THE GEOLOGY OF THE LEWISIAN ROCKS NORTH OF LOCH TORRIDON, ROSS-SHIRE, SCOTLAND

by

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ABSTRACT

The Lewisian rocks of Loch Torridon consist of banded acid gneisses enclosing a number of basic and ultrabasic bodies and cut by a swarm of NW-SE trending basic dykes and by a later set of pegmatite dykes and a granite sheet.

No definite conclusion has been reached as to whether the gneiss complex was derived from igneous or sedimentary parent rocks or a combination of both, although previously described metasedimentary gneisses are considered to be possibly magmatic derivatives of early basites (in the case of the "epidotites") and deformed quartz veins (in the case of the "quartzites").

The dyke swarm is believed to have been derived from two distinct tholeiitic parent magmas; the earlier type-TD basite suite owes its origin to a normal magmatic differentiation process, whereas the later type-TB basite and ultrabasite suite may have formed by an abnormal magmatic differentiation process involving possibly the crystallization of hydrous minerals (hornblende).

The rocks of the complex have been affected by at least nine deformation episodes of which five (D_1-D_5) occurred prior to the dyke intrusion and the remainder (D_6-D_9) after the dyke intrusion. In most of the deformation episodes, folds, lineation and axial-planar foliation have been produced.

The earliest structure, S_1 foliation, has been inferred from the form of interference structures formed in the D_3 deformation. The S_2 foliation, although never found undeformed, is believed to have had an original NW-SE steeply dipping attitude. The S_3 foliation, which is predominant in the north of the area has been affected by a flattening phase (D_3A) and large-scale folding (D_3B) about an axis plunging moderately SW. D_4 has produced small-scale folds and related NW-SE striking S_4 axial-planar foliation. The attitude of S_4 and style and scale of F_4 folds show variations through the area suggesting that in the north F_4 was formed under brittle conditions, whereas in the south the conditions favoured plastic flow.

S_4 shows large-scale variations in attitude which are thought to be a result of D_4 rather than of later large-scale folding. It is believed that the maximum compressive stress during D_4 was along a N-S shallow dipping axis. D_5 has produced both major and minor F_5 folds with SE-plunging axes, affecting sub-horizontal belts of S_4. L_5 is co-axial to L_4 within individual belts.

The post-dyke structures revealed from a study of the dykes involved four separate episodes, D_6-D_9. The S_6 foliation is parallel or sub-parallel to dyke margins but only occasionally can be positively identified since S_7 is also parallel to dyke margins and is thus generally co-planar to S_6. D_7 comprises F_7 folds, S_7 axial-planar foliation and L_7 lineation in the dykes which increase in intensity towards the south. S_7 is co-planar to S_4 and S_6 and L_7 is co-axial to L_4 in the associated gneisses. The D_8 structures are restricted to narrow NW-SE striking belts and consist of F_8 minor folds and L_8 lineation. The last penetrative structure is the S_9 mylonite banding affecting certain NW-SE striking belts and is co-planar to S_4 and S_7.

The earliest metamorphic episode is M_4 which is syntectonic to D_4. Further metamorphic episodes occur syntectonically with D_6 (M_6), D_7 (M_7) and a retrogressive episode occurs between D_8 and D_9. M_4, M_6 and M_7 are of almandine amphibolite facies, whereas the late retrogressive metamorphism is of greenschist facies. The distinction between M_4, M_6 and M_7 is made mainly on textural grounds, although the formation of garnet in M_6 distinguishes it from M_4 and M_7. The earliest recognizable migmatitic episode pre-dates D_3. Following D_3 there occurred a phase of migmatization which was in part magmatic, producing lit-par-lit trondhjemitic pegmatites, and in part metasomatic, producing feldspar augen in the acid gneisses. A third migmatitic phase accompanying M_4 has produced syntectonic granitization in the acid gneisses and early basites in the south, producing rocks of dioritic composition from the early basites. In the north, this migmatization is post-tectonic, producing thin pegmatite veins parallel to F_4 axial planes. Finally a potassic metasomatism and late retrogressive metamorphism has produced microcline-muscovite-quartz-bearing assemblages of all rock types.

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I. INTRODUCTION

A. History of research

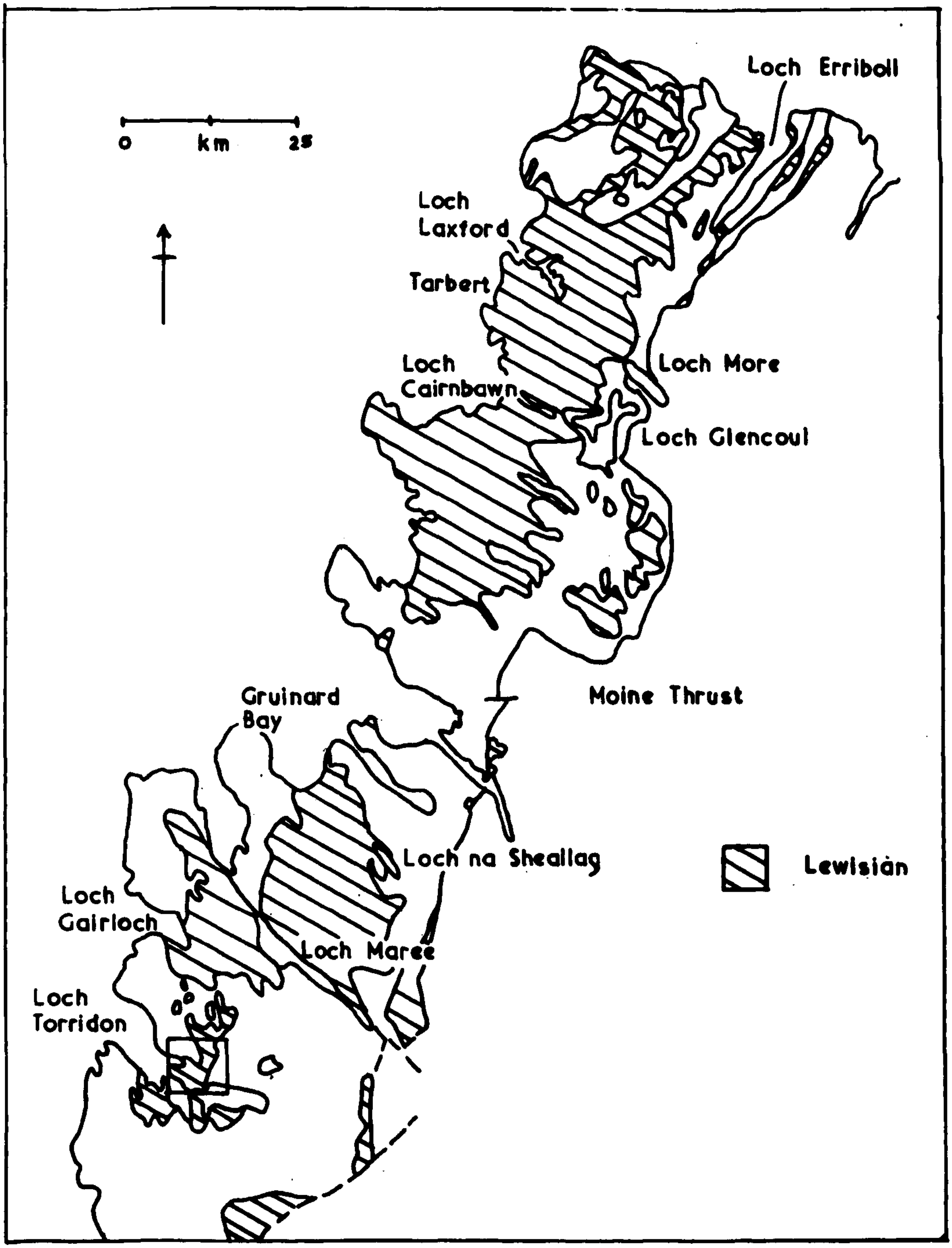
The Geological Survey (Peach and others, 1907, pp.126-7 and pp. 172-190) recognized three major zones in the Lewisian complex of the North-West Highlands. These are (see Fig.I-1) (i) the northern zone extending from Cape Wrath to a line between Tarbert and Ben Dreavie, (ii) the central zone, extending 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 the remaining outcrops of Lewisian rocks. The Survey distinguished these zones by differences in gneissic types and in the relationships between the gneisses and a series of dykes intruded into the complex. Thus in the northern zone grey biotite-gneisses, hornblende-biotite gneisses and amphibolites occur intruded by later pegmatites which are abundant towards the southern margin. The central zone consists of grey pyroxene-granulites and pyroxene-gneisses cut by dolerite dykes. The southern zone is broadly similar to the northern except for the occurrence of a series of metasediments in the Gairloch and Loch Maree districts and of occasional patches of pyroxene granulites. Also, granites are less common than in the north.

Sutton and Watson (1951A, p.292) from studies at Scourie and Loch Torridon [redacted], proposed a metamorphic history for the Lewisian based on the relationships of the basic dykes to the members of the complex and the progressive metamorphism of these dykes, as follows:-

(i) The Scourian granulite-facies metamorphism.
(ii) The intrusion of a series of NW-SE trending dykes.
(iii) The Laxfordian almandine-amphibolite facies metamorphism.

The broad geological history established by the above authors for the Lewisian rocks was partly confirmed by radiometric dates. Giletti and others (1961, p.241) obtained a range of ages from 1900 to 2460 m.y. from pegmatites occurring in the Scourian, while pegmatites from the Laxfordian yielded ages from 1160 to 1620 m.y. These authors suggested

Fig.I-1. Outcrop map of the Mainland Lewisian of the North-West Highlands.


0 km 25
Loch Erriboll
Loch Laxford
Tarbert
Loch More
Loch Cairnbawn
Loch Glencoul
Moine Thrust
Gruinard Bay
Loch na Sheallag
Lewisian
Loch Gairloch
Loch Maree
Loch Torridon

that the Scourian metamorphism occurred at least 2460 m.y. ago and the Laxfordian metamorphism between 1600 and 1500 m.y. ago. More recent age determinations have revealed the following information:-

(i) Scourie dykes were intruded shortly before 2190 m.y. while emplacement of other dyke types followed over a period until as late as 1950 m.y. (Evans and Tarney pp.638-41, 1964).

(ii) The Scourian granulite-facies metamorphism took place at least 2600 m.y. ago at Lochinver, Sutherland. A third metamorphism (the Inverian metamorphism) involving retrogression of the granulite-facies assemblage to amphibolite facies occurred at 2200 m.y. These two events were separated by potassic pegmatites formed about 2250 m.y. The intrusion of the dykes followed the Inverian metamorphism. The Laxfordian metamorphism occurred at about 1580 m.y. (Evans 1965, p.54).

(iii) From Lewisian rocks at Loch Torridon Moorbath and others (1967, pp.389-412) obtained dates of 1504±45 m.y. from hornblendes in a Laxfordian metamorphosed basic dyke, and 1148±30 m.y. from chloritized biotite in acid gneisses which are cut by the dyke. Ages in the vicinity of 1200 m.y. have also been obtained from the Lewisian rocks of Gairloch (Evans and Park, 1965), confirming the presence of a late episode affecting the gneisses.

Several distinct events have thus been established from radiometric age determinations and from structural and petrological analysis of the Lewisian rocks. These are:

1. The Scourian granulite-facies metamorphism occurring 2460 to 2600 m.y.
2. Intrusion of potassic pegmatites at 2250 m.y.
3. The Inverian amphibolite-facies metamorphism at 2200 m.y.
4. The intrusion of a dyke swarm between 2190 and 1950 m.y.
5. The Laxfordian amphibolite-facies metamorphism occuring between 1600 and 1500 m.y.
6. The Late Laxfordian greenschist-facies metamorphism occurring between 1100 and 1200 m.y.

The hypothesis of Sutton and Watson (op.cit.) that the Laxfordian rocks represent Scourian rocks transformed by the Laxfordian metamorphism and that there is only one anorogenic swarm of dolerite dykes intruded between the two metamorphisms has been questioned. Bowes (1962) has suggested, without detailed evidence, that the Laxfordian complex was formed from reconstructed Scourian gneisses. The role played by dykes as stratigraphic marker horizons has also been questioned. Park (1961, 1964, 1969), Bowes and Khoury (1965) and Wright (1962) have suggested that there is more than one set of dykes in the Laxfordian which can be distinguished on tectonic grounds. Peach et al. (op.cit.), O'Hara (1962) and Tarney (1963) considered that the dykes in the Scourian complex of the central belt are not all of the same age, Tarney considering that the dykes of Assynt were intruded at great depth under varying metamorphic conditions which was reflected by varying mineral assemblages.

Sutton and Dearnley (1964) proposed a revised sequence based upon sequences established in the Lewisian of the mainland and the Outer Hebrides (see Table I-1). Dearnley and Dunning (1967) create some confusion in nomenclature by describing events of "pre-Scourian" age in the Outer Hebrides. Since Scourian, according to the definition of Sutton and Watson (op.cit.), refers to rocks earlier than the dykes, all pre-dyke events are by definition Scourian.

Detailed structural work in small areas (Park 1964, 1969, Bhattarcharjee 1968 and Khoury 1967) indicates that the Lewisian has a much more complex history than was originally believed. Recently, Bowes (1968) has attempted a widespread correlation of the Lewisian based upon established radiometric and structural studies on the mainland.

The Lewisian complex around Loch Torridon was initially described by Hinxman (in Peach et al. op.cit. pp.253-59) who made a subdivision of the rocks in space and time into:-

(a) Those affected by a NE-SW foliation-producing event.

(b) Intrusion of basic dyke swarm.

(c) Those affected by a NW-SE foliation producing event.

Period	Mainland	Outer Hebrides
Late-Laxfordian c.a. 1600±m.y.	NW-SE folding; amphibolite facies retrograde metamorphism; migmatization and formation of granites and pegmatites.	NW-SE folding and some cross folding (NE-SW); amphibolite facies retrograde metamorphism; migmatization and formation of granites and pegmatites.
Early Laxfordian (age not yet determined)	Clouding of feldspars and formation of garnet coronae and metamorphic minerals in Scourie dykes of central zone.	Granulite-facies metamorphism of South Harris igneous complex and associated basic intrusions; main NW-SE folding.
Non orogenic phase c.a. 2100±m.y.	Intrusion of tholeiitic and ultrabasic Scourie dykes.	Intrusion of South Harris igneous complex and associated tholeiitic sills and dykes.
Late Scourian c.a. 2200±m.y.	Intrusion of potash pegmatites and local amphibolite facies retrograde metamorphism.	Not yet recognized.
Early Scourian c.a. 2600±m.y.	Granulite facies metamorphism and main folding; formation of palingenetic migmatites and agmatites.	Metamorphism and main folding; formation of palingenetic migmatites and agmatites (blocks of earlier banded basic and ultrabasic rocks in agmatites). Deformation of microcline pegmatites (see below).
?Late orogenic phase	Layered basic and ultrabasic intrusions.	Banded ultrabasic and basic rocks.
Pre-Scourian (?perhaps as old as 3000 m.y.)	Earliest recognizable complex into which the layered basic and ultrabasic rocks were intruded.	Earliest recognizable complex ('grey gneisses') intruded by banded basic and ultrabasic rocks. Microcline pegmatites now gneissic owing to Early Scourian folding and metamorphism.

Table I-1. Lewisian Chronology according to Sutton and Dearnley (in Bowes, Wright and Park 1964).

From observations in the Lewisian at Loch Torridon, Sutton (in Sutton and Watson op.cit.) made a similar tripartite division of the rocks into those produced in the first metamorphism, the dolerite dykes, and those produced in the second metamorphism, thus:-

The complex produced in the first metamorphism

This is represented in the north of the area and consists of acid to basic gneisses with a NW-SE-striking foliation. Many of these gneissic rocks were believed to represent migmatized metasediments of which several groups ranging from quartzites through flaggy-quartz-epidote rocks to calc-silicate granulites were recognized. The mineral assemblage developed in the gneisses was that of the amphibolite facies.

The dolerite dykes

After the first metamorphism the complex became rigid enough to be fractured along NW-SE trending lines along which basic magmas were intruded. As a result of a second metamorphism the dykes were progressively deformed and metamorphosed to varying degrees.

A study of the metamorphism of the dykes led Sutton to divide the various products into seven steps:-

1. Autometamorphic changes resulting in the formation of corona structures.
2. Replacement of pyroxene by amphibole and destruction of corona structures.
3. Formation of sphene around ilmenite.
4. Recrystallization of lath-like plagioclase.
5. Conversion of dykes into hornblende-schist.
6. Production of epidote and biotite in dykes.
7. Migmatization of dykes.

The complex produced in the second metamorphism

As a result of the varying intensity of the second metamorphism Sutton was able to define three zones, the An Ruadh Mheallan, Loch Diabaig and Loch Torridon zones. In the Loch Torridon zone and in parts of the Loch Diabaig zone migmatization and metamorphism of the amphibolite facies accompanied deformation, whilst in the An Ruadh

Mheallan zone the complex remained rigid and yielded to fold movements by the development of shear planes. Towards the end of the second metamorphism an alkali-metasomatic phase produced microcline in all the rocks of the complex.

The final phase of the second metamorphism resulted in a post-crystalline deformation producing mylonite gneisses, mylonites and ultramylonites.

According to Sutton the migmatization associated with the second metamorphism advanced from the south, stopped in the Loch Diabaig zone and subsequently retreated, leaving behind rocks in every state of alteration.

B. Aims of the present investigation

The Lewisian rocks described in this thesis lie at the southern extremity of the belt of gneisses running along the western seaboard of Northern Scotland. The area studied covers approximately 14 sq. km. and occupies an inlier within the Torridonian on the north shore of Loch Torridon. It lies entirely in the southern zone of the Survey and occupies the whole of the An Ruadh Mheallan and Loch Diabaig zones and part of the Loch Torridon zone of Sutton (1951A), and thus has features of both Scourian and Laxfordian as defined by Sutton and Watson (op.cit.).

Although the outcrop of the Lewisian in this belt is not extensive because of the Torridonian cover, the rocks are particularly well exposed as a result of ice-action. Discontinuities in exposure within the inlier are due to masking by either glacial drift, particularly around Loch na h'Umhaig, or more commonly, by peat. On average, 60% of the rock is exposed but south of Creag Fhraoich towards Loch Torridon the exposure increases to 70%. Coastal exposures are generally unbroken and on the hill, Meall Ceann na Creag, continuous exposures up to 100 metres long occur.

A large proportion of the gneisses occur at an altitude of 600 feet, but at An Ruadh Mheallan, gneiss exposures rise to 1700 feet above sea level.

Although previous work on the rocks of the Lewisian indicate a quite complex history, radiometric dating reveals a span of time between the Scourian and Laxfordian of at least 1100 m.y. so that an even more complex history was to be expected. Problems were posed by the apparent conflict between the Survey view that the gneisses were of magmatic origin and the view of Sutton and Watson that they represented sediments transformed by metasomatism and migmatization. Previous writers relied upon the occurrence of dykes as stratigraphic marker horizons in the unravelling of the structural sequence, without paying much attention to their validity as such. Since dykes are abundantly developed in the Loch Torridon Lewisian, the writer has attempted to determine the validity of the dykes as stratigraphic marker horizons, by studying the effects of deformation upon them and the structural controls which affect their emplacement.

Field mapping was supplemented by detailed petrological examination of all rock types by geochemical investigation of the dyke rocks and by a statistical analysis of the structures.

C. Methods of Research

1. Field techniques

Mapping of the area was carried out by using areal photographs on a scale of 6 inches to a mile, the information from this was then transferred to a 6 inch ordnance survey sheet. This map was then enlarged to 12 inches to a mile to accommodate the structural detail.

Rock specimens for the structural analysis were collected according to the instructions of Turner and Weiss (1963).

A compass and Dollar clinometer were used to measure the orientation of structures, each structure being measured two or three times and averaged. Structures measured include foliation, mineral lineation, fold hinges, pinch-and-swell structure, long axis of boudins and slickensides, together with non-penetrative planar discontinuities (eg. dyke and pegmatite margins). Lineations were measured on the foliation surface either in terms of their pitch, where the foliation dip was steep, or their plunge where it was shallow. Axial planes of folds because of their nature cannot be measured directly, but were obtained either by the measurement of a related axial-planar foliation or by measuring the trace of the axial surface on two or more of the surfaces and also the plunge or pitch of the fold hinge of the fold and then computing the axial planes by means of the stereogram.

2. Petrographic techniques

Thin sections were made from over 450 hand specimens. The rocks were cut at right angles to the foliation and lineation (where present). The thin sections were examined by conventional methods to determine the minerals present, together with their mutual relationships, approximate proportions and textures.

The universal stage was employed in the determination of the optic angle of pyroxenes, the extinction angle of plagioclase feldspar and the optic orientation of quartz (for petrofabric study). Plagioclase composition was determined from the curves of Poldervaart. Rocks for petrofabric study were oriented in the field and were cut normal to the foliation and mineral lineation. The foliation trace and the normal to this direction on the surface were then marked and used as reference axis for cutting and mounting of the thin sections. Within each thin section between 200 and 400 quartz optic axes were measured, plotted on an equal area net and contoured by the free-contouring method.

3. Structural analysis

From the data obtained from field mapping it has been possible to divide the area into subareas. The structural data obtained from the field study were analysed for each of the subareas. The poles to the foliation planes were plotted on an equal-area stereographic net and contoured. Individual measurements of the linear structures related to the foliation were plotted on the same diagram but left uncontoured. Where the foliation poles fall on a great circle the related lineations fall on the axis to this great circle. The linear structures must, therefore, be parallel to the axes of the folds, and the folds are considered to be cylindroidal. The choice of the subareas has been made so as to show the variation in geometry of the structures from place to place.

Specimens of folds collected for further analysis were cut normal to the fold axis, and where necessary, a section was also taken parallel to this surface.

In one gneissic specimen isogonal lines were constructed for one folded layer according to the methods of Ramsay (1967) (see Chapter V. C). This band was traced from the fold and enlarged. Isogonal lines were then produced by constructing surfaces of inclination from 0° to 90°, in 10° intervals, for the upper and lower surfaces of the folded layer. The isogonal lines were then constructed by joining points on the upper surface to those of the lower surface for equal inclinations.

4. Modal analysis

Some of the chemically analysed specimens 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 1800 and 2500 points were counted usually over one thin section. In general, the total area traversed was 400 sq. mm. or more.

5. Collection and preparation of dyke material for chemical analysis

Specimens were collected during field mapping and a detailed record was made of locality and field relations of each dyke specimen. Grain size was the most important factor in deciding the weight or size of specimen required. Since the grain size of the dyke rocks was always considerably less than 1 cm., the specimen weight was of the order of 1 kilogram (cf. Smales and Wager 1960).

When a specimen was chosen for analysis it was washed, dried and broken into 1 cm. cubed pieces. From the pieces of material 150 to 300 gm. were taken, all weathered material being discarded. After the material was crushed to 120 mesh in a tema mill, the powder produced was coned and quartered.

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

6. Chemical analysis

The following scheme of chemical analysis based on the methods of Riley (1958A and 1958B) and Shapiro and Brannock (1956) as used in the geochemical laboratory at the University of Keele was used (Table I.1).

Oxide	Method
SiO_2	Riley (1958A)
Al_2O_3	Riley (1958A)
Total iron as Fe_2O_3	Riley (1958A)
FeO	Shapiro and Brannock (1956)
MgO, CaO	Riley (1958A)
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)

Table I.1.

The method for determination of SiO_2 (Riley 1958A) was slightly modified. Solution A was prepared following Riley (1958A) except that the acid used to neutralize fused caustic cake (25 ml. of 2·5N H_2SO_4) was replaced by 20 ml. 50 percent HCl. Solution A is used to determine SiO_2 using Riley's molybdenum blue method and the change made in the preparation of solution A required a slight adaption to be made to the acid molybdate reagent which was prepared as follows:-

8 gm. ammonium molybdate A.R. were dissolved in 500 ml. water; 20 ml. concentrated HCl A.R. and 12·5 ml. N H_2SO_4 were added and the whole diluted to 1,000 ml.

The determination of FeO by the method of Shapiro and Brannock (1956), was slightly modified as follows:-

After weighing 0·500 gm. of the rock powder into a platinum crucible 10 ml. 50% H_2SO_4 and 50 ml. 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.

In the determination of MnO (Riley 1958A) by oxidation of Mn^{4+} to Mn^{7+} the stability of the permanganate colouring was not at first achieved. It was found that the glass ware had to be thoroughly cleansed before the determination was carried out.

7. <u>Discussion of the methods of chemical analysis</u>

To determine the precision of each complete chemical analysis, one of the rock powders was analysed in duplicate and a specimen BCR-1 (American diabase standard) was also partially analysed. The evidence from Table I.3 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%. The limits of 99% to 101% set by the laboratories of the United 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. All standards were produced as suggested by Riley (1958A).

The optical densities of each standard were frequently checked against those recommended by Riley (1958A) and were generally found to be in close agreement.

SiO_2	49·51	49·50
TiO_2	1·56	1·54
Al_2O_3	13·40	13·63
Fe_2O_3	10·51	10·48
FeO	2·88	2·88
MnO	0·22	0·22
MgO	6·97	7·09
CaO	9·65	9·71
Na_2O	2·40	2·32
K_2O	1·08	1·08
P_2O_5	0·12	0·11
H_2O	0·86	0·88
Total	99·16	99·44

Table I-3. Duplicate analyses of type-TD basite (TD.5).

8. Presentation of chemical 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% (Burri 1959). From the cation percentages the catanorm can be calculated (Burri 1959) which, according to Hietenan (1962) compares with the CIPW norm and thus may be used to compare with CIPW norms in the literature. In the present investigation the catanorms of all the analyses were calculated. Niggli numbers (Niggli 1954) based on molecular proportions were also calculated for all analyses. In the calculation of Niggli numbers and cation percentages, the equivalent molecular proportions and equivalent atomic proportions of the weight percentages of each oxide were obtained from tables drawn up by Burri (1959).

D. Theoretical aspects of deformation in dykes

Before the structural analysis of the rocks was completed, the writer found it necessary to investigate the range of possible structures which may be produced in the dykes, since the interpretation of these is essential to a correct evaluation of the structural sequence in the complex.

The deformation structures which may form in the dykes would appear to depend upon:-

(i) The initial attitude of the dyke and the nature and attitude of any inherited structures occurring in the dykes.

(ii) The initial attitude of the structures in the gneisses in relation to the overall form of the dykes (ie. concordant or discordant margins).

(iii) The type of deformation and the attitude of the structures it produces in the dykes and gneisses and the effects it has on the earlier structures.

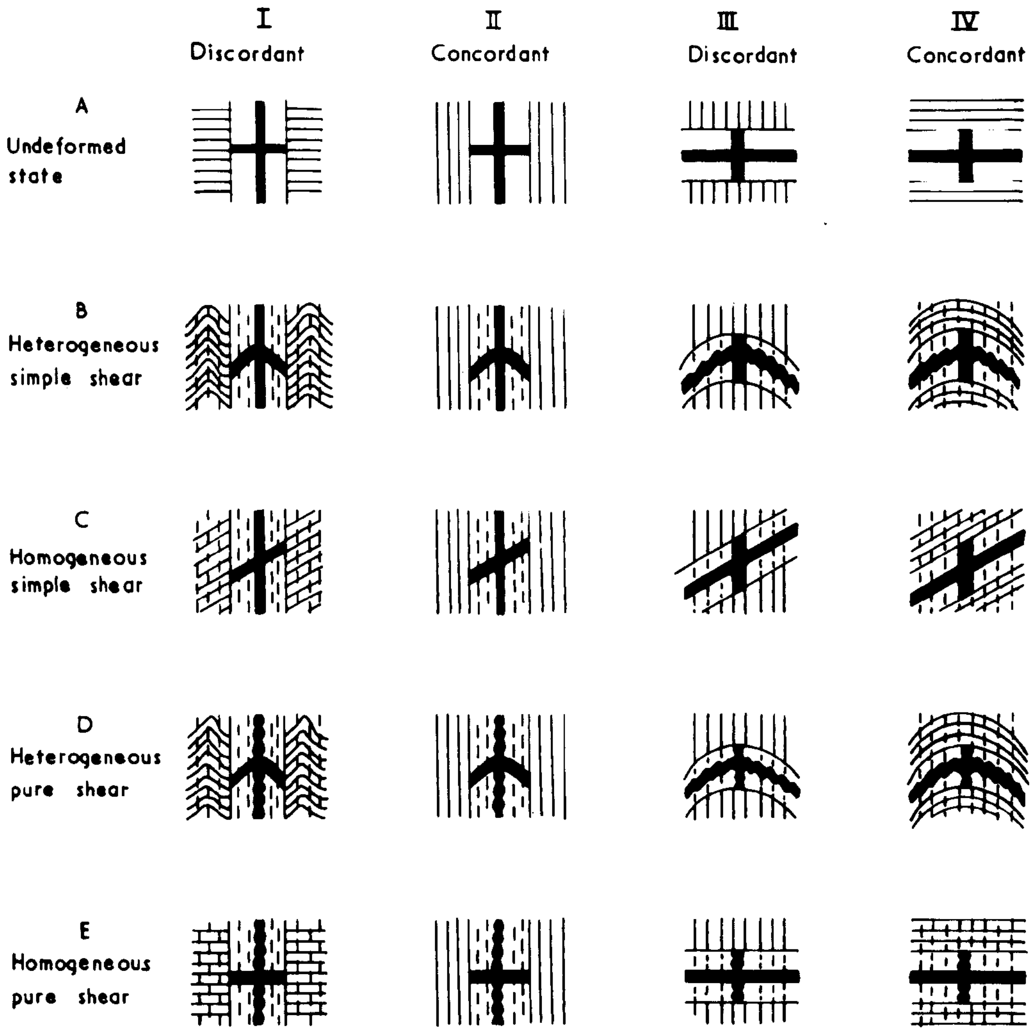
The writer has, therefore, examined theoretically the effects of heterogeneous and homogeneous deformation on dykes with concordant and discordant margins to associated host gneisses with varying attitudes of new structures. The deformations chosen are simple shear and pure shear. FigsI-2-BI-IV to EI-IV represent hypothetical examples of dykes with either concordant (II and IV) or discordant margins (I and III) deformed by either heterogeneous or homogeneous pure or simple shear, with the attitude of the new structures formed either parallel or normal to the dyke margins.

Thus FigI-2-BI-IV examines the effects of heterogeneous simple shear on discordant and concordant dyke margins producing structures whose attitudes are either parallel or normal to the dyke margins. In each of these figures the effects on certain inherited structures within the dykes is shown. The initial form of the dyke, of the inherited structures and the attitude of the structures in the gneisses are shown in FigI-2-AI-IV.

Boudinage and pinch-and-swell structure are only likely to be formed in rocks where a mechanism of pure shear has been operating (see FigI-2-DI-IV and EI-IV) and where there is a considerable competence difference between the rocks concerned. Furthermore, although not shown in these diagrams, if the deformation and competence difference between the dykes and host gneisses are large enough, the dykes will become boudinaged.

Thus the figures give a variety of structural relationships that may develop in the dykes and associated gneisses, but the simple geometry of these structures does not itself indicate the nature of the deformation and initial form of the structures in the gneisses and dykes. For instance, structures in FigI-2-CI are similar to those of FigI-2-CII although the initial attitude of the dyke to the gneiss foliation is different. Other evidence, therefore, must be sought to define the relationships of the foliation in the gneisses to that in the dykes.

Fig.I-2. Theoretical models for dyke deformation. In all cases the maximum resolvable compressive stress is normal to the post-dyke foliation (dashed line).


I
Discordant
II
Concordant
III
Discordant
IV
Concordant
A
Undeformed state
B
Heterogeneous simple shear
C
Homogeneous simple shear
D
Heterogeneous pure shear
E
Homogeneous pure shear

E. Summary of the structural sequence

The following structural sequence has been found in the Lewisian rocks at Loch Torridon:-

1. D_1 deformation episode producing S_1 foliation.
2. D_2 deformation episode producing F_2 folds and S_2 foliation.
3. D_3 deformation episode producing F_3 folds and S_3 axial-planar foliation, followed by a phase of D_3A flattening and major folding D_3B.
4. D_4 deformation episode producing F_4 folds and S_4 axial-planar foliation.
5. D_5 deformation producing F_5 major and minor folds and S_5 foliation.
6. D_6 deformation episode producing F_6 folds and S_6 foliation.
7. D_7 deformation episode producing F_7 folds and S_7 axial-planar foliation.
8. D_8 deformation episode producing cataclasites and mylonite banding (S_9).

A unique dyke swarm was intruded after D_5 and before D_6.

F. Basis for the subdivision of the main rock types

From field observations in the Lewisian rocks of Loch Torridon it has been possible to subdivide the rocks into the following groups:-

1. Acid gneisses
   a. Massive gneiss
   b. Banded gneiss
2. Quartzites and epidotites
3. Early basites
4. Early ultrabasites
5. Migmatitic derivatives of the acid gneisses, early basites and ultrabasites
6. Dykes
7. Granite sheet and pegmatites

The acid gneisses and early basites have been further subdivided on structural grounds into those which have a dominant S_3 foliation and those with a dominant S_4 foliation, so as to show the variation in each group. Thus the acid gneisses have been subdivided as follows:-

1. Acid gneisses
   a. Those with a dominant S_3 foliation
      (i) Massive gneisses
      (ii) Banded gneisses
   b. Those with a dominant S_4 foliation
      (i) Massive gneisses
      (ii) Banded gneisses
      (iii) Finely-foliated gneisses
      (iv) Quartzites and epidotites

II. THE PRE-DYKE PETROLOGY OF THE COMPLEX

The rocks emplaced before the intrusion of the dyke swarm are described in this section. The dykes, the late pegmatites and granites, and those processes affecting the pre-dyke rocks after the dyke intrusion are discussed in later chapters.

The classification of these rocks is based primarily on composition and on structural setting.

A. Acid Gneisses
   1. Acid gneisses with dominant S_3 foliation.
   2. Acid gneisses with dominant S_4 foliation.
   3. Gneisses of possible sedimentary derivation.

B. Basite and Ultrabasite Bodies.

C. Pre-Dyke Migmatites.

A. The Metamorphic Petrology of the Acid Gneisses

1. Introduction

Marked variations in texture, mineral proportion, and mesoscopic structure, are revealed by the acid gneisses of the complex, which have been subdivided into:-

(a) Massive gneisses

(b) Banded gneisses

(c) Gneisses of possible sedimentary derivation

In addition to the presence or absence of banding, the massive and banded gneisses are distinguished by differences in mineral composition, the banded gneisses being comparatively rich in mafic constituents. The acid gneisses fall into Group IV of the Geological Survey classification of the Lewisian rocks (Peach et al. 1907).

2. Acid gneisses with dominant S_3 foliation

(a) Distribution

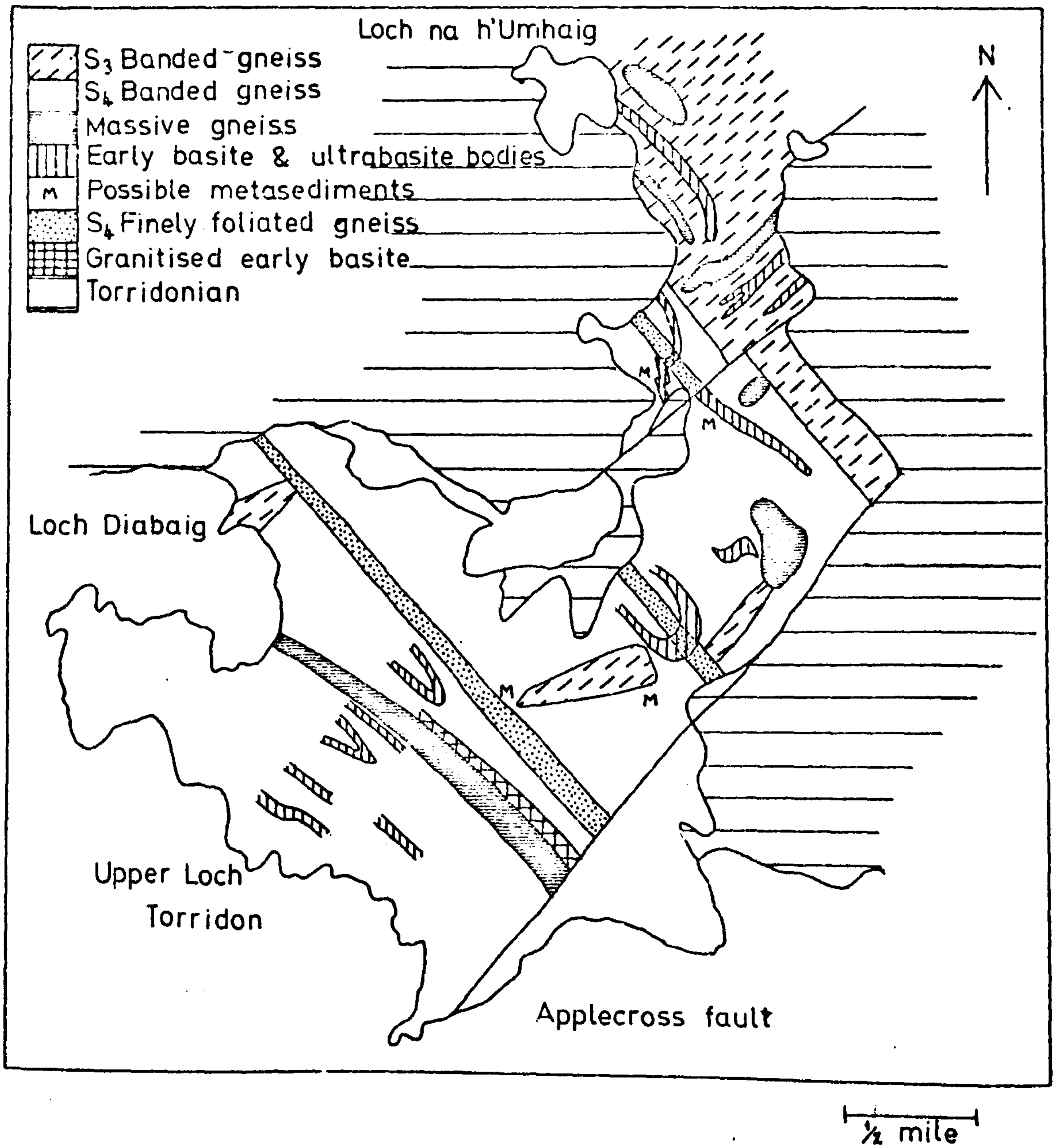
The distribution of the acid gneisses is shown in Fig.II-1, the gneisses forming four separate belts. The largest of these belts is found in the extreme north, occupying an area from Loch na h'Umhaig extending south-eastwards until it is cut off by the Torridonian in the vicinity of the Alligin River. Its southerly border with the S_4 gneisses strikes approximately NW-SE and is found south of Loch Airidh Eachainn. The other three isolated belts of S_3 gneisses occur in (a) a narrow NE-SW belt extending south-west of Loch a'Choire Bhig to the Alligin Road at Creag Dharach, (b) an approximately NE-SW belt 150 metres north-west of Loch na Beiste, (c) a NE-SW belt at Diabaig.

Mappable exposures of massive gneisses are found in the north-east in the vicinity of An Ruadh Mheallan and Loch na h'Umhaig, where three separate belts occur, the belts being concordant with the regional S_3 foliation. A further belt of massive gneisses is found 150 metres east of Loch a'Choire Bhig. These belts of massive gneisses rarely exceed 200 metres in width and the contact between the massive and banded gneisses is very sharp. Plate II-1a illustrates a concordant junction of massive and banded gneisses with the S_3 foliation, whereas Plate II-1b shows an F_3 fold affecting the junction between massive and banded gneisses with the S_3 axial-planar foliation discordant to the junction.

(b) Petrology of massive gneisses

The massive gneisses are very homogeneous in appearance (Plate II-2a) and show no segregation of the mafic and felsic constituents. This homogeneity often masks the S_3 foliation, but close observation of preferably oriented biotite flakes, flattened quartz aggregates and quartz rods on weathered surfaces reveals the S_3 foliation. As a result of biotite occurring as isolated flakes the rocks typically appear lineated rather than foliated. The lineation produced by quartz rods and biotite flakes cannot be related to any D_3 or pre-D_3 internal structures of the rock, but where mesoscopic F_4 folds are observed the lineation is found to be parallel with their axes. This and other

Fig.II-1a. Distribution of the pre-dyke rock units.



Loch na h'Umhaig
S_3 Banded gneiss
S_4 Banded gneiss
Massive gneiss
Early basite & ultrabasite bodies
M Possible metasediments
S_4 Finely foliated gneiss
Granitised early basite
Torridonian
N
Loch Diabaig
M
Upper Loch Torridon
Applecross fault
½ mile

characteristics of these gneisses indicate that they have been recrystallized during the M_4 metamorphism of the complex.

(i) Mineralogy

The following mineral assemblage is exhibited by the massive gneisses; biotite, epidote, chlorite, sphene, tourmaline, iron ore, apatite, plagioclase, quartz and microcline. Microcline and chlorite were formed as a result of post-dyke effects and will not be further discussed in this section.

Biotite forms up to 6% of the rock, with an average value of 3%. It has subidioblastic to xenoblastic form and occurs in typically isolated flakes although occasional aggregates of two or three interlocking flakes are found. Statistically the biotite flakes have a preferred orientation parallel to the S_3 foliation. The pleochroic scheme is x - straw, y - brown, z - deep brown with very little variation. Biotite flakes range up to 1·0 mm. in length with an average dimension of 0·4 mm. Inclusions of epidote, sphene and magnetite are found.

Muscovite forms up to 4% of the rock, although it is absent in many of these gneisses. It has two modes of occurrence, (a) subidioblastic flakes, commonly interlocking with biotite flakes and (b) muscovite-quartz symplectites. The latter mode of occurrence is related to post-dyke effects and will not be discussed here. Muscovite may form inclusions in plagioclase xenoblasts and there is no indication that its formation is related to sericitisation of the feldspar. Grains range up to 0·7 mm. with an average size of 0·4 mm.

Epidote forms approximately 3% of the gneisses and is generally associated with biotite flakes. It shows varying degrees of idiomorphism, with occasional development of orthite cores and angular inclusions of quartz. It is predominantly a colourless variety although a rare pale yellow pleochroic variety is found. Grains have maximum dimensions of 0·4 mm. and an average of 0·2 mm.

Apatite, sphene, iron ore and tourmaline occur in accessory proportions, rarely making more than 1% of the mineral assemblage. Tourmaline is only found in one gneiss specimen, forming idioblastic, tetragonal-shaped grains with the pleochroic scheme x - pale blue, z - deep blue. Subidioblastic granules of sphene are always associated with biotite and epidote.

Plagioclase forms 25% to 65% of the massive gneisses with an average of 50%. It forms aggregates of large, irregular, xenoblastic grains with varying degrees of alteration. The plagioclase is a sodic-rich variety, An_{22-24}, falling in the oligoclase range. It has smooth to serrated, rounded or lobate edges against quartz, but straight, slightly frayed edges against adjacent plagioclase grains. Approximately 25% of plagioclase grains have albite twins developed, the twinning being revealed by alternate lamellae showing varying degrees of alteration to a brown dusty unidentifiable material and secondary mica. Rounded quartz xenoblasts with serrated edges are common inclusions in plagioclase. Grains range up to 1·8 mm. with a mean dimension of 1·0 mm.

Quartz forms 25% to 55% of the gneisses with an average of 30%. It forms aggregates of irregular, xenoblastic grains, the aggregates being flattened in the plane of the foliation. Quartz and plagioclase often have interpenetrative margins. Grains of quartz range up to 2·5 mm. with an average grain size of 1·0 mm.

(c) Petrology of banded gneisses

The banded gneisses are the predominant members of rocks which possess the S_3 foliation and have widespread occurrence in the ground around An Ruadh Mheallan (Fig.II-1). The features revealed by the banded gneisses show no noticeable variations over the area.

The banded gneisses are characterised by the presence of a well defined penetrative foliation which is reflected by the preferred orientation of minerals, flattened mineral aggregates and alternating mafic and felsic rich laminae. The pre-existing s-surfaces and various pegmatitic bodies have clearly influenced the nature of the S_3 banding. Thus in Plate II-2b, a folded pegmatite has been partly extended in

Plate II-1a-b. Contacts between S_3 banded (B) and massive gneiss (M) from the neighbourhood of An Ruadh Mheallan. In (a) contact is concordant to S_3 (82606144), whereas in (b) it is discordant and of fold form (82686143).


B
M

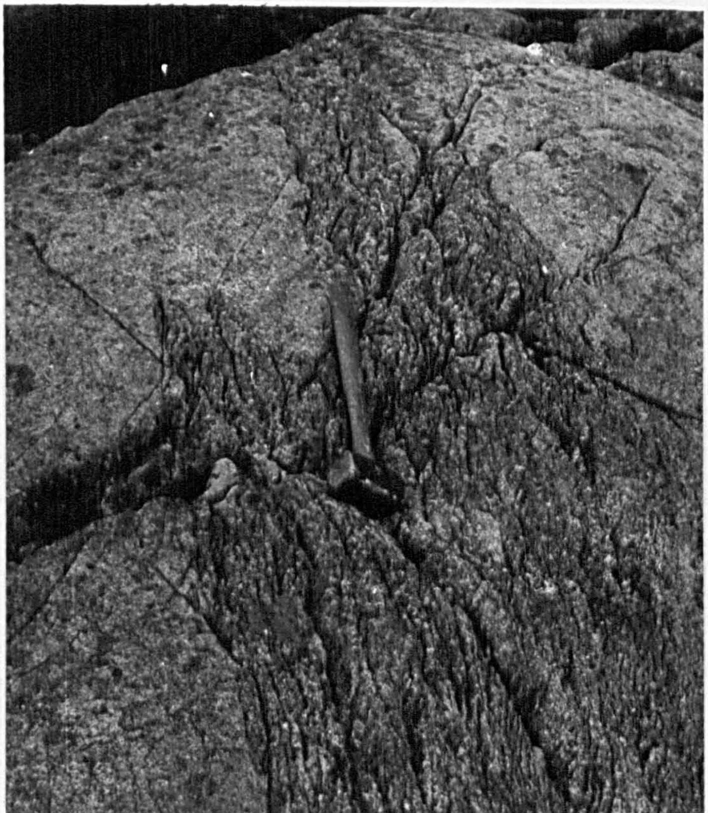
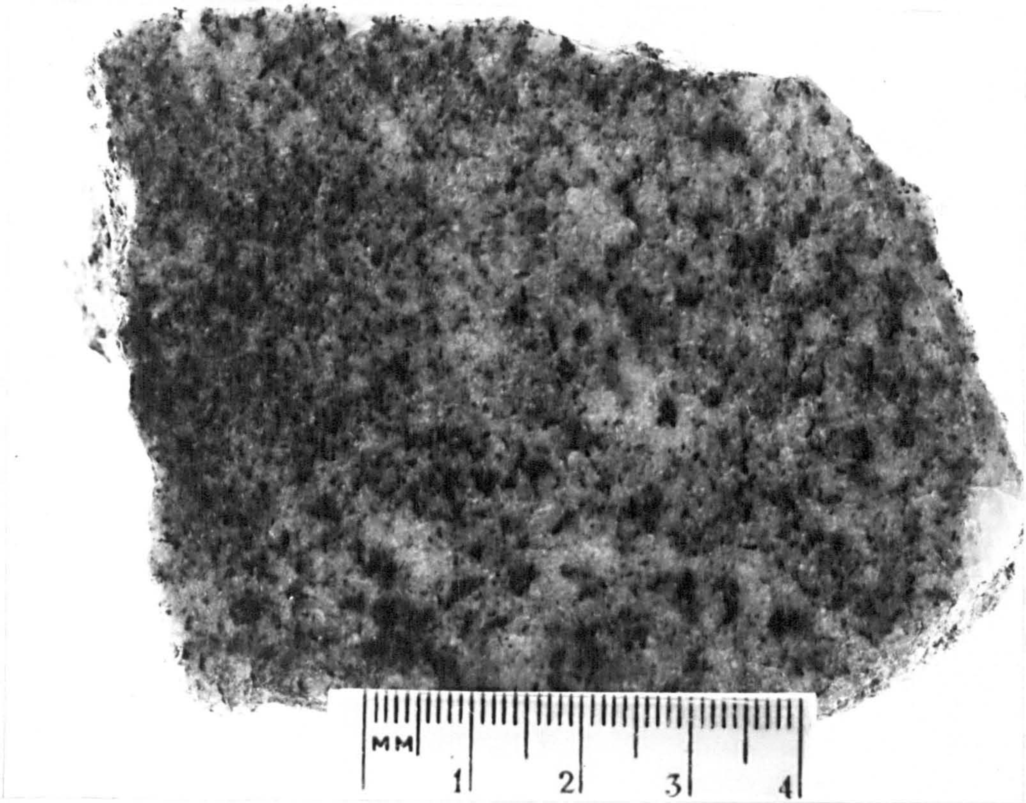


Plate II-2a. Homogeneous S_3 massive gneiss from the neighbourhood of An Ruadh Mheallan.

Plate II-2b. F_3 folded pegmatite in S_3 banded gneiss from the neighbourhood of An Ruadh Mheallan (82836137).


MM
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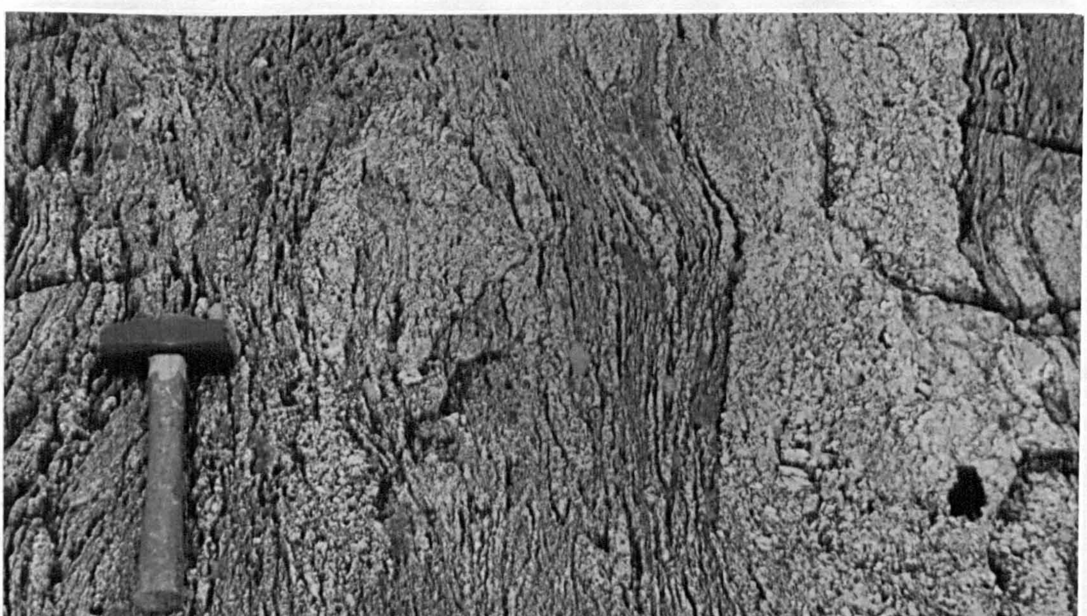

the plane of the S_3 foliation producing a broad felsic lamina, and where the pre-S_3 foliation has been only slightly affected by pegmatites, the S_3 foliation takes on a much finer laminated appearance. Similarly in Plate II-3a the S_2 banding is very coarse, and where it has been transposed by the S_4 foliation at the left-hand side of the illustration, the banding remains coarse.

The most characteristic feature of the banded gneisses is the presence of alternate mafic and felsic-rich laminae, which are predominantly parallel to the S_3 foliation, although where S_2 has not been completely transposed, a clear discordance between the laminae and the S_3 foliation exists (eg. at F_3 fold noses). The mafic laminae consist of interlocking grains of biotite, epidote and magnetite up to 3·0 mm. thick, with an average thickness of 1·0mm. The felsic laminae consist of flattened quartz and feldspar aggregates up to 5·00 mm. thick, with a mean thickness of 2-3 mm. Biotite and epidote have a well developed preferred orientation of their grains parallel to the S_3 foliation. Biotite flakes when observed on the S_3 foliation surface are clearly lineated, resulting from the parallelism of these flakes.

The quartz aggregates which weather out on the S_3 surfaces are similarly lineated, being parallel to the biotite lineation. The lineation is related to the D_4 fold episode and is a result of the intersection between S_3 and S_4. The banded gneisses are generally coarse-grained and inequigranular.

(i) <u>Mineralogy</u>

The following minerals have been observed in the banded gneisses: biotite, hornblende, epidote, chlorite, iron ore, apatite, sphene, muscovite, plagioclase, microcline and quartz. Microcline, chlorite and some of the muscovite were developed in a post-dyke event.

<u>Biotite</u> forms up to 15% of the rock with an average of 10%. In the mafic laminae it occurs as aggregates of stout to slender, subidioblastic to xenoblastic, interlocking flakes and in the felsic laminae as

occasional isolated, subidioblastic flakes, the flakes in the mafic laminae being notably larger than those found in the felsic laminae. Biotite varies in the pleochroic scheme it exhibits:-

straw	brown	deep brown
x - straw	y - brown	z - greenish brown
pale green	green	green

The biotite is generally free of inclusions apart from iron ore formed along thecleavage traces. In some instances, however, biotite has been forced apart along the cleavage and lenses of prehnite are developed at these sites. Hall (1965) discussed the assemblage biotite-prehnite and attributed their association to the low temperature metasomatic alteration of hornblende. Biotite flakes range up to 1·5 mm. with an average grain size of 0·4 mm.

Hornblende. Banded gneisses with hornblende that are not spatially related to any basite or ultrabasite are very rare. Hornblende forms xenoblastic grains with the pleochroic scheme x - straw, y - green, z - bluish green. It is generally associated with biotite and plagioclase.

Epidote forms up to 6% of the rock with an average of approximately 4%. It is associated with biotite in the mafic laminae and forms idioblastic to xenoblastic grains. The epidote is a colourless variety with occasional cores of orthite and inclusions of angular quartz. Grains range from 0·05-0·8 mm. with a mean size of 0·3-0·4 mm.

Muscovite is not developed in all the banded gneisses examined, but may form up to 3% of the rock. It forms subidioblastic flakes up to 0·2 mm. in length, associated with biotite.

Magnetite, apatite and sphene are developed in accessory quantities associated with the mafic laminae.

Plagioclase forms 20% to 60% of the gneisses with an average of 45%. The grains are inequidimensional, irregular and xenoblastic with smooth edges which have straight, curved to lobate shapes against quartz, whereas straight, ragged edges are developed against adjacent plagioclase

The plagioclase is an oligoclase variety, An_{22-27}, with albite and albite-pericline twinning occasionally developed. Rounded quartz, sphene and epidote are found as inclusions, the feldspar having a mean grain size of 1·0 mm. with a maximum grain size of 3·0 mm.

Quartz forms 20% to 30% of the banded gneisses with an average of 25%. It occurs in felsic areas forming aggregates of two to four grains, although isolated grains are also developed. The grains and the grain aggregates are elongated in the plane of the S_3 foliation, with maximum elongation parallel to the lineation direction in the gneiss. Individual grains have irregular xenoblastic form, with smooth, curved to angular edges against adjacent grains. Grains range up to 2·5 mm. with a mean size of 1·0 mm.

(d) Comparison between massive and banded gneisses

The massive and banded gneisses have the same mineral assemblage, the difference between the groups being in the proportions of the minerals developed (see Table II-1).

The following differences between the gneisses occur:

(i) The massive gneisses are poorer in mafics (hornblende-biotite-epidote).

(ii) The massive gneisses are more acidic.

(iii) The plagioclase in the massive gneisses is slightly more albitic.

The grain size of the two groups exhibits no notable difference.

3. Acid gneisses with dominant S_4 foliation

The massive and banded gneisses are found to develop a penetrative S_4 foliation when deformed in the D_4 fold episode. As well as these two groups of gneisses a further group, finely-foliated gneisses may be recognized in terrains which have a dominant S_4 foliation. They are distinguished from the massive and banded gneisses by their finer-grained and homogeneous appearance.

(a) Distribution

The S_4 acid gneisses occupy the larger proportion of the complex

	MASSIVE GNEISSES				BANDED GNEISSES			
	Percentage		Grain size (m.m.)		Percentage		Grain size (m.m.)	
	Max.	Av.	Max.	Av.	Max.	Av.	Max.	Av.
BIOTITE	6	3	1·0	0·4	15	10	1·5	0·4
EPIDOTE	3	2	0·4	0·2	6	4	0·8	0·3
			An22-24				An22-27	
PLAGIOCLASE	65(25)	50	1·8	1·0	60(20)	45	3·0	1·0
QUARTZ	55(20)	30	2·5	1·0	30(20)	25	2·5	1·0
HORNBLENDE	Never found		-	-	occasionally found		3·0	-

Table II-1. Comparison between massive and banded gneisses.

extending southwards from an approximate NW-SE-striking line just south of Loch Airidh Eachainn (Fig.II-1). There are also narrow NW-SE-striking belts within the dominantly S_3 foliated gneisses north of Loch Airidh Eachainn.

From Fig.II-1 it is apparent that the massive gneisses are subordinate to the banded gneisses, forming a NW-SE-striking belt some 150-200 metres south of Creag an Fhraoich. This belt of massive gneisses can be followed north-westwards to Loch Diabaig and south-eastwards to the Applecross Fault.

The fine-foliated gneisses are restricted to three isolated NW-SE-striking belts whose widths are approximately 100-200 metres; these occur south of Loch Airidh Eachainn, north of Loch an Dharach and south of Loch na Beiste.

The coarse-banded gneisses form that part of the S_4 foliated complex which is devoid of the previous rock groups and early basite-ultrabasite bodies. The nature of the banding in these gneisses is illustrated on Plate II-3b. The banding in the coarse-banded gneisses is the result of alternation of mafic and felsic-rich laminae which are easily distinguished in hand specimen. The banding is a result of transposition of the S_3 surface. In Plate II-4a-b the pre-existing foliation is represented by detached fold noses which have been flattened in the plane of the S_4 foliation. The elongation and transposition of F_4 folds in the S_4 foliation has resulted in the dislocation of the pre-existing surface producing feldspathic augen. Augen formed by disruption of folded feldspathic layers with their alignment parallel to local fold axis have been recorded elsewhere by Naha and others (1967).

The width of the mafic and felsic laminae in the coarse-banded gneisses varies from north to south, the laminae being much broader south of Creag an Fhraoich. There is also an increase in grain size of the gneisses from north to south, however this increase is often masked as a result of a later migmatization.

The banding and S_4 foliation in the gneisses are generally parallel, although the banding may bear any angular arrangement to the foliation. In Plate II-3b the banding is represented by alternating mafic and felsic laminae, whereas the foliation is defined by drawn out quartz aggregates and oriented mica flakes, the foliation being parallel to the banding. However, in Plate II-4a the foliation and banding are clearly discordant. Mafic and felsic laminae are also developed in the finely-foliated gneisses, but are very thin and discontinuous.

On the S_4 foliation surface there is a well formed lineation which consists of elongated feldspathic augen (Plate II-5), aligned mica flakes and quartz rods. These lineations are b-lineations since they are parallel to the F_4 fold axes.

The S_4 acid gneisses contain biotite, chlorite, epidote, sphene, orthite, iron ore, apatite, muscovite, plagioclase, microcline and quartz. Chlorite, microcline and some of the muscovite were produced in a later retrogressive metamorphic episode and will not be discussed further here.

The petrology of the finely-foliated, banded and massive gneisses will be described in turn.

(b) Petrology of the finely-foliated gneisses

Biotite is formed in almost all the gneisses, making up to 25% of the gneisses with an average of 10%. It generally forms stout to slender, isolated, idioblastic to subidioblastic flakes (Plate II-6a) which are aligned in the plane of the foliation, rarely forming aggregates of interlocking flakes. Two pleochroic varieties of biotite have been found,

x - straw / pale green	y - brown / green	z - deep brown / deep green

Biotite is the predominant member of the association biotite-epidote-muscovite-iron ore.

Muscovite is found in almost all the finely-foliated gneisses and may form up to 5% of the rock. It forms idioblastic to xenoblastic flakes associated with biotite either in interlocking flakes or in overgrowths

Plate II-3a. Complex F_3 folding of S_2 migmatite banding from the neighbourhood of Diabaig (79885974).

Plate II-3b. Alternating biotite-rich and feldspathic-rich layers in S_4 banded gneiss. Quartz aggregates in the feldspathic layers are drawn out in the plane of the S_3 foliation. Specimen from coastal section, south of Diabaig (80005932).

