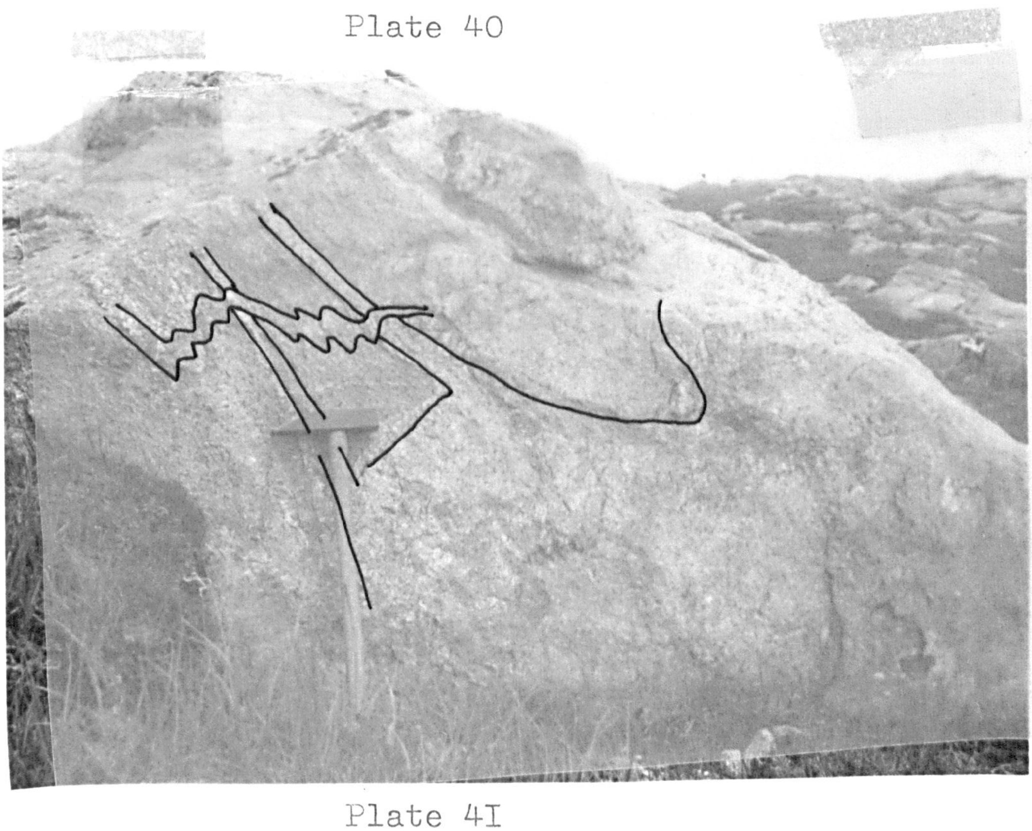


Plate 4I

PLATE 42

Node of granite in microgranite; Laxford Bay.

PLATE 43

Discordant sheet of granite: Laxford Bay.

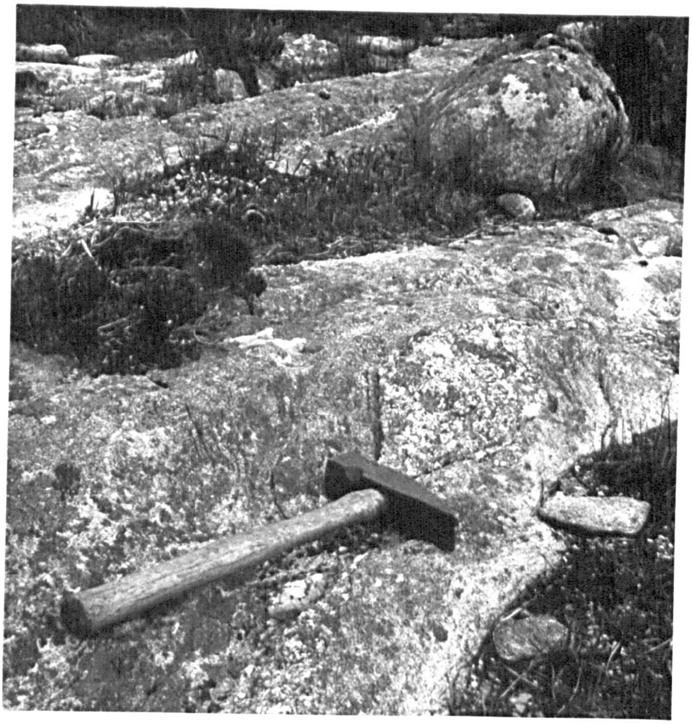


Plate 42

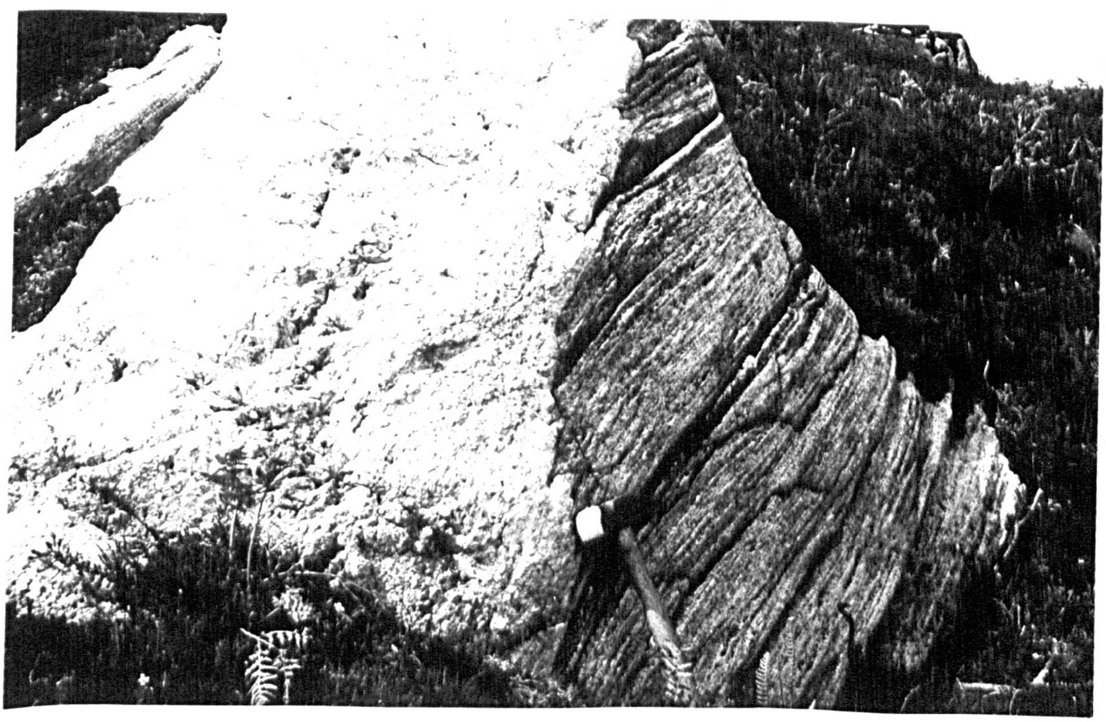


Plate 43

PLATE 44

Streak of potash feldspar (coloured grey at lower edge) in thin vein of granite; Weaver's Bay. (x1)

PLATE 45

Cracks radiating from allanite; 150 metres north of Badnabay. (x2.5)

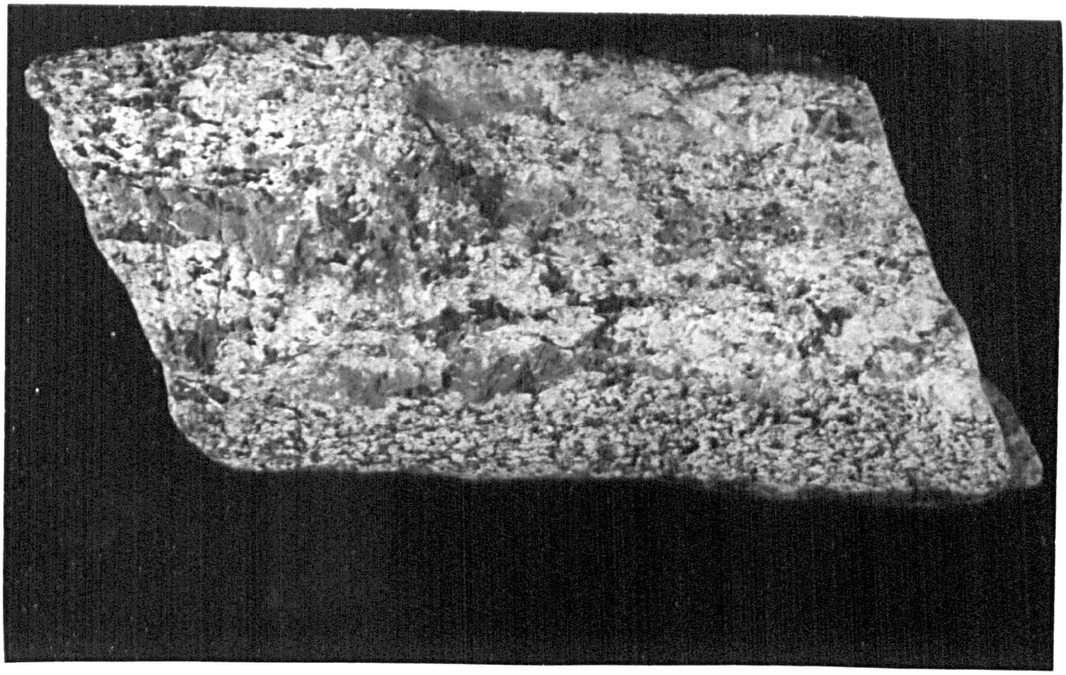


Plate 44

Plate 45

PLATE 46

Close association of pegmatite and micro-granite; roadside, north of Laxford Bay. (x1)

PLATE 47

Granulated quartz and plagioclase (crossed nicols, X75). Cnoc nan Cro microgranite; 100 metres SE of Cnoc nan Cro.

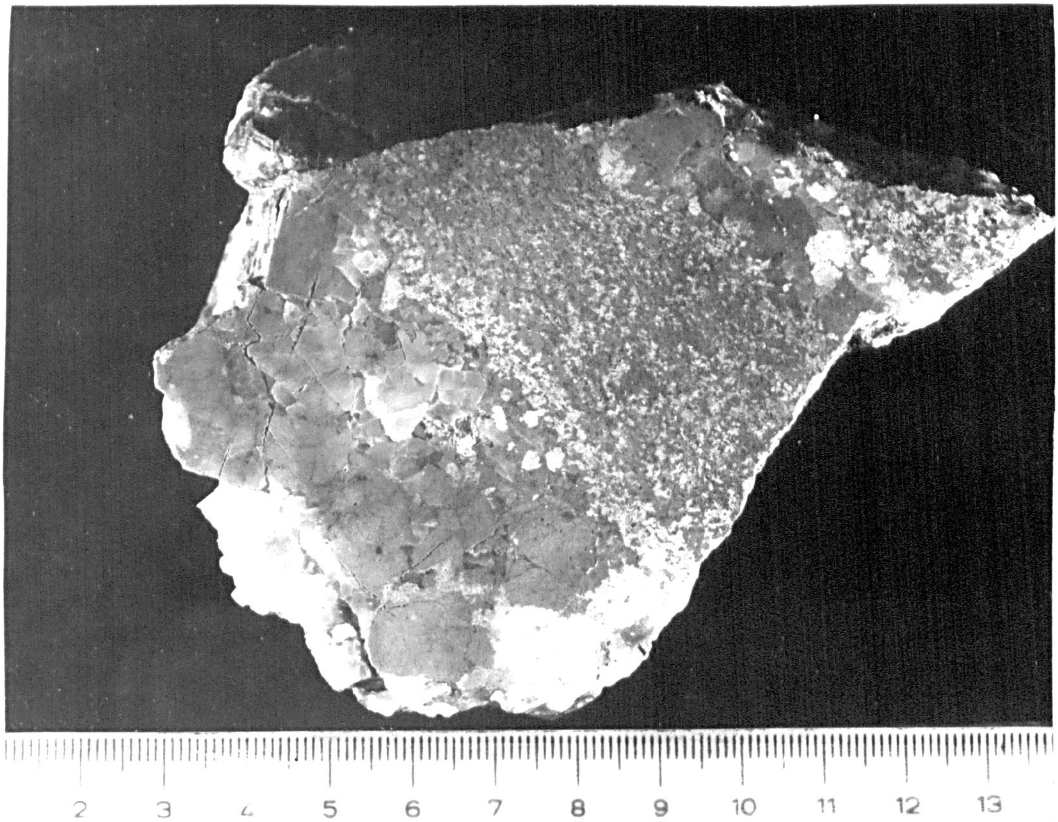


Plate 46

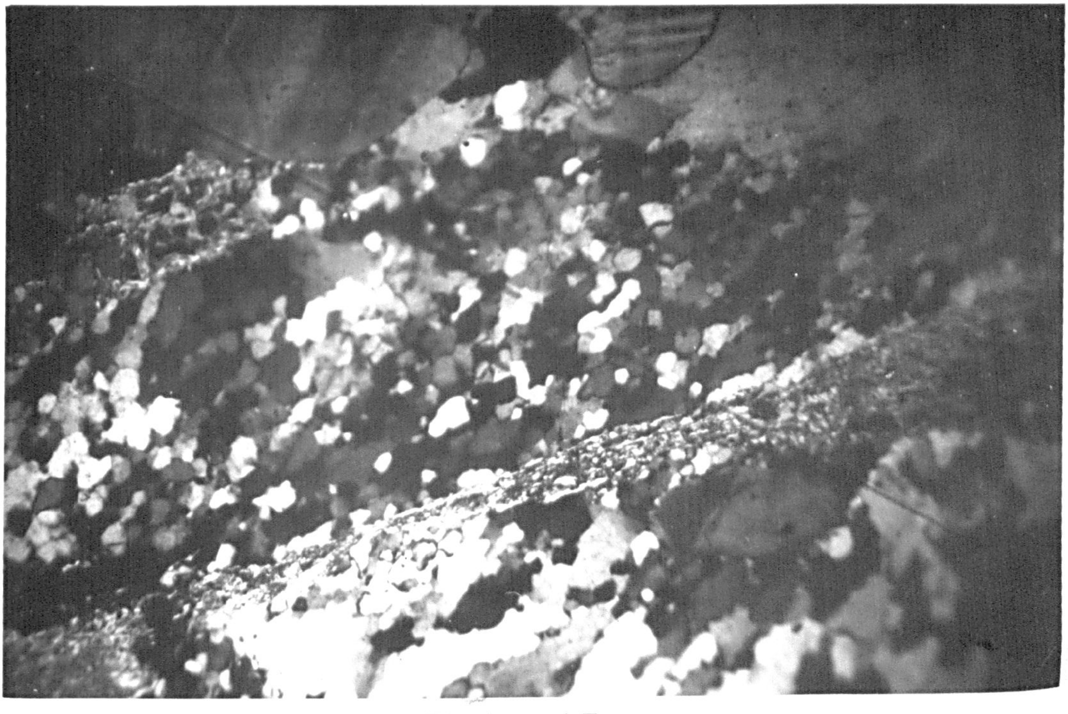


Plate 47

Microscopic petrography of Cnoc nan Cro group

The description of the mineral constituents and textural features of the Cnoc nan Cro group is based on data obtained from the microgranites. Any variations that occur in the granites and pegmatites are described in the relevant paragraph. The textures in all rock-types are metamorphic rather than igneous, but usually a granoblastic texture is seen only in the microgranites and some of the granites. A series of modal analyses (Table 18) shows that there are only slight mineralogical variations within the microgranites and between them and the granites. The minerals may be partly granulated (Plate 47).

Quartz occurs in several distinct habits: (1) small rounded grains in both kinds of feldspar (2) small, sub-rounded grains that occur either separately or in clusters (3) fairly large grains or patches consisting of several grains (4) myrmekitic intergrowths with plagioclase (Plate 48) (5) symplectitic intergrowths with epidote (Plate 49) and (6) vermicular intergrowths with muscovite (Plate 50). Undulose extinction can be observed in most of the grains, but not in the quartz that forms intergrowths. Strongly sutured margins are an early stage in post-crystallization deformation that gave rise to mylonites. Many of the larger grains have trains of tiny unidentifiable inclusions and occasionally contain inclusions of biotite, plagioclase and microcline, towards which these grains are often lobate and bulbous (Plate 51).

Plagioclase has the composition of oligoclase, varying from An_{20} to An_{25}. Less than 50% of the grains are twinned, twinning occurring mainly on the albite law or occasionally on the pericline law. Twin lamellae often taper consistently in one direction. Plagioclase is variably altered to an unidentifiable dust, sericite, or occasionally saussurite. Alteration is sometimes confined to, or is more intense along alternate lamellae. When plagioclase is in contact with microcline a clear unaltered rim often forms on it and a myrmekitic intergrowth of oligoclase and quartz is often associated with this phenomenon, the myrmekite forming within the oligoclase but not the clear rims. As these features occur only when microcline is in contact with oligoclase it is considered that the presence of microcline is essential for their formation (fig. 18a). With a few exceptions the clear rim is more sodic than the main part of the plagioclase, as seen from a very sharp Becke line or, in some cases, from the fact that the rim is unaffected by either the sodium cobaltinitrite or potassium rhodizonate stain. The clear rim may be twinned or untwinned, the latter being rather more common. In the twinned varieties the twin lamellae are either optically continuous with the lamellae of the core going into extinction at the same time (Plate 51) or continuous from core to rim with the extinction reversing on crossing from core to rim (fig. 18b). As noted by Shelley (1964) any grain that has an oligoclase core and albite rim will show a reversal of extinction of twin lamellae. If reversal of extinction does not occur on passing from core to rim, for example in plate 51, the rim must be only slightly more albitic in composition than the core. In the example shown there is no detectable difference in the angle of extinction between the twin lamellae of the core and rim. The clear rims are rarely of constant thickness and in a few cases microcline forms an indented margin with the rim occasionally penetrating it to come in contact with the core of plagioclase (Plate 51).

Plagioclase encloses small round quartz grains and occasionally grains of microcline. It also contains orientated inclusions of microcline (Plate 52) a feature rare in the microgranites, but common in the coarser grained rocks. In some cases the twin lamellae of plagioclase continue uninterrupted through the small inclusions of microcline (Plate 53). It is significant that these inclusions occur in oligoclase, often highly altered and not in fresh, unaltered albite.

Plagioclase is often intimately associated with muscovite in a manner not seen between the latter mineral and microcline (fig. 18c). It contains white mica that varies in size from very small flakes (sericite) to much larger flakes, which penetrate into the feldspar grain.

In many of the granites and pegmatites some of the plagioclase is albite in composition. The relative amounts of albite and oligoclase are difficult to determine.

Microcline is assumed to be the only variety of potash feldspar present in the granitic rocks. However, several writers have described the occurrence of both orthoclase and microcline in the one granite (Schermerhorn, 1956; Marmo, 1962a) and both Marmo and Schermerhorn describe the gradual transformation of orthoclase into microcline. According to Schermerhorn (1956, p.327) "the first indication of microclinization is the development of a shadowy, undulatory extinction in the potash feldspar crystals".

Since Watson (1949) mentions the presence of orthoclase in the Rudha Ruadh sheet a similar transformation in the granitic rocks of the Laxford area cannot be excluded. However, in several grains of both twinned and untwinned potash feldspar the optic angle is never less than 77° (Table 19). Grains showing either no twinning or undulatory twinning have a range of optic angles which is slightly lower than that for grains showing well developed grid-twinning.

TABLE 19

Grain type	2Vx in degrees
Untwinned portion of grain	79 ± 2
Twinned portion of same grain	80 ± 2
Undulatory twinning	77 - 83 ± 2
Untwinned grains	77 - 84 ± 2
Well developed grid - twinning	80 - 85 ± 2

Microcline commonly exhibits well-developed grid-twinning, but more than 50% of the grains are either vaguely twinned or untwinned. It is always clear, fresh and unaltered and may occur as small interstitial grains, less than 0.5 mm in size, as large individual grains, usually less than 1 mm in size, or as patches consisting of several grains that are linked to adjacent grains or patches by thin veins of microcline. Many of the grains are perthitic, flame perthite being the only variety present in the microgranites although string, film or parch perthite may be present in the granites and pegmatites. In some cases only an occasional flame or stringer of albite is present while in other cases 60% of the perthite grain is composed of flames of albite. The more significant features of flame perthite are:

1. The flames are irregularly distributed both between grains and within single grains.

2. Many of the flames broaden towards the edge of the grains, sometimes coalescing with other flames (Plate 54) with the coalescing albite forming a partial rim to the grain.

In a few thin-sections, some spindles of the grid-twinning are flexured, some grains exhibit undulose extinction and the grid-twinning fractured, all being due to post-crystallisation deformation.

Microcline often forms smooth, curved contacts with plagioclase, but in some cases it completely encloses that mineral, the boundary being irregular and indented (fig. 18d) while in other cases it irregularly penetrates the same mineral. It sometimes contains many small, highly altered inclusions that appear to be in optical continuity (Plate 55) albitic stringers extending from the inclusions.

Biotite, usually dark brown in colour, occurs as disseminated flakes commonly in an approximately parallel alignment. The felsic minerals mould themselves on it. Muscovite often forms a narrow fringe along the sides of biotite flakes and occurs as numerous small flakes at the ends. Biotite may be altered to a green pleochroic variety of chlorite.

Epidote occurs as small irregular grains and often forms a symplectitic intergrowth with quartz (Plate 48).

Muscovite occurs as small flakes of white mica or as large poikiloblastic plates, usually associated with plagioclase. It occasionally forms a vermicular intergrowth with quartz (Plate 49). It rarely penetrates the other minerals.

The accessory minerals are dominantly allanite and apatite. Allanite which may be zoned, is usually present as small grains which may be partly or completely fringed by epidote. Apatite usually occurs as small sub-rounded grains, but occasionally as prismatic grains. Small granules of sphene are occasionally observed, together with interstitial calcite. Ore minerals include ilmenite, partly altered to leucoxene, magnetite, iron pyrites and haematite. Pyrites with a core of magnetite and rimmed by haematite is a rare accessory (Plate 56). Zircon and monazite may be present.

Fig. 18

P= Plagioclase

Q= Quartz

M= Microcline

A= Albite

Musc= Muscovite

(a) Albitic rim to plagioclase in contact with microcline , Cnoc nan Cro microgranite.

(b) Albitic rim showing reversal of twinning , Cnoc nan Cro microgranite.

(c) Extensive muscovitization of plagioclase, Cnoc nan Cro microgranite.

(d) Microcline encloses and penetrates plagioclase, Cnoc nan Cro microgranite.

(e) Network habit of microcline , Badnabay microgranite.

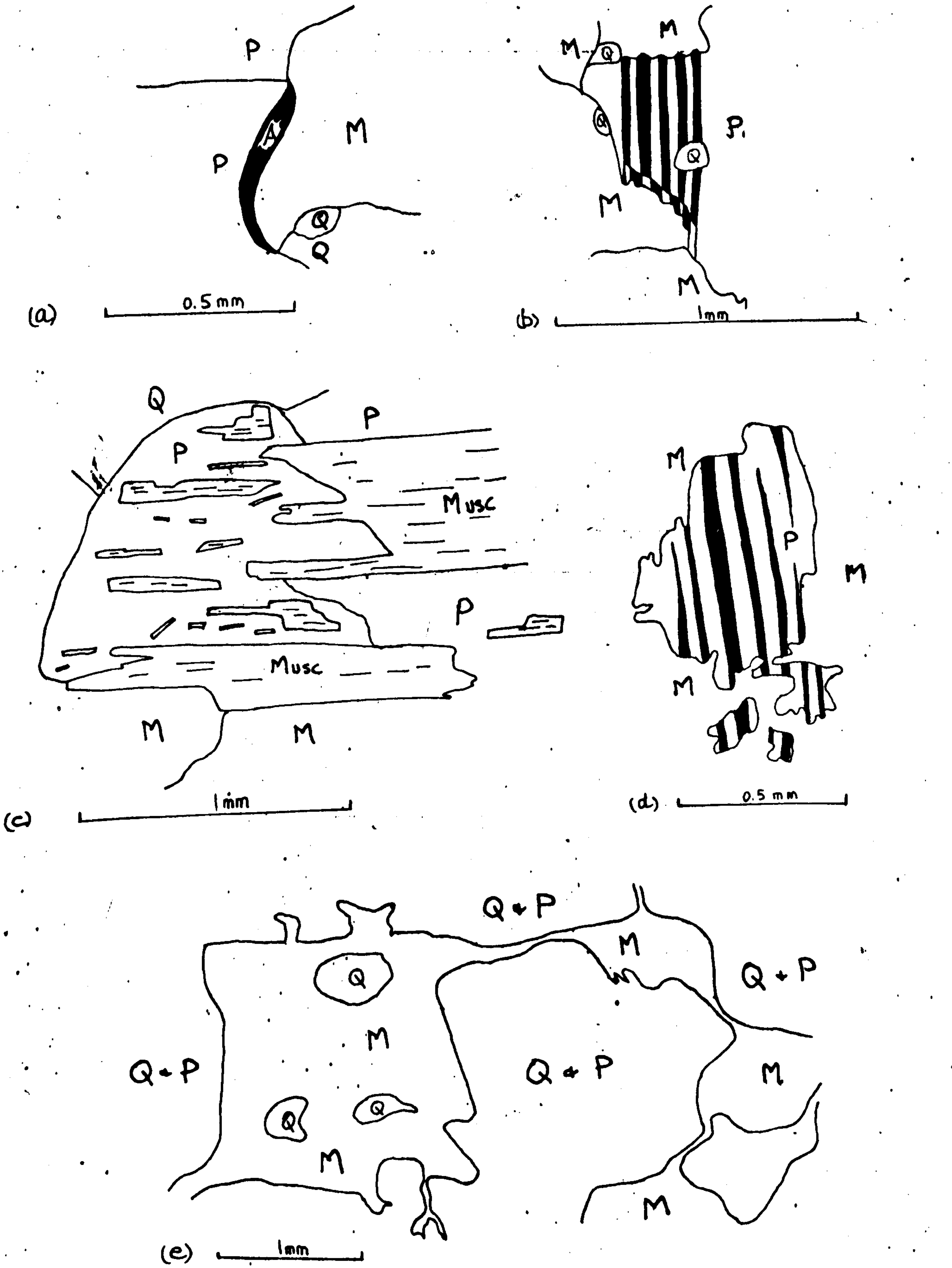


Fig. 18 Mineral relations in the granitic rocks.

PLATE 48

Myrmekitic intergrowth of quartz and plagioclase (crossed nicols, X50). Cnoc nan Cro granite; Laxford Bay.

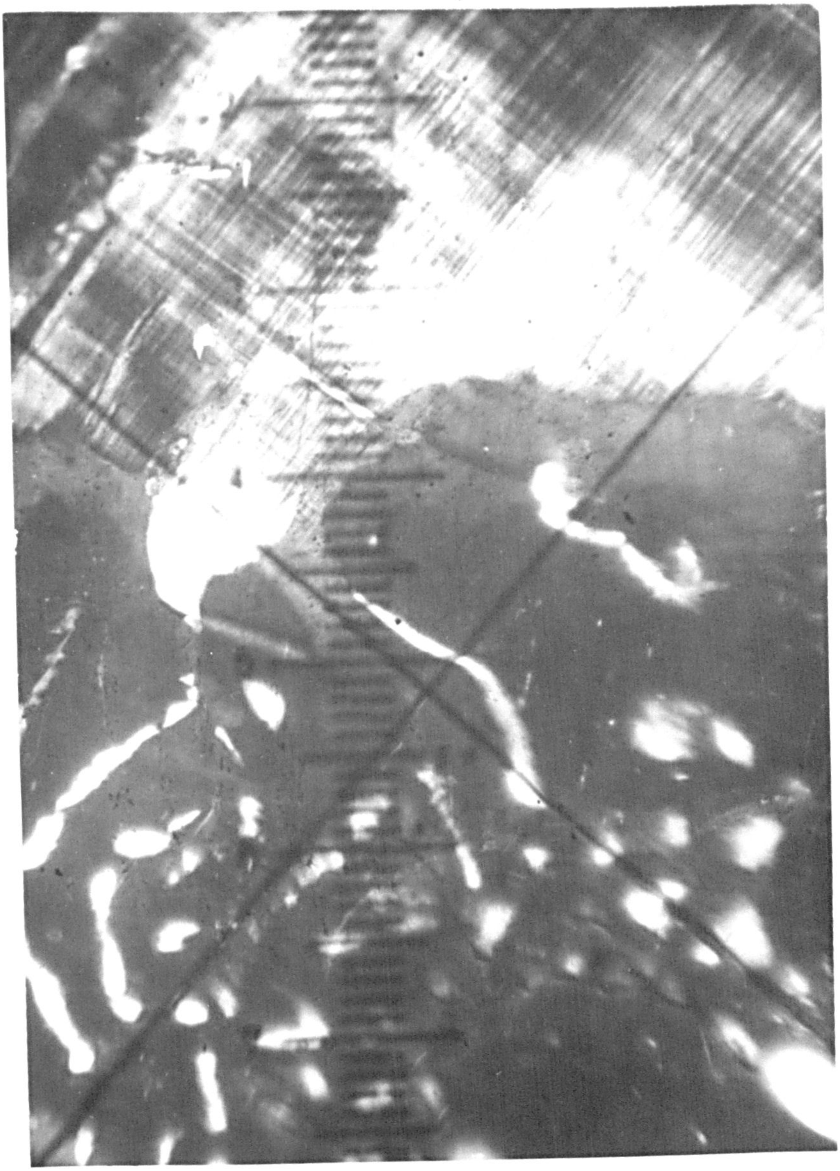


Plate 48

Plate 49

Symplectitic intergrowth of quartz and epidote (crossed nicols, X75). Cnoc nan Cro micro-granite; Cnoc nan Cro.

Plate 50

Vermicular intergrowth of quartz and muscovite (crossed nicols, X120). Cnoc nan Cro microgranite; Cnoc nan Cro.