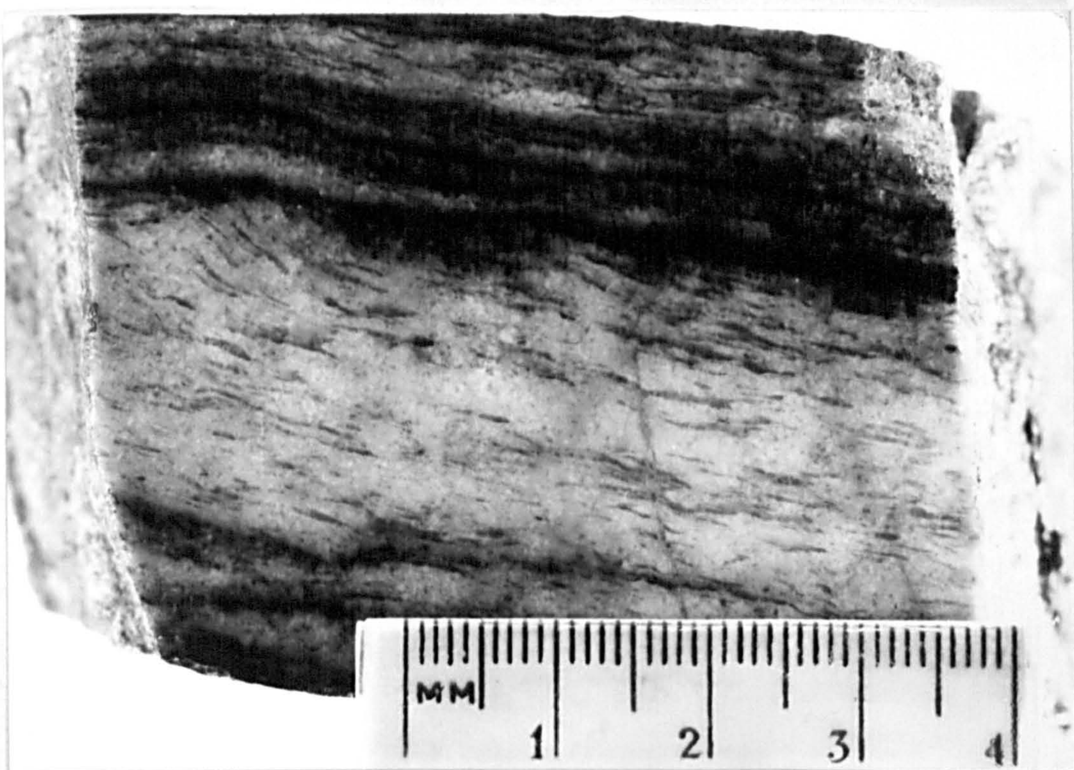
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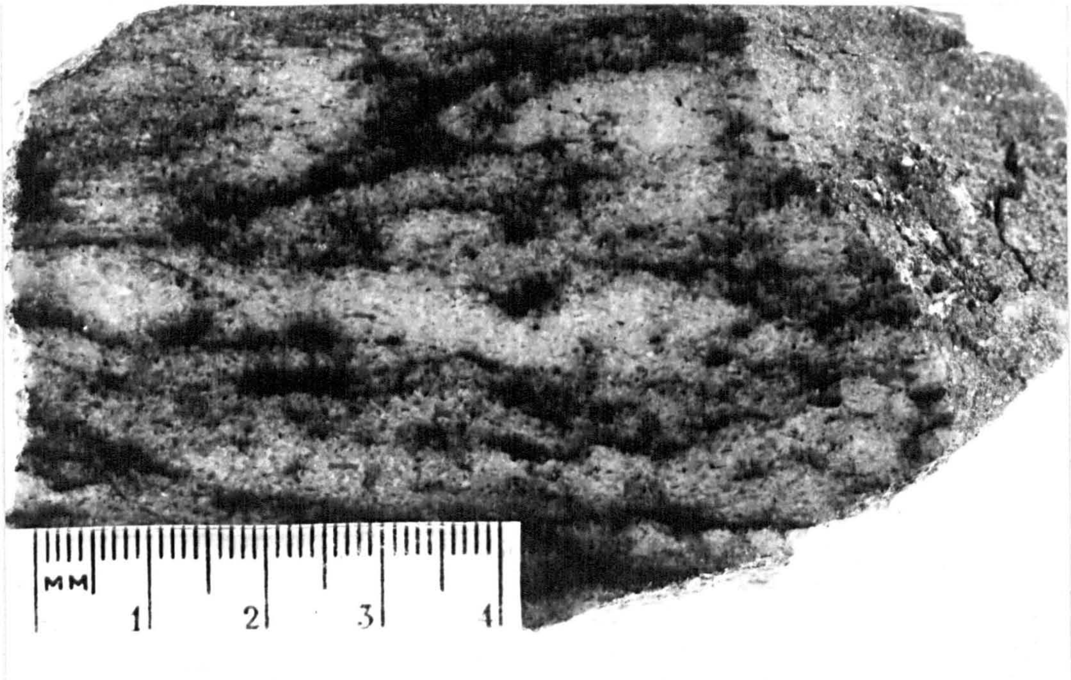
Plate II-4a. Irregular S_4 banded gneiss from the coastal section, south of Diabaig. Biotite is developed in schlieren, rather than laminae parallel to S_4

Plate II-4b. S_4 banded gneiss with feldspathic augen produced by detachment of F_4 fold noses. From coastal section, south of Diabaig (80005921).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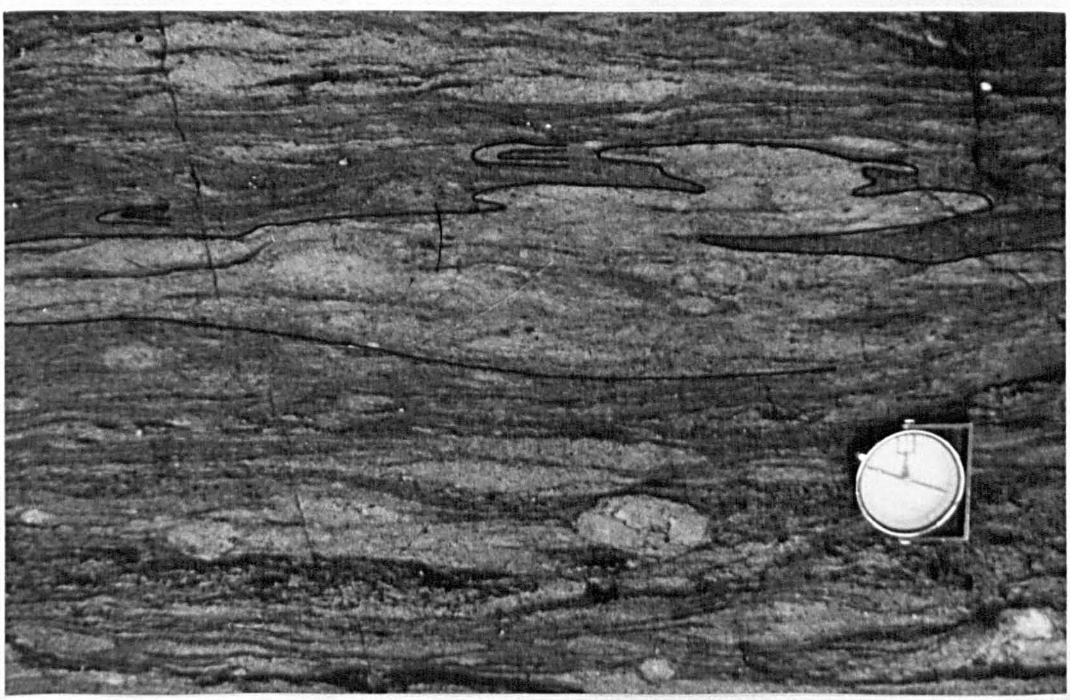


Plate II-5. South-easterly plunging L_4 lineation (feldspar augen) on S_4 foliation surface, produced by rolling out of early feldspathic layers during F_4 folding. From the neighbourhood of Rudha na h-Airde (58725929).

of the latter. The muscovite overgrowths are either quartz-muscovite symplectites or dactylitic and are believed to be generated in a post-dyke metamorphic episode. Grains of muscovite range up to 0·9 mm. with a mean grain size of 0·3 mm.

Hornblende is only rarely developed, being found in one gneiss examined, forming 5% of this rock. It is associated with the other mafics of the gneiss and shows the pleochroic scheme x - straw, y - green, z - bluish green.

Epidote forms up to 15% of the gneisses with an average of 3%. It is nearly always associated with the mafic minerals of the rock, in particular biotite. It forms idioblastic to xenoblastic grains with inclusions of angular quartz grains and cores of orthite. Epidote is predominantly the non-pleochroic variety although the pale yellow pleochroic variety is found. The grains range from 0·1 to 0·8 mm. with a mean grain size of 0·3 mm.

Plagioclase forms 25% to 65% of the finely-foliated gneisses with an average of 40%. The present amount may not reflect the initial quantity of plagioclase since the latter has undergone varying degrees of replacement by microcline. It has irregular, xenoblastic form, the grains having a maximum dimension in the plane of the foliation. The margins against quartz are smooth to serrated, with straight to generally sub-rounded or lobate outlines, features which are also shown by inclusions of quartz. Albite twinning is more commonly developed in these gneisses than in the others with approximately 25% to 30% of the grains twinned. The plagioclase is an oligoclase variety, An_{22-30}, without zoning. Grains form up to 2·0 mm. with a mean dimension of 0·3 to 0·4 mm.

Quartz forms 5% to 50% of the gneisses with an average of 25%. It forms irregular, xenoblastic grains which are elongated in the plane of the S_4 foliation, with smooth, sub-rounded to lobate edges against other grains. Grains range up to 2·0 mm. with a mean grain size of 0·45 mm.

(c) Petrology of banded gneisses

The banded gneisses are inequigranular and possess alternating mafic and felsic laminae. In the felsic laminae there is segregation into monomineralic quartz and feldspar aggregates, the aggregates being elongated in the plane of the foliation.

Biotite forms up to 15% of the banded gneisses with an average of 8% to 10%. Biotite forms subidioblastic to xenoblastic, slender to stout interlocking aggregates of flakes. Isolated flakes are rare in the mafic laminae but are more common in the felsic laminae. The aggregates of biotite may be concentrated in continuous mafic laminae or in streaks or schlieren. It shows the following variability in pleochroism

	x	y	z
pleochroism	pale green	green	green
	x - straw	y - greenish brown	z - greenish brown
	straw	brown	deep brown

It is generally found that one of the above pleochroic varieties is restricted to a rock sample, although a few instances have been observed where all three varieties occur in the same hand specimen. Inclusions of quartz and iron ore are formed along the cleavage trace. Biotite is the predominant member of the association biotite-epidote, being the most consistent (Plate II-6b). Flakes range up to 1·8 mm. with a mean grain size of 0·4 mm.

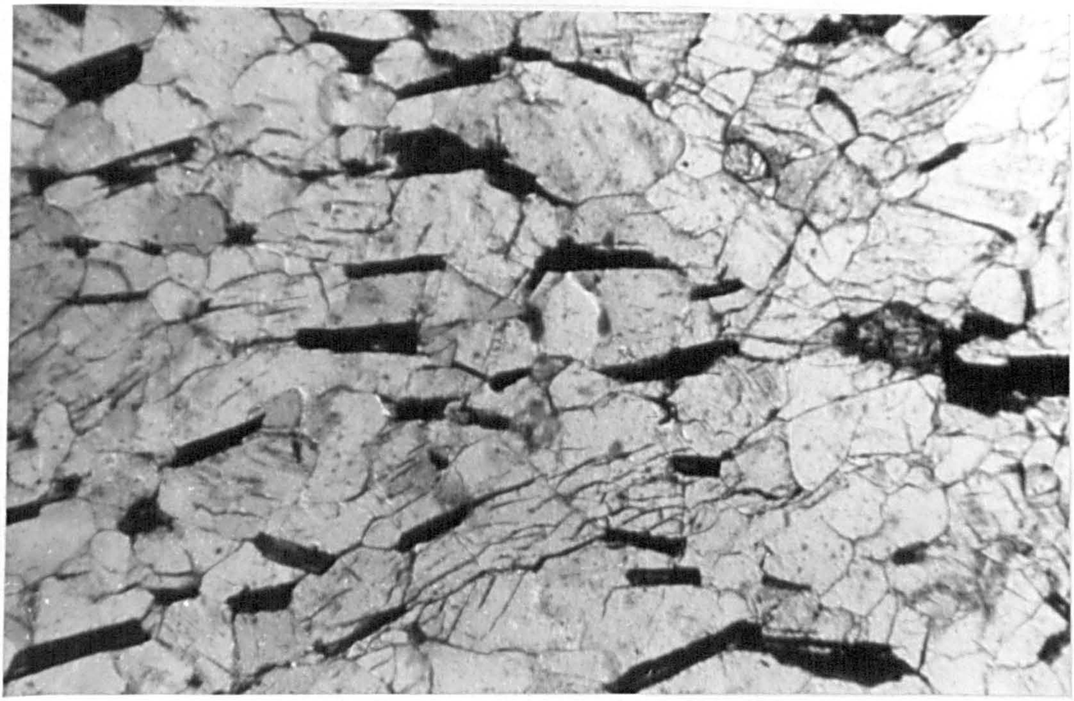
Epidote forms up to 6% of the rock with an average of 3%. It is always associated with biotite in the mafic aggregates and forms idioblastic to xenoblastic grains. It generally has angular inclusions of quartz and orthite or iron ore cores. Grains range up to 2·5 mm. with a mean grain size of 0·4 mm.

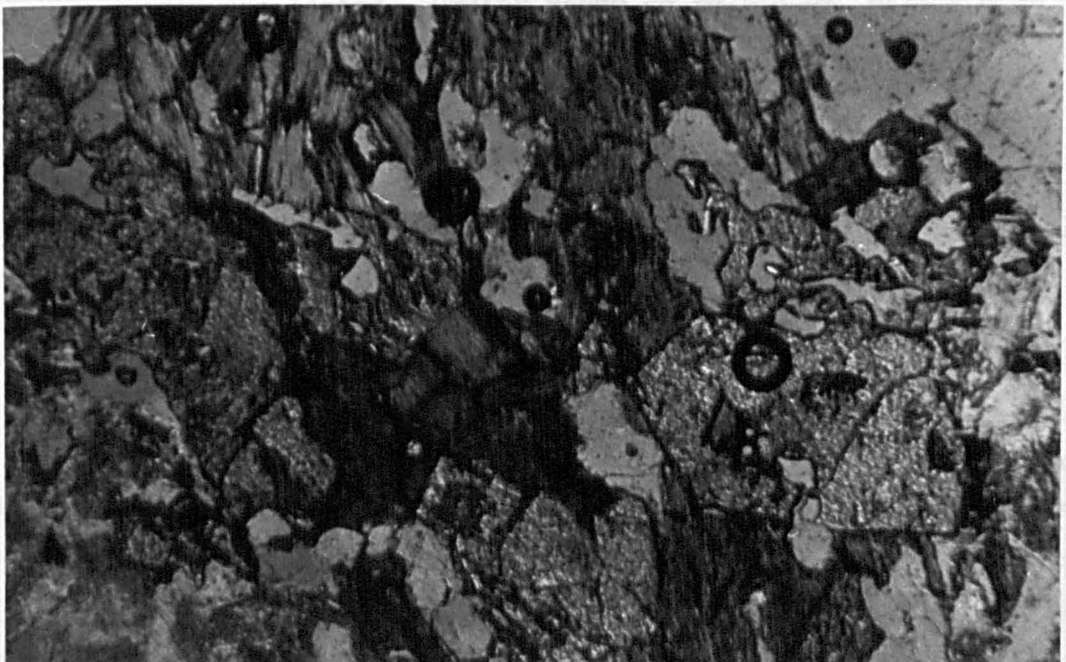
Muscovite is generally associated with biotite and has the same two modes of occurrence as in the finely-foliated gneisses. Flakes are up to 1·2 mm. long with an average length of 0·4 mm. and form up to 5% of the gneisses.

Sphene, apatite and iron ore occur in accessory proportions, commonly associated with the mafic aggregates.

Plate II-6a. S_4 finely-foliated gneiss from the coastal section south of Diabaig. Biotites are generally aligned parallel to S_4 (x25 P.P.L.).

Plate II-6b. Aggregates of biotite (chlorite)-epidote in S_4 banded gneiss from the neighbourhood of Lochan Dharach (x25) (82625913).





Plagioclase forms 25% to 60% of the banded gneisses with an average of 35%. The monomineralic aggregates consist of irregular xenoblastic grains, the individuals being elongated in the plane of the foliation. Where the gneisses have not been affected by the post-dyke brittle deformation episode the plagioclase grains have smooth, curved to rounded edges against quartz, whereas edges against adjacent plagioclase grains are smooth, straight and rarely interpenetrative.

Two forms of alteration affects the plagioclase: (a) clouding of the feldspar by an unidentifiable brown dust, and (b) development of small secondary mica flakes. The former alteration develops preferentially along alternate albite lamellae. The plagioclase is an oligoclase variety, An_{22-33}, with twinning on the albite and combined albite-pericline laws. Rounded quartz is found as inclusions as well as muscovite overgrowths, grains ranging up to 3 mm. with a mean grain size of 0·5 to 0·6 mm.

Quartz may form up to 60% of the rock with an average of 25% to 30%. It occurs as aggregates of irregular, xenoblastic grains having smooth to serrated edges against plagioclase and sometimes developing lobate protrusions into the latter. Grains range up to 5·0 mm. with a mean grain size of 1·0 mm.

(d) Petrology of massive gneisses

The petrology of the massive gneisses with an S_4 foliation is identical to that of the S_3 foliated massive gneisses (see section IIA 2b) and will not be separately described.

4. Gneisses with a possible sedimentary derivation

(a) Previous classification

Sutton (1951) claimed that certain members of the complex were of sedimentary derivation. He classified the sedimentary derivations into the following groups:-

(i) Massive or slightly foliated quartzites

Biotite-bearing quartzites

Muscovite-bearing quartzites

Hornblende-bearing quartzites

(ii) Flaggy quartz-epidote rock

(iii) Semipelitic granulites

Biotite-oligoclase granulite

Muscovite-oligoclase granulite

(iv) Calc-siliceous granulite

Hornblende granulite

Hornblende-zoisite granulite

Garnetiferous-hornblende-zoisite granulite

Diopside-epidote-hornblende granulite

The writer tentatively regards groups (i) and (ii) as possible sedimentary derivatives and groups (iii) and (iv) as of uncertain origin since they show neither texturalnor compositional peculiarities that would indicate a derivation from a sedimentary parent.

(b) Distribution

Five separate occurrences of belts of possible metasedimentary gneisses have been found in the area (see Fig.II-1). All the metasedimentary gneisses have a penetrative S_4 foliation developed and occur as narrow belts up to 10 metres wide and cannot be traced parallel to their strike for any considerable distance. The metasedimentary gneisses have been grouped as follows:-

(i) Foliated quartzites

Hornblende quartzites

Biotite quartzites

Muscovite quartzites

Magnetite quartzites

(ii) Epidotites

These two groups correspond to groups (i) and (ii) of Sutton's classification.

(c) Petrology

Foliated quartzites

All the quartzites have a well developed planar S_4 foliation, but pre-existing s-surfaces have not been observed in them. Alternating quartz and feldspar and mafic-rich stripes each 1·0 mm. thick are developed parallel to the foliation.

(1) Hornblende quartzites

Hornblende quartzites are found 400 metres south-west of Loch Airidh Eachainn and 300 metres north-west of Loch na Beiste. This group has the mineral assemblage hornblende-quartz-epidote-iron ore-sphene-apatite-plagioclase. Hornblende and quartz make up more than 95% of the quartzites, the other minerals occurring in accessory quantities.

Quartz forms 70% to 95% of the rock having a preferred orientation revealed by elongated grains parallel to the plane of the foliation (see Plate II-7a). It forms large, irregular, xenoblastic grains with curved to angular edges against adjacent grains. The grains are markedly inequigranular with a maximum size of 5·0 mm.

Hornblende forms up to 5% of the quartzites having subidioblastic to xenoblastic form with the pleochroic scheme x - straw, y - green, z - bluish green. Grains up to 2·5 mm. are developed with a mean size of 0·3 mm.

Plagioclase forms up to 25% of the quartzites. It has a xenoblastic habit and is generally turbid as a result of the development of sericite. It forms isolated grains in the quartz-rich stripes, but forms aggregates of grains in the feldspar-rich stripes. Grains have a maximum size of 0·7 mm.

(2) Biotite quartzites

There is only one belt of biotite quartzites in the area, located approximately 400 metres south of Lochan Dharach. It consists of biotite, quartz, epidote and plagioclase with a similar texture to the hornblende quartzites.

Biotite forms subidioblastic to xenoblastic flakes with a preferred orientation parallel to the S_4 foliation. It has the pleochroic scheme x - straw, y - brown, z - deep brown with grains ranging from 0·1 to 0·6 mm.

Plagioclase forms xenoblastic grains being an oligoclase variety with a composition of An_{22-24}.

(3) Muscovite quartzites

These are similar to the biotite quartzites except that muscovite has taken the place of biotite.

(4) Magnetite quartzites

These resemble all the other quartzites except that magnetite xenoblasts take the place of the mafic minerals.

Epidotites

Epidotites have been found associated with the basite body 250 metres north of Loch nan Tri-eileanan. Quartz, epidote, iron ore and sphene are the only minerals developed and the arrangement and habit of these show the development of the S_4 foliation (see Plate II-7b).

Epidote makes up more than 90% of the rock, having subidioblastic to xenoblastic habit. The majority of the grains are colourless and non-pleochroic, but the occasional occurrence of a pale yellow pleochroic variety. Grains are equidimensional and range from 0·2 to 0·3 mm.

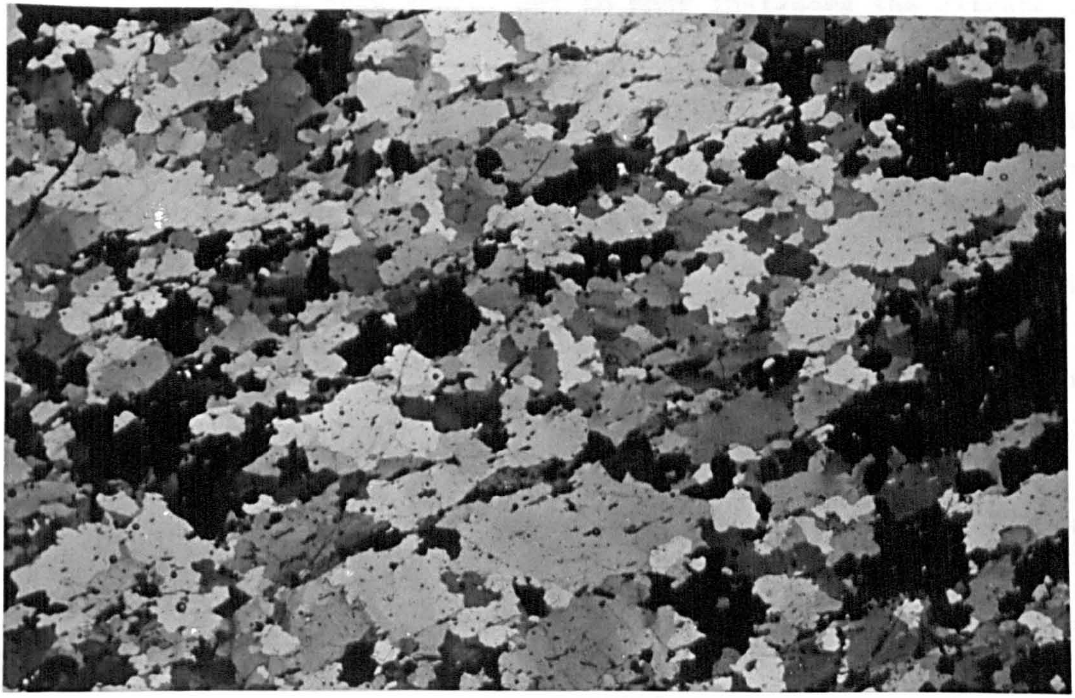
B. The Metamorphic Petrology of the Early Basite and Ultrabasite Bodies

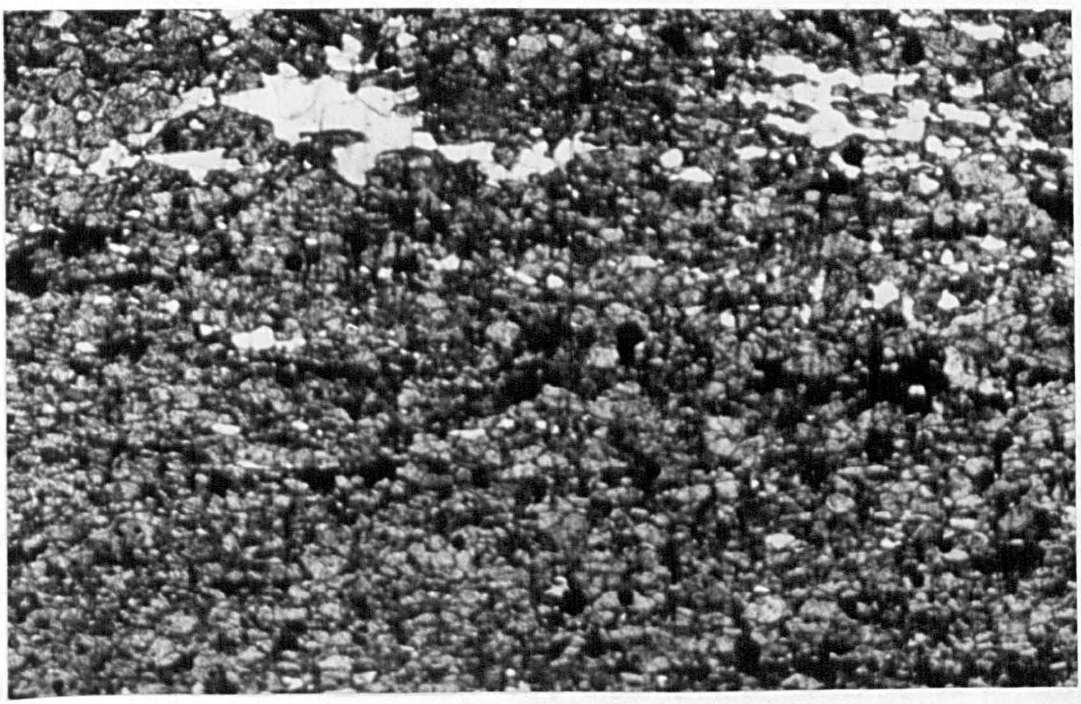
1. Distribution and general structural relations

The early basite and ultrabasite bodies form a minor part of the complex and are generally sheet-like bodies rarely more than 40 to 50 metres thick, except at the apices of large scale F_3B folds (basite body found at Lochan Dharach). They can be traced 400 to 500 metres along their strike being concordant to the prevalent structures in the acid gneisses. The early basite and ultrabasite rocks also occur as boudinaged bands, as isolated pods and balls, the pods and balls bearing variable structural relations to the acid gneisses. The foliation in the basite balls may bear any relationship to that in the acid gneisses from concordant to sharply discordant, but the plane of elongation of these balls is found to be concordant with the foliation in the acid

Plate II-7a. S_4 foliated quartzite from the neighbourhood, south of Lochan Dharach (x25) (82626034).

Plate II-7b. S_4 foliated epidotite associated with the early basite body north-east of Loch nan Tri-eileanan (x25 P.P.L.) (82586030).





gneisses. The contacts between the acid gneisses and the basite-ultrabasite bodies is very sharp, but in many instances the ultrabasite bodies have unexposed margins.

The present attitude of the bodies appears to have been controlled partly by their original form and partly by the deformation which they have suffered.

In the north of the area several bodies are associated with gneisses having a prevalent S_3 foliation. These are very simple in form and strike parallel to the S_3 foliation. The ultrabasite sheet north-east of Loch Airidh Eachainn is found to bifurcate towards the south-west, the body terminating very abruptly. The bifurcation of the body is thought to be a result of the original form of the body rather than an affect of deformation. As a result of the F_3B folding, the bodies south of An Ruadh Mheallan to Loch Torridon have a fold shaped outcrop pattern.

The S_4 axial-planar foliation has not been developed extensively within the ultrabasite-basite bodies even where the S_4 foliation is penetrative in the acid gneisses. However, where intense flattening and transposition of the S_3 foliation has been achieved the ultrabasite-basite bodies have developed a penetrative S_4 foliation. Since many of the large scale F_3B folds are very tight, almost isoclinal, the limbs of the large scale folds are in fact S_3 foliation concordantly transposed to the S_4 foliation.

2. <u>The ultrabasite bodies</u>

Only one sheet-like body, which has resisted migmatization in part, has been found. The body extends from south-east of Loch na h'Umhaig some 350 metres south-eastwards parallel to the strike of the foliation in the associated gneisses. At the south-easterly extension, where it achieves a maximum thickness of 40 metres, it swings round into a NNE-SSW strike as a result of large-scale F_3B folding. The ultrabasite is banded parallel to the foliation in the gneiss. There are two types of bands (Plate II-8a), thin massive bands up to 25 cm. thick and broad foliated bands up to 2 metres thick.

(a) The Ultrabasite sheet at Loch na h'Umhaig

The massive bands

The massive bands reveal a crude foliation caused by the disposition of certain minerals. The minerals of the massive bands are amphibole, olivine, serpentine, chlorite and magnetite.

Olivine grains are considerably or completely altered to antigorite and chrysotile, whereas the amphibole appears very fresh and stable in association with olivine. It has idioblastic to subidioblastic grains which are zoned with a core of pale green pleochroic actinolite and mantle of tremolite (see Plate II-8b) which appears to be replacing the former. The amphibole grains are up to 1·0 mm. with a mean size of 0·7 mm., the amphibole forming approximately 70% of the rock.

Colourless chlorite flakes with subidioblastic form make up to 2% of the massive bands, and occur at olivine and tremolite grain boundaries. Small isolated xenoblasts of magnetite are scattered throughout the amphibole areas forming up to 10% of the massive bands.

The foliated bands

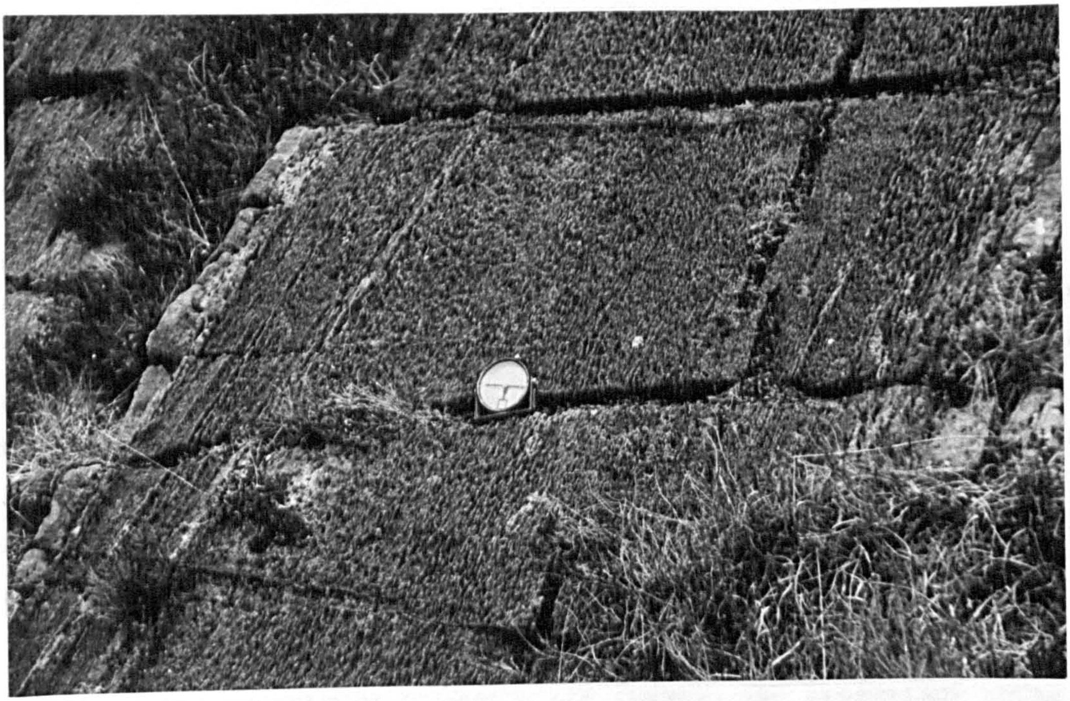
These have a well developed foliation revealed by the crystalloblastic development of olivine and tremolite. The mineralogy shows slight differences from the massive bands with olivine, hypersthene, tremolite, actinolite, spinel, iron ore, talc, chlorite, calcite and serpentine developed. The foliated bands may also be differentiated into olivine-rich, amphibole-rich and hypersthene-rich bands.

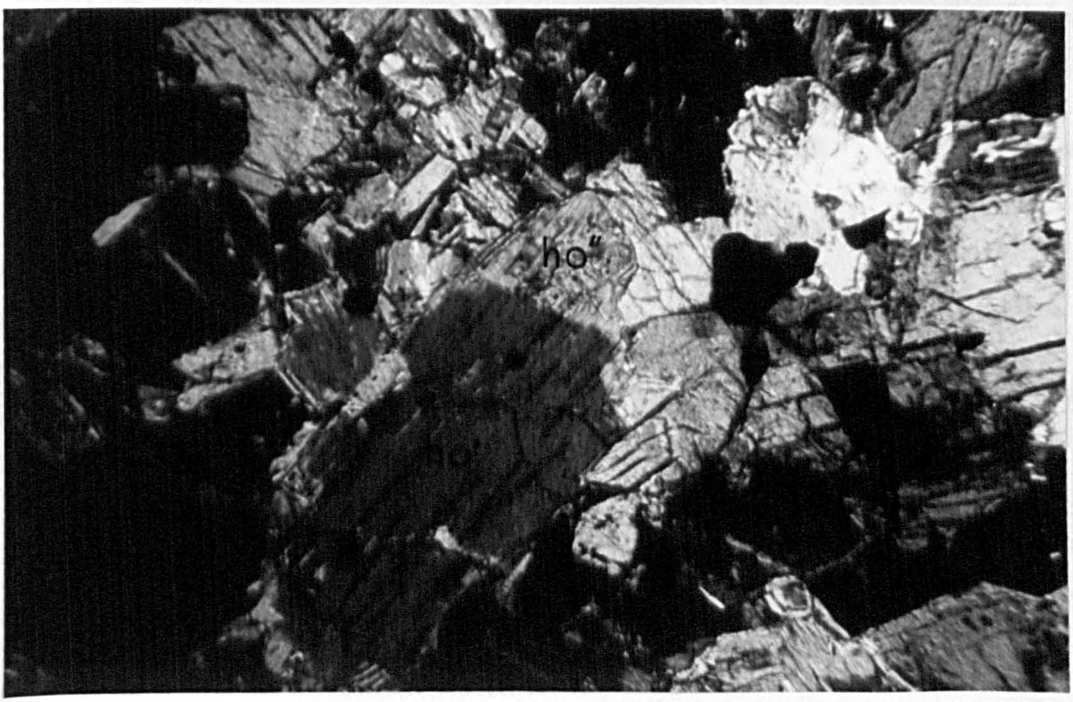
The amphibole is zoned as in the massive bands, but tremolite is more commonly developed. It shows varying degrees of idiomorphism and alteration to antigorite which develops at the grain margins and along the cleavage directions in the tremolite.

Olivine is a forsteritic-rich variety and as a result of alteration has xenoblastic habit. Where it has undergone little alteration to antigorite, it shows sharp relations to tremolite and appears to be stable with the latter.

Plate II-8a. Banding in the early ultrabasite body south-east of Loch na h'Umhaig (82706161).

Plate II-8b. Zoned hornblendes (ho^{1} and ho^{11}) from the early ultrabasite body near Loch na h'Umhaig (x25 X.P.L.) (82706161).




ho"

Hypersthene forms aggregates of small granules which are altered to a chrysotile-calcite matt.

Spinel forms small xenoblastic granules, being the green pleonaste variety and is located either as inclusions in olivine or at olivine grain boundaries.

Serpentinisation of the olivine (see Plate II-9a), hypersthene and tremolite takes place either along veins discordant or parallel to the banding, producing chrysotile, antigorite, talc, calcite, chlorite and magnetite. A feature of the discordant veins is the production of different alteration products in different bands. For example, in the olivine-rich bands the assemblage talc-chlorite-calcite-magnetite is found, whereas in the hypersthene-rich bands the assemblage chrysotile-calcite is developed. Pleonaste is altered to magnetite.

At the margins of the ultrabasite body, olivine, spinel, hypersthene and serpentine minerals are absent, the assemblage being represented by monomineralic tremolite rock. The tremolite is unzoned, with a preferred orientation producing the S_3 foliation (see Plate II-9b).

(b) Petrology of the ultrabasite pods and balls.

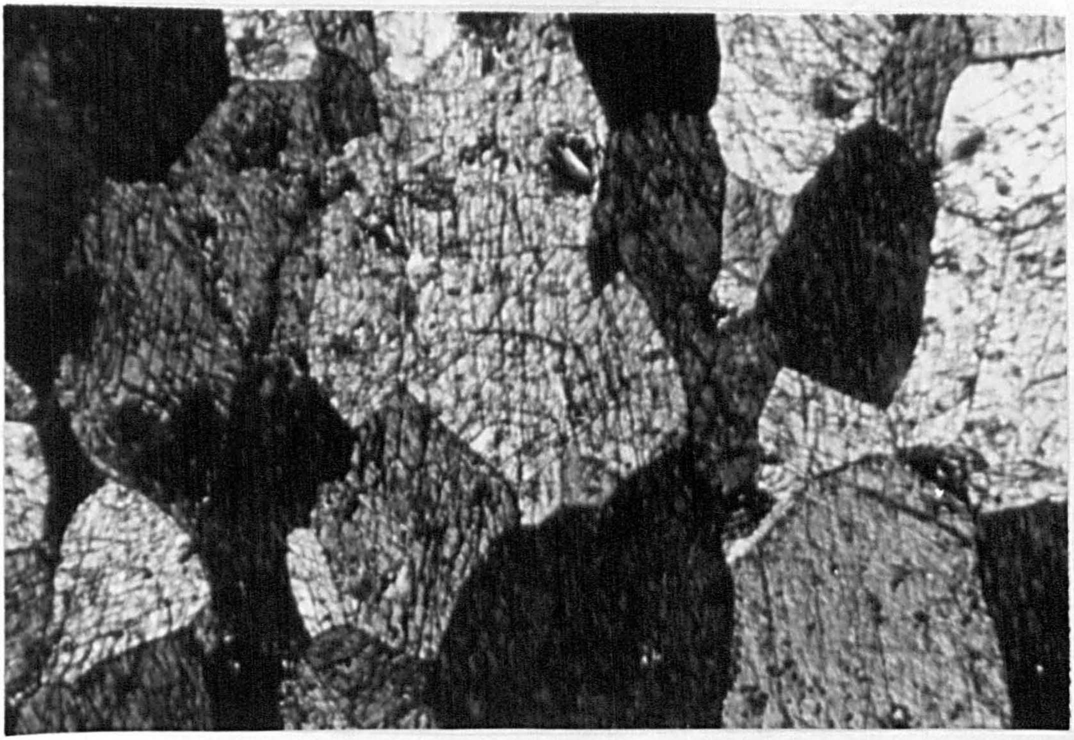
These bodies are developed throughout the complex and show variations in mineralogy from north to south. In the S_3 gneisses the ultrabasite pods are monomineralic consisting of idioblastic to xenoblastic interlocking tremolite grains. Progressively southwards the pods show changes in mineralogy and the nature of the amphibole believed to be a result of metasomatic exchanges between the host gneisses and the pods. These changes have produced a zonal arrangement of minerals in the ultrabasite pods, with the formation of an outer biotite sheath passing into monomineralic tremolite at the core (see Plate II-10a). Zoning of a similar nature has been described by Read (1954) in ultramafite balls at Unst, Shetland Islands.

Biotite forms subidioblastic flakes with the pleochroic scheme

Plate II-9a. Mineral assemblage, hornblende (ho)-olivine (ol)-serpentine (se), from the early ultrabasite body near Loch na h'Umhaig. Olivine is partly converted to serpentine (x25 X.P.L.) (82706161).

Plate II-9b. Hornblendite margin of the early ultrabasite body near Loch na h'Umhaig (x25 P.P.L.) (82736165).


se
ol
ho



x - straw / pale green	y - brown / green	z - deep brown / green

It varies from 0% to 100% of the pods depending on the degree of metasomatism and the position relative to margin of the pods. At the margins of the pods there is generally a sheath of monomineralic biotite, the proportions of which drop rapidly towards the core. Where the ultrabasite pods have been extensively flattened in the plane of the S_4 foliation they are found to consist of monomineralic biotite.

<u>Amphibole</u>. The proportion of amphibole varies through the pods bearing an inverse relationship to the amount of biotite developed. In the cores of the pods it is colourless tremolite but towards the margin, it is actinolitic with the pleochroic scheme x - straw, y - green, z - bluish green.

In the least zoned ultrabasite pods biotite rarely exceeds 5% of the rock and appears to be interstitial to the amphibole. Sphene, magnetite and quartz are developed in accessory quantities.

The following mineral assemblages appear to be developed with increasing metamorphism and metasomatism.

Olivine Hypersthene	→ serpentine-talc-chlorite-calcite-magnetite
Tremolite Spinel	→ Tremolite → Tremolite / Biotite → Actinolite / Biotite → Hornblende / Biotite → Biotite

3. <u>The basite bodies</u>

Early basite bodies which retain the fabric inherited by the D_3 deformation are well developed in the north of the area. Progressively southwards the fabric and mineralogy are adjusted in a similar manner to that found in the ultrabasites. These changes will be discussed under the following headings:-

(a) Early basite bodies associated with S_3 acid gneisses.

(b) Early basite bodies associated with S_4 acid gneisses.

 (i) Bodies in the area south of Loch Airidh Eachainn to Loch Torridon.

(ii) The early basite body 250 metres west of Loch a'Bhealaich Mhoir (79845885).

(a) Petrology of early basite bodies associated with S_3 acid gneisses

The early basite bodies have registered at least two phases of agmatisation and intrusion by tronhjemitic magma. They are finely-foliated hornblende schists, the foliation being represented by the development of a nematoblastic hornblende-plagioclase fabric. The basite bodies consist of hornblende, epidote, sphene, magnetite, plagioclase, quartz and microcline, the latter mineral being formed in a post-dyke episode.

Hornblende makes up 30% to 90% of the early basite bodies forming idioblastic to generally xenoblastic grains which have a preferred orientation in the plane of the foliation. The degree of idiomorphism and the pleochroic scheme exhibited by hornblende appears to be related to the amount of epidote present. Where only a small proportion of epidote is found hornblende shows the pleochroic scheme x - straw, y - green, z - bluish green, but where it is abundant the scheme x - colourless, y = z - pale green is found. The xenoblastic grains have ragged edges developed against adjacent epidote grains, inclusions of rounded quartz and epidote subidioblasts are found in the hornblende. Grains range up to 1·5 mm. with a mean grain size of 0·5 mm.

Epidote forms as a result of epidotisation of hornblende and makes up to 60% of the early basites. Epidote forms idioblastic to subidioblastic grains mantling and replacing hornblende-rich areas (see Plate II-10b). Simple twins of epidote are occasionally developed and some show slight zoning, with a colourless core and pale yellow pleochroic mantle. Grains rarely exceed 0·6 mm. with a mean dimension of 0·2 mm.

Plagioclase is an oligoclase-andesine variety, An_{28-33}, forming 35% to 40% of the rock and generally having regular xenoblastic grains. Plagioclase xenoblasts are interstitial to epidote and hornblende, the shape of the grains being controlled by the latter minerals. Grains range up to 1·0 mm. with a mean size of 0·8 mm.

(b) Petrology of the basite bodies associated with S_4 gneisses

(i) South of Loch Airidh Eachainn to Loch Torridon

These differ from the early basites of group (a) in that the mineral assemblage shows differences, notably because biotite is present. Hornblende and epidote have similar development to group (a), but some of the epidote in these bodies appears to be genetically related to biotite. The assemblage biotite-epidote is not completely diagnostic since many of the early basites examined are biotite-rich but contain no epidote.

Some of the early basites have a mineral banding formed as a result of alternating mafic and felsic laminae. Plate II-11a, indicates the form of the banding. In the felsic-rich bands the S_3 foliation is preserved and is clearly discordant to the banding. The banding appears to have resulted from F_4 folding of the S_3 foliated basite, the biotite recrystallising in alternate stripes.

Biotite forms 5% to 10% of the early basites having the pleochroic scheme x - straw, y - brown, z - deep brown or x - pale green, y = z - green. It forms subidioblastic interlocking flakes developed at the grain boundaries of hornblende or as inclusions of the latter. Small subidioblastic to xenoblastic granules of epidote are intimately associated with the biotite aggregates. Biotite flakes have maximum lengths of 1·0 mm. with a mean of 0·6 to 0·7 mm.

Quartz is also more common in these early basites than those of group (a). It is developed in a migmatitic episode and will not be discussed further here.

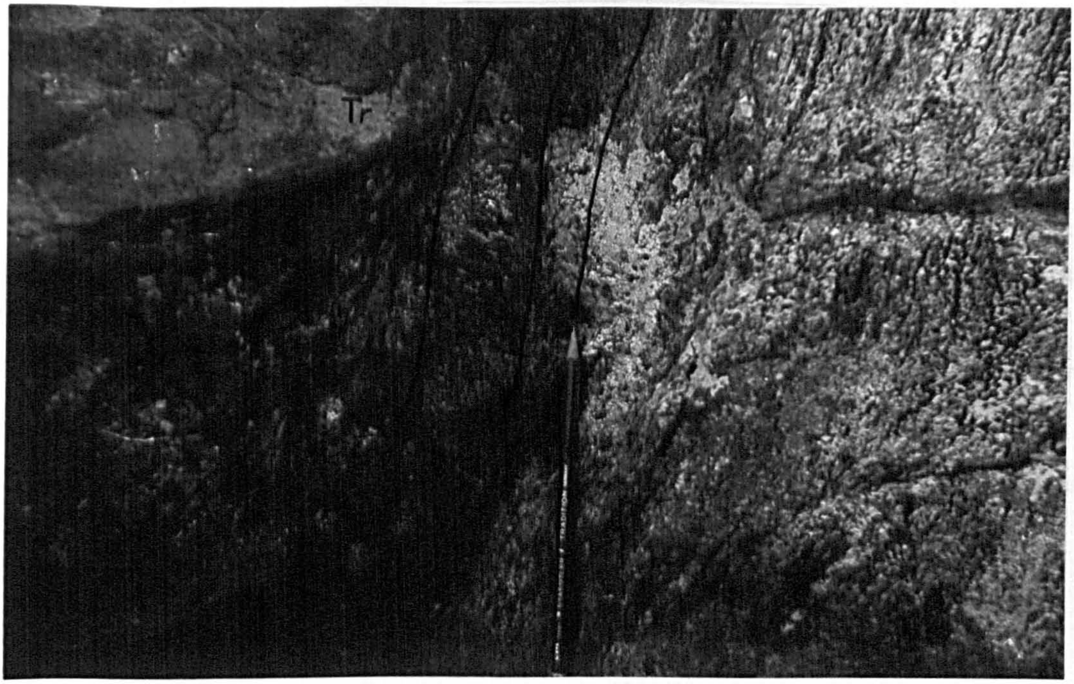
(ii) The early basite body 250 metres west of Loch a'Bhealaich Mhoir

Approximately 250 metres west of Loch a'Bhealaich Mhoir is a small, concordant early basite body which has a well developed S_4 foliation. The body illustrates the development of biotite-epidote assemblage from the breakdown of hornblende, and consists of hornblende, biotite, epidote, sphene, plagioclase and magnetite.

Hornblende shows increasing development towards the centre of the body

Plate II-10a. Ultrabasite pod with a marginal biotite sheath (Bi), tremolite-actinolite zone (Act) and tremolite core (Tr). Ultrabasite pod occurs in gneisses near Loch Diabaig (79575882).

Plate II-10b. Hornblende-epidote rock in early basite body south-west of An Ruadh Mheallan. Epidote is replacing hornblende (x25) (83006125).


Tr

where it forms up to 50% of the basite, but towards the margin the hornblende decreases until it becomes absent (see Table II-2). It forms idioblastic to xenoblastic grains with the pleochroic scheme x - straw, y - green, z - bluish green. It genemally forms aggregates of grains, but towards the margin of the body it occurs as isolated grains.

Epidote forms 5% of the basite at the core but towards the margin increases and may form up to 70%. It forms subidioblastic interlocking grains, some of which have zoning developed. Epidote is generally colourless although the pale yellow variety is occasionally developed.

Biotite may form up to 25% of the rock at the core of the basite increasing to 60% at the margin (see Table II-2). It forms aggregates of randomly oriented interlocking flakes which have the pleochroic scheme x - straw, y - brown, z - deep brown at the core through x - colourless, y - pale yellow, z - yellowish brown to x - pale green, y = z - green at the margins.

Plagioclase does not vary greatly through the body, forming 15% to 20% of the basite. It forms isolated xenoblastic grains although aggregates of two or three grains are occasionally found. Because of this isolated occurrence the form of the plagioclase depends upon the enclosing mafic minerals. Albite twinning is common and reveals reverse zoning in the plagioclase, with a core having a composition of An_{24-37} and mantle An_{31-51}. The nature of the zoning in the plagioclase indicates that it has been recrystallized in a post-dyke metamorphic episode (see Chapter II, section 2(a)).

C. The Pre-Dyke Migmatitic Effects in the Complex

1. Terminology

The terminology to be used in this section is the one developed in the Symposium on Migmatite Nomenclature (Inter. Congr. Norden. 1960) and from the works of Sederholm. The following terms and their meanings will be used throughout this thesis.

Agmatite - migmatite with the appearance of a breccia. Sederholm (1923)

CENTRE												BORDER
	%	Grain Size										
HORNBLENDE	50	2·5 mm. 1·5 av.	25	0·6 0·3	10	1·5 0·8	10	0·5 0·3	-		5	1·2 0·7
EPIDOTE	5	0·5 0·2	35	0·7 0·3	73	0·7 0·3	55		65	2·5	5	0·5 0·3
BIOTITE	25	2·0 1·0	20	2·0 1·0	5	1·5 0·5	20		20	2·0 0·7	60	1·8 1·0
PLAGIOCLASE	20	1·5 0·5	20	1·8 0·6	6	1·2 0·6	15		15	0·8 0·5	30	1·5 0·6
SPHENE	-		3		1		3		-		-	
APATITE	-		-		±		-		-		-	
MAGNETITE	-		-		3		-		-		-	

Table II-2. Variation in mineral proportions through the early basite.

coined this term to refer to basic rocks which have been brecciated by the action of a granitic magma.

Arterite - migmatite, the more mobile portion of which was injected magma. Sederholm (1926) distinguished these from agmatites in that an arterite has a schistose nature and has been subdivided along the planes of the foliation, whereas agmatites have been broken into angular fragments.

Anatexis - melting of rock.

Assimilation - process whereby a magma is modified by digestion or solution of solid rock, other magma, liquid or gas.

Composite Gneiss - gneiss which was once constituted by at least two different materials.

Embrechite - migmatite in which some textural components of the pre-existing rocks are preserved.

Feldspathisation - metasomatism manifested by the formation of feldspar.

Granitisation - any process or group of processes involving entry and exit of material and by which solid rock is converted (or transformed) to a granitic rock without passing through a magmatic stage.

Injection - movement of mobile material into surrounding rocks.

Metasomatism - replacement of one or several elements by others that migrated in solution or as free ions from outside sources (ie. transformation of solid rocks by volume exchange of introduced and released materials of different compositions).

Migmatite - megascopically composite rock that once consisted of geochemically mobile and immobile parts.

Mobilisation - pertaining to an increase in migration capacity of rocks or parts of a rock with no genetic implications concerning the state of aggregation of the rock or the mechanism of mobilisation.

Nebulite - migmatite characterised by indistinct inclusions.

Neosome - younger part of a composite rock.

Permeation - passage of geochemically mobile materials through or into solid rocks.

Venite - migmatite, the mobile portion(s) of which were formed by exudation (secretion) from the rock itself.

There are at least four pre-dyke generations of migmatites affecting the complex. These are:

(i) The pre-D_3 migmatites.

(ii) The post-D_3, pre-D_4 migmatites.

(iii) The D_4 syntectonic and post-tectonic migmatites.

(iv) The D_5 migmatites.

2. The pre-D_3 migmatites

The pre-D_3 migmatites are only found in areas where the S_3 foliation has not completely transposed earlier structures. They are represented by folded pegmatites in the acid gneisses and deformed agmatites.

3. The post-D_3, pre-D_4 migmatites

The post-D_3, pre-D_4 migmatites have discordant relations to the S_3 foliation and are folded in the D_4 deformation.

(a) Distribution

Migmatites belonging to this episode are well developed in the belt of S_3 gneisses at An Ruadh Mheallan, being particularly abundant in the triangle bounded by Loch Airidh Eachainn, Loch na h'Umhaig and Loch a'Mheallain. In this area the acid gneisses have a composite nature and the basite and ultrabasite bodies are agmatitic.

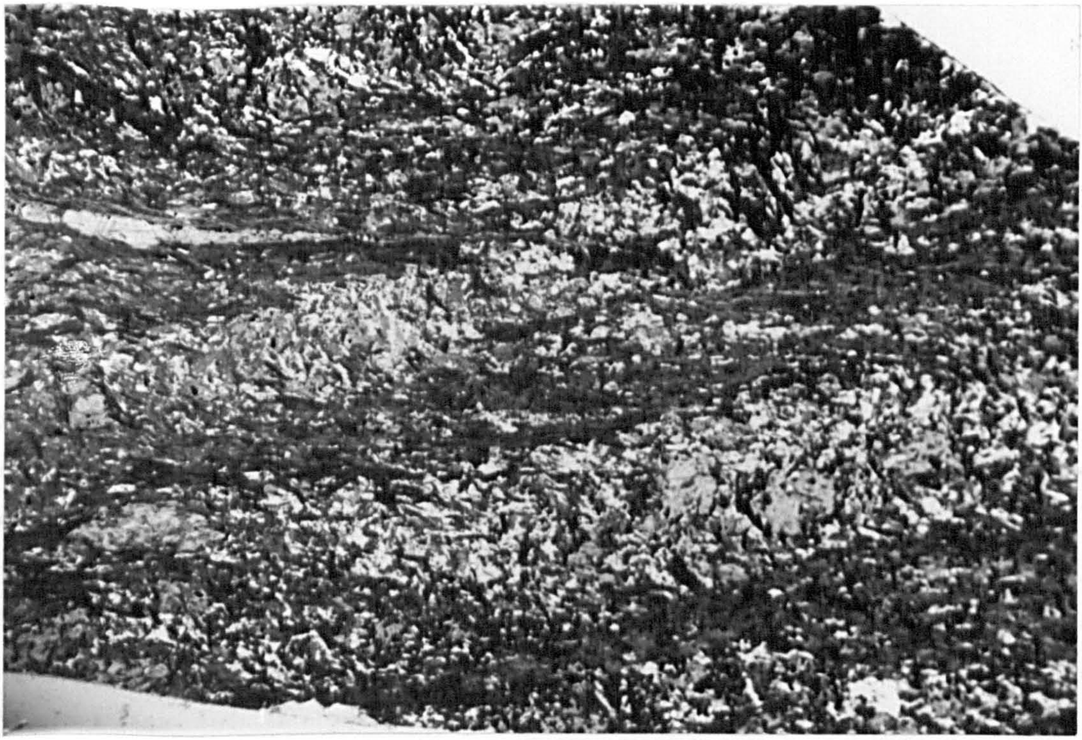
(b) Migmatitic effects in acid gneisses.

(i) General description

The migmatization in the acid gneisses has produced trondhjemitic pegmatites and augen gneisses. The form of the augen gneisses is shown in Plate II-11b where the S_3 banded gneisses show the development of feldspar megacrysts. These plagioclase megacrysts overgrow the S_3 foliation although they are elongated parallel to it

Plate II-11a. Banding produced by metamorphic differentiation in early basite body from the neighbourhood of Lochan Dharach. Note that felsic minerals are concentrated in the short limbs of F_4 folds, whereas mafic minerals occur in fold long limbs (82475932).

Plate II-11b. Migmatitic S_3 banded gneiss from the neighbourhood of An Ruadh Mheallan. Plagioclase porphyroblasts grew in the post D_3-pre D_4 migmatitic event (82616153).



and have been found to have diameters of 15 cm. They are found in both the massive and the banded gneisses. The trondhjemitic pegmatites are broadly concordant to the S_3 foliation in the associated acid gneisses (see Plate II-12a) although sharply discordant margins are occasionally developed. They rarely exceed 4 metres in width having an average thickness of 15-30 cm. and can be traced for long distances parallel to their strike.

The discordant nature of these pegmatites is revealed in Plate II-12a where the pegmatite clearly cuts the foliation in the gneisses, the broad form of the pegmatite being concordant. No chilled marginal facies of the pegmatites against the gneisses have been observed, the margin between the two phases generally being very sharp. In Plate II-12b a sharply discordant pegmatite has inclusions of semi-digested xenoliths of acid gneiss, with a sharp margin against the acid gneisses, but the other margin is of a transitional nature. Where margins with transitional features are developed the series massive granitoid rock - embrechite - banded gneiss can be observed (see Plate II-13a).

The majority of the pegmatite sheets are parallel-sided, but some have a bulbous and irregular form, thinning laterally (see Plate II-13b). These forms cannot be explained by deformation effects (ie. pinch-and-swell structures) since they show no characteristic features diagnostic of the latter. However, they would appear to be a result of mobilisation of the pegmatite as shown for example by discordant margins.

The above mentioned features suggest that the migmatites are arterites, the mobilised fraction of which is of magmatic derivation.

The arteritic gneisses are restricted to areas where S_3 banded gneisses are found. It would seem that the well developed banding in the banded gneisses has influenced the location of the pegmatites. Ramberg (1956) suggested that the localisation of pegmatites depended on the mechanical properties of the rocks in which they are formed and this appears to be the case with the above pegmatites.

Plate II-12a. Discordant pegmatite in S_3 banded gneiss from the neighbourhood of An Ruadh Mheallan (82616153).

Plate II-12b. Pegmatite sheet cutting S_3 banded gneiss showing assimilation of gneissic xenoliths in the pegmatite. From acid gneisses south-west of An Ruadh Mheallan (83046072).

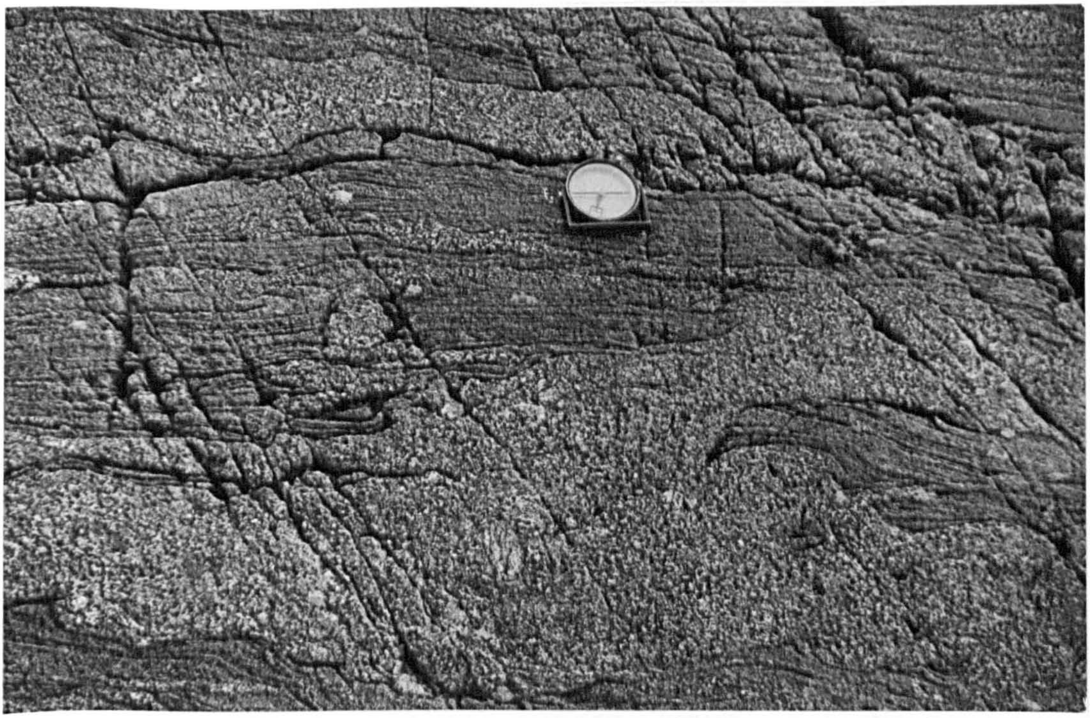
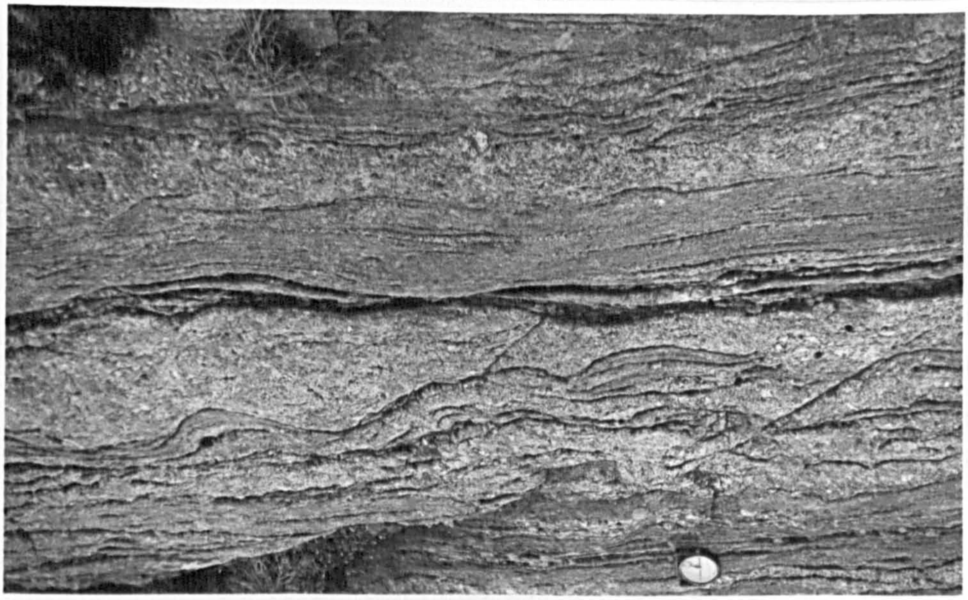
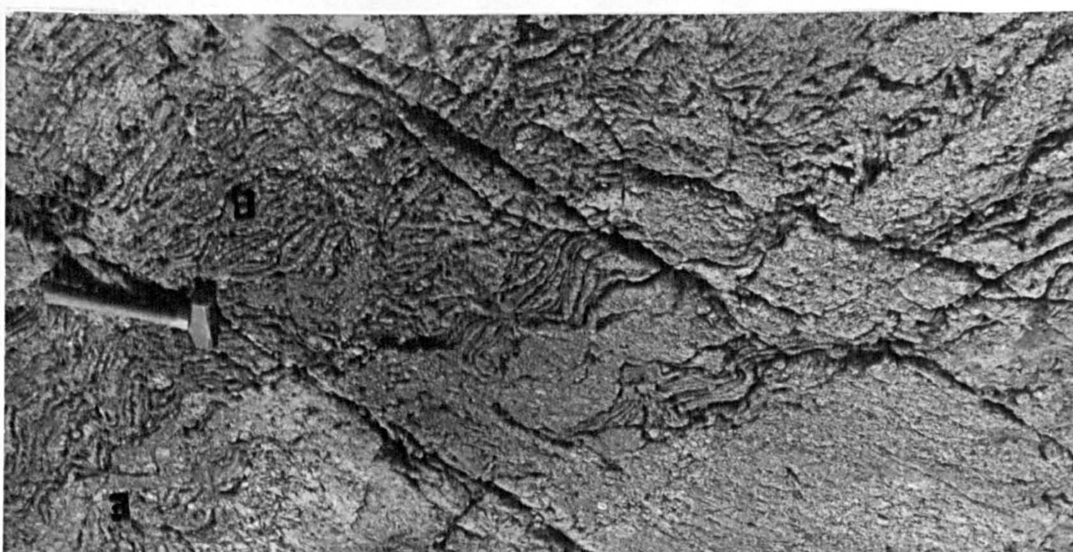


Plate II-13a. S_3 banded gneisses exhibiting pre-D_4, post-D_3 migmatitic effects which have produced the series; banded gneiss (B)-embrechite (E)-massive granitoid rock (G). From acid gneisses west of An Ruadh Mheallan (82556162).

Plate II-13b. Concordant pre-D_4, post-D_3 pegmatite sheets from gneisses west of An Ruadh Mheallan. Note the bulbous form of these sheets (82616153).




a
a
b

(ii) Petrology of the trondhjemitic pegmatites

In hand specimen the pegmatites have a massive, coarse, leucocratic appearance (see Plate II-14a) with no discernible structural features. They have the mineral assemblage plagioclase, quartz, microcline, muscovite, epidote, chlorite, and sphene. Microcline, muscovite, chlorite and epidote were developed in a post-dyke episode and will not be discussed in this section. The mafic minerals, biotite and sphene, when formed, occur in schlieren which consist of aggregates of these minerals. The felsic fraction of the pegmatites is differentiated into feldspar and quartz aggregates.

Biotite forms 0% to 4% of the pegmatites, forming idioblastic to subidioblastic flakes in interlocking aggregates. It has the pleochroic scheme x - straw, y - green, z - greenish brown and is always found at plagioclase grain boundaries. Grains form up to 1·0 mm. in length with a mean of 0·8 mm.

Plagioclase forms between 55% to 65% of the pegmatites. It occurs in aggregates of irregular, inequigranular, xenoblastic grains. The plagioclase is generally altered as a result of the development of small sericite scales and minute unidentifiable brown dust. The plagioclase is oligoclase, An_{22}, with inclusions of rounded quartz grains. Grains vary in size from 0·3 to 5·0 mm.

Quartz forms 25% to 40% of the pegmatites, developed in aggregates of irregular, inequigranular, xenoblastic grains. It has sub-rounded to angular edges against plagioclase, the boundaries being either smooth or serrated. Grains range up to 5·0 mm.

(iii) Petrology of augen gneisses

The augen gneisses have the same mineralogy and fabric as the S_3 acid gneisses but differ in possessing megacrysts of plagioclase feldspar. The megacrysts show exactly the same features as the plagioclases in the pegmatites.

(c) Migmatitic effects in the early basites and ultrabasites

It has already been stated (Section II.B.1.) that [redacted] when traced southwards from areas where the S_3 foliation predominates, into areas where the earlier foliation in the acid gneisses has been completely transposed into the S_4 foliation, the basites retain the earlier features they have inherited (eg. S_3 foliation and migmatitic effects). For these reasons the bodies which retain early features in areas of predominantly S_4 foliation will be discussed here. The migmatitic effects are therefore grouped into:-

(i) Effects on early basites and ultrabasites in S_3 foliated areas.
(ii) Effects on early basites and ultrabasites in S_4 foliated areas.

(i) Effects on early basites and ultrabasites in S_3 foliated areas

The distribution of these bodies has been described in section II.B.1. The early basites and ultrabasites have been disrupted and veined by pegmatitic material forming agmatites (see Plates II-14b and II-15a). As a result of agmatisation the bodies now consist of isolated lumps, balls and pods of early basite and ultrabasite rock. The pegmatites have been introduced parallel to the S_3 foliation of the early basites and ultrabasites and also obliquely, resulting in the rotation of many of the disrupted blocks. The contacts between the introduced leucosome and melanosome fractions are very sharp, and few assimilative features appear to be developed.

In hand specimen the pegmatite fraction of the agmatites is coarse grained, massive and leucocratic, feldspar, quartz and mafic schlieren being easily distinguished (see Plate II-15b). The most noticeable textural feature exhibited by the pegmatites is the aggregation of felsics into plagioclase-rich and monomineralic quartz areas. The mafic schlieren are believed to have formed by the assimilation of basite and ultrabasite material by the mobile fraction of the agmatites and are formed in the feldspathic areas. They consist of aggregates of biotite, epidote, sphene and magnetite, forming up to 35% of the leucosome.

Plate II-14a. Pegmatite from acid gneisses west of An Ruadh Mheallan (82616153).

Plate II-14b. Agmatite produced [redacted] by disruption during the D_3 fold movements and migmatization in the post-D_3, pre-D_4 migmatitic event. From the gneisses west of An Ruadh Mheallan (82836137).


MM
1
2
3
4

Plate II-15a. Pre-D_4, post-D_3 migmatitic effects in the early basite body east of Loch a'Choire Bhig (83025924).

Plate II-15b. Pre-D_4, post-D_3 pegmatite associated with the early basite body east of Loch a'Choire Bhig (83025924).


MM
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Biotite may form up to 30% of the pegmatites, but rarely exceeds 5%. It forms aggregates of stout to slender, interlocking flakes with the pleochroic scheme varying from x - straw, y - brown, z - deep brown to x - pale green, y = z - green. Flakes range up to 1·5 mm. in length with a mean of 0·6 mm.

Epidote is always associated with biotite aggregates and may form up to 5% of the pegmatites consisting of subidioblastic to xenoblastic grains. Grains range up to 0·4 mm. with a mean grain size of 0·2 mm.

Plagioclase forms 35% to 60% of the pegmatites and is developed in aggregates of inequigranular, irregular, xenoblastic grains which show varying degrees of alteration to sericite. The plagioclase shows both zoned and unzoned grains, the unzoned grains being oligoclase, An_{22-29}. In the reverse-zoned grains the cores have the composition An_{19-26} and the mantle An_{22-34}. The margins between plagioclase and quartz grains are very irregular, occasionally with serrated edges (see Plate II-16a), but smooth margins are more common. Plagioclase grains range up to 4·0 mm. with a mean of 1·5 mm.

Quartz forms 30% to 65% of the pegmatites with an average of 35%, developed as aggregates of inequigranular, irregular, xenoblastic grains. Grains range up to 8·0 mm. with a mean of 1·0 mm.

(ii) Effects in early basites and ultrabasites in S_4 foliated areas

The mobile fraction of the agmatites resembles the pegmatites of S_3 areas in that the minerals are differentiated into mafic and felsic aggregates. There are, however, slight differences in mineralogy since the bodies in the S_4 gneisses develop both garnet and muscovite.

Garnet forms large idioblastic to xenoblastic grains which are generally partially retrogressed to a biotite-magnetite-epidote assemblage.

Plagioclase, quartz, biotite and epidote have a similar mode of occurrence to that of the previous group, plagioclase being an oligoclase variety, An_{22-30}.

4. The D_4 syntectonic and post-tectonic migmatites

(a) General description

The D_4 syntectonic and post-tectonic migmatites are developed throughout the complex and exhibit varying characteristics from north to south. They can be subdivided into two phases, an earlier phase of granitization and a later phase of pegmatite development. The earlier phase appears to have developed in part contemporaneously with the D_4 fold episode (ie. syntectonic) and continued until the fold episode had subsided. The pegmatite phase was intruded post-kinematically and cuts granitized material and D_4 structures.

The granitization effects show considerable variations from north to south.

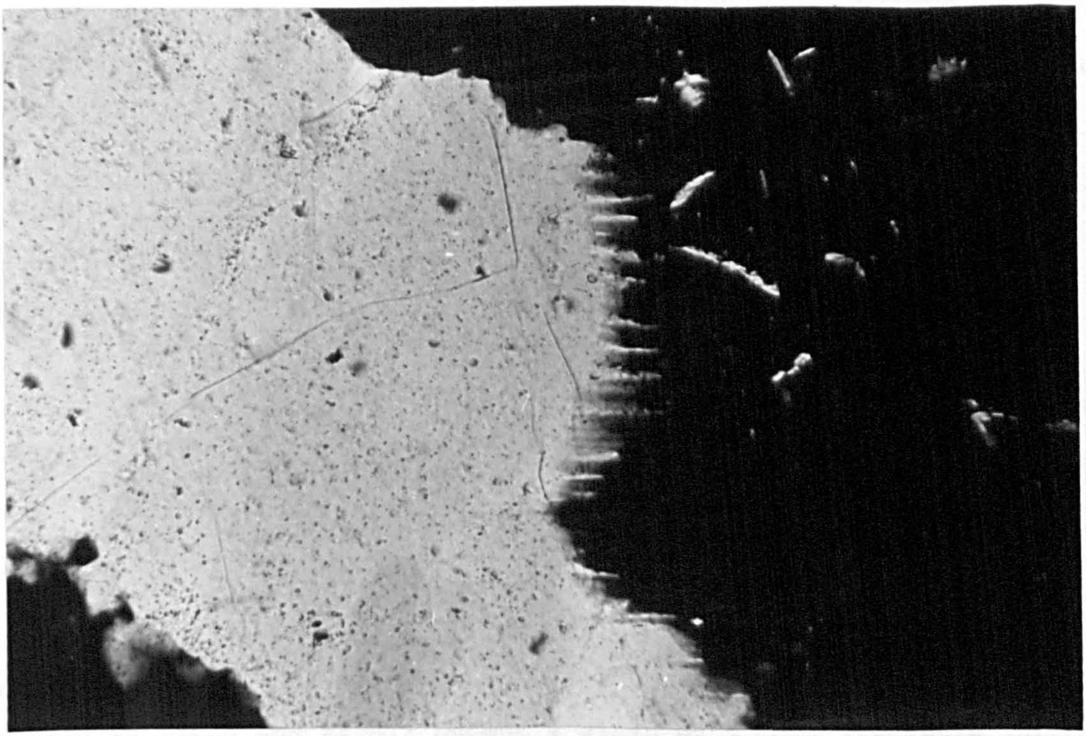
In the south of the complex, the migmatization was syntectonic and the dual effects of granitization and deformation produced irregular plastic F_4 folds (see Plate II-16b) as well as more regular plastic flow folds. The acid gneisses appear to have behaved so plastically along certain belts that they have resisted the shearing which was necessary to produce the S_4 foliation. Thus instead of being transposed, the S_3 foliation was retained but was squeezed and stretched in such a way that the original uniform S_3 banding became modified. The early basites and ultrabasites in this area have been so extensively granitized that they have lost their original form and become rocks of dioritic composition.

Further north, the syntectonic granitization appears to be less clearly developed whereas the post-tectonic phase is very pronounced. The effects of this granitization here were to transform the acid gneisses into massive, homogeneous, granitoid rocks passing through an intermediate stage of <u>embrechites</u> and <u>nebulites</u>. The associated early basites and ultrabasites appear to have resisted these effects.

In the extreme north of the area, the granitization becomes less pronounced, without the production of granitoid rocks, embrechites and nebulites, and is here represented by thin pegmatites developed along

Plate II-16a. Serrated edges occurring at quartz-plagioclase boundary, indicating that quartz replaced plagioclase during D_4 syn-and post-tectonic migmatitic event. From migmatitic acid gneiss east of Lochan Dharach (x100 X.P.L.) (82645910)

Plate II-16b. F_4 "flow" folds from the neighbourhood of Meall Ceann na Creige (80585982).



sheared F_4 fold limbs (cf. Engel and Engel 1958).

(b) Distribution of the migmatites

Sutton (1949, 1951) regarded the formation of the D_4 syntectonic and post-tectonic migmatites as post-dyke effects. However, the migmatization related to the D_4 deformation is interpreted as a pre-dyke phenomenon since the dykes cut S_4 and are unaffected by the migmatization (see chapter II.B.). Sutton subdivided the Torridon area into three zones; An Ruadh Mheallan; Loch Diabaig and Loch Torridon zones primarily on what he regarded as a result of varying Laxfordian effects on the complex. This three-fold zonal arrangement is a satisfactory framework for discussing the D_4 syntectonic and post-tectonic migmatites.

(i) An Ruadh Mheallan zone

In this zone the migmatization was mild and has produced thin pegmatites in the acid gneisses. The pegmatites are developed along sheared F_4 limbs and rarely exceed a width of 2 cm., and traceable for only short distances along their strike (see Plate II-17a). The pegmatites reflect the composition of the host acid gneisses and consist of a quartz-plagioclase assemblage. They are texturally and compositionally similar to the pegmatites developed in the post-D_3 and pre-D_4 migmatization.

(ii) Loch Diabaig Zone

In this zone the granitization effects are more pronounced. The acid gneisses are granitized uniformly and migmatitic rocks occur in irregular patches throughout the zone, the patchy areal distribution being common further north, whereas to the south the migmatitic effects are more widespread. The granitization has produced embrechites, nebulites and trondhjemitic masses from the S_4 foliated gneisses. The series foliated acid gneiss-embrechite-nebulite-trondhjemite rock is characteristic, the passage between the members being sharp (see Plate II-17b). The effects associated with granitization have not

Plate II-17a. F_4 folded acid gneiss with pegmatite veins generated parallel to F_4 fold axial planes. From the gneisses west of An Ruadh Mheallan (82636152).

Plate II-17b. F_4 folded gneiss from the neighbourhood of Lochan Dharach. The series banded gneiss-embrechite-massive granitoid rocks has been produced during the D_4-syn- and post-tectonic migmatitic event (82585912).

resulted in an extensive introduction or removal of material, the end products reflecting the composition of the host acid gneisses. The most pronounced result is a recrystallization of the acid gneisses.

(iii) The Loch Torridon zone

The Loch Torridon zone differs from the Loch Diabaig and An Ruadh Mheallan zones in that widespread granitization of acid gneisses and early basites has occurred. In the host acid gneisses the migmatization has not resulted in the introduction of material, the rocks retaining their initial trondhjemitic composition.

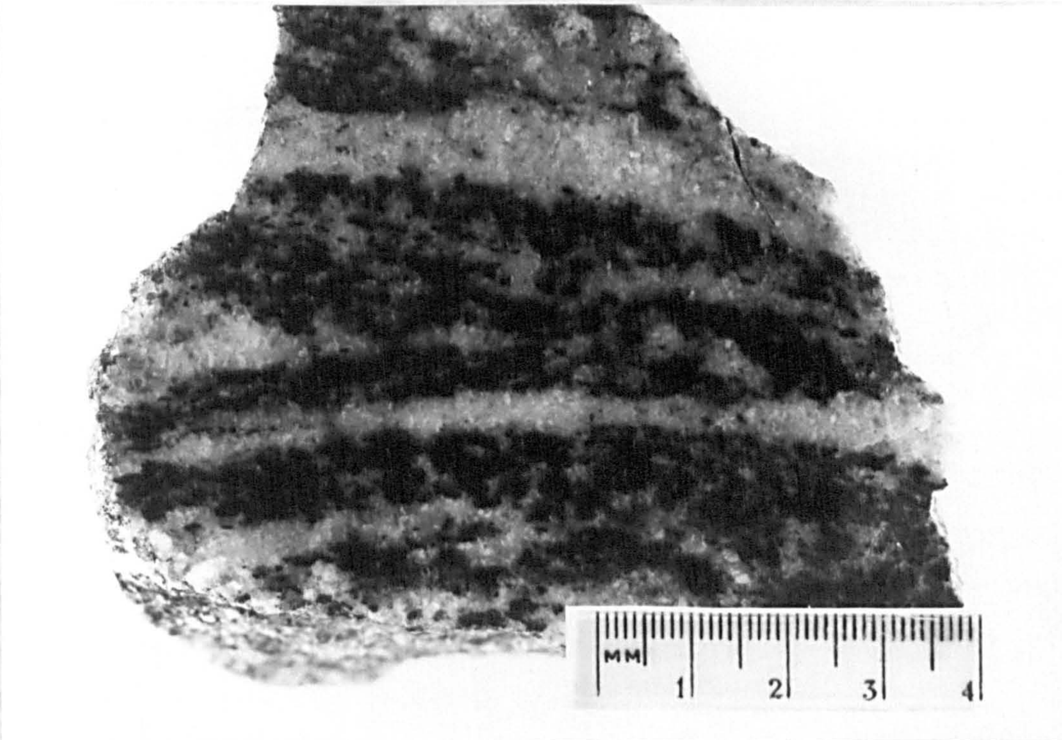
On the other hand, the early basites have undergone notable introduction of material, the NW-SE belt north of the massive gneisses (see Fig.II-1) revealing extensive granitization which has led to the production of rocks with dioritic and appinitic affinities. The introduction of quartzo-feldspathic material has either taken place parallel to the S_4 foliation producing a banded rock (see Plate II-18a) or has caused irregular permeation producing a mottled gneiss (see Plate II-18b).

(c) Petrology of the granitized early basites

The granitized early basites consist of hornblende, biotite, sphene, epidote, magnetite, plagioclase, microcline and quartz.
Hornblende may be absent, where granitization has been extensive, but may form up to 45% of the early basites. It forms subidioblastic to xenoblastic grains which are aligned in a preferred orientation parallel to the S_4 foliation. Hornblende shows slight variation in pleochroism x - straw, y - green, z - bluish green or olive green. Inclusions of quartz, plagioclase, magnetite and epidote are present, grains ranging up to 5·0 mm. with a mean size of 1·5 mm.

Biotite forms 5% to 20% of the basites with an average of 10%. It forms aggregates of subidioblastic to xenoblastic interlocking flakes associated with hornblende and epidote. The pleochroic scheme exhibited by biotite varies from x - pale green, y = z - green through x - straw, y - greenish brown, z - greenish brown to x - straw, y - brown, z -

Plates II-18a-b. D_4 syntectonically-migmatized early basites. In (a) granitization has produced pegmatitic material along the S_4 foliation, whereas in (b) permeation has been more thorough. From the early basite body south-south-west of Creag an Fhraoich (82715844).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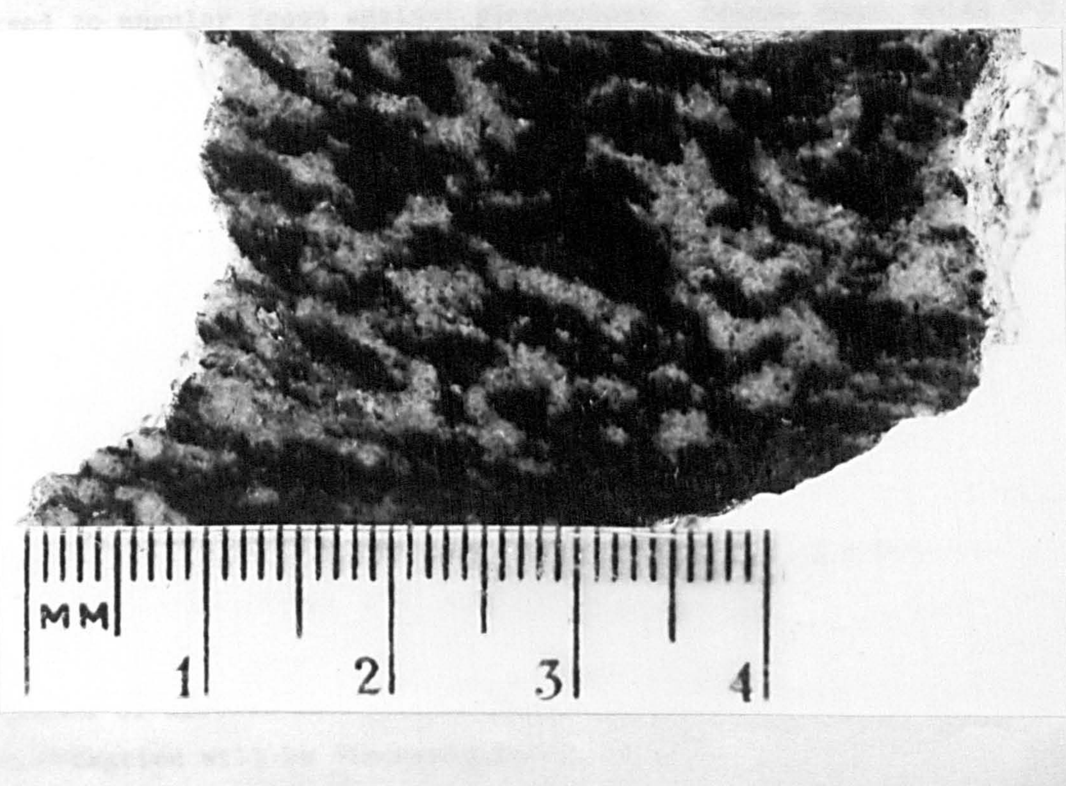
MM
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deep brown. Biotite may either have a preferred orientation parallel to the S_4 foliation or be [redacted] unoriented to any mesoscopic structure. Grains up to 1·0 mm. are developed with a mean size of 0·3 mm.

Epidote is always associated with the mafic constituents and forms 1% to 20% of the early basites with an average of 5%. Grains range up to 1·5 mm. with a mean size of 0·4 mm.

Sphene has a similar mode of occurrence to epidote, forming up to 5% of the early basites with an average of 2%. The association hornblende-epidote-sphene-biotite is a characteristic feature of the granitized early basites.

Plagioclase forms 35% to 65% of the early basites with a mean of 40%. It forms large, irregular, xenoblastic grains generally developed in aggregates. The plagioclase is oligoclase, An_{22-31}, with albite and combined albite-pericline twinning common. Grains range up to 3·5 mm. with a mean size of 1·0 mm.

Quartz forms 20% to 25% of the rocks occurring as aggregates of irregular, xenoblastic grains with smooth to occasionally serrate, curved to angular faces against plagioclase. Grains range up to 1·5 mm. with a mean grain size of 0·8 mm.

(d) Mineralogical changes in the complex as a result of granitization

Granitization of the acid gneisses has not resulted in any extensive change of the mineralogy and mineral proportions. Since they were migmatized by granitizing fluids which produced trondhjemitic rocks, the acid gneisses which were initially trondhjemitic show no noticeable changes. Gneisses of possible sedimentary derivation appear to have acted as resisters to migmatizing agents.

The early basites have definitely been affected by the granitization [redacted]. The original unmigmatized early basites consist of hornblende, epidote and plagioclase, but when traced southwards show slight differences notably as a result of the development of biotite. The presence of biotite as a result either of regional metamorphism or migmatization will be discussed later.

The following changes in mineralogy and mineral proportions result from increasing granitization, from the An Ruadh Mheallan to the Loch Torridon zone (see Table II-3):-

(i) Biotite increases from the Loch Diabaig to the Loch Torridon zone, being rare or absent in the An Ruadh Mheallan zone.

(ii) Hornblende decreases from the An Ruadh Mheallan zone to the Loch Torridon zone where it may be absent.

(iii) Plagioclase increases towards the Loch Torridon zone.

(iv) Quartz is developed in the Loch Diabaig zone and increases in the Loch Torridon zone.

(v) Epidote varies irregularly.

The grain size of the individual minerals also increases with increasing granitization.

5. Generation of pegmatites associated with D_5 structures

There are a few localized occurrences of pegmatite secretions associated with early basite bands and pods which can be assigned to a granitization episode associated with the formation of D_5 structures. These secretions are either in the form of irregular bodies developed around boudinaged early basites or vein-like pegmatites developed along F_5 fold axial planes.

The secretions developed around early basite and ultrabasite pods are similar to occurrences described by Ramberg (1956) who believed that the bodies grew in the pressure shadows of rigid inclusions. The secretions fade gradually into the host acid gneisses and reflect the composition of these host gneisses.

Mineral	An Ruadh Mheallan zone %	Loch Diabaig zone %	Loch Torridon zone %
Hornblende	30 - 90	50 - 80	0 - 45
Biotite	-	5 - 10	5 - 20
Epidote	0 - 60	5 - 10	1 - 20
Plagioclase	10 - 40	10 - 40	35 - 65
Quartz	rare	0 - 10 rare	20 - 25
Sphene	rare	0 - 5	0 - 5

——— Granitization increase ———→

Table II-3. Compositional variations in the early basites

III. THE DYKES

A. Introduction

The significance of periods of dyke intrusion providing stratigraphic marker horizons in the structural analysis of Pre-Cambrian complexes cannot be over-emphasized. Dykes have been used in this way for more than half a century in tectonic synthesis (e.g. Peach et al. 1907, Sederholm 1923). Recent contributions (Sutton and Watson 1951A, 1962, Berthelsen 1957 and Park 1969) to the study of the Pre-Cambrian have centred on the use of dykes, particularly in areas of homogeneous granite gneisses where stratigraphic methods are unsatisfactory (Kranck 1957).

Park (1964) pointed out the dangers of assuming that all the dykes of the Lewisian complex were of the same age, particularly as correlations between widely separated areas had been made (Sutton and Watson 1951A), and implied that the structural relationships between dykes and host gneisses over small, continuous areas must be established in detail before generalizations concerning widespread correlation can be made.

Two conditions must be satisfied before dykes may be used as structural marker horizons:

(i) The age relations between individual dykes must be established.

(ii) The structures exhibited by the dykes must be carefully analysed before correlations can be justified.

Conversely, the mineral composition, form and texture exhibited by the dykes do not provide a satisfactory method of correlating the dykes.

The dykes in the Loch Torridon area form a NW-SE-striking swarm and show wide variations in structural relationships to the host gneisses. Compositional differences and cross-cutting relations between the different dykes have led to their sub-division into:-

(i) Type-TD Basites* (main suite of basic dykes)

(ii) Type-TB Basites* (later basic dykes)

(iii) Ultrabasites

The type-TD basites form by far the major proportion of the dyke swarm, whereas the ultrabasite - type-TB basite association forms rare, isolated bodies. The dykes were intruded in the sequence type-TD basite - type-TB basite - ultrabasite, indicating an increase in basicity with successive injections. Most of the dykes can be described as amphibolites.

The shapes of the bodies have been controlled by the pre-existing form of the complex (cf. Poldervaart and Wilcox 1958, Reynolds 1931, Buddington 1962 and Gates 1967) and the variations exhibited by them reflect the structural variations of the complex. Certain type-TD basites have been emplaced by multiple injection (cf. Peach et al. 1907, p.204). The ultrabasite and type-TB basites generally form composite dykes although ultrabasites may form isolated bodies.

All members of the dyke swarm have been affected by three correlatable metamorphic events (M_6, M_7 and M_8) and three associated deformational episodes (D_6, D_7 and D_8) and since their sequence of intrusion can be established, the conditions which enable them to be used as structural marker horizons are satisfied.

The compositional variations shown by the dyke swarm have been noted from other areas on the mainland (Peach et al. 1907, p.155, Sutton and Watson 1951A, O'Hara 1962 and Tarney 1964) at Scourie, Assynt and Gruinard Bay, although there is no previous record of ultrabasite and type-TB basite dykes at Loch Torridon.

B. The Type-TD Basites

The type-TD basites form the predominant proportion of the dyke swarm and occur throughout the area. Their widespread development is of great assistance in understanding the deformational history of the complex.

* The labels 'TD' and 'TB' are used merely to distinguish between the two generations of basites.

1. Distribution of the dyke swarm

The distribution of the dyke swarm has been controlled by the pre-existing form of the complex which is a result of the superposition of at least five pre-dyke fold episodes (see Chapter V. B-D). The areal distribution of the pre-dyke structures has led to the recognition of several domains, each of which shows diagnostic characteristics. These characteristics have been developed from:

(i) The relationship of the dykes to the gneissic complex: whether margins are concordant or discordant.

(ii) The degree of deformation exhibited by the dykes: whether sub-ophitic texture or schistose.

(iii) Whether the dykes are simple or complex in form.

(iv) The orientation of the dykes.

(v) The thickness of the dykes.

(vi) The separation and areal density of the dykes.

(vii) The age relationships of the dykes: whether simple, composite or cross-cutting.

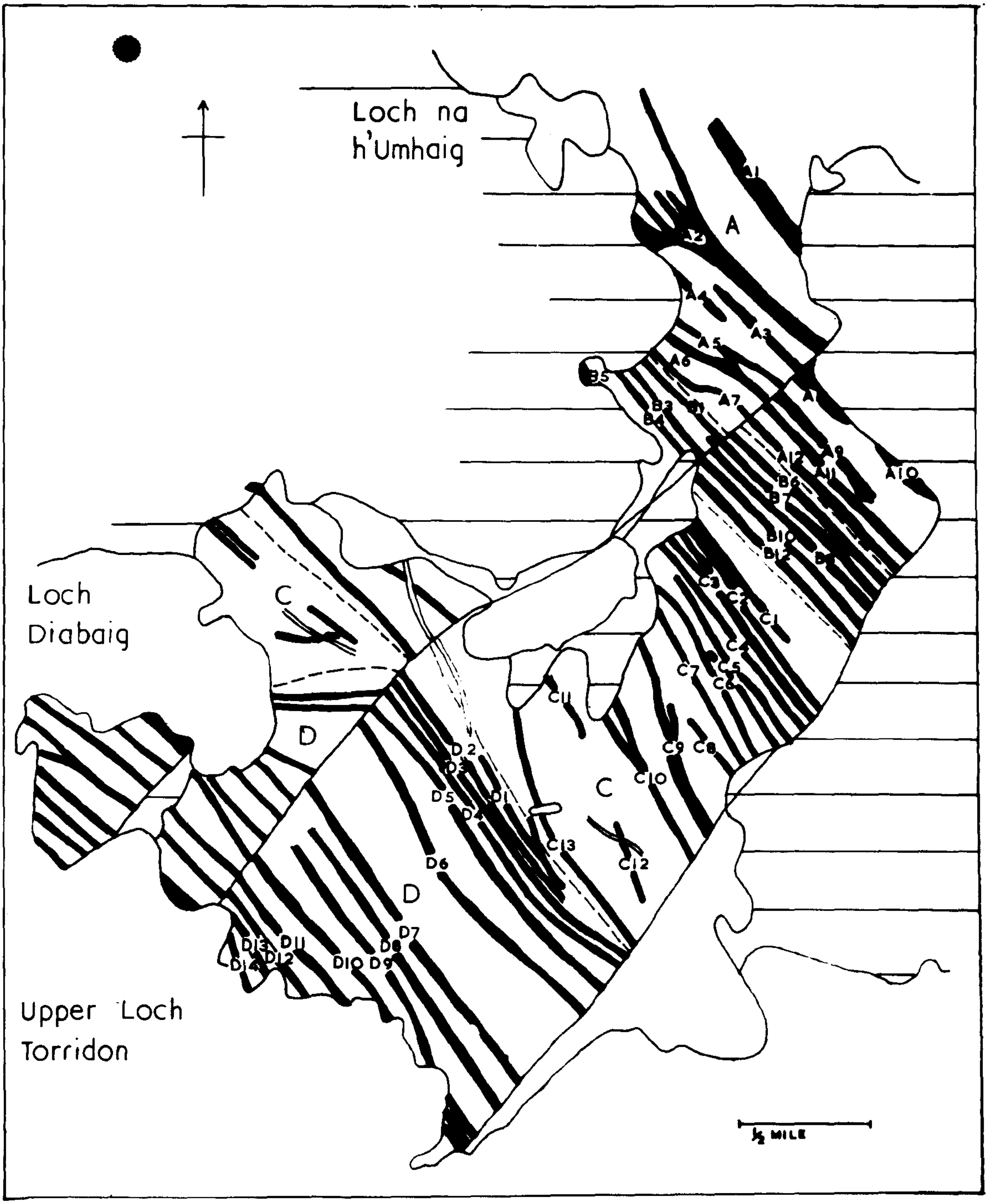
The boundaries separating dyke domains are often drawn arbitrarily since the above characteristics show progressive variations from one domain to another. The limits of the four established domains are illustrated in Fig.III-1.

Domain A

Domain A predominantly consists of S_3 foliated gneisses which have been affected by a large-scale F_3B fold whose northerly limb strikes approximately NW and southerly limb approximately N to NE. This large-scale structure is the dominant factor influencing the disposition of the dykes, which have a NW-SE strike and dip at variable angles NE (Fig.III-2a).

All the dykes developed in the NNE-striking limb of the F_3B fold are macroscopically discordant (see Plate III-1), except where intense small-scale F_4 folding and axial-planar foliation are developed (see domain B). However, localized mesoscopic concordance between the dyke margins and associated S_3 gneisses is occasionally found.

Fig.III-1. Distribution of the dykes and the dyke domains for the area.


Loch na
h'Umhaig
Loch
Diabaig
Upper Loch
Torridon
A
C
D
A1
A3
A4
A5
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A7
A9
A10
A11
A12
B3
B4
B5
B6
B7
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D10
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D12
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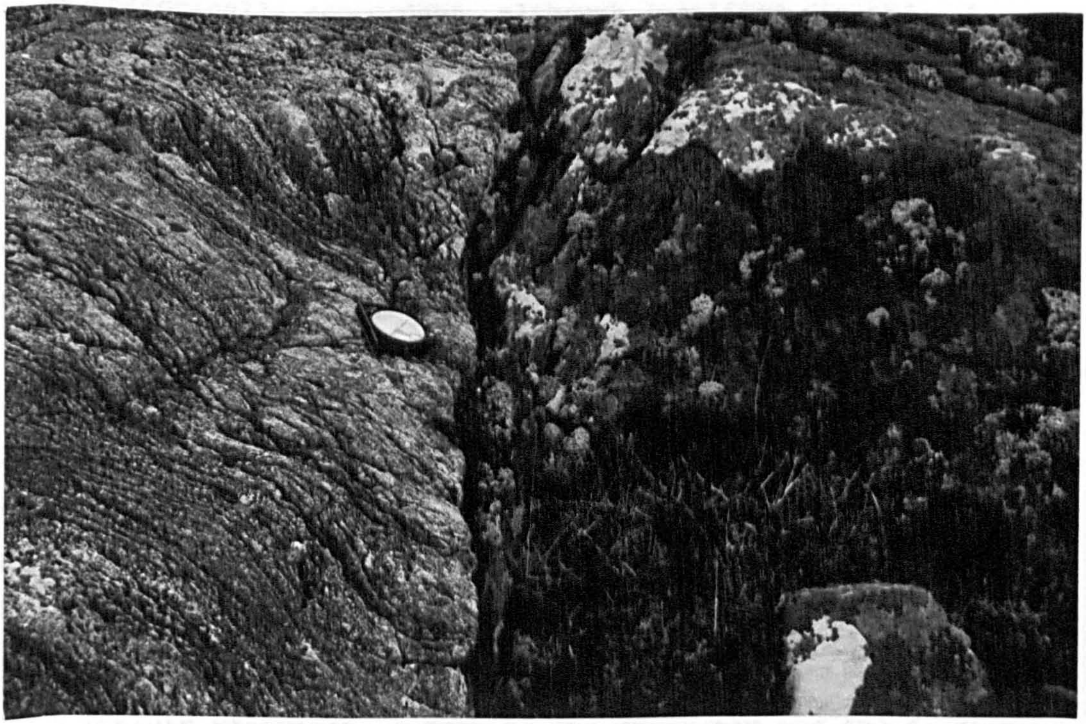
D14
½ MILE

Plate III-1. Type-TD basite dyke exhibiting sharply discordant margin to S_3 foliated acid gneisses. S_7 is parallel to basite margin and disappears towards the dyke centre (Domain 1).



On the NW-striking limb of the F_3B fold, dykes are mesoscopically and macroscopically concordant, although localized discordancies are found. Since this limb dips SW at variable angles and the dykes dip consistently NE, discordant margins would be expected. As a result of the large scale F_4 folds, with NW-SE-striking axial planes and shallow plunging fold axes which are developed on this major limb, NE and SW dipping limbs are produced. The dykes have been intruded parallel to the NE-dipping limbs of these F_4 folds (see Fig.III-3d).

Dykes A1 and A2 (Fig.III-4) illustrate the controlling influence of the F_3B fold on their configuration. Dyke A2 has its maximum thickness where it discordantly cuts the N to NE limb of the fold. When traced north-west, parallel to the strike, the dyke splits on the NW-striking limb of the F_3B fold. The ability of the dyke to furcate into thin dykes reflects the ease with/ which the gneisses part parallel to the foliation to allow emplacement.

A feature exhibited by some of the dykes (A3 and A9) is the ability of the bodies to split when they die out laterally.

Dykes are more commonly found in domain A where narrow belts of S_4 foliated gneisses are developed, being concordant and thinner than usual (e.g. 1 metre).

Figs.III-3a-c and 5a-c illustrate the various dyke-acid gneiss contact relationships.

The type-TD basites in domain A are the thickest and least deformed, with a maximum thickness of 100 metres observed in dyke A1, although most bodies are between 25 to 30 metres. The thickness and degree of deformation in the dykes appears to be related to the attitude of the host gneisses. Where the foliation is concordant, the dykes are relatively thin and at least partly schistose, whereas those dykes associated with discordant acid gneisses are thick and undeformed. All the undeformed dykes have a well-developed sub-ophitic texture (see Plate III-2a) and chilled margins (see Plate III-2b). One multiple type-TD basite (A2) has been found in domain A, in the

Plate III-2a. Undeformed centre of type-TD basite with ophitic texture. Pyroxenes are still preserved in the centres of mafic areas (Domain C; 82715943).

Plate III-2b. Undeformed margin of type-TD basite. Igneous pyroxenes completely uralitized, whereas igneous lath-like plagioclase remains unaltered (Domain A).

vicinity of the small lochan north of Loch Airidh Eachainn (G1558140).

Domain B

In domain B the dykes are generally concordant to the foliation in the adjacent acid gneisses. They differ from the dykes of domain A in being thinner and more deformed and in their concordance with the structures in the gneisses. The foliation in the gneisses strikes predominantly NW-SE dipping approximately 60°NE. In the north of the domain the dykes are generally discordant to the gneisses and resemble the type-TD basites of domain A, but progressively southwards the dykes become generally concordant to the S_4 acid gneisses, although discordance is not uncommon (compare Fig.III-5d with e). Plate III-3a and b illustrate slight discordance between the S_4 acid gneisses and type-TD basites.

In the north of the domain a variety of structures are developed in gneissic xenoliths in the type-TD basites (see Fig.III-5f, g and h). In Fig.III-5h the type-TD basite has bifurcated at the nose of an F_4 fold and been emplaced sub-parallel to the limbs of the fold. Further south where the S_3 foliation has been folded and transposed into the S_4 foliation, the gneissic xenoliths also have an S_4 foliation (see Plate III-4a), the dykes being emplaced parallel to the S_4 foliation.

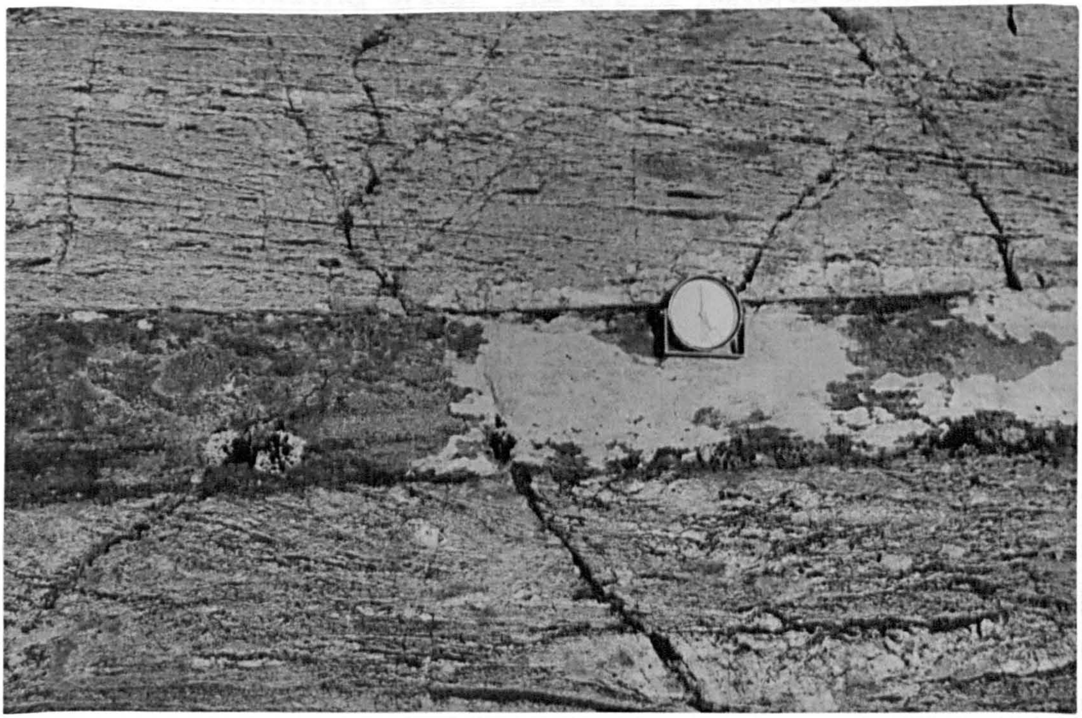
The dykes in domain B rarely exceed 20 metres in thickness with a mean of 10 metres, although thin bodies, 2 to 5 cm, are developed where the S_4 foliation predominates. These thin dykes, which can often be seen to be apophyses to larger dykes, can be traced for long distances parallel to their strike and commonly show very little deformation. The separation between the dykes in this domain is considerably less than in domain A and can be explained by the different structural environment, since in this area the predominant foliation (S_4 foliation) is parallel to the course of the dykes.

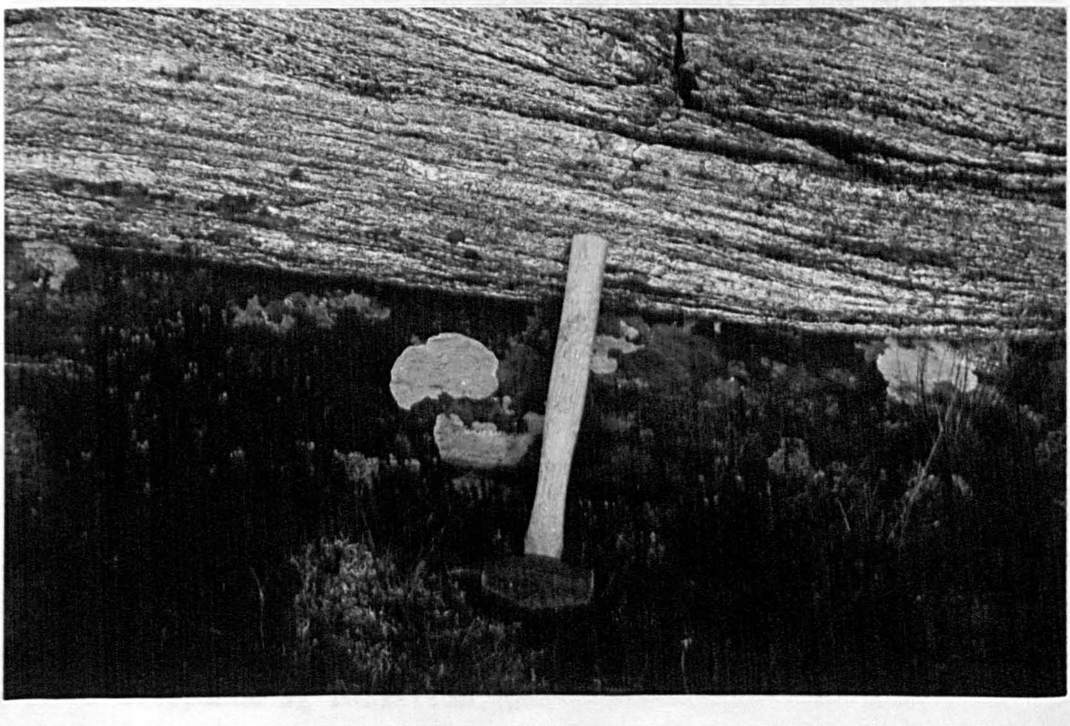
Domain C

This domain extends from the dyke B12 north of Loch nan Tri-eileanan to Loch na Beiste (see Fig.III-1). The dykes exhibit some of the characteristics of domains A and B as well as feature of their own.

Plate III-3a. Thin, type-TD basite which has been intruded sub-parallel to S_4 in the acid gneisses. S_7 foliation in the dyke is parallel to the margin (Domain C; 83295947).

Plate III-3b. Slightly discordant type-TD basite margin (Domain C).





Domain C resembles domain A in having thicker, widely spaced, less deformed and bifurcating dykes. The hybrid features which domain C dykes display can be accounted for by the nature of the pre-dyke structures in the gneisses. The S_3 and S_4 foliations in the domain are widely developed, but the S_4 foliation assumes a different attitude to that of domain A and B, becoming progressively shallower in dip southwards and approaching a horizontal attitude in the vicinity of Loch na Beiste. The type-TD basites are markedly discordant to the S_3 foliation but where the S_4 foliation is present the dykes have been intruded concordantly, appearing as sill-like bodies.

The difference between domains B and C arise as a result of the variation in attitude of the S_4 foliation. The dykes have been emplaced parallel or sub-parallel to the S_4 foliation throughout domain B and the north of domain C (see Fig.III-3c), even where the S_4 foliation dips at angles of the order of 30°NE. Progressively southwards the foliation approaches the horizontal and the type-TD basites have been emplaced with a marked discordance to the S_4 foliation (e.g. on Meall Ceann na Creige and in the vicinity of Loch na Beiste).

A factor which affects the dyke emplacement in the belt of sub-horizontal S_4 foliation is the development of F_5 asymmetric folds producing steep limbs dipping NE. The ultrabasite 250 metres NNE of Loch a'Choin Duibh has been intruded parallel to the NE dipping limb of an F_5 asymmetric fold. Similarly, the dykes C11 and the ultrabasite-basite composite dyke on Meall Ceann na Creige (see Fig. III-3e and Plate III-4b), have been intruded sub-parallel to the steep limb of F_5 asymmetric folds.

Domain C differs markedly from the other domains in areal distribution of the dykes. Domains A and B have uniformly distributed dykes although the areal separation of the type-TD basite is different in the two domains, whereas in domain C the distibution is very variable. In the south of the domain where sub-horizontal S_4 foliation is found, dykes are scarce, whereas in the north the dykes are more common as a result of steepened S_4 foliation.

The dykes are thicker and more deformed than those of domain B often showing bifurcation along their courses.

Domain D

The dykes of domain D resemble those of domain B in many respects but contrast sharply with those of domains A and C. All the type-TD basites in the domain are macroscopically concordant (see Fig.III-2e) and generally also mesoscopically concordant. Even where the dykes bifurcate, their courses are concordant to the foliation in the adjacent gneisses. The dykes are much thinner than in domains A and C except for the type-TD basite on the promontary at Rudha na h-Airde Glaise which is at least 100 metres thick. The dykes are much more closely spaced than in the other domains and are developed in larger numbers concentrated in belts where the early s-surfaces have been completely transposed into the S_4 foliation. Plate III-5a illustrates a thin, discordant type-TD basite cutting F_4 folded acid gneisses. The dykes are very schistose in this domain irrespective of whether they are discordant (see Plate III-5b) or concordant, sub-ophitic texture being uncommon.

On the Airde peninsula dykes have been intruded into a large F_5 asymmetric fold. The dykes are more widely spaced and thicker than the other dykes of domain D and are discordant to the S_4 foliation in the gneisses.

The close spacing, rather thin nature and extensively deformed state of the dykes in this domain appears to be related to the apparent tendency of the S_4 foliation to facilitate emplacement of the magma.

Table III-1 shows the distribution of dyke characteristics in the four domains.

Summary

The dykes of the Torridon area show a set of characteristics which appear to show variations over the area in such a manner that a sub-division into four domains can be made, each of which can be differentiated from the others. This sub-division into dyke domains is

Plate III-4a. Type-TD basite intruded parallel to S_4 in acid gneisses. Gneissic xenoliths in basite have S_4 foliation which is parallel to the trend of the dyke. S_7 in dyke is co-planar to S_4 in acid gneisses (Domain C; 82415974).

Plate III-4b. Ultrabasite-type-TB basite composite dyke from Meall Ceann na Creige with discordant margin to steeply dipping S_4 (Domain C; 80505968).

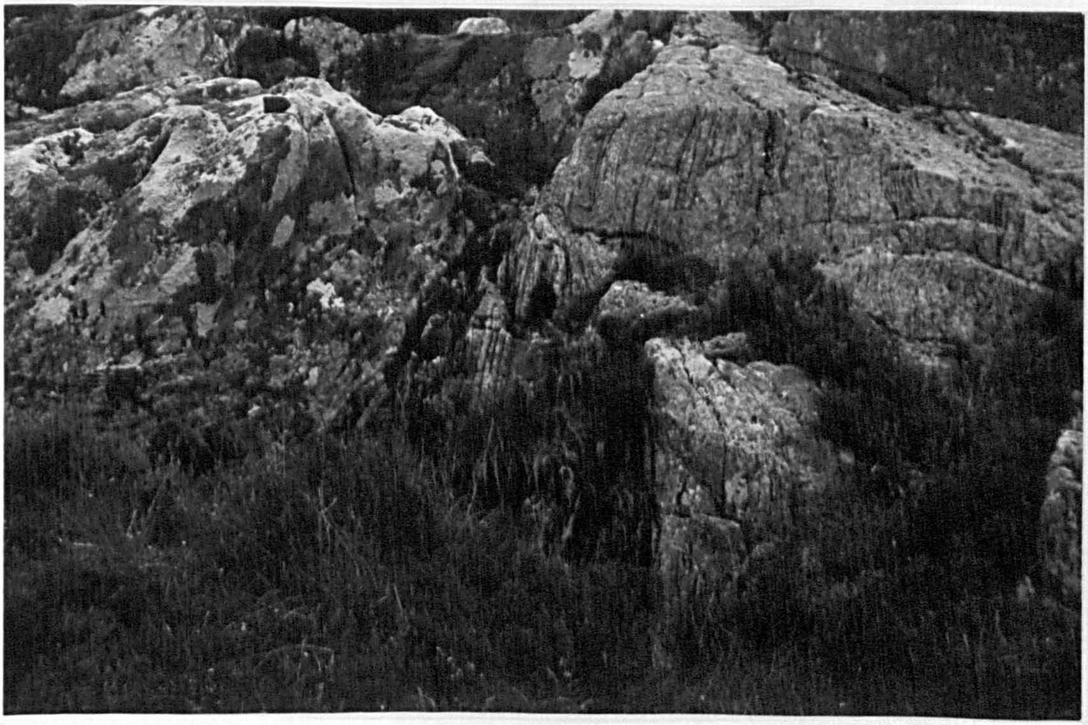
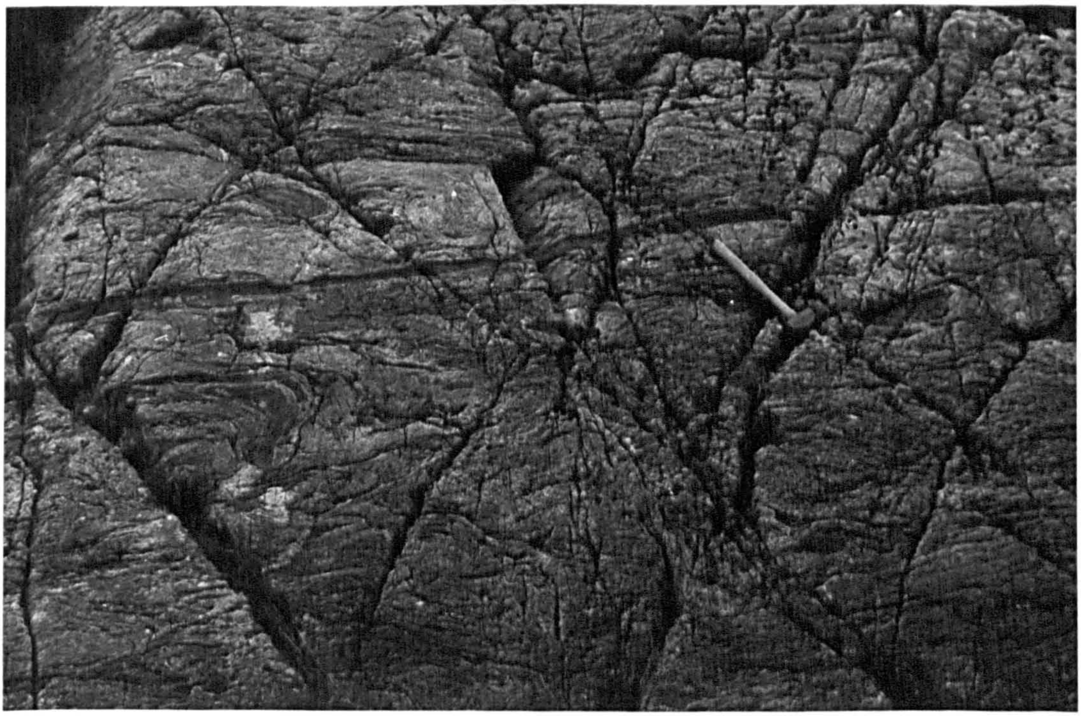


Plate III-5a. Thin type-TD basite dyke cutting D_4 deformed migmatitic gneisses. Note the regular thickness and attitude of the dyke (Domain D; 80055832).

Plate III-5b. Type-TD basite cutting S_4 foliated acid gneisses. The dyke has a penetrative S_7 foliation parallel to margins (Domain D-; 80735768).



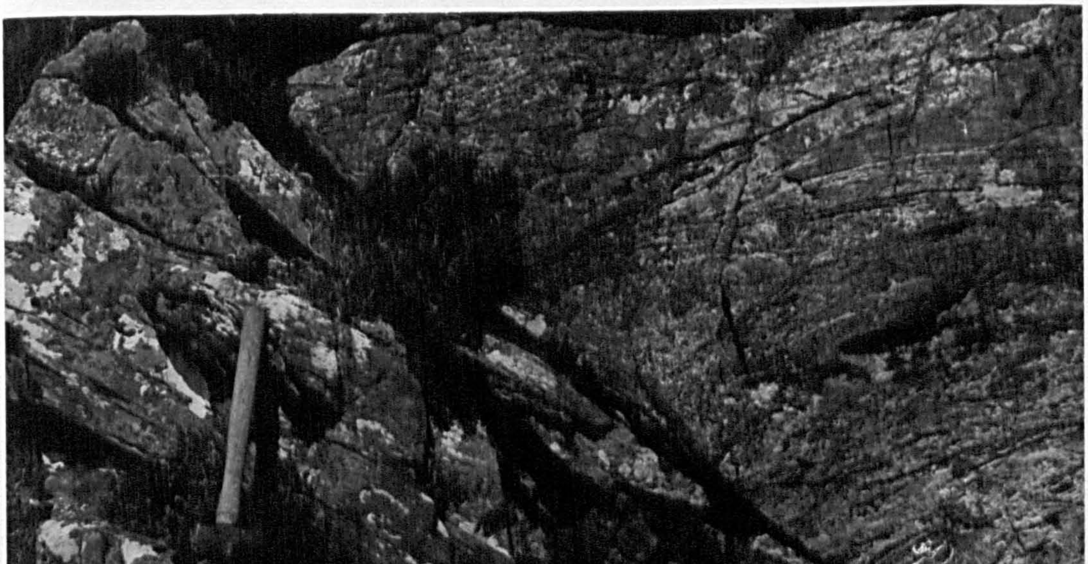


Fig.III-2. Poles to dyke margins. Discordant dyke margins for (a) domain A (b) domain B (e) whole area. Concordant dyke margins for (c) domain D; 40 poles contoured at intervals of 1, 6, 12½ and 14% and (d) whole area; poles contoured at intervals of ½, 1, 2½, 7 and 12%.

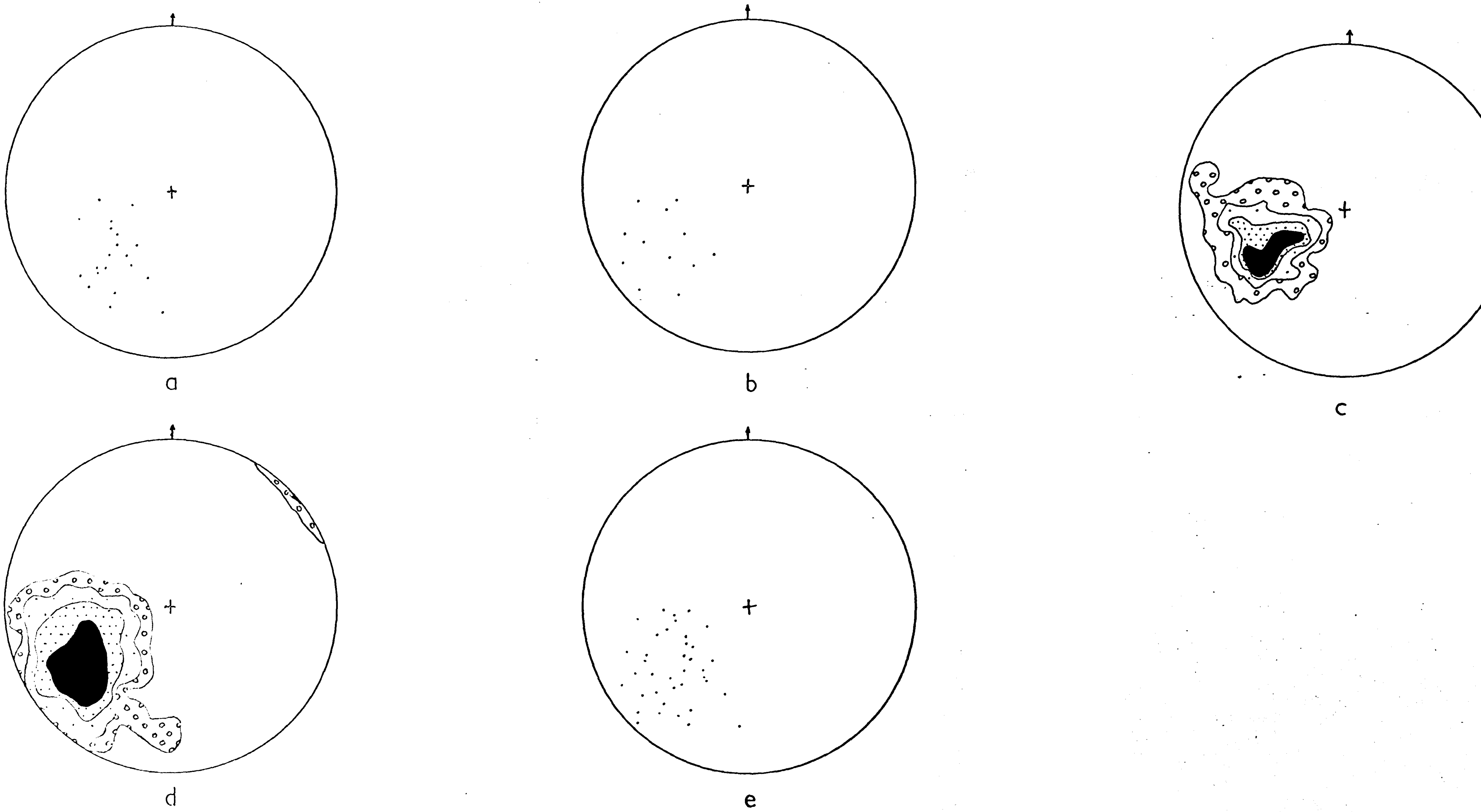

a
b
c
d
e

Fig.III-3. The variable dyke relationships to pre-dyke structures in the gneisses.

(a) (d) dykes cutting F_4 folds (Domain 1).

(b) dyke cutting S_3, with S_7 parallel in dyke and parallel to margin (Domain 1).

(c) dyke intruded parallel to S_4, S_7 in dyke is parallel to S_4.

(e) dyke cutting F_5 fold, although in part concordant to S_4. S_7 parallel to dyke margin (Domain 3).