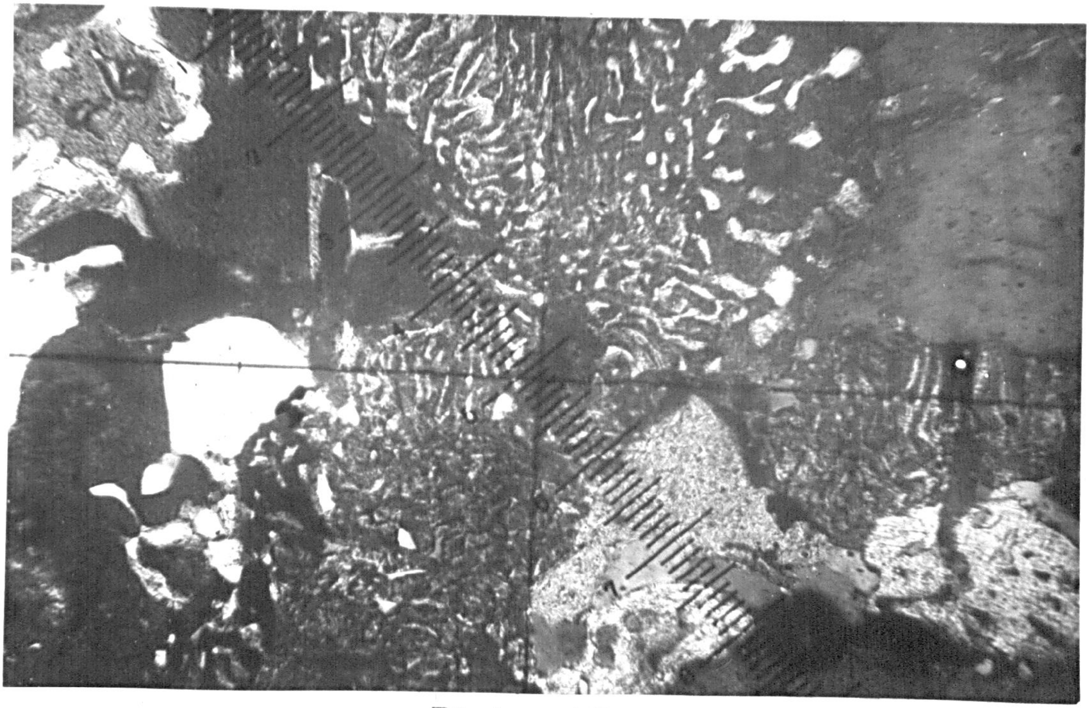


Plate 49

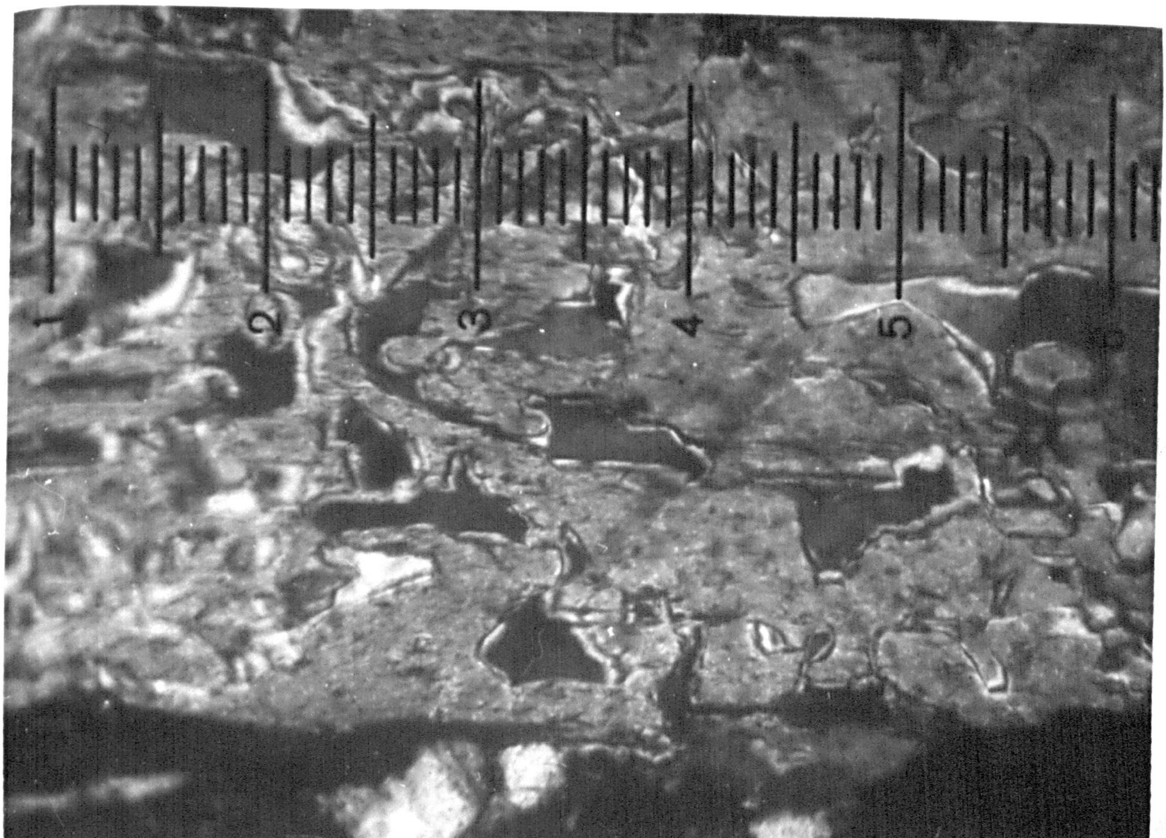


Plate 50

PLATE 51

Microcline penetrates a clear sodic rim to come in contact with normal plagioclase. Albite twinning is not reversed. Note the serrated edges to the quartz grains within plagioclase. At the bottom of the photomicrograph there is a lobate and bulbous grain of quartz (Crossed nicols, X75). Cnoc nan Cro microgranite, near Laxford Bridge.

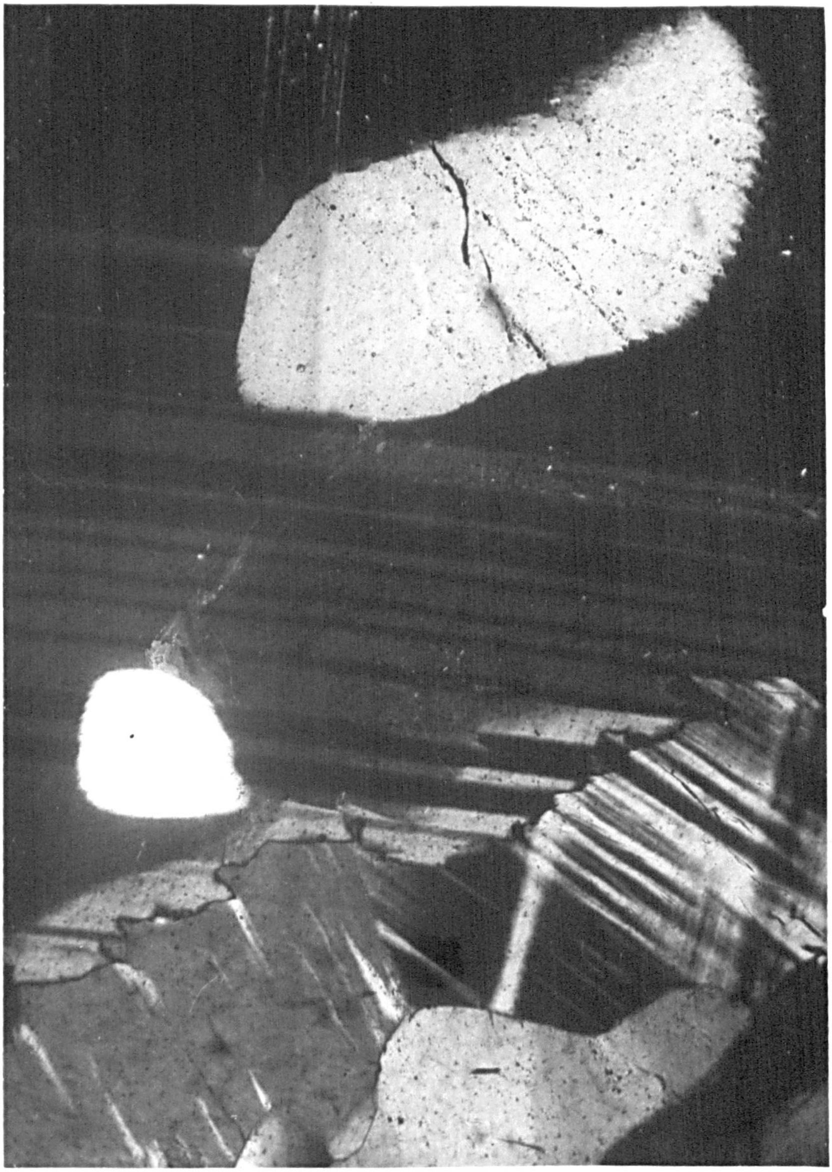


Plate 5I

PLATE 52

Antiperthite, in which the "inclusions" of microcline are in optical continuity (crossed nicols, X75). Cnoc nan Cro granite; Laxford Bay.

Plate 52

PLATE 53

Antiperthite, in which the albite twin lamellae of plagioclase continue through microcline (crossed nicols, X75) Cnoc nan Cro microgranite; Weaver's Bay.

PLATE 54

Microcline perthite, in which the flames of albite(white) broaden towards the edge of the grain and also coalesce (crossed nicols, X75) Cnoc nan Cro microgranite; Traighe Bad na Baighe.

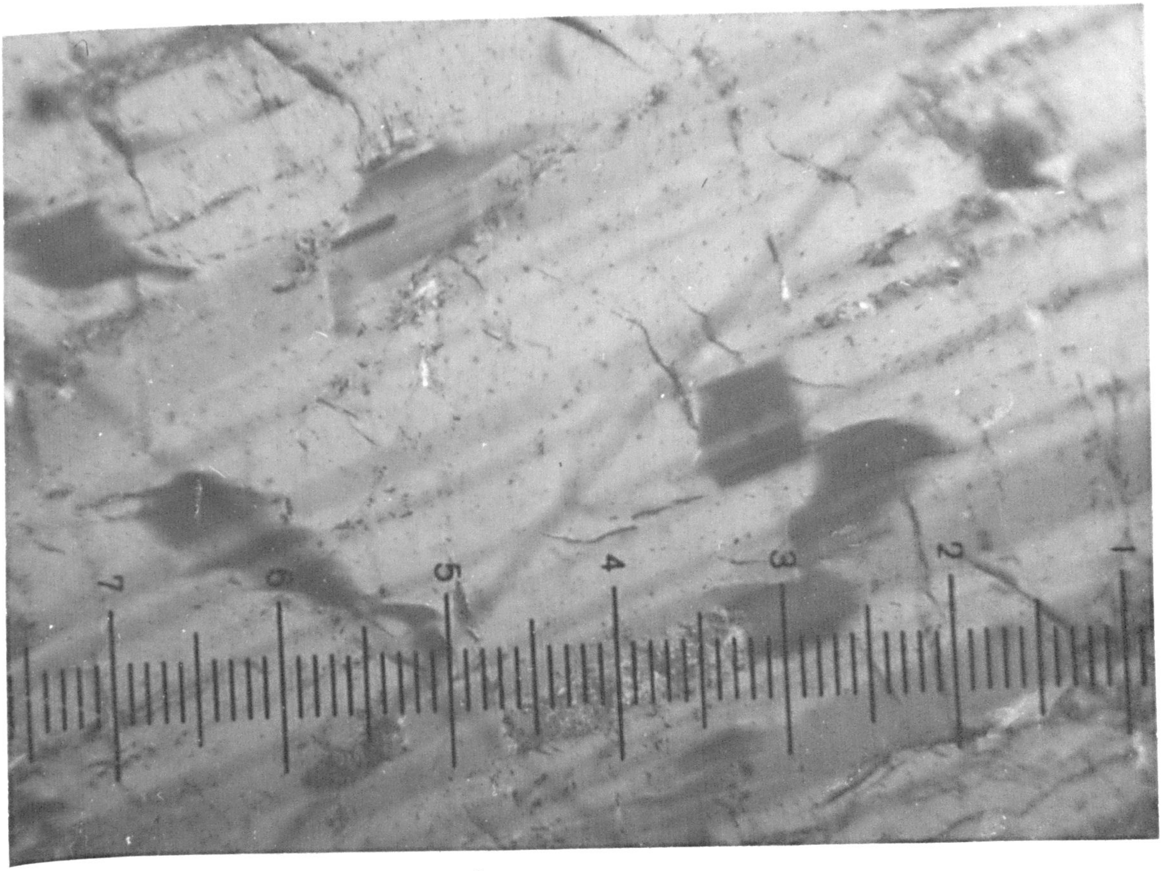


Plate 53

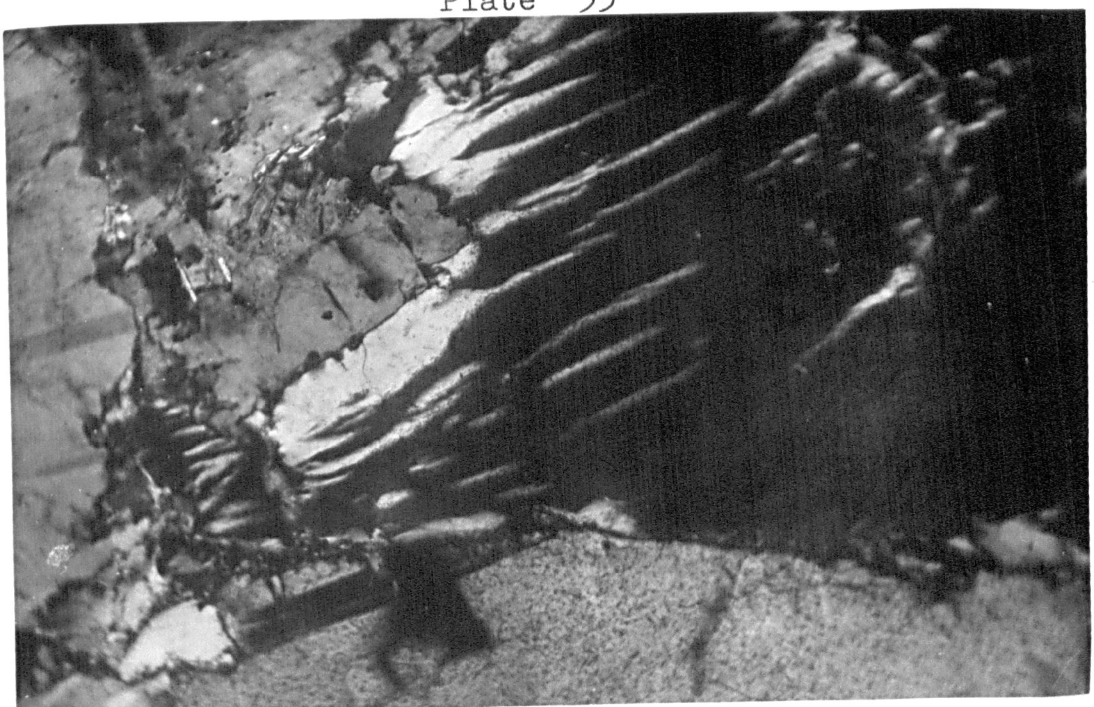


Plate 54

PLATE 55

Small rounded inclusions of altered plagioclase in microcline. Occasionally albitic stringers extend from the inclusion (crossed nicols, X120). Cnoc nan Cro microgranite; Cnoc nan Cro.

PLATE 56

Iron pyrites (greyish-white), rimmed by haematite (dull black) which is in turn rimmed by magnetite (speckled black) (reflected light, X 50). Cnoc nan Cro microgranite; Traighe Bad na Baighe.

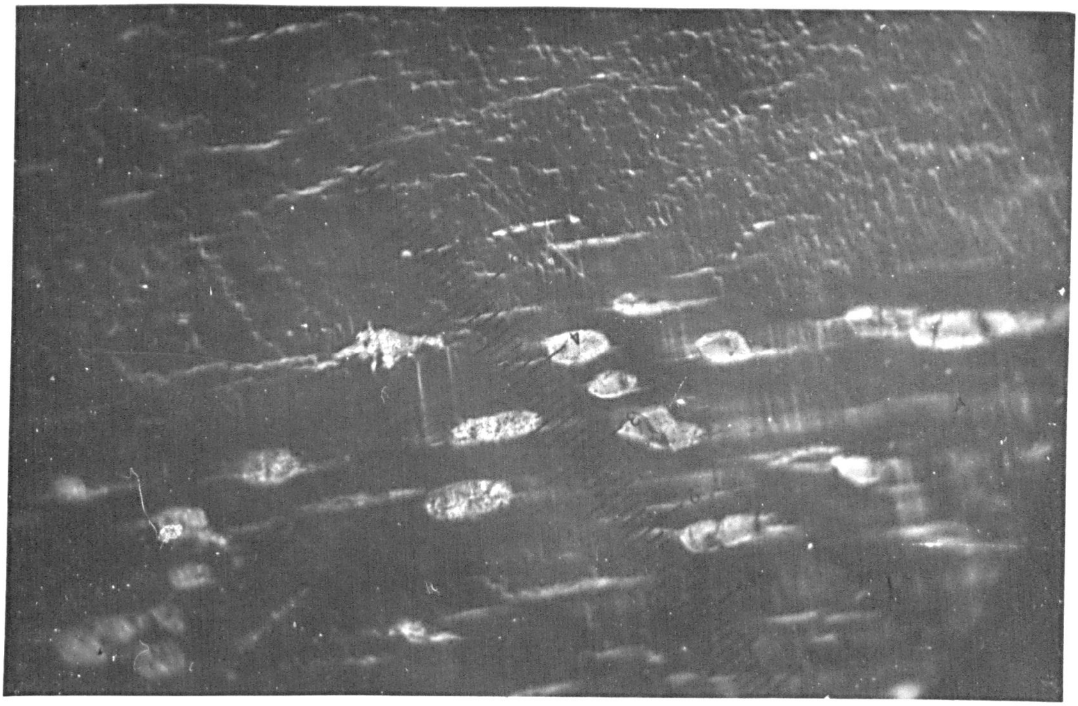


Plate 55

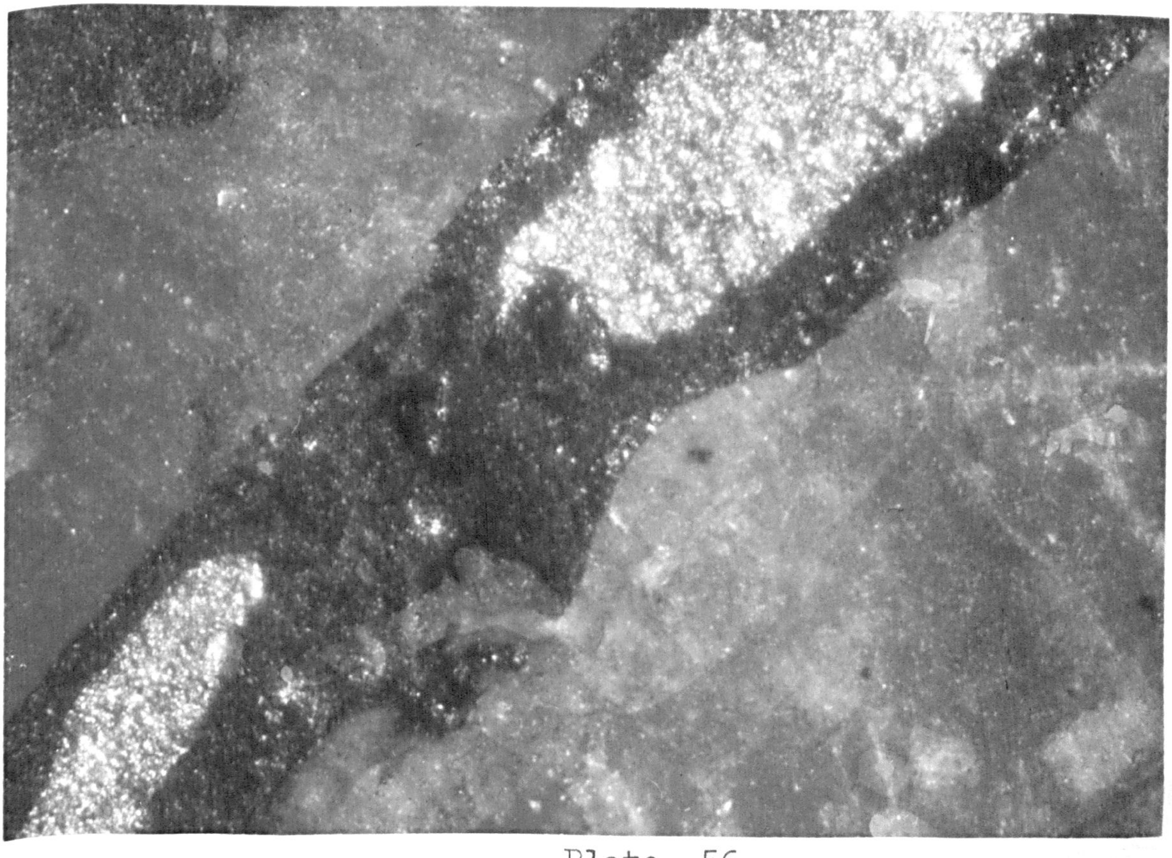


Plate 56

The Badnabay Group

The Badnabay Group includes the Loch na Seilge sheet, the Rudha Ruadh sheet, the microgranites, granites and pegmatites and microsyenites between these two sheets and to the south-west of the Loch na Seilge sheet, and a few microgranites that crop out immediately north-east of the Rudha Ruadh sheet.

Microgranites, exhibiting a granular texture, predominate in the Badnabay group. They are almost always dull red in colour when fresh; the weathered surface may also be red, but more often it has been bleached to light-brown or straw. Their red colour and their apparent homogeneity enable the thicker sheets to be easily recognised in the field, but with the thinner sheets (10 cm. or less) distinction is more difficult when the red colour is absent. Fortunately their texture and weathered surface enable them to be distinguished in most cases, final confirmation being obtained by the staining technique.

Microsyenites and leuco-microgranites are also fairly common, the former being dull-red and the latter pink in colour. They are usually associated with the microgranite, forming either the adjacent sheets or part of the same sheet. All the microgranodiorites, granodiorites and granites contain less then 5% by volume of the mafic minerals and can, therefore, be described as leucocratic. Pegmatites are rather sparsely distributed.

As the Rudha Ruadh and Loch na Seilge sheets are by far the largest, they are described separately and the remaining sheets are grouped together (see Map 1).

The Rudha Ruadh sheet

The Rudha Ruadh sheet forms low lying, peat covered ground and as a result, although well exposed along the coast it is poorly exposed inland. The contact between the upper edge of the sheet and the overlying gneisses is marked by a ridge with the gneisses forming an overhang. Although this allows the approximate position of the south-western margin to be traced easily the actual contact is usually seen only in coastal exposures. Near Badnabay and at Weaver's Bay microgranites a few metres from this contact have been intensely sheared and granulated, occasional stringers and patches of quartz being developed. The lower or north-eastern contact is more difficult to trace, partly because of the lack of good inland exposure and partly because interdigitation of microgranite and gneiss is common near the contact. At Weaver's Bay, where the contact is well exposed the edge of the sheet appears to be concordant with the foliation of the underlying gneisses. Discordant contacts have not been observed at either the upper or lower edges of the sheet.

The Rudha Ruadh sheet varies in thickness; it is never less than 90 metres thick and rarely more than 120 metres. The sheet is composed of all the rock-types present in the Badnabay group, microgranite predominating, followed in volume by microsyenite.

The typical dull-red colour may be bleached to a light-brown colour by weathering, but the depth of bleaching is never more than 1 cm. All rock-types are remarkably fresh and in many cases there is only the thinnest veneer of weathering. Small cavities occur in several rock-types comprising the sheet. They increase in number as the mafic content of the rock increases; thus they are sparse in the leucocratic rocks, but relatively abundant in the microsyenites where as many as fifteen may be present in a square centimetre (Plate 57). Many of the cavities are a millimetre in diameter, some being larger, some smaller. As these cavities could not have been present at the depth at which the Rudha Ruadh sheet formed they must have been filled by some mineral which was present in greatest amounts in the microsyenites and which was preferentially removed when the microsyenite had reached its present position in the crust.

The sheet is rudely foliated as a result of the alignment of biotite flakes or clots of hornblende and its foliation is often emphasised by the parallel elongation of small lenses of quartz. Numerous thin ribs of leucocratic material occur parallel or near-parallel to the foliation, which appears to be parallel to the margins of the sheet and to the foliation of the gneisses.

Biotite-micrograntes and hornblende-microgranites are easily distinguished in the field except when the mafic mineral is completely chloritized. Biotite tends to be dominant towards the margins of the sheet, while hornblende predominates in the centre. The most abundant type of micrognanite contains less than 10% mafics. Feldspar makes up about 70%; while potash feldspar and plagioclase usually occur in approximately equal amounts (Plate 58), in some varieties the former mineral is clearly dominant. Quartz varies antipathetically with the mafics, but rarely makes up more than 20% of the rock; it is never more abundant than either of the feldspars. Epidote and ore minerals are occasionally found, while sphene can be seen at the coastal exposures near Badnabay.

The microgranites grade into microsyenites by an increase in the mafic content and a decrease in the quartz content. Although all gradations occur there is always a sharp contact between the granitic and syenitic varieties in the field (Plate 59). The microsyenites contain less than 10% quartz and more than

15% mafics, the remainder being composed of feldspar. Potash feldspar is always dominant over plagioclase, the ratio being 4:1 or greater. Hornblende is the most common mafic mineral, but biotite occasionally predominates towards the centre of the sheet. Epidote and pyroxene can also be distinguished in some specimens.

Microgranite also grades into leucocratic microgranite in which the mafics make up less than 5% of the total.

The leuco-microgranites, microgranites and microsyenites have similar textures. They are all granular and relatively homogeneous in hand specimen (with the exception of the banded microgranites (p. 151)), and in all varieties the mafics tend to form clots, although biotite and epidote are occasionally disseminated evenly throughout. In one specimen from near Badnabay cores of epidote, 1.5 mm. in diameter, are partly or completely rimmed by small flakes of biotite. Clots of hornblende are typically developed in the syenitic varieties where they reach several millimetres in size. In one example the core of an aggregate of hornblende, 1 cm. in size, has been replaced by an aggregate of biotite, epidote and sphene. The clots are usually aligned and elongated parallel to the foliation.

In the microgranites quartz is usually lenticular, the lenticles being elongated parallel to the foliation.

Potash feldspar exhibits a small degree of segregation and patches of it are often linked by narrow necks of the same mineral. Plagioclase also exhibits slight segregation and many of the grains exhibit pale blue schillerization.

Within the Rudha Ruadh sheet three sheets of microsyenite can be distinguished. They vary in thickness from 5 metres to 12 metres and one of them thins to zero south-east of Allt na Suileig. They are well exposed at Allt na Suileig and can be traced south-east to the edge of the area and north-west to Bad Lonanach (Map 1) where exposures are poor. At the coastal exposures of Badnabay and Weaver's Bay microsyenite sheets are only 1 to 2 metres thick and cannot be correlated directly with those at Allt na Suileig .

In a few localities the microgranite has a striped or streaky appearance (Plate 60) and occasionally the shape of the mafic stripes suggests relict folding. The mafic stripes and streaks are syenitic in composition.

Relict layers of gneiss that are found in several localities, for example Weaver's Bay, vary in thickness from 5 cm. to 1 metre. They are generally quartz-dioritic or amphibolitic in composition, although there is some evidence of potassium enrichment (see p. 227). The striping and foliation of each relict layer is parallel to the foliation of the surrounding microgranite. In one or two instances the layers are seen to wedge out downwards.

Thin ribs, both concordant and slightly discordant, of leucocratic material are very common throughout the Rudha Ruadh sheet, as previously described by Clough (1907) and Watson (1951). They are often more resistant to weathering than the host microgranite or microsyenite and so stand out on a weathered surface. The discordant ribs appear to be slightly later for in general they tend to cut across the concordant ribs. The ribs vary in thickness from 2 mm to 15 cm; the thinner ribs are very common throughout the sheet, often occurring as closely spaced lenticles which emphasise the foliation. Many of the ribs, especially the thicker ones, exhibit a series of bulges along their length. Watson (1951, p.287) terms these bodies "noded pegmatites" and states that they "exhibit a rhythmic series of swellings;"strictly speaking they are not rhythmic as the wavelength of the "swellings" varies along the length of any one noded rib. In some cases the nodes are cut by a concordant rib.

The ribs are composed of leucocratic microgranite, granite, microgranodiorite and granodiorite. Within the microsyenites three varieties occur: (1) a variety in which the amount of potash feldspar is approximately the same as the host, that is, that mineral predominates over plagioclase (Plate 57) (2) a variety of microgranite in which potash feldspar and plagioclase occur in approximately equal amounts and (3) a variety in which plagioclase predominates over potash feldspar. The first variety is by far the most common although a similar predominance of potash feldspar is rare in the ribs that occur in the microgranites. Ribs with a grain-size similar to that of the microgranites and microsyenites are at least as common as those of coarser grain. Quartz is always more abundant in the ribs than in the host rock. Mafic minerals, usually rather sparse, occur as clots of hornblende with occasional biotite and epidote in the ribs present in microsyenite or as disseminated flakes of biotite and grains of hornblende in those present in microgranite and microsyenite.

Granites, comprising about 15% of the Rudha Ruadh sheet, also occur as large irregular patches, grading into pegmatites which usually remaining subordinate. They often contain lenticular patches of microgranite, showing that there is an intimate relationship between them.

The Loch na Seilge sheet

This sheet, generally forming low-lying ground, but well exposed in some localities, for example south-west of Badnabay, is over 175 metres thick in many places. An important feature of this sheet, which has been previously described by Clough (1907, p.144), is the occurrence of relict bands and lenses of gneiss. In the south-east of the area these relict bands are sparsely developed, but towards the north-west they increase in size and distribution until gneiss exceeds microgranite in volume (Map 1) and, at the western edge of the area, the sheet is finally represented by a few narrow sheets of microgranite, rarely more than 1.5 metres thick. Where the main sheet breaks up into thinner sheets migmatites are formed.

Although contacts between the main Loch na Seilge sheet and the adjacent gneisses are not often visible the margins of the sheet can be easily traced in the field and mapped on aerial photographs with reasonable accuracy. Where the single sheet is replaced by several sheets, south-west of Badnabay, contacts are seen in a number of places. Most contacts suggest that the microgranites are concordant: only in a few localities are discordant relations seen. Exposures showing a vertical section usually afford the best examples of discordant sheets because, while most of the microgranites appear concordant parallel to the strike of the foliation, they occasionally cut the foliation downwards.

The Loch na Seilge sheet is composed of microgranite which occasionally grades into granite. Microsyenite is absent in the main part of the sheet, but near the western edge of the area it occurs in a few thin sheets.

Hornblende-microgranite is the dominant variety in the main part of the sheet, but further north-west the thin individual sheets are composed of either hornblende or biotite-bearing varieties. In a number of sheets that crop out on the hills to the west of Badnabay leucocratic microgranite occurs.

The Loch na Seilge sheet and the other sheets exhibit a rude foliation similar to that of the Rudha Ruadh sheet. The parallel orientation of quartz lenses, biotite flakes, clots of hornblende and the presence of numerous ribs aligned in the same direction all emphasise this foliation, parallel to which there are numerous grooves which vary in width and do not appear to reflect a differing mineral composition (Plate 61).

Two types of striping are recognised in the microgranites of the Loch na Seilge sheet. The first similar to that seen in the Rudha Ruadh sheet, is due to the distribution of the mafic minerals and can also be observed in the coarser grained varieties (Plate 62), 500 metres south of Stac an t-Seabhaig. The second is due to the streaky distribution of potash feldspar and can be seen in a few of the thin sheets to the west of Badnabay.