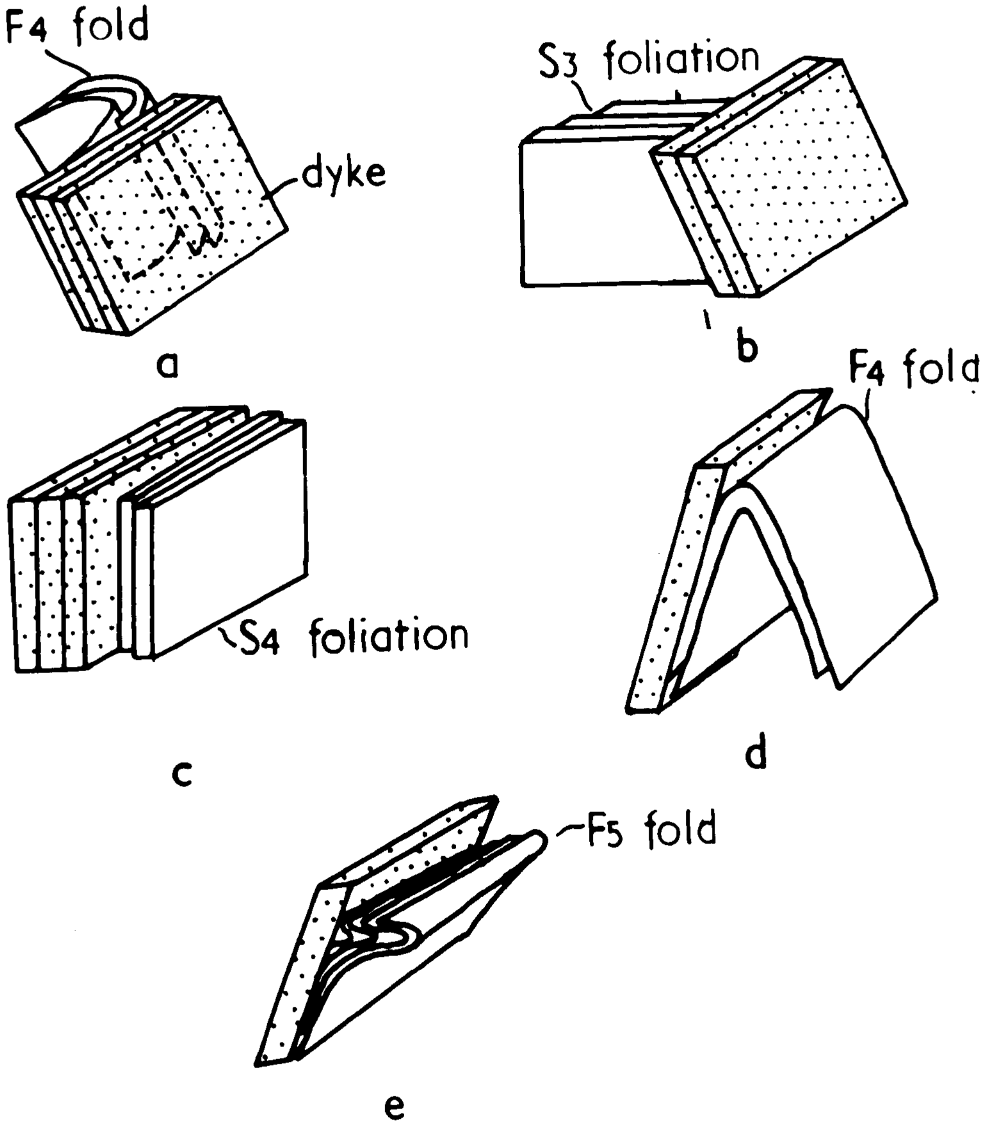
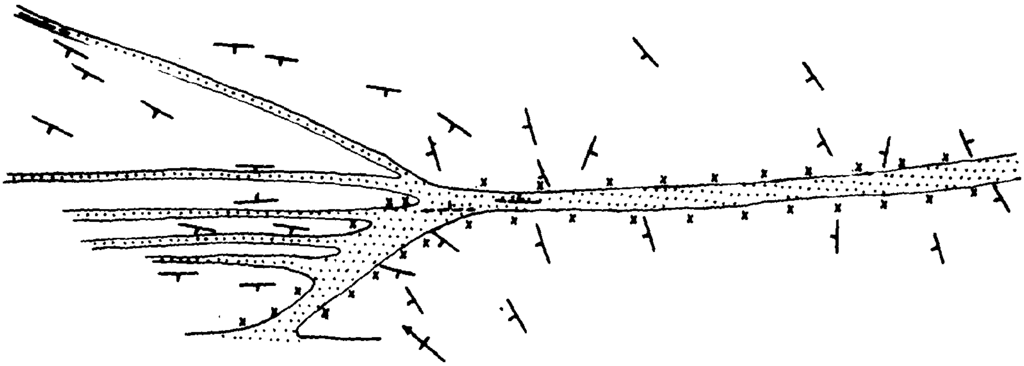

F4 fold
dyke
a
S3 foliation
b
F4 fold
S4 foliation
c
d
F5 fold
e

Fig.III-4. Two type-TD basite dykes exhibiting variable structural relationships to the adjacent acid gneisses and demonstrating the control of the pre-dyke structures on their form.



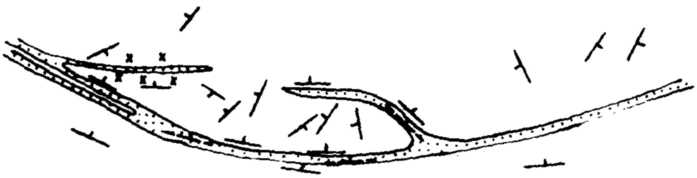
a Dyke A2, domain A.

— S3&4 foliations

---- S7 foliation

x Discordant dyke margin

1/4 mile



b Dyke Di, domain D.

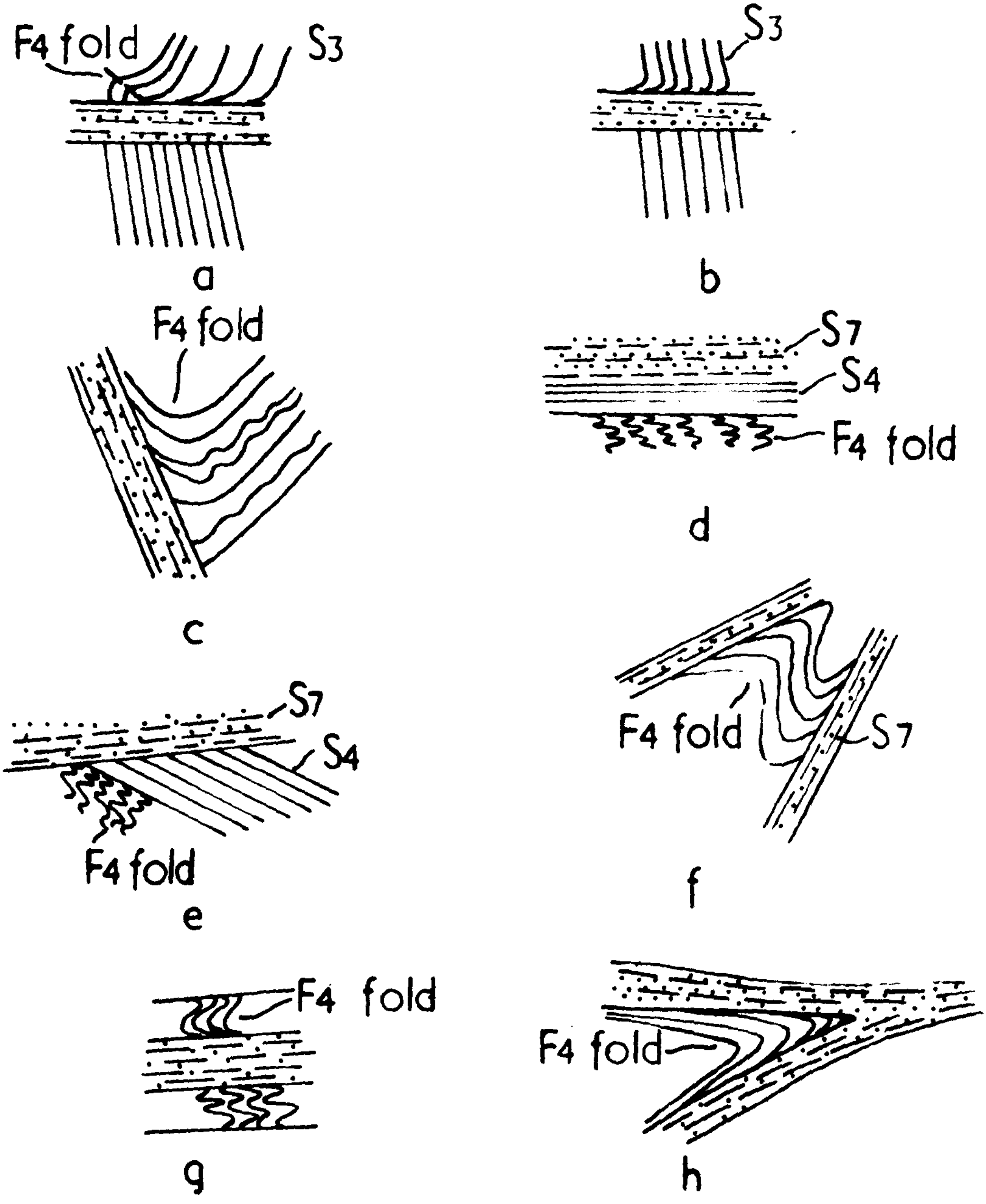
Fig.III-5. Relationship between F_4 folds, S_3 and S_4 foliations and the dykes.

(a) (b) (c) (f) (g) (h) dykes intruded at sites of F_4 folds.

(d) dyke intruded concordant to S_4.

(e) dyke intruded discordant to S_4 (S_4 and S_7 are co-planar).

In all cases, S_7 is parallel to dyke margins.



F4 fold
S3
a
S3
b
F4 fold
c
S7
S4
F4 fold
d
S7
S4
F4 fold
e
F4 fold
S7
f
F4 fold
g
F4 fold
h

Table III-I. Distribution of characteristics in the dyke swarm. The subdivision of the area into four domains, which have distinct dyke characteristics, has been based upon the distribution of the various pre-dyke structures in the complex. Thus in areas where the S_4 foliation is the predominant structure (as in domains B and D) the dykes are numerous, nearly always concordant, rarely interconnected and bifurcating, relatively thin and uniformally distributed. In areas where the predominant pre-dyke structure is S_3 (as in domains A and C) the dykes are less frequent, discordant, often interconnected and bifurcating, thick and irregularly distributed.

CHARACTER	DOMAIN A	DOMAIN B	DOMAIN C	DOMAIN D
MESOSCOPICALLY CONCORDANT	Rare	Common	Common	Common
MESOSCOPICALLY DISCORDANT (see Fig.2e)	Common	Rare	Common	Rare
MACROSCOPICALLY CONCORDANT	Rare	Common	Common	Common
MACROSCOPICALLY DISCORDANT	Common	Rare	Common	Absent
INTERCONNECTED -BIRFURCATED	Common	Uncommon	Common	Uncommon
THICKNESS (m.) maximum	100	20	40	20
THICKNESS (m.) minimum	30	10	20	10
DEGREE OF DEFORMATION	characteristically undeformed where concordant generally schistose	characteristically deformed. Undeformed centres common	characteristically deformed even when markedly discordant undeformed centres	All deformed Rarely find undeformed centres
SEPARATION (metres)	100-200	generally less than 50 metres	Up to 500 metres	10-30
AREAL DENSITY	Uniform	Uniform	Irregular	Uniform
DYKE TYPE	Type-TD basites	Type-TD basites	Type-TD basites Type-TB basites Ultrabasites	Type-TD basites Type-TB basites Ultrabasites
STRIKE AND DIP	NW-SE steep NE	NW-SE steep to moderate NE	NW-SE moderate NE	NW-SE and E-W steep to gentle
MULTIPLE OR COMPOSITE	Multiple found	Multiple found	Composite	Composite

Table III-1. Distribution of characteristics among the dyke swarm.

also reflected in the distribution of the pre-dyke structures of the area.

In domain A the predominant structure is a NE-SW to E-W-striking S_3 foliation which is cut by the dykes, whereas in domain B the predominant structure is a NW-SE-striking, moderately steep-dipping, S_4 foliation, the dykes being emplaced concordant to this foliation. Domain C has similar characteristics to both domains A and B in that both S_3 and S_4 foliations are present, the latter being predominant. The differences, however, appear to arise from the variable attitude of the S_4 foliation, which is moderately steep dipping in the north but becomes shallower southwards such that it is horizontal in the southern extremes of the domain. A further pre-dyke deformation episode D_5 is also found in the south of the domain which produces asymmetric fold belts, the dykes being intruded parallel to the fold steep limbs. Furthermore, in belts of horizontal S_4 foliation the dykes are sharply discordant to this foliation.

Domain D is very similar to domain B in that the foliation almost totally belongs to the D_4 deformation episode. It differs, however, because the S_4 foliation attitude varies from steep to shallow dipping in the south of domain D whereas in domain B the variation in attitude is not so pronounced.

The pre-dyke structural variations, which have given rise to the domain sub-division of the dykes, have also produced other variations in the dykes. Where dykes are sharply discordant to the foliation in the associated gneisses (generally S_3 foliated) the dykes are considerably thicker than those which are concordant with the associated gneissose foliation. Bifurcating dykes are also found where foliations are sharply discordant to the general trends of the dyke. The separation of the dykes is also related to the structural environment in which they are found. Thus in belts of discordantly foliated gneisses the dykes have greater separation than those occurring in areas of concordantly foliated gneisses.

As well as the pre-dyke structures being responsible for the primary features of the dykes, they also appear to control the degree of post-dyke deformation in the dykes. For instance, where the associated gneissic foliation is related to the D_4 deformation the dykes are invariably more deformed than those which have been intruded discordantly to the foliation in the gneisses (generally the S_3 foliation).

The conclusions which may be drawn from field evidence is that the present characteristics displayed by the dykes have been controlled by the pre-dyke structure of the complex.

2. Igneous and metamorphic petrology

All the members of the dyke swarm appear to have been affected by three deformational and metamorphic episodes. These fold episodes D_6, D_7 and D_8 and associated metamorphisms M_6, M_7 and post-D_8 metamorphism and alkali-metasomatism have retrogressed the initial mineralogy of the dykes and none have remained unaffected.

However, the dykes have been affected to varying degrees by these subsequent metamorphisms in such a way that the individual events can be analysed.

The type-TD basites are classified into:

(a) Type-TD basites with sub-ophitic texture

- (i) The least altered type-TD basites.
- (ii) Type-TD basites in which pyroxenes are replaced by hornblende, and garnet is developed.
- (iii) Type-TD basites in which garnet has disappeared, pyroxenes have been completely replaced by hornblende and sphene formed around ilmenite.
- (iv) Type-TD basites in which lath-like plagioclase has been recrystallized into polygonal grains.

(b) Development of schistose type-TD basites

- (i) Type-TD basites in which mafic and felsic aggregates are drawn out into plane of the foliation.

(ii) Type-TD basites which have been converted into finely-foliated hornblende schists.

(iii) Type-TD basites with microcline.

(iv) Type-TD basites with a retrogressed mineral assemblage.

(a) Type-TD basites with sub-ophitic texture

The least altered type-TD basites

No dyke swarm has been found which does not register the effects of at least one of the metamorphic episodes, the least altered showing some effects of the M_7 metamorphism. The initial state of the type-TD basites can be assessed by subtracting the effect of metamorphism and deformation.

The least altered type-TD basite is found in the centres of dykes found in domains B and C. They have a well developed sub-ophitic texture and consist of orthopyroxene, clinopyroxene, ilmenite, biotite, amphibole, quartz, apatite, plagioclase and alkali-feldspar. Much, if not all of the amphibole has a metamorphic origin. The type-TD basites show varying amounts of mafic and felsic constituents, the mafic minerals forming 30% in the leucocratic basites (see Plate III-6a) to between 60% and 70% in the normal type-TD basites.

The ophitic texture is defined by mafic areas consisting of large, irregular pyroxene grains interpenetrated by lath-like plagioclase.

Clinopyroxene forms up to 35% of the least altered type-TD basites although much of it has been uralitized and never reveals the original crystal habit. It commonly has simple twins (010) and rarely multiple twins with fine exsolution lamellae developed parallel to 001, the combination of the latter two producing "herringbone" structure in some of the clinopyroxene grains. It is generally clouded with grains of minute unidentifiable material, a feature which has been noted amongst many Pre-Cambrian metamorphosed dolerites (Poldervaart 1954). The clinopyroxene is a non-pleochroic colourless variety with 2V(+)=49.

Orthopyroxene is only rarely found, and never exceeds 5% of the least altered dykes. It has an irregular habit as a result of partial uralitization (see Plate III-6b). The pleochroic scheme is x - colourless, y - pale brown, z - brown with a 2V(-)=50 (measured on two grains). Small granules of magnetite occur along the cleavage traces and the surfaces between orthopyroxene and amphibole.

Ilmenite is only found in the mafic areas and forms large, irregular skeletal growths up to 0·7 mm. It may form up to 7% of the type-TD basites with an average of 5%.

Biotite forms up to 7% of the rock with a mean of 3% and occurs as a sheath around skeletal ilmenite. It consists of interlocking subhedral flakes with the pleochroic scheme x - straw, y - brown, z - deep brown, The biotite sheath is rarely more than 2 mm. thick, with individual flakes up to 1·0 mm. in length.

Plagioclase forms 25% to 70% of the rocks and occupies the majority of the felsic areas. It forms euhedral to subhedral laths which are often arranged as interlocking aggregates (see Plate III-7a). In the centres of the plagioclase laths are many minute rod- or speck-like inclusions which produced clouding in the feldspar. However, the margins of the laths are clear and free of such inclusions. Albite, combined albite-pericline and baveno twinning are developed in the plagioclase laths, revealing the zonal habit of the feldspar with a core of An_{33-57} and mantle of An_{24-38}. Laths range up to 2·5 mm. in length with a mean of 1·5 mm.

Quartz either occurs as angular anhedra or as a graphic intergrowth with an alkali feldspar in the interstices between the plagioclase laths (see Plate III-7b). It forms up to 7% of the type-TD basites with a mean of 5%, with grains ranging up to 0·6 mm. in size.

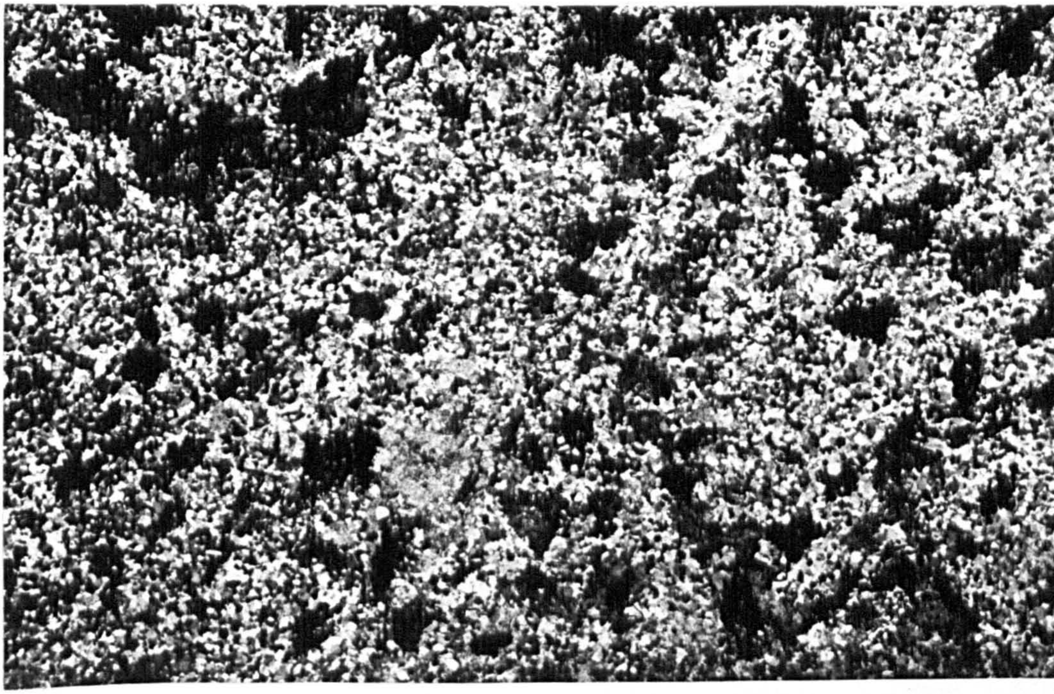
Apatite occurs in accessory quantities and forms long slender lath-like euhedra developed in the felsic areas, often as inclusions of plagioclase.

(ii) Type-TD basites in which pyroxenes are replaced by hornblende and garnet is developed

The sub-ophitic texture of the type-TD basites is still preserved and shows no sign of deformation.

Plate III-6a. Leucocratic type-TD basite (x10) (Domain B; 82626054).

Plate III-6b. Relict hypersthene (hy) with mantle of hornblende (ho) and garnet (gr). Plagioclase (pl) has relict igneous lath-like habit. Undeformed centre of type-TD basite dyke (x100) (Domain C; 82515942).



pl
gr
ho

Plate III-7a. Undeformed centre of type-TD basite dyke with an ophitic texture indicated by the lath-like habit of plagioclase (x25) (Domain C; 82515942).

Plate III-7b. Alkali-feldspar-quartz intergrowth occurring in the mesostasis of plagioclase laths (x100).

The original igneous pyroxenes, lath-like plagioclase and quartz-alkali feldspar intergrowths are still retained, but the pyroxenes are increasingly affected by uralitization.

Garnet forms distinct idioblastic dodecahedra (see Plate III-8a) which are disposed about the periphery of the mafic areas, separating the amphibole from the felsic components of the type-TD basite. The margins of the plagioclase laths associated with the garnet are clear. Garnet is generally only developed where ilmenite is located in the mafic areas. It may form up to 15% of the type-TD basites with a mean grain size of 0·4 mm.

Amphibole is found at the periphery of the mafic areas and is a result of the uralitization of the pyroxenes. In the completely uralitized pyroxenes, the hornblende matt consists of a large central grain which has pseudomorphed the form of the pyroxenes and has inclusions of quartz and plagioclase. This central grain is surrounded at the margin by more discrete subidioblastic laths and prisms of hornblende.

The pleochroic scheme exhibited by the amphibole varies from X - straw, Y - pale green, Z - pale blue-green at the centre of the matt to X - straw, Y - green, Z - blue-green at the border. The uralitization process affecting the pyroxene can be observed at the interface between it and the peripheral hornblende. The junction between the two minerals is very irregular and jagged with veinlets of hornblende projecting from the peripheral matt of hornblende along the cleavage and fractures in the pyroxenes. The boundary between the hornblende and pyroxene is often occupied by minute magnetite granules which are probably formed by exsolution from the uralitized pyroxene.

In some type-TD basites the mafic matt of hornblende has been completely recrystallized into subidioblastic hornblende laths and prisms.

The relict orthopyroxene of one type-TD basite has been replaced by biotite with the pleochroic scheme X - pale green, Y=Z - green.

Garnet appears to have developed before the uralitization of the igneous pyroxenes since it does not vary in amount from type-TD basites with abundant pyroxenes to those in which the pyroxenes have been completely replaced by hornblende. This may indicate that garnet prefers to develop in an anhydrous environment, followed by hydrous conditions which induced the uralitization of pyroxene.

The development of hornblende and garnet by partial replacement of the original igneous minerals in the type-TD basites has resulted in the development of reaction rims which appear to have formed by re-adjustment of the igneous paragenesis to metamorphism, the nature of the rims indicating that the mineral assemblage had not reached equilibrium. The minerals found in the reaction rims are pyroxenes, ilmenite, biotite, hornblende, garnet and plagioclase.

The following reaction rims occur (block capitals indicate igneous phases).

(i) ILMENITE-BIOTITE-PYROXENE-garnet-PLAGIOCLASE

(ii) ILMENITE-garnet-PLAGIOCLASE

(iii) ILMENITE-BIOTITE-PYROXENE-hornblende-garnet-PLAGIOCLASE

(iv) ILMENITE-BIOTITE-hornblende-garnet-PLAGIOCLASE

(v) ILMENITE-BIOTITE-garnet-PLAGIOCLASE

(vi) ILMENITE-hornblende-garnet-PLAGIOCLASE

(vii) PYROXENE-hornblende-PLAGIOCLASE

(viii) ILMENITE-hornblende-PLAGIOCLASE

(ix) ILMENITE-BIOTITE-hornblende-PLAGIOCLASE

It was stated in section IIB(a)(2) that garnet develops in close proximity to ilmenite suggesting that it is an iron-rich variety such as almandine. Where ilmenite is found at the margins of the mafic areas type (ii), (v) reaction rims occur. Assemblages (iii), (iv), and (vi), are found where ilmenite is centrally placed in the mafic areas.

The reaction rims in the type-TD basites are in many ways similar to coronite structures found in basites which have undergone a granulite-facies metamorphism (Murthy 1958, Buddington 1962, Reynolds and Frederickson 1962). They differ in that relict igneous minerals form part of the reaction rims and in this respect are similar to the metamorphic effects on epidiorites discussed by Rast (1958).

(iii) Pyroxene and garnet completely replaced by hornblende and sphene developing around ilmenites.

The type-TD basites of this group still have their sub-ophitic texture preserved. Chilled margins of the least metamorphosed dykes show this stage of metamorphism.

They are distinguished by the lack of pyroxenes and garnet and by the development of sphene.

Hornblende forms 35% to 75% of these type-TD basites with a mean of 55%. The mafic matts which were formerly occupied by pyroxenes are represented by aggregates of hornblende grains which show differing habits depending upon their situation in the mafic areas. At the centre of the aggregates large xenoblasts of hornblende are found which have pseudomorphed the original form of the pyroxenes, often preserving the simple and multiple twins exhibited by the original pyroxenes.

At the periphery of the large xenoblastic grains is a zone of subidioblastic laths and prisms of hornblende (see Plate III-8b) which radiate out from the matt occasionally penetrating the felsic areas. The laths and prisms of hornblende have a mean grain size of 0·2 mm. The outer hornblende zone has the pleochroic scheme x - straw, y - green, z - bluish green or olive green whereas the central grains show slightly paler pleochroic scheme colours.

Ilmenite is developed in the mafic matts and forms skeletal shaped grains which have a sheath of biotite. The association differs from that of group a(2) in the development of a thin veneer of sphene (see Plate II-9a), at the interface between biotite and ilmenite or about the latter irrespective of whether biotite is present.

Plagioclase forms 25% to 60% of these basites and retains the subhedral lath-like habit and clouded nature which was common in the least altered dykes.

Plate III-8a. Undeformed centre of type-TD basite dyke with relict ophitic texture. Pyroxenes completely replaced by hornblende with ilmenite forming nuclei of mafic areas. Idioblastic garnets form a rim around mafic minerals, separating them from plagioclase (x25) (Domain D).

Plate III-8b. Undeformed type-TD basite dyke with hornblende pseudomorphs of pyroxenes. The mafic areas consist of a central hornblende grain with poikiloblastic inclusions of quartz and plagioclase, surrounded by inclusion-free zone of subidioblastic grains of hornblende (x25) (Domain B; 83196054).

Some of the type-TD basites are cut by thin irregular veins of amphibole (see Plate III-9b) and polygonal grains of plagioclase (An_{27}).

(iv) Type-TD basites in which lathlike plagioclase has been recrystallized into polygonal grains.

The type-TD basites belonging to this group are found throughout the area and occur in undeformed centres of dykes in domain D. The segregation into mafic- and felsic-rich areas, a reflection of the initial sub-ophitic texture, is still preserved, but the lath-like habit of the plagioclase has been destroyed.

Hornblende forms 50% to 70% of the rocks and occupies the majority of the mafic areas. It retains many of the characteristics of the hornblende of the previous group, forming a matt consisting of a central poikiloblastic xenoblastic grain surrounded by small, discrete, subidioblastic laths and prisms. In many of these basites the central poikiloblastic grain has been recrystallized into a mozaic of very small (0·05 mm.) interlocking, subidioblastic grains which have the pleochroic scheme x - straw, y - green, z - bluish green or olive green.

In the large basite dyke (A1) at An Ruadh Mheallan an unusual texture is developed consisting of an array of large interlocking subidioblastic laths of hornblende which have poikiloblastic inclusions of plagioclase (see Plate II-10a). The usual association of biotite with mafic components is not found in this example, the biotite occurring at grain boundaries in the feldspathic rich areas.

Iron ore is concentrated in the mafic matts and consists of either ilmenite or magnetite, the former having a mantle of sphene and biotite whereas the latter sometimes has a mantle of epidote. The mantle of sphene about skeletal ilmenite is much broader than in the previous groups, hematite occasionally being found in this association. The occurrence of xenoblasts of calcite in the mafic matts has been recorded.

Plagioclase forms 30% to 40% of the rocks and occupies the majority of the felsic areas. It differs from the original lath-like plagioclase in two ways:-

(i) It forms equidimensional polygonal grains with a grain size range of 0·1 to 0·4 mm. replacing the original lath-like plagioclase.

(ii) It differs in composition from the original igneous plagioclase in having reverse zoning (see Plate III-10b). In Fig.III-6 the composition of the core has been plotted against that of the mantle for individual grains, and the linear scatter of points illustrates that the composition of the mantle is directly related to that of the core.

Quartz forms up to 7% of the rocks and occurs either as recrystallized equant xenoblasts in the felsic areas or as inclusions in hornblende. Grains range up to 0·4 mm. with an average grain size of 0·2 mm.

Apatite occurs in felsic areas and has been recrystallized into small (0·1 mm.) subidioblastic grains.

(b) Schistose type-TD basites

The change in fabric from a relict sub-ophitic texture to a basite with a schistose structure distinguished these from stage (a) dykes. There are no new mineral phases associated with the formation of the schistosity.

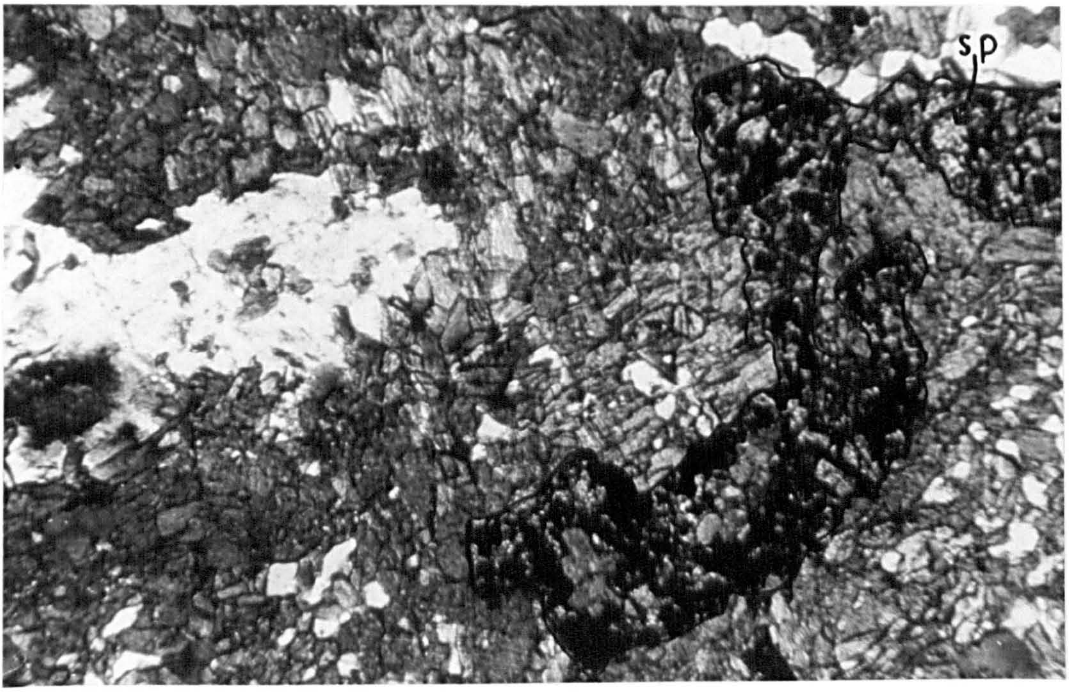
(i). Type-TD basites with mafic and felsic aggregates drawn into the plane of the foliation

The type-TD basites of this group occur throughout the area but are more widely developed in the south. They still retain the aggregation into felsic and mafic components inherited from the initial sub-ophitic texture.

In the plane of the new foliation there is a lineation produced by the alignment of hornblende and biotite crystals and by the drawing out of felsic aggregates into lenticular shapes whose longest dimensions are statistically aligned.

Plate III-9a. Type-TD basite with hornblendes recrystallized into equidimensional idioblastic to subidioblastic grains. Skeletal ilmenite is surrounded by a rim of sphene (sp) (x25) (Domain C).

Plate III-9b. Type-TB basite with amphibolite mineral assemblage, cut by a vein of oriented hornblende laths (x25) (Domain A; 82896169).


s,p

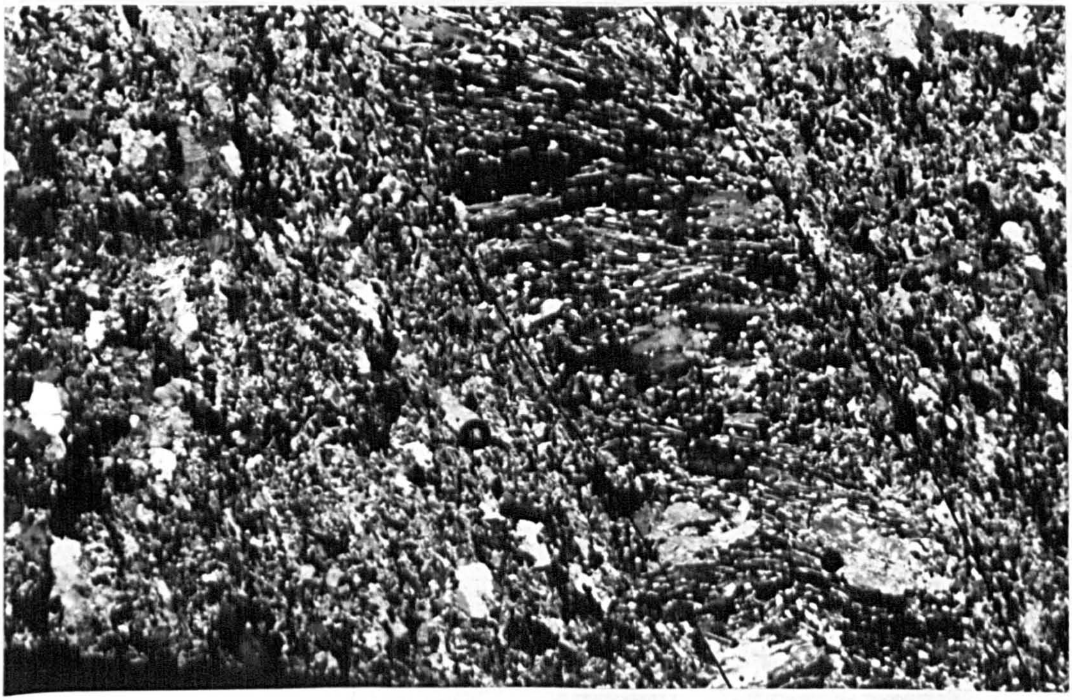
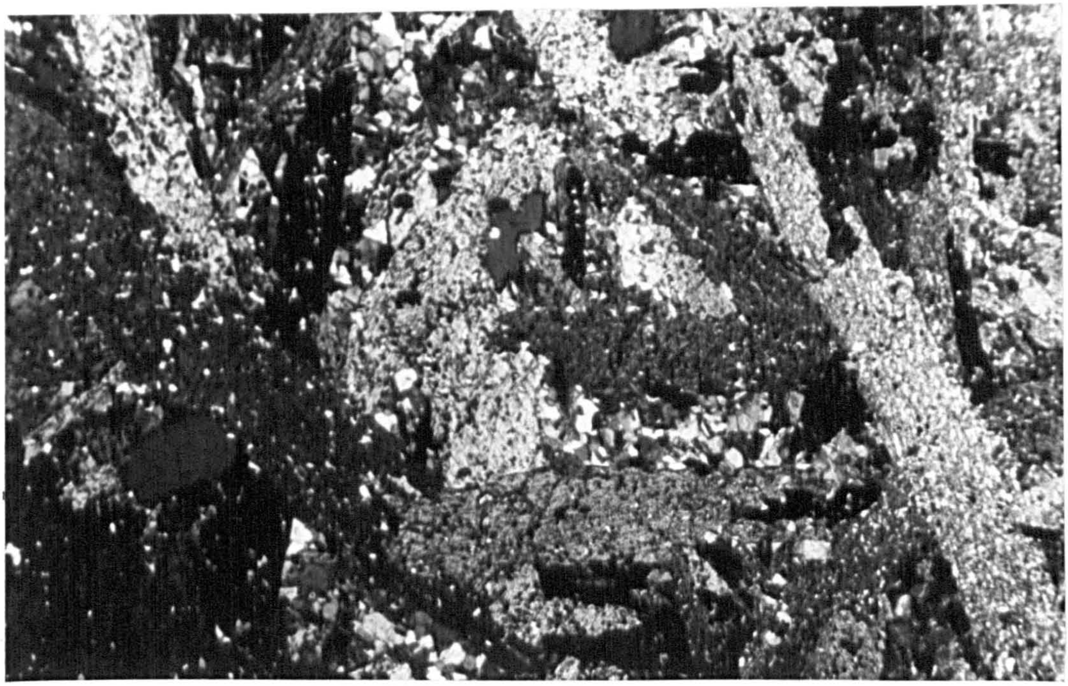


Plate III-10a. Interlocking hornblende laths with poikiloblastic inclusions of plagioclase in a type-TD basite (x25) (Domain A; 82626149).

Plate III-10b. Recrystallized polygonal-shaped grains of plagioclase with reverse-zoning in a type-TD basite. The mantle (Ma) and core (Co) of the zoned plagioclase are shown (x100) (Domain D).



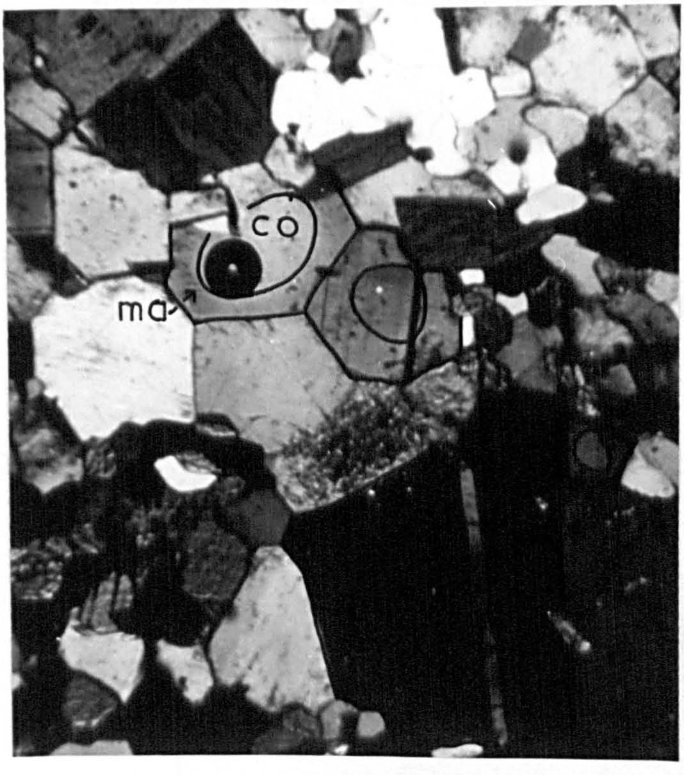
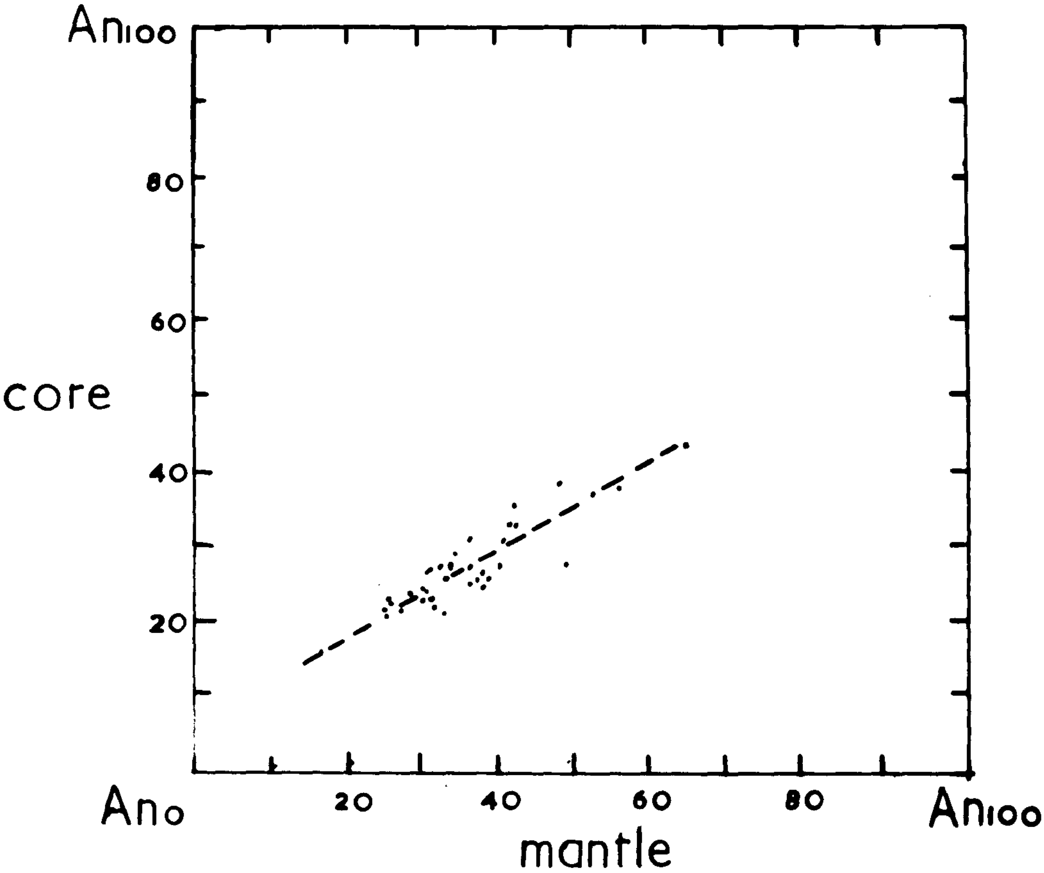

co
ma

Fig.III-6. The composition of core and mantle in plagioclases of M_7 recrystallized type-TD basites.



An100
80
60
core
40
20
An0
20
40
60
80
An100
mantle

The lineations are parallel to axes of folds which have a well developed penetrative axial-planar foliation. Hornblende forms 50% to 60% of the rock and has been recrystallized into aggregates of interlocking, subidioblastic laths and prisms which have the pleochroic scheme x - straw, y - green, z - bluish green or olive green. Some of the hornblende grains have taken up a unique orientation parallel to the foliation, whereas other grains are randomly oriented. Grains range up to 0·5 mm. with an average grain size of 0·3 mm.

In an epidote-rich type-TD basite the associated hornblende has been bleached of its pleochroic colours, probably as a result of leaching of iron by epidote.

Biotite forms up to 5% of the rocks and has subidioblastic to xenoblastic lath-like form with the pleochroic scheme x - straw, y - brown, z - deep brown. It appears to have been separated from its initial association with sphene and ilmenite.

Ilmenite, sphene and magnetite show no notable variation from group (a) type-TD basites except for further replacement of ilmenite by sphene.

Plagioclase forms 25% to 40% of the rocks and occurs as flattened lenticular aggregates drawn out in the plane of the foliation. It forms a mozaic of equidimensional polygonal grains which often show slight turbidity at the centre of the grains as a result of development of sericite and brown unidentifiable dust. Grains range up to 0·4 mm. with a mean grain size of 0·3 mm.

(ii) Type-TD basites converted into finely-foliated hornblende schists.

Basites which have been converted to foliated hornblende schists are found over the whole area, but particularly in domains B and D.

The hornblende schists differ from the type-TD basites of the previous group in the mode of formation of hornblende which forms a nematoblastic fabric in these rocks (see Plate III-11a). The felsic aggregates have been drawn out into thin discontinuous laminae and sphene granules are drawn into trails parallel to the foliation.

Hornblende forms subidioblastic laths and prisms which are aligned in the plane of the foliation. It has the pleochroic scheme x - straw, y - green, z - bluish green or olive green with a mean grain size of 0·4 mm.

Biotite forms subidioblastic flakes which are aligned parallel to the foliation. Grains range up to 0·5 mm. with a mean grain size of 0·3 mm.

Plagioclase occurs in thin discontinuous laminae one to two grains thick parallel to the foliation. It forms equidimensional polygonal xenoblasts twinned on either albite or combined albite-pericline laws, with distinct zoning with a core, An_{21-33} and mantle An_{24-37}. Unzoned grains of plagioclase fall in the range oligoclase to andesine An_{24-37}.

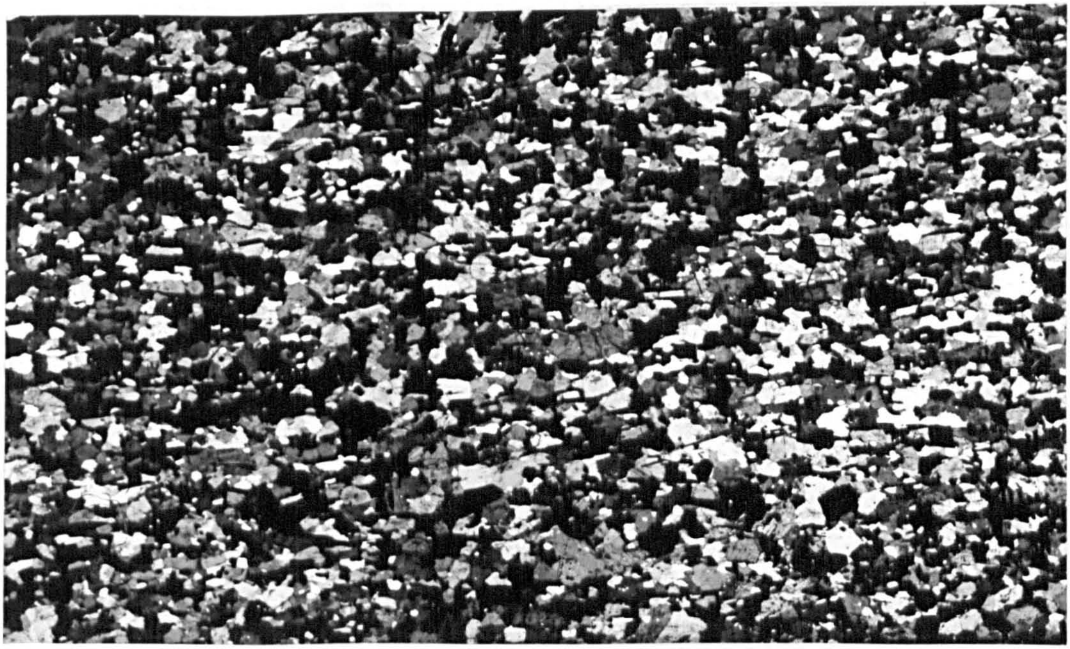
In domain B, particularly north of Loch nan Tri-eileanan, hornblende schists with garnets are developed. The garnet forms large, rounded xenoblastic grains many of which are partly or wholly retrogressed. The garnets are also flattened in the plane of the foliation, indicating that they were developed prior to the flattening phase (see Plate III-11b). The retrogression which affects the garnet has led to the formation of aggregates of biotite, amphibole and epidote. The amphibole which is associated with the garnets has also undergone changes as a result of retrogression. The original hornblende is the variety with pleochroism x - straw, y - green, z - bluish green or olive green but has exsolution lamellae developed parallel to (001). The lamellae are fine although occasionally broad such that a second colourless amphibole occurs in patches enclosed in the hornblende.

(iii) Type-TD basites with microcline.

Type-TD basites which have undergone metasomatic changes are very uncommon and are either found adjacent to potash-rich pegmatites or in belts which have reacted to the D_8 fold episode. The metasomatised dykes are only found in domain D and have the mineral assemblage and fabric of the previous sub-group, but differ in the nature of the feldspar component of the rock.

Plate III-11a. Foliated type-TD basite with S_7 indicated by the nematoblastic fabric of the basite (x10) (Domain D).

Plate III-11b. Type-TD basite with M_7-retrogressed spheroidal-shaped garnets which have been flattened in the plane of the S_7 foliation (x10), (Domain D).



Plagioclase forms 10% to 25% of the rock depending on the intensity of microclinitisation, and shows irregular xenoblastic form.

Microcline has formed by replacement of plagioclase, the latter becoming irregular in form with increasing microcline development. The onset of microclinitisation is marked by the formation of blades or veinlets of the potash feldspar within plagioclase grains, either oriented parallel to 010 or 001 in the host grain. In some cases the blades or veinlets are not oriented in any crystallographic direction in the plagioclase. Further replacement of plagioclase results in coalescence of the penetrating elements into individual xenoblastic grains; the process may continue until all the plagioclase has been made over to microcline. The development of myrmekite and clear albite rims in the plagioclase (see Plate III-12a) appears to be coeval with microclinisation.

The individual microcline grains are xenoblastic with grid twinning commonly developed. Many of the microcline grains are perthites with flames of exsolved albite developed which generally coalesce at the microcline margin. Microcline may form up to 35% of the type-TD basites, the exsolved albite component of microcline may form up to 50% of the host grain.

In type-TD basites which have a large amount of microcline developed, hornblende and chloritized biotite have also registered changes in accordance with the environment. Hornblende is partially altered to chlorite with hematite and magnetite developed along cracks and cleavage in the grain, whereas chloritized biotite is often replaced and pseudomorphed by quartz (see Plate III-12b).

(iv) Type-TD basites with a retrogressed mineral assemblage.

The retrogression of biotite to chlorite in the basites is registered in all the previously discussed dykes to varying degrees. The retrogression of hornblende, however, is very rare and is accompanied by the development of a chlorite-epidote assemblage (see Plate III-13a).

Plate III-12a. Metasomatized type-TD basite with microcline (mi) replacing plagioclase (pl) and with the formation of myrme kite (x100) (Domain D; 80925879).

Plate III-12b. Intensely microclinized type-TD basite with quartz (qu) replacing chlorite flakes (x100) (Domain D; 80925879).


pl
mi


qu
pl
mi

3. The multiple type-TD basites

Three multiple type-TD basite dykes have been found, occurring:-

(i) at the north-east extremity of dyke A4.

(ii) in parts of dyke A11.

(iii) in parts of dyke B6.

The form of the multiple dykes indicates that there has been at least two separate intrusions of magma. The earlier type-TD basite intrusion has chilled margins against the host acid gneisses with a coarse ophitic texture in the centre. This is followed by further intrusion of magma parallel to the course of the dykes and in their centres. The second intrusion of type-TD basite has chilled margins against the earlier intrusion (see Plate III-13b), and is much finer-grained. The contact between the intrusions is very sharp and is often represented by a thin band of hornblende-schist.

C. The Ultrabasite and Type-TB Basites

The ultrabasite and type-TB basite dykes form a minor proportion of the dyke swarm and occupy narrow depressed tracts of ground, rarely having exposed contacts with the host acid gneiss.

Four separate dykes have been found, two of which reveal a clear relationship to the type-TD basites:-

(a) An ultrabasite 150 metres east of Loch na Beiste.

(b) An ultrabasite adjacent to Loch a'Mullach and extending south-east of Loch na Leirg.

(c) An ultrabasite-basite composite dyke 400 metres east-south-east of Loch a'Bhealaich Mhoir.

(d) An ultrabasite-type-TB basite composite dyke at the summit of Meall Ceann na Creige.

These dykes cannot be traced for large distances parallel to their strike and never exceed 25 metres in thickness.

In hand specimen, the ultrabasite and basites are easily distinguished from the type-TD basites; the latter are black whereas the

Plate III-13a. Type-TD basite dyke with the mineral assemblage epidote (ep)-chlorite (chl)-plagioclase (pl)-quartz produced in the post-D_8 retrogressive metamorphism (x25) (Domain D; 83156000).

Plate III-13b. Type-TD multiple basite dyke. (Domain B; 83186012).


pl
chl
ep

former has an olive-green colour. The ultrabasites and basites are either massive or have a well defined schistosity.

1. Petrology

(a) The ultrabasite 150 metres east of Loch na Beiste

This ultrabasite has been intruded parallel to the steep limb of an F_5 asymmetric fold and dips moderately NE. It varies in thickness from 5 to 10 metres being concordant to the foliation in the associated acid gneisses where the margins are exposed. There is an increase in grain size from the margin to the centre.

The rock contains amphibole, chlorite, biotite and iron ore.

Amphibole forms 85% at the centre to 95% at the margin of the ultrabasite, and forms a matt of inequigranular idioblastic to xenoblastic grains. At the margin the amphibole has the pleochroic scheme x - straw, y - pale green, z - pale bluish green and at the centre these colours are slightly deeper. The grain size of the amphibole varies from 0·05-1·0 mm. at the margin to 0·1-2·5 mm. at the centre of the dyke.

Biotite is absent from the margin of the dyke, but forms 4% of the ultrabasite centre. It forms small subidioblastic flakes with pleochroic scheme x - pale green, y = z - green, the flakes being clouded with minute granules of magnetite. Grains range up to 0·6 mm. in the centre of the dyke.

Chlorite is associated with biotite and appears to be stable with the latter, forming 7% of the ultrabasite centre. At the margin the pleochroic scheme exhibited by chlorite is x - colourless, y=z - pale green, whereas at the centre it is x - colourless, y=z - green. Multiple twins with (001) twin plane (see Plate III-14a) are well developed in the chlorite flakes. The grain size of the chlorite varies from a maximum of 1·2 mm. at the margins to 2·5 mm. at the centre of the dyke.

Iron ore forms small distinct xenoblastic granules forming 5% of the rock.

(b) <u>The ultrabasite dyke adjacent to Loch a'Mullach and extending south-east to Loch na Leirg</u>

This ultrabasite dyke resembles the above body in the form and properties exhibited by the amphibole. It has a penetrative S_6 foliation which has been folded by F_7 folds, and partly transposed by the S_7 foliation.

(c) <u>The ultrabasite, type-TB basite composite dyke 400 metres east-south-east of Loch a'Bhealaich Mhoir</u>

This dyke can be traced for 30 metres along its strike. The ultrabasite forms an outer carapace to the dyke, and the contact with the basite is very sharp, the ultrabasite chilling against the basite. The basite has feldspathic [redacted] bands which strike approximately parallel to the dyke, the bands never exceeding 10 cm. in thickness (see Plate III-14b).

(i) <u>The ultrabasite</u>

The ultrabasite consists of amphibole, plagioclase, biotite, chlorite and iron ore developed in varying amounts throughout the dyke.

<u>Amphibole</u> makes up more than 95% of the rock forming a matt of interlocking idioblastic to subidioblastic prisms and long slender laths. The amphibole has the pleochroic scheme x - straw, y - pale green, z - pale green. The amphibole appears to be an actinolitic variety with grains ranging up to 2·5 mm.

<u>Biotite</u> is absent at the margins but forms 5% of the centre of the body. It forms subidioblastic flakes with pleochroic scheme x - straw, y=z - green, the grains ranging up to 0·8 mm.

<u>Plagioclase</u> is absent from the margins but may form up to 5% at the centre.

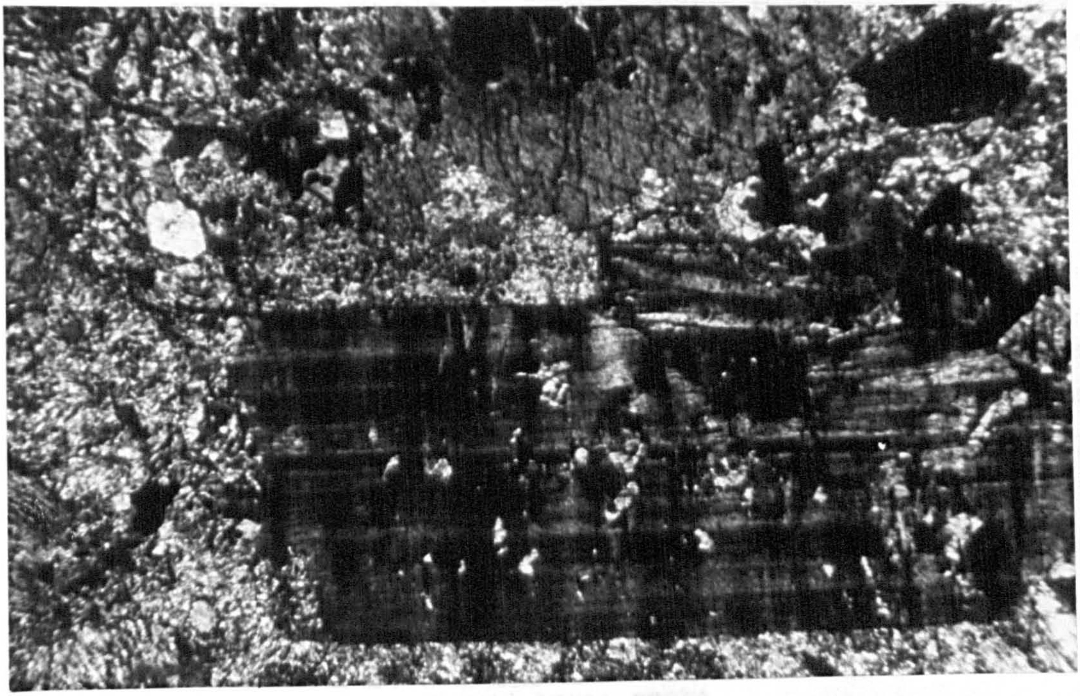
<u>Magnetite</u> occurs in accessory quantities.

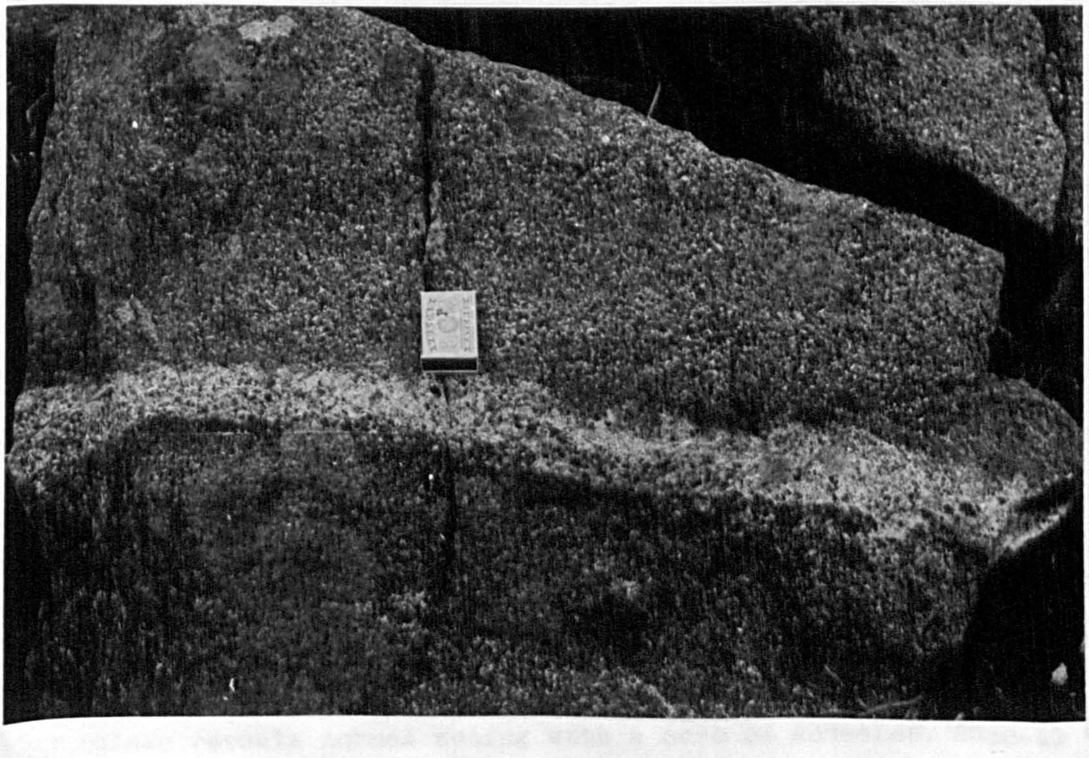
(ii) <u>The basite</u>

The basite consists of amphibole, chlorite, biotite, rutile and plagioclase in varying amounts through the body.

Plate III-14a. Ultrabasite dyke with hornblende-chlorite-iron ore assemblage. Chlorite megacrysts have polysynthetic twinning (x25) (Domain C; 81675846).

Plate III-14b. Centre of type-TB basite with feldspathic band, sub-parallel to the margin of the dyke (Domain D; 80535832).





Amphibole forms 45% to 65% of the basite as aggregates of interlocking grains. The aggregates consist of large slender subidioblastic laths and prisms of amphibole held in a matt of fine interlocking needles of amphibole. At the edges of the mafic matts the amphibole needles and laths penetrate into the felsic aggregates. The amphibole is also developed as inclusions in plagioclase which form slender needle-like grains either parallel to (010) or along pericline twin direction in the plagioclase grain (see Plate III-15a).

The amphibole has the pleochroic scheme x - straw, y - pale green, z - pale olive green and generally has exsolution lamellae parallel to (001) cleavage. These lamellae may either be fine or extremely coarse leading to the formation of patchy areas where a second amphibole is formed (see Plate III-15b), which is colourless and may form 5% to 10% of the total amphibole. Similar occurrences of two co-existing amphiboles, hornblende and cummingtonite have been described by Setsaari (1954) from metamorphosed basic rocks.

Amphibole grains range up to 2·5 mm. in length with an average of 1·0 mm.

Biotite forms 3% to 15% of the rock occurring as interlocking subidioblastic flakes within the mafic matt. Its pleochroic variety x - straw, y=z - yellowish brown being concentrated at the peripheries of the mafic matts. Grains range up to 2·0 mm. with a mean of 1·0 mm.

Chlorite is generally associated with biotite forming up to 5% of the rock. It is a colourless variety with grains varying from 0·5 to 1·0 mm.

Rutile forms small xenoblastic granules in the mafic matts. It may form up to 5% of the rock with an average of 2%. Grains range from 0·05 to 0·3 mm. with a mean size of 0·1 mm.

Plagioclase forms 25% to 55% of the rock with an average of 30%. It forms aggregates of approximately equidimensional xenoblastic grains which have albite and combined albite-pericline twinning. The plagioclase reveals normal zoning with a core of andesine, An_{30-43} and

Plate III-15a. Hornblende needles overgrowing and formed parallel to 010 cleavage in host plagioclase grain. From type-TB basite dyke (x25) (Domain D; 80535833).

Plate III-15b. Host pale blue-green hornblende (ho^{1}) enclosing co-existing patches of colourless hornblende (ho^{11}) which occur parallel to 001 exsolution lamellae. From type-TB basite dyke (x100) (Domain D; 80535833).


ho'
ho"

a mantle of oligoclase-andesine, An_{23-32}.

From the nature of the normal zoning and the relation between amphibole and the feldspar, the plagioclase is believed to be the original igneous phase.

Grains range up to 2·0 mm. with an average size of 0·8 mm.

(d) The ultrabasite-basite composite dyke at Meall ceann na Creige

The composite dyke at Meall ceann na Creige cuts a type-TB basite dyke, itself intruded parallel to the steep limb of an F_5 monoclinal fold. The ultrabasite occurs on the north-east margin of the dyke and has chilled margins against the type-TB basite (see Plate III-16). The basite is coarser-grained than the ultrabasite and has a banding developed approximately parallel to its north-east margin. The banding is cut by the ultrabasite (see Plate III-16) and consists of alternating feldspar and mafic-rich bands, the mafic bands being up to 15 cm. thick whereas the feldspathic bands rarely exceed 1 cm. in thickness. The basite when traced towards its south-west margin loses the banding and becomes gradually more basic until it consists of ultrabasite similar to that found at the north-east margin.

(i) The ultrabasite

The rock consists of amphibole, biotite, chlorite and magnetite. Amphibole forms more than 90% of the rock and occurs as an aggregate of interlocking, xenoblastic grains with the pleochroic scheme x - straw, y=z - pale green.

Biotite forms 8% of the rock and has the pleochroic scheme x - pale green, y=z - green. It is generally associated with pale green pleochroic chlorite which in some instances appears to replace the biotite.

(ii) The basite

The basite contains amphibole, biotite, chlorite, iron ore, rutile, quartz and plagioclase.

Amphibole forms 60% to 75% of the rock. At the north-east margin where the body appears schistose, the amphibole grains are aligned in a

Plate III-16. Type-TB basite-ultrabasite composite dyke showing sharp margin of chilled ultrabasite against basite dyke. Type-TB basite has feldspathic-rich bands sub-parallel to the margins of the dyke (Domain C; 80475973).

preferred orientation parallel to the foliation, forming idioblastic to subidioblastic laths and prisms with the pleochroic scheme x - straw, y - green, z - bluish green. Towards the more basic margin the amphibole changes in form and exhibits the pleochroic scheme x - straw, y - pale green, z - pale bluish green. It forms a matt of unoriented, interlocking, xenoblastic grains which are partly recrystallized into discrete idioblastic to subidioblastic laths and prisms.

Biotite forms 5% of the rock on the north-east margin, increasing to 30% on the more basic south-west margin. It forms subidioblastic flakes with the pleochroic scheme x - pale green, y=z - green. Grains range up to 1·0 mm. with a mean size of 0·5 mm.

Magnetite forms up to 7% of the rock and has xenoblastic form.

Plagioclase forms 35% of the rock on the north-east margin and steadily decreases until it is absent at the south-west margin. It forms aggregates of xenoblastic, polygonal grains in the foliated basite, but in the undeformed part of the dyke it occurs both as original igneous grains and as recrystallized polygonal grains. The original igneous grains are often crowded with inclusions of amphibole, whereas the polygonal grains are free of such inclusions. Polygonal grains range up to 0·3 mm. with a mean size of 0·2 mm., whereas the igneous grains range up to 0·6 mm. with a mean size of 0·4 mm.

D. The effects of polyphase metamorphism on the dykes

The effects of individual metamorphic episodes may be determined by careful analysis of the structures and mineral assemblages of the dykes. Two of the metamorphic episodes, M_6 and M_7 are difficult to separate since both have produced similar mineral assemblages, but garnet was formed in the M_6 metamorphism and retrogressed in the M_7 metamorphism. The M_8 metamorphism is easily distinguished since it retrogresses the pre-existing mineral assemblages.

Type-TD basites which have a schistose nature as a result of the D_6 deformation are best developed in domain B.

1. <u>Type-TD basites transformed into hornblende schist in the D_6 deformation episode</u>

These type-TD basites consist of hornblende, biotite, plagioclase, ilmenite, garnet, sphene, apatite and quartz. They have a well developed foliation, S_6, which is represented by felsic and mafic aggregates drawn out into discontinuous laminae. The schistose nature and mineral assemblage in these basites is similar to that of group (b)2. The transition between ophitic type-TD basites and hornblende schists is generally very rapid (see Plate III-17). The development of garnet in the sub-ophitic metadolerites and the partial uralitization of the pyroxenes (see group (a)(2)) is believed to have resulted from the effects of the M_6 metamorphism, for where garnets occur in schistose type-TD basites they are partly or wholly retrogressed by the M_7 metamorphism.

2. <u>Type-TD basites transformed in the M_7 metamorphism</u>

Garnets and exsolution effects in the hornblende often serve to distinguish the type-TD basites which have been transformed in the M_6 metamorphism from those whose assemblage is wholly or partly formed in the M_7 metamorphism.

3. <u>Type-TD basites retrogressed by the M_8 metamorphism</u>

The M_8 metamorphic effects are easily distinguished from the other metamorphic effects in the dykes. They retrogress the earlier metamorphic assemblage such that hornblende and biotite are replaced by a chlorite-epidote assemblage (see group (b)(4) basites).

E. <u>Geochemistry</u>

Major element analyses of 24 dyke specimens (see Table III-2) were made to determine whether there was any variation in chemistry within individual dykes or within the dyke swarm as a whole, and whether the type-TD basites, type-TB basites and ultrabasites formed part of the same igneous suite or constituted three chemically distinct groups (ie. whether there was one or more primary magmas responsible for the chemical variations in the dyke swarm). 17 analyses of type-TD basites, 5 of

Plate III-17. Type-TD basite dyke showing the relationship between the S_7-foliated and undeformed ophitic basite (Domain B; 83636072).

type-TB basites, 2 of ultrabasite and 1 early basite were made.

1. Variation in chemistry within type-TD basites, type-TB basites and ultrabasites

a. The ultrabasites

Analyses TU.1 and TU.2 (see Table III-2A) represent the centre and margin of the ultrabasite dyke in the vicinity of Loch na Beiste (grid ref.81685842). Chemically they are similar to picrites (see analyses A and B, Table III-2A) being high in magnesium and low in silica. There is very little difference between the dyke centre and margin except that the total alkalis are higher and CaO lower in the centre. The difference in alkalis is reflected by the increased proportion of biotite in the mode of the dyke centre (see analyses TU.1-2, Table III-2A).

b. The type-TB basites

Analyses TB.1-5 (see Table III-2A) are representative samples of type-TB basites. They are chemically distinguished from the ultrabasite dyke by having higher SiO_2 and total alkalis; and low total iron, CaO, P_2O_5 and TiO_2. The average composition of this basite group is given by C, Table III-2A, and corresponds approximately with an average effusive tholeiite recorded by Nockolds (1951).

c. The type-TD basites

Analyses TD.1-17 were chosen to represent the variation in chemistry of the type-TD basites. In Table III-2A analysis E gives the average chemical composition of the group as a whole which corresponds closely with the average for effusive tholeiites as suggested by Nockolds. Many of the analyses include samples from the same dyke, for instance TD.1-3 and TD.7-8 are from different parts of two dykes and TD.3/4-6 are from a multiple dyke. From these analyses it can be seen that there is no regular variation in chemistry within the dykes. In analyses TD.7-8 the margin appears to be slightly more basic than the centre as indicated by the total alkalis and MgO. The notable differences between the earlier and later parts of the multiple dyke is reflected in total iron, the earlier basite being more iron-rich. In all the dykes examined the margins are richer in total iron than the rest of the dyke.

The type-TD basites are distinguished from the ultrabasite dykes by being more aluminous and siliceous and by having higher total alkalis and distinctly lower MgO. They are distinguished from type-TB basites by being more aluminous, slightly more siliceous and by having higher total iron and alkalis, but lower MgO.

2. Mineralogical and chemical features of the groups

a. Type-TD basites

The type-TD basites when plotted in the calc-alkali-silica diagram (Tilley 1950) (see Fig.III-7) have a broad distribution and fall in the field of alkali-olivine-basalt and those rocks intermediate in composition between alkali-olivine-basalts and tholeiites. Based on the scheme of Yoder and Tilley (1962) two of the type-TD basites are alkali-basalts, 13 are olivine-tholeiites and two are tholeiites.

Where the type-TD basites still preserve the initial igneous mineralogy and texture, olivine has never been found. Essentially, they are two-pyroxene dolerites with quartz or quartz-feldspar intergrowth occurring in the mesostasis of plagioclase laths. The petrographic aspects of these rocks tend to indicate that they are tholeiites rather than of the alkali-basalt type.

b. Type-TB basites and ultrabasites

These basites and ultrabasites when plotted in the calc-alkali-silica diagram have a linear variation of CaO and total alkalis against SiO_2 which distinguishes them from the type-TD basites. They fall in the field of tholeiites and have an alkali-lime index of 57·5 and thus are calc-alkaline in character. Normatively (see Table III-2D) they are olivine-bearing, quartz and nepheline-free basalts and therefore olivine-tholeiites according to the scheme of Yoder and Tilley (op.cit.).

3. Chemical variation in the dyke groups

a. Type-TD basites

In order to show the chemical variation within the type-TD basite group, several methods of plotting have been employed. These include

Explanation of Table III-2.

Chemical analyses of major elements, Niggli numbers, catanorms, cationic percentages and modes of type-TD basites (TD.1-7), -TB basites (TB.1-5), ultrabasite (TU.1-2) and early basite (TE.1).

TU.1-2. Ultrabasite dyke margin (TU.2) and centre (TU.1); ultrabasite dyke 100 metres east of Loch na Beiste (81655850).

TB.1-3. Basite dyke; 400 metres south-west of Loch a'Mheallain (82936167).

TB.4-5. Basite from ultrabasite-type-TB basite composite dyke; 450 metres south-east of Loch a'Bhealaich Mhoir (80525837).

TD.1-3. Basite dyke centre; 200 metres north-north-west of Loch a'Choire Bhig (82705936). TD.1 nearer to margin than TD.2-3 respectively.

TD.4-6. Basite multiple dyke; 450 metres north-east of Loch nan Tri-eileanan (83065981).

TD.3 and 5. earlier basite intrusion.

TD.4. later basite intrusion.

TD.7-8. Basite dyke margin (TD.7) and centre (TD.8); 150 metres west of Loch Airidh Eachainn (82446088).

TD.9. Basite dyke; 350 metres east of Loch a'Choire Bhig (83225915).

TD.10. Basite dyke; 400 metres east-north-east of Loch a'Choire Bhig (83105951).

TD.11. Basite dyke; 400 metres south-west of Loch Airidh Eachainn (82336068).

TD.12. Basite dyke; Loch an t-Sithean (83475967).

TD.13. Basite dyke; 500 metres north-east of Diabaig (80136025).

TD.14. Basite dyke; 450 metres south of Diabaig (80005941).

TD.15. Basite dyke; 600 metres west of Lochan Dharach (81835913).

TD.16. Basite dyke; 450 metres north of Loch nan Tri-eileanan (82675968).

TD.17. Basite dyke; 500 metres south of Loch Airidh Eachainn (82786048).

TE.1. Early basite body; 350 metres north of Loch nan Tri-eileanan (83706027).

A. Picrite. Top contact of Ingia intrusion Ubekendt Ejland. Analyst: W.H. Herdsman. (Picrite Minor Intrusion (Drever and Johnston) in Wyllie 1967).

B. "Kylite", Dalmellington. Analyst: Dittrich (Tyrell 1912). (The Ultrabasite Facies in some Sills and Sheets (Drever and Johnston) in Wyllie 1967).

C. Average of 5 analyses of type-TB basites.

D. Effusive Tholeiite (Nockolds 1954).

E. Average of 17 analyses of type-TD basites from Loch Torridon.

F. Average of 19 analyses of basites from Gairloch (in Park 1966).

G. Average of 34 analyses of Scourie Dykes from the Lewisian from D.J. Burns (in Dearnley 1963).

	TU.1	TU.2	TB.1	TB.2	TB.3	TB.4	TB.5	TD.1	TD.2	TD.3	TD.4	TD.5
SiO_2	43·49	43·78	46·62	47·10	47·86	49·41	49·56	49·18	47·57	48·03	48·13	49·51
TiO_2	1·34	1·29	0·76	0·87	0·62	0·61	0·37	1·76	1·94	1·67	1·82	1·56
Al_2O_3	11·62	11·09	11·17	11·74	12·62	11·41	12·11	14·25	15·55	14·06	14·49	13·52
FeO	9·50	9·34	9·90	10·16	8·69	8·26	8·26	12·51	9·50	11·59	12·17	10·51
Fe_2O_3	5·18	5·18	2·24	2·82	2·55	1·76	1·37	2·48	4·01	3·10	4·20	2·88
MnO	0·21	0·21	0·21	0·21	0·20	0·19	0·14	0·27	0·25	0·22	0·26	0·22
MgO	15·44	15·68	15·95	14·57	12·71	15·34	14·96	6·55	6·68	6·52	5·09	6·97
CaO	8·18	9·95	9·03	9·38	10·22	8·02	7·49	8·15	8·68	8·84	8·33	9·65
Na_2O	2·50	1·89	1·81	1·69	1·97	2·67	2·53	2·51	3·07	3·08	2·80	2·40
K_2O	0·96	0·13	0·58	0·26	0·78	0·37	0·80	1·52	1·37	0·83	1·09	1·08
P_2O_5	0·13	0·17	0·08	0·09	0·05	0·08	0·05	0·20	0·15	0·19	0·12	0·11
H_2O	0·81	1·23	1·25	1·56	1·62	0·87	1·10	1·23	1·03	0·84	0·67	0·86
Total	99·36	99·94	99·58	99·65	99·89	98·99	98·86	100·61	99·67	98·97	99·17	99·01

	TD.6	TD.7	TD.8	TD.9	TD.10	TD.11	TD.12	TD.13	TD.14	TD.15	TD.16	TD.17
SiO_2	48·49	48·96	48·34	51·41	49·73	49·24	49·00	48·61	47·72	47·97	47·22	48·19
TiO_2	1·53	1·30	1·42	1·44	1·96	1·37	0·99	1·48	0·63	0·78	2·05	1·66
Al_2O_3	13·74	13·70	14·35	14·29	14·62	14·23	15·19	14·38	14·65	14·07	14·05	17·15
FeO	11·39	11·32	11·64	11·39	11·64	10·78	10·04	10·69	7·78	8·06	11·69	9·30
Fe_2O_3	3·60	3·25	3·76	3·88	3·14	4·00	2·30	3·55	3·38	3·64	4·33	3·29
MnO	0·22	0·25	0·25	0·23	0·25	0·23	0·21	0·23	0·23	0·18	0·25	0·18
MgO	6·49	6·42	4·65	5·04	5·17	6·12	8·26	5·89	7·61	11·14	5·23	4·05
CaO	8·89	10·47	10·25	7·94	8·03	9·42	9·78	9·15	10·40	9·84	8·36	8·10
Na_2O	2·73	2·08	2·77	2·79	2·32	2·67	2·63	2·94	2·82	2·27	3·32	4·47
K_2O	1·42	1·06	1·09	1·43	1·46	1·49	0·74	1·59	1·92	1·31	1·59	1·07
P_2O_5	0·12	0·12	0·20	0·16	0·28	0·10	0·09	0·13	0·04	0·08	0·20	0·21
H_2O	1·33	1·01	1·24	0·27	0·60	1·02	0·65	0·68	1·05	0·87	0·83	1·54
Total	99·95	99·94	99·96	100·27	99·20	100·67	99·88	99·32	100·98	100·21	99·03	99·21

	TE.1	A	B	C	D	E	F	G
SiO_2	55·03	44·92	44·18	48·11	50·83	48·69	49·0	48·9
TiO_2	1·31	1·15	1·30	0·65	2·03	1·49	1·4	1·9
Al_2O_3	14·27	12·25	10·67	11·81	14·07	14·47	13·9	12·6
FeO	7·72	9·19	10·03	9·05	9·06	10·71	10·2	10·9
Fe_2O_3	4·70	2·02	0·97	2·15	2·88	3·46	4·4	4·5
MnO	0·15	0·28	n.d.	0·19	0·18	0·23	0·16	0·24
MgO	3·20	16·12	17·77	14·70	6·34	6·35	6·0	6·4
CaO	7·50	9·93	9·75	8·63	10·42	9·08	8·9	9·7
Na_2O	3·92	1·54	2·37	2·13	2·23	2·80	2·9	2·5
K_2O	1·10	0·10	1·23	0·56	0·82	1·30	0·9	0·56
P_2O_5	0·19	0·14	0·38	0·08	0·23	0·15	0·13	0·18
H_2O	0·63	0·79 (H_2O-) 1·55	0·97	1·28		0·93	2·0	1·20
Total	99·72	99·93	99·62	99·41				

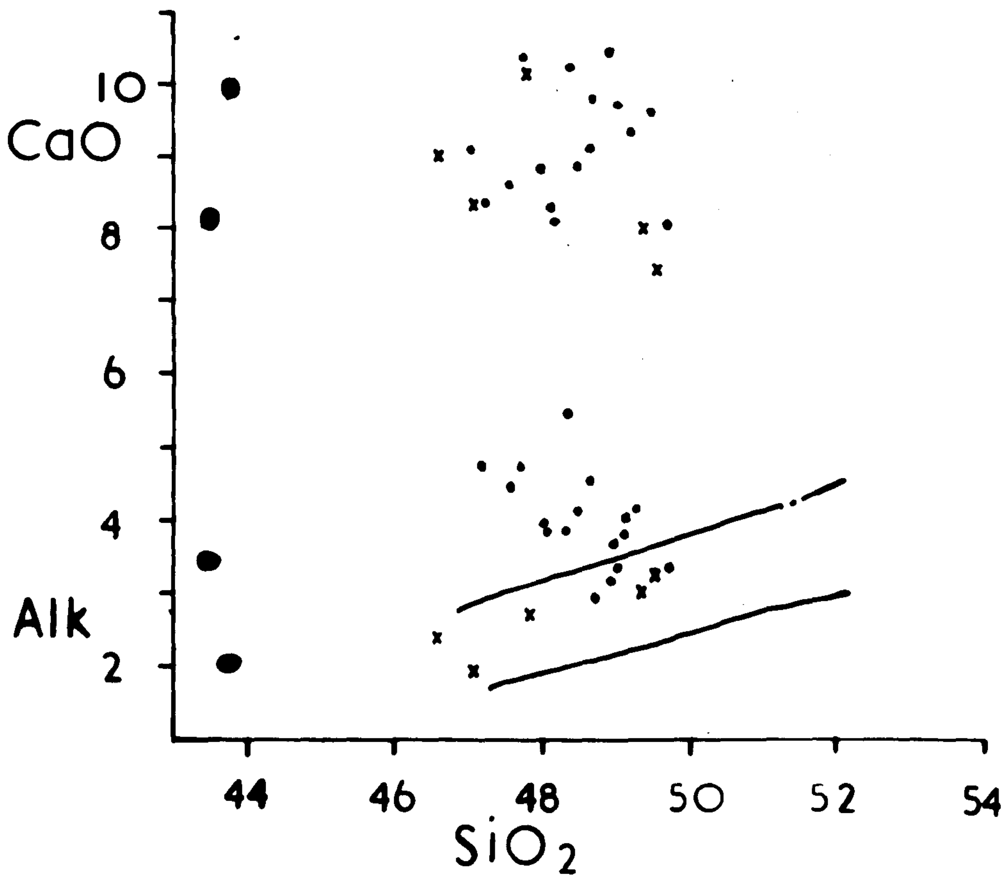
A. Chemical Analyses

	TU.1	TU.2	TB.1	TB.2	TB.3	TB.4	TB.5	TD.1	TD.2	TD.3	TD.4	TD.5
Si^{4+}	[illegible]	40·6	45·1	44·0	44·6	45·3	45·7	46·8	45·0	46·0	46·3	47·4
Al^{3+}	[illegible]	12·1	12·2	12·9	13·9	12·3	13·2	16·0	17·4	15·8	16·4	14·9
Fe^{3+}	3·5	3·6	1·6	2·0	1·8	1·2	1·0	1·8	2·8	2·2	3·4	2·1
Fe^{2+}	7·5	7·4	7·8	[illegible]	6·9	5·6	5·5	9·9	7·7	9·4	10·0	8·6
Mg^{2+}	21·4	21·8	21·9	20·3	17·6	20·9	20·5	9·4	9·5	9·4	7·3	10·0
Ca^{2+}	8·4	9·9	8·9	8·4	10·2	7·9	7·4	8·3	9·8	9·1	8·6	9·9
Na^{+}	4·4	3·5	3·2	3·0	3·6	4·9	4·4	4·7	5·7	5·7	5·2	4·5
K^{+}	1·1	0·1	0·7	0·3	0·9	0·4	0·9	1·8	1·7	1·0	1·4	1·4
Ti^{4+}	1·1	1·0	0·7	0·6	0·5	0·4	0·3	1·3	1·4	1·2	1·3	1·2
P^{5+}	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1

	TD.6	TD.7	TD.8	TD.9	TD.10	TD.11	TD.12	TD.13	TD.14	TD.15	TD.16	TD.17	TE.1
Si^{4+}	46·3	46·8	46·5	47·5	47·9	46·6	45·2	46·3	45·4	44·3	45·5	45·9	52·6
Al^{3+}	15·5	15·4	16·3	15·5	16·2	15·9	16·9	16·1	16·4	15·3	16·0	19·2	16·1
Fe^{3+}	2·6	2·4	2·7	2·7	2·9	2·8	1·7	2·5	2·3	2·6	3·1	2·4	3·1
Fe^{2+}	9·2	9·2	9·6	8·9	9·6	8·7	8·1	8·7	6·3	6·4	9·6	7·6	6·3
Mg^{2+}	9·3	9·2	6·7	9·7	7·5	8·7	11·8	8·4	10·8	15·5	7·6	5·8	4·6
Ca^{2+}	9·1	10·7	10·6	7·9	8·3	9·5	10·0	9·4	10·6	9·8	8·6	8·3	7·7
Na^{+}	5·1	3·9	5·2	5·0	4·3	4·9	4·8	5·4	5·2	4·1	5·9	8·3	7·2
K^{+}	1·7	1·3	1·4	1·7	1·9	1·8	0·9	2·0	2·3	1·6	2·0	1·3	1·4
Ti^{4+}	1·1	0·9	1·0	1·0	1·4	1·0	0·7	1·1	0·5	0·6	1·5	1·2	0·9
P^{5+}	0·1	0·1	0·2	0·1	0·2	0·1	0·1	0·1	-	0·1	0·2	0·2	0·2

B. Cationic percentages

Fig.III-7. Plot of $Na_2O + K_2O$ (Alk) and CaO against SiO_2 for the type-TD basites (·), type-TB basites (X) and ultrabasites (●).


10
CaO
8
6
4
Alk
2
44
46
48
50
52
54
SiO2

the evaluation of Niggli numbers for the analyses and the plotting of Niggli si against mg, ti, alk, c and fm (Fig.III-8b) and mg against p, k, c, alk and ti (see Fig.III-8a); the solidification index ($MgO \times 100/MgO + FeO + Fe_2O_3 + Na_2O + K_2O$) against oxide values, e.g. MgO, (see Fig.III-9) which may be used as an indicator of the degree of solidification within a suite of rocks (Wager and Deer 1960); felsic index 100(Na + K)/Ca + Na + K against mafic index $100(Fe^{2+} + Fe^{3+})/Mg + Fe^{2+} + Fe^{3+}$ (Simpson 1954) (see Fig.III-10).

In terms of Niggli numbers, the most notable variations were obtained from plots of mg against p, alk and si (see Fig.III-8a).

Niggli mg (i) decreases with increasing si.
(ii) increases with increasing p.
(iii) increases with decreasing alk.
(iv) increases with decreasing ti.

A comparison of the trends in Niggli numbers with those for the Karroo dolerites (see Evans and Leake 1960) reveal similar trends suggesting a similarity in magmatic differentiation of the two series. In the Karroo dolerites (Walker and Poldervaart 1949) magmatic differentiation leads to high iron concentration in the middle and late stages of the fractionation series. Osborn (1959) found that water pressure will affect the stage at which magnetite crystallizes from a magma. Thus at high water pressures magnetite is crystallized early leading to a depletion of iron in the magma, and conversely, low water pressures leads to enrichment of iron. It would seem that in the Karroo dolerites and Torridon type-TD basites the suites were magmatically differentiated under the influence of low water pressure.

Increase in the solidification index results in a linear increase in MgO (see Fig.III-9), a feature revealed by all differentiating basalts (cf. Kuno 1968). Similarly, increase in the felsic index also results in an increase in the mafic index (see Fig.III-10).

The trends exhibited by the type-TD basites indicate that they represent a normal magmatic differentiation series of a tholeiitic parent magma under low water pressure producing high iron concentration in the middle to late stages of fractionation (Osborn op.cit.) and are approximately parallel to the trends of the Karroo dolerites. The trends are the expression of progressive crystallization of olivine, pyroxene and plagioclase, each phase changing in composition with progressive fractionation, the reaction relation of Mg-olivine and Ca-poor pyroxenes (i.e. orthopyroxene and pigeonite) being dominant in the differentiation process. The mineral assemblage of the least altered type-TD basites closely parallels the mineral assemblage of the Karroo quartz-dolerites where orthopyroxene (olivine free)-Ca-poor augite-plagioclase (An_{60})-micropegmatite is present.

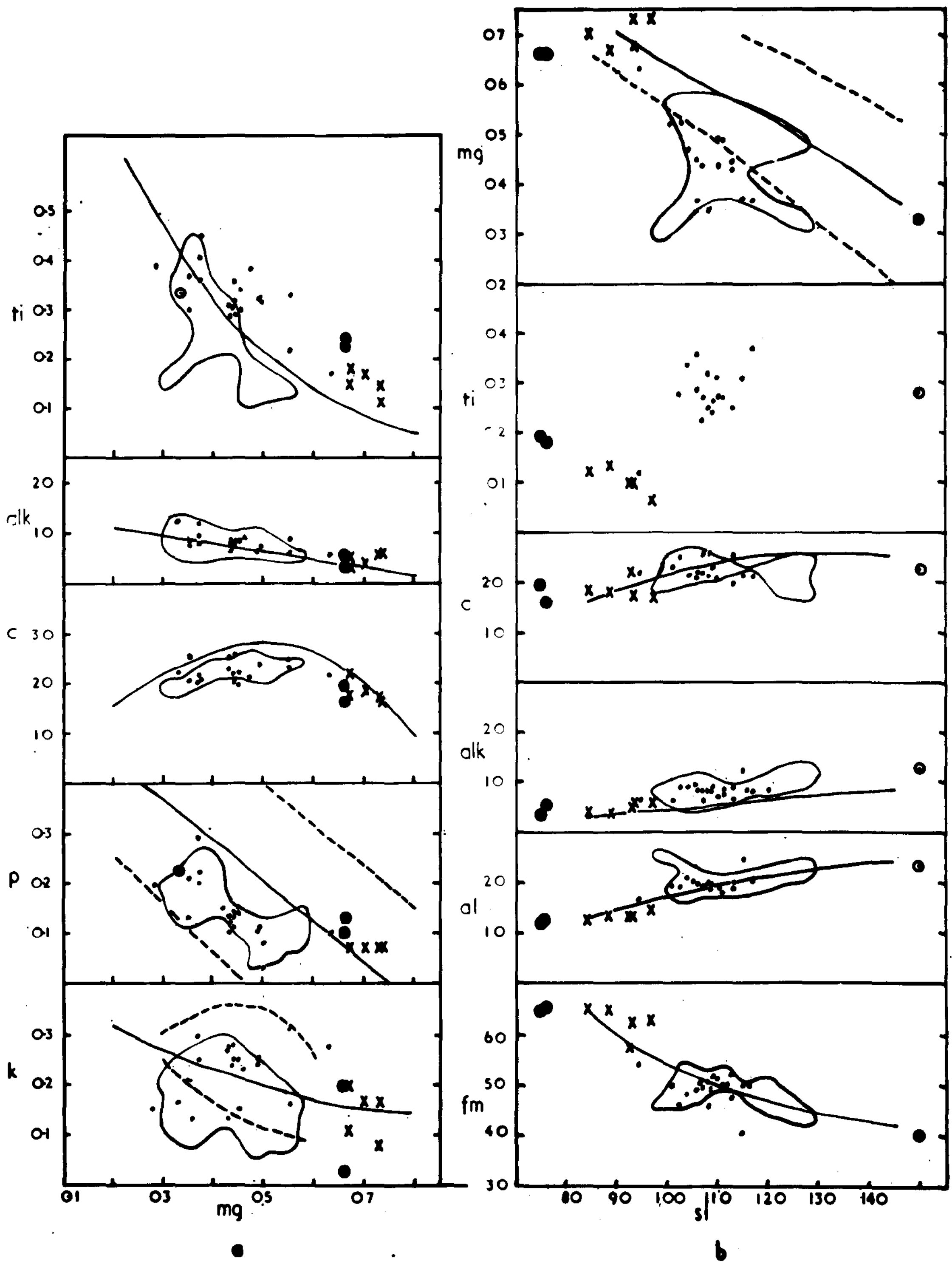
b. Ultrabasites and type-TB basites

These basites and ultrabasites may be distinguished from the type-TD basites by the trends they exhibit in the calc-alkali-silica diagram and from the Niggli diagrams (see Fig.III-7 and 8a-b). Their chemical variations are imperfectly expressed by the Niggli diagrams except in the diagram si against al, alk, and ti. With increasing si, al and alk increase whereas ti decreases, the latter variation clearly distinguishing them from the type-TD basites.

Chemical variations in the suite are best expressed by plotting cationic percentages. In Fig.III-11a-f cationic percentages of Ti^{4+}, Na^{+} + K^{+}, Ca^{2+}, Fe^{2+}, Mg^{2+} + Fe^{2+}, Ca^{2+} + Mg^{2+} + Fe^{2+} are plotted against Si^{4+}. The significant feature of these variations is represented in a negative slope with the ultrabasite dyke margin TU.1 falling constantly on the composition trend. These variations tend to indicate that the ultrabasite and basite dykes are part of the same suite and have arisen as a result of magmatic differentiation.

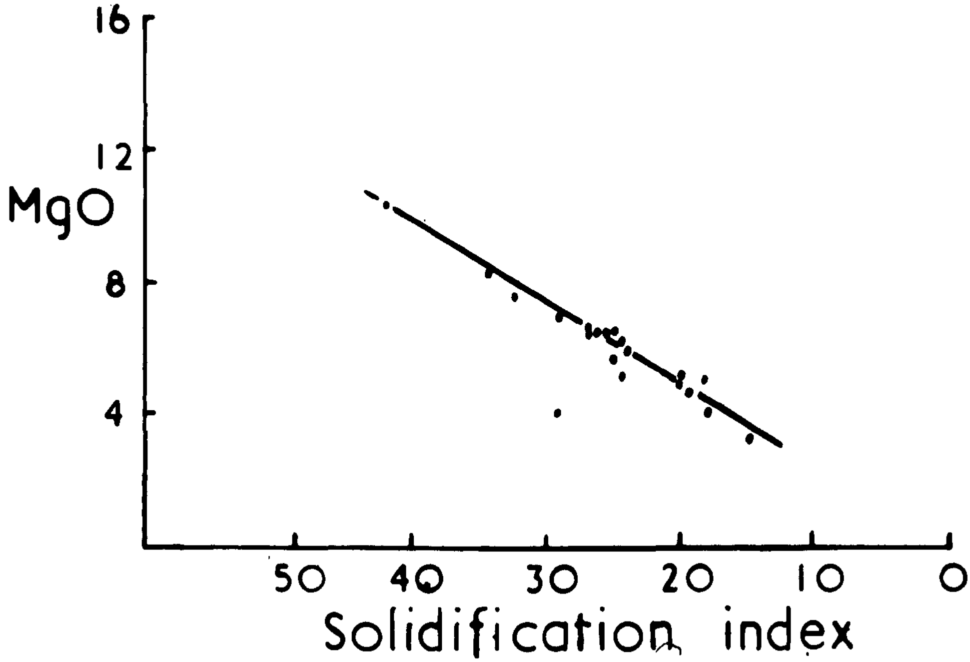
From Fig.III-11a-f it is clear that as Si^{4+} increases, Ti^{4+}, Ca^{2+}, Fe^{2+}, (Fe^{2+} + Mg^{2+}) and (Ca^{2+} + Mg^{2+} + Fe^{2+}) decrease and (Na^{+} + K^{+}) increase. The slight curvature of the trends of (Ca^{2+} + Mg^{2+} + Fe^{2+}) and (Mg^{2+} + Fe^{2+}) suggests that the separating phases responsible for the differentiation trend change in composition or that ratios of two contrasting separating phases are changed with fractionation.

Fig.III-8a-b. Plots of ti, p, k, alk and c against mg (a) and c, alk, ti, fm and mg against si (b) for the type-TD basites (·), type-TB basites (X) and ultrabasites (●). The trends for the Karroo dolerites (full line) and the field for the Gairloch Basites (enclosed areas) are inserted for comparison. Where the Karroo dolerite field is large the limits are indicated by dashed lines. Early basite (⊖).



ti
alk
c
p
k
mg
fm
al
si
a
b

Fig.III-9. Plot of MgO against solidification index ($MgO \times 100/MgO + FeO + Fe_2O_3 + Na_2O + K_2O$) for the type-TD basites.



16
12
MgO
8
4
50
40
30
20
10
0
Solidification index

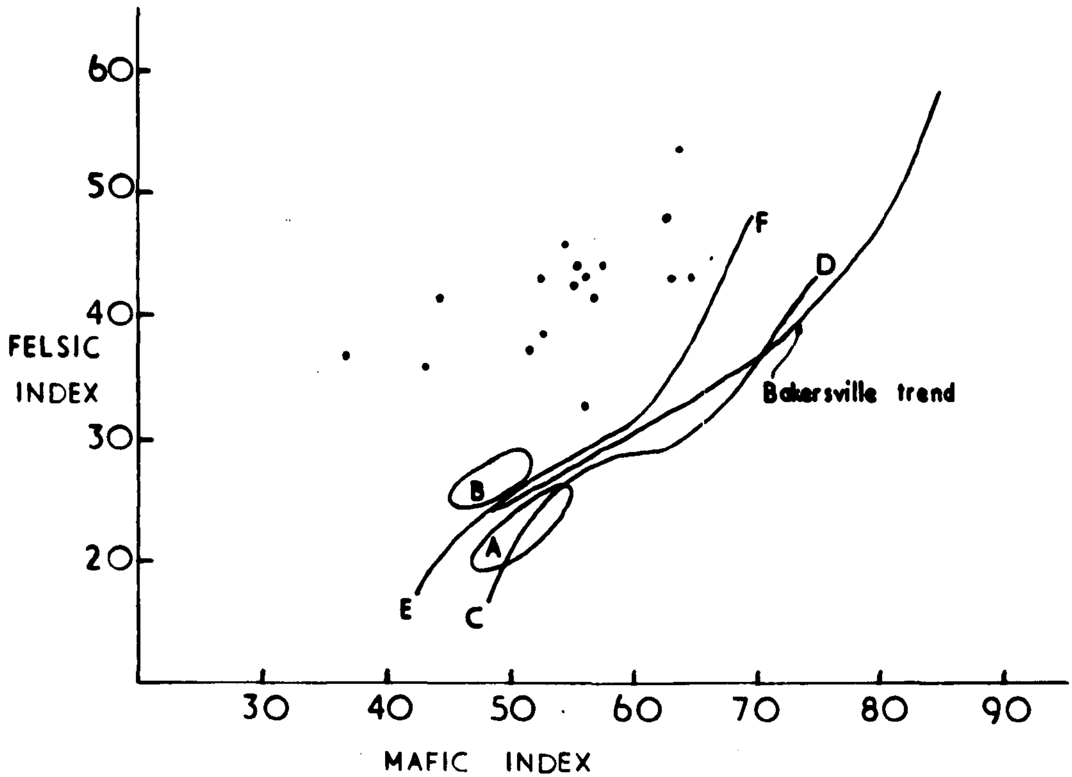
Fig.III-10. Plot of felsic index (100(Na+K)/Ca+Na+K) against mafic index (100(Fe^{3+}+Fe^{2+})/Mg+Fe^{2+}+Fe^{3+}) for the type-TD basites.

(A. Average of Hawaiian tholeiites

B. Average of Hawaiian alkali-olivine basalts

CD. Average Hebridean tholeiite series of successive factionation stages

EF. Average Hebridean alkaline-olivine basalt series of successive faction series. From Wyllie, 1967, p.78.)



60
50
40
30
20
FELSIC
INDEX
F
D
Bakersville trend
B
A
E
C
30
40
50
60
70
80
90
MAFIC INDEX

The compositional trends exhibited by the cationic percentages are those which would normally be shown by a differentiating tholeiite magma with the exception of Fe^{2+} and Mg^{2+} against Si^{4+}. A normal differentiating tholeiitic magma would show an increase in Fe/Mg ratio with progressive fractionation. However, the ratio $Fe^{2+} + Fe^{3+}$ (as Fe^{2+})/Mg^{2+} (see Fig.III-11) decreases with cationic Si^{4+}. It seems, therefore, that the normal magmatic differentiation process where Fe/Mg increases with progressive fractionation does not appear to be applicable to this suite.

The compositional variation within the suite would appear to imply that differentiation was probably controlled by the separation of femic phases. The variation in the femic phases is controlled in magmatic differentiation by the Fe/Mg ratio and calcium, magnesium invariably decreasing with increasing silica. However, in this suite Mg^{2+} shows no appreciable variation (see Fig.III-11h), in spite of differentiation control by the phases pyroxene and olivine.

4. <u>Possible methods of differentiation in the suite</u>

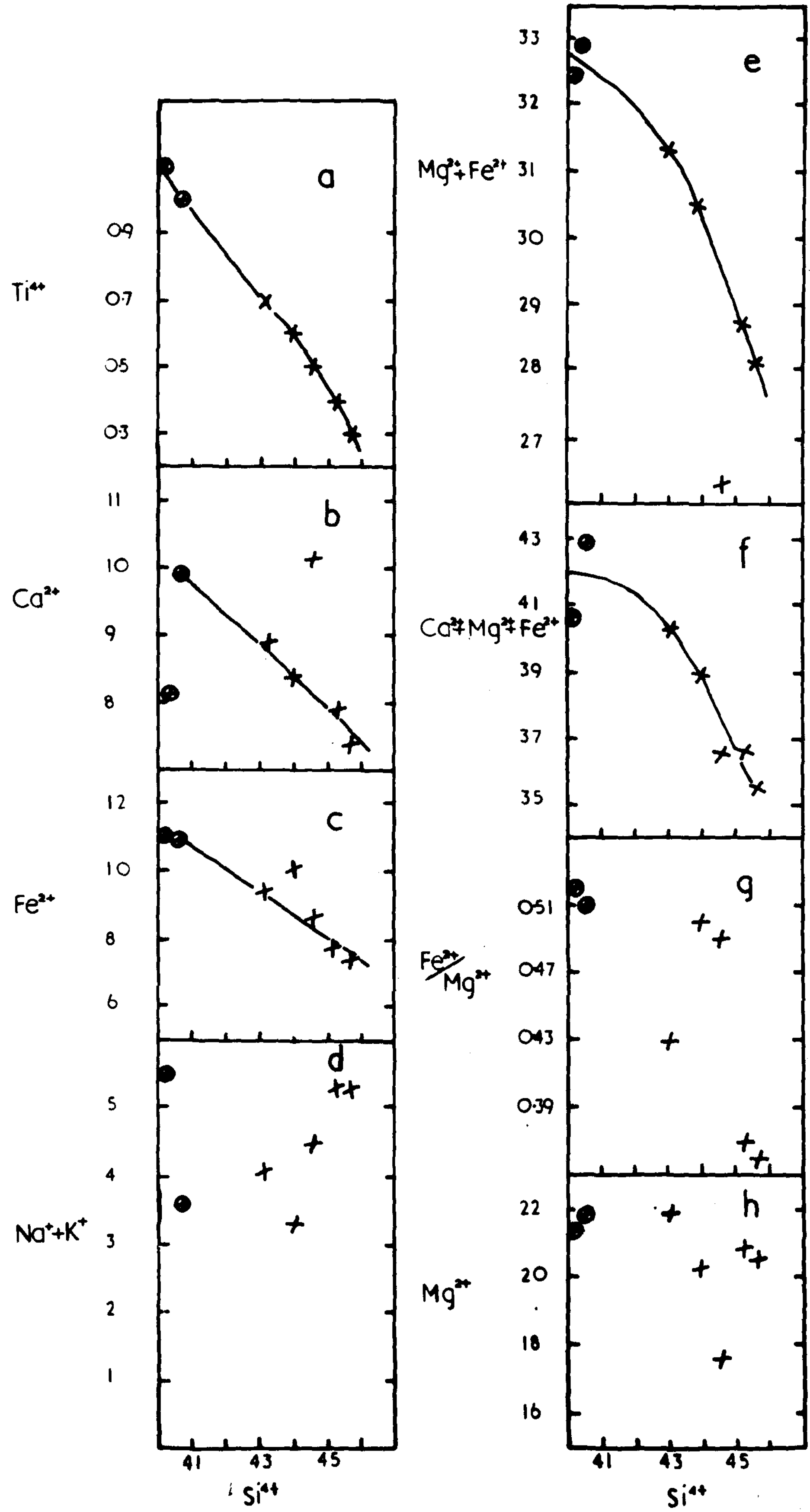
It must first be decided whether the compositional variations in these rocks are fortuitous or represent a true differentiation trend. If the variations are fortuitous we may be dealing with two magma types in these rocks, a picrite parent magma (cf. Drever and Johnston 1968) for the ultrabasite dyke and a tholeiitic magma for the basites. There are two disadvantages in appealing to an origin involving more than one magma type:

(i) Although the basites and ultrabasites form a very minor proportion of the dyke swarm they are constantly associated in the field suggesting a genetic relationship between them.

(ii) The variation in cationic proportion and Niggli numbers also suggests a common genesis in that the anomalous trend is not dependent on the plotting of the ultrabasites and basites together, but is also characteristic of the basites when considered separately.

If the compositional variations are a result of magmatic differentiation then there appears to be two possible mechanisms.

Fig.III-11a-h. Plot of cationic percentages Si^{4+} against Ti^{4+}, Ca^{2+}, Fe^{2+}, $Na^{+} + K^{+}$, $Mg^{2+} + Fe^{2+}$, $Ca^{2+} + Mg^{2+} + Fe^{2+}$, Fe^{2+}/Mg^{2+} and Mg^{2+} for the type-TB basites (X) and ultrabasites (●).


a
b
c
d
e
f
g
h
Ti4+
Ca2+
Fe2+
Na++K+
Mg2++Fe2+
Ca2++Mg2++Fe2+
Fe2+/Mg2+
Mg2+
Si4+
Si4+

(a) Early separation of magnetite or ilmenite

If magnetite or ilmenite did not crystallize from the parent magma in the early stages of differentiation, an increase of total iron and TiO_2 will occur since other minerals, notably pyroxene or olivine, which are likely to crystallize early during magmatic differentiation do not contain sufficient iron and titanium. Since total iron and TiO_2 decrease with increasing fractionation, then magnetite or ilmenite crystallization may be responsible for these variations. The stage of magnetite crystallization is probably controlled by oxygen pressure of the magma (Osborn 1959, 1962). Higher oxygen pressure would produce earlier crystallization of magnetite. If then, the parent magma had a high oxygen pressure, magnetite and/or ilmenite would separate early, effectively reducing the Fe/Mg ratio in the magma. If the oxygen pressure was then decreased such that further excessive magnetite crystallization was prevented, the Fe/Mg ratio would increase as found in the pyroxenes and olivines of a normal differentiation series.

The chemical trends exhibited in these dykes may thus be explained in terms of early separation of magnetite, thus lowering the Fe/Mg ratio in the magma, accompanied and followed by the separation of pyroxenes and possibly olivines.

(b) Primary crystallization of amphibole

Yoder and Tilley (1962), in discussing the effects of partial melting of basalt systems under high water pressure, emphasised the role played by amphibole in the differentiation of basaltic systems (see also Watterson 1968). If the separation and accumulation of amphibole is responsible for the differentiation in the ultrabasite-basite suite then the amphibole would require to be titaniferous and iron-rich. The only likely iron-rich and titaniferous amphiboles are barkevikite and kaersutite. Wilkinson (1961) in discussing some aspects of amphibole development suggested that barkevikite forms in magmas with high Fe/Mg ratios whereas kaersutite which has a lower Fe/Mg ratio develops in more hydrous conditions than barkevikite. Yagi, (in Deer, Howie and Zussman, p.331,

1963) found that in certain dolerites a sequence of genesis was barkevikite, followed by kaersutite.

If the basite-ultrabasite suite at Loch Torridon owes its differentiation to the crystallization of amphibole, then early separation of barkevikite would be expected, the accumulation of which produced the ultrabasite dykes. As a result of the change in Fe/Mg ratio in the magma, the composition of the amphibole would change from barkevikite to kaersutite with increasing fractionation. Because of the lack of knowledge of the stability limits of these minerals, this suggestion must be regarded as tentative.

5. Mineralogical evidence for the possible cause of differentiation in the ultrabasite-basite suite.

Because of the state of metamorphism of the ultrabasite-basite dykes, the femic component of rocks is predominantly amphibole. The only mineral which is readily identified as of igneous parentage is plagioclase which remains preserved in most of these dykes. In basite specimens TB.4-5 the plagioclase falls in the range of oligoclase-andesine which is notably more Ab-rich than basalts having similar chemical compositions.

The femic minerals in these dykes may have been represented originally by pyroxenes and olivines (see norms, Table III-2D) or by amphiboles or by all three minerals. It is problematical whether the existing amphiboles were formed by uralitization of pyroxenes or by retrogression of an initial igneous amphibole. In the dyke A1 at An Ruadh Mheallan (see Fig.III-1), which at 100 metres wide is the largest in the area, no relict pyroxenes have been observed although it occurs in a belt of rocks where the post-dyke metamorphism is very mild compared with rocks further south. However, much thinner type-TD basites in close proximity to dyke A1 have relict pyroxenes present in their centres. This evidence although by no means conclusive, may indicate that the predominant igneous femic mineral in the dyke A1 might have been amphibole.

Watterson (1968) considers that the chemical variation exhibited by dykes in the Ilordleq Area of W. Greenland was controlled by primary crystallization and separation of amphibole. Within these dykes the hornblendes have been formed by the exsolution of titanium from the igneous amphibole (kaersutite) which had been retrogressed in an amphibolite-facies metamorphism. In a similar way, the rutile aggregates present in the Torridon type-TB basites may have been formed as a result of exsolution of titanium from an original titaniferous amphibole. A further feature of the dykes of the Ilordleq Area is that the igneous plagioclase is oligoclase-andesine whereas the norms of these rocks suggests a plagioclase of labradorite composition which corresponds to the situation in the Torridon type-TB basites.

6. Origin of the suite

It is believed that the fractionation within the ultrabasite type-TB basites producing oversaturated end-members may have been achieved by the primary igneous crystallization of either ilmenite/magnetite with olivine and pyroxene or by amphibole. The ultrabasite dykes are believed to be cumulates developed in the magma chamber either by the accumulation of ilmenite, pyroxene and olivine or by the accumulation and separation of a titaniferous-amphibole. The cumulate phases were then emplaced as a crystal mush, the presence of a chilled margin possibly indicating that flow differentiation (Bhattarcharji and Smith 1964) was effective during intrusion. Fractionation in the magma chamber and intrusion of the tholeiitic magma at different periods has then produced the basite TB.1 to 5. Thus:

Barkevikite $\xrightarrow{Fe \rightleftharpoons Mg}$ Kaersutite
(amphibole separation)

Primary magma ⟶ Type-TB basites TB.1-5

↓ accumulation of either pyroxene, ilmenite and olivine or barkevikite

or separation of ilmenite, pyroxenes and olivine

ultrabasites TU.1-2

7. Similarities between the Torridon type-TD basites and those from other basic rocks of the Lewisian

Park (1936) in dealing with basites of uncertain origin from Gairloch followed the methods of Evans and Leake (op.cit.) in distinguishing ortho- from para-amphibolites, and found that they showed comparable chemical variation trends with the igneous trends of the Karroo dolerites and were therefore likely to be of igneous origin. Figs.III-8a-b illustrate the compositional fields exhibited by the Gairloch Basites which are duplicated by the Torridon type-TD basites and approximate to the means of the Karoo dolerite trend.

In Table III.2A analyses E, F and G are the averages for the Torridon type-TD basites, Gairloch Basites and Scourie Dykes (Burns, in Dearnley 1963, table 10). These analyses are very similar except that the Torridon type-TD basites have slightly higher Al_2O_3 and alkalis (Na_2O + K_2O).

IV. PETROLOGY OF THE POST-DYKE CHANGES

A. The M_6 and M_7 metamorphisms of the acid gneisses, early basites and ultrabasites

The acid gneisses and early basites which are affected by the M_6 and M_7 metamorphisms have an irregular distribution. The early basites, which have dominant S_3 foliation (see Chapter II.B3), have never been found to register the M_7 effects, whereas the acid gneisses, irrespective of whether they are massive, banded or pegmatitic develop the M_7 metamorphic effects readily.

The M_6 metamorphic effects are very difficult to identify in the acid gneisses and early basites, and have only been found with any degree of certainty at one locality in the early basite 150 metres north-north-east of Loch nan Tri-eileanan.

The previous structure of the gneisses appears to have controlled the intensity of the M_7 metamorphism which is more pronounced in the S_4 gneisses than in the S_3 gneisses and pegmatites. In Fig. IV-1 the close correspondence between mylonite belts and gneisses with the M_7 fabric is illustrated. By comparing Fig.IV-1 with Fig.II-1 it appears that M_7 metamorphosed gneisses duplicate the positions of S_4 finely-foliated gneisses. The belt of finely-foliated gneisses, south-east of Diabaig has been completely recrystallized by the M_7 metamorphism. There is a general increase in M_7 metamorphic effects on the complex progressively south-westwards.

2. Petrology

(a) The M_6 metamorphism

The identification of the M_6 metamorphic effects in the early basite body mentioned above, has been made by comparison with similar effects exhibited by the dyke swarm where the development of garnet during the M_6 metamorphism distinguishes the latter from M_7 in which garnet was retrogressed.

The early basite north-north-east of Loch nan Tri-eileanan has spheroidal xenoblastic garnets up to 3 cm. in diameter developed (see

Fig.IV-1. Distribution of M_8 recrystallization belts, late pegmatites, granite-sheet and mylonite belts.

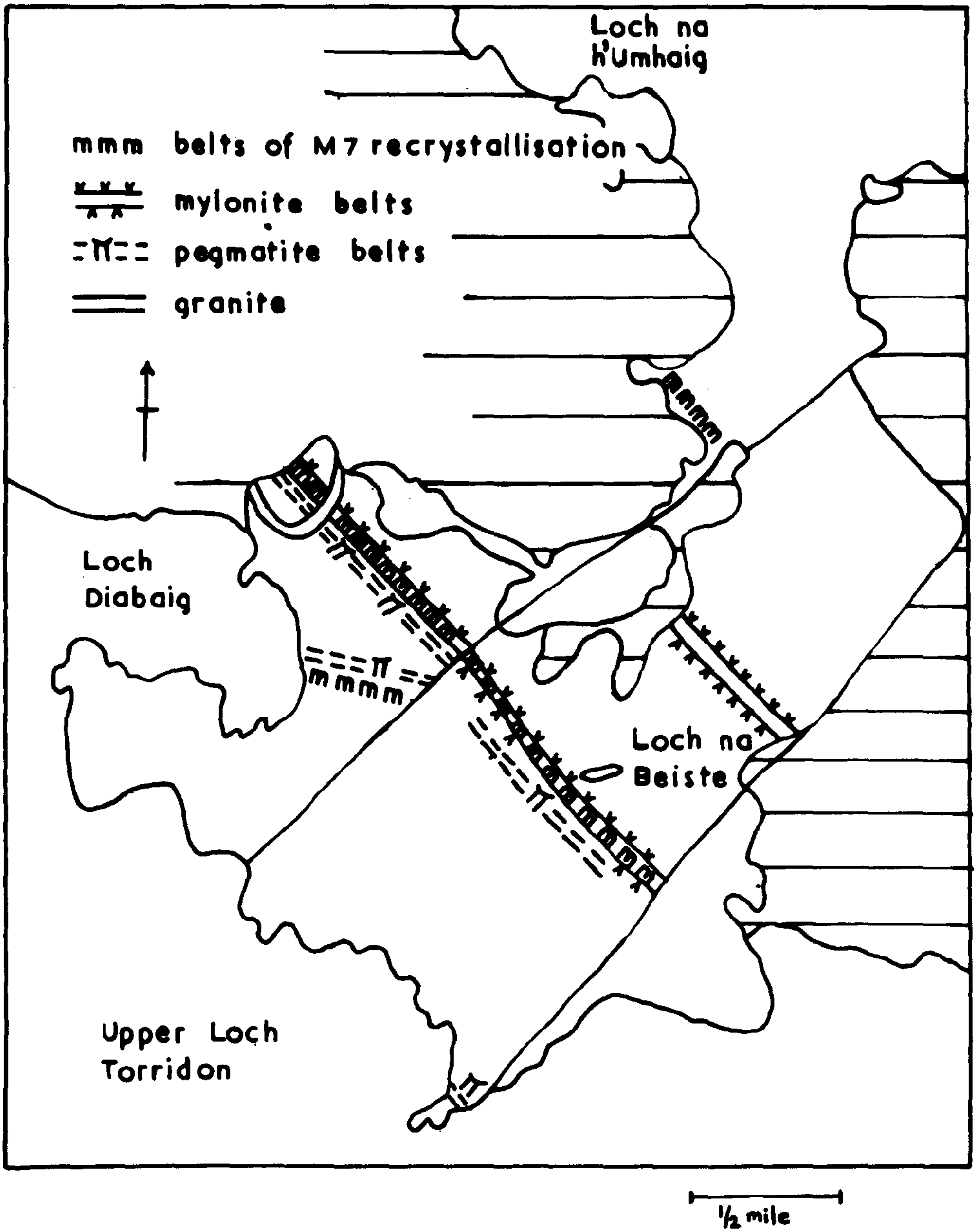

Loch na h'Umhaig
mmm belts of M7 recrystallisation
mylonite belts
pegmatite belts
granite
Loch Diabaig
Loch na Beiste
Upper Loch Torridon
1/2 mile

Plate IV-1a). These garnets are generally crowded with inclusions of quartz which are aligned in a preferred orientation within the host grain, which indicates that garnet has overgrown a pre-existing fabric in the rock. Examination of the trails of inclusions reveals that they may bear any relationship to the mesoscopic structures in the early basite, although they are frequently parallel to the foliation in the rock (see Plate IV-1b). The variable orientation exhibited by the inclusion trails would indicate that they have been rotated. However, there is no evidence that the garnets were being recrystallized during rotation since spiral-shaped trails have not been found.

The garnets are generally partly or wholly retrogressed to biotite, hornblende and iron ore by the M_7 metamorphism. The hornblendes associated with the retrogressed garnet are flattened around the latter and show the development of exsolution lamellae similar to those described in the dykes (see Chapter III.B2).

(b) The M_7 metamorphism

The distinction between the M_7 and the pre-existing pre-dyke metamorphic effects is difficult to make since it is not based upon the development of new mineral phases during the recrystallization of the pre-existing assemblage. The only visible difference is in texture and is related to the recrystallization of plagioclase (see Chapter III.B2). The mafic minerals of the recrystallized gneisses show no notable differences from those in the pre-dyke gneisses; biotite, hornblende, epidote and sphene having similar properties and textures in all the members of the complex.

Plagioclase is the predominant mineral in the acid gneisses and differs from that formed in the pre-dyke metamorphism(s) and migmatizations both in texture and composition.

(i) Textural differences

The plagioclase feldspar associated with the pre-dyke gneisses, irrespective of the gneiss type, forms aggregates of large, xenoblastic, irregular grains. Since the gneisses have responded in varying degrees,

Plate IV-1a. Spheroidal garnets occurring in the early basite body north-north-east of Loch nan Tri-eileanan (82916063).

Plate IV-1b. Photomicrograph of garnets in the early basite body (x10)(X.P.L.).

depending on the type and situation of the gneisses in the complex, to the M_7 metamorphism, the recrystallization of the initial M_4 feldspar may be observed in several stages. This recrystallization results in a diminution of grain-size of the feldspar.

The S_3 massive gneisses and post-D_3, pre-D_4 migmatites show the initial stage of recrystallization of the feldspar which results in the formation of approximately equigranular polygonal grains along margins and fractures in the M_4 xenoblastic feldspar (see Plate IV-2). Progressive recrystallization leads to the formation of a mozaic of granoblastic, equigranular, polygonal grains completely replacing the initial plagioclase (see Plate IV-3b). Some of the grains have poikiloblastic inclusions of quartz which are generally elongated parallel to the albite twin planes in the host grain (see Plate IV-3a). The plagioclase grains range up to 0·5 mm. with an average size of 0·3 mm.

The twinning in plagioclase shows the following characteristics; twinning on either albite or albite-pericline law; abundant multiple twinning; uniformly thick, slender and regular lamellae; thin tapering lamellae often dying out before grain boundary. Vance (1961) made a comparative study of twinning due to growth and recrystallization in feldspar (primary twinning) and that due to post-crystallization deformation (secondary twinning). The features revealed by the polygonal grains resemble those shown by the secondary twinning of Vance, which is consistent with the post-crystallization deformation in the complex (see chapter IV.H).

(ii) Composition

The composition of the pre-dyke feldspars is as follows:

S_3 banded gneisses	An_{22-27}
S_3 massive gneisses	An_{22-24}
S_3 early basites	An_{28-33}
Post-D_3-pre-D_4 pegmatites in acid gneisses	An_{22}
Post-D_3-pre-D_4 pegmatites in S_3 basites	An_{22-30}

Plate IV-2. Recrystallization of M_4 porphyroblastic plagioclase into M_7 polygonal-shaped plagioclase (x25).

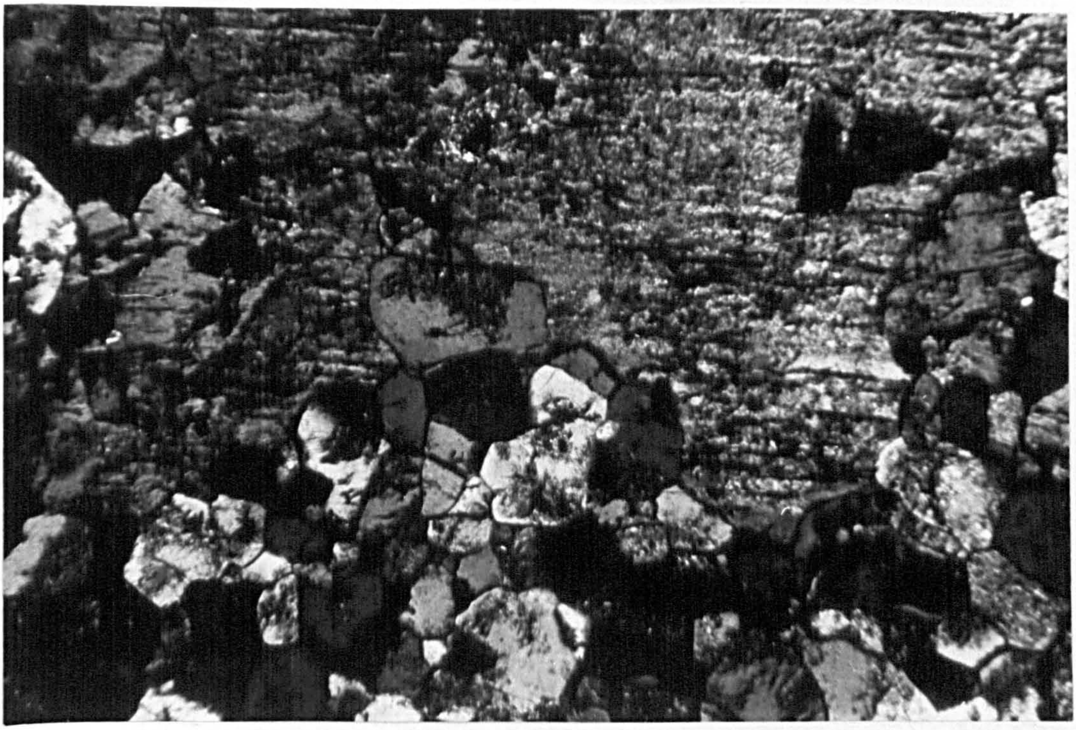
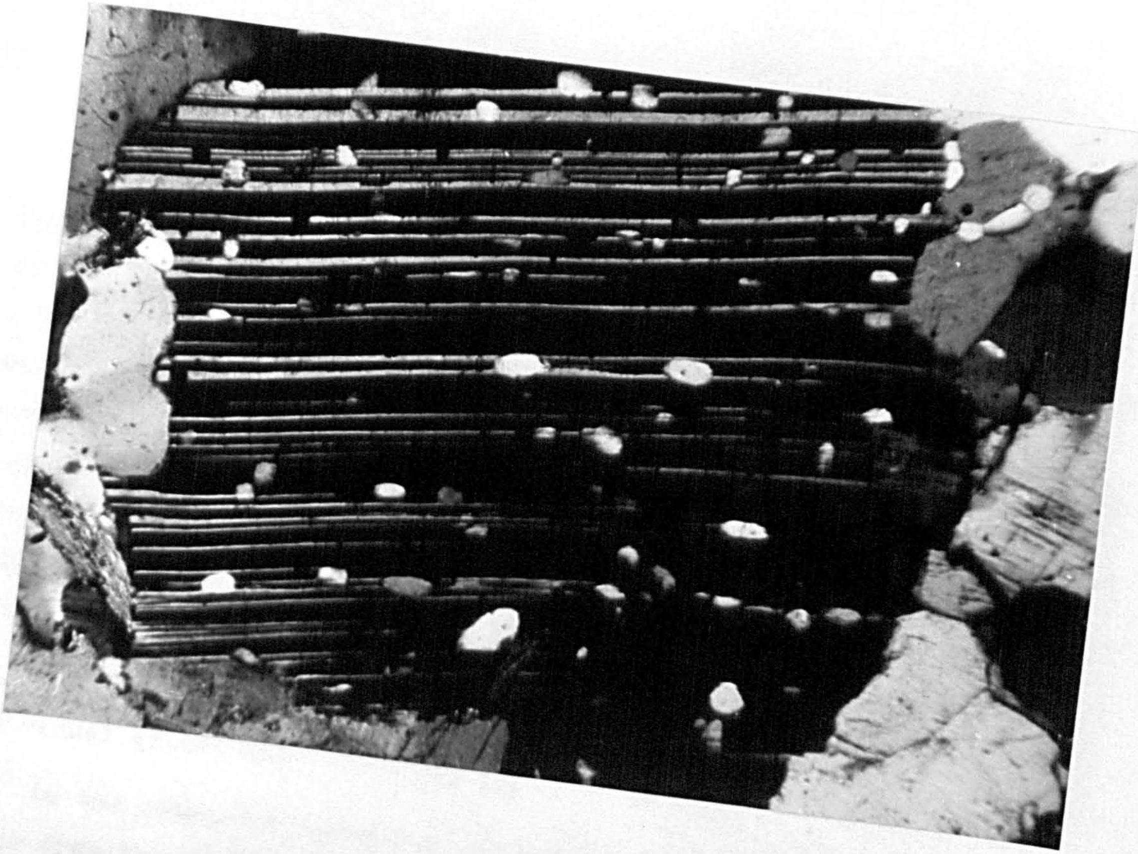
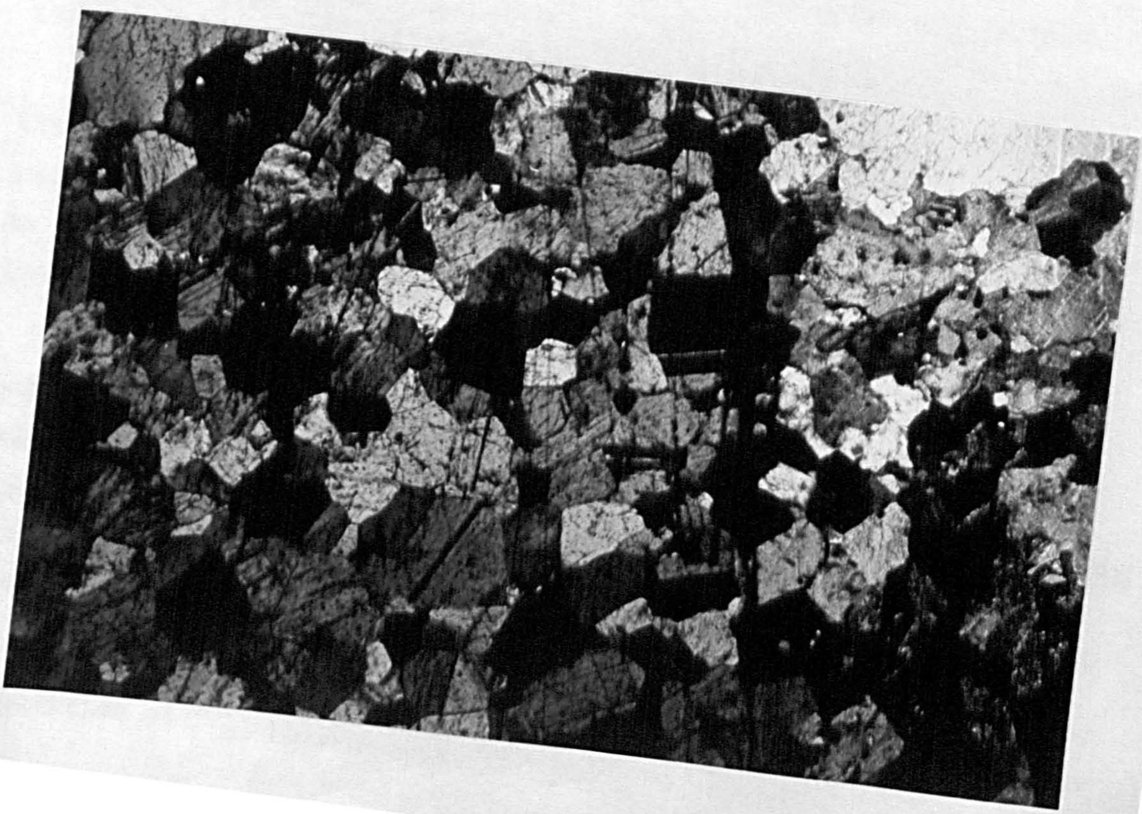


Plate IV-3a. M_7 plagioclase with albite twinning and poikiloblastic inclusions of quartz (x25).