The mineral composition of the microgranites and microsyenites is rather similar to those present in the Rudha Ruadh sheet. Quartz does not appear to exceed

20% and the feldspars occur in approximately equal amounts in most microgranites although occasionally potash feldspar predominates. The mafic minerals, which occasionally form clots (Plate 63), do not exceed 10% and may be chloritized. Epidote and iron ore are occasionally recognisable. In the microsyenites, potash feldspar always predominates and together the feldspars form about 70% by volume. Quartz forms less than 10% and the dark minerals between 20% and 25%.

Ribs of microgranite and granite, similar to those present in the Rudha Ruadh sheet, are common in the Loch na Seilge sheet (Plate 64). None of the examined specimens was granodioritic although this variety may be present. One discordant rib contains wisps of mafic minerals that are continuous from the host microsyenite into the granite.

The Minor Badnabay sheets.

The minor Badnabay sheets are rarely more than 5 metres thick and many are only a few centimetres thick. The thicker sheets can often be traced over distances of about 100 metres, but most of the thin sheets cannot be traced from one outcrop to the next. Although the granitic rocks do not cut across and penetrate the host gneisses to the same extent as the Cnoc nan Cro group, they form migmatites in several localities.

Contacts, both concordant and discordant, with the gneisses are common, but chilled margins have not been seen. They are always sharp with no evidence of migration of material from the microgranite or microsyenite into the gneiss. Some of the sheets contain relics of gneiss.

The sheets have a rude foliation which is parallel to that in the gneisses. Although clear examples of folding have not been seen, several sheets are flexured in the same manner as the foliation in the gneisses.

Hornblende-, biotite-, and hornblende-biotite-bearing microgranites form the majority of the sheets, while a few are composed of granite or microsyenite. Hornblende microgranites predominate in a belt, 70 metres wide and adjacent to the Rudha Ruadh sheet, that can be traced throughout the entire area. Elsewhere all the varieties of microgranite are well developed. In this belt are several sheets of microsyenite, composite sheets, composed of microgranite, leucocratic microgranite and microsyenite, and sheets of striped microgranite/microsyenite. The striping of these rocks, which are dull-red in colour and rich in potash feldspar, is identical with that present in the gneisses. This feature is considered to be important evidence in support of a metasomatic, rather than magmatic origin for some of the granitic rocks.

A particularly well developed granite sheet crops out to the north-east of Loch Bad an t-Seabhaig and can be traced from there north-westwards to near Badnabay. It is pegmatitic in some parts, but towards the north-west there is a diminution in grain-size.

Plate 57 Microsyenite with leucocratic ribs. There are numerous holes in the microsyenite portion (black). Microcline (grey)is evenly distributed throughout the specimen. Near Badnabay.

Plate 58 Micrognanite from near Badnabay. Quartz (dark grey), plagioclase (white), and microcline (pale grey) are evenly distributed throughout.

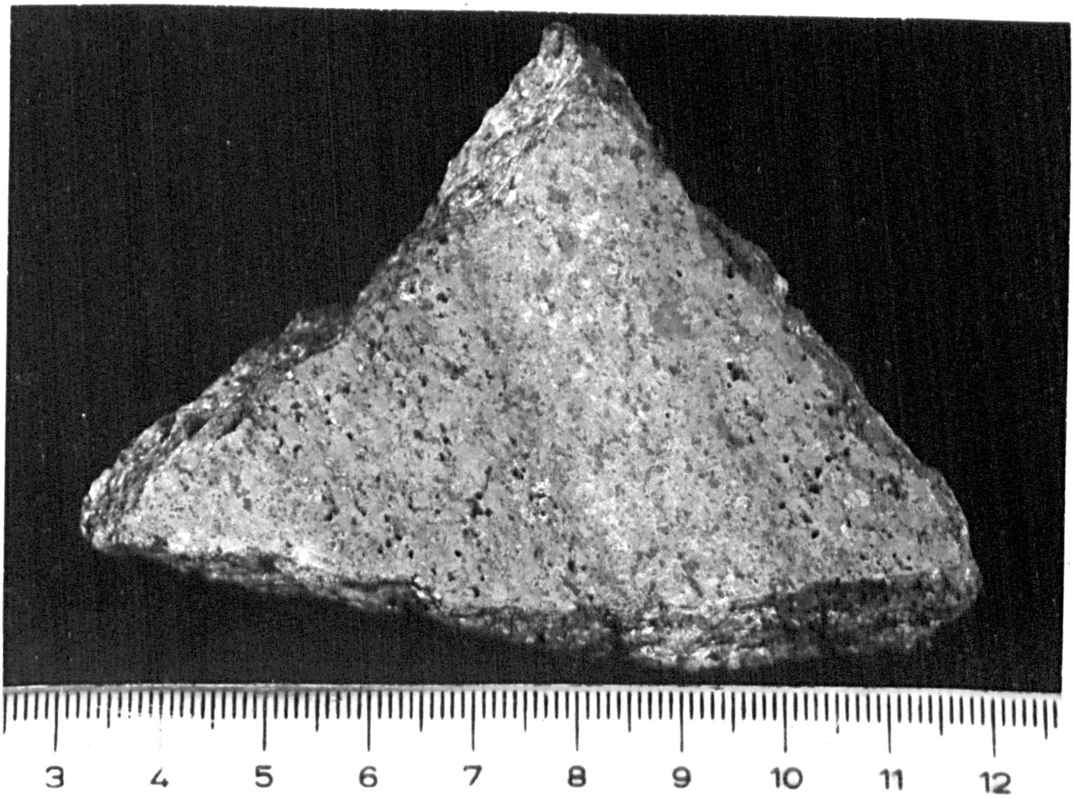


Plate 57

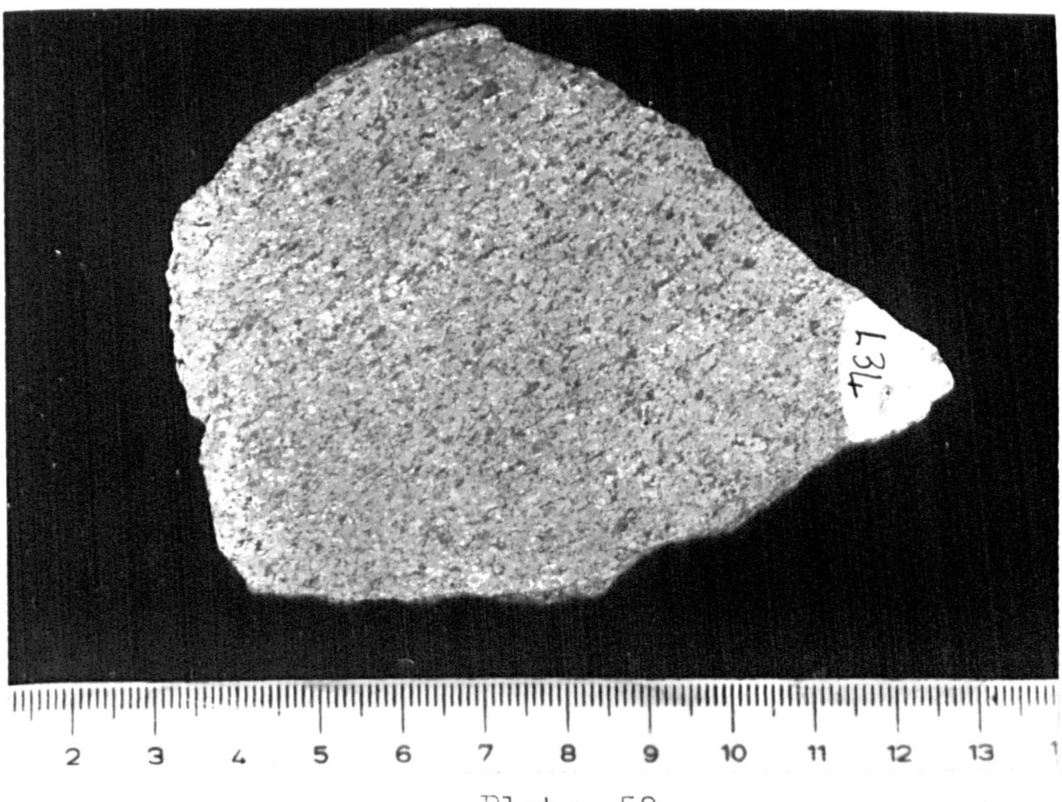


Plate 58

Plate 59 A sharp contact between micrognanite and microsyenite, being parallel to the foliation. Near Allt na Suileig.

Plate 60 Striping in the Badnabay group. Near Badnabay.

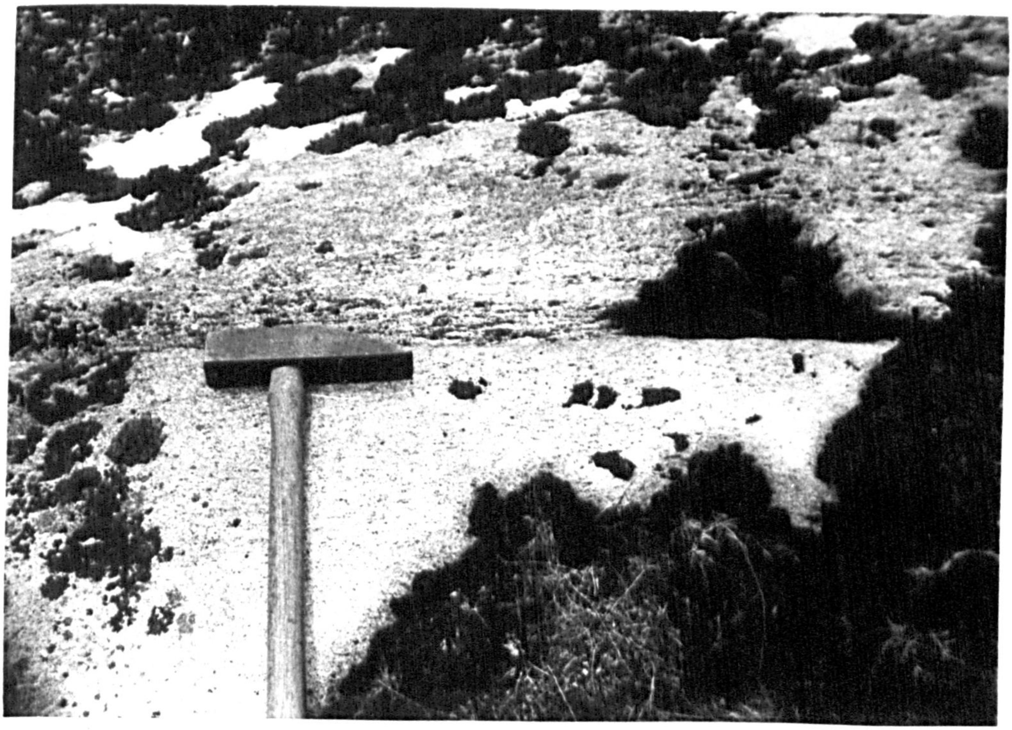


Plate 59

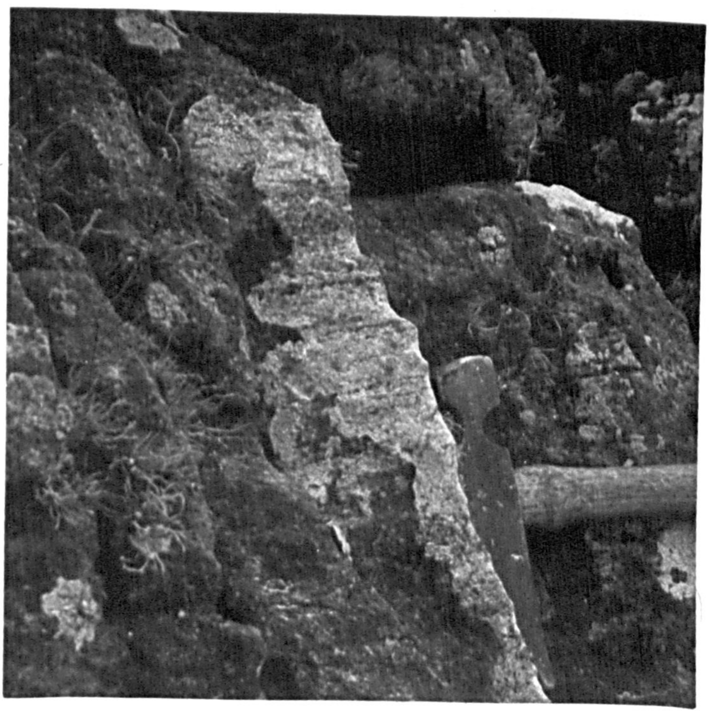


Plate 60

Plate 61 Grooving, parallel to the foliation, in a microgranite from the Loch na Seilge sheet.

Plate 62 Striping in the Loch na Seilge sheet.

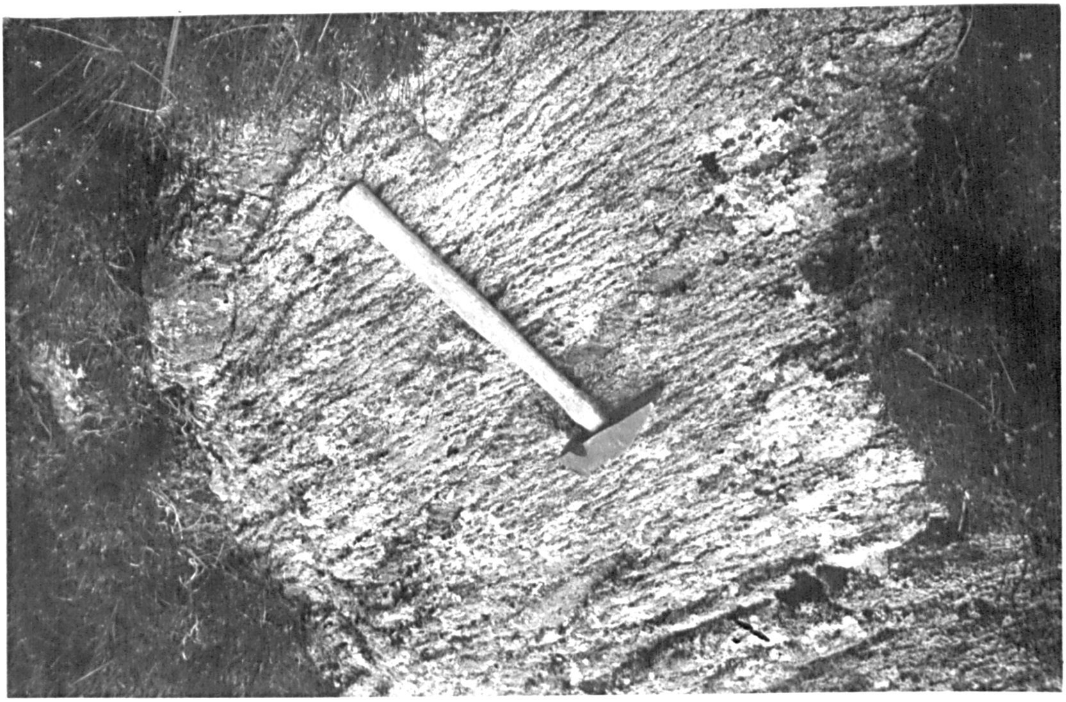


Plate 6I

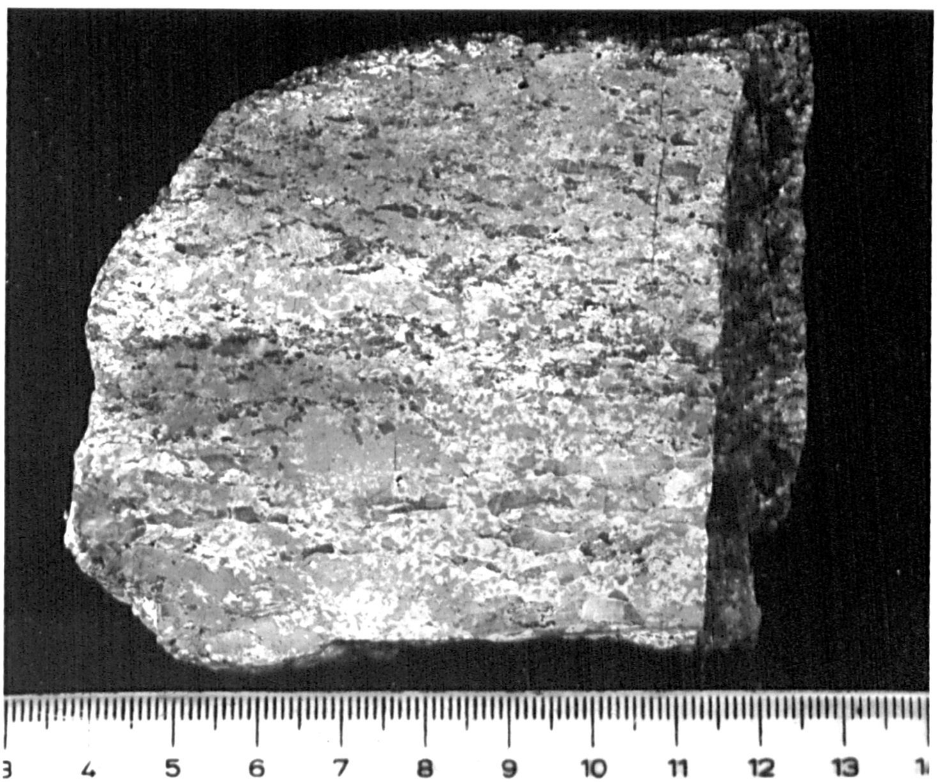


Plate 62

Plate 63 Clots of mafic minerals in a microgranite from the Loch na Seilge sheet.

Plate 64 Concordant ribs of leucocratic material in the Loch na Seilge sheet. Above Loch Bad ant-Seabhaig.

Plate 63

Plate 64

Microscopic Petrography

The mineral composition of the rock units of the Badnabay group is highly variable in contrast to that of the Cnoc nan Cro group (Table 18) whereas the texture is similar being essentially granoblastic except in many of the granites and pegmatites where it becomes crystalloblastic. Many of the grains are coated with a thin film of haematite that gives rise to the distinctive red colour.

Quartz, usually exhibiting undulose extinction, occurs as small, isolated, sub-rounded or rounded grains that may be enclosed by hornblende, plagioclase and microcline, as interstitial grains, and as large bulbous patches that are locate towards the other minerals (c.f. Cnoc nan Cro group).

Plagioclase is oligoclase in composition, varying from An_{25} to An_{30} and there appears to be little variation from the fine-grained to the coarse-grained varieties or from granitic to granodioritic to syenitic varieties. It may be either fresh, partly altered, or highly altered. In some cases, the alteration is patchy while, in other cases, it is either confined to or more intense in alternate twin lamellae. In a few cases, it takes the form of minute specks that give the feldspar a herring-bone appearance due to the opposing angles they make with alternate lamellae. Twinning on the albite law is predominant in the twinned grains, which usually form less than 50% of the total plagioclase, while pericline twinning is subordinate. When plagioclase is in contact with microcline it may have a clear, unaltered rim or form a myrmekitic intergrowth with quartz (cf. Cnoc nan Cro group, pp. 134-5). Plagioclase occasionally penetrates an albite flame in flame perthite.

Microcline is assumed to be the only variety of potash feldspar present in this group, as suggested by optic angle determinations in several grains (Table 20). Although it commonly exhibits well developed grid twinning, about 50% of the grains are either untwinned or show an undulatory wavy twinning, this percentage being lower in the microsyenites. Microcline encloses and penetrates all other mineral constituents except aegirine-augite, (Plate 65). Perthite, of the flame or string varieties, is fairly common and exhibits the feature described for the Cnoc nan Cro group (p.137). In some cases, patches and grains of microcline are linked together by intergranular veinlets (fig. 18).

Aegirine-augite is the pyroxene, as indicated by its extinction angle ($Z \wedge c$) of 32° and optic angle of $70^{\circ} \pm 2^{\circ}$. It is bright green and non-pleochroic and is present only in the microsyenites where it forms grains of about 0.5 mm in size, most of which have rounded smooth boundaries unembayed by other minerals. It not

Grain type	2Vx in degrees
Untwinned portion of grain	78-± 3
Twinned portion of same grain	80 ± 2
Undulatory twinning	79 - 84 ± 2
Untwinned grains	77 - 83 ± 2
Well developed grid-twinning	80 - 84 ± 3

Table 20 Optic angles of microcline in the Badnabay group.

only encloses small flakes of biotite and small grains of hornblende, but also cuts across both these minerals.

Hornblende, occurring as irregular or crystalloblastic grains, exhibits two pleochroic schemes as follows:-

X	Y	Z
Yellow	Green	Bluish green
Yellowish green	Green	Dark green

The bluish green variety predominates in the microsyenites and the dark green variety in the microgranites. Examples of hornblende and biotite in close association are rarely found in the microgranites, but are common in the microsyenites, where they usually occur with epidote and sometimes also apatite and sphene. In one case, hornblende is almost completely rimmed by epidote and is almost colourless in portions marginal to the contact. It is often cut by both biotite and epidote. Co-existence of hornblende and microcline is a common feature of this group. In a few microsyenites, hornblende is partly or completely altered to a penninitic variety of chlorite.

Biotite occurs as small flakes, usually brownish green in colour, in the microgranites and as large, usually reddish brown, flakes in the microsyenites where they form an intimate association with the other mafic minerals (see above). Flakes commonly have ragged ends, but occasionally the ends are concave towards quartz, microcline and plagioclase. Biotite may be penetrated or cut across by epidote. Flakes are occasionally puckered and may be partly or completely altered to chlorite.

Epidote, varying in colour from neutral or very pale green to yellow (contrast Watson, 1949) is the most widely distributed mafic mineral, occurring in almost every thin-section. It forms small isolated grains in the micrograntes and grains, 1 mm. or so in size in the microsyenites. It sometimes forms a symplectitic intergrowth with quartz, particularly when in contact with microcline. In one thin-section of microsyenite it forms an aggregate of grains surrounded by numerous flakes of reddish brown biotite. Epidote often partly or completely rims allanite.

The accessory minerals are common to all rock types, but in the microsyenites they form an important part of the rock, apatite, sphene and allanite being the most common. Apatite, a concentration of which is often considered characteristic of hybrid rocks (Nockolds, 1933), occurs in two habits (1) as small, sub-rounded oval grains that are enclosed by the feldspars and (2) as large rounded or oval grains upon which some other minerals are moulded. Sphene also exhibits two habits, occurring as (1) small oval granules which occur as individuals or in clusters (Plate 66) or (2) large well-formed, wedge-shaped crystals that reach a size of 2 mm. or more and often enclose plagioclase, quartz and microcline. The occurrence of allanite is similar to that seen in the Cnoc nan Uro group. Complex ore mineral relationships are similar to those described previously (p. 139). In one thin-section the opaque ore forms a dust-like aggregate.

Chlorite is the predominant ferromagnesian mineral in several of the Badnabay micrograrites and microsyenites. In one micrograaite patches of chlorite with either streaks or specks of iron ore are associated with clinozoisite which forms a symplectitic intergrowth with quartz. In the microsyenites chlorite sometimes exhibits the anomalous blue colours typical of penninite and often occurs in a radial habit.

Plate 65 Plagioclase penetrated by microcline.
Badnabay microgranite. (X 100)

Plate 66 A cluster of granules of sphene.
Badnabay microsyemite. (X 50)

Plate 65

Plate 66

The Laxford Quartzofeldspathites.

The Laxford Quartzofeldspathites, which are predominantly associated with the Badnabay and Weaver's Bay gneisses, include irregularly shaped bodies that bulge into and cut across the foliation of the gneisses and amphibolites and many narrow veins that are probably related to similar bulbous masses which are not visible. The bulbous bodies often have tongue-like projections that may be either concordant or discordant to the foliation of the other gneisses (Plate 67) while many of the tongues appear to fade into the gneisses (Plate 68). Many of the bulbous bodies are almost coarse-grained, a grain-size of 4 mm. to 5 mm. being quite common, but usually the associated tongues have a smaller grain-size, up to 3 mm. There may be a thin mafic film, usually biotite, at the margins of the bodies, particularly when they are in contact with amphibolite. The composition varies from trondhjemitic to granitic, granodioritic types predominating. Often a single body is composed of more than one variety of acid material and when there is a variation in the mineral composition of a tongue or isolated vein, the junction between the two types is usually parallel to the margins, which are normally deficient in potash feldspar relative to the inner part.

Biotite is the mafic mineral except in some of the bodies that occur in amphibolite in which case small amounts of hornblende are present. Quartz and feldspar occur in varying amounts, but total feldspar is never less than 50% nor quartz less than 20%. Potash feldspar may exhibit a streaky distribution and occasionally forms porphyroblasts 1 cm. or so in size. Except in a few instances potash feldspar occurs in amounts greater than 5%.

Potash feldspar sometimes exhibits a streaky distribution that can be seen only in stained hand specimens. The distribution of this mineral throughout the Laxford quartzofeldspathites can be established only by staining every specimen and is beyond the scope of this work. Preliminary studies suggest that the amount of potash feldspar present in the quartzofeldspathites does not depend on the mineral composition of the host rock. No significant differences in the feldspar content of those in amphibolites compared with those in gneisses. has been noted.

PLATE 67

Bulbous Laxford quartzofeldspathite body with tongues of material penetrating along and cutting across the foliation of the host gneisses.

PLATE 68

Discordant Laxford quartzofeldspathite (pale grey) that appears to fade into the gneisses. Overlay shows the shape of the body.

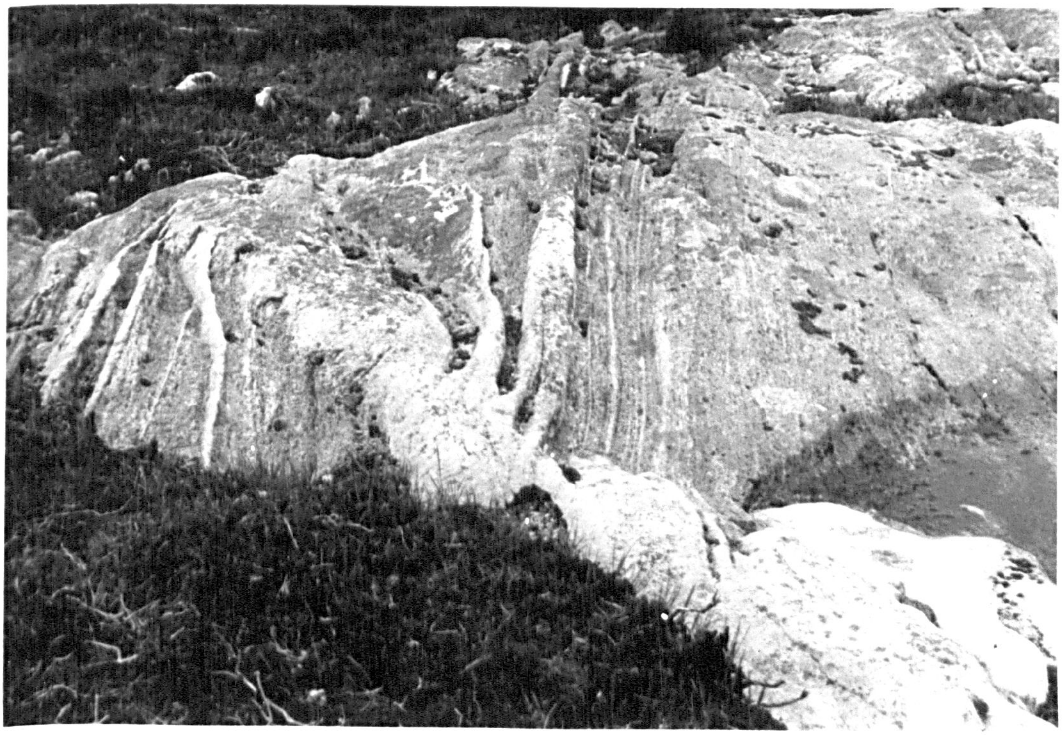


Plate 67

Plate 68

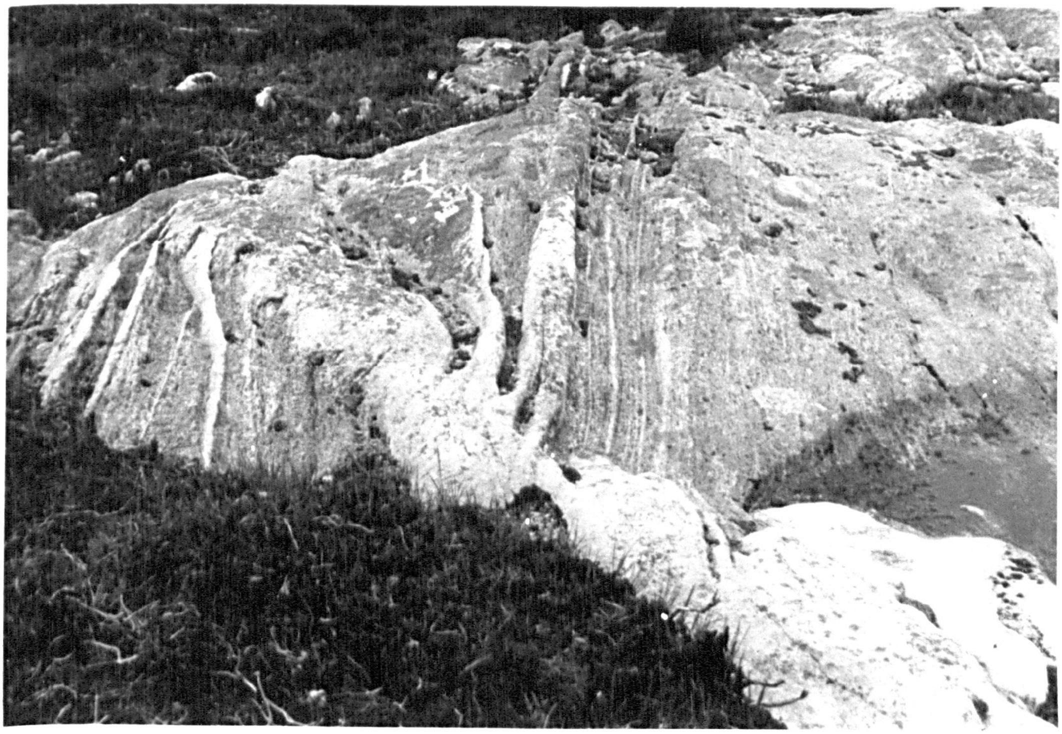


Plate 67

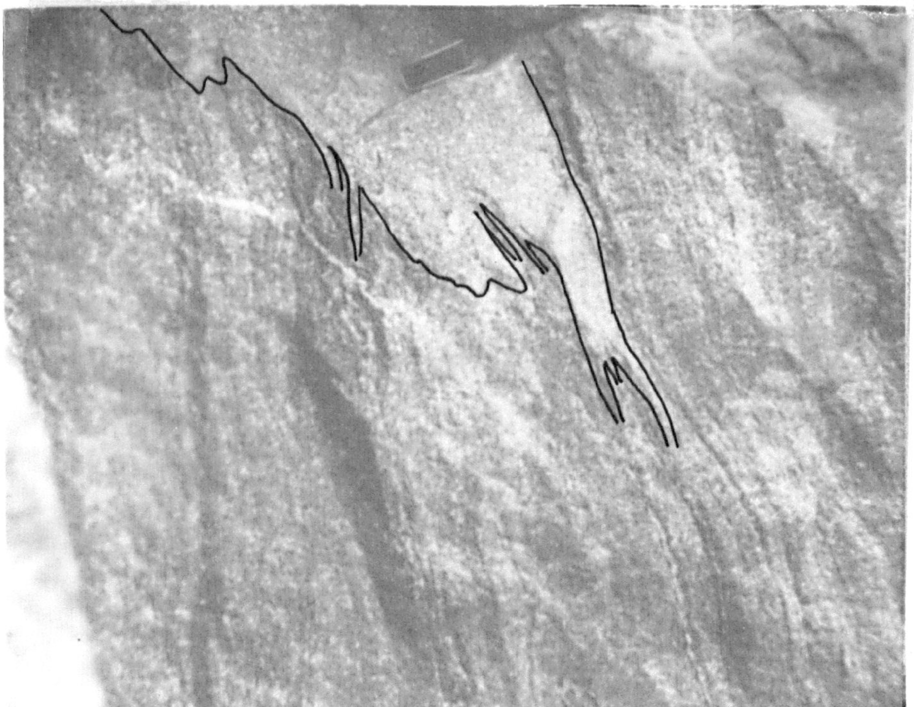


Plate 68

Microscopic petrography

The texture of the quartzofeldspathites is granoblastic and sometimes partly crystalloblastic, particularly in the coarse-grained varieties. The maximum grain-size of this group is about 5 mm. As can be seen from the modal analyses, the quartzofeldspathites are leucocratic (Table 18) and usually contain more than 20% quartz.