Plate IV-3b. Mozaic of equidimensional M_7 polygonal-shaped plagioclase grains (x25).





S_4 banded gneisses	An_{22-33}
S_4 finely foliated gneisses	An_{20-30}
S_4 syn- and post-kinematic pegmatites in early basites	An_{22-31}

The polygonal grains may either be unzoned or reverse-zoned, the two only occasionally being present in the same thin section. Zoning is generally represented in the form of a distinct core and mantle with a sharp junction between them. The mantle zone may be very narrow to exceedingly broad when nearly all the grain consists of mantle. Grains with more than one core are not uncommon and the core may be sited at various places within the polygonal grains. The presence of oscillatory zoning has been recorded although it is exceedingly rare and consists of a core and mantle of similar composition with an intermediate more calcic zone.

In Fig.IV-2a and b the compositions of core and mantle in individual grains have been plotted.

In the finely-foliated gneisses the unzoned polygonal grains range from An_{23} to An_{31} which corresponds with the composition of the initial feldspar in the finely-foliated gneisses (ie. An_{20-30}).

Unzoned polygonal grains in the banded gneisses, although very little statistical data is available on these rocks, have a range An_{26-31}. Similarly, the range of composition exhibited by these fall in the broad field of the initial feldspar in the S_4 banded gneisses (ie. An_{22-33}).

The early basites rarely have polygonal grains and therefore no information is available for these. However, the post-D_3, pre-D_4 pegmatites which have affected the early basites have registered varying degrees of recrystallization of plagioclase and the unzoned polygonal grains in these bodies have a composition An_{35-41} which is notably more basic than the initial feldspar (An_{22-30}).

In the S_3 banded gneisses unzoned polygonal grains have a range in composition of An_{31-32} although few determinations have been possible.

The zoned feldspars have a range in composition in the acid gneisses from core to mantle of An_{20-26} and An_{22-35} respectively (see Fig.IV-2b) whilst the post-D_3 - pre-D_4 pegmatites in the early basites have a core (An_{23-34}) and mantle (An_{33-46}) (see Fig.IV-2a).

In Fig.IV-2d the composition of mantle and core have been plotted for all the zoned plagioclases over the area. From the figure, the relative composition of the zoned feldspar appears to be related to the initial composition of the rock (eg. the type-TD basites have a broad spread in composition and are more calcic than the acid gneisses). It can also be established from the figure that the composition of the core is directly related to that of the mantle, that is, there is a linear relationship between them.

Fig.IV-2c represents a plot of mantle and core of similarly reverse-zoned plagioclase grains examined in gneisses from Laxford Bay, Sutherland. It is clear from this figure that reverse-zoned feldspars occur over a wide area, and that they have mantles and cores whose compositions are related.

Relationship between unzoned and zoned plagioclase

In Fig.IV-3 a hypothetical unzoned plagioclase of composition represented by the line x-y has been chosen in association with a reverse-zoned plagioclase which may fall in any of the fields a to f.

In field c the core of the feldspar has a constant composition which falls in the field of the unzoned grains, but the mantle has a variable composition.

In field a the composition of the core is variable and that of the mantle constant and in the same range as the unzoned plagioclase.

In field b the composition of either the core or the mantle is related to the composition of the unzoned plagioclase.

In fields d, e and f the composition of neither core nor mantle corresponds with the composition of the unzoned plagioclase.

In Fig.IV-4a-e the composition of the unzoned and zoned polygonal

Fig.IV-2a-d. Graphical presentation of mantle-core compositions of reverse-zoned M_7 plagioclase.

(a) pegmatite fraction of migmatites.

(b) acid gneisses.

(c) gneisses from Laxford Bay.

(d) pegmatite fraction of migmatites (O), acid gneiss (X) and type-TD basite dykes (•).

Diagonal line demarcates fields of reverse and normal-zoned plagioclases.

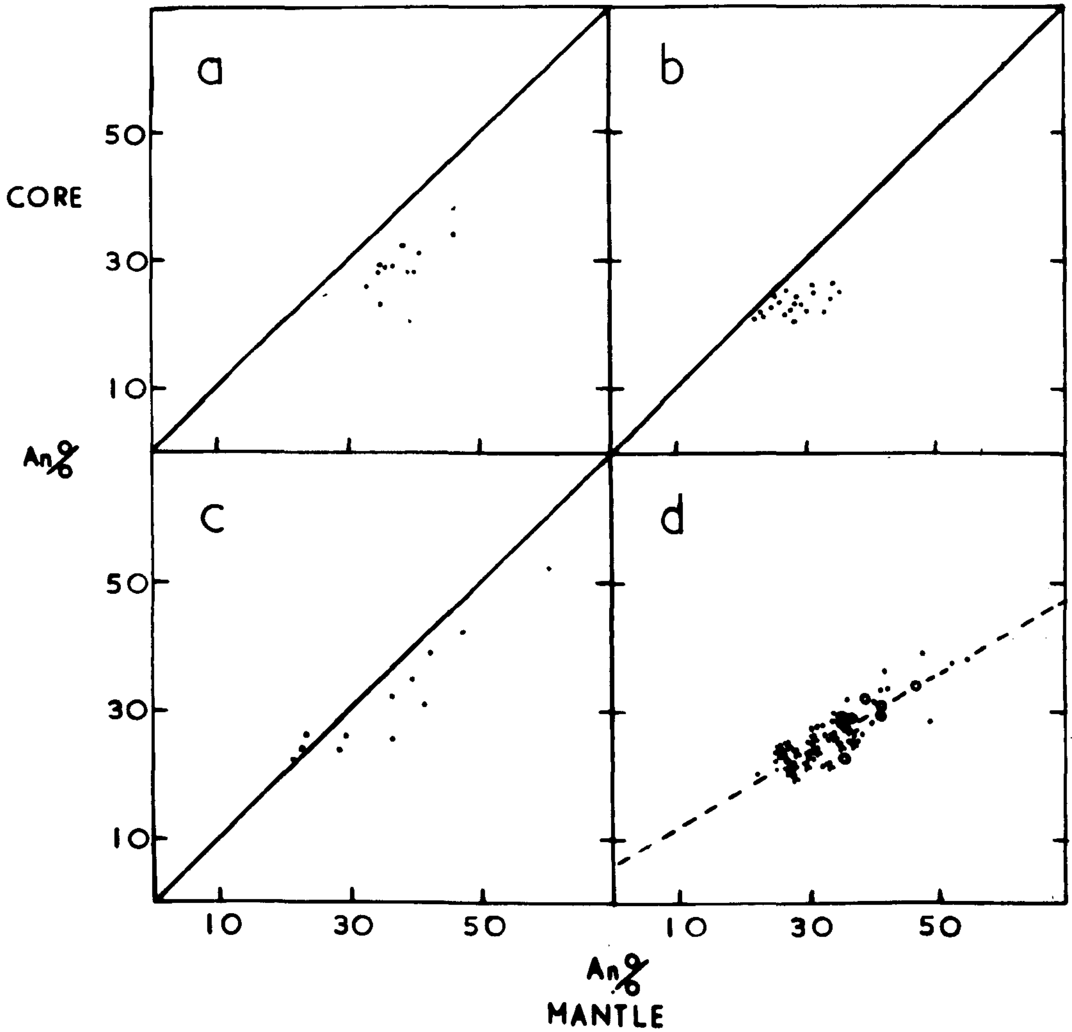
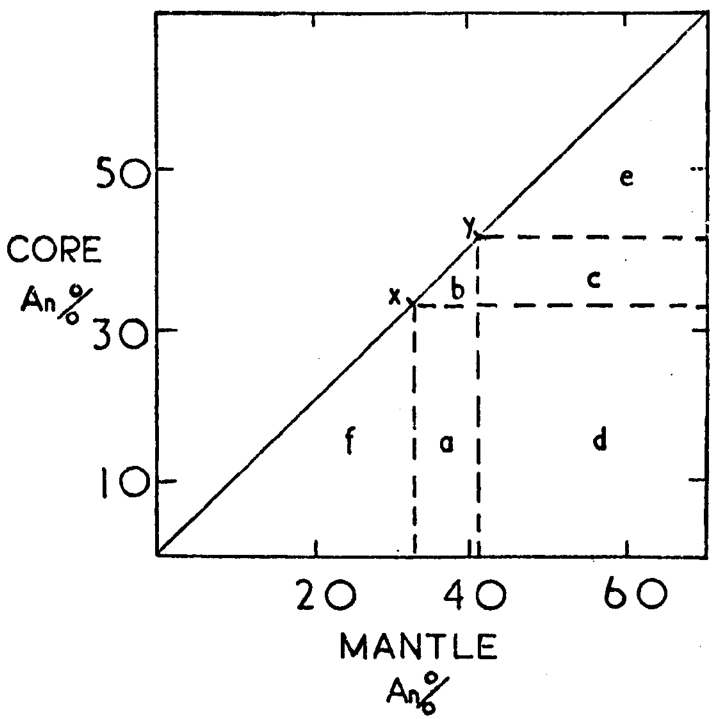
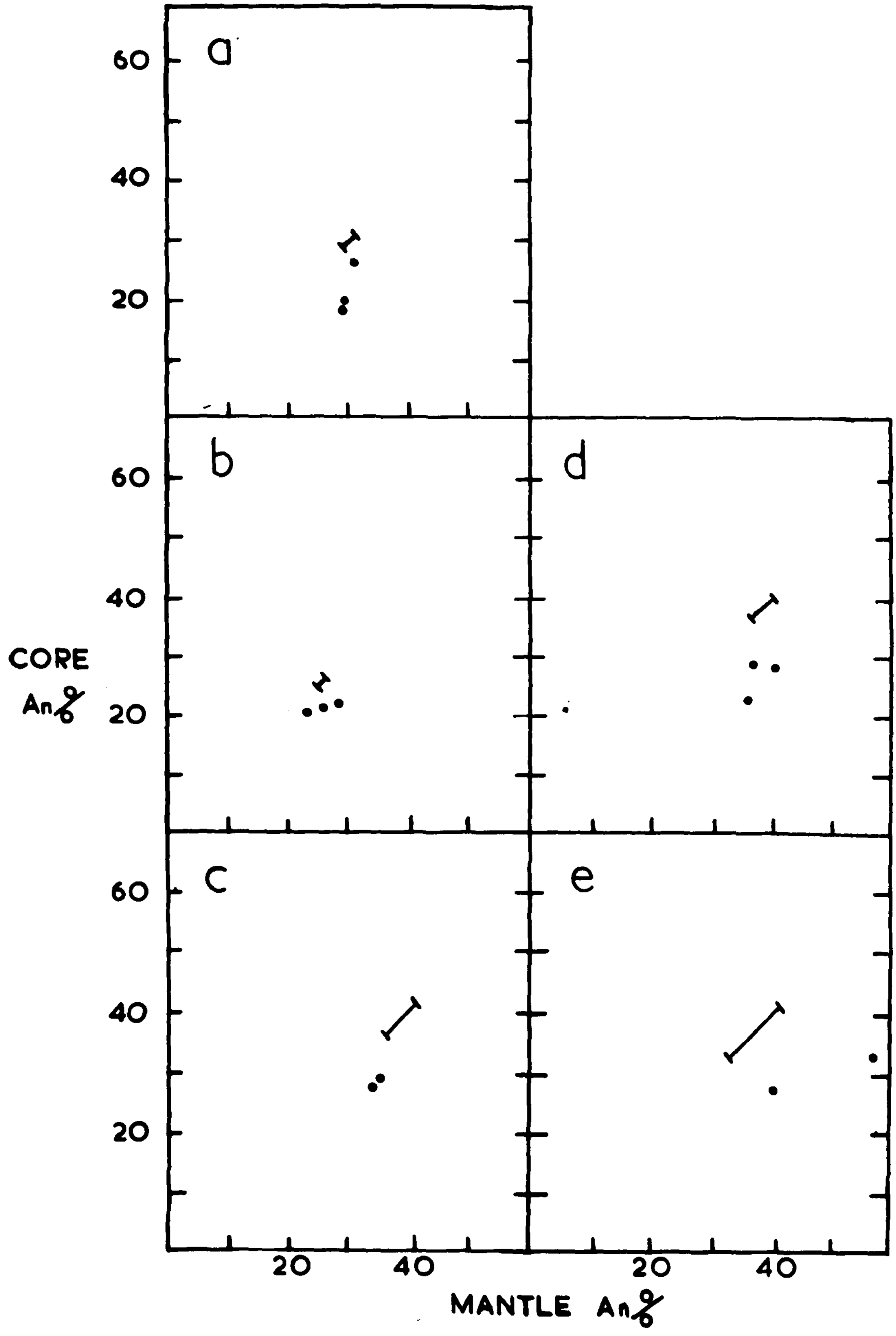

a
b
c
d
CORE
An%
50
30
10
50
30
10
10
30
50
10
30
50
An%
MANTLE

Fig.IV-3. Hypothetical representation of the composition of reverse-zoned plagioclases. Unzoned plagioclase of composition in the range x-y associated with reverse-zoned plagioclase falling in any of the fields a to f.



50
30
10
CORE
An%
20
40
60
MANTLE
An%
x
y
a
b
c
d
e
f

Fig. IV-4a-e. Comparison of unzoned plagioclase (⊢⊣) with associated reverse-zoned plagioclase (·) in
(a)-(b) acid gneiss
(c)-(e) post-D_3, pre-D_4 pegmatites in early basites.



a
b
c
d
e
60
40
20
CORE
An%
20
40
MANTLE An%

grains have been plotted for five groups of acid gneisses and pegmatites. The zoned plagioclase grains in nearly all cases fall in field (a) of the hypothetical example with a core of variable composition and mantle of constant composition, the mantle falling in the range of the unzoned feldspar for the rock.

Thus it would appear that the mantle of the plagioclase is replacing the core.

Origin of zoning in the feldspar

Zoning is not a common feature in metamorphic rocks (Rast 1964, Turner and Weiss 1963) since it is believed to represent disequilibrium. There are some records of zoned feldspars occurring in metamorphic rocks (Leake 1964, Strand 1948, Leclandam 1968, Wyckoff 1952) ranging in facies from amphibolite to charnockite. However, little is known about the origin of the zoning.

The following characteristics have been observed in the reverse-zoned plagioclase of the complex:-

(i) The unzoned plagioclase generally reflects the range in composition of the pre-existing feldspar within a given group of gneisses.

(ii) The mantle of the zoned plagioclase reflects the composition of the unzoned plagioclase.

(iii) Textural evidence suggests that the cores of the zoned plagioclase are being replaced by the mantle leading to the formation of an unzoned grain.

(iv) For a given rock the composition of the mantle appears constant whereas the core is variable.

(v) The compositions of the core and the mantle have a constant relationship.

(vi) The formation of zoned plagioclase appears to bear no relationship to the fabric nor to the mineralogical evolution of the rocks during the M_7 metamorphism (see metamorphism of dykes, Chapter III.2).

There are two possible explanations for the development of reverse zoning in plagioclase:-

(i) Growth of a new feldspar in a changing metamorphic environment.

(ii) Adjustment in a later process of an already crystallized feldspar.

Leclanandam (op.cit.) briefly reviewed the origins of reverse zoning in plagioclase and listed the following possible causes; progressive metamorphism (Myashiro 1958 and Shido 1958); grade-dependent breakdown of co-existing hornblendes (Binns 1965); addition by short range diffusion of "anorthite building" substance (Misch 1964); diaphthoresis accompanying sudden release of pressure (Hills 1936) and structural differences as a result of strain and compositional differences during crystal growth (Hsu 1955).

The suggestion made by Hills may be dismissed here since it was applied to a magmatic environment, whereas the zoning in these plagioclases has a metamorphic origin.

The modes of origin suggested by Myashiro, Shido and Hsu imply that reverse zoning developed at the time of growth of the feldspar, whereas the writer regards the nucleation and growth of plagioclase as a distinct episode which is unrelated to the formation of the reverse zoning.

However, the suggestion made by Binns involving the breakdown of co-existing hornblende may have some bearing on the origin of reverse zoning in this case since hornblendes showing exsolution features and formed during the M_7 metamorphism occur in the complex (see section IV. A.2).

It is apparent, from the fact that the least deformed dykes are only schistose at the margins whereas the more highly deformed dykes are schistose throughout, that the schistosity develops at the margins of the dykes and progresses towards the centre with progressive deformation. The foliated dykes have a metamorphic fabric which suggests that they have been recrystallized syntectonically and that the groups 1a to 2c (see Chapter III.B2) represent a continuous series of increasing recrystallization and deformation. It follows that polygonization of plagioclase must have taken place at different times depending on the relative position in the series.

The development of reverse zoning in plagioclase, in the writer's opinion, would seem to be grade-dependent. If it is suggested that reverse zoning developed contemporaneously with nucleation and growth of polygonal plagioclase grains, then it would also be expected that the variation of grade would be in phase with the variation of deformation in the dykes. That is, at the margin, nucleation and growth, with concomitant reverse zoning of plagioclase, would occur earlier than similar effects in the dyke centre. However, the metamorphic grade variation at the margin and the centre would then not correspond and this seems highly improbable since temperature (which must be the principal control on grade) can hardly vary appreciably across a narrow dyke.

If temperature is the most significant variable that controls metamorphic grade, it would seem unlikely that deformation has similar controls. The latter will tend more to be controlled by anisotropies in the complex. The writer, therefore, dismisses the view that the grade variation responsible for reverse zoning in plagioclase is in phase with the progressive deformation. This wouldimply that nucleation and growth of the feldspar is unrelated to the development of zoning and that the zoning owes its origin to a later episode.

There still remains the second explanation in which reverse zoning arises by adjustment of an already recrystallized polygonal feldspar in a later process. The formation of a reverse-zoned feldspar from an already probably unzoned feldspar must require the substitution of CaAl for NaSi at the grain boundaries, that is, introduction of CaAl and removal of NaSi. The occurrence of veins of albite cutting the S_7 foliation in the gneisses may owe their formation to the removal of NaSi from the polygonal feldspar. In a search for the source of CaAl three possibilities appear to be available. These are hornblende minerals, epidote or an extraneous source. The presence of co-existing hornblendes, which developed during M_7 by exsolution processes, may have involved the freeing of CaAl which could have been made available to the feldspar. However, co-existing hornblendes are uncommon as compared with epidote, which occurs in all gneissic types. The occurrence of reverse-zoned feldspar in acid gneisses with neither hornblende nor epidote tends to invalidate the latter minerals as the cause of reverse zoning, and may suggest an extraneous source of CaAl.

In conclusion, the writer considers that reverse zoning in feldspars is a result of a post-nucleation and growth, grade-dependent process in which addition of CaAl and removal of NaSi occurred. The latter may be a result of the reaction relations between co-existing feldspars and hornblendes or epidotes, or by the action of an extraneous fluid rich in CaAl on the feldspar.

B. The granite sheet and pegmatites

1. Distribution and field relations

There is only one granite sheet in the area and this forms a collar around An Torr (Fig.IV-1), The pegmatites are, however, more common and occur in narrow belts striking NW-SE at (i) Creag an Fhraoich, (ii) north of the large metadolerite dyke at Rudha na h-Airde Glaise, (iii) 400 metres south-east of Diabaig and (iv) north of Meall Ceann na Creige (see Fig.IV-1).

The granite sheet never exceeds 25 metres in thickness and the pegmatites range from a few cms. up to 10 metres in thickness.

The granite sheet is sharply discordant to the steep belt of gneisses at An Torr (see Plate IV-4a) and post-dates the D_7 deformation episode. It has a sub-horizontal attitude, with sharp margins against the gneisses but no chilled margins.

The pegmatites, on the other hand, are nearly always situated in belts of steep foliation particularly where the foliation is steepened rapidly (eg. the F_5 asymmetrical folds at Meall Ceann na Creige) and where intrusion has been facilitated by the attitude of this foliation. They are generally concordant to the foliation in the gneisses although local discordancies may occur (see Plate IV-5b). In Plate IV-5a a thir pegmatite dyke has intruded an S_7-foliated type-TD basite, being slightly discordant to the foliation in the dyke. The pegmatites generally have very sharp contacts against the host gneisses and have no chilled margins.

The granite sheet at An Torr feeds the associated pegmatites which are intruded concordantly with the steep foliation.

2. Petrology

(a) The granite sheet

The granite is a pink, leucocratic, coarse-grained, inequigranular rock commonly with a graphic texture (see Plate IV-4b). It consists of chlorite, epidote, plagioclase, quartz, microcline, muscovite and iron ore.

Plagioclase forms between 10% to 45% of the granite depending on the amount of microcline present. It is oligoclase-andesine, An_{29-33}, and forms large, irregular anhedra which are generally partly altered to a brown unidentifiable dust or to sericite flakes. Grains range up to 2·5 mm. with an average size of 1·0 mm.

Microcline forms 15% to 35% and generally has an irregular, xenoblastic habit. It has serrated edges against plagioclase and replaces the latter, often forming a patchwork of inclusions, in optical continuity with each other, in plagioclase producing antiperthite. Microcline generally has cross-hatch twinning and is a perthite, with frequent exsolved albite flames.

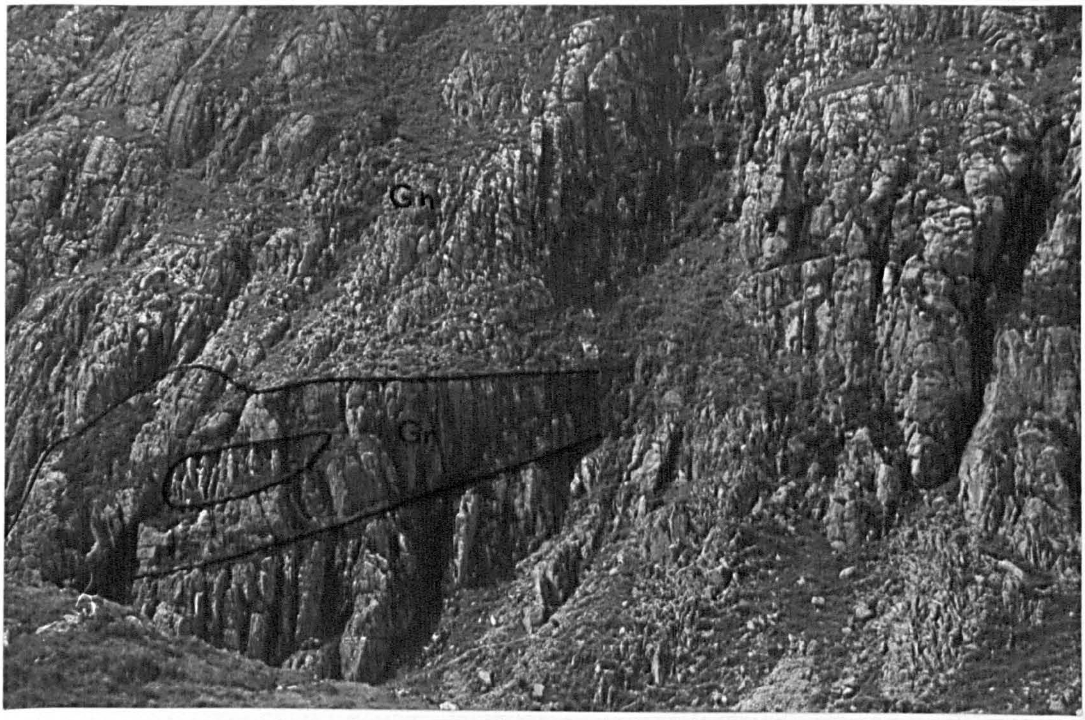
Quartz forms 25% to 35% and occurs as large, irregular, xenoblastic grains and as sub-rounded inclusions in the plagioclase.

Muscovite may form up to 4% although it may be absent. It forms large plates which generally overgrow plagioclase and quartz, and is therefore later than the latter minerals.

Chlorite, epidote and iron ore occur as accessory minerals.

Plate IV-4a. Granite sheet (Gr) cutting steep belt of S_4 foliated gneisses (Gn) in the neighbourhood east of Diabaig (802603).

Plate IV-4b. Graphic granite from the granite sheet (802603).


Gn
Gr

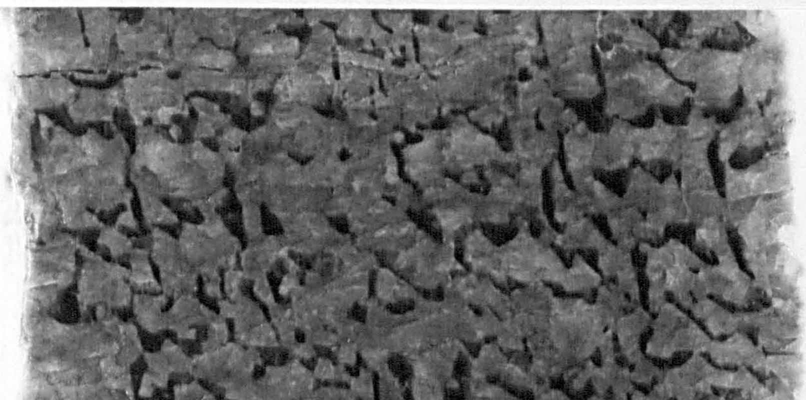
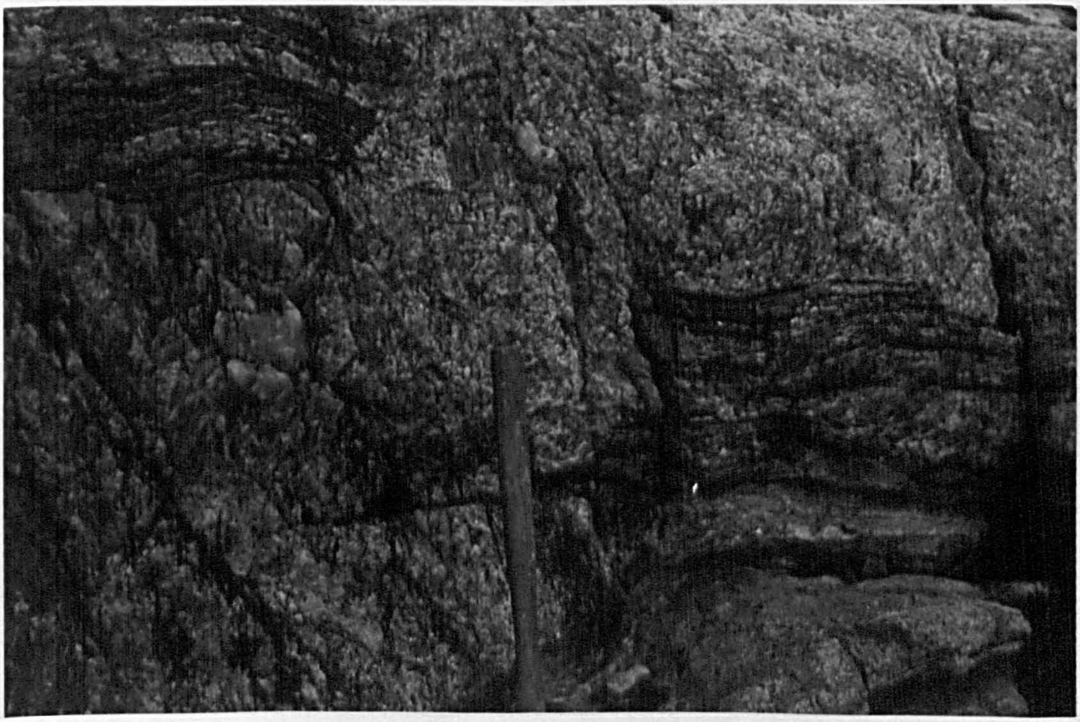

MM
1
2
3
4

Plate IV-5a. Late pegmatite dyke cutting type-TD basite. From the neighbourhood of Creag an Fhraoich (809589).

Plate IV-5b. Late pegmatite cutting S_4 finely-foliated gneisses north of Meall Ceann na Creige (598808).



(b) The pegmatites

In hand specimen the pegmatites are similar to the granites and are of the simple type. They are generally uniform in their mineral assemblage throughout each body, but in the belt south of Creag an Fhraoich are several zoned pegmatites with quartz cores. The pegmatites occasionally have dark mafic schlieren consisting of chloritized biotite, muscovite, epidote and magnetite. Plagioclase, quartz and microcline form the major part of the rock, with garnet as an accessory in some bodies. The felsic minerals resemble those developed in the granite sheet.

C. Post-D_8 retrogressive metamorphism and alkali metasomatism

1. Introduction

The presence of microcline, chlorite and muscovite is widespread in the complex and few rocks, except for members of the dyke swarm and the metasediments, are unaffected. Textural evidence indicates that they are late in the petrological evolution of the complex, although the inter-relationships of muscovite, chlorite and microcline are obscure. Since their formation is incomplete in numerous examples, it is possible to examine the stages of development of the assemblage.

The development of the low temperature mineral association of microcline, muscovite and chlorite in rocks with a high temperature fabric indicates that the earlier mineral assemblages have been telescoped (cf. Schermerhorn 1960).

2. Distribution and field relations

The distribution of the various gneissic units of the complex has been discussed in Chapter II.

65% to 75% of the acid gneisses of the complex have registered chloritization of biotite. The S_3 and S_4 banded gneisses, S_4 finely-foliated gneisses and the massive gneisses show no notable differences in the effects of chloritization (Fig.IV-5a). Similarly, the acid gneisses show a positive correlation in the development of muscovite and microcline (Fig.IV-5b-c). There is no uniform directional increase in microcline in the complex (eg. the acid gneisses in the far north show no notable differences in their proportion of microcline from those in the extreme south). It appears that the gneiss type does not have any control on the distribution of microcline in the complex.

Although there is no directional increase in microcline proportions in the complex, it has been found that the distribution is not random. In Fig.IV-6 the microcline proportion in individual rocks has been plotted in the area between Loch nanTri-eileanan, Loch a'Choire Bhig and Loch na Beiste. It is clear that certain areas are more rich in microcline than others and that several NW-SE belts of microcline-rich and microcline-poor rocks alternate. However, further south the distribution is less regular, although there is still an apparent NW-SE trend exhibited by microcline-poor areas. It appears that the form of the distribution is related to the structure exhibited by the gneisses in this area. In the north, the gneisses have a predominant NW-SE foliation which may have produced a directional control on the formation of microcline, whereas in the south where the gneisses are characteristically flat-lying with irregular strike, the distribution of microcline is less regular.

There appears to be no correlation between the distribution of the dykes or of early basites with microcline distribution.

3. Petrology

(a) Microcline

The variation in microcline proportion in the acid gneisses is shown in Fig.IV-7. Microcline is most frequently developed in proportions of 0% to 10%. The proportion ranges in the various rock types are: S_3 banded gneisses - 0% to 25%, S_4 banded gneisses - 0% to 50%, massive gneisses - 0% to 55%, S_4 finely-foliated gneisses - 0% to 50% and post-D_3-pre-D_4 pegmatites in acid gneisses - 0% to 65%. There is thus considerable variation in the acid gneisses, but in the early basites (0% to 10%) the variation is considerably less.

Fig.IV-5. Graph illustrating the proportion of rocks which have chlorite, microcline and muscovite developed.

a. S_3 banded gneisses.

b. S_4 banded gneisses.

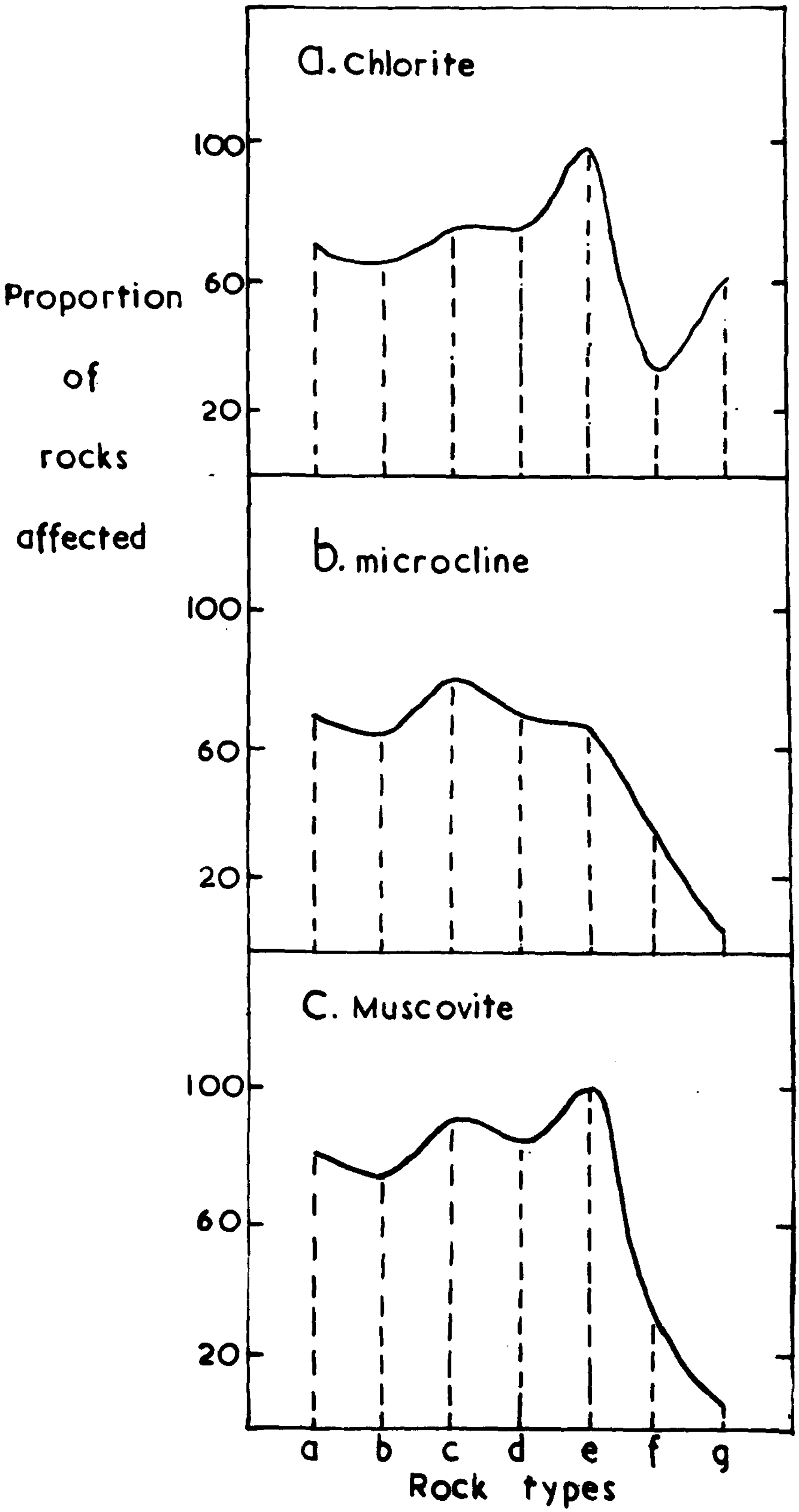
c. Massive gneisses.

d. S_4 finely-foliated gneisses.

e. Post-D_3, pre-D_4 pegmatites in acid gneisses.

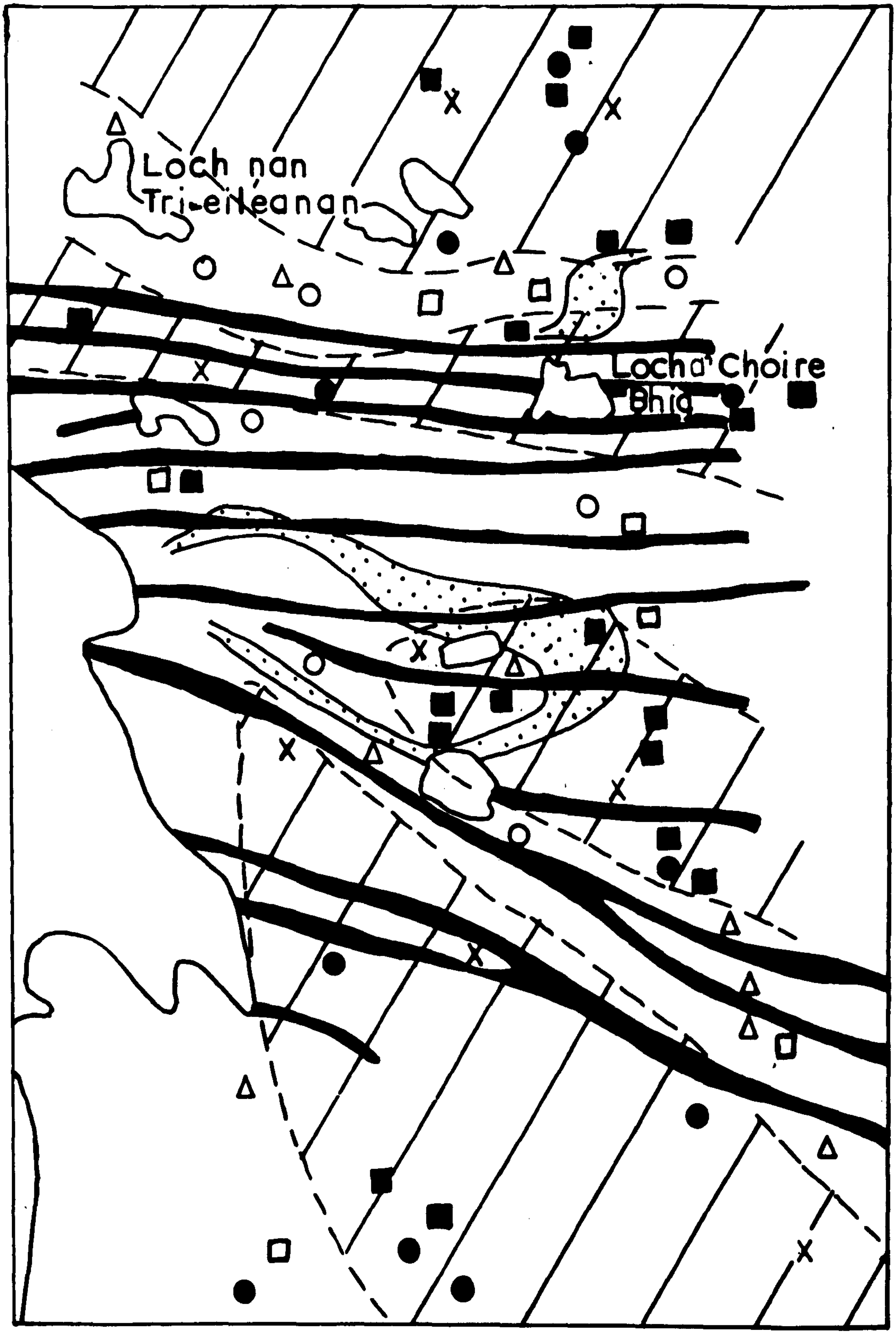
f. Post-D_3, pre-D_4 pegmatites in early basites.

g. Early basites.



a. Chlorite
b. microcline
c. Muscovite
Proportion of rocks affected
100
60
20
a
b
c
d
e
f
g
Rock types

Fig.IV-6. Distribution of microcline in the gneisses from the area between Loch na Beiste and Loch nan Tri-eileanan. Rocks with 0(Δ), 0-5 (□), 5-10 (O), 10-20 (●), 20-30 (X) and 30 percent or more (■) of microcline are represented. Areas with more than 10 percent have been demarcated from those with less.



6 inches to mile

Observations of the textural relations of microcline to plagioclase suggest that the first development of microcline is indicated by the formation of antiperthite (see Plate IV-6a). The microcline inclusions in the plagioclase may take several forms:-

(i) patchworks, in which individual tabular grains of microcline are elongated parallel to albite twins (010) or (001) directions in the plagioclase grains.

(ii) bladelike inclusions which are arranged in parallel, but are unrelated to any visible crystallographic direction in the host plagioclase grains.

(iii) irregular patches unrelated to any direction in the host grains.

The inclusions of microcline within a grain are all in optical continuity and the inclusions generally have serrated edges against the host plagioclase grain.

Further microclinitization leads to coalescence of the inclusions producing discrete grains which are generally interstitial to the plagioclase aggregates. Increasing development of microcline leads to the partial or complete replacement of plagioclase being reversed from the initial antiperthite development. This widespread formation of microcline produces isolated aggregates of xenoblastic, regularly shaped, often polygonal grains of microcline (see Plate IV-6b).

That microcline forms at the expense of plagioclase is suggested by the abundant textural evidence and by the frequency curve of distribution of microcline (see Fig.IV-7).

A common feature of the acid gneisses and particularly the banded gneisses is the presence of large plagioclase augen (see Chapter II.C), where intense microclinization has occurred, these augen have been partially or wholly replaced by microcline (see Plate IV-7a). Plate IV-7a illustrates the behaviour of microcline to be concentrated in bands parallel to the foliation in well foliated gneisses. This would tend to indicate that the foliation was active during the production of the microcline.

Plate IV-6a. Antiperthite. Plagioclase (pl) with inclusions of replacing microcline (mi) (x25 X.P.L.).

Plate IV-6b. Regular shaped xenoblastic microcline with cross-hatch twinning (x25 X.P.L.).

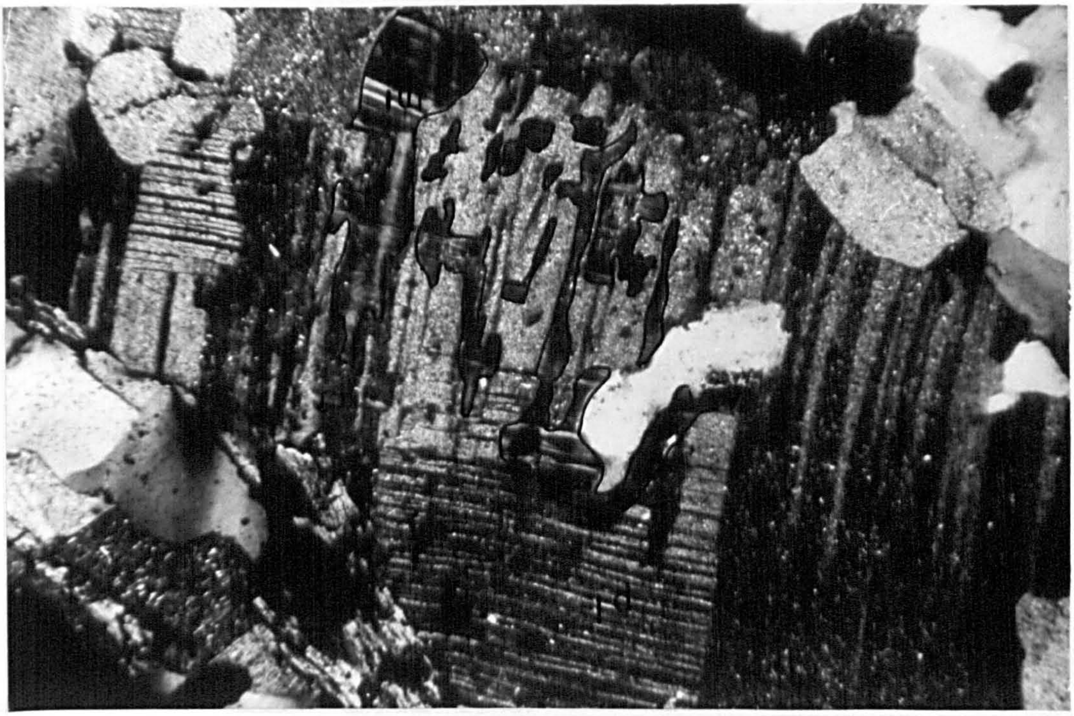
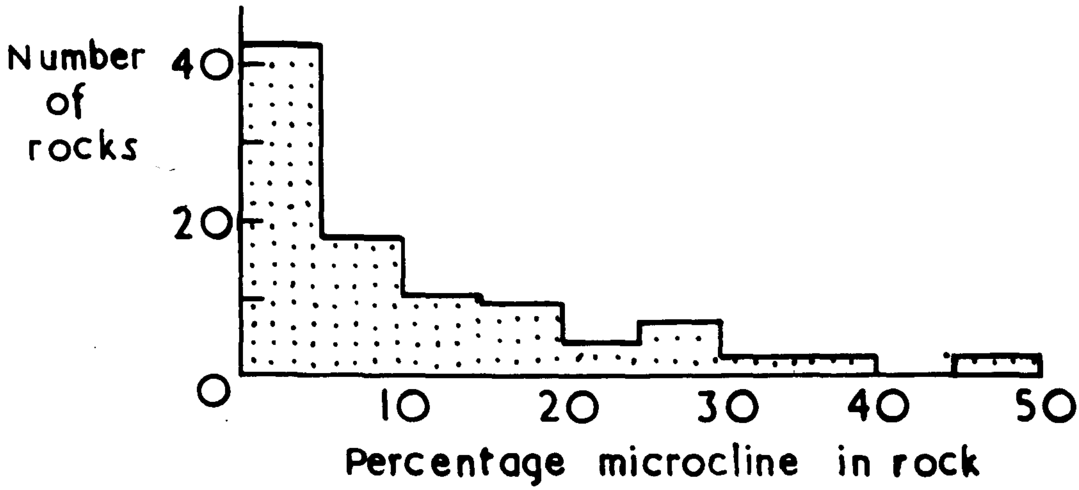


Fig.IV-7. Distribution of proportions of microcline in the acid gneisses of the complex.


Number of rocks
40
20
0
10
20
30
40
50
Percentage microcline in rock

Where intense microclinitization has taken place, granular epidote is commonly found at the intergranular boundaries of microcline and may have formed from the exsolution of calcium from the replaced plagioclase (see Plate IV-7b). Approximately 50% of the microcline grains are flame perthites (see Plate IV-7b). The occurrence of exsolved albite varies in amount which appears to be related to the degree of brittle deformation exhibited by the gneisses (see Chapter V.H) (cf. Chayes 1952). In the more intensely brittle-deformed gneisses, flame perthites are generally exceedingly well developed and may form up to 60% of the host microcline grain. In microclines in which flame perthites are sparse, the flames are isolated and form towards the margin of the grain. Increased exsolution leads to more widespread flames which are often arranged en echelon within the grain. Towards the margin of the grain the flames often coalesce forming a rim of albite. The flames of albite are generally oriented parallel to one of the twin directions in the host microcline.

(i) Formation of alkali rims around plagioclase

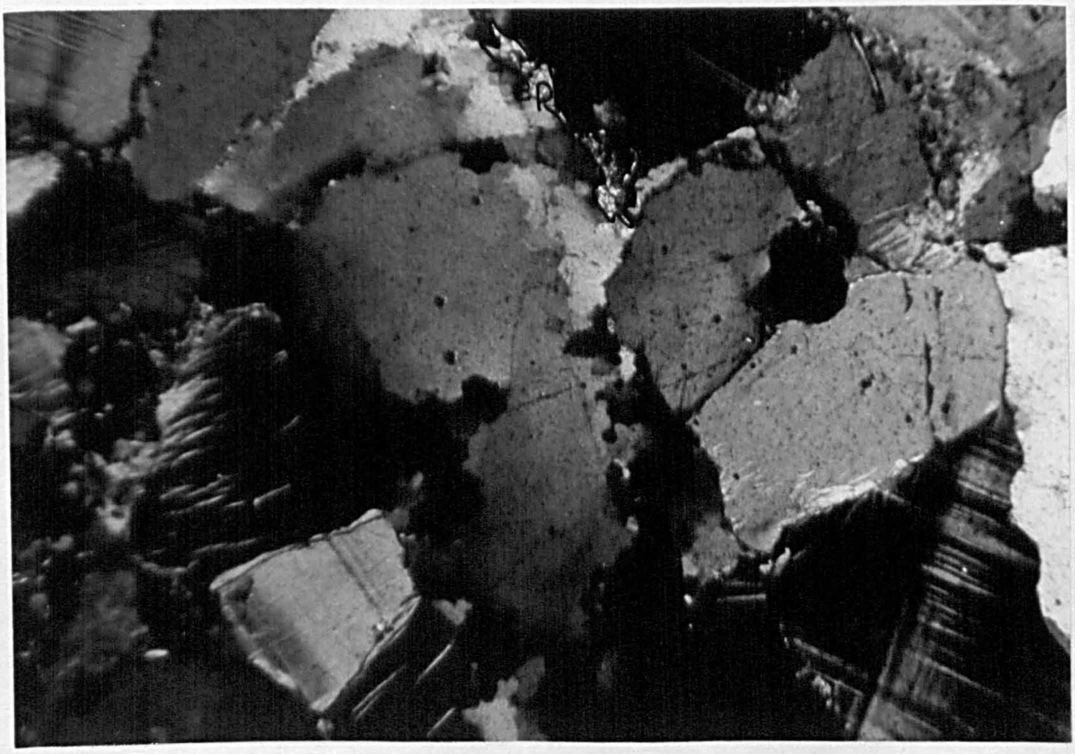
The formation of alkali rims around plagioclase associated with the metasomatic development of microcline have been recorded by a number of writers (eg. Stand 1948, Scotford 1956, Coombs 1950, Marmo 1961, Rogers 1961, Schermerhorn 1961 and Cheng 1943). The rims are only formed where microcline is adjacent to the feldspar, and in Plate IV-8a where a plagioclase grain adjoins quartz and microcline, the alkali rim is only found adjacent to the microcline grain which suggests that there is a genetic relationship between the microclinitization and the development of alkali rims.

The alkali rims vary in thickness, which appears to be directly related to the intensity of microclinitization in the rock. That is, where microcline is widely developed the alkali rims are broad and may in fact form complete grains, but where microcline is sporadically developed the rims are thin. There also appears to be a similar correlation between the formation of flame pethites and alkali rims (eg. Plate IV-8a).

Plate IV-7a. Microcline porphyroblasts occurring in S_4 finely-foliated gneisses. Microcline (Mi) is also developed in bands parallel to S_4 (x10 X.P.L.).

Plate IV-7b. Microcline flame perthites with late epidote (Ep) formed at grain boundaries (x25 X.P.L.).


mi
mi



The host plagioclase grain may or may not be turbid as a result of alteration, whereas the associated alkali rims are always clear and free of alteration which would tend to indicate that the sericitization of the plagioclase pre-dated the formation of alkali rims.

The twinning present in the alkali rim is confluent with that of the host plagioclase grain although the extinction within the twin lamellae may be reversed. The variation in composition of the alkali rim is An_{3-15} and there appears to be no correlation between the composition of the alkali rim and that of the host plagioclase, (see Fig.IV-8).

(ii) Formation of myrmekite

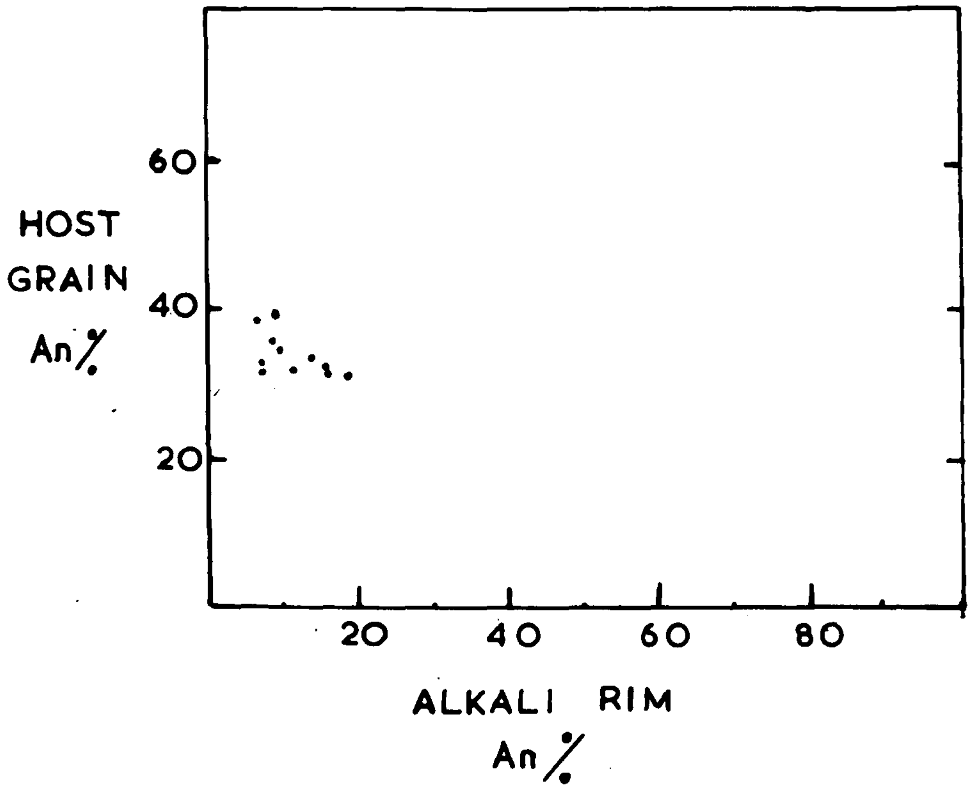
Myrmeckite is frequently found in gneisses which have suffered intense potassium metasomatism. It forms within the host feldspar and is never found in the alkali rims. It consists of a plexus of quartz rods enclosed in plagioclase.

(b) Chlorite

Chlorite occurs in all the acid gneisses, early basites, migmatitic derivatives of acid gneisses and early basites, and in those dykes which have biotite in the mode. It nearly always forms as a result of the retrogression of biotite and to a much lesser extent of hornblende. It pseudomorphs the form of biotite and has the pleochroic scheme x - pale green, y=z - green with anomalous blue polarization colours which are diagnostic of penninitic chlorite. The development of chlorite takes place first along certain cleavage traces in biotite and continues until all the biotite has been replaced.

In many metamorphic terrains where retrogression has resulted in the formation of chlorite-bearing rocks, the assemblage is often spatially related to belts of cataclasites. However, chlorite bears no direct relationship to the degree of brittle deformation exhibited in the Torridon rocks - chlorite is often developed in rocks which show no indication of brittle deformation and conversely, biotite remains stable in rocks which have undergone intense deformation.

Fig. IV-8. Graphical presentation of the composition of host plagioclase grain and alkali rims about them.


HOST
GRAIN
An%
60
40
20
20
40
60
80
ALKALI RIM
An%

(c) Muscovite

Muscovite has been developed in two separate generations (see Chapter II.A1), the later of which is represented in the granite sheets and pegmatites which suggests that muscovites with similar modes of occurrences in the acid gneisses are also of late formation.

In nearly all the cases examined, the late muscovite overgrows quartz, plagioclase or biotite-chlorite flakes. It has two modes of occurrence - either feather-like overgrowths or large flake-like grains which are in part symplectites with quartz. Muscovites with a feather-like habit are generally found as overgrowths of biotite-chlorite flakes, whereas the flake-like muscovites overgrow quartz and plagioclase. These flake-like muscovites (see Plate IV-8b) have the symplectite developed either in the centre or at the margins of the flakes.

The formation of the symplectites pre-dates the D_9 deformation episode since the flakes are often kinked and bent (see Chapter V.H).

4. Relations between microcline, muscovite and chlorite

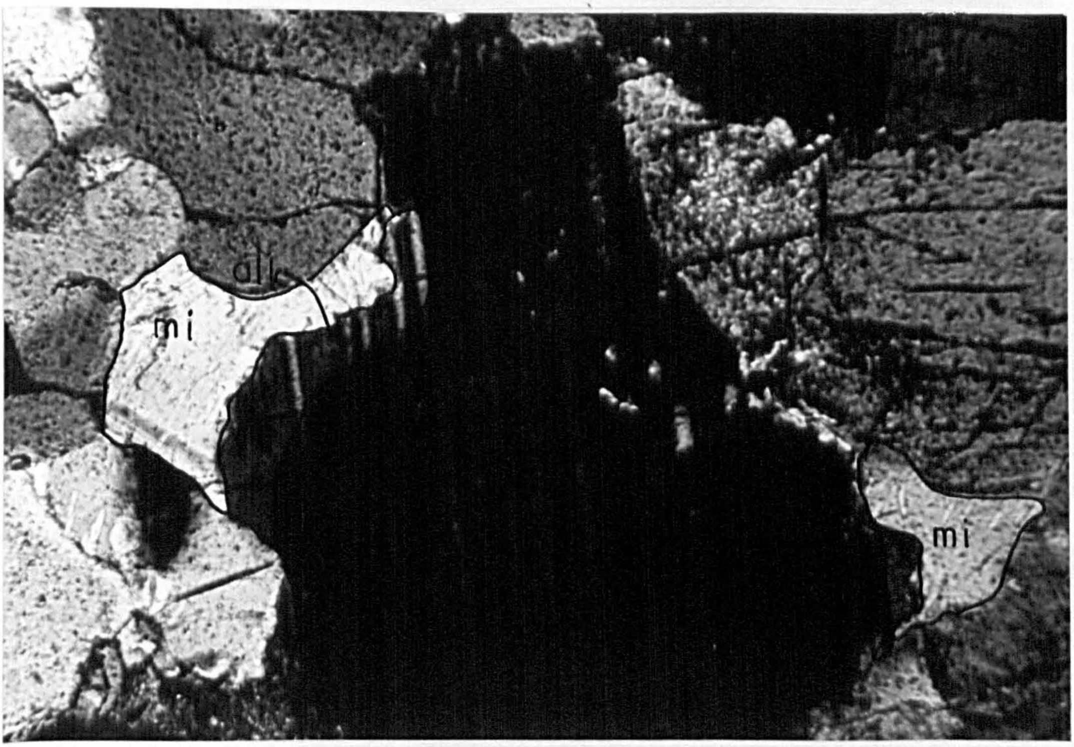
The common association of muscovite, microcline and chlorite in the gneisses might suggest a common genesis. However, observations of textures in the gneisses haverevealed little or no evidence to support this, except to reveal that the minerals were formed in the period between the D_8 and D_9 deformation episodes.

It has already been established (Chapter III.B2) that either the microclinitization and addition of quartz carried on after the cessation of the chloritization either that the chloritization pre-dated the microclinization and represents a separate event.

A further possibility is that chloritization of biotite commenced earlier than the microcline metasomatism but continued during the latter event. Since the textural evidence alone does not offer convincing evidence as to which alternative is correct, a quantitative determination of the distribution of muscovite, microcline and chlorite may throw some light on the problem. Contemporaneous development of muscovite, microcline and chlorite would be suggested by the following:

Plate IV-8a. Alkali rims (Alk) which have been developed around plagioclase. Rim is only found where microcline (Mi) is adjacent to plagioclase (x100 X.P.L.).

Plate IV-8b. Muscovite-quartz symplectite


alk
mi
mi

If muscovite, microcline and chlorite were formed together, the association muscovite, microcline and chlorite, or muscovite and microcline, muscovite and chlorite, microcline and chlorite would be found more frequently than if the association was by chance.

It has been suggested that re-organization of potassium from the breakdown of biotite to chlorite may produce muscovite or microcline (Chayes 1955).

From Figs.IV-9a-c the following conclusions can be drawn:-

(i) In the variety of gneisses in the complex muscovite, microcline and chlorite all show a decrease in proportion from acid gneisses to early basites.

(ii) There is a positive correlation between microcline-muscovite (Fig. IV-9a), muscovite-chlorite (Fig.IV-9b) and microcline-chlorite (Fig.IV-9c).

(iii) Fig.IV-9b indicates that the formation of chlorite is slightly more widespread than muscovite in the gneisses.

(iv) Similarly in Fig.IV-9a the formation of microcline is more widespread than muscovite.

(v) Microcline and muscovite do not appear to be related.

There is a positive correlation between the occurrence of muscovite, microcline and chlorite suggesting that they developed contemporaneously. It appears that chlorite is more widespread than the others, and that microcline is more widespread than muscovite.