Quartz, usually exhibiting undulose extinction, occurs as grains of various sizes and shapes, many of the smaller grains being enclosed by the feldspars. Large lobate grains are particularly prominent but, in some cases, rounded and sub-rounded grains of quartz are set in a network of feldspar.

Plagioclase is oligoclase in composition varying from An_{20} to An_{25} or up to An_{30} in some cases. It is often altered and about 50% of the grains are untwinned. At contacts with microcline the same features that are seen in the Unoc nan Uro group occur. In addition orientated inclusions of microcline are enclosed by plagioclase as in that group.

Microcline, often exhibiting grid-twinning, is common in many of the quartzofeldspathites. It tends to occur interstitially, but can occasionally be seen penetrating plagioclase. Flame perthite is sparsely developed.

The mafic minerals include hornblande, biotite and epidote, which are all present in varying amounts. Hornblende is only found in a few of the quartzofeldspathites that occur in amphibolites. It is identical to the hornblende of the host amphibolite and is usually associated with a symplectitic intergrowth of quartz and epidote. A greenish brown biotite is the predominant mafic mineral and is usually evenly distributed in the rock. Epidote occurs in small amounts and occasionally rims allanite.

The accessory minerals which include apatite, allanite, sphene and iron ore, are sparse. They occur in similar habits to those of the Cnoc nan Uro group.

Microgranite/trondhjemite bodies

One of the more unusual features of the trondhjemites is the occurrence of layers of microgranite in many of the veins and sheets. In hand-specimen quartz and total feldspar occur in approximately equal amounts throughout. Staining, however, often reveals a sharp contact between trondhjemite and microgranite (Plate 69) and it is significant that this difference cannot be otherwise observed since the other mineral constituents including biotite do not vary noticeably in amount from trondhjemite to microgranite. Muscovite is occasionally present thus emphasising the close similarity to the microgranites of the Cnoc nan Cro group. The type of variation often seen in a sheet is shown in fig. 19 Here the sheet clearly cuts across the foliation of the amphibolite in which it occurs, in places tonguing along the foliation. B205a from the centre of the lens is trondhjemite, while L16 is partly microgranite and partly trondhjemite, the contact being crescent shaped. B205c, from the north-westerly sheet, is composed of microgranite. L14 and B205a, from near the margin of the south-easterly sheet, are composed of microgranite and trondhjemite, the contact being straight and parallel to the margin of the sheet. In this case, as in most cases, trondhjemite occurs adjacent to the edge.

Veins composed partly of microgranite and partly of trondhjemite occur throughout the Laxford area. Invariably, when microgranite occurs in a vein that cuts either gneisses or amphibolites, there is an outer edge of trondhjemite. In some veins the microgranite portion forms a wedge while in other veins the trondhjemite contains numerous streaks composed almost entirely of potash feldspar (Plate 70).

Microscopic Petrography

The mineral composition (Table 18) and textural relationships of the minerals in this group are similar to those of the microgranites of the Cnoc nan Cro group and are not described in detail at this stage.

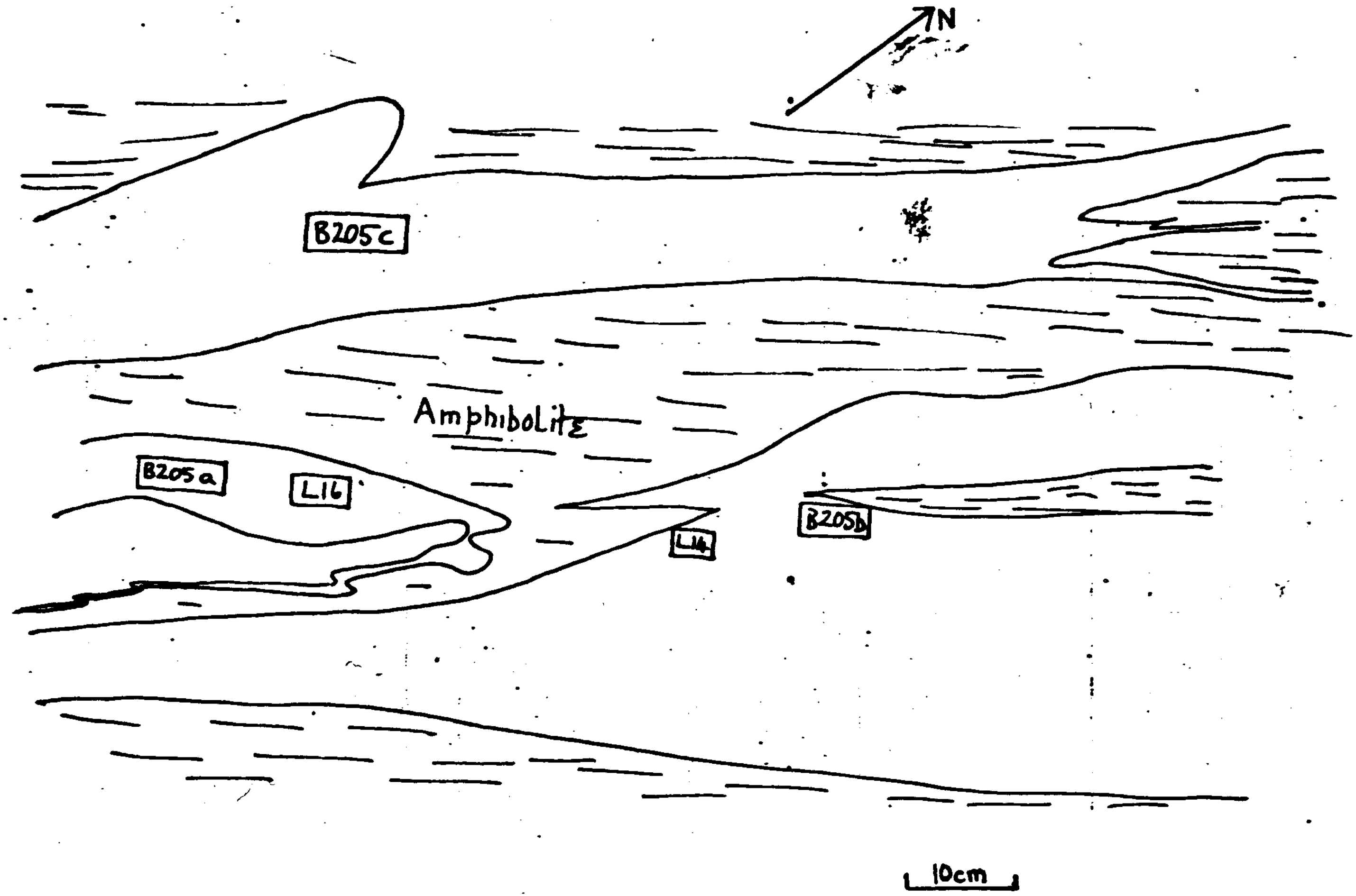


Fig 19. Microgranite/trondhjemite body, showing positions of specimens referred to in text (p. 162).

PLATE 69

Specimen of microgranite-trondhjemite, showing sharp contact between microgranite (grey portion) and trondhjemite (white portion). Yellow colour of stained potash feldspar shows grey in plate.

PLATE 70

Trondhjemite with streaks of potash feldspar (grey).

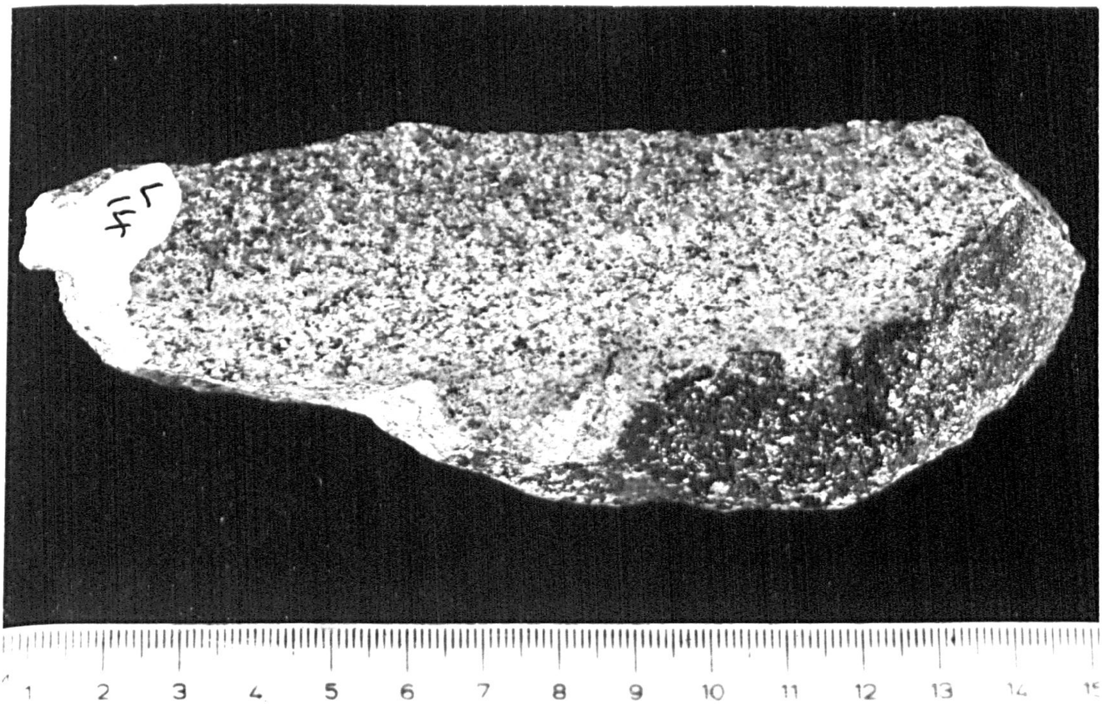


Plate 69

Plate 70

NE-SW Pegmatite Dykes

The latest phase of granitic activity was the intrusion of a number of NE-SW trending vertical dykes of pegmatite that probably filled late joints or fractures. The dykes, varying from 20 cm. to 1.5 metres in thickness, occur sporadically throughout the area. They clearly cut the Cnoc nan Cro microgranites and associated granites and pegmatites (for example 450 metres north-west of Lochan Glac na Lann) but they have not been observed to cut the Badnabay granitic group.

These pegmatites are generally very coarse-grained, but often between the large cyrstals there is some interstitial material with a grain-size as small as 2 mm. They consist essentially of quartz, microcline, plagioclase with accessory hornblende, biotite, muscovite, epidote, allanite and iron ore. Microcline, sometimes perthitic, predominates. Epidote is particularly conspicuous and occurs either as large crystals, up to 3 cm. in size, or as much smaller crystals. It occasionally forms a layer, a few millimetres thick, on the faces of a megacryst of microcline.

Contacts with the host rock are always sharp and there is no evidence of a diminution in grain-size towards the margin. Generally the pegmatites contain larger amounts of the mafic minerals than the Cnoc nan

Cro pegmatites and this, together with the presence of hornblende in some of them, suggests that they may be contaminated by inclusions of host rock.

The Geochemistry of the granitic rocks

The chemical composition in weight percentage, cation percentages, catanorm, mesonorm, Niggli numbers and trace-element values for analysed specimens of the various groups is given in Table 18

The chemical composition of the Cnoc nan Cro microgranites is remarkably constant throughout the area (Table 18); they bear a close chemical resemblance to the late-kinematic granites of Fennoscandia (Table 18). The average value for the ratio K:Na is 0.9, but it may be as high as 1.3 or as low as 0.7. The microgranites are typified by the occurrence of corundum (C) in both the catanorm and mesonorm and the fact that Fe^2 is greater than Fe^3 except for S72 (Table 18). The microgranites generally fall within the range of values given by Eskola (1950) for "ideal" granites (Table 18) - although Na_2O is usually slightly high and K_2O low, total alkali ($Na_2O + K_2O$) is in the correct range. The chemical composition of the analysed granite is rather similar to that of the microgranites, except that it has the composition of a leucocratic variety, that is Si is higher while Fe^2, Fe^3, Mg and Ti are lower in amounts. The Cnoc nan Cro pegmatite shows the potassium enrichment commonly seen in these rock-types (Table 18), it is similar to the pegmatite analysed by Robertson (1945) from the roadside just north of Laxford Bay (Table 18).

A plot of Na against K for the group brings out the trend from microgranite to pegmatite (fig. 20).

Analysed specimens of the Badnabay group show a considerable variation in chemical composition, being divisible into four distinct types: (1) microgranites (2) microsyenites, (3) granodioritic varieties and (4) leuco-microgranites. In the microgranites the ratio K:Na varies from about 0.7 to 2.2 while a plot of Na against K has a linear trend converging on that for the Cnoc nan Cro group at the higher values of K (fig. 20). The range of values of K for the Badnabay microgranites is similar to that exhibited by the Cnoc nan Cro group taken as one unit. A number of the microgranites have a composition similar to that of the "ideal" granite defined by Eskola (1950), but these rocks are not similar to the late-kinematic granites. The chemical composition of the microsyenites cannot be related to that of the microgranites, the low values of Si, the high values of K, P and Ti, and the ratio Ca:K being distinctive in the former types. A plot of Na against K for the microsyenites emphasises the relative constancy of the value of K, although the ratio K:Na varies from 2.1 to 4.4. The granodiorites exhibit a ratio K:Na ranging from 0.22 to 0.45, but otherwise closely resemble the leuco-microgranites (Table 18). Both types exhibit low values for Fe^2, Fe^3, Mg and Ti while Si values are notably higher than for the microgranites.

The Laxford quartzofeldspathites exhibit higher values for Si and lower values for Fe^2, Fe^3, Mg and K relative to the Cnoc nan Cro microgranites, thus tending towards a leucocratic, granodioritic composition.

The chemical composition of the microgranites from the microgranite/trondhjemite bodies is closely similar to that of the same rock types from the Cnoc nan Cro group (Table 18).

The elements P and F show rather interesting variations from one group to the other and are described in more detail later (pp.253-4).

Plots of Niggli numbers alk against si (fig.20a) and alk against al (fig.20b) bring out some of the differences between the granitic groups.

The Quartz-Albite-Orthoclase diagram

The system quartz-albite-orthoclase-water has been studied experimentally by Tuttle & Bowen (1958) with reference to the origin of granitic rocks. It was shown that minimum crystallization takes place with quartz, albite and orthoclase crystallising together at temperatures varying from 760°C to 640°C at water vapour pressures varying from 500 kg/cm^2 to 4000 kg/cm^2. Above pressures of 3600 kg/cm this minimum becomes isobarically a ternary eutectic and as the water vapour pressure increases, its composition moves towards the albite apex (Tuttle & Bowen, 1958, p.74). This suggests that if granitic rocks, sensu lato, were formed largely by crystallization of quartz, albite and orthoclase at a ternary minimum from a granitic magma containing a relatively low water content, then their composition would correspond with the minimum composition at low water vapour pressures. Therefore, when the analyses of such rocks are plotted on this diagram they should lie at or near the ternary minima for various water vapour pressures. Conversely, a wide scatter of plots may, but do not necessarily indicate that the analysed rocks are non-magmatic.

Plots, based on the catanorm and mesonorm, of the Cnoc nan Cro and Badnabay groups and Laxford quartzofeldspathites are shown in fig. 21 . Briefly, the Cnoc nan Cro microgranites and granites plot near the isobaric ternary minima for various water vapour pressures while the Cnoc nan Cro pegmatites plot near the orthoclase apex. The Badnabay group shows a wide scatter of points, few of which fall near the isobaric ternary minima. The Badnabay microsyenites plot near the quartz sideline and towards the orthoclase apex. Of the Laxford quartzofeldspathites two analyses (L78 and L76) plot near the isobaric ternary minima while the other two anlyses (L74 and L213) plot on the quartz-albite side of that line. The significance of these results is discussed later.

Trace elements

Of the trace elements determined, only Co, Ga, Ni and V have values within the range quoted by Clifford and others (1962) for granites from various parts of the world. They also suggest values of 200 p.p.m. for Rb are unusually low and such values occur in almost every microgranite of the Laxford area. Ba and Sr show notably high values and it appears that a value for Ba of about 3000 p.p.m. can be used to distinguish the Cnoc nan Cro and Badnabay groups, leucocratic varieties being excepted. While the higher values of Ba appear to be related to the higher values of K it should be noted that in the Cnoc nan Cro pegmatite the value for Ba is only 1585 p.p.m.

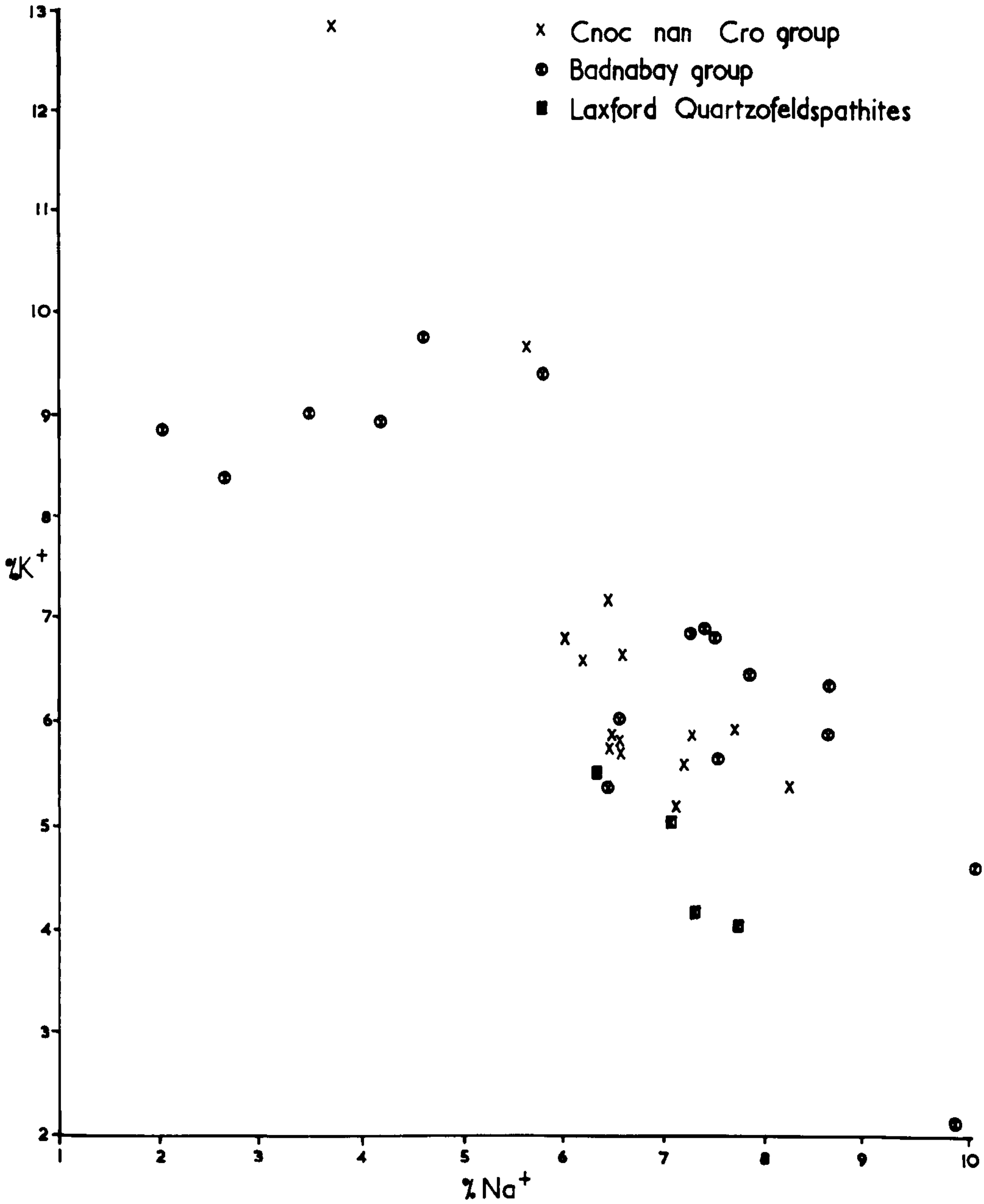
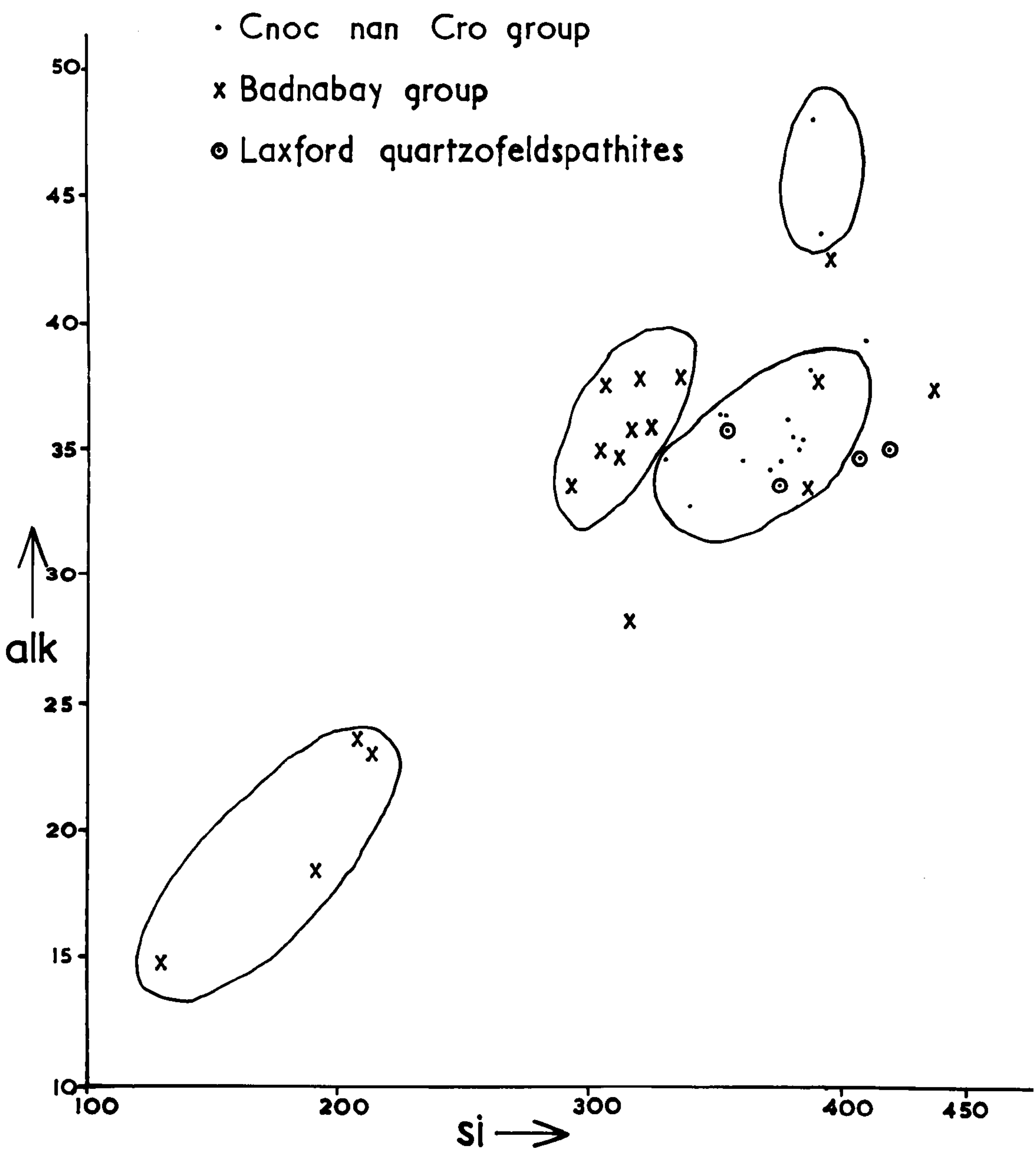


Fig.20 A plot of Na against K for the granitic rocks.



ig. 20 a lots of alk against si.

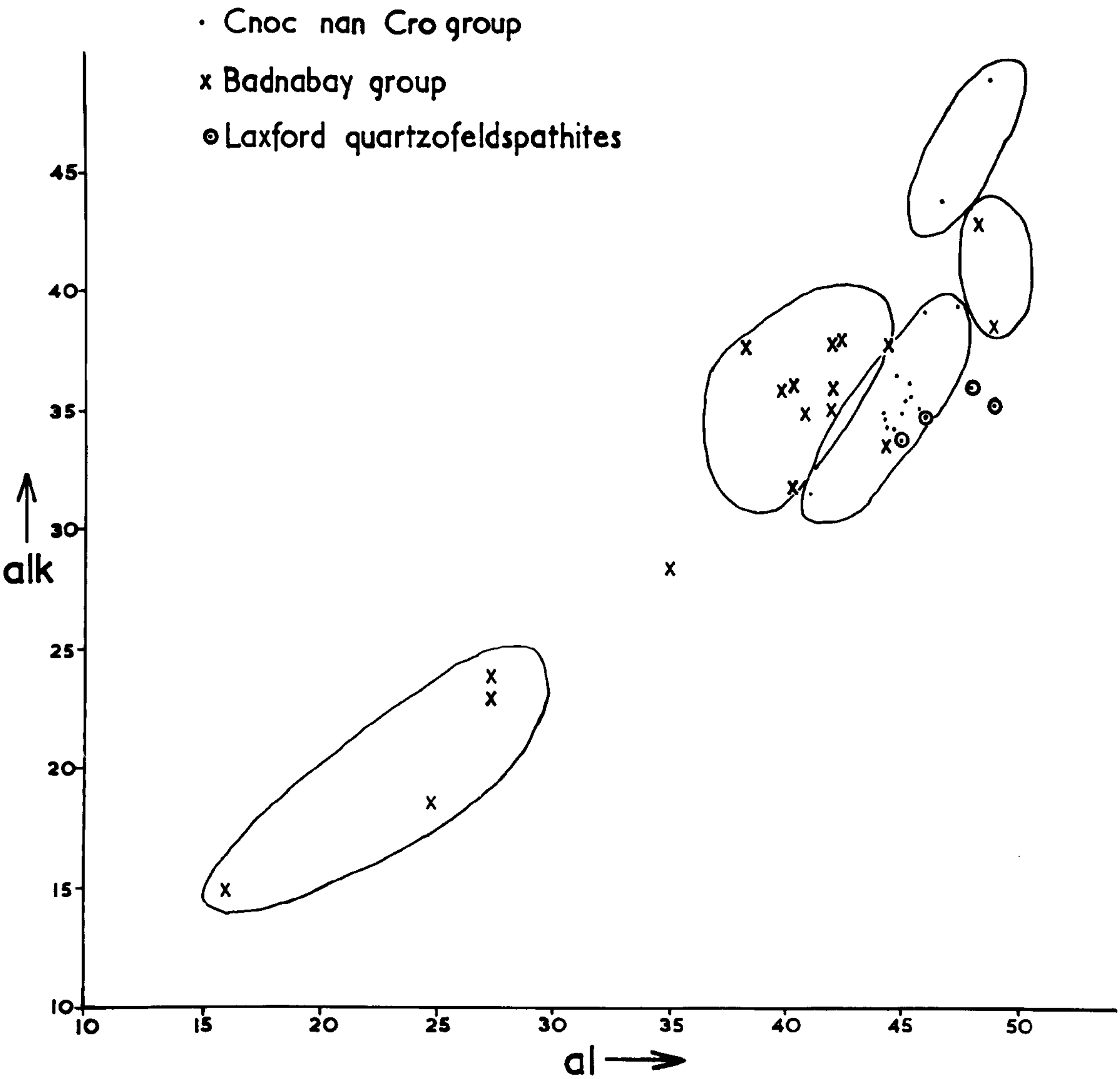


Fig.2Ub Plots of alk against al.