Origin of muscovite and microcline in the complex

There are three possible modes of origin of muscovite and microcline in the gneisses:-

(i) Breakdown of previous mineral(s) by retrogression.

(ii) Breakdown of biotite to chlorite releasing potassium for the

Fig.IV-9a-c. Graphical presentation of the relationships between muscovite, microcline and chlorite. The relationships between muscovite and microcline (a), chlorite and muscovite (b) and chlorite and microcline (c) are shown.

In (a) full-line shows the proportion of rocks with muscovite and microcline present; dotted line muscovite present, microcline absent; dotted-dashed line muscovite absent, microcline present; and dashed line muscovite absent, microcline absent.

In (b) full-line shows the proportion of rocks with chlorite and muscovite present; dotted line chlorite present, muscovite absent; dotted-dashed line chlorite absent, muscovite present and dashed line chlorite absent, muscovite absent.

In (c) full-line shows the proportion of rocks with chlorite and microcline present; dotted line chlorite present, microcline absent; dotted-dashed line chlorite absent, microcline present; and dashed line chlorite absent, microcline absent.

a. S_3 banded gneisses.

b. S_4 banded gneisses.

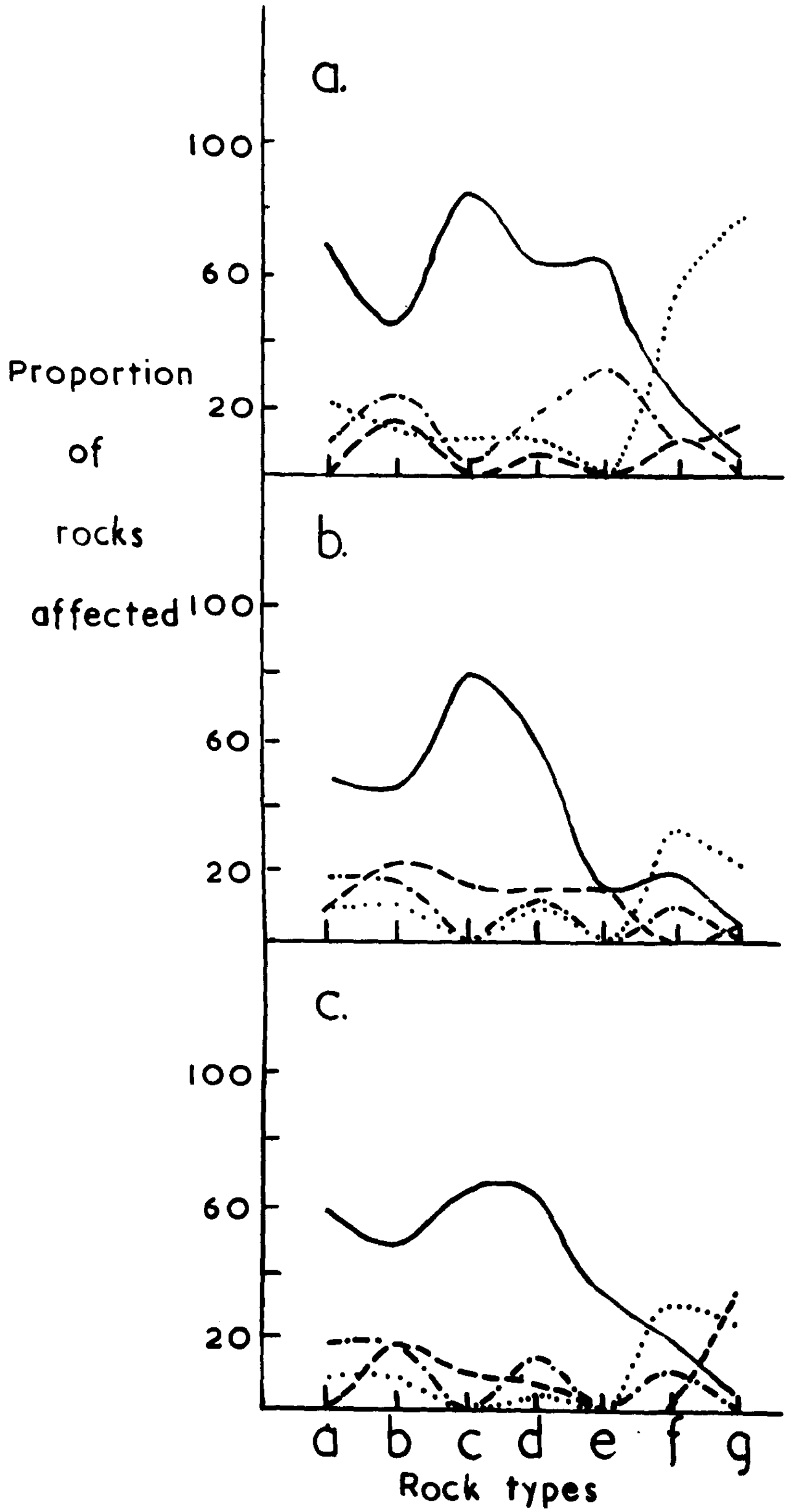
c. Massive gneisses.

d. S_4 finely-foliated gneisses.

e. Post-D_3, pre-D_4 pegmatites in acid gneisses.

f. Post-D_3, pre-D_4 pegmatites in early basites.

g. Early basites.


a.
100
60
20
Proportion
of
rocks
affected
b.
100
60
20
c.
100
60
20
a b c d e f g
Rock types

formation of muscovite and/or microcline.

(iii) Metasomatic derivation from an extraneous source.

There is no microscopic evidence for the breakdown of previous minerals by retrogression leading to the formation of microcline and muscovite in the gneisses and therefore this origin is unlikely.

There is, however, abundant evidence for the breakdown of biotite to chlorite and for the development of muscovite and microcline in the gneisses. There is sufficient breakdown for the supply of potassium for the formation of muscovite provided there is also sufficient excess aluminium in the rocks. However, the amount of microcline developed in some gneisses (in excess of 50%) is far too high for them to have received all their potassium from biotite.

Thus a metasomatic derivation of potassium from extraneous sources appears to be the most likely mode of origin of microcline and possibly muscovite.

V. STRUCTURAL GEOLOGY

A. Introduction

Structural analysis, by detailed exposure mapping, of the Lewisian rocks of Loch Torridon has revealed the presence of at least nine successive deformations. The criteria by which the structural sequence has been determined are based upon the recognition of stratigraphic marker horizons (eg. the dyke swarm), fold style, orientation of s-surfaces and lineations, and by the unravelling of successive superposed deformations.

A variety of penetrative and non-penetrative s-surfaces and lineations have been used:-

	Penetrative	Non-penetrative
s-surfaces	Foliation	Pegmatites and granites
		Early basites and ultrabasites
		Dykes
		Massive and banded gneisses
Lineations	Boudins	
	Augen	
	Mineral lineations	
	Fold axes	
	Quartz rods	
	Slickensides	

An analysis of the distribution and mutual relations of the rocks and minor structures indicates that the present disposition of the rocks results from at least nine episodes of deformation (D_{1-9}) which are briefly outlined below:-

1. D_1 deformation producing S_1 foliation.
2. D_2 deformation producing F_2 folds and S_2 axial-planar foliation.
3. D_3 deformation producing F_3 folds and S_3 axial-planar foliation, followed by a phase of D_3A flattening and major folding (D_3B).

4. D_4 deformation producing F_4 folds with S_4 axial-planar foliation.
5. D_5 deformation producing F_5 major and minor folds and S_5 foliation.
6. D_6 deformation producing F_6 folds and S_6 foliation.
7. D_7 deformation producing F_7 folds and S_7 axial-planar foliation.
8. D_8 deformation producing F_8 minor folds.
9. D_9 deformation producing cataclasites and mylonite banding S_9.

A unique dyke swarm (see Chapter III.B) was intruded after D_5 and before D_6.

For simplicity of description, the S_3 foliation, because it is the earliest widespread structure, will be described first, together with its relationship to the earlier structures. The following structures D_4 to D_9, will be discussed in chronological sequence.

An attempted correlation of the structural sequence of the Torridon Lewisian, with sequences established from other areas will be made in Chapter VI.

B. The D_3 and pre-D_3 structures

Structures arising as a result of the D_3 deformation episode occur predominantly in the vicinity of An Ruadh Mheallan and are recognized in several isolated belts at Loch a'Choire Bhig, north and north-east of Loch na Beiste and east of Diabaig. For the general characteristics and distribution of the S_3 foliation see Chapter II and Fig.II-1. The foliation varies in strike from NE to NW and also shows considerable dip variation. A statistical analysis of S_3 foliation at An Ruadh Mheallan (see domain 1, Fig.V-1) reveals that it has undergone major folding about a fold axis plunging 45°SW (see Fig.V-2a). A further examination of the foliation throughout the whole area confirms the above girdle pattern (see Fig.V-2b).

The major folding of the S_3 foliation is also revealed by the outcrop patterns of early basites and ultrabasites. The early basites south-west of Loch Airidh Eachainn, north-east of Loch a'Choire Bhig, in the neighbourhood of Lochan Dharach and two hundred and fifty metres south-west of Loch na Leirg all have fold form. [redacted]

Fig.V-1. Domain divisions in the area.

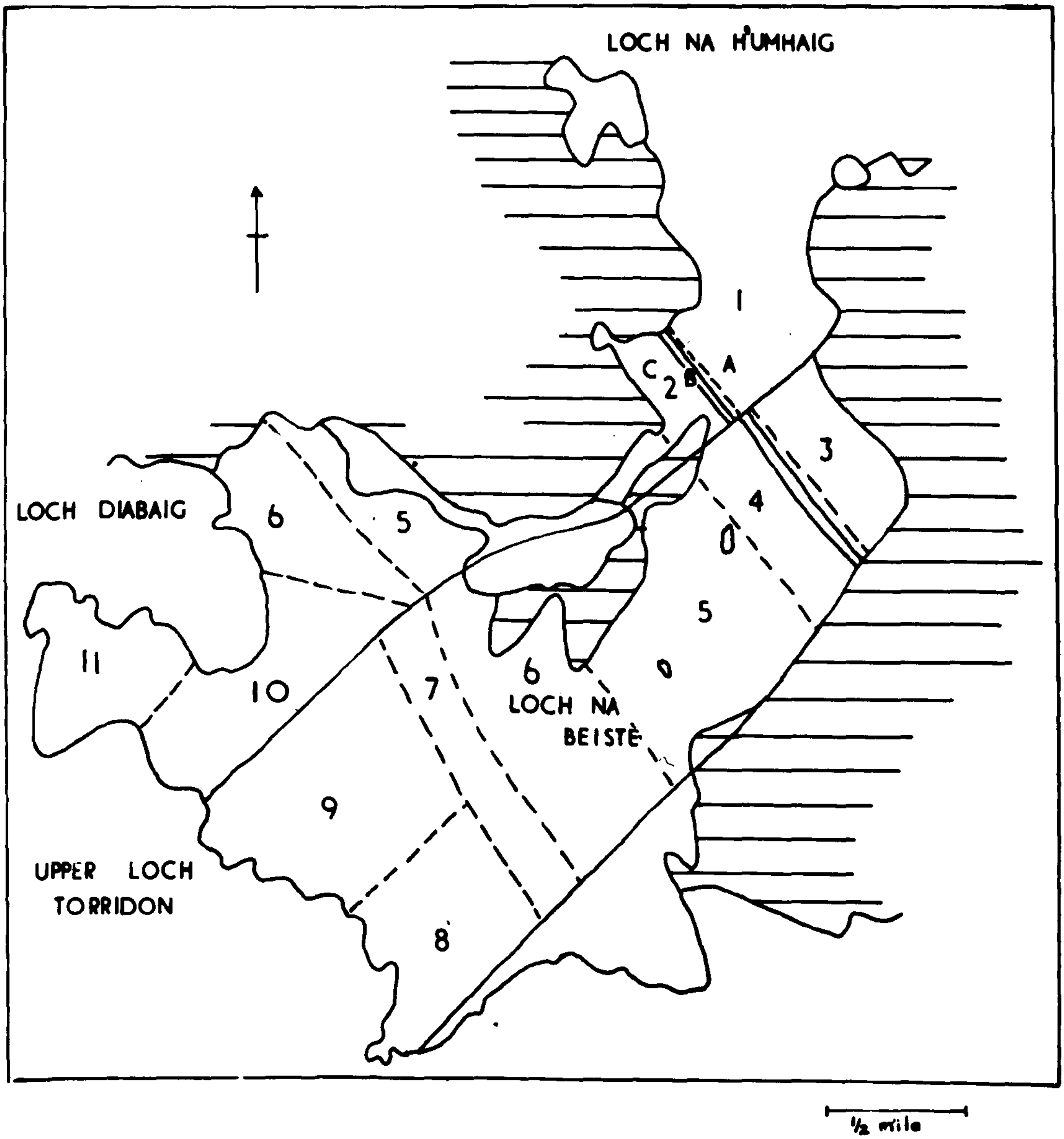
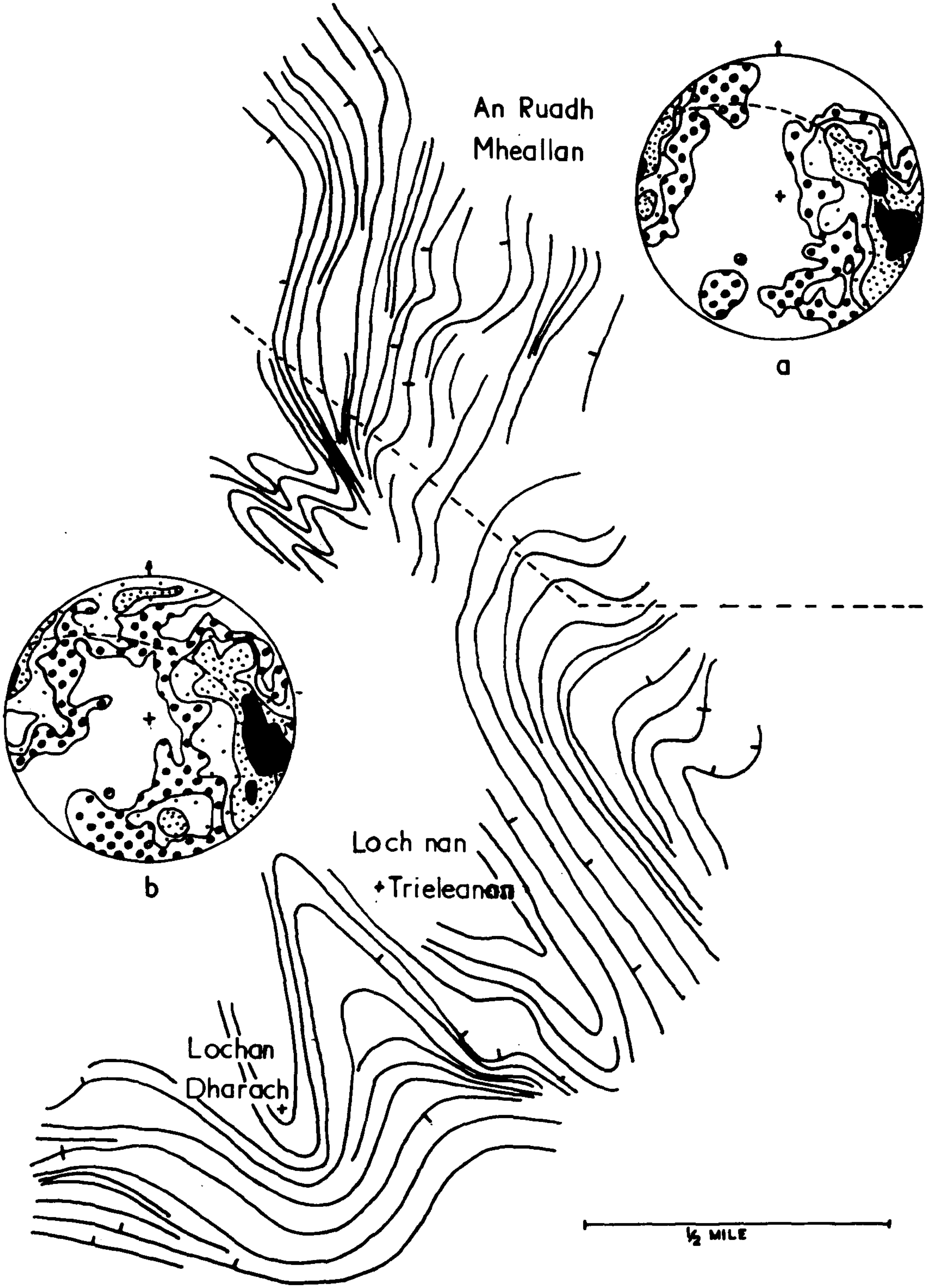

LOCH NA H'UMHAIG
LOCH DIABAIG
LOCH NA BEISTE
UPPER LOCH TORRIDON
1
2
3
4
5
6
7
8
9
10
11
A
B
C
0
½ mile

Fig.V-2. F_3B major folds affecting S_3 from the neighbourhood between An Ruadh Mheallan and Lochan Dharach. Poles to S_3, contoured at intervals of $\frac{1}{2}$, 1, 2 and 4%. The girdle distribution of the points indicate the plunge (O) of the F_3B fold (a) in the neighbourhood of An Ruadh Mheallan (249 poles) and (b) for the whole area (292 poles).

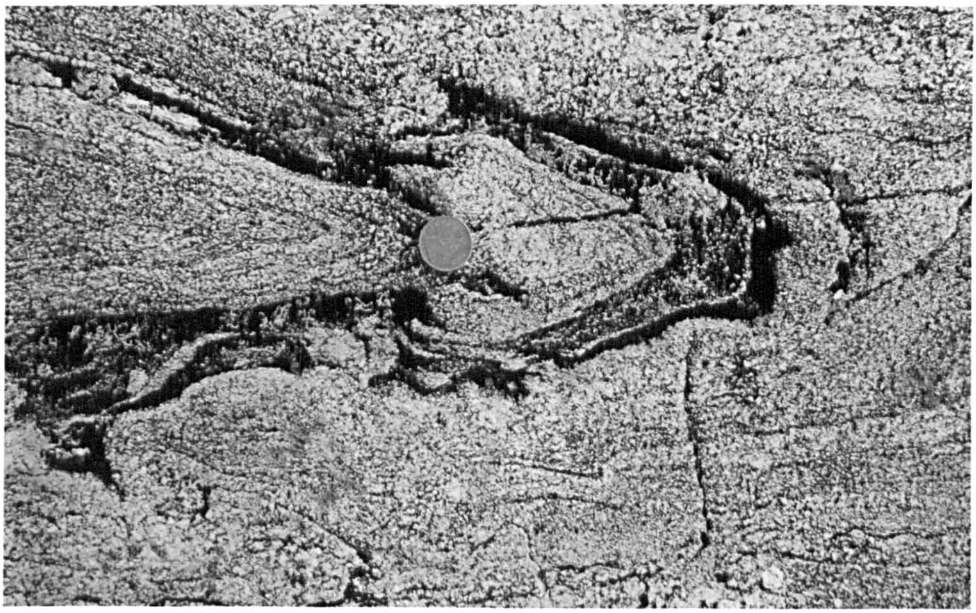


An Ruadh
Mheallan
a
b
Loch nan
Trieleanan
Lochan
Dharach
½ MILE

and by examining the variation in S_3 foliation attitude in the acid gneisses it is possible to reconstruct the F_3B major folds affecting the S_3 foliation. Fig.V-2 shows the reconstruction of major folds for the belt of gneisses from An Ruadh Mheallan to Loch na Beiste. A synthesis of the individual major fold axes reveals that they have variable plunges from south-west to east.

Mineral lineations formed on the S_3 foliation surface are not spatially related to F_3 fold axes and for reasons given later (see section V.C6) are considered to be unrelated to the D_3 fold movements. The earlier s-surfaces, S_1 and S_2, which are folded in the D_3 deformation episode produce variably oriented fold axes, depending on whether they are related to S_1 or S_2 foliations or to interference structures produced by interaction between S_1, S_2 and the D_3 fold movements. Generally the more conspicuous intrafolial folds to S_3 involve the folding of the S_2 foliation producing fold axes of constant attitude over the area plunging 60° to 70°SE. The S_1 foliation on the other hand, because of the intensity of the D_2 and D_3 deformation episodes can only be identified from intrafolial interference folds to the S_3 foliation. Because the gneisses are very homogeneous in appearance and are rarely stratified, these folds are often difficult to identify. In Plate V-1a where a clear separation into hornblende-rich and feldspathic-rich layers occurs, the form of interference patterns is sharp, whereas in Plate V-1b the banding in the gneiss is indistinct and thus the problem of identification is increased. All the interference structures found are of similar profile, that of type 2 of Ramsay (1962), and are "mushroom" shaped. They are symmetrical in form suggesting that the angle between F_2 and F_3 axial planes and F_2 and F_3 fold axes is approximately 90°. Holmes and Reynolds (1954) pointed out that the mean trend of first fold hinges can be determined by finding the direction of the join of the ends of the lobate outcrop shapes where they occur at the same topographical level. From the F_3 intrafolial "mushroom" shaped folds the trend of this direction is found to be NW-SE. Since the F_3 fold axes plunge 60° to 70°SW, then assuming that the a-direction of the

Plate V-1a-b. D_3 "mushroom" shaped interference structures produced by the superposition of F_2 and F_3 folds in banded gneiss with (a) clear contrasting banding (b) poorly contrasting banding; west of An Ruadh Mheallan (a) (82856140) and (b) (82856143).



D_3 fold movements was approximately normal to these fold axes the pre-D_3 attitude of the S_2 foliation can be calculated to strike NW-SE and dip 60° to 70°SW.

As a result of the superposition of at least two or three fold movements and migmatizations, the gneissic banding often appears complex in form and difficult to interpret, whereas in other gneisses where the structures are less complex, as many as three fold movements may be deduced. For example, in Plate V-2 coarse-banded S_3 gneisses have intrafolial folds due to refolding of F_2 folds by D_3 fold movements, the resulting S_3 axial-planar foliation being deformed by open F_4 folds.

In Chapter II.C3 it was stated that the formation of S_3 foliation was post-dated by a migmatitic episode. This was followed by further deformation (D_3A) of the S_3 foliation which has produced boudinage and pinch-and-swell structure in rocks whose banding has contrasting competency. For instance, in early basites boudinage and pinch-and-swell structures occur, whereas in concordant pegmatite sheets only pinch-and-swell structures are formed. Fig.V-3 illustrates the occurrence of pinch-and-swell structures in concordant pegmatite sheets in acid gneisses. The pegmatites have been thickened and thinned along their lengths indicating that they have a more competent nature than that of the associated gneisses. These gneisses have been deformed in such a way that, adjacent to the pegmatites, open folds occur which die out away from the pegmatites. In the swell regions of the pegmatites, the adjacent gneissic banding is thinned, whereas in the pinch regions the banding is thickened. This form of folding has been described by Ramberg (1963) and is believed to result from a mechanism known as bend folding in which the maximum compressive force is normal to the banding.

C. The D_4 structures

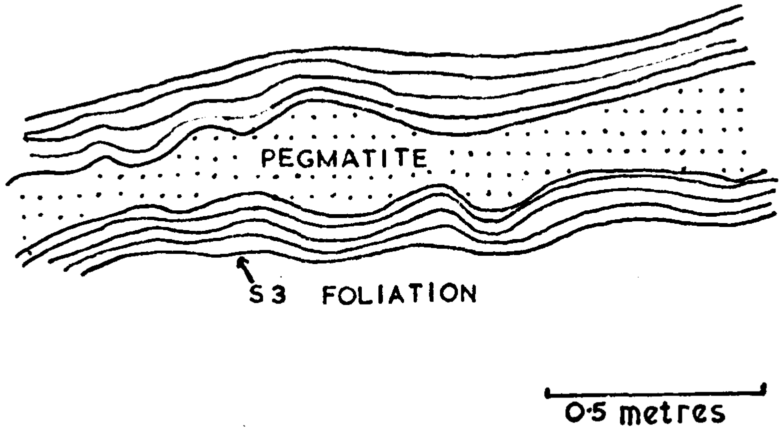
1. Introduction

The D_4 deformation episode has produced the predominant structures

Plate V-2. Superposed folds produced by interference between F_3 and F_2 (intrafolial fold to S_3) and interference of F_4 open folds with these earlier structures; belt of gneisses south of Diabaig (79885972).


F4
F2
F3

Fig.V-3. F_3A pinch-and-swell structure in a pegmatite sheet from gneisses 400 metres west of Lochan Dharach (820587).


PEGMATITE
S3 FOLIATION
0·5 metres

in the area, which are registered to varying degrees becoming more intense south-eastwards. As well as a change in intensity of D_4 structures there also occur changes in style and attitude. The changes in style are believed to be related to a phase of syntectonic metamorphism and migmatization which shows similar variations over the area (see Chapter II.4b).

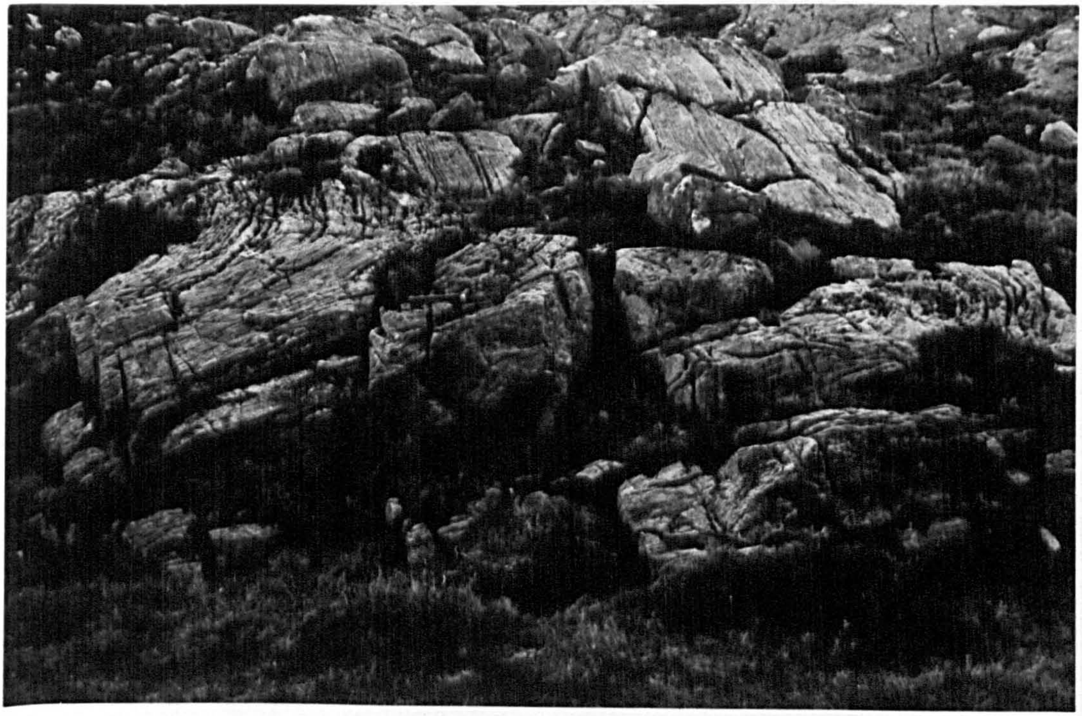
The D_4 movements have produced the following structures in the complex:- penetrative S_4 foliation, F_4 folds, dislocation augen, quartz rods and mineral lineations, some of which have been discussed in Chapter II. It has been necessary to subdivide the area into several domains (see Fig.V-1) to illustrate the variations in the effects of the D_4 movements.

2. F_4 fold style

According to Turner and Weiss (1963) the style of a fold is recognized especially from its form and general character as seen in profile. The F_4 folds vary in style and scale over the area in such a manner that several distinctive zones may be recognized. In Fig.V-1 zones A, B and C represent three such zones. The zone boundaries are based primarily on changes in fold scale, the change in style being more gradual. In zones A and C the minor folds are rarely greater than 0·5 metres in wavelength and are generally about 0·25 metres. In zone B which is approximately 20 to 30 metres wide, much larger folds occur (see Plates V-3a-b) having wavelengths of 5 to 10 metres and attenuated NW-SE-striking limbs, particularly where they are asymmetrical (see Figs.V-4a-b). A similar belt of larger-scale folds is found on the NW-SE limb of the major F_3B fold at An Ruadh Mheallan (see Plate V-4a).

The F_4 minor folds may be divided into two categories based upon the relationship between the axial surface and the limbs of the fold - asymmetric folds, where the limbs are not bisected by the axial surface and symmetric folds where the axial surface bisects the angle between the limbs. These two categories arise as a result of differences in limb lengths and limb thickness.

Plate V-3a-b. F_4 folds from (a) 500 metres north-east of Loch nan Tri-eileanan (83106016) and (b) 400 metres south-east of Loch Airidh Eachainn (83026054).



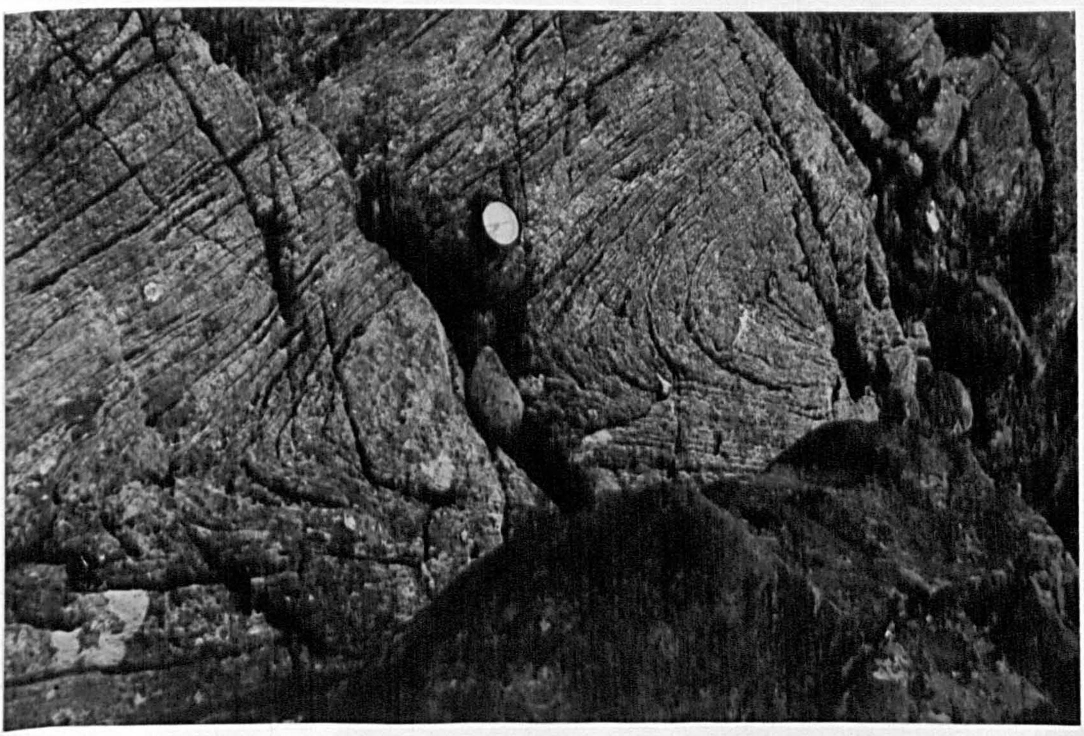
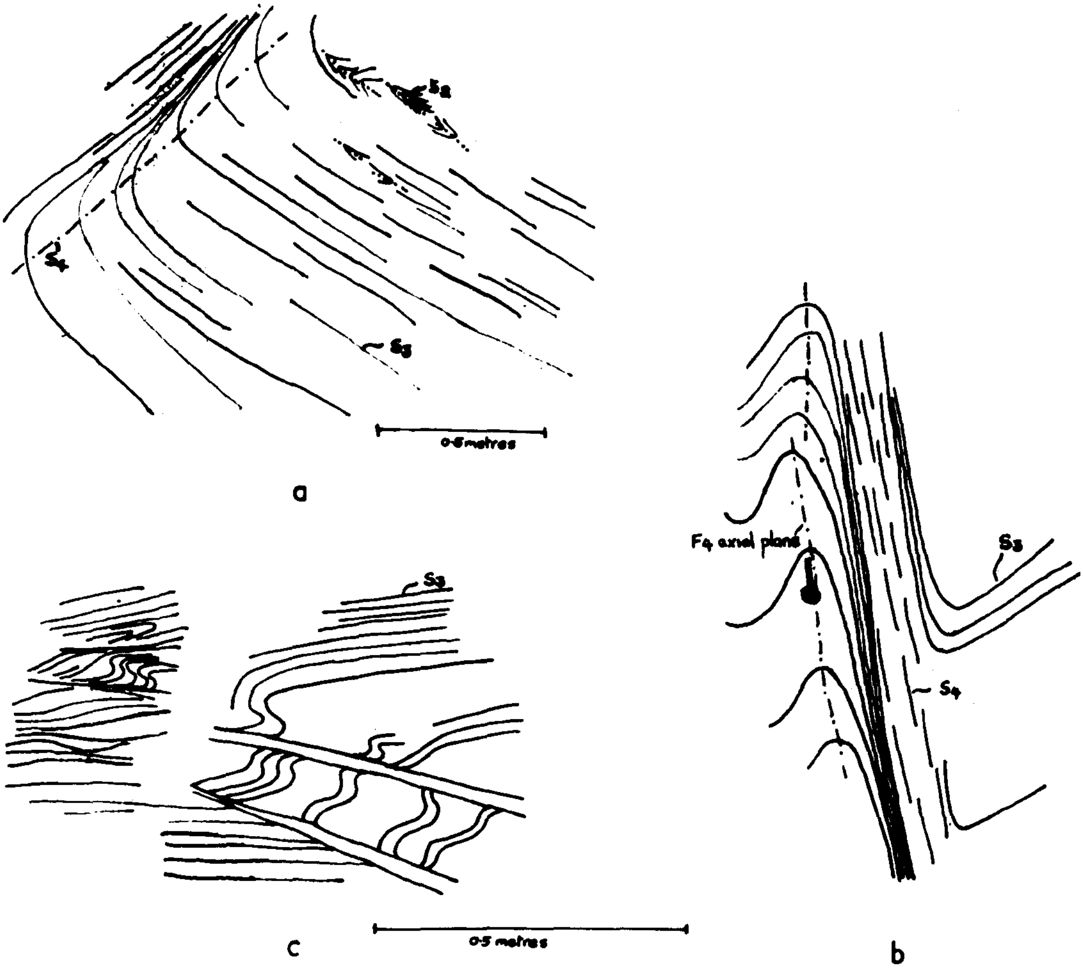


Fig.V-4a-b. Asymmetric F_4 folds with attenuated NW-SE limbs (a) from the neighbourhood of Loch Airidh Eachainn (824609).

(b) 450 metres north-east of Loch nan Tri-eileanan (832602).

(c) In this F_4 minor fold pegmatite veins have been intruded parallel to the NW-SE limb: 350 metres north-east of Loch nan Tri-eileanan (831600).



S2
S4
S3
0·5 metres
a
F4 axial plane
S3
S4
b
S3
0·5 metres
c

(a) Asymmetric folds

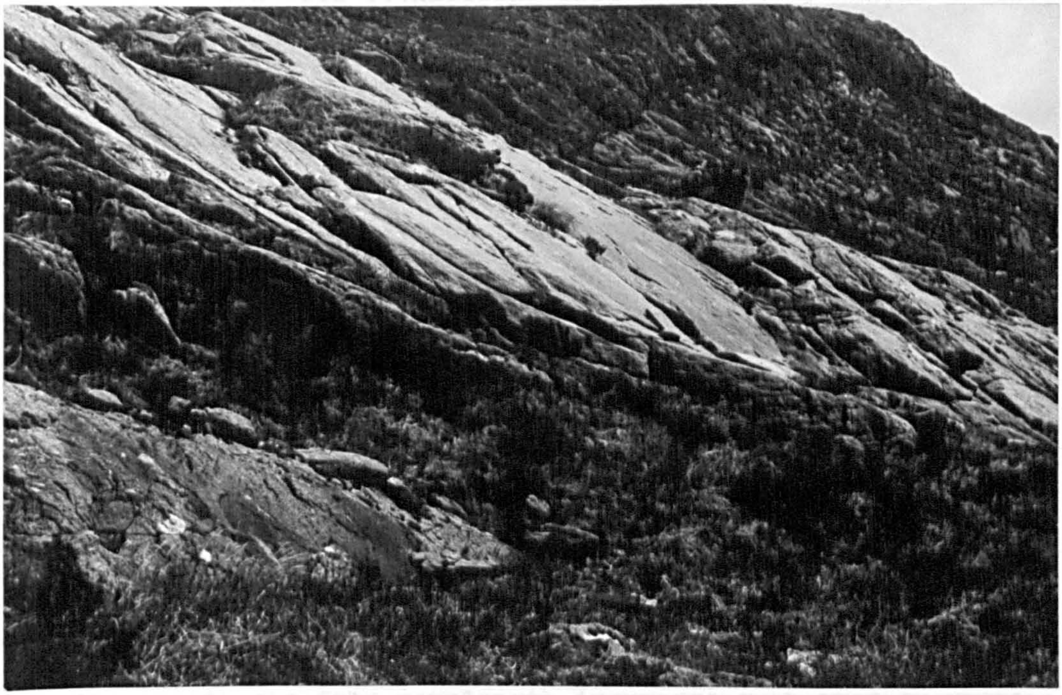
Plate V-4b illustrates an early stage of development of F_4 asymmetric folds. These folds resemble the parallel fold type in that they die out along the axial surface, but differ in that the thickness of the S_3 banding varies within each layer. The initial orientation of the S_3 foliation is shown away from the fold. The fold consists of two unequal limbs of which the shorter has been rotated clockwise out of the initial attitude of S_3. On the longer limb of the fold the banding is markedly thinner as a result of attenuation. The movement sense which can be reconciled with the form of the F_4 minor fold in Plate V-4b is illustrated in the Plate.

In Plate V-5a several minor F_4 asymmetric folds from domain 1 are illustrated. These folds have undergone more intense deformation than those in the previous example. They vary in wavelength from 10 to 25 cm., the long limbs of the folds being markedly attenuated such that they are drawn out into narrow movement zones striking NW-SE. The degree of attenuation of these limbs is so intense that they are now sub-parallel to the axial surfaces of the folds. The short limbs of the folds, which are sub-parallel to the initial orientation of S_3 in the least deformed types (see far left of Plate V-5a), have been thickened and in some cases rotated clockwise away from the initial attitude of the S_3 foliation. Many of these folds when traced parallel to the axial surface, along the fold profile, have a disharmonic appearance.

A further factor which appears to affect the form of minor folds is the initial orientation of the foliation (cf. Ramsay 1956). It has been established that the major F_3B folding of the S_3 foliation, prior to the D_4 fold movements produced variable attitudes of S_3. In the examples so far discussed the initial orientation of the S_3 foliation was at a marked angle to the F_4 axial surfaces. However, where S_3 has a NW-SE strike (eg. the NW limb of the major F_3B fold in the vicinity of An Ruadh Mheallan and Loch Airidh Eachainn and parts of domain 4)

Plate V-4a. Large-scale F_4 fold affecting NW-SE limb of F_3B fold at An Ruadh Mheallan (82626188).

Plate V-4b. F_4 minor fold affecting S_3 foliated acid gneiss; 300 metres south of Loch Airidh Eachainn. (82836055).



the minor folds either are formed at small angles to S_3 or are not formed at all. Fig.V-4c illustrates such minor folds having a style similar to the previous examples, being affected by movement zones which, in this case, have been granitized.

Further south the asymmetric minor folds become more similar in style (see Plate V-5b) but resemble the above types in having attenuated long limbs sub-parallel to the axial surface, and thickened banding in the hinge zones of the folds.

(b) Symmetric folds

In domain 2 the F_4 minor symmetric folds have small wavelengths, 2 to 5 cms., and resemble the asymmetric folds by having longer and shorter limbs in some cases, but in the general case limbs of equal length. Plate V-6a illustrates symmetric folds which are cut by a penetrative S_4 axial-planar foliation.

Further south the fold wavelength increases such that in domains 9 and 10 the wavelengths are in the region of 50 cm. Plate V-6b illustrates F_4 symmetric folds from domain 5 having a wavelength intermediate between those of the extreme north and south. In nearly all the symmetric folds in the north of the area there is an axial-planar foliation, but in domains 9 and 10 some of the F_4 folds have no associated penetrative foliation (see Plate V-7a) and resemble the "flow folds" of Wynne-Edwards (1963). Such folds, although intensely deformed and of similar style, may have been produced by flexural folding involving flow within the layers - flexural flow (Donath and Parker 1964) rather than by slip along planes parallel to fold axes (Ramsay 1967, p.430) since an axial planar foliation is not found in these folds.

Fig.V-5c illustrates the profile of an F_4 minor symmetric fold cut normal to the fold axis with isogonal lines constructed through one of the bands. In Fig.V-5a the value $T^1 = T\alpha/T_0$, the ratio of the thickness of the band at the hinge zone is plotted against α, the angle of inclination of the layer. Similarly, in Fig.V-5b the value $t\alpha/to$, the ratio of the distance between the tangents to the folded layer at

Plate V-5a-b. F_4 minor folds from

(a) 300 metres south of Loch Airidh Eachainn (82856056).

(b) 300 metres north-east of Loch na Beiste (81705887).

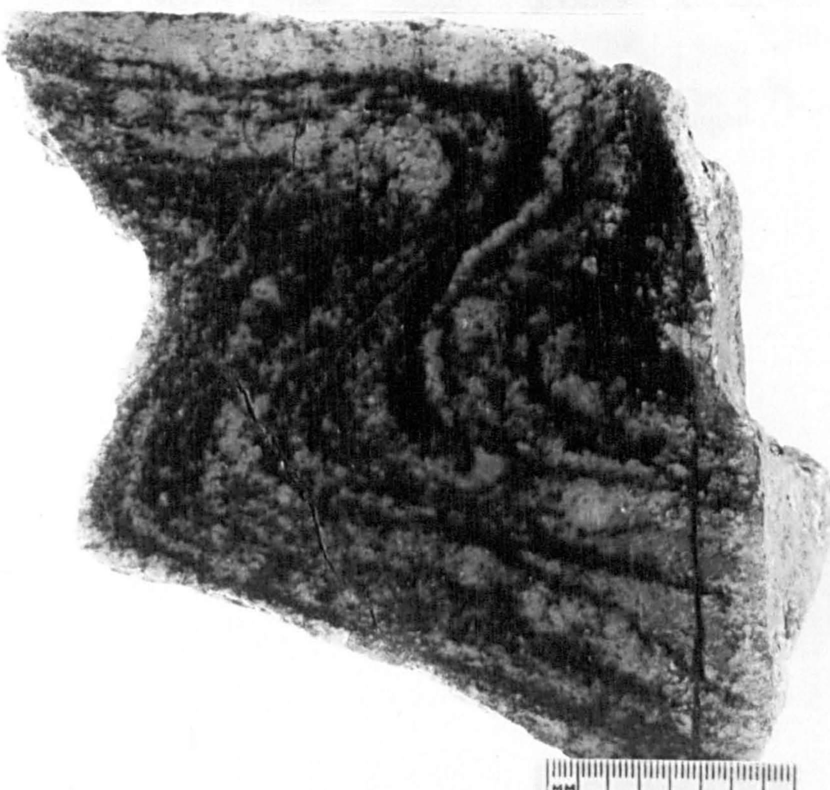

mm
1
2
3
4

Plate V-6a-b. F_4 minor folds from (a) 150 metres south-west of Loch Airidh Eachainn (82476086) (b) 100 metres west of Lochan Dharach (82575906).

the angle α to the distance between the tangents drawn at the fold hingeplotted against the angle of inclination α of the layer. The figures also show the fields of the various fold classes of Ramsay (1967). It is apparent from these figures that the fold falls in class 2 of Ramsay (op.cit.) and is therefore of similar type in which isogonal lines are parallel to the axial surface of the fold.

(c) Box folds

A further group of folds which do not fall into the two previous groups have been found in domain 6. They resemble folds described by Ramsay (op.cit.) as box folds and have two fold axes, wide hinge zone, and a change in shape along their axial surface such that the twin axial surfaces converge.

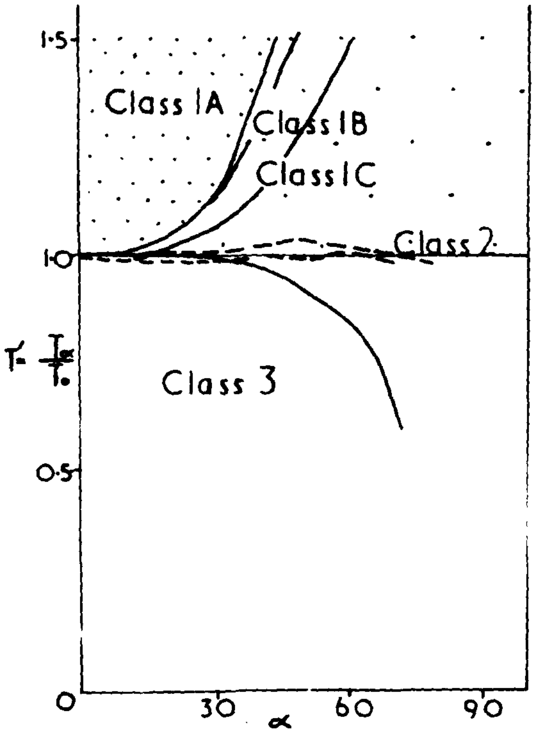
(d) Disharmonic folds

A feature of disharmonic folds noted in the literature is that they are generally restricted to rocks having alternating competent and incompetent bands. They are believed to owe their form to a large layer thickness in relation to fold wavelength. Although disharmonic folds have been found in rocks where interlayered competent and incompetent material occurs (see Fig.V-6a-b) they are more widespread in acid gneisses where there is no apparent competency differences in the bands (see Fig.V-6b). It is difficult to reconcile these disharmonic folds with an origin relating to differences in competence and layer thickness in stratified rocks. It has already been indicated that many of these folds are of the similar class and the only generally accepted model of similar folding is based upon flow parallel to the axial surfaces. However, the disharmonic nature of the folds might be explained by differential flow along lines parallel to the axial surface.

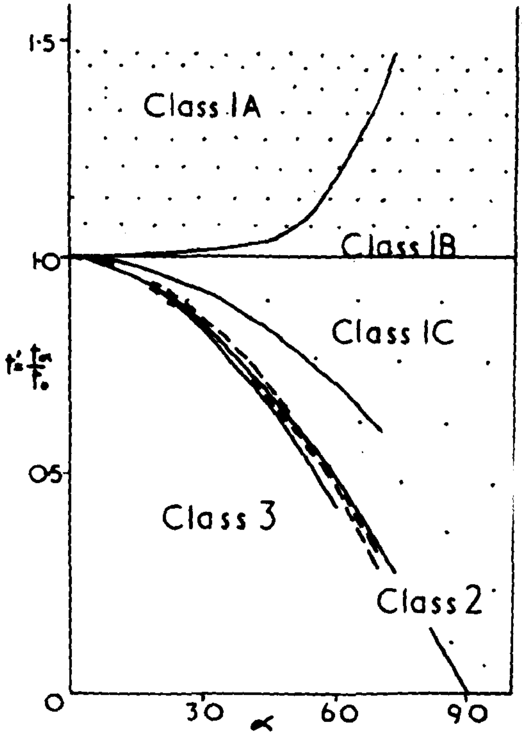
3. F_4 minor folding of early basites and migmatites

Since the complex has been affected by at least three phases of deformation and two of migmatization before the D_4 fold movements, many of the early basites have been disrupted and agmatized. As a result,

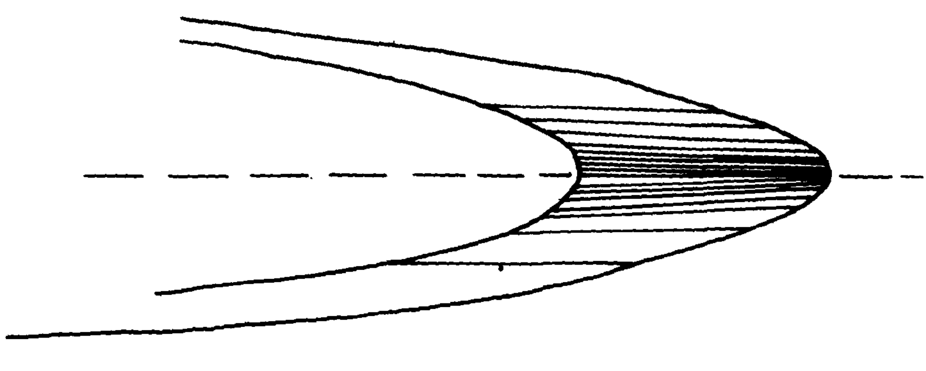
Fig.V-5a. Constructed isogonal lines for F_4 minor fold. Isogonal lines are sub-parallel to the trace of the axial surface (c). Plots of T^1 (a) and t^1 (b) against α for F_4 minor fold. The fold classes of Ramsay (1967) have been superimposed on these figures.


1·5
1·0
0·5
0
30
60
90
α
Class 1A
Class 1B
Class 1C
Class 2
Class 3
T' = T_α / T_0

a

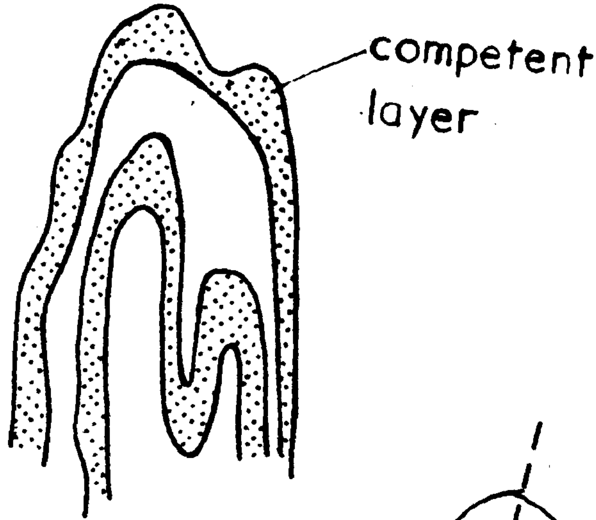

1·5
1·0
0·5
0
30
60
90
α
Class 1A
Class 1B
Class 1C
Class 3
Class 2
T' = T_α / T_0

b

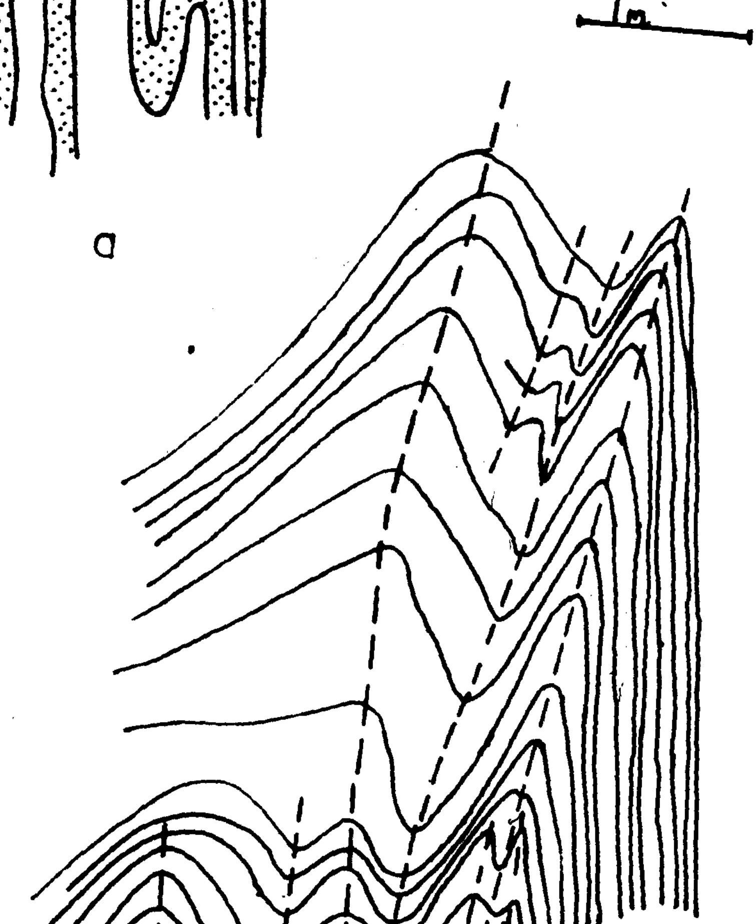


c

Fig.V-6a-b. Disharmonic F_4 minor fold from (a) the neighbourhood south of Loch Diabaig (799589) (b) gneisses near Loch a'Bhealaich Mhoir (803586).



a



b

the early basites register the D_4 deformation effects in a different manner to the acid gneisses. In Plate V-7b several disrupted early basite blocks have been folded by D_4 fold movements. The associated gneisses have acquired the S_4 foliation whereas the early basites retain the S_3 foliation. Similarly, Plates V-8a-b, 9a illustrate the effects of D_3 deformation (Plate V-8a), post-D_3-pre-D_4 migmatization (Plate V-8b) and finally the D_4 deformation episode producing recumbent F_4 minor folds in the agmatized early basite (Plate V-9a).

Pegmatites formed in the acid gneisses during the post-D_3, pre-D_4 migmatization have resisted the effects of the D_4 deformation episode more than the associated acid gneisses which are transformed by penetrative S_4 foliation. The pegmatites, on the other hand, only register the fold effects. Plate V-9b illustrates the variable style of F_4 minor folds which have affected migmatized acid gneisses. Where the post-D_3, pre-D_4 pegmatites are in the form of lenticular concretionary bodies, the S_4 foliation is generally deflected around them (see Plate V-10a), the pegmatites registering a foliation only at their margins.

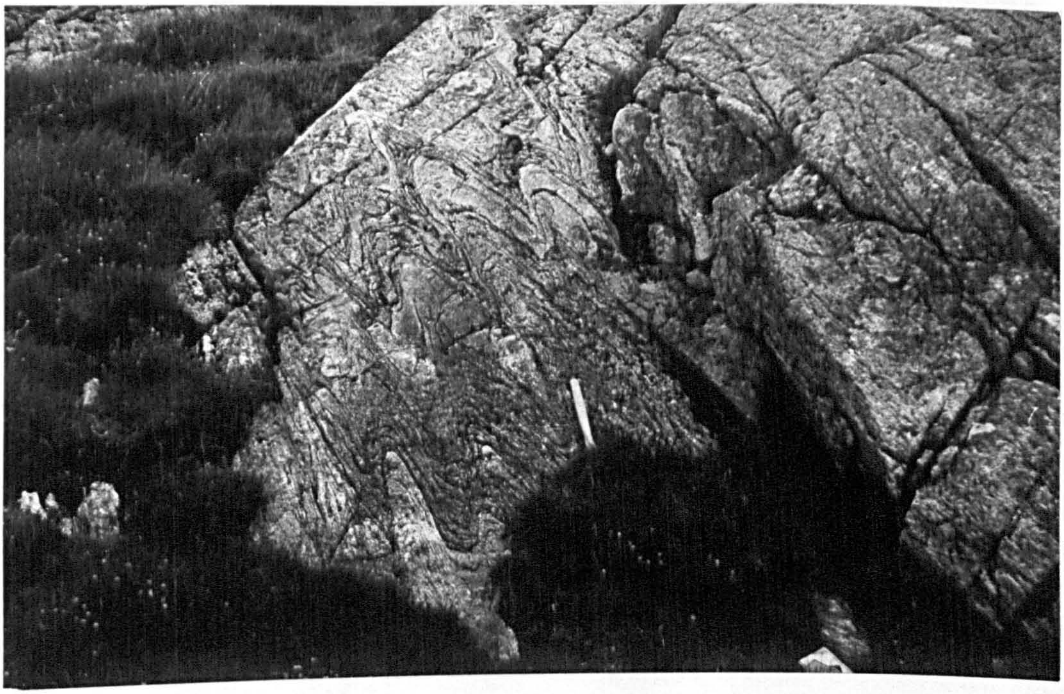
4. <u>F_4 superposed folds</u>

Folds of this type are formed by the interference of a pre-D_4 folded surface with F_4 folds of like scale. As a result of this superposition, a variety of interference structures occurs in the acid gneisses. All three classes of interference patterns recognized by Ramsay (1962) occur in the F_4 folded gneisses (see Plates V-10-11). For example, Plate V-10b shows an eyed [redacted] D_4 interference pattern occurring in domain 11, whereas Plate V-11a and b shows other forms of D_4 superposed folds occurring in the gneisses. Because of the degree of migmatization in the gneisses, interference patterns are often obscured, for example in Fig.V-7, where class 3 interference patterns are illustrated in a nebulite; the only recognizable banding is that illustrated in the figure.

The diversity of interference patterns produced in the D_4 deformation episode reflects the variable attitude both of the pre-D_4 folded surface and of the F_4 folds over the area.

Plate V-7a. F_4 minor folds in acid gneiss 450 metres west of Loch a'Bhealaich Mhoir (79605864).

Plate V-7b. F_4 folded early basite boudins, acid gneiss with a penetrative S_4 foliation; 400 metres west of Loch a'Bhealaich Mhoir (79705885).



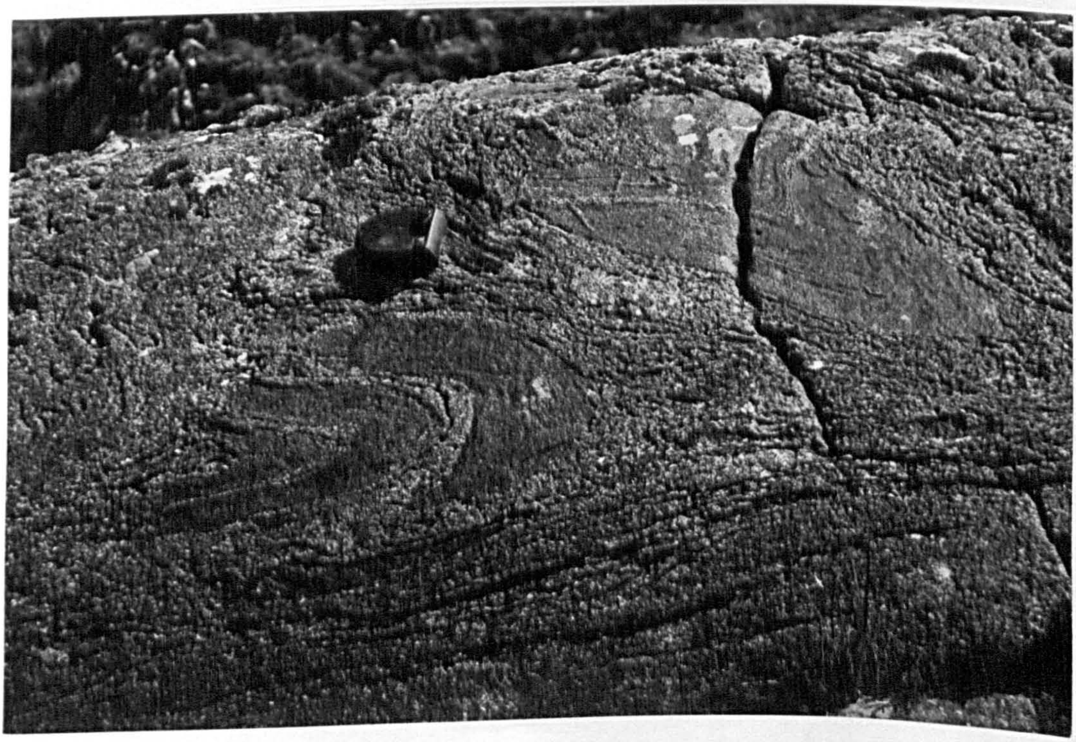
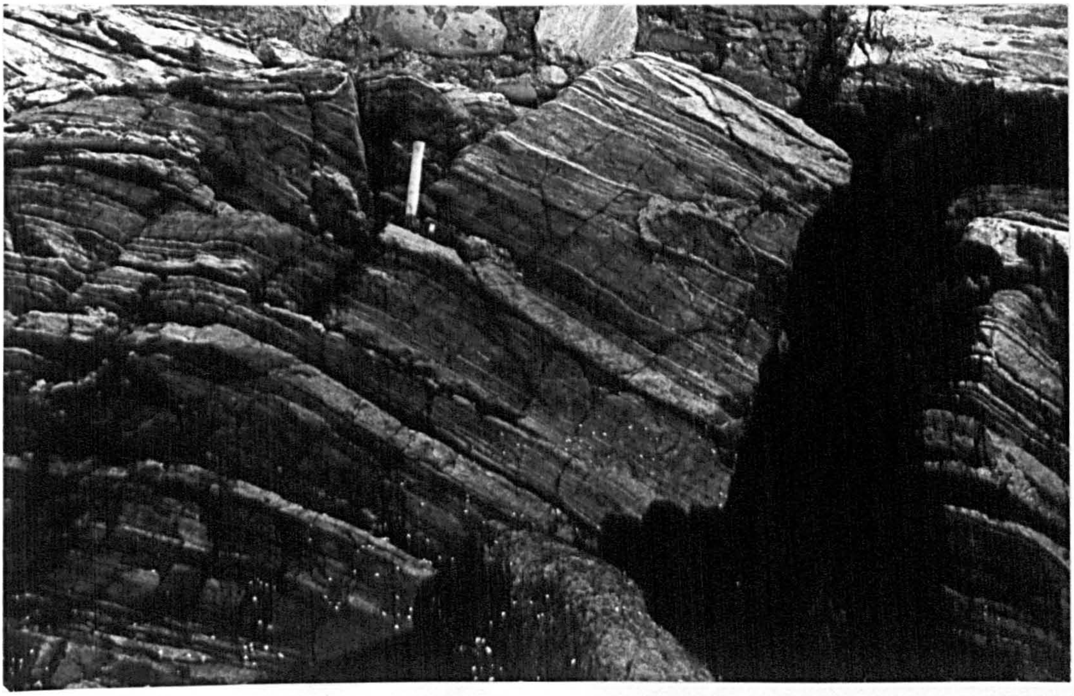


Plate V-8a. Banded early basite body with S_3 foliation parallel to banding; Diabaig Pier (79665984).

Plate V-8b. Early basite in Plate V-8a, which has been agmatized by post-D_3, pre-D_4 migmatization (79745886).