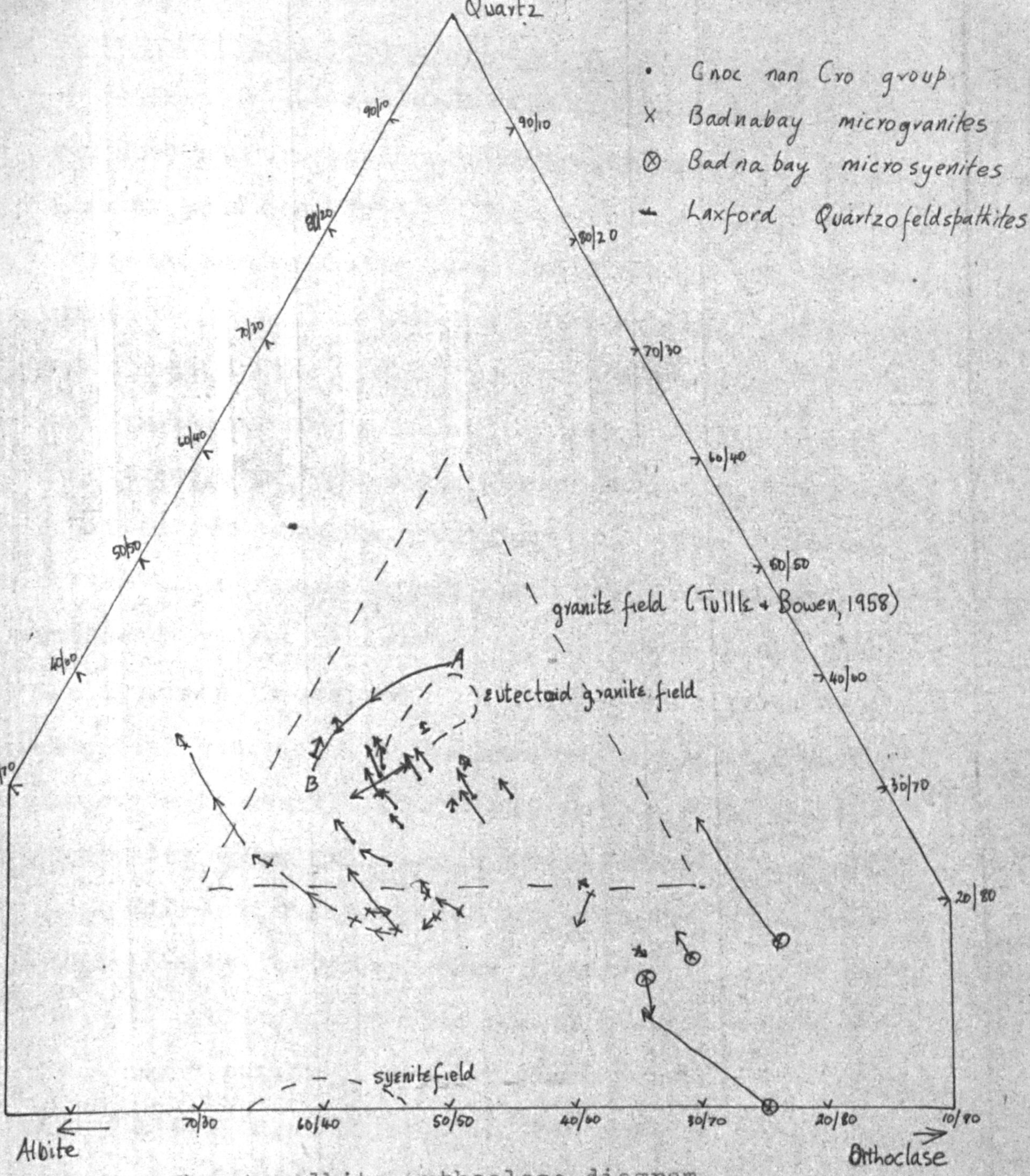


Fig.21 Quartz-Albite-Orthoclase diagram.
AB is the locus of the minimum-melting compositions at water vapour pressures between 500 and 4000 bars. Arrow head indicates position of mesonorm; bottom of arrow is position of catanorm.

Distinguishing features of the granitic groups

Most of the features that can be used to distinguish the Cnoc nan Cro group from the Badnabay group have already been described. For convenience they are now summarised in tabular form (Table 21). The Laxford quartzofeldspathites are best distinguished from those two groups in the field, where their bulbous, discordant and fingering nature is readily seen. In addition, they are leucocratic, often coarser grained than the micro-granites and commonly granodioritic. The microgranites of the microgranite/trondhjemite veins and sheets are not readily distinguishable in the field except when the specimen is stained. Although these rocks are essentially similar to the Cnoc nan Cro microgranites muscovite is usually sparse or absent. The NE-SW pegmatites dykes are readily identified in the field.

While this division of the granitic rocks is valid in that the groups show notable differences, this does not preclude a genetic relationship (see later). There are a number of similarities, particularly textural, that support this suggestion. For example, no difference in the range of optic angles could be established between the microcline of the Cnoc nan Cro and Badnabay groups, perhaps indicating that this mineral formed under similar physical conditions in both cases.

	Cnoc nan Cro group	Badnabay group
Field	Crop out as homogeneous sheets, resistant to weathering.	Form low-lying ground. Sheets are homogeneous and heterogeneous.
Mineralogy	Muscovite, biotite, and epidote. Equal amounts of quartz, microcline, and plagioclase (about 30%). An_{20-25}.	Hornblende, aegirine-augite biotite, and epidote. Variable amounts of quartz, microcline, and plagioclase. Quartz less than 20%. An_{25-30}.
Rock types	Microgranites, granites, and pegmatites.	Microgranites, granites, pegmatites, microsyenites, and granodioritic types.
Chemistry	Ba $<$ 3000ppm. F $<$ 400ppm. Si $>$ 64.5%	Ba $>$ 3000ppm. F $>$ 400ppm. Si $<$ 64.5% K generally higher.

Further differences in the chemistry are shown in Table 18b which summarises the range in composition.

Table 21 A summary of the differences between the two main granitic groups.

Table 18

Complete data on the granitic rocks.

Chemical composition, cation percentages, Niggli numbers, mesonorm, mode, trace element values, and catanorm are listed in order on the following pages.

Analyses 1-12	:	Microgranites of the Cnoc nan Cro group
Analysis 13	:	Granite of the Cnoc nan Cro group
Analyses 14-15	:	Pegmatites of the Cnoc nan Cro group Al : Robertson, 1945.
Analyses 16-18	:	Leucomicrogranites of the Badnabay group
Analyses 19-21	:	Microgranites from the Rudha Ruadh sheet
Analysis 22	:	Microgranite from the Loch na Seilge sheet
Analyses 23-25	:	Microgranite sheets of the Badnabay group
Analyses 26-28	:	Granitoid ribs in the Rudha Ruadh sheet
Analyses 29-32	:	Microsyenites of the Badnabay group
Analyses 33-34	:	Micrograanites from microgranite-trondhjemites.
Analyses 35-38	:	Laxford quartzofeldspathites
Analysis 39	:	Late-kinematic granite, Fennoscandia (Parras, 1958).
Analysis 40	:	Ideal granite (Eskola, 1950).

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Ranges of composition

	CNOC NAN CRO			BADNABAY			
	microgranite	granite	pegmatite	microgranite	microsyenite	leucomicrogranites	granodiorites
Si	64.39-67.79	68.52	66.32-67.04	62.30-64.51	47.61-57.60	67.28-69.45	67.28-70.01
Al	15.90-17.74	16.00	16.05-16.75	16.00-17.40	11.87-15.12	15.53-15.60	15.73-16.56
Fe^3	0.23-1.06	0.34	0.03-0.48	0.59-1.05	1.16-1.67	0.26-0.75	0.09-0.26
Fe^2	0.38-1.25	0.09	0.21	0.44-0.83	2.06-3.27	0.25-0.32	0.20
Mg	0.60-1.37	0.45	0.20-0.55	0.44-0.83	2.93-10.69	0.10-0.33	0.17-0.29
Ca	1.07-1.68	1.34	0.28-0.40	1.63-2.46	4.57-10.07	1.46-2.04	0.84-1.61
Na	5.60-8.21	6.56	3.42-5.54	4.53-8.57	2.00-4.12	6.04-7.49	9.83-10.05
K	5.22-7.28	6.75	9.70-13.07	5.91-9.81	8.39-9.06	5.65-6.52	2.18-4.63
Ti	0.04-0.30	0.03	0.01	0.22-0.31	0.53-1.36	0.06-0.16	0.01-0.05
P	0.02-0.08	0.01	0.01	0.03-0.17	0.85-2.43	0.02-0.03	0.01
Mn	0.01-0.02	0.01	0.01	0.01-0.03	0.05-0.07	0.01-0.01	0.01

Averages

	CNOC NAN CRO		BADNABAY			
	microgranite	pegmatite	microgranite	microsyenite	leuco- microgranites	granodiorites
Si	66.85	66.68	63.65	52.79	68.38	68.65
Al	15.84	16.40	16.64	13.99	15.56	16.15
Fe^3	0.56	0.26	0.77	1.51	0.50	0.18
Fe^2	0.80	0.11	0.68	2.40	0.28	0.20
Mg	0.88	0.38	1.41	6.61	0.22	0.23
Ca	1.38	0.34	2.02	6.72	1.75	1.22
Na	6.78	4.47	7.13	3.04	6.77	9.94
K	6.03	11.38	7.35	8.81	6.08	3.41
Ti	0.23	0.01	0.27	0.89	0.11	0.03
P	0.06	0.01	0.12	1.31	0.02	0.01
Mn	0.01	0.01	0.02	0.06	0.01	0.01

Table 18b Ranges of composition and averages for the two main granitic groups.

V. THE ORIGIN AND DEVELOPMENT OF THE COMPLEX

The rocks under discussion in this thesis lie entirely within the Laxfordian complex as defined by Sutton & Watson (1951). The origin of this complex has recently been the subject of several controversial discussions (Dearnley, 1962 and Park 1964). Since the Laxford area can be considered as the type area for the complex the conclusions reached in this thesis are relevent to the present controversy regarding the Laxfordian complex. However, it must be emphasised that these conclusions are based on research in the Laxford area only and it is considered unwise to extend the arguments to the Laxfordian complex in other parts of the North-west Highlands.

While there is evidence of more than one period of folding and metamorphism the characteristic features of the complex are Laxfordian in age. The Laxfordian metamorphism, which occurred about 1600 m.y. ago (Giletti et al., 1961) has obscured all the textural and most of the mineralogical and structural features of earlier metamorphisms, the details of which can, therefore, be discussed in only general terms.

Peach and others (1907) have divided the Lewisian rocks of the North-west Highlands into (1) a Fundamental Complex, (2) a series of metasediments and (3) a number of later intrusions. In the Laxford area, these authors would include the four groups of gneisses (see Chapter 2), the metaperidotites (see pp. 74 - 75) and some of the garnet-pyriclasites and amphibolites (see pp. 81 - 94) in the Fundamental Complex. They group the later intrusions into a basic and ultrabasic series, an intermediate series and a later acid series (Peach and others, 1907, p.36); these are tentatively equated with many of the amphibolites, the metadiorites and the granitoid rocks respectively in the present study.

The gneisses and early igneous rocks described in this thesis can be equated with those components of the Laxfordian Complex of Watson (1951) that pre-date the granitoid rocks.

The origin of the Lewisian Complex in the Laxford area has been discussed by the Geological Survey (Peach and others, 1907) and Watson (op. cit.),while Sutter (1953) reached certain conclusions on the origin of the granitic rocks, Hitchon (1960) on the pegmatites, and Bowes, Wright and Park (1964) on certain layered basic and ultrabasic bodies. The more significant conclusions of these authors have been summarised in Chapter 1 (pp. 1-7).

THE ORIGIN OF THE GNEISSES

Gneissic terrains may represent foliated but unmetamorphosed igneous rocks or highly metamorphosed igneous or sedimentary rocks and there is often controversy over their interpretation. For example, certain gneisses of the Svecofennides of Fennoscandia are interpreted by Simonen (1948, 1960) as representing a series of plutonic intrusions that penetrate pre-existing gneisses and later develop a gneissosity, whereas Marmo (1962a) considers that the same gneisses predominantly represent a metamorphosed sedimentary sequence.

In recent years most gneissic terrains have been considered to represent metamorphosed sedimentary sequences (Deitrich, 1963). In many cases, such an origin has been established following the recognition of intercalated bands of undoubted sedimentary origin, for example marbles and graphite schists (Marmo, 1962b; Engel & Engel, 1960). In other cases metasediments have been traced through increasing metasomatism into gneisses (Park, 1964).

Previous workers in the Laxford area do not produce any conclusive evidence in favour of either a sedimentary or an igneous origin for the gneisses. The Geological Survey favour an igneous origin (Peach and others, 1907) although Teall (op.cit., P.65) suggests that gneisses, in which biotite is the predominant ferromagnesian mineral, may represent metamorphosed grits whose sedimentary characteristics have been obscured. Watson (op.cit) concludes that the gneisses of the Laxford area are reconstituted Scourian gneisses, for which she considers a sedimentary origin to be more likely. Hitchon (1960) states that the Laxfordian pegmatites intrude orthogneisses, but produces no evidence to support this statement.

A hypothesis on the origin of the gneisses can be produced only if all the available field, petrographical and geochemical data are used in conjunction. Evidence from one source alone is considered to be insufficient in the present case.

The chemical composition of the gneisses of the Laxford area is similar to that of gneisses from various parts of the world, most of which are considered to represent metasedimentary rocks (cf. Wahlstrom & Kim, 1959; Crowder, 1959; Marmo 1962b). The gneisses are very closely similar to gneisses from Seirra Leone (Marmo, 1962b) and Fennoscandia (~~Marmo, 1956~~ Simonen, 1960) - see Table 13. The gneisses are granodioritic or trondhjemitic in nature, the high Na:K ratio being distinctive.

Howie (1955) considers that if a series of analyses fall on reasonably smooth curves when plotted on triangular variation diagrams of (Fe^2+Fe^3), Mg, and (Na+K) and Ca, Na and K, the analyses represent rocks that form part of an igneous series. The analyses of the Loch Laxford gneisses when plotted on the triangular variation diagram of (Fe^2+Fe^3), Mg and (Na+K) (fig. 5b p.63) show a linear relationship. When plotted on the triangular variation diagram of Ca, Na and K (fig. 5a p. 65), the analyses show a random scatter. This method of approach, therefore, gives conflicting evidence which cannot be used to support conclusively a magmatic origin for the gneisses. A characteristic feature of a magmatic granodiorite is considered to be a low Mg: (Fe^2+Fe^3) ratio, usually around 0.5 or less (Mercy, 1960). The Loch Laxford granodioritic gneisses have a Mg : (Fe^2+Fe^3) ratio which varies from 0.75 to 1.65, the ratio showing little variation from group to group (fig. 4a p. 63). This suggests that there has been no iron enrichment in the gneisses, an essential feature of fractional crystallization, according to Mercy (op.cit.). In addition, the lack of correlation between Na and K appears to be inconsistent with fractional crystallisation of a magma (cf. Mercy, op.cit.). One feature that does support crystallization from a melt or crystallization under conditions of equilibrium is the high degree of linear correlation between Mg and Fe^2+Fe^3 (fig. 4a). This, however, may also be explained by the recrystallization of a mineral in which the ratio was previously fixed, for example, granulite facies pyroxenes. Thus, the geochemical data for the gneisses are not entirely consistent with a magmatic origin.

Although field evidence is rather scanty, the presence of flaggy, striped quartzites and epidote-plagioclase-quartzites and occasionly quartz-plagioclase rocks with layers rich in magnetite suggests that certain gneisses, at least, are metasedimentary in origin.

The mineralogical composition of the gneisses also has an important bearing on their origin. Hornblende, biotite and epidote are the principal mafic minerals and the gneisses have been divided into groups partly on the basis of their distribution. Watson considers that biotite is indicative of an influx of potassium (Watson, 1951, pp. 290 - 291). However, the present study suggests that the presence of biotite in the gneisses cannot always, or even in the majority of cases, be used to indicate that hornblende has been altered during potassium metasomatism because in many cases, where hornblende and microcline occur in juxtaposition, the former mineral appears to be stable (p. 55). The presence of hornblende or biotite in the gneisses may, therefore, depend on the relative amounts of chloritic or sericitic material respectively in original metasediments, although the Ca : K ratio does not confirm this suggestion. Furthermore, from an examination of the analyses tables, it would appear that there is no simple relationship between percentage of K and percentage of biotite. The highly variable mineralogical composition of alternating layers of the gneisses can best be ascribed to original differences in sedimentary layers accentuated by metamorphic processes.

As most of the evidence is not compatible with a magmatic origin for the gneisses, it is concluded that they are medasedimentary in origin. The gneisses appear to represent metamorphosed greywackes for the following reasons:-

1. Greywacke is the sediment that requires least addition and subtraction of material tp produce gneisses with the chemical composition of the Laxford gneisses (cf. Table 13).

2. The chemical compositions of all analysed gneisses are rather similar, suggesting that the rocks in question are the result of the metamorphism of sediments of similar composition. This is particularly true when ratios of elements are considered.

3. The gneisses represent a great thickness of metasedimentary rocks and thick, monotonous sequences of greywackes are common.

Although the choice of greywackes minimises the amount of metasomatism necessary for the development of the gneisses, it is quite possible that the same rocks could be produced from other sedimentary types, for example, pelites (cf. Marmo 1962a). When the chemical composition of the Laxford gneisses is compared with the average composition of greywacke quoted by Pettijohn (1957) (Table 13), it is clear that some movement of material would be required to transform the latter into a Laxford gneiss. Si, Al, Ca and Na would have to be added and Fe^{2+}, Mg and K subtracted. Although the use of the "average composition of greywacke" has recently been criticised (see discussion in Butler, 1965) its use here seems justified, being preferable to choosing one particular greywacke and terming that rock the parent.

Using the average chemical composition of greywacke to indicate that the Laxfordian metamorphism was allochemical can also be criticised. However, the lack of correlation between Na and K supports the relative movement of these two minerals and attests to, at least, local metasomatism (cf. Mercy, 1960). An alternative hypothesis is that the gneisses are the products of direct, isochemical recrystallization of greywackes of the appropriate chemical composition, but there is a scarcity of greywackes of the required composition (see Pettijohn, 1957).

In the Laxford gneisses Na increases relative to both metagreywackes and Scourian gneisses suggesting that sodium metasomatism has occurred. Sodium metasomatism during a metamorphic episode in which there was sufficient time for chemical equilibrium to be established, would account for two important features of the gneisses, that is (1) the approximately uniform distribution of Na and (2) the very small variation in the anorthite content of plagioclase. Sodium metasomatism may also account for the trondhjemitic trend in the gneisses, as suggested by the analyses (p. 64). Porphyroblasts of plagioclase, attesting to at least local movement of Na^+, although present in a number of gneisses (Plate 12) are rather uncommon.

Potassium metasomatism of the gneisses is indicated by two characteristics: (1) a general increase in the amount of K relative to Na, as seen in the Weaver's Bay and Laxford Bay gneisses and (2) a local increase in potash feldspar. K% increases with increasing Si% in many of the gneisses and this granitic trend appears to complement the trend towards a trondhjemitic composition (Fig. 7).

The introduction of K into the gneisses is indicated partly by the development of biotite from hornblende and particularly by the prominence of microcline in many of the gneisses. Where microcline abuts against plagioclase sodic rims to the latter are often observed and in certain cases myrmekite is present within plagioclase. Microcline is often of the flame perthite variety. The origin of the sodic rims, the albite flames and myrmekite are considered in a later section because similar features are also present in the granitic rocks.

A notable feature of the chemistry of the gneisses is that the Claise Fearna and Badnabay groups can be distinguished from the Weaver's Bay and Laxford Bay groups on the basis of the Na : K ratio, a value of 5.5 : 1 marking the division. Although this division has not been substantiated statistically, an examination of stained hand specimens suggests that K, in the form of biotite and potash feldspar, is higher on average in the Weaver's Bay and Laxford Bay gneisses, particularly the latter, than in the Claise Fearna and Badnabay gneisses. However, within the two last-mentioned groups there are gneisses rich in potash feldspar (for example, p. 37 and Plate 7), some being termed striped microgranites (p. 151). Porphyroblasts and streaks of potash feldspar are considered as evidence supporting at least local potassium metasomatism.

Sodium metasomatism has affected all the gneisses, whereas potassium metasomatism has been localised, many gneisses showing no evidence of the latter metasomatism.

The Laxford gneisses are associated with basic and ultrabasic rocks that contain relict granulite facies (≡ Early metamorphism) and upper amphibolite facies (≡ Laxfordian) mineral assemblages (see pp. 195-6). Thus it can be concluded the gneisses contained granulite facies mineral assemblages prior to the Laxfordian metamorphism. The present mineral assemblages attest to the retrograde, hydrous nature of this metamorphism because biotite and hornblende with lesser amounts of epidote are the mafic minerals.

Thus, the gneisses of the Laxford area are considered to have developed from a greywacke parent through metamorphic and metasomatic processes. There is evidence that an Early, granulite facies metamorphism was followed by a later, amphibolite facies metamorphism.

The mechanism involved in the formation of the streaks and stripes of the gneisses is extremely difficult to establish. Deitrich (1960,a,b; 1963) in a series of papers, considers that banding represents original compositional differences in most gneisses, banding in Deitrich's terminology being equivalent to striping in the present usage. He postulates that the original bedding is usually indicated by the bands (≡ stripes) and foliation. It is possible that striping is due in this instance to original compositional differences in the parent greywackes, possibly reflecting variations in the relative amounts of chloritic and sericitic material.

Engel & Engel (1962a) have shown that metamorphic differentiation is a very important process in rocks reconstituted above the epidote-amphibolite facies. Mafic metasomatism accompanies metamorphic differentiation and produces alternating layers of mafic-rich and mafic-poor stripes.

In the gneisses of the Laxford area, particularly those of Laxford Bay, the mafic minerals often form clots, pods or lenses. North of Laxford Bay flattened hornblendic pods predominate in certain layers of the gneisses (p. 46). In the absence of a dominant structural control it seems likely that the segregational process, whose mechanism is unknown, results in the occurrence of such clots, pods and lenses of mafic minerals. However, if this process occurs under strong structural control, striping is more likely to develop as in the Badnabay gneisses. Again the presence of this structural control may result in the development of streaks rather than clots and lenses of potash feldspar during the phase of potassium metasomatism.

One of the more significant features of the gneisses is the distribution of epidote which is particularly prominent in the Weaver's Bay and Laxford Bay gneisses (p.49). There appears to be at least two generations of epidote, as shown by the differing birefringence schemes exhibited by what appears to be one grain. Furthermore, different pleochroic schemes occur. A second generation of epidote probably accounts for the development of quartz-epidote symplectites that fringe normal epidote (Plate 21).

Epidote may form through a process of saussuritization of the anorthite molecule of plagioclase (cf. Barth, 1952). This process requires the introduction or redistribution of iron. However, it is thought that epidote is primarily a metasomatic mineral, forming as one of the breakdown products of hornblende during potassium metasomatism. Epidote, biotite, hornblende sphene and apatite are often found in close association in the Laxford gneisses and may be the result of the decomposition by either of the following reactions:-

1. hornblende + potassium + water → biotite + epidote (+sphene)(+apatite)

2. hornblende + water → epidote + chlorite + quartz.

The second reaction can be observed in several gneisses where a transition along the following lines can be seen:-

strongly coloured green hornblende→pale coloured green hornblende→quartz - pale green hornblende symplectite → quartz - epidote symplectite.

Teall (1907, p.61) considers that epidote is an original constituent whereas, in this thesis it is thought to be a secondary and metasomatic mineral. Further evidence in support of a metasomatic origin for epidote comes from the fact that this mineral often partly or completely surrounds allanite which is rarely present in sediments (Pettijohn, 1957) and has not been described from Scourian gneisses. Allanite and therefore epidote formed during the Laxfordian metamorphism.

While quartz-epidote symplectitic intergrowths are probably best explained by a process of simultaneous growth, the common occurrence of such intergrowths in contact with microcline suggests that other factors may be involved.

The Laxfordian metamorphism has produced textures and mineral relationships that vary from group to group (pp.48 - 59). The general increase in grain-size and absence of polygonal grains in the gneisses that crop out in the north-eastern part of the area indicates an increase in the degree of post-deformational recrystallization in this direction. There is evidence that this is associated with the occurrence of late intergranular fluids. The texture of the Claise Fearna gneisses suggests that recrystallization following the main phase of deformation is limited in this group.

The interstitial and enveloping habit of potash feldspar together with its occurrence as thin films indicates the former presence of late potassium-bearing interstitial fluids and is seen in all groups of gneisses. The serrated margins at plagioclase-quartz boundaries found in some Badnabay and Weaver's Bay gneisses (p. 51) are thought to be a metasomatic feature indicating the former presence of an interstitial fluid, the serrations being produced by the activity of silicon along certain preferred directions (cf. Gates & Scheerer, 1963).

Sutured boundaries and mortar structure in many of the gneisses (p. 51) are thought to indicate a post crystallisation deformation in the gneisses as does undulose extinction in most of the quartz grains.

In summary the Laxford gneisses represent greywackes that have suffered at least one period of granulite facies metamorphism followed by a hydrous, amphibolite facies metamorphism.

THE EARLY IGNEOUS ROCKS

The early igneous rocks recognised in the Laxford area are peridotites, pyroxenites (or hornblendites), alkaline and tholeiitic basalt types, anorthosites and diorites.

The Ultrabasic rocks.

Metaperidotites of the Laxford area have not been analysed. Bowes et. al. (1964) state that the ultrabasic (metaperidotitic) rocks in this area occur as small isolated masses. In some cases it has been found that garnet-pyriclasites and certain amphibolites occur in close proximity (pp. 71-72) although an actual contact has not been seen. For this reason the metaperidotites are considered to form part of a peridotite-gabbro-anorthosite suite similar to those described by Dearnley (1963) from South Harris and Bowes et al. (1964) from the Scourie-Lochinver district.

In the relatively unaltered metaperidotites prominent mineralogical layering is present, similar to that interpreted as primary igneous mineralogical layering by Bowes et al (1964). In those that have suffered an extensive hydrous metamorphism mineralogical layering is apparently absent. The vertical nature of the mineralogical layering of the metaperidotites is attributed to NW-SE fold movements of Laxfordian age by Bowes et al. (1964).

Hornblendites occur as isolated bodies or in proximity to metaperidotites, garnet pyriclasites and certain amphibolites. In the latter case they may be considered to form part of the peridotite-gabbro-anorthosite suite (cf. Bowes et al., 1964, p.161). In the former case they may represent parts of the same suite that have become detached either prior to final emplacement or during a post-consolidation phase. There is no evidence either that they originally crystallised as hornblendites or that they represent pyroxenites that recrystallised as hornblendites during the Laxfordian metamorphism.

The small pods and lenses of hornblende are considered to have been formed by metamorphic segregation (p. 185) but this mode of origin is discounted for the larger hornblendites mainly because of their size and close association with other basic and ultrabasic rock types.

Certain metaperidotites have an olivine-orthopyroxene mineral assemblage that appears to indicate a former granulite-facies metamorphism. However, they have suffered a retrogressive, hydrous (= Laxfordian) metamorphism which has produced tremolite-actinolite-chlorite-iron ore rocks and phlogopite-tremolite-chlorite-iron ore rocks as end products, in the formation of which several intermediate stages are seen. The former group probably represents an approximately isochemical transformation, apart from the addition of the hydroxyl molecule, whereas the latter involves an allochemical transformation with the addition of potassium and the hydroxyl molecule. Relict granulite facies mineral assemblages indicate that portions of the metaperidotite have resisted the retrogressive metamorphism. Ultramafic rocks are now represented by hornblendites or biotite-rich rocks in shear zones that facilitated the introduction of potassium. Watson (op.cit.) suggests that hornblende and biotite predominate north of Laxford Bridge whereas biotite and actinolite predominate to the south. Present investigations show rocks bearing those mineral varieties can be found at various localities throughout the area.

<u>The garnet-pyriclasites and amphibolites.</u>

It is difficult to establish conclusively a mode of origin for amphibolites, the more so as the intensity of metamorphism and metasomatism increases. Walker et al. (1960) have tried several methods in an attempt to determine the origin of all the amphibolites from North-western Queensland and, although no method was entirely successful, they conclude that amphibolites unaffected by metasomatism have certain chemical properties, in particular their trace-element content, that can be considered diagnostic of basic igneous

Outer Hebrides can be classified as metatholeiites and garnet-pyriclasites of the Scourie district as metagabbros (cf. Bowes et al., 1964).

Since the amphibolites are (1) chemically similar to certain groups of igneous rocks (2) do not exhibit any sedimentary feature and (3) are often closely associated in the field with other meta-igneous types, namely metaperidotites, plagioclasites and garnet-pyriclasites, it seems probable that they represent metamorphosed igneous rocks. However, it has been suggested by Walker and others (1960) that a very low TiO_2 content and the presence of scapolite may indicate a sedimentary origin for the amphibolite. B412 is such an amphibolite but, as sedimentary rocks rarely have as high Cr and Ni values as those of B412 (Table 14) it is concluded that this specimen is more probably igneous, its high Cr content suggesting that it is an early differentiate from the parent alkali-basalt magma.

Some of the amphibolites are discordant and such evidence may support an igneous origin. However, Engel and Engel (1962 a) describe minor discordances at gneiss-amphibolite contacts, suggesting a tectonic origin for them and it is possible that many of the discordances in the Laxford area originated in the same way.

Garnet-pyriclasites from the Laxford area have not been analysed. At this stage they are tentatively correlated with similar rocks from the Scourie district and, therefore, termed metagabbros. The possibility that these rocks are metatholeiites is of great significance and is discussed later (p.205). L12, L15 and B412 contain a pale green, non-pleochroic augite and in this thesis the pyroxene-bearing amphibolites are regarded as the amphibolite facies equivalents of gabbroic rocks while the garnet-pyriclasites are the granulite facies equivalents. Certain garnet-pyriclasites are flanked or enclosed by amphibolite. It seems probable that the gabbroic types were transformed first into garnet-pyriclasites under granulite facies conditions (≡ early metamorphism) and later, partly or completely, to amphibolites (metagabbros) by a retrogressive amphibolite facies hydrous metamorphism (≡ Laxfordian). The metagabbros of the Laxford area are similar to the metagabbros of the Outer Hebrides (Dearnley, 1963) and of the Scourie district (Bowes et al., 1964).

The chemical compositions expressed as weight per cent norms and trace-element contents of the three meta-tholeiites (L50, L77 and B355) are remarkably similar to those of the Scourie dykes analysed by

O'Hara (1961a) and Burns (1958) (Table 14) and probably represent the metamorphosed equivalents of the Scourie dyke suite of Sutton & Watson (1951). They are also similar to the dyke rocks from the Outer Hebrides (Dearnley, op.cit.).

Assuming that metasomatism has played only a minor role in the development of the amphibolites (c.f. Leake, 1964) and garnet-pyriclasites, it can be concluded that these metamorphic rocks are representatives of two suites of basic igneous rocks; they are either meta-gabbros or meta-tholeiites. The present mineralogy and chemistry of these rocks is the result of the Laxfordian metamorphism.

The mineralogical relationships indicate that the metamorphism first produced a granoblastic, in some cases garnetiferous, hornblende-plagioclase rock, but a phase of more intense (= Upper amphibolite) metamorphism resulted in the formation of a pale-green augite that replaced and enclosed hornblende in a number of amphibolites. However, the widespread occurrence of epidote-oligoclase assemblages in the acid gneisses suggest that epidote-amphibolite facies conditions prevailed during the latter stages of the Laxfordian metamorphism. Scapolitization appears to have affected the gabbroic amphibolites but not the tholeiitic varieties.

Chemically and mineralogically the amphibolites are similar to those from the North-west Adirondack Mountains as described by Engel & Engel (for example, 1962 a). The main mineralogical difference is that the Laxford amphibolites tend to be slightly more sodic. Engel & Engel (1962a) suggest that the mineral assemblage green hornblende-andesine-quartz-ilmenite is stable at 525°C and that a pale green, apparently nonpleochroic clinopyroxene first appears at 550°C (Engel, Engel & Havens, 1964). It appears possible that similar temperatures were attained during the Laxfordian metamorphism although the more sodic plagioclase may indicate the occurrence of a temperature of less than 500°C on the assumption that plagioclase becomes more sodic as the temperature decreases (cf. Engel & Engel, 1962a). It is significant that the appearance of a pale green clinopyroxene coincides with the disappearance of quartz, indicating that quartz decreases with increasing metamorphic grade (c.f. Engel & Engel & Havens, 1964).

The Plagioclasites

The Cnoc nan Cro gneisses, consisting of striped muscovite and/or scapolite-bearing rocks, form a distinct belt and represent the main development of plagioclasites. As noted by Edwards and Baker (1954) regional scapolitization must be rather unusual for it is rarely described in the literature. While the scapolite-bearing rocks of the Laxford area cannot be described as regionally developed their thickness and extent makes them locally important. Further examples of scapolite-bearing rocks have been described by Davidson (1943) and Dearnley (1963) from the Outer Hebrides.

Other plagioclasites in the Laxford area usually occur (1) interbanded with amphibolites (2) as the felsic component of striped amphibolites and (3) as felsic streaks in amphibolites.

The several modes of occurrence of the plagioclasites suggest that these rocks have originated through more than one process or a combination of processes.

A high alumina content is a feature common to the five analysed plagioclasites and probably to all plagioclasites. The only possible sedimentary parent is a residual, alumina-rich clay, but it is unlikely that such a clay could accumulate in the same sedimentary environment as greywackes (see pp.179-80). These plagioclasites are, therefore, more likely to be either igneous or metamorphic in origin.

Davidson (1943, p.89-90) describes the anorthosite gneisses of South Harris as consisting "essentially of a glassy plagioclase, sometimes in part replaced by scapolite", with variable amounts of ferromagnesian mineral constituents. As the latter, particularly pyroxene, garnet, and hornblende, increase, the anorthosites pass into rocks that "might be better termed feldspathic metagabbros". A similar range in the proportions of felsic and mafic mineral constituents is seen in the Cnoc nam Cro gneisses. In addition the striping, which varies from 1 mm. or so to several centimetres and, by including the interlayered amphibolites, grades into banding, is similar in both series of gneisses (c.f. p.97 and Dearnley, 1963, p.282). An important difference between the South Harris anorthosite gneisses and those of Laxford is to be found in the anorthite content of the plagioclase. The plagioclase from South Harris lies in the labradorite-bytownite range, varying from An_{61} to An_{74} (Dearnley, 1963, p.264) whereas the plagioclase from Laxford lies in the andesine range, varying from An_{32} to An_{37}. Another difference is that the ferromagnesian mineral constituents are represented predominantly by hornblende, epidote and biotite in the

Laxford area. Both these differences probably reflect variations in the metamorphic facies, for the anorthosite gneisses of South Harris are granulite facies rocks (Dearnley, 1963, p.293) whereas in the Laxford area the plagioclasites are amphibolite facies rocks.

The chemical composition of the Cnoc nan Cro gneisses is similar to that of the anorthositic gneisses of South Harris, except that the former gneisses contain rather more FeO, Fe_2O_3, MgO and K_2O (p.103). The amounts of FeO, Fe_2O_3 and MgO in the pure plagioclasites are thought to be negligible. The analyses correspond to the "felspathic metagabbros" of Davidson (1943). The high values of K_2O reflect the partial or complete alteration of scapolite to muscovite (p.102). The analyses are similar in many ways to those of a number of anorthosites (Table 16). Thus, the geochemistry appears to indicate an igneous origin.

The consistent occurrence of striping, similar to that of the acid gneisses, in the Cnoc nan Cro gneisses suggests that this feature is at least partly metamorphic in origin. Striping in the amphibolites of Connemara is considered by Evans & Leake (1960) to be metamorphic in origin whereas Dearnley (1963, p.282) considers that similar banding (= striping) of anorthosites and accumulative gabbros in South Harris is mainly igneous in origin. There is, however, insufficient information on the striping in this area for any conclusion to be drawn.

While thin streaks or stripes of plagioclasite may be either tectonic in origin or due to metamorphic differentiation it seems unlikely that thick bands (60 cm.) of plagioclasite interlayered with amphibolite are not metamorphic in origin. However, in one case a gradual increase in the volume of mafic minerals present in a plagioclasite band towards the amphibolite was noted, although there was a sharp, distinct contact between the two rock types (p.96). Fig.14 shows the cationic and trace-element variation between these two rocks. A very extensive movement of material must have taken place if these rocks are the products of metamorphic segregation (local metasomatism). The alternative hypothesis that these rocks represent two different igneous rock types with the variation within the plagioclasite being explained by igneous differentiation or local mafic metasomatism is preferred.

The close association of plagioclasites with amphibolites, as is commonly observed within the Cnoc nan Cro gneisses, suggests that they may be genetically related, thus emphasising the hypothesis of an igneous origin for many of the plagioclasites.

No goechemical work has been done on the plagioclasites that form the minor part of a unit. However, they display features similar to those described by Bowes and Park (1966) from the Loch Kerry basite sheet, to which an origin through metamorphic segregation is ascribed. It is possible, therefore, that some of the plagioclasites are the products of localised metamorphic segregation.

It is concluded that many of the plagioclasites (including all the Cnoc nan Cro gneisses) represent anorthosites that have been extensively altered during the Laxfordian metamorphism. The alteration of the anorthosites can be considered in three stages thus: (1) scapolitization, (2) decalcification and (3) potassium metasomatism.

Scapolite is a common constituent of the Cnoc nan Cro gneisses and other plagioclasites. In L231 and X1 the ratio CaO : Na_2O suggests that the scapolite present in these rocks is probably of the meionite variety.

Scapolitization is considered to be a metasomatic phenomenon. It is possible that the Na metasomatism affecting the gneisses of the Laxford area (p.182) (cf. Edwards & Baker, 1953) involved large amounts of volatiles, particularly Cl_2 and SO_3 and produced scapolitization of the anorthosites and associated amphibolites

(= metagabbros?) by the following reaction:
labradorite-bytownite + volatiles (+Na)→ Ca-rich scapolite + oligoclase-andesine.

Many of the plagioclasites contain plagioclase of the oligoclase-andesine varieties and their analyses show correspondingly higher values for Na_2O (Table 16 analyses 1&3). This suggests that a decalcification process has affected the anorthosites. Presumably Na metasomatism played an important role in this process and it seems probable that scapolitization and decalcification occurred at the same time. Decalcification has followed two trends thus: (1) plagioclasites, in which oligoclase-andesine is the feldspar, have been formed and Ca has been removed from the system and (2) plagioclasites, in which oligoclase-andesine in the feldspar and Ca has been fixed in epidote, have been formed.

The plagioclase of the Cnoc nan Cro gneisses is often strongly sericitized and scapolite may be altered to muscovite. The intense sericitization and muscovitization are considered to be the result of K metasomatism that is associated with the intrusion of the Cnoc nan Cro micrograntes. This indicates that the scapolitization occured prior to the intrusion of the granitic rocks.

The Metadiorites

The geochemistry of the metadiorites resembles that of the gneisses which are considered to represent metamorphosed metagreywackes (pp. 179-80); for example the ratios Na : K and Mg : Fe^2+Fe^3 are very similar. However, these rocks are clearly distinguishable from the gneisses in the field. In fact their homogeneous nature allowed the use in the field of the term metadiorite with its obvious genetic significance. A sedimentary origin was considered doubtful from field evidence.

Further support for an igneous origin is as follows:-

1. The metadiorites are mineralogically and chemically similar to the tonalites of the Outer Hebrides, as described by Dearnley (1963) (Table 17).

2. While further confirmation is necessary, plots of K against Na (fig. 15) suggest that K decreases as Na increases and this appears to indicate an igneous trend.

3. The rocks can be classified as diorites chemically and normatively (Table 17).

It is concluded that the metadiorites are probably igneous in origin. The Laxfordian metamorphism has produced granoblastic hornblende-biotite-plagioclase rocks (cf. Dearnley, 1963). The extent to which the presence of biotite reflects K metasomatism is conjectural because much of that mineral may have been formed during the mineralogical reorganisations that occur under amphibolite facies metamorphic conditions.

The Significance of the data on amphibolites and garnet-pyriclasites

The use of a period of dolerite dyke intrusion as a time marker in distinguishing the Laxfordian from the Scourian metamorphism by Sutton & Watson (1951) has been strongly criticised recently (Bowes 1962a) on the grounds that the (meta-) dolerites (or amphibolites) may not represent one intrusion. The present study has shown that the amphibolites of the Laxford area fall into two groups, conveniently termed the meta-tholeiites and meta-gabbros.

Several amphibolites in the Laxford area contain a core of garnet-pyriclasite. If these rocks are metatholeiites belonging to the Scourie dyke suite a granulite-facies metamorphism post-dates this intrusion, an event recognised in the Outer Hebrides by Dearnley (1963) but not on the mainland. In the absence of further evidence supporting this hypothesis it is considered that these rocks should be classified as metagabbros.

The most noticeable effect of the Laxfordian metamorphism is the production of similar looking amphibolites from gabbroic and tholeiitic rocks. Some of the gabbroic varieties contain stout prisms of hornblende, whereas many of the tholeiitic varieties contain granular hornblende, but these features cannot be considered diagnostic. From their field relations, and mineralogy, it is virtually impossible, in some cases, to distinguish one suite from the other. It seems unwise, therefore, that all the amphibolites of the Laxford area should be considered as the metamorphosed equivalents of the Scourie dyke suite until their geochemistry is known in detail.

The early igneous rocks as a series.

The meta-igneous rocks of the Laxford area are similar in many respects to the orthogneisses of the Outer Hebrides. Dearnley (1963) believes that these gneisses are related and belong to an igneous complex. Each member of this complex has a counterpart in the Laxford area where the metaperidotites, occasional ultramafic bodies, garnet pyriclasites, certain amphibolites and the plagioclasites are closely associated in the field and from their geochemistry they could be related in the same way, although geochemical evidence similar to that of Dearnley is lacking.

For the rocks of the Laxford area, the Niggli values fm, al, c, alk and mg have been plotted against si (fig. 11). The graphs of fm, al and alk suggest an igneous trend, particularly when the trondhjemitic rocks are included. While the trondhjemitic rocks are thought to represent a sodic injection complex (pp. 213-4) the possibility that some of these bodies may be end-members of an igneous complex cannot be completely discounted.

The basic rock-types also resemble the metamorphosed representatives of a peridotite - gabbro - anorthosite suite described by Bowes and others (1964) from the Scourie district.

It, therefore, seems reasonable to conclude that a number of the meta-igneous rocks of the Laxford area form part of an igneous series. Since the meta-tholeiites have not suffered a granulite facies metamorphism they do not form part of the igneous series. Trends of evolution may be similar to those postulated for the Lewisian intrusive suite of the Outer Hebrides by Dearnley (op.cit.). It can be concluded that after the series intruded the host gneisses there occurred the Early granulite facies metamorphism followed in turn by an amphibolite facies (Laxfordian) metamorphism.

The Granitoid Rocks

Sutton & Watson (1962) consider that "granitic" rocks were emplaced throughout the Laxfordian metamorphism. The oldest "granitic" rocks are those that are folded and the youngest are the "late-foliated granites" that are thought to fill late shears. It has been shown in this thesis that the granitoid ("granitic") rocks can be divided into two distinct and unrelated groups: (1) the sodic (trondhjemitic) varieties and (2) the potassic (granitic) varieties.

The Trondhjemites

In the Laxford area trondhjemites and coarse grained trondhjemites are extensively developed and commonly cut the foliation of the gneisses and amphibolites (p. 72). Their discordant nature suggests that they may be magmatic. The alternative hypothesis is a metamorphic-metasomatic mode of origin that involves either a feldspathization of interlayered quartzites (Gavelin, 1960) or a segregation of quartzo-feldspathic material from gneisses and amphibolites (Ramberg, 1956).

In addition, there is the complication that the trondhjemites can be divided into two main types thus: (1) those that are either folded or intimately associated with the host rock and (2) those that cut the folds, the foliation or both. In the absence of other evidence, it is considered that the formation of trondhjemite started in the early stages of the Laxfordian metamorphism and continued until the folding and foliation had developed. Certain trondhjemites that cut across the Laxfordian foliation are themselves folded (p. 72).

The evidence from the contorted trondhjemites containing wisps of crenulated biotite flakes, from trondhjemites in which streaks and wisps of biotite are particularly abundant near the margins, and from trondhjemites that intimately vein and penetrate basic material, attests to the interaction between these trondhjemites and their host rocks, usually amphibolites. Three further important facts are (1) the streaks and wisps of biotite may carry small amounts of hornblende, (2) hornblende is occasionally present in small pods or lenses of trondhjemite in amphibolite and (3) in certain trondhjemites plagioclase forms a linked network that entirely encloses quartz and the other mineral grains.

A linked network of plagioclase is often interpreted as indicating feldspathization (eg. Coombs, 1955) although this feature can also be explained by assuming that plagioclase was the last mineral to crystallise or recrystallise. Lenses of trondhjemite, particularly when they contain the minerals of the host rock, have been interpreted as metamorphic segregations (Ramberg, 1956). Feldspathization, particularly through a process of metamorphic segregation, receives support from the fact that basic material associated with the intense network-veining of trondhjemite in an agmatitic structure usually contains considerably more hornblende than the normal amphibolite.

The mineralogical and chemical composition of the trondhjemite shows considerable variation, although most of the discordant varieties have a composition similar to that of L14, L136a and B2B1 (see Table 18a). The highly variable plagioclase content of the trondhjemites could be due to feldspathization. The process envisaged could be similar to that described by Gavelin (1960) whereby quartzite veins associated with the host rocks are feldspathized, the feldspathic material being produced by the latter, or simply by metamorphic segregation. However, as the amount of quartz present in the trondhjemites (40% or more in certain varieties) is rather more than could reasonably be expected to be derived from basic rocks by metamorphic segregation, the presence of this mineral is due to its introduction either as vein quartz or as a component of a trondhjemitic fluid. The occurrence of vein quartz necessitates the introduction of the components of plagioclase eg., by feldspathization or sodium metasomatism.

The trondhjemites that occur as concordant or discordant veins and sheets are usually homogeneous and chemically similar and, thus, appear to be magmatic in origin. Assuming that most of the homogeneous trondhjemites are magmatic the other heterogeneous trondhjemites can be explained in two ways:-

1. They may represent various stages of metamorphic segregation of quartzo-feldspathic material, the homogeneous trondhjemites being the mobile end-members.

2. They may represent the various stages of reaction between a watery, volatile-rich metasomatic fluid of approximately trondhjemitic composition and the amphibolites.

The agmatitic developments and wisps of biotite containing relics of hornblende are considered to support the latter hypothesis. There may be a gradation from a magmatic to a metasomatic fluid, with the occasional trondhjemitic pegmatites representing intermediate products. This interpretation differs from that of Bowes & Park (1966) who conclude that metamorphic segregation produced similar occurrences of quartzo-feldspathic material in the Loch Kerry Basite.

Sodium metasomatism has also played an important part in the development of the gneisses and early igneous rocks in which scapolitization is a common feature of this metasomatism. Thus, it can be reasonably concluded that the trondhjemitic rocks are manifestations of a trondhjemitic injection complex and associated metasomatism. The features of this igneous and metasomatic activity are comparable with those produced by the granitic injection complex.

Migmatites in which trondhjemite forms the granitoid part are not easily recognised because of the general predominance of plagioclase in the gneisses.

In a few cases migmatites have been seen, but it is concluded that they are rather poorly developed. Thus, this is one instance where there is a notable difference between the trondhjemitic and granitic injection complex.

The injection of trondhjemitic material is perhaps the earliest manifestation of the Laxfordian metamorphism. While the composition of the trondhjemitic material remained essentially constant throughout the injection phase, there is evidence that variations in the composition of the metasomatic fluids do occur, as shown by the variation in the plagioclase content from about 55% to almost 100% (if rocks with such high plagioclase content can still be termed trondhjemites). The composition of the normal trondhjemite is considered to be that of L136a or L14 (Table 18a) and it can be concluded that these analyses represent the composition of the trondhjemitic magma.

THE GRANITIC ROCKS

In the descriptive section of this thesis the granitic rocks have been divided into five groups: (1) the Cnoc nan Cro Group, (2) the Badnabay Group, (3) the Laxford Quartzo-feldspathites, (4) the Micrograhite/trondhjemite bodies and (5) the NE-SW Pegmatites. The division is based on field and petrographical differences and is confirmed by the geochemistry; it indicates that the formation of granitic and allied rocks has been a complicated process or combination of processes.

Clough (op.cit.) recognises one group of magmatic granites and Peall (op.cit.) concludes that the intrusive magma was homogeneous. Watson describes two groups of granitic rocks, namely the Rudha Ruadh granite gneisses of the Badnabay zone, which she considers representative of "the most strongly metasomatised parts of the banded complex", parts of which became mobilised (Watson, op.cit., p.287), and the late-foliated granites of the Laxford zone, which she considers to be intrusive and presumably magmatic. Clearly, similar evidence has been interpreted in different ways.

General criteria for the origin of the granitic rocks.

Granitic rocks may be magmatic, anatectic or metasomatic in origin (Read, 1957). In the Laxford area many of the features of each group of granitic rocks can be attributed to any of these modes of origin. However, certain general criteria that have been used to establish an origin for each group can be listed.

A magmatic origin is probable if the following conditions are satisfied:-

1. The chemical composition of the rocks is such that the Q - Ab - Or ratios plot near the eutectic minima for various water-vapour pressures in the Q - Ab - Or - H_2O system of Tuttle & Bowen (1958) i.e. the rocks have a "true granite" composition.

2. The rocks are essentially homogeneous.

3. Potash feldspar does not show petrographic evidence that would indicate it to be much younger than the other minerals.

4. There is evidence of mobility.

5. Pressure-temperature conditions were such that a magma of the required composition could exist at the site of crystallization.

Evidence that favours a metasomatic origin is difficult to evaluate, but such an origin is probable if the following conditions are satisfied:-

1. The rocks do not satisfy the conditions necessary for a magmatic origin. Although this is a negative condition, it is probably the most useful.

2. The rocks contain relics of unaltered rocks. This condition can only be used to support other evidence since relics (or inclusions) are present in many magmatic granites, for example the Donegal granite (Pitcher & Read, 1959).

3. The rocks exhibit relict features which have their counterparts in the unaltered rocks.

An anatectic origin is probable if the following conditions are satisfied:-

1. There is evidence in favour of local small-scale melting, that is the bodies are small.

2. The bodies are strongly discordant with a bulbous habit.

These criteria can be discussed with reference to each group.

At this stage it can be concluded that an origin by anatexis in situ for the Cnoc nan Cro and Badnabay Groups is extremely unlikely because potassium-poor gneisses can produce only small amounts of granitic material by this process. The evidence and conclusions bearing on the origin of the Cnoc nan Cro and Badnabay groups are listed in Table 22.

EVIDENCE	CONCLUSIONS	Cnoc nan Cro group	Badnabay group
Limited compositional range.	Homogeneous sheets of similar composition support a magmatic origin.	x	o
Wide compositional range.	Wide range of compositions suggests either a metasomatic origin or a sequence of intrusions from a differentiating source.	o	x
Textures tend to be granoblastic.	Metasomatic or late-stage magmatic activity was important.	x	x
Mineral relationships are complex.	Very complex history of formation.	x	x
Cataclastic deformation affecting granitic sheets but not adjacent gneisses.	Possibly post-crystallization movement within each sheet.	x	o

EVIDENCE	CONCLUSIONS	Cnoc nan Cro group	Badnabay group
The sheets are discordant to the gneisses and occasionally furcate.	Indicative of movement of material, either liquid or semi-solid.	x	o
The rocks are foliated, the foliation usually being parallel to the margins	In the case of discordant sheets foliation developed during movement. The last movement occured in a solid medium.	x	x
The contacts between the granitic rocks and the gneisses are always sharp and there is no diminution of grain-size at the edges of the granitic sheets.	No reaction between the granitic rocks and gneisses, the former having attained equilibrium withiin the pressure-temperature conditions of the epidote-amphibolite facies.	x	x
Migmatites are developed.	Authors have used this criterion in favour of both magmatic and metasomatic origins.	x	o
Parallel inclusions of amphibolite and gneiss, showing no evidence of contamination, occur.	Reactions between the granitic rocks have been minimal if not entirely absent.	x	x
Inclusions of amphibolite show an increase in potash feldspar.	Occasionally there is evidence of potassium metasomatism.	–	o
Heterogeneous nature of the sheets, e.g. banding and mafic streaks.	Support for a metasomatic origin or (post-?)magmatic differentiation.	o	x
The sheets may be folded and veins within a sheet are apparently folded.	Suggests a deformative period during the late stages of formation and may apply to both modes of origin.	x	x
The composition of the granitic rocks is near the minimum-melting composition in the granite system.	Crystal-liquid equilibrium may have determined the composition of the granitic rocks.	x	o
Wide variety of plots on the Q-Ab-Or triangular diagram, consistently below the minimum-melting composition.	Supports a metasomatic origin although a process of magmatic differentiation is also possible.	–	x

– = absent

o = poorly expressed

x = well developed

Table 22 A summary of the evidence and conclusions from the granitic rocks.

the Cnoc nan Cro Group.

The plots of the Q - Ab - Or ratios of the Cnoc nan Cro microgranites, particularly those derived from the mesonorm, fall so close to the position of minimum melting at different water-vapour pressures (fig.21) that crystal-liquid equilibrium seems probable. Further, the addition of normative An displaces the minimum melting composition towards the Or apex of the triangle (cf. a personal communication by Bowen in Eskola,1956), bringing the plots of the Cnoc nan Cro microgranites even closer to the minimum melting compositions at different pressures. This approximation of the composition of the Cnoc nan Cro microgranites to the experimentally determined minimum melting composition provides strong evidence in favour of a magmatic origin. In connectioh with the applicability of the experimental data of Tuttle & Bowen (1958) to these microgranites , it is interesting to compare the average mineralogical and chemical composition of the Cnoc nan Cro microgranites with that of the granite used by Tuttle and Bowen (1958), thatis, the

Westerly granite which is also around 1 mm. in grain-size and considered to be magmatic in origin (Chayes, 1952). From Table 23 it is clear that they are similar and it is likely that if a Cnoc nan Uro microgranite had been used by Tuttle & Bowen in their experiments rather than the Westerly granite a similar melting curve would have been established for compositional differences between them are no greater than between the Westerly and Quincy granites, both of which gave the same minimum melting curve, within experimental error. Moreover, this curve coincides with the minimum melting curve found for the isobaric quaternary minimum in the system albite - orthoclase - quartz - water.

Therefore, the Cnoc nan Uro microgranites have a composition which is consistent with formation from a granitic melt.

Since the normative composition of the microgranites does not lie at the "ternary" eutectic at 4,000 kg/cm^2 water vapour pressure or near the minimum at 3,000 kg/cm^2 (fig. 21), the granitic magma, according to Tuttle & Bowen (1958), could not have been saturated with water. However, considerable water must have been present to account for the large amounts of biotite and muscovite present in the microgranites. In addition, it is considered unwise to attempt to establish the water content of an anorthite-bearing microgranite by projecting its composition into an anorthite-free system.

	Westerly granite	Cnoc nan Cro microgranite
SiO_2	72.34	71.26
Al_2O_3	14.34	14.86
Fe_2O_3	0.63	0.91
FeO	1.13	0.92
MgO	0.37	0.62
CaO	1.52	1.40
Na_2O	3.37	3.75
K_2O	5.47	5.21
TiO_2	0.26	0.30
MnO	0.02	0.02
H_2O^+	0.30	0.59
H_2O^-	0.06	
Quartz	27.1	26.5
K feldspar	35.0	31.2
Plagioclase	32.2	31.1
Others	5.8	11.1

Table 23 A comparison of the chemical and modal composition of the Westerly granite and the Cnoc nan Cro microgranite (average).

The Cnoc nan Cro granite (L118) plots within the field of the microgranites when plotted on the Q - Ab - Or triangular diagram (Fig. 21). Most other granites have a mineralogical composition similar to L118, and, therefore, would probably also fall within the field of the micro-granites.

The Cnoc nan Cro pegmatites are potash-rich and plots of the Q - Ab - Or ratios lie towards the Or apex of the Q - Ab - Or triangular diagram. However, this evidence is not sufficient to preclude the possibility of a magmatic origin for these pegmatites since similar rocks are often considered to be the result of rather unusual magmatic conditions (Hatch et al, 1961).

The microgranites appear to be homogeneous and very similar to one another in the field, giving the impression that they are closely related and represent the intrusion of a series of sheets of material derived from a common source, presumably a granitic melt of some kind. The thin ribs of granitic material that vary in grain-size from 2 mm. to 6 mm. (p. 128) are also usually homogeneous. Similarly patches and sheets of granite are essentially homogeneous although potash feldspar exhibits a streaky distribution in a few narrow veins of granite (p. 129). Pegmatites are as homogeneous as can be expected in very coarse-grained rocks although the highly variable grain-size does not allow an accurate determination of homogeneity to be made. Therefore, the Cnoc nan Cro group essentially fulfills the magmatic condition of homogeneity.

Evidence of mobility can be seen in the discordant relationships with the host rock. The Cnoc nan Cro sheets commonly cut across the host gneisses and several sheets are seen to furcate (p.124) so that there can be little doubt that they were fairly mobile. Although the Cnoc nan Cro sheets displayed considerable mobility there is no evidence in favour of a forceful intrusion of mobile material. Rather the field evidence of relict blocks of gneiss, which vary in dimensions from 15 cm. across by 25 cm. long to 10 cm. across by 50 metres long and which retain their original orientation (p.127), suggests either a passive introduction of material or a directionally controlled intrusion. Such relics can also be interpreted as bodies that have resisted the processes whereby homogeneous granitic rocks are produced by potassium metasomatism (c.f. Read, 1957). However, in the case of the Cnoc nan Cro microgranites and granites this interpretation can be discounted by the apparent absence of even slight potassium metasomatism in the relics in contrast to similar gneisses outside the granitic sheets (p.127). Relict patches of gneiss in pegmatite are considered by Ramberg (1956) to indicate the development of the pegmatites in situ. Relics of gneiss in the Cnoc nan Cro pegmatites are not always aligned parallel to the foliation of the adjacent gneisses and in some cases occur parallel to the margins of strongly discordant pegmatites, so that structural control must be ruled out. Pegmatites, therefore, may be metasomatic in origin or, possibly magmatic if a process is invoked whereby a granitic magma can produce a highly mobile liquid which is substantially enriched in volatiles, particularly water, and other hyperfusibles. Such a liquid may approach the composition of the agent of potassium metasomatism.

Temperature-pressure conditions at the time of formation of the granitic rocks are, unfortunately, difficult to establish. There are no chilled contacts to the granitic sheets and the host rocks show no signs of contact metamorphism. Therefore, the temperature of the melt, the existence of which is suggested by the previous evidence, was probably not much higher than the then-existing temperature of the host gneisses.

The gneisses at present belong to the epidote-amphibolite facies of Ramberg (1952) or to the staurolite-quartz sub-facies of the almandine-amphibolite facies of Fyfe et al.(1958), although evidence from the basic rocks suggests that the epidote-amphibolite facies was preceded by the amphibolite facies of Ramberg (1952). Fyfe et al. (1958) consider the minimum temperature for the above-mentioned facies to be 500°C at 6,000 bars P_{H_2O} whereas Ramberg considers that temperatures above 500°C are uncommon in the amphibolite facies. Thus the maximum temperature prevailing in the gneisses during the Laxfordian metamprphism was probably in the region of 500°C to 550°C.

Although muscovite often forms after plagioclase and can thus be considered to be a late-stage mineral, as it is also cut by biotite, one of the first minerals to form, some muscovite is early and probably represents a primary phase. Thus a temperature in the region of 650 - 700°C may reasonably be proposed for the granitic sheets (Yoder & Eugster, 1955), during formation.

A water-rich granite is liquid at temperatures of approximately 650°C at depths greater than 13 km. (Tuttle & Bowen, 1958). Assuming a geothermal gradient of 30°C/km. and a rate of increase of geothermal gradient of 6°C/km/km (Tuttle & Bowen, op.cit.), gneisses at a depth of 10 km. would be at a temperature of 570°C. Although the rate of increase of geothermal gradient may decrease with depth, it appears unlikely that the gneisses were at a depth much greater than 10 km. during the formation of the Cnoc nan Cro granitic rocks. Thus, if these rocks are magmatic, their state at the time of emplacement was probably a mush of crystals and liquid rather than a melt.

In summary, at this stage, the evidence from the Cnoc nan Cro group of granitic rock favours a magmatic origin.

The Badnabay Group

The plots of the Badnabay micrognanites and associated rocks on the Q - Ab - Or triangular diagram show a wide scatter, emphasising the heterogeneity of this group. With the exception of the leucocratic varieties, the relative quartz content is less than 20%, so that the plots fall below the triangle within which all granites should lie, according to Tuttle & Bowen (1958)(see fig. 21). They suggest that such rocks be given different names to distinguish them from the "granites proper". Globally they are rare "compared with the 'average' granite or rhyolite" (Tuttle & Bowen, 1958), but in the Laxford area they probably occupy an area as large in extent as the rocks which are 'granites' in Tuttle & Bowen's classification. Most of the rocks of the Badnabay sheets are considered to be microgranites for reasons previously given (p. 119) although rocks with a similar quartz content have been described by Buddington (1948) as quartz-syenites. In the diagram it is significant that the one established trend is towards the Q - Ab sideline (S24→S26), the opposite to what might be expected during a magmatic differentiation-crystallization history. There is a wide discrepancy between the plots of the Badnabay microsyenites and the plots of other syenites, presumed to be of magmatic origin(fig. 21). The plots of the Badnabay leuco-microgranites, however, fall close to the locus of the minimum melting compositions for different pressures (fig. 21), indicating that crystal-liquid equilibrium possibly existed in these microgranites and that for these varieties a magmatic origin is possible.

Most of the members of the Badnabay group, therefore, do not satisfy the first requirement for a magmatic hypothesis.

Many of the Badnabay sheets are homogeneous, being composed of either microgranite or microsyenite and the greater proportion of both the Rudha Ruadh and Loch na Seilge sheets is composed of both these homogeneous varieties. However, occasional sheets are composed of layers, 10 cm. to 1 metre thick, of microgranite, microsyenite and leucocratic microgranites, striping analogous to that in the gneisses is seen in the microgranites at several localities (p. 151) and the geometry of certain mafic streaks in the Rudha Ruadh sheet suggests relict folding (p. 145). Usually the mafic stripes and streaks contain amounts of potash feldspar similar to those present in the more leucocratic portions. Such a homogeneous distribution of potash feldspar regardless of the mineral composition is considered to be due to a potash feldspar enrichment after the stripes had formed. In addition the highly variable nature of the leucocratic ribs (p. 146) is not easily explained on a magmatic hypothesis.

Evidence of mobility in the sheets can be seen in the discordant relations with the host gneisses. Furcation is not seen and in general the Badnabay group shows discordant relations less commonly than the Cnoc nan Cro Group, although this may be partly due to the lack of suitable exposures and, in particular, vertical section.

Temperature-pressure conditions during the formation of the Badnabay group were probably similar to those of the Cnoc nan Cro group. However, in the absence of muscovite or another mineral suitable for geothermometry, the crystallization of minerals above 500°C, the temperature of the metamorphism, cannot be established. Therefore, the temperature-pressure conditions must remain hypothetical for this group.

Thus the evidence in favour of a magmatic origin is rather contradictory and some features, particularly the mafic stripes and streaks, are considered to be irreconcilable with such an origin. Therefore, the first requirement of a metasomatic origin is partially satisfied (p. 217).

Many of the Badnabay sheets contain relict patches and lenses of gneiss and amphibolite. Most of the relics do not show evidence of potassium enrichment relative to similar adjacent rocks. However, certain relict patches of amphibolite in the Rudha Ruadh sheet show various stages of potassium enrichment in the form of potash feldspar, the culmination of which may be the formation of the more mafic microsyenites. Thus, there is some evidence that at least the microsyenites of the Badnabay group may be metasomatic in origin.

Other relict features that support a metasomatic hypothesis have already been described (p.226).

The Laxford Quartzofeldspathites

The Laxford Quartzofeldspathites have been separated from the trondhjemites and the granitic rocks on the basis of field relationships and mineralogical composition. However, the quartzofeldspathites exhibit rather similar mineral relationships to those rocks, indicating that the processes in action during the latter stages of formation were rather similar in all cases.

From their field relationships the quartzofeldspathites are parautochthonous "granites" as defined by Read (1957), that is they are rocks that have moved only slightly from the site of their formation. While a certain degree of mobility is indicated by the occurrence of bulbous bodies with tongue-like projections that penetrate along or across the foliation of the host rocks, other quartzo-feldspathites "fade" into the gneisses, the sharp contact indicative of mobility being absent.

The chemical composition of the quartzofeldspathites is variable, but a few plot near the eutectic minima for various water-vapour pressures in the Q - Ab - Or - H_2O system of Tuttle & Bowen (1958). Thus, while there is a tendency for some of the rocks to have a "true granite" composition, the first condition for a magmatic origin is not fully satisfied. The quartzofeldspathites are streaky and variable in composition within each body and, therefore, the second condition is not satisfied.

Petrographic criteria are suspect and there is no direct evidence for the third criterion, although it must be noted that microcline is not obviously much younger than the other minerals. The criterion of mobility is considered to be partly satisfied. As concluded earlier (p.223) the pressure-temperature conditions were probably such that a melt could exist. The conclusion reached from the above evidence is that the Laxford quartzofeldspathites were not derived from a magmatic source although there is evidence that the rocks passed through a partially-fluid stage.

The first condition for a metasomatic origin is satisfied in that a magmatic origin is unlikely. However, since relics of unaltered host rock or relict structures are absent, the second and third conditions are not satisfied. The streaky and variable distribution of potash feldspar is best ascribed to potassium metasomatism. The time at which this event occurred is discussed below.

An anatectic origin is favoured because the Laxford quartzofeldspathites are strictly localised occurrences and are often bulbous and markedly discordant. Anatexis both on a small-scale and a large-scale has been considered as an important mechanism in the origin of granitic rocks (see Read, 1957). Furthermore, there does not appear to be any important theoretical argument against anatexis, particularly after the work of van Platen and others (see von Platen, 1963) on experimental anatexis . Von Platen investigated the experimental anatexis of two gneisses from Rognstrand, Norway, obtaining leucocratic melts of compositions varying from aplitic, through granitic and granodioritic to tonalitic (≡ trondhjemitic?) as the chemistry of the original gneiss and pressure-temperature conditions during the experiments varied. At 2,000 bars water-vapour pressure melting of the gneisses started at temperatures ranging from 690°C to 730°C. Von Platen mentions a value of 640°C as a minimum temperature for the beginning of anatexis. These temperatures are considerably higher than those deduced for the metamorphism of the gneisses (about 500°C) although it should be noted that von Platen considers that the metamorphism of muscovite-biotite gneisses occurred at temperatures of the order of 600°C, a value similar to that ascribed by Fyfe and others (1958) to amphibolite-facies metamorphism.

Since the temperature, at which the metamorphism of the gneisses occurred, is probably 500°C to in the Laxford area, it is considered here that some additional factor must have influenced the onset of anatexis. The local accumulation of volatiles at a high temperature may have been sufficient to produce anatexis. Variations in (1) the chemistry of the rocks undergoing selective fusion (an increase in the anorthite content results in an increase in the quartz and potash feldspar content of the melt) (2) the pressure-temperature conditions and (3) the composition of the volatiles, may all affect the composition of the anatectic melt. Much of the streaky distribution may be due to the intermittent introduction of potassium, as a component of the volatile phase, during the development of the Laxford quartzofeldspathites.

NE - SW Pegmatite dykes

The NE - SW pegmatite dykes are not obviously related to any of the other granitic rocks. The available evidence is that they are discordant and thus satisfy one criterion for a magmatic origin. In the absence of further evidence it is concluded that they are the final manifestation of magmatic activity. They are parallel to a series of NE - SW vertical fracture planes and there seems little doubt that the pegmatitic fluids were intruded along certain of those planes.

The dykes are few in number and do not appear to have any direct bearing on the problems of origin of the other granitic rocks.

The Microgranite/trondhjemite Bodies

The origin of the microgranite portion of the microgranite/trondhjemite bodies has an important bearing on the problem of the origin of the granitic rocks, primarily because of the mineralogical and chemical similarity between that portion and microgranite of the Cnoc nan Cro Group.

The validity of the following discussion rests on the fact that the microgranite portion developed after the formation of the trondhjemite. The evidence in support of this is:-

1. Microgranite/trondhjemite veins occur throughout the area and always show a gradation from veins composed entirely of trondhjemite to veins composed mainly of microgranite with narrow edges of trondhjemite. The veins are usually discordant.

2. North of Laxford Bridge thin discordant veins of microgranite are closely associated with pegmatites that appear to be the final development of granitoid rocks for they display discordant relationships to all other rock types. Trondhjemites are not seen in this situation.

3. No examples of microgranite forming both edges and trondhjemite forming the central portion of a vein have been seen, although examples in which microgranite forms one edge occur.

4. Trondhjemites containing streaks of pure potash feldspar have been seen. This appears to indicate potassium metasomatism.

5. The microgranite/trondhjemite veins do not have a consistent attitude in the field; the trondhjemite veins likewise cut the host rocks in several directions whereas the microgranite veins and sheets of the Cnoc nan Cro group dip to the SW at approximately 45° and those of the Badnabay group are essentially concordant. Thus, the microgranite portion has adopted the attitude of the trondhjemite veins and is, therefore, later. Thus, unless these bodies are the result of metamorphic differention within each body microgranite post-dates trondhjemite.

Before discussing the origin of these bodies it is interesting to consider the cationic variation between microgranite and trondhjemite in the same vein. Two examples are considered (fig. 22). In both cases, Si, Ca and Na decrease and K increases in the micro-granite relative to the trondhjemite. Of the other cations considered, Fe^3 remains more or less constant while Fe^2, Mg and Al, in one case, increase in the microgranite relative to the trondhjemite and decrease in the other, changes being small except for Al. It seems reasonable to conclude that the chemistry of the microgranites and trondhjemites essentially shows an

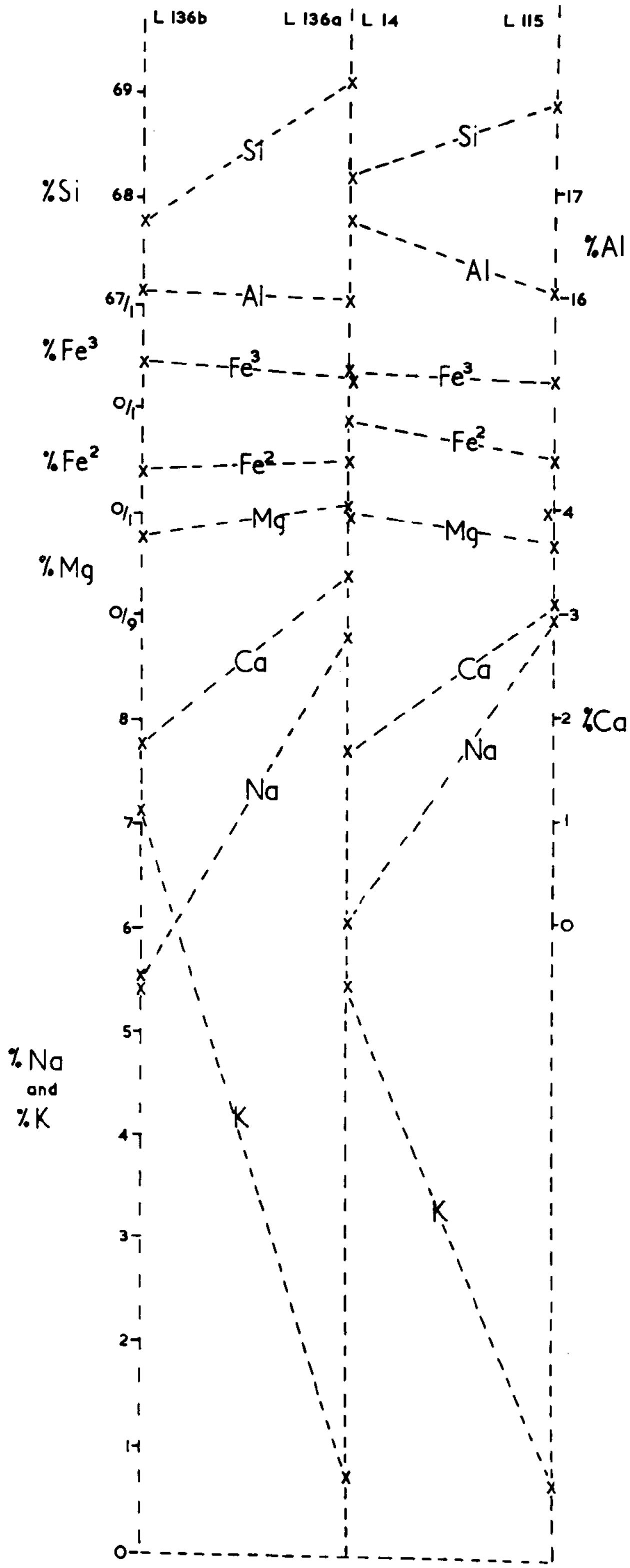

Fig. 22 Major and trace element comparison between trondhjemites (L136a, L115) and microgranite (L136b, ...

increase of K and a decrease of Si, Ca and Na in the former relative to the latter. This variation is almost cation for cation (difference in K : 6.37%; a difference in Si + Ca + Na: 6.46) between L136a (trondhjemite) and L136b (microgranite).

On the Q - Ab - Or triangular diagram both microgranites fall close to the position of minimum melting at different water-vapour pressures (fig. 21) and the first condition for a magmatic origin is considered to be satisfied. All the microgranites are homogeneous and, therefore, the second condition is also satisfied. As is the case for the Cnoc nan Cro microgranites, there is no conclusive petrographic evidence that would indicate that microcline is much younger than the other minerals; thus, the third condition is satisfied. Since the microgranites occur within veins of trondhjemite there is no evidence of mobility; thus, the fourth condition is not satisfied. Pressure-temperature conditions cannot be deduced from the available evidence.

The evidence presented above points to the possibility of a magmatic origin for the microgranite position.

The first condition for a metasomatic origin is not satisfied because there are indications of a magmatic origin. Neither relics nor relict features have been seen in these microgranites; therefore, the second and third conditions are not satisfied. Thus, it appears that a magmatic origin is more likely than a metasomatic for the microgranites. However, two problems remain: (1) the production by magmatic activity of the streaks of potash feldspar in certain trondhjemites and (2) the mechanism by which the granitic magma penetrated the trondhjemite veins.

The streaks of potash feldspar are considered to represent a metasomatic phenomenon as, for example, in the gneisses. They are so rarely developed that it is extremely unlikely that they represent metamorphic segregation of a homogeneous granitic rock. Some structural or metamorphic control must have also been in operation to produce the streaks.

For a magmatic origin the mechanism may be envisaged as follows:-

A magma can be considered as intruding gneisses, amphibolites and other rock-types, veined by trondhjemite. This magma would move along paths of least resistance, which, in this case, are likely to be the contacts between the trondhjemite vein and the host rock. This is confirmed by the fact that when specimens of trondhjemite are collected in the field they usually break at the contact with the host rock; that is, the contacts are not fused.

It would appear that those veins with edges of trondhjemite and centres of microgranite do not reflect the intrusion of a granitic magma, but represent the development of microgranite from trondhjemite by metasomatism or granodiorite by metamorphic differentiation.

One further point of note is that ribs of coarser-grained granitoid material have never been seen in the microgranite/trondhjemite bodies. This tends to confirm that these veins and sheets are related to the trondhjemites, in which ribs of coarser material are absent, rather than the microgranites in which such ribs are extremely common (for example, the Cnoc nan Cro microgranites).

Thus, it would appear that a magmatic hypothesis does not adequately explain the origin of the microgranite portion of these bodies. A hypothesis that the microgranite/trondhjemite bodies are the result of the metamorphic differentiation (local metasomatism) of granodiorite veins is discounted on the grounds that (1) granodiorite veins exhibiting the various attitudes of these veins have not been seen, (2) a great variation in the composition of the granodiorite veins would be necessary and account for the variation in the amount of microgranite present in the compound bodies and (3) the hypothesis does not account for the close field relationships between trondhjemite veins and the compound veins.

Potassium metasomatism is the remaining mechanism for the origin of the microgranite/trondhjemite bodies. It is thought that streaks of potash feldspar in trondhjemite veins are due to potassium metasomatism. The sharp contact between microgranite and trondhjemite is difficult to explain by metasomatism. However, recent experiments by Orville suggest that sharp contacts are possible given certain physical or chemical conditions and sufficient time for local equilibrium to be established (See Orville, 1962, figs. 6 - 10).

Significant Petrographic features

Certain petrographic features, especially replacement phenomena, have a bearing on the problem of the origin of the granitic rocks.

Two features in the Badnabay group are notable because they appear to support a metasomatic origin for the group: (1) the coexistence of hornblende and microcline, which are usually incompatible, can be explained by a potassium metasomatism that was arrested before hornblende was transformed into biotite; various stages of arrest are shown by the presence of variable amounts of biotite in association with hornblende. The reaction can be represented as follows:-

1. $2(2CaO.\ 3(Mg,Fe)O.\ 2Al_2O_3.\ 6SiO_2.\ H_2O + K_2O + H_2O$

$= K_2O.\ 6(Mg,Fe)O.\ Al_2O_3.\ 6SiO_2.\ 2H_2O + 4CaO.\ 3Al_2O_3.\ 6SiO_2.\ H_2O$

Evidence of this reaction is afforded by the close association of hornblende, biotite and epidote, together with apatite and sphene in many cases, and by the occurrence of an aggregate of epidote grains almost completely surrounded by biotite (p.156). The reaction is only approximate for not only does epidote require some Fe but sphene and apatite also require Ca, Ti, Si and P. In many thin sections, however, it is usual to find hornblende coexisting with microcline and so it is possible that some catalytic effect is required to produce the above reaction. The catalyst was possibly present in the volatile phase, fluorine, phosphorous, or both being possible agents. The occurrence of hornblende almost completely rimmed by epidote with the colour of the hornblende removed in the parts adjacent to epidote may represent stages of replacement similar to that seen in the gneisses (p.187).

2. The network habit and intergranular films of microcline support the presence of a pervasive fluid with components necessary to form microcline, that is potassium metasomatism.

Replacement phenomena are seen in all groups of granitic rocks. Plagioclase occasionally replaces microcline (p.135) but most of the evidence indicates that microcline corrodes and replaces plagioclase (P.138 and Plate 65). It is notable that in the microsyenites microcline is not enclosed or penetrated by plagioclase. The occurrence of both orientated and unorientated inclusions of microcline and oligoclase within one another (P.135 and P.138) could be interpreted as examples of replacement of one mineral by the other. These features are fairly common in the Cnoc nan Cro group and the Laxford Quartzofeldspathites, but not the Badnabay group and are particularly well developed in the coarser varieties. These features may indicate that (1) microcline is replaced by plagioclase (2) plagioclase has replaced microcline or (3) Perthite or antiperthite has unmixed. Plagioclase inclusions in microcline may be unorientated whereas microcline inclusions in plagioclase have a parallel orientation and are in optical continuity (Plate 53). When microcline encloses or penetrates plagioclase there are often signs of intense corrosion by microcline (fig. 18d) whereas when oligoclase encloses microcline corrosion appears to be less intense. This phenomenon probably occurred during the later stages in the formation of the granitic rocks and presumably attests to the greater activity of potassium at this time. It is notable that in the microsyenites microcline is not enclosed or penetrated by plagioclase. Thus the feldspars of the granitic rocks exhibit a complex series of replacement phenomena. In the present study it is considered that replacement phenomena, particularly replacement of plagioclase by microcline, cannot be accepted as conclusive evidence (cf. Cheng, 1944) that metasomatism has taken place. The evidence can be explained equally well by the activity of late-stage deuteric liquids within a crystallizing magma (= metasomatic stage of Schermerhorn (1956) in magmatic crystallization).

Microcline is commonly perthitic. Anderson (1928) has suggested that perthites could form by three processes (1) by exsolution (2) by eutectic crystallization (3) by replacement. In more recent years exsolution and replacement have received the most support (Gates, 1953; Tuttle & Bowen, 1958; Robertson, 1959). Although Tuttle & Bowen (1958) have proved experimentally that exsolution is possible such an origin is not consistent with the petrographical evidence of the present study. The fact some grains contain no flames while others contain as much as 60% albite is more in keeping with a replacement origin.

As Muscovite is present in the Cnoc nan Cro but not the Badnabay group, further elaboration is necessary. The amount of muscovite present in a given rock can be computed from the chemical analysis of that rock. 1.3% normative corundum is equivalent to 4.6% muscovite; thus the maximum amount of muscovite in the Cnoc nan Cro microgranites does not exceed about 12%. According to Yoder & Eugster (1955) there is a limit to the amount of muscovite in a granite but since similar values for muscovite have been found by Chayes (1952) in the "finer-grained, calcalkaline granites of New England" it is considered that the amounts present in the Cnoc nan Cro microgranites are consistent with the amounts present in other granitic rocks. Muscovite is not present in sufficiently large amounts for a metasomatic origin to be considered likely. Only one process has apparently been involved since all gradations occur from plagioclase containing small amounts of dispersed flakes (= sericite) to plagioclase more or less completely replaced by muscovite.

The vermicular intergrowths of quartz and muscovite formed at a late-stage and at temperatures below 650°C (cf. Deer et. al., 1962). In addition it must be noted that muscovite does not display similar relations with microcline or quartz. Thus it appears likely that muscovite formed before microcline and that its presence is due to the late-stage activity of potassium ions, with the following reactions possibly accounting for its formation:-

(2) $2NaAlSi_3O_8 + K_2O + 2H_2O + 2Al_2O \rightarrow 2KAl_3Si_3O_{10}(OH)_2 + Na_2O$

(3) $CaAl_2Si_2O_8 + K_2O + 2H_2O + 2Al_2O_3 + 4SiO_2 \rightarrow 2KAl_3Si_3O_{10}(OH)_2 + CaO$

A process involving the conversion of the small amounts of potash feldspar or potassium always present in sodic plagioclase to muscovite cannot by itself account for the occurrence of muscovite because sodic plagioclase is often almost completely replaced by that mineral. However, such potash feldspar is almost certainly converted into muscovite. Schermerhorn (1956) suggests that muscovite forms during a stage of formation that he terms metasomatic which is the water-rich final stage of magmatic crystallization. The large platy network of muscovite in the Cnoc nan Cro group supports such an origin.

Hornblende, probably a sodic variety, is one of the first formed minerals in the Badnabay group and is shown by the fact that it is often penetrated or completely enclosed by plagioclase, microcline and quartz and cut by biotite and epidote. As already shown the latter two minerals are probably secondary in this group.

In the Cnoc nan Cro group biotite is a primary mineral and one of the first formed, occurring as flakes upon which the other minerals are moulded. Although Teall (op. cit.) considered that epidote is a primary constituent it is usually considered to be secondary (Barth, 1952; Marmo, 1962a) forming either by autohydrothermal alteration of calcic plagioclase or by the decalcification of that feldspar by potash feldspar as follows:-

(4) $4Ca\ Al_2Si_2O_8 + 4H_2O \rightarrow 2Ca_2Al_3Si_3O_{12}.OH + 2Al(OH)_3 + 2SiO_2$

(5) $4Ca\ Al_2Si_2O_8 + KAl\ Si_3O_8 + 2H_2O \rightarrow 2Ca_2Al_3Si_3O_{12}.OH + KAl_3Si_3O_{10}(OH)_2 + 2SiO_2$

Some epidote of the Badnabay group may have formed in this way, but it is thought that the most occurrences of this mineral are the result of a reaction similar to that depicted by equation (1) of this section.

In the microsyenites, aegirine-augite gives the impression of being one of the last formed minerals because it is not penetrated by other minerals and often encloses small flakes of biotite and grains of hornblende (p.154 - 155).

The accessory minerals, particularly apatite and sphene, are very common in the microsyenites (p.156), increase in amount being accompanied by increase in size. The amounts of apatite and sphene are related to the amounts of the ferromagnesian minerals for in the banded microgranites an increase of those accessory minerals is seen in the mafic bands relative to the felsic bands. It is considered that these minerals were formed from the ferromagnesian minerals during the metasomatic development of the Badnabay group. Apatite and sphene appear to have grown late by pushing aside the other minerals although in some cases epidote and microcline appear to be moulded on to larger grains (p.156).

While chlorite is usually an accessory mineral, it is occasionally the predominant ferromagnesian mineral. It is most probably results from the hydrothermal decomposition of hornblende as follows:-

(7) Hornblende + water $\rightarrow$ zoisite + iron ore + chlorite + quartz.

All products on the right hand side of the equation are not always seen together but such associations have been seen (p.157).

Quartz has formed at various stages in the development of the rocks, for example small rounded grains represent an early generation and large lobate patches represent a very late phase of formation.

Granites, Pegmatites and Aplites

Ribs of granitic, pegmatitic and aplitic material are common to both the Badnaba and Cnoc nan Cro groups. In the former group the ribs vary in composition from sodic to potassic, commonly containing an amount of microcline similar to the host microgranite; in the latter group the ribs typically contain approximately equal amounts of quartz, plagioclase and microcline.

Pegmatites and aplites are found almost exclusively in subsolvus granites and indicate a hydrous environment according to Tuttle & Bowen (1958, p.139). Experimental evidence has shown that K is extracted from a liquid by a vapour in preference to Na and that K and other constituents can travel rapidly through the vapour in response to a temperature gradient (Jahns & Tuttle, 1963, p.90). This mechanism may account for the sodic aplites of the Badnabay group.

It seems possible that the ribs of granite, pegmatite and aplite were derived from the same source, probably pegmatitic, containing substantial amounts of dissolved water or other volatile constituents. A variation in the temperature gradient would produce a fluid of the necessary composition. Variations in the percentage of dissolved volatiles and in the confining pressure would produce the variation in grain size. Prior to any loss of volatiles pegmatitic fluids would be at temperatures of 600° - 800°C at fairly high confining pressure. If this fluid were to lose volatiles through a drop in confining pressures its liquid temperature would rise, rapid crystallization would occur (cf. Jahns & Tuttle, op.cit.) and aplite would be formed. This would occur either during or after emplacement (cf. Emmons, 1940, pp. 5 - 8). A structural or metamorphic control must have been present during the formation of the ribs.

Pegmatites are particularly common in the Cnoc nan Cro group where many of the smaller pegmatites occur as irregular masses grading down into clots and lenses. The bodies fall within the group described as concretion and segregation pegmatites by Ramberg (1956) and Barth (1961). These authors postulated their origin as being due to diffusion of material from the country rocks during a metamorphic episode. If necessary the pegmatites pushed aside the country rocks in a plastic manner to make room for themselves. Some pegmatites in the Laxford area are found with stringers that penetrate along the foliation while others contain relict patches of gneiss. Both these types could be considered to be examples of replacement pegmatites of metasomatic origin. A few of the larger pegmatites occur as thick continuous sheets within which a gradation from pegmatite into granite is occasionally seen. These pegmatites are probably magmatic in origin. North of Laxford Bridge sheets of microgranite either cut or are cut by irregular masses or sheets of pegmatites. It is thought that the granitic magma was modified by a large increase in the volatile constituents, producing a pegmatitic fluid that possibly links a magmatic fluid to a metasomatic fluid (see also p. 260). The small streaks and pods of granitic and pegmatitic material either have been derived from the pegmatitic fluid or are metasomatic in origin. A magmatic origin for the pegmatites supports the conclusion of Hitchon (1960) who suggests that the pegmatites are better termed coarse-grained granites which commenced crystallization at temperatures above 800°C. This temperature is considerably above that postulated earlier for the microgranites, but it receives support from Erdzhanov and Satrapinskaya (1960) who consider that the presence of allanite in pegmatites indicates a high temperature of formation.

Since certain pegmatites contain relics of gneiss it is possible that they not only intruded, but also replaced the gneisses. Thus it is probable that crystallization occurred under open-system conditions to allow the removal of the replaced ions.

It is unlikely that the granites, pegmatites and aplites of the Cnoc nan Cro and Badnabay groups developed through radically different processes. In particular, the occurrence of ribs in both groups suggests that there is a genetic relationship between them (see pp. 258-63).

Layering in the granitic rocks.

Layering in granitic rocks has been described by several authors (Emeleus, 1963; Jahns and Tuttle, 1963) and is generally considered to be a magmatic phenomen.

The streaking and striping in the Badnabay group bears some resemblance to the layering in the Greenland granites (Harry and Emeleus, 1960 ; Emeleus, 1963). The mineral constituents are similar but in the Greenland granites plagioclase exhibits oscillatory zoning (Emeleus, 1963, p.26) and in general there is an igneous texture in these rocks. These layered granites are interpreted by Emeleus (1963) as crystal accumulates, the presence of water and fluorine and slow cooling of the magma being important factors in their development. However the absence of graded bedding, cross bedding and other sedimentational features suggests that gravitational crystal settling during the primary crystallization of a magma cannot satisfactorily account for the streaking and striping in the Badnabay group. Moreover, the mafic streaks in that group display features that resemble relic folds.

In the Cnoc nan Cro group many of the observed relationships within a granitic sheet are closely similar to those described by Jahns & Tuttle (1963) from layered pegmatite-aplite intrusives (for example, see fig.1, p.80 in Jahns & Tuttle, 1963), the more so because the aplite described in their paper has been identified as fine grained granite by other writers (Jahns & Tuttle op.cit. p.80). Mineralogical composition of the aplites, expressed as percentages, is not given by Jahns & Tuttle, but it is possible that many of the Cnoc nan Cro microgranites would approximate in composition to aplites described by those authors. Most of the relationships seen in the Cnoc nan Cro group are similar to those in the group of pegmatite-aplite intrusives that are recognised as composite bodies representing multiple injection of magma from external sources. The magmatic origin of this gross multiple layering is partly confirmed by the following evidence:-

(a) In many localities the several rock-types may be separated by thin screens of country-rock.

(b) When the various types are in contact each retains its own identity and there is usually a fairly sharp, often planar contact between each type.

(c) The same rock types often display discordant relationships to one another, confirming that age differences exist.

This type of layering is clearly seen in the field. Two further types of layering exist in the Cnoc nan Cro group thus:

(1) Certain types of layering show a gradual passage from coarser microgranite into the normal finer grained microgranite in one direction and an abrupt change in the opposite direction (Plate 38). This type of layering may reflect some kind of localised fractional crystallization in which the density of the larger and early formed crystals played an important role.

(2) A streakiness is often present in the microgranites and could be described as a type of layering (cf. Jahns & Tuttle, op.cit.). These layers (Plate 39) are thin, usually discontinuous and slightly coarser in grain-size. Only rarely do they display compositional differences. Such layering could be ascribed to flowage during the consolidation of the microgranites (cf. Jahns & Tuttle, op.cit.). Layering of these kinds may also be explained by variable concentrations of volatiles in the late stages of consolidation, with flowage or some structural mechanism controlling the attitude of the layering.

The Fluorine and Phosphorus content of certain granitic and syenitic rocks.

The fluorine content of a number of Cnoc nan Cro microgranites and pegmatites and Badnabay microgranites and microsyenites has been determined (Table 24a). Generally high and low values of F can be correlated respectively with high and low values of P_2O_5. Most of the P_2O_5 is contained in apatite, as shown by the good agreement between modal and normative amounts (Table 24b). However, apatite can only account for small amounts of F - analyses of fluor-apatite quoted by Deer, Howie & Zussman (1962) indicate that the ratio P_2O_5 : F usually exceeds 10 : 1, whereas this ratio in the Laxford granitic rocks, varies from 0.75 : 1 to 5.5 : 1 (Table 25). Presumably much of the fluorine is associated with the ferromagnesian constituents, particularly hornblende and biotite.

Visselius and Hurst (1964) have shown that granitic rocks are near a natural closed system if (1) P_2O_5 exhibits a strong negative correlation with SiO_2 and positive correlations with Al_2O_3, TiO_2, Fe_2O_3, FeO, MgO and CaO (2) similar correlations exist when P_2O_5 and the major oxides of the granitic rocks are divided by oxygen. Their results also show (1) that the phosphorous content increases as the amount of ferromagnesian minerals present in the rock increases, a conclusion similar to

24a

Badnabay group	F	P_2O_5
B346	1.74	3.07
B215	0.44	1.11
L56	0.35	1.27
B121	0.23	1.22
S24	0.20	0.21
L83	0.17	0.16
L43	0.12	0.19
L33	0.11	0.18
L162	0.07	0.20
S16	0.04	0.03
L149	0.04	0.06
L158	0.03	0.06

Cnoc nan Cro group	F	P_2O_5
L126	0.05	0.11
L113	0.04	0.08
S72	0.04	0.12
L40	0.03	0.09
S74	n.d.	0.02

24b Apatite values

	mode	mesonorm
B346	6.5	6.48
B215	2.7	2.27
L56	2.4	2.59
L83	0.4	0.21
L43	0.6	0.42
L33	0.3	0.38
B121	1.4	2.56

	mode	mesonorm
L126	0.4	0.22

Table 24 a) F and P_2O_5 values for the granitic rocks.

b) Apatite values.

Badnabay group		Cnoc nan Cro group	
B346	1.76	L126	2.02
B215	2.53	L113	2.00
L56	3.63	S72	3.00
B121	5.31	L40	3.00
S24	1.05	S74	-
L83	0.94		
L43	1.58		
L33	1.64		
L162	2.86		
S16	0.75		
L149	1.50		
L158	2.00		

Table 25 P_2O_5 : F ratios for the granitic rocks.

that reached by Vogt (1931) who found that as the basicity of granitic rocks increased so also did the the content of P_2O_5 and (2) the higher the content of the quartz, the lower the content of P.

Because of the close similarity of all Cnoc nan Cro microgranites in chemical composition correlation graphs could not be obtained. However, in the Badnabay group, P_2O_5 exhibits a strong negative correlation with SiO_2 and Al_2O_3 and positive correlations with CaO, MgO, TiO_2 and FeO. In this group, the other results are similar to those found by Vistelius and Hurst (1964). Thus, only the strong negative correlation P_2O_5 exhibits with Al_2O_3 points against the possibility of the Badnabay group forming in a natural closed system. This would appear to indicate a magmatic origin for the group.

However, the same correlations can also be explained by the metasomatic introduction of P in association with F into pre-existing gneisses and, since these elements combine essentially with the constituents of ferromagnesian minerals and Ca, this could give rise to the positive correlation that exists between P_2O_5 and CaO, MgO, FeO and TiO_2. An increase in the ferromagnesian constituents in gneisses is balanced by a decrease in quartz and feldspar and this could account for the negative correlation that exists between P_2O_5 and SiO_2 and Al_2O_3.

Brecciation of the granitic rocks

Many of the granitic rocks show signs of brecciation and mylonitization. Since this feature is usually confined to the granitic rocks themselves, it is probable that it is related to their formation.

(a) Brecciation of the Badnabay Group.

Mortar structure and cracks which produce displacement of the twin lamellae in the feldspars are the first indications of brecciation. In the extreme cases of brecciation the rocks have been intensely granulated and the feldspar highly altered. Microcline could not be identified in those cases, although it may be represented by some of the highly altered, granulated material.

Haematite is associated with the brecciation and is so common in some microgranites that it produces a very deep red to maroon colour. Often haematite occurs with highly altered material, probably mainly plagioclase which is surrounded by fresh microcline and quartz. Microcline is occasionally affected by haematitization. Chlorite, biotite, epidote, calcite and a serpentinous mineral are probably the products of brecciation. Usually epidote forms fairly large grains in the brecciated rocks with the granulated or wispy minerals "flowing" round these grains. Also associated with the brecciation is the development of small irregular patches and veins of quartz.

In the Badnabay group, brecciation appears to be confined to the micrograntes and has only been seen in the Rudha Ruadh and Loch na Seilge sheets. In the Rudha Ruadh sheet, it is confined to the margins, being best developed a few feet from the contacts. In the Loch na Seilge sheet it occurs at various points within the sheet and also in a few of the thinner sheets that replace the thick sheet in a North-westerly direction. It seems likely that brecciation is due to late readjustments within the sheets, perhaps during upward movement.

(b) Brecciation of the Cnoc nan Cro Group.

In the Cnoc nan Cro Group all stages of brecciation occur from minor granulation and displacement of twin lamellae in the feldspars to complete mylonitization. Even in cases where mylonite is produced, brecciation of the adjacent gneisses has not been seen. Brecciation can be traced over long distances within one sheet, for example, a sheet composed almost entirely of mylonite can be traced to the north-west from Laxford Bridge for a distance of 800 metres.

Granulation affects all the minerals although at an intermediate stage in the formation of mylonite, quartz and plagioclase appear to be rather more easily granulated. For example, a specimen from a sheet that crops out on Cnoc nan Cro, contains small granules of quartz, plagioclase and occasionally microcline, larger grains of microcline, thin wavy micaceous films that flow round lenses and pods of granulated material.

Brecciation or granulation is usually confined to certain parts of a sheet and often cannot be traced over more than several metres.

Haematite, as shown by the red colour of the rock, occurs in mylonite, but is a rare constituent of the other brecciated microgranites.

Since it is confined to the microgranite sheets, the brecciation is probably related to the upward intrusion of largely solid granitic material and may be used to support the earlier conclusion that the temperature of the magma was only just above the minimum value.

Summary of the evidence on the origin of the granitic rocks.

The evidence described above appears to favour a magmatic origin for the Cnoc nan Cro group, a metasomatic origin for the Badnabay Group, an anatectic-metasomatic origin for the Laxford Quartzofeldspathites, a metasomatic origin for the microgranite portion of the microgranite/trondhjemite veins and sheets, and a magmatic origin for the NE - SW pegmatite dykes. Thus, granitic rocks, closely associated in the field and so similar that they have been mapped as one group by the Geological Survey (Peach et al., 1907), appear to have evolved by different processes.

The simplest solution to the problem of the multiplicity of rock-types is that the various rock-types belong to one igneous series and represent differentiation products of the same parent magma (cf. Buddington & Leonard, 1962). However, the evidence does not support a magmatic origin for each group, although contamination could be invoked to explain the variety of rock-types and the relict features of the Badnabay Group.

However, the preferred hypothesis is that the components of the Cnoc nan Cro Group are magmatic in origin and form a granitic injection complex; the Badnabay Group, the microgranite portion of the microgranite/trondhjemite bodies, having developed through potassium metasomatism which is thought to be an emanation from the granitic magma (see later), are related to that group. The NE-SW pegmatite dykes probably represent the last manifestation of the granitic magma. The Laxford Quartzofeldspathites have been derived by local anatexis, but have been modified by potassium metasomatism.

The granitic injection complex has been divided into (a) the intrusive sheets, composed predominantly of microgranite (b) the migmatites and (c) the pegmatites. Chemically the granites and microgranites are very similar to the late-kinematic granites of Fennoscandia (p.166). They are not genetically related to the other rock-types of the Laxford area - a conclusion similar to that reached by many other writers in comparable areas (for example, Simenon, 1960; Marmo, 1962a; and Dearnley, 1963) - for the following reasons:

(1) Their enormous volume makes their derivation from the gneisses or their position as an end-member of the igneous-complex unlikely.

(2) Their composition, particularly the high $K_2O : Na_2O$, is radically different from that of the metadiorites and any late-stage trondhjemites of the igneous complex, in which the ratio $Na_2O : K_2O$ is high.

(3) Their homogeneous nature is markedly different from the heterogeneous striped nature of the gneisses.

(4) The percentage of mafic minerals in a granitic sheet is considerably less than that present in an equal thickness of the gneisses.

From the chemical data it is significant to note that normative anorthite, which varies from 10% to 16% of the plagioclase molecule, is lower than the petrographically determined anorthite content of the plagioclase which varies from An_{20} to An_{25}. This discrepancy may be accounted for by assuming that albite occurs in considerable amounts in microcline perthite or as rims round plagioclase.

Migmatites are extensively developed both south of Laxford Bridge where the granitic material almost always occurs as discrete veins and sheets of microgranite and to the north where granitic material is often more intimately associated with the gneisses, occurring as streaks and pods. The latter phenomenon is probably due to the higher percentage of volatiles associated with the granitic material in this area. An increase in K has usually accompanied the increase in volatiles so that the streaks and pods are often very rich in potash feldspar. Further increases in volatiles and K may have produced a K metasomatism. Thus, it is suggested that K metasomatism is genetically related to the granitic and pegmatitic rocks of the injection complex.

There may have been an overlapping of K and Na metasomatism, but since there is no direct evidence to support this suggestion it is simpler to conclude that Na metasomatism and injection of trondhjemites had essentially ceased prior to the onset of the K metasomatism. Since (1) the Cnoc nan Dro microgranites do not appear to have produced K metasomatism in either adjacent gneisses or inclusions of gneiss and (2) the inclusions of gneiss contain similar amounts of potash feldspar to those gneisses outside the sheets of microgranite, it is possible that K metasomatism preceded the injection of granitic material. A metasomatic front of K with granitic magma following in its wake has been described several times in the literature (Read, 1957). K metasomatism has affected the gneisses and many of the meta-igneous rocks, producing granitic rocks of varying aspect, in its final expression.

The nature of the fluid that has produced the metasomatic effects must remain conjectural. However, evidence from streaks of pure potassium feldspar in the gneisses suggest that it was extremely rich in K. Perhaps the fluid was basically composed of K and several volatiles, for example H_2O, F, Cl and CO_2, other elements being incorporated as the fluid reacted with the minerals of the host rock. K metasomatism post-dated the folding and foliation and, since the development of potassium feldspar was parallel to the foliation, was influenced by an active structural control.

The results of K metasomatism as exhibited by the Laxfordian gneisses are:-

(1) Streaks of pure potassium feldspar and stripes containing variable amounts of that feldspar are well developed.

(2) Biotite and epidote have formed from hornblende.

(3) Myrmekite and sodic rims to plagioclase are commonly developed.

The most important result of the metasomatism has been the development from the gneisses of a series of granitic and syenitic rocks that have been termed the Badnabay group. There are, at present, very few homogeneous potash-poor gneisses and it is, therefore, unlikely that such rocks existed prior to metasomatism. Thus, if the Badnabay group is metasomatic in origin the processes involved must have been such that homogenization could take place. Large amounts of water vapour and other volatiles may have produced partial melting at temperatures below 600°C (Tuttle & Bowen, 1958, p.126) although the amount of liquid present could not have been sufficient to produce complete homogenization (op.cit.,p.125) so that relict features would remain in many cases. Partial melting would probably produce granitic rocks sufficiently mobile to effect discordant relations with the adjacent gneisses.

Experimental data suggest that CaO, MgO, P_2O_5 and perhaps Fe oxides are relatively insoluble in the hydrous vapour phase (Tuttle & Bowen, op.cit., p.91) and this fact may account for the concentration of P_2O_5 in the micro-syenites.

The Origin of the Granitoid Magmas

The origin of magma of granitoid composition has been as controversial as the origin of the rocks themselves. The source of the magma is of no great significance in this study and, therefore, the possible origins are discussed only briefly.

A magma of granitic composition can evolve by a process of either (1) magmatic differentiation or (2) differential fusion of crustal material (= anatexis). Bowen (1928)was the chief exponent of the magmatic differentiation hypothesis, against which the main argument has been the absence of sufficiently large volumes of basic material associated with the granitic material, because the volume of granitic magma produced by differentiation from more basic magma is small in comparison with that material. Recent work suggests that differential fusion of crustal material is more likely (Tuttle & Bowen, 1958; Lacy, 1960). Granitic rocks are almost always present in the gneissic terrain evidence which tends to suggest that gneisses are involved in the formation of granitic magma. This appears to be the case in the Laxford area.

In this study, it is believed that granitic magma was evolved at depth by the differential fusion of gneisses, perhaps of chemical composition similar to those now present in the Laxford area. This process was probably catalysed by the presence of volatiles, which are thought to be of considerable importance in in the development of the granitic rocks of the Laxford area. The source of the volatiles is unknown.

A magma of trondhjemitic composition can also evolve by either of the processes mentioned above. The occurrence of trondhjemites in gneissic terrain again suggests the probability of differential fusion of crustal material. There is no clear reason why two magmas of differing composition should be produced in the same area one after the other. Possibly an explanation can be found in the recent experimental work of von Platen (1964) who has shown that the composition of the resultant magma will depend on several factors including the chemistry of the original gneiss and the pressure - temperature conditions.

Metasomatism

Both sodium and potassium metasomatism are considered to have played an important role in the development of the Laxfordian complex.

Metasomatism is considered to take place either by solid diffusion (Perrin & Roubault, 1949) or through an aqueous phase (Read, 1957). Recent experimental data suggest that solid diffusion rates are too slow to be effective in large-scale transformations (Fyfe et.al., 1958), whereas small-scale metasomatism by fluid has been proved experimentally by Orville (1962, 1963), who shows cation exchange reactions are of fundamental importance in metasomatism. He has demonstrated conclusively that Na^{+} and K^{+} ions will migrate relative to one another under certain conditions, for example a thermal gradient or a variation in the anorthite content of plagioclase within a rock mass, K ions diffusing towards the low temperature end of a thermal gradient of only 30°C in the presence of a chloride solution. He states that hot alkali-bearing fluids in equilibrium with two alkali feldspars will, on cooling, result in the sodic plagioclase being replaced by potash feldspar as follows:-

$NaAlSi_3O_8 + K^{+} \rightarrow KAlSi_3O_8 + Na^{+}$

If SiO_2 is absent from the fluid no other reaction can take place. In gneisses, replacement of sodic plagioclase by potash feldspar may be due to the introduction of alkali-bearing, hot volatiles which cannot attain equilibrium with both oligoclase and microcline until the K/Na ratio in the fluid phase is lowered. It should be noted that "increasing anorthite-content of the plagioclase phase corresponds to increasing K/Na ratio in the vapour phase and is therefore parallel to the effect of increasing temperature" (Orville, 1962, p.301). Metasomatism in those cases is explained by the mechanism of "transport by flowing fluid". In other cases, metasomatism can be explained by "transport by diffusion in static fluid" i.e. metasomatism within a volume of rock that can be considered to be a chemically closed system. If a thermal gradient exists within a rock mass in which microcline and oligoclase are evenly distributed metasomatism results in oligoclase being replaced by microcline in the cooler part and microcline being replaced by oligoclase in the hotter part (Orville, op.cit.).

Although small-scale metasomatism has been demonstrated experimentally and several mechanisms for metasomatism propounded, the mechanism involved in large-scale metasomatism remains undetermined. Perhaps the most important argument against metasomatism is that the rate of diffusion of ions through an intergranular fluid might be too slow to be of importance geologically. However, if this difficulty can be overcome (cf. Walton, 1960) metasomatism can be considered to be of great importance in metamorphic terrain.

Further evidence in support of metasomatism comes from the work of Donnay, Wyant and Sabatier (1959) who have found experimentally that water acts as a catalyst in the substitution of Al and Si in silicate lattices; OH ions enter the SiO_4 tetrahedra, creating strong polarising effects which weaken the bonds and facilitate movement of Al and Si through the lattices. The formation of silicates through diffusion of Al and Si in the solid state is thus greatly facilitated by the presence of small amounts of water. Bowen & Tuttle (1958) have shown the crystallization temperature of feldspar is lowered by the presence of water under pressure. Diffusion rates are again uncertain but perhaps a process of feldspathization would be catalysed by the presence of water. In the present study while feldspathization (= metasomatism) is possible, it is considered unlikely that the process took place in the solid state (cf. Fyfe et.al., 1958); the presence of an intergranular fluid was probably essential.

Several features of the Laxford granitic rocks and gneisses suggest the operation of potassium metasomatism during the Laxfordian metamorphism. Potash feldspar and, to a lesser extent, biotite and epidote, the formation of which has already been described (p.240), are the products of this metasomatism.

In thin section microcline appears to be the only variety of potash feldspar. It may be significant that a much higher percentage of microcline grains in the gneisses than in the granitic rocks exhibit grid twinning. For example - in a 2mm. thick layer composed almost entirely of microcline every grain showed perfect grid twinning whereas in the microgranites 20 - 30% of the microcline grains show no twinning and ill-defined grid twinning. Goldsmith and Laves (1954), on the basis of crystallographic considerations, conclude that grid-twinned microcline has passed through a monoclinic stage (orthoclase), the transition taking place around 525°C under hydrothermal conditions. If these experimental data are correct the apparent absence of orthoclase suggests that 525°C can be taken as the upper temperature limit during the Laxfordian metamorphism. However, Mackenzie and Smith (1961) question the validity of this conclusion. They also state that microcline is likely to be composed of almost pure potash feldspar.

Perthite is uncommon in the microcline of the gneisses; when present it is of the flame variety. In the granitic rocks, however, perthite (also of the flame variety is prominent. The common occurrence of microcline, which may or may not be of the flame perthite variety, with plagioclase rimmed by more sodic feldspar and myrmekite suggests that this association is of genetic significance (see later). Of particular interest is the source of albite (see pp.272-4).

Potassium metasomatism is commonly considered to be an important mechanism in metamorphic terrains (Mercy, 1959) and is considered to have occurred in the Lewisian of Gairloch (Park, 1963). In the Laxford area potassium metasomatism appears to have produced large-scale modifications of the pre-existing gneisses, the end-products being striped microgranites, leucocratic microgranites, microgranites and microsyenites and associated rocks.

In the present research it has been shown from a study of stained specimens that relative to other gneisses inclusions within the Cnoc nan Cro microgranites do not appear to have suffered potassium metasomatism nor do the gneisses immediately adjacent to even the broadest sheets, for example the Rudha Ruadh sheet. This conclusion does not preclude the possibility of a general potassium metasomatism. An exception to this conclusion can be seen in certain relics within the Rudha Ruadh sheet that appear to represent intermediate stages in the development of the microsyenites.

A general potassium metasomatism is suggested by the facts that (1) there is more potash feldspar in many of the Laxford area gneisses than in the gneisses of the Scourie area (presumed to be equivalent to the parent rock of the Laxford gneisses) (2) the ratio K/Na is higher for the Laxford Bay and Weavers Bay gneisses than for the Claise Fearna and Badnabay gneisses, and (3) the Badnabay group of granitic rocks is considered to represent rocks that have suffered extensive modification by potassium metasomatism.

The relatively high values of F in the Badnabay group (Table 23) are significant in the light of Orville's experiments which were carried out in the presence of chloride solutions (Orville, 1962, 1963). Chlorine has not been determined in the rocks from Laxford, but it is considered that fluorine would be at least as active and probably more so in a metasomatic process.

The Source of Albite.

A hypothesis on the source of albite must explain the following facts:-

1 Albite occurs as flames in microcline perthite and as intergranular material between grains of microcline.

2) Albite occurs as sodic rims to plagioclase at microcline-plagioclase contacts, with myrmekite occasionally developing within the normal plagioclase. The sodic rims may be albitic or only slightly more sodic than the core. There are three possible sources of albite: (1) from an originally homogeneous alkali feldspar, (2 from plagioclase or (3 from a late-magmatic or metasomatic fluid.

Microcline is associated with all occurrences of albite and, therefore, it can be reasonably concluded that the presence of microcline is essential for the development of albite. Thus, it is possible that albite was derived from a homogeneous alkali feldspar that was present at high temperatures, but unmixed to produce soda and potash feldspar at lower temperatures. However, it is extremely unlikely that microcline in the gneisses passed through a homogeneous alkali feldspar stage or even a high temperature stage since (1) in the gneisses there are treaks, 2 mm. or so thick, composed almost entirely of microcline and (2 the temperature that prevailed during the metamorphism of the gneisses was about 500°C. Furthermore, amounts of albite (60% in some cases) in microcline perthite are greater than in homogeneous alkali feldspar. Shelley (1964) considers that myrmekite is due to the incorporation of recrystallizing quartz in growing albite that has exsolved from orthoclase. In the Laxford area the complete absence of myrmekite from sodic rims does not support this conclusion and it is concluded that albite was not derived from a homogeneous alkali feldspar.

A late-magmatic or metasomatic fluid carrying the necessary ions could produce sodic rims to plagioclase and penetrate microcline to form flame perthite. Evidence against this is that sodic rims are present only at microcline/plagioclase contacts whereas it is likely that they would be present at other contacts if this hypothesis is correct.

The variable composition of the sodic rims suggests that the original plagioclase could have been the source of albite. Late-stage magmatic or metasomatic fluids, although they do not provide the component ions of the sodic rims, are considered necessary to effect decalcification of the rim. Inter-ionic exchange may take place as follows:-

$$Na\ Al\ Si_3O_8 + K^+ \rightarrow Na^+ + KAl\ Si_3O_8$$
$$Ca\ Al_2Si_2O_8 + 2K^+ + 4SiO_2 \rightarrow Ca^{2+} + 2KAl\ Si_3O_8$$
$$2Ca\ Al_2Si_2O_8 + K^+ \rightarrow 2Ca^{2+} + KAl\ Si_3O_8 + 3Al^{3+} + Si^{4+} + 4O_2$$

If only Ca ions are released from plagioclase sodic rims will form. However, where microcline corrodes plagioclase (for example, pp.241-2) both Na and Ca ions will be released, the former possibly replacing K in K Al Si_3O_8 to form the albite of flame perthite. All Ca ions probably form epidote.

Myrmekite, which is present only in the granitic rocks may represent a late stage effect forming by either the enclosing of quartz by plagioclase during recrystallization of those minerals or the penetration of plagioclase by silica. This event appears to have occurred either before or during the formation of sodic rims.

VI. THE METAMORPHIC AND IGNEOUS HISTORY OF THE COMPLEX

The Metamorphism

The number of periods of folding and metamorphism that have affected the Lewisian complex in the Laxford area cannot be established with certainty because the final (Laxfordian) metamorphism has obscured much of the evidence of earlier metamorphisms.

The mineralogical evidence from a few basic and ultrabasic rocks shows that the complex has suffered an Early granulite facies metamorphism which could be equivalent to the Scourian metamorphism as defined by Sutton & Watson (op.cit.) and dated by Giletti, Moorbath & Lambert (1961) at 2,600 million years.

There is no evidence relating to the deformation of this period.

During the Later metamorphism (Laxfordian as defined by Sutton & Watson (op.cit.) amphibolite facies conditions prevailed. This metamorphism is essentially retrograde and is considered by Giletti et. al. (1961) to have occurred 1600 m.y. ago. The presence in a number of basic rocks of a pale green clino-pyroxene containing relics of hornblende suggests that the metamorphism increased in intensity, as time progressed, to upper amphibolite - lower granulite facies grade, a temperature of 540°C being reached (cf. Engel & Engel, 1962a). The absence of this mineral in many basic rocks shows that there was a return to a lower metamorphic grade which is of the epidote-amphibolite facies as indicated by the fact that the acid gneisses invariably contain epidote in close association with oligoclase (p.69).

The Nature of the Complex Prior to the Laxfordian Metamorphism.

Fundamental to a discussion on the Laxfordian metamorphism, particularly if metasomatism is involved, is a knowledge of the rock types prior to the metamorphism. There are, at present, two radically opposed hypotheses on the nature of the rocks that were involved in the metamorphism. Watson (op.cit.) considers that those rocks were Scourian gneisses consisting of two groups, the charnockitic gneisses belonging to one and hornblende- and biotite-granulites to the other. She suggests that they formed during the same metamorphic episode and it is probable that granulite facies conditions persisted during this metamorphism. Bowes (1962a) suggests that the rocks were sediments derived from Scourian gneisses and other rock types.

The majority of the Laxford gneisses appear to be sedimentary in origin, a greywacke-type being the most likely (pp.175-180). The relict granulite facies mineral assemblages of certain intercalated basic and ultrabasic rocks in the Laxford area indicate that granulite facies metamorphic conditions prevailed at some time prior to the Laxfordian metamorphism and that the metagreywackes were granulite facies gneisses at this stage.

Associated with the early granulite facies gneisses was a series of meta-igneous rocks which included metaperidotites, ultramafic rocks, a metagabbro-plagioclasite complex, metatholeiites and metadiorites. All except the metatholeiites are thought to be genetically related (pp.207-208) forming an early igneous complex, similar to that described from the Outer Hebrides by Dearnley (1963) (p. 207). In the Laxford area the meta-igneous series pre-dates the Early (Scourian?) metamorphism whereas the metatholeiites post-date this metamorphism.

Thus, prior to the Laxfordian metamorphism, the rocks that cropped out in the Laxford area were enderbitic and trondhjemitic to quartz-dioritic gneisses, metaperidotites with olivine-orthopyroxene mineral assemblages, pyroxenites and/or hornblendites, garnet-pyriclasites, anorthosites, metadiorites and an intrusive suite of tholeiitic rocks.

The Laxfordian Complex

The Laxfordian complex developed during the Laxfordian metamorphic episode by the textural and mineralogical reconstitution of granulite facies gneisses and basic and ultrabasic rocks, the development of granitic and syenitic rocks from pre-existing rocks, the intrusion of trondhjemitic, granitic and pegmatitic material with associated metasomatic activity, the scapolitization of the anorthositic and gabbroic rocks and the development of a new set of structural elements (see fig. 22).

The principal features of the episode are

(1) The development of the structure of the complex. It is primarily the development of the Laxfordian NW-SE folds and associated axial plane foliation that dips to the SW but also includes a late phase of folding and phase of jointing.

(2) The development of trondhjemitic rocks and an associated sodium metasomatism that modified the gneisses and early igneous rocks. This may be termed the "trondhjemitic injection complex".

(3) The development of granitic rocks and an associated potassium metasomatism that modified the gneisses, early igneous rocks, and trondhjemites, producing in many cases granitic and syenitic rock-types. This may be termed "the granitic injection complex".

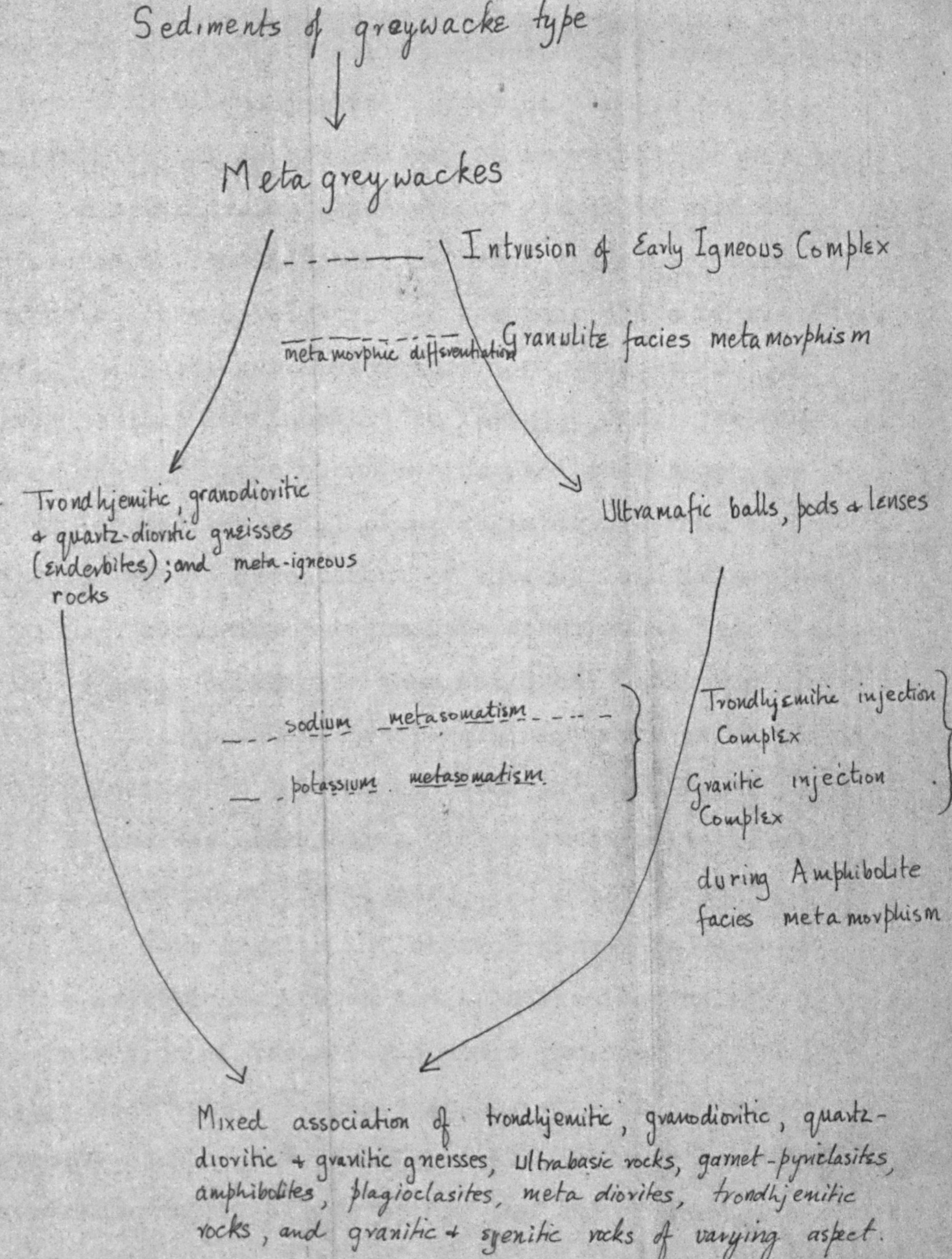

Fig.22 Schematic development of the Laxfordian complex.

The time relationships between the phases of folding, the trondhjemitic injection complex and the granitic injection complex may be summarised as follows:-

The Laxfordian metamorphism commenced with the injection of trondhjemitic material which continued throughout the development of the main phase of folding; sodium metasomatism also occurred at this time. Trondhjemites continued to be intruded after the main phase of folding as shown by the fact that they cut the folds and the axial plane foliation. This was followed by the development of the granitic injection complex; potassium metasomatism occurred at this time. A minor phase of folding then followed, producing foliation flexures and local warping. The final episode in the Laxfordian metamorphism was the development of NE - SW and WNW -ESE joints with pegmatitic material filling certain of the former.

The complete lack of contact phenomena adjacent to the injection granites and trondhjemites points to the intrusion of the material into gneisses at a fairly high temperature and this together with widespread textural similarities in all rock-types suggests that intrusions occurred long before the end of the metamorphism.

Sutton & Watson (1962) state that the development of "granitic rocks" started at the beginning of and continued throughout the Laxfordian metamorphism. From their figures, it appears that they have included both trondhjemitic and granitic (sensu stricto) varieties in their "granitic rocks" (Sutton & Watson, op. cit. figs. 5) It has been shown in this study that the trondhjemitic and granitic injection complexes form two independent units that are not genetically related. While the granitoid rocks developed throughout the metamorphism the granitic injection complex appeared only after the main folding and foliation had developed, whereas the trondhjemitic injection complex occurred concomitantly with the folding and foliation. Potassium metasomatism also occurred after the formation of the Laxfordian folds and foliation.

Metasomatism has played an important role in the development of the complex. It is suggested in this study that potassium metasomatism is due to a fluid that is very closely related to a pegmatitic fluid and extremely rich in water and volatiles. More water and volatiles may mean higher temperatures and, therefore, more potassium (cf. Orville, 1962).

The Structure of the Complex

Although a structural study of the complex has not been attempted field mapping was essentially concerned with the relationships of the granitoid rocks to the structure. Little can be added to the details recorded by Watson (op.cit.).

Watson's conclusion that the Laxfordian structure is due to the folding of an earlier foliation is confirmed in this study. Several examples of the present foliation cutting the fold noses and lying parallel to the axial plane have been seen (p.35). The foliation throughout the area is considered to be Laxfordian for no apparent differences could be observed throughout the area, except in the attitude of the foliation (contrast Watson, op.cit). This phase of folding has produced NW - SE folds plunging SE and an associated axial plane foliation that dips to the SW.

Sutton & Watson (op.cit.) also describe a late phase of E-W folding, which has been recognised in this study. The E-W folding affects the granitic sheets and therefore occurred after the injection of granitic rocks. It can be seen in a number of localities, for example, 100 metres WNW of Badnabay where the foliation swings through 90°, the dip becoming vertical or almost so. The E-W folding is less well developed in many cases being represented by slight flexures of the foliation. In these cases the direction of the fold axes is difficult to determine, but these flexures are clearly related to the more obvious E-W folds.

NE-SW and WNW-ESE jointing has given rise to many prominent topographic features. The joints post-date all magmatic and metasomatic activity apart from the intrusion of a few pegmatites along certain NE-SW joints.

ADDENDA

TO

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