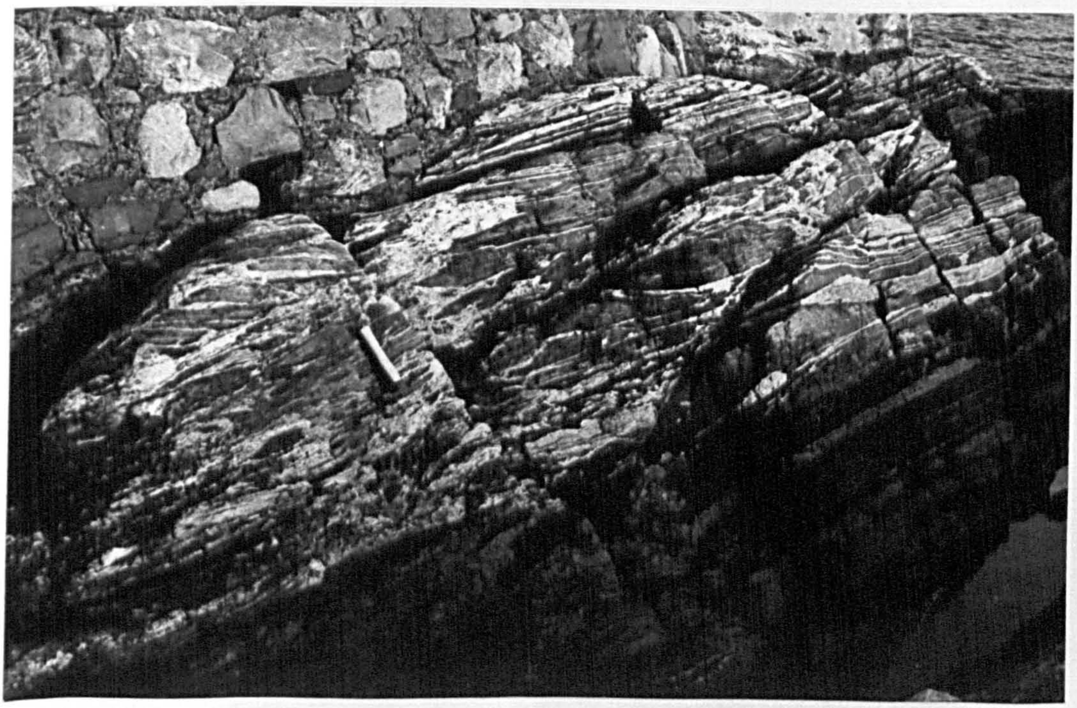
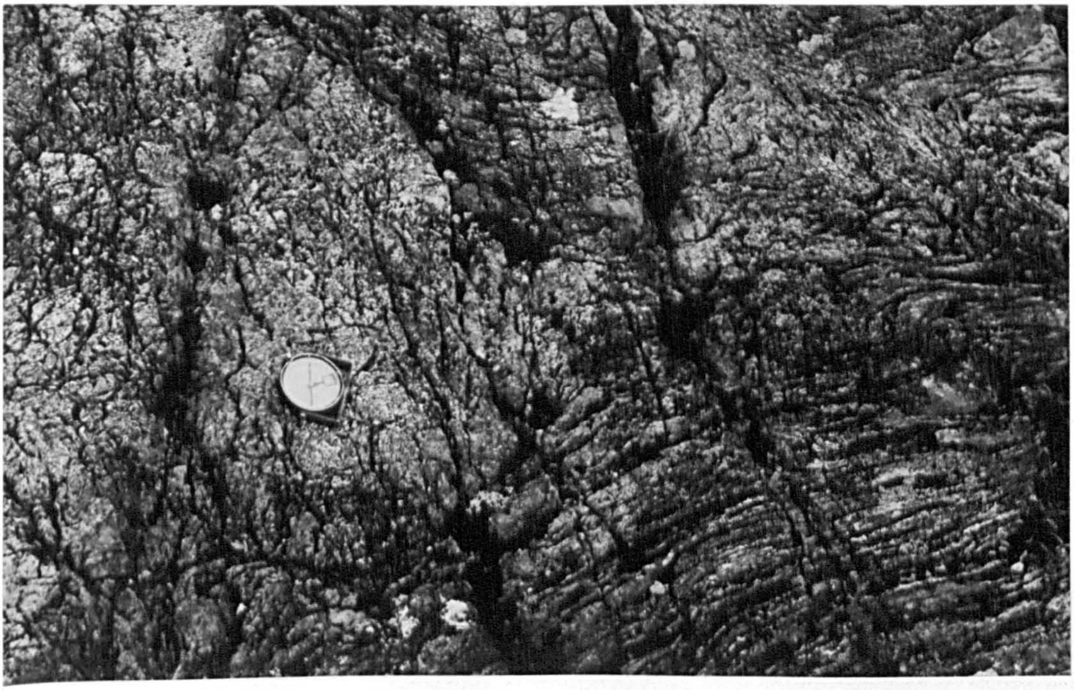


Plate V-9a. Early basite body at Diabaig Pier, has been deformed producing F_4 recumbent folds (79785887).

Plate V-9b. F_4 minor folding of migmatite; 400 metres north-east of Loch na Beiste (81805887).

Plate V-10a. S_4 foliation deflected around post-D_3, pre-D_4 pegmatite in acid gneiss; 250 metres south-east of Lochan Dharach (82715985).

Plate V-10b. F_4 "eye-shaped" superposed fold; 300 metres west-south-west of Meall na h-Airde (78745923).



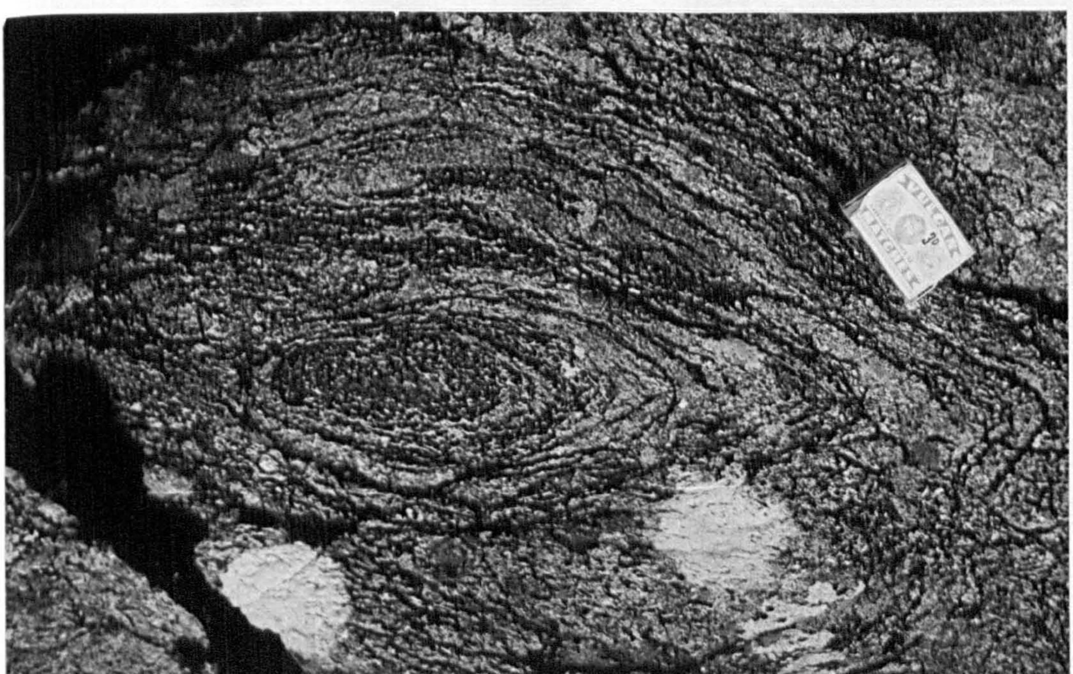


Plate V-11a. F_4 superposed fold produced by the interference of F_3 and F_4 folds; 300 metres north-east of Loch nan Tri-eileanan.

Plate V-11b. Variable shaped profiles of F_4 superposed folds; 100 metres north-east of Lochan Duibh.

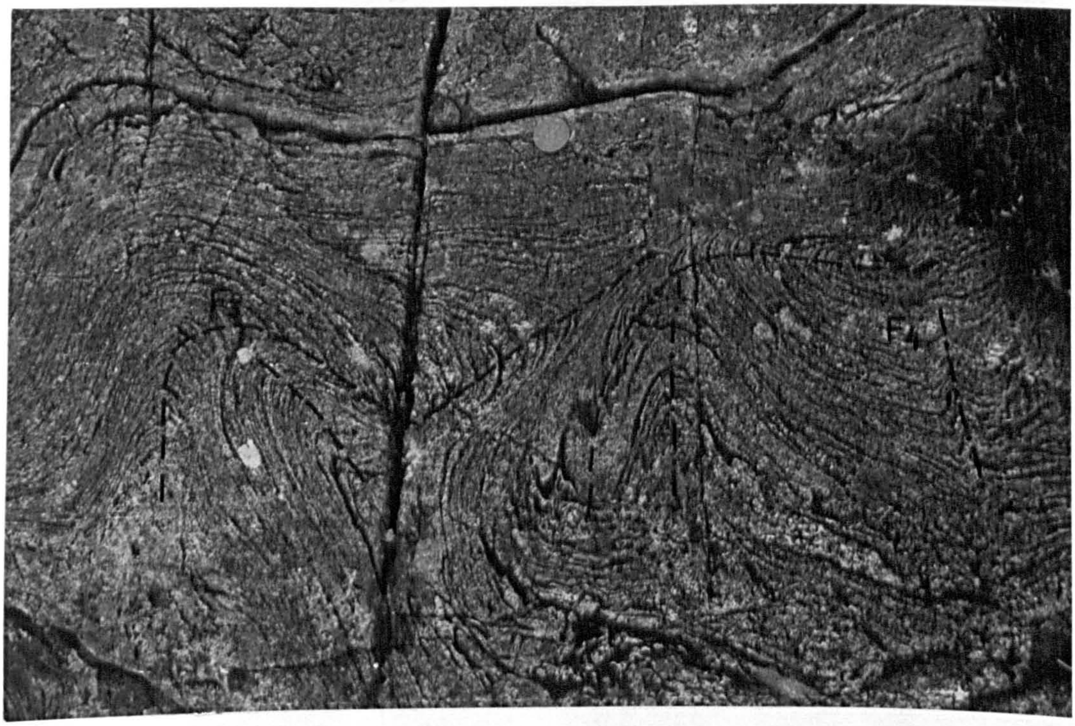
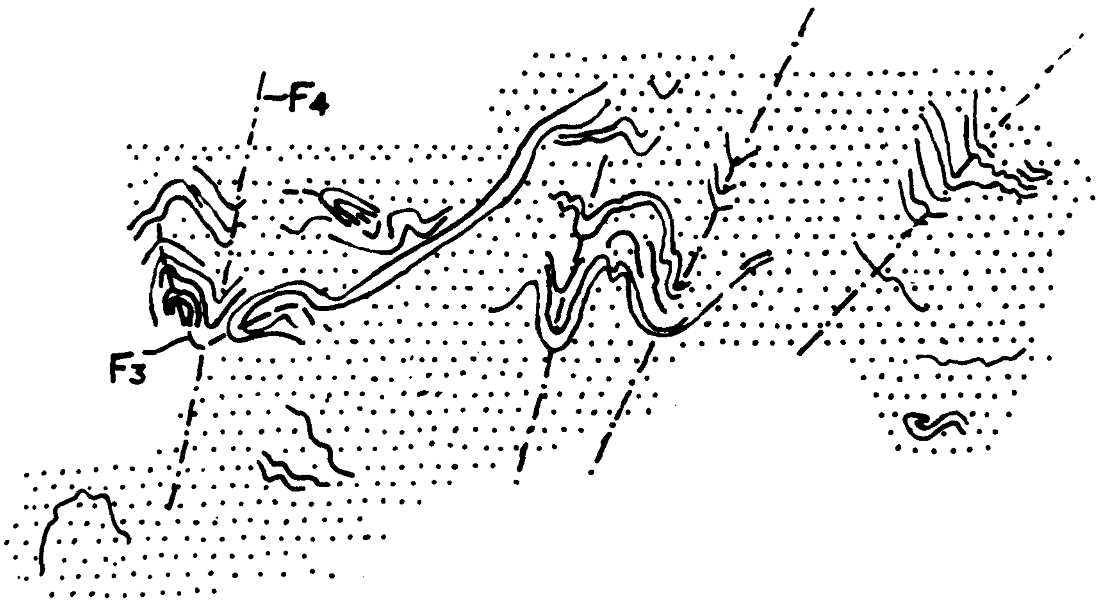

F4

Fig.V-7. F_4 superposed folds in nebulite found north-east of Lochan Dharach (826592).



F4
F3

5. The relationship between F_4 folds and S_4 foliation

The relationship between the penetrative S_4 foliation and the associated F_4 minor folds shows considerable variation over the area. In domain 1, a penetrative S_4 foliation is rarely present, occurring only in narrow movement zones (see Plate V-5a) parallel to attenuated long limbs of F_4 minor folds. This foliation is of the axial planar type since the axial surfaces of the minor folds are sub-parallel to the attenuated long limbs of the folds. Further south, in domain 2, folds are found to be [redacted] tighter in profile (see Plate V-12a) and the foliation penetrates gneisses as a whole [redacted] completely destroying the earlier S-surfaces, the F_4 minor folds appear intrafolial to the S_4 foliation and are either M, S or Z-shaped in profile. The S_4 foliation is axial planar to F_4 minor folds (see Plate V-12b), the folds generally approximating to the similar type.

Further south-eastwards the belts of axial-planar foliation in which the early s-surfaces have been completely transposed increase in width, the foliation retaining a fine laminated appearance through domains 4 and 5 (see Plate V-13a).

In domains 8, 9 and 10 the axial-planar foliation occurs in increasingly wider belts and is of a different nature. NW-SE-striking belts, up to 100 metres wide, with F_4 folds transposed into the S_4 foliation,alternate with belts of F_4 minor folds which have no associated penetrative foliation. The gneisses are coarser-grained than those found in similar belts in the north of the area.

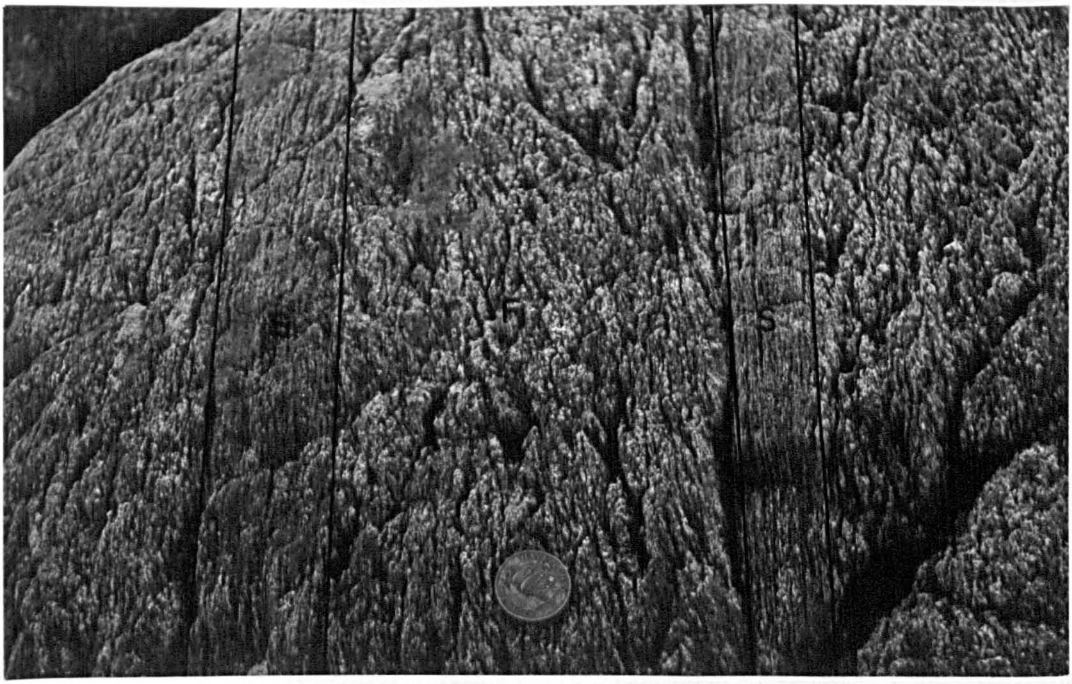
6. Regional attitude of S_4 foliation, F_4 fold axes, augen and mineral lineation

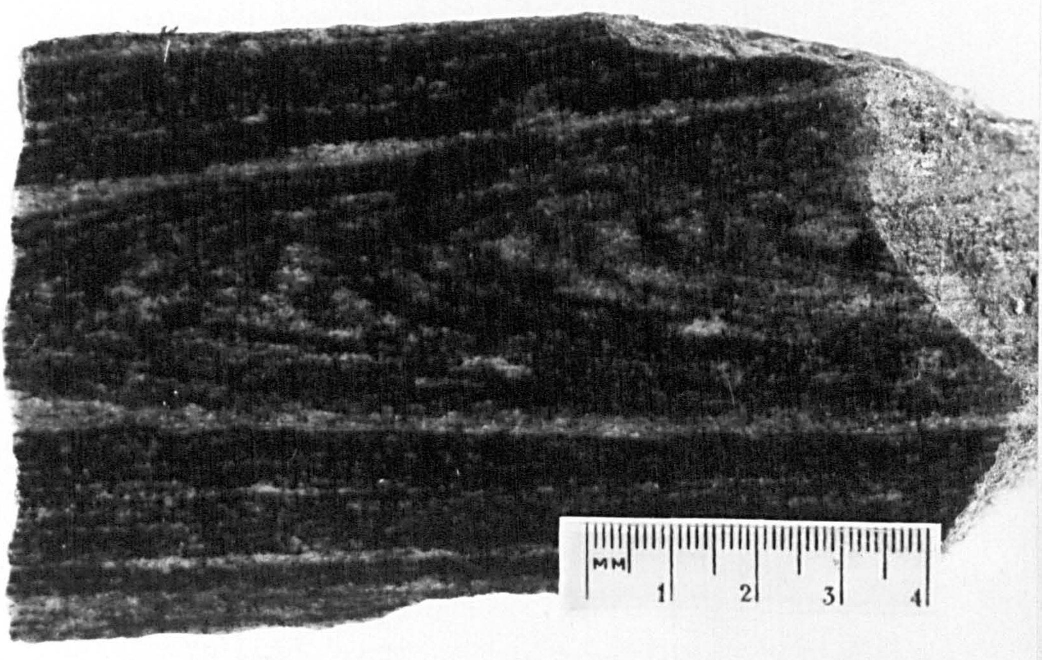
The characteristics of the S_4 foliation, mineral lineation and augen and their mutual relations have already been discussed in Chapter II. The mineral lineation and feldspathic augen are parallel to F_4 fold axes and are therefore b-lineations.

Since the S_3 foliation has a variable attitude over the area as a result of major folding, the F_4 fold axes whose attitude is controlled

Plate V-12a. Alternating belts of S_4 foliation (S) with belts where F_4 minor folds have not been completely transposed into S_4 (F). From acid gneisses 200 metres west-south-west of Loch Airidh Eachainn (82526079).

Plate V-12b. F_4 minor fold with S_4 axial planar foliation.


F
S


MM
1
2
3
4

by the S_3 foliation also show a considerable variation. Not only the fold axes, but also the axial surfaces show variation. When the plunge of the F_4 fold axes are plotted against their axial surfaces (cf. Fleuty 1963) a very broad scatter of points is produced (see Fig. V-8) indicating that the folds vary from gently inclined and gently plunging to upright and steeply plunging structures.

The attitude of the S_4 foliation, F_4 fold axes and mineral lineations over the area are plotted in Fig.V-9a-f. From the attitude of the foliation in the individual domains and from the disposition of the domains themselves, it is apparent that foliation varies regularly in attitude from the north-east to south-west, such that in the north-east the S_4 foliation is steep to vertical and becomes progressively less steep south-westwards until in domain 6, in the vicinity of Meall Ceann na Creige and Loch na Beiste it is sub-horizontal. It then steepens sharply in domain 7 and again decreases in dip progressively towards the shore of Loch Torridon.

Figs.V-10a-b show the variation in attitude of S_4 foliation and F_4 fold axial surfaces respectively over the area, both indicating a girdle distribution of the poles to these surfaces whose axis plunges at a shallow angle to the south-east. The variation in attitude of S_4 throughout the area is summarized in Fig.V-11.

There are three possible explanations for the attitude of the S_4 foliation:-

(i) Major folding of S_4 foliation about a fold axis gently plunging south-east.

(ii) Formation of S_4 foliation in its present variable attitude without any subsequent major folding.

(iii) A combination of (i) and (ii).

It is extremely difficult to establish criteria which would enable a choice to be made between these possible explanations. Evidence such as refolded lineations and s-surfaces are valueless in this respect because of their earlier complex distribution. However, in small domains

Fig.V-8. Variation in F_4 fold attitude for the area.

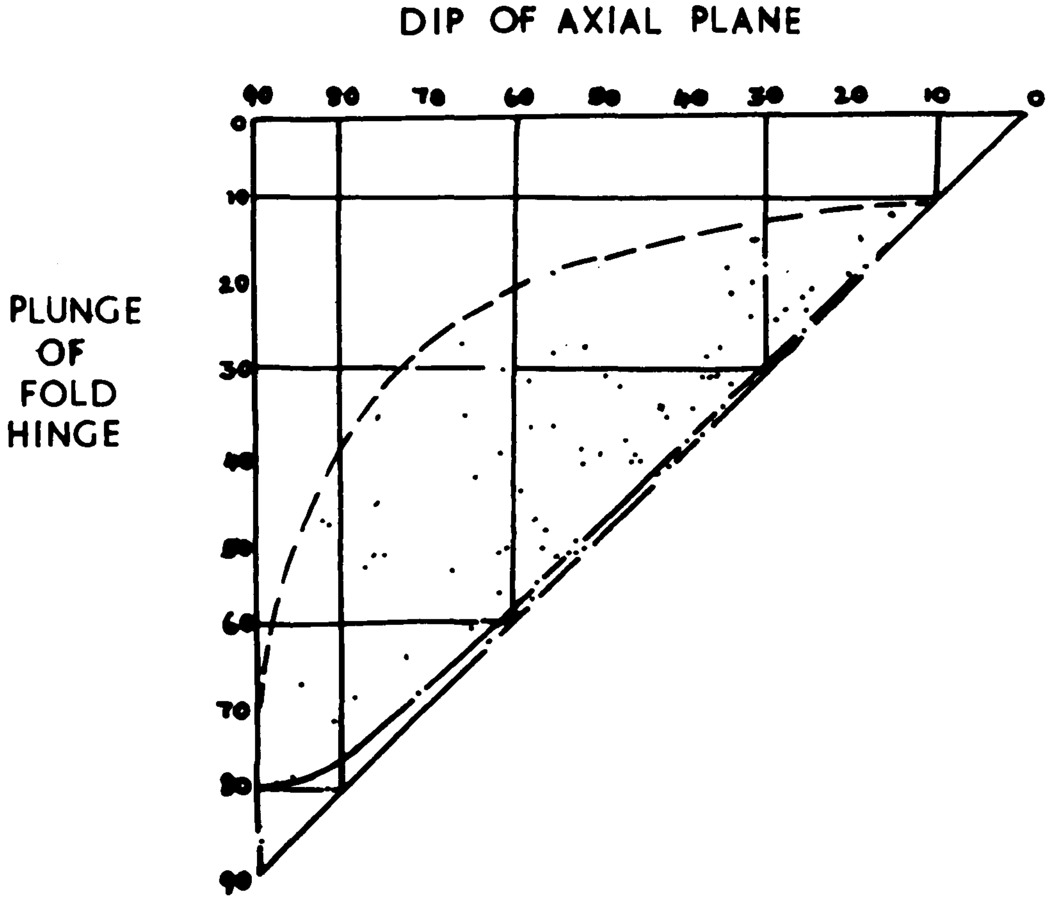

DIP OF AXIAL PLANE
90 80 70 60 50 40 30 20 10 0
PLUNGE OF FOLD HINGE
0 10 20 30 40 50 60 70 80 90

Fig.V-9a-f. Contoured poles to S_4 foliation and L_4 lineation (·) for:

(a) domains 2 and 4; 127 poles, contoured at intervals of ½, 2, 8 and 12%.

(b) domain 5; 131 poles contoured at intervals of ½, 4, 8 and 12%.

(c) domains 1, 2, 3, 4 and 5; 392 poles, contoured at intervals of ½, 1, 5, 7½ and 10%.

(d) domain 6; 104 poles, contoured at intervals of ½, 2½, 6 and 10%.

(e) domain 7; 193 poles, contoured at intervals of ½, 1, 2½, 5 and 10%.

(f) domains 8 and 9; 113 poles, contoured at intervals of ½, 2½, 9, 18 and 32%.

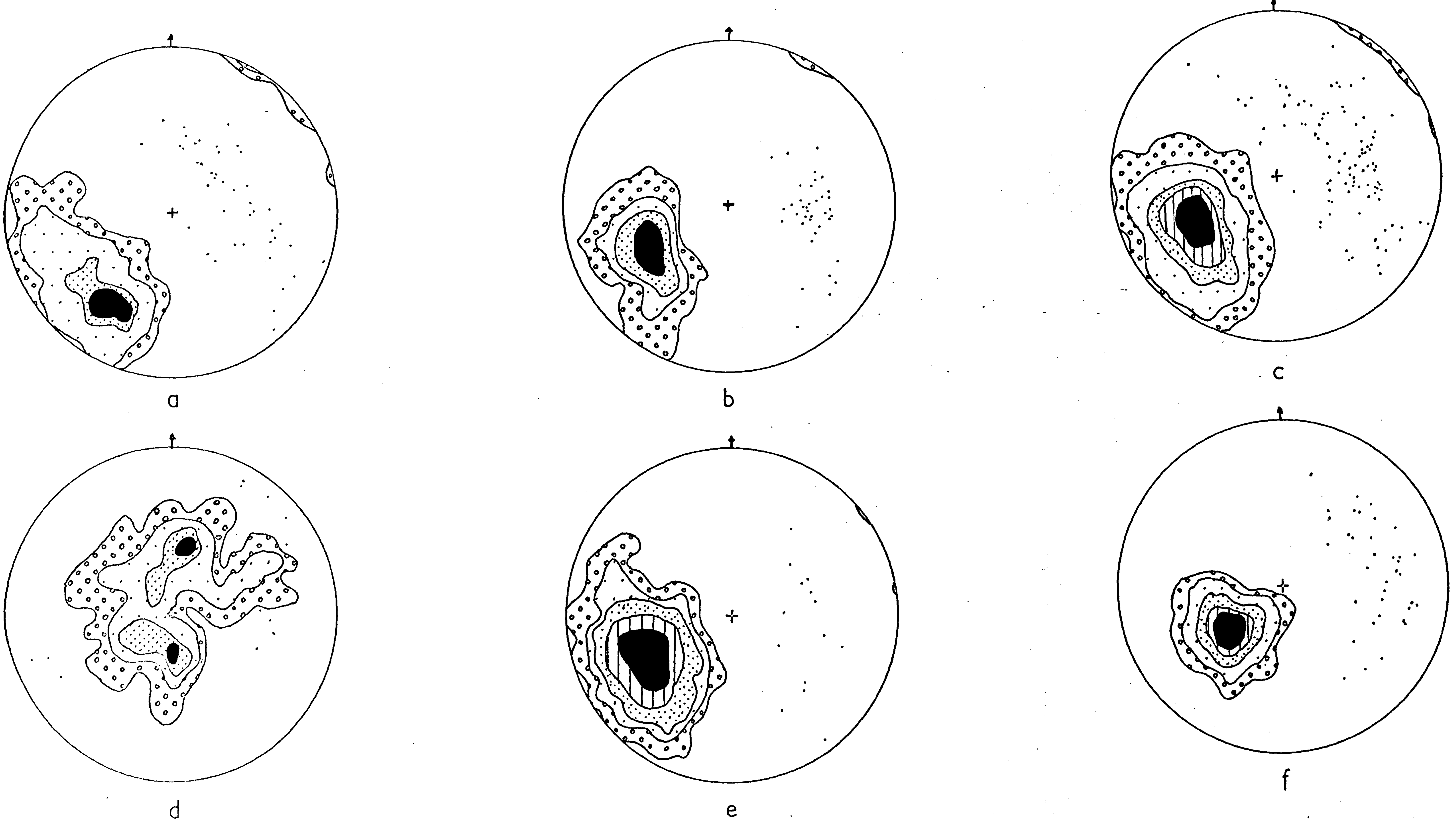
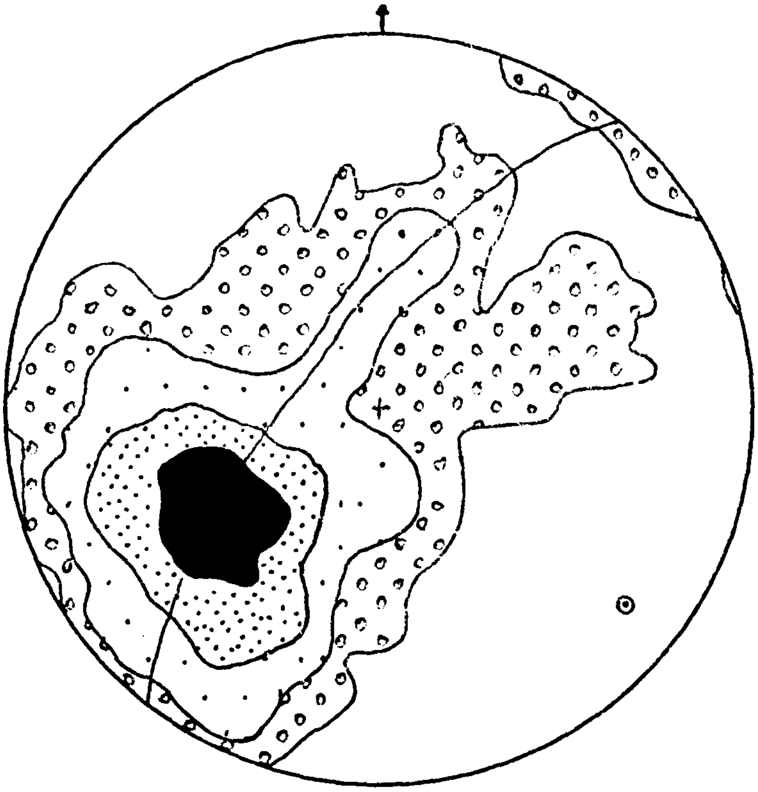
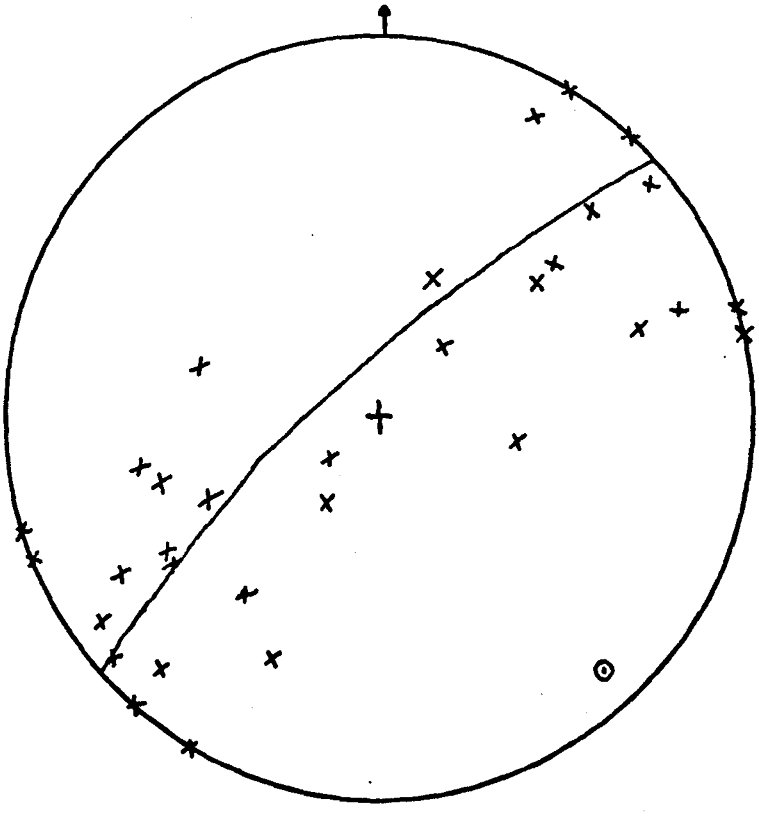

a
b
c
d
e
f

Fig.V-10a-b. Variation in S_4 foliation poles (a) and F_4 fold axial surfaces (b) for the whole area. In (a) 732 poles are contoured at intervals of $\frac{1}{4}$, 1, 3 and 7%.

(b) the F_4 fold axial surfaces (X) have a similar girdle distribution to S_4.

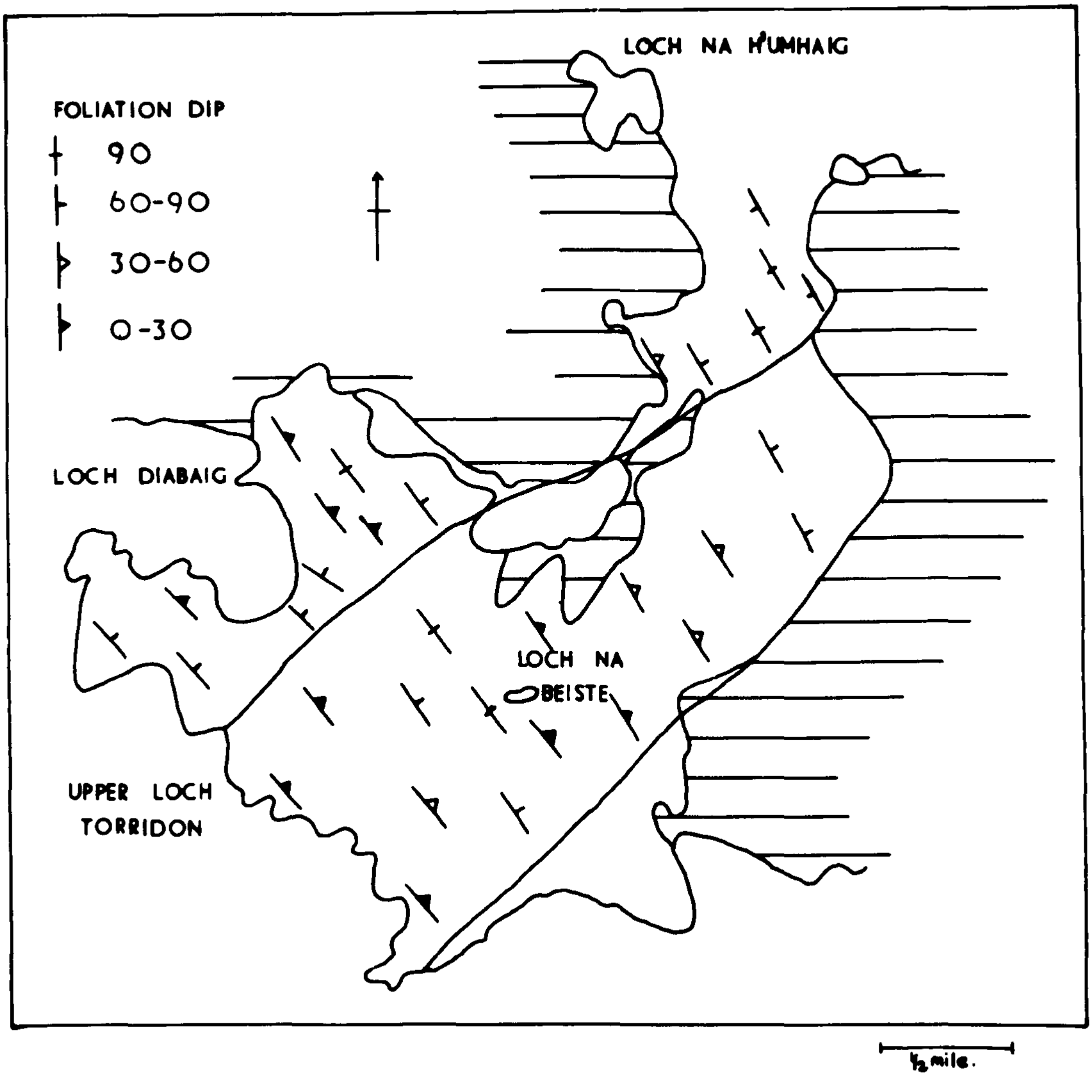


a



b

Fig.V-11. Variation in attitude of the S_4 foliation for the area.


LOCH NA H'UMHAIG
FOLIATION DIP
90
60-90
30-60
0-30
LOCH DIABAIG
LOCH NA
BEISTE
UPPER LOCH
TORRIDON
½ mile.

(see Fig. V-12c) the foliation attitude is very variable in a way that cannot be reconciled with major folding since the nature of the variation is not as regular as would be expected if major folding had been responsible. Further, the actual variation observed in S_3 does not conform to a distribution that would have been produced by post-D_4 major folding. The writer therefore prefers an explanation whereby the formation of S_4 foliation in its present position was achieved without any subsequent major folding.

Where the mineral lineation and F_4 fold axes are associated, they are always parallel, but in numerous cases where S_3 is unaffected by the D_4 fold movements a mineral lineation is present on the S_3 foliation surface. This lineation cannot be spatially related to any F_3 intrafolial folds, but where F_4 fold axes occur in proximity, they are found to have a similar trend to the lineations. When a small domain is chosen and the mineral lineation on S_3 is measured and plotted on a stereogram, it is found that the lineations fall on a common girdle which parallels the attitude of the adjacent S_4 foliation. For example, in Fig.V-12a mineral lineations from a small domain 300 metres west of Lochan Dharach are found to fall on a common girdle. The above two lines of evidence, together with the petrological information (see Chapter II.A2(b)) suggest that this mineral lineation is associated with the D_4 fold movements.

When larger domains are chosen, the lineation distribution becomes irregular because of the variation in attitudes of the F_4 fold axial surfaces and of the S_4 foliation. In Fig.V-12b, the mineral lineations and fold axes of F_4 minor folds are plotted for domain 1 and show a girdle distribution of points. A similar girdle pattern is shown in Fig.V-12c which includes the axial surfaces of the F_4 minor folds. The origin of the girdle pattern could lie in the superposition of F_4 minor folds on the F_3B folds affecting the S_3 foliation in this area. However, the variation in attitude of F_4 axial surfaces would produce a much broader variation in attitude of F_4 fold axes than is observed (compare Fig. V-12b with Fig. V-12d) and therefore superposition alone cannot explain this distribution. The girdle could, in fact, reflect the mechanics of formation of F_4 fold structure (see section V.C7).

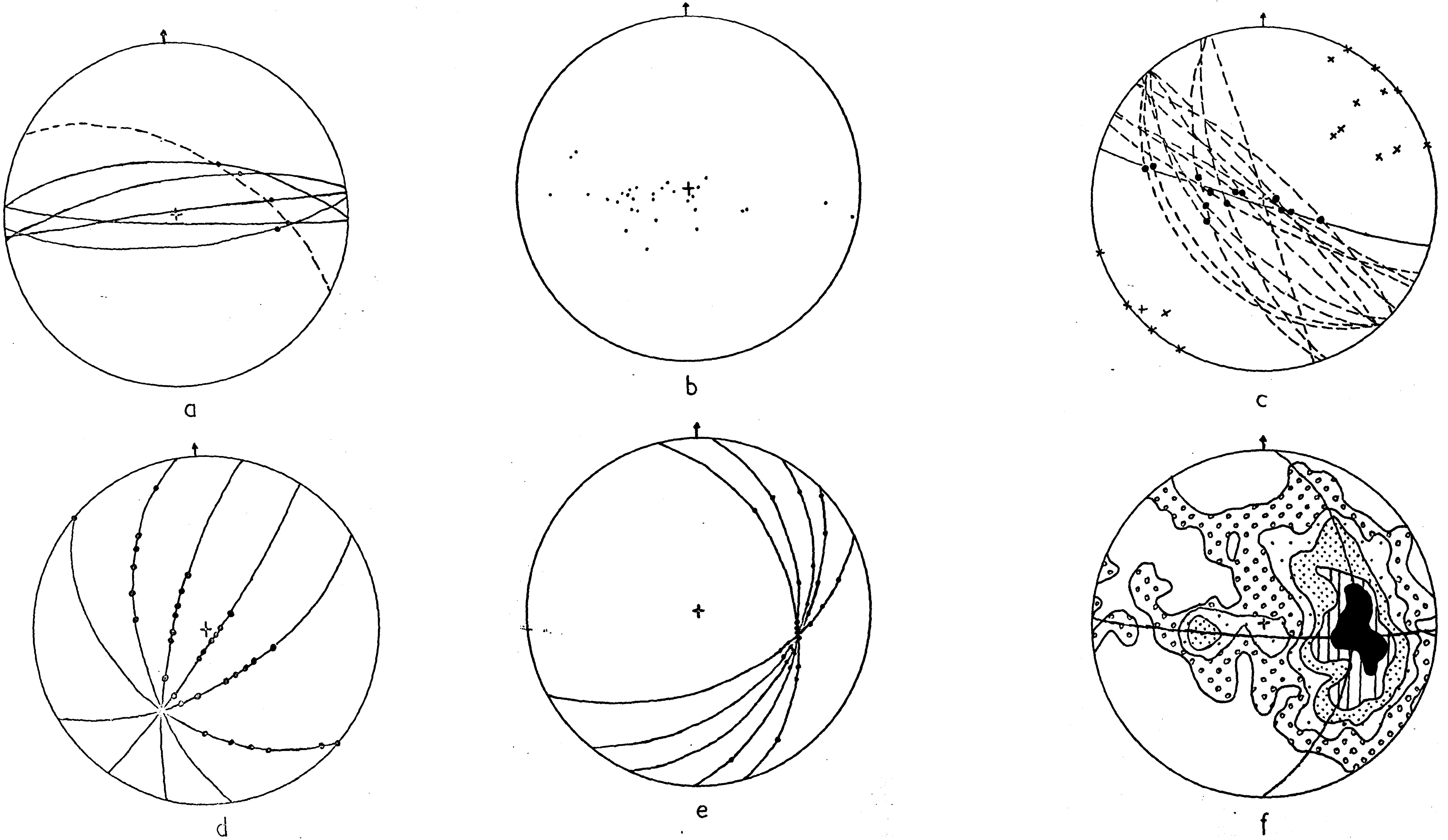
The L_4 lineations for the whole area show a cross-girdle pattern (see Fig.V-12f), the girdles being approximately normal to each other. Since the lineation is a b-lineation whose attitude is defined by the intersection of S_3 and S_4 foliations, the N-S girdle pattern of the figure could be produced by superposition of F_4 folds on the F_3B folds of S_3 foliation (see Fig.V-12e). However, the E-W lineation girdle cannot be simply explained by superposition.

7. Interpretation of the D_4 tectonite fabric

Since D_4 structures in the north of the area, unlike those of the south, have only registered mild effects of the D_4 deformation episode, it is possible to construct a course of development of F_4 minor folds and related structures.

The folds of domain 1 are dominated by movement-zones parallel to attenuated long limbs of F_4 folds. The least deformed D_4 structures are represented by parallel movement-zones. A probable course of development of F_4 minor folds is shown in Fig. V-13a-f. The mildest effects produced in the gneisses by the D_4 deformation episode are narrow parallel movement-zones which have a uniform separation (see Fig.V-13a). The S_3 foliation between the movement-zones retains the initial orientation, but with increasing deformation attenuated long limbs become more attenuated and the S_3 foliation between the movement-zones has been displaced in a clockwise manner from the initial attitude (see Fig.V-13b). Further deformation (Fig.V-13c) appears to produce folds of the S_3 foliation between the movement-zones, the latter becoming more closely spaced. Continued deformation produces increasingly tighter folds, finally resulting in a thoroughly foliated gneiss (see Fig.V-13f) with intense elongation in the plane of the foliation producing isolated fold noses and dislocation augen in the gneisses.

Although the F_4 folds may have passed through all the above stages,


a
b
c
d
e
f

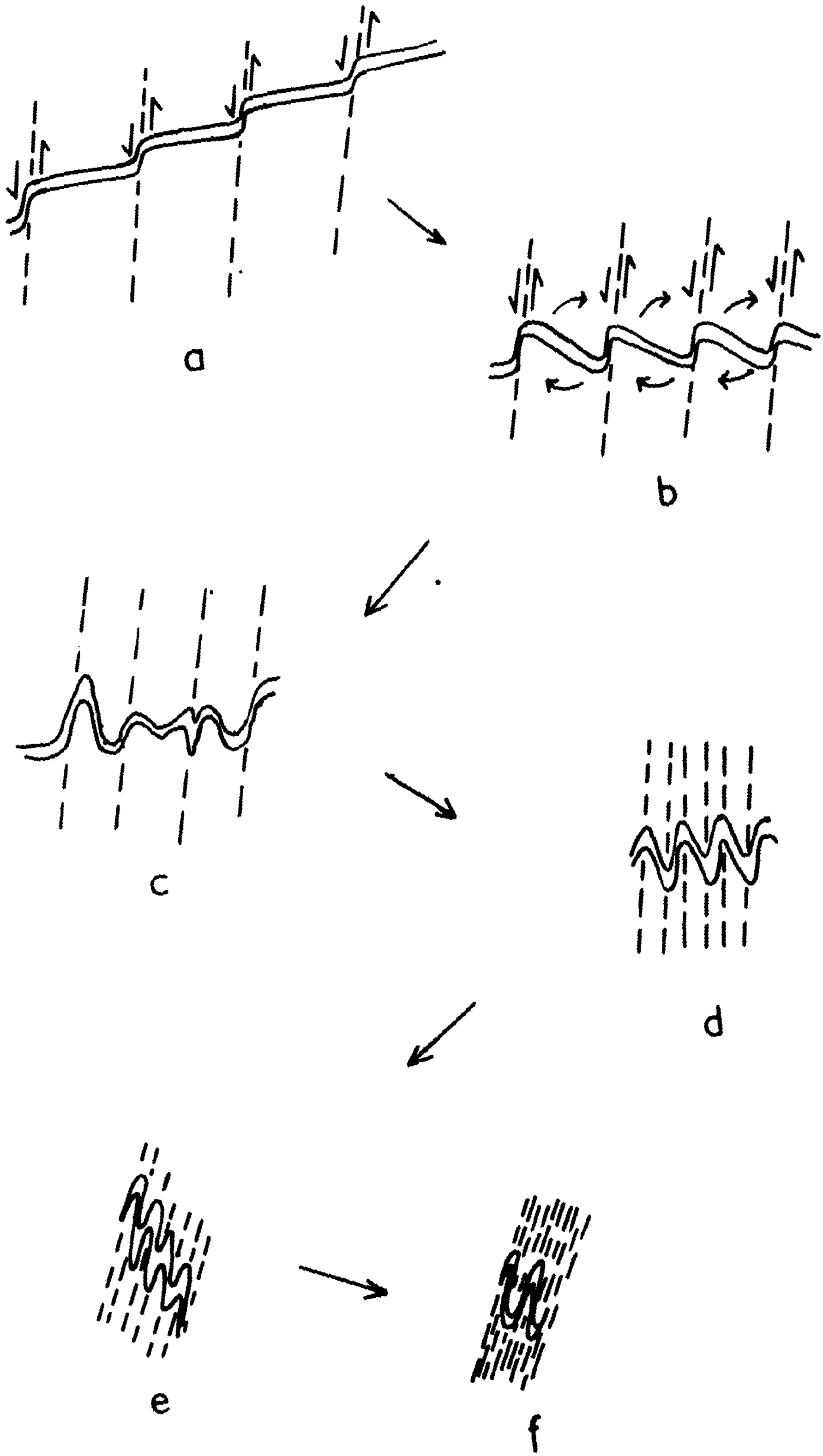
it is not intended to imply that all the more severely deformed styles, particularly in the south of the area, passed through all these stages.

Ramberg (1963) analysed the possible stress and strain relationships which may be associated with the development of foliation and suggested that foliation may be either parallel to the two longer axes in triaxial strain ellipsoid, parallel to one of the directions of maximum shear movement in the strain ellipsoid, parallel to one of the directions of maximum shear stress or normal to the maximum compressive stress in the stress ellipsoid. Since the gneisses affected by the F_4 fold movements lack deformed objects whose initial form may be determined (eg. deformed oolites and boudins), the proposed relationship between the strain ellipsoid and the D_4 structures must, therefore, be tentative.

Features exhibited by the S_4 foliation and F_4 folds suggest a formation by simple shear, particularly those folds which are least deformed (see Fig.V-13a-b). If this were the case, it would seem unlikely that foliation would be parallel to the two longer axes in the triaxial strain ellipsoid or normal to the maximum compressive stress, since these planes have no resolvable shearing stress parallel to them. It would, therefore, seem more likely that the foliation was formed parallel to a direction of resolvable shearing stress in the stress ellipsoid. This plane would probably be parallel to a plane of maximum shearing stress whose attitude depends upon the local variation in attitude of the stress ellipsoid, environment (eg. temperature and depth of burial) and upon pre-existing anisotropies in the rocks.

The L_4 lineation pattern may reveal more information as to the relationship between the foliation and the stresses which produced it. From deformation experiments conducted by McBirney and Best (1961) it was found that the orientation of linear elements was defined by the intersection of layering with the plane normal to the direction of maximum shortening and was independent of the position of Y or Z. Adapting these views to Fig.V-12b it would seem likely, since the F_4 lineations fall on a girdle, that X or direction of maximum shortening is normal to the girdle and that Y and Z lie in the plane of the girdle. However, this lineation girdle pattern is only representative

Fig.V-13a-f. Possible stages in the formation of F_4 folds with (a) representing least deformed structures (with arrows indicating movement-sense), and (f) the more intensely deformed structures. (It is not intended to imply that the more intensely deformed folds pass through all these stages; see text).


a
b
c
d
e
f

of domain 1 and therefore any conclusions drawn from it cannot be applied to the whole area.

The F_4 minor folds of much of the area south-west of domain 1, particularly those of domain 9, differ markedly in style from those of the former domain and are not so clearly reconciled with the mechanism proposed above. In fact, the writer has already indicated that F_4 folds in the south-west of the area appear to have formed under conditions where rocks are more plastically deformed, whereas those in the north-east have been deformed under more brittle conditions. This alone suggests that the course of deformation may have varied throughout the complex.

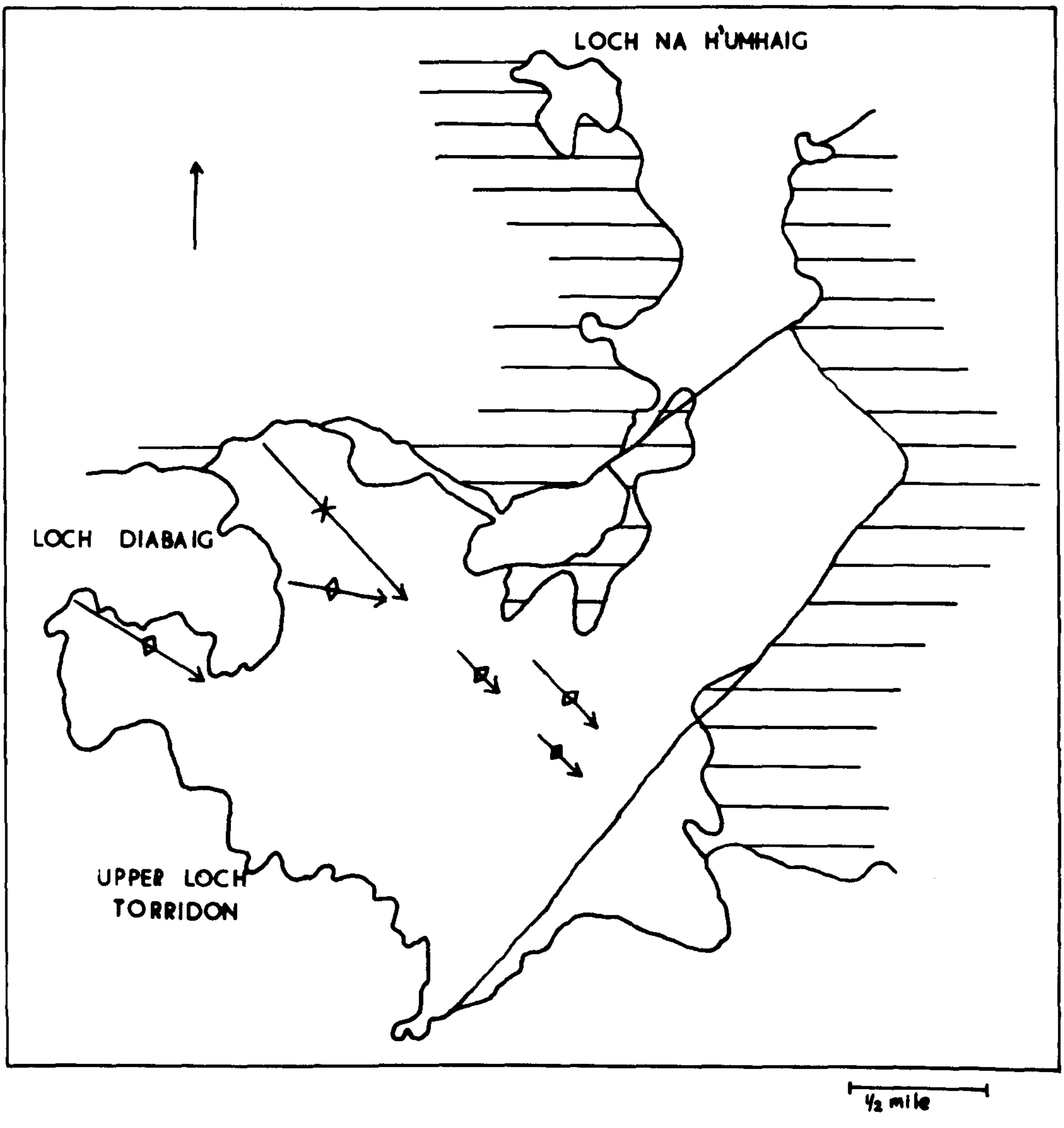
D. The D_5 Structures

The D_5 fold movements are restricted to domains 6 and 7 and 11 (Fig.V-1) where the S_4 foliation is predominantly sub-horizontal. Both major and minor folds occur, the former being traceable for distances of up to 800 metres parallel to their axes. Fig.V-14 shows the distribution of the F_5 major folds.

As a result of the D_5 deformation episode, the sub-horizontal S_4 foliation is steepened up to produce asymmetric major folds. The steep limbs of these major folds dip NE and are generally attenuated and occasionally sheared producing the S_5 foliation. Because of the scale of these folds, the relationship between the limbs can rarely be observed, but the hinge of the synformal fold north-east of Meall Ceann na Creige can occasionally be seen (see Plate V-13b).

In all the examined and measured examples, the major F_5 folds are found to plunge towards the east or south-east at angles from 10° to 35° (see Figs.V-15a-c). An interesting feature revealed by the π-diagrams of S_4 in the F_5 folded belt near Meall Ceann na Creige is that the domain of sub-horizontal foliation is demarcated by two such major folds which have variably striking axial surfaces (see Fig.V-14). The axial surfaces of the F_5 major folds dip from 20° to 30°NE except for the one on the north-east margin of domain 6, whose axial surface dips moderately south-westwards.

Fig.V-14. Distribution of F_5 major folds.



LOCH NA H'UMHAIG
LOCH DIABAIG
UPPER LOCH
TORRIDON
1/2 mile

Plate V-13a. S_3 foliation (upper half of plate) transposed into the S_4 foliation (lower half of plate) by F_4 folding: 200 metres west of Lochan Dharach (82695906).

Plate V-13b. Major F_5 folding of sub-horizontal S_4 foliation resulting in steepening up of S_4: 400 metres north of Meall Ceann na Creige (80356013).

A further characteristic of these major folds is that they are co-axial with the L_4 lineations, the L_7 lineations and the F_8 folds (see Fig.V-15b-c).

Associated with the F_5 major folds is a set of minor folds whose axes are parallel to those of the larger structures. They are either open flexures (Plate V-14a) or fairly tight plastic folds which possess either an axial-planar foliation or pegmatite sheets parallel to their axial surfaces (see Chapter II.C5). The folds have a very wide hinge zone and the competent bands, particularly in early basites, generally have a constant orthogonal thickness (see Plate V-14b) indicating a parallel style, although interlayered incompetent bands are thickened in the axial regions and possess a penetrative S_5 foliation. The majority of F_5 minor folds have shallow south-east-plunging axes, but other folds with a like style affecting the sub-horizontal S_4 foliation have a shallow plunge to the south-west or north-east and form shallow basin-and-dome-like interference structures with the south-easterly plunging minor folds.

In some instances where F_5 minor folds are box-like in profile, careful examination reveals that this shape is a result of interference of F_5 folds with F_4 minor folds (see Fig.V-16).

E. <u>The D_6 Structures</u>

There are only a few exposures where evidence of the S_6 foliation is available, although the spread of L_7 lineations suggests the widespread occurrence of a post D_5, pre-D_7 fabric. Conclusive evidence of its presence is found in two well exposed dykes, one of which (dyke B1 in Chapter III., Fig.III-1) occurs in domain 2 (82606074) and the other, the ultrabasite dyke north of Loch na Leirg is in domain 7. Where the S_6 foliation is undeformed it is found to be parallel or sub-parallel to the dyke margins, but where F_7 folds of S_6 are found it appears to have been discordant to the dyke margin.

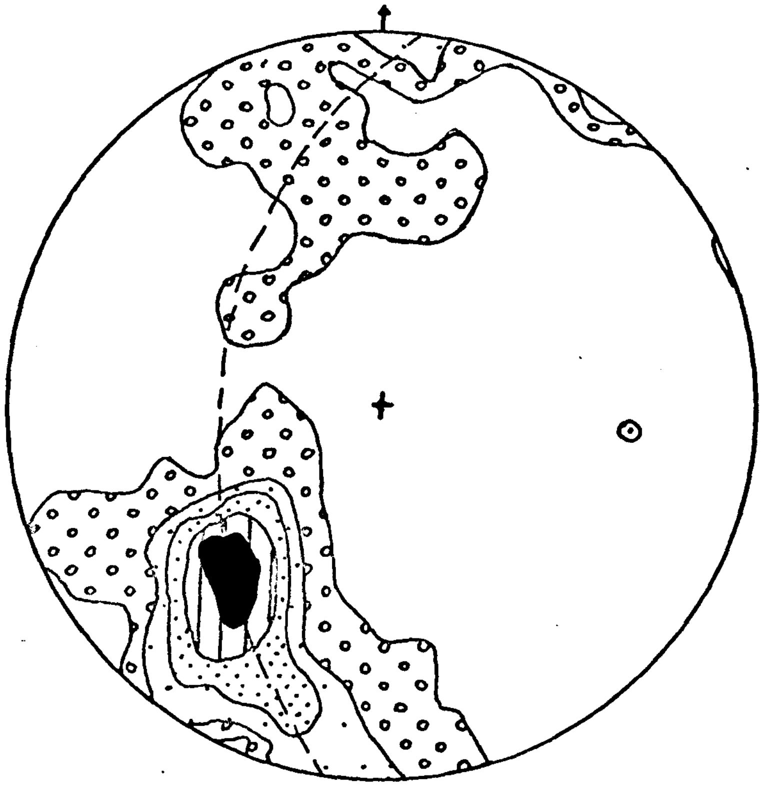
In the dyke B1 (see Fig.V-17) the S_6 foliation is sub-parallel to part of the dyke margin, but markedly discordant to other parts. Towards the south-west margin of the dyke, the S_6 foliation is intensely

Fig.V-15a-c. Contoured S_4 poles from areas of major F_5 folding (a) from the neighbourhood south of Meall Ceann na Creige; 107 poles, contoured at intervals of ½, 1, 2, 4 and 6%.

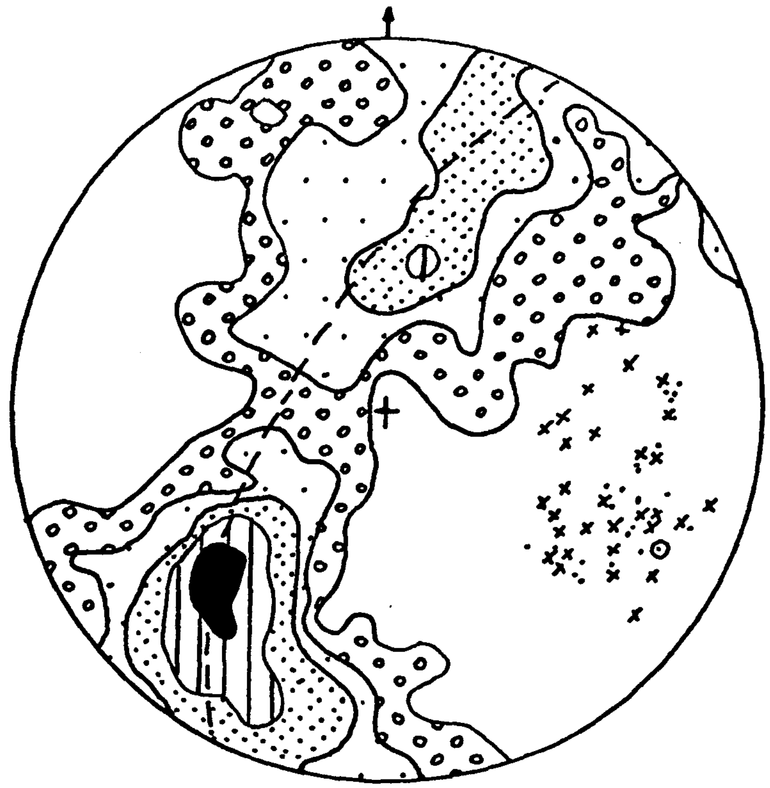
(b) from belt of gneisses north-east of Meall Ceann na Creige; 232 poles, contoured at intervals of ½, 1, 2½, 5 and 10%.

(c) from belt of gneisses at Meall na h-Airde (790591); 67 poles, contoured at intervals of ½, 1½, 2½ and 5%.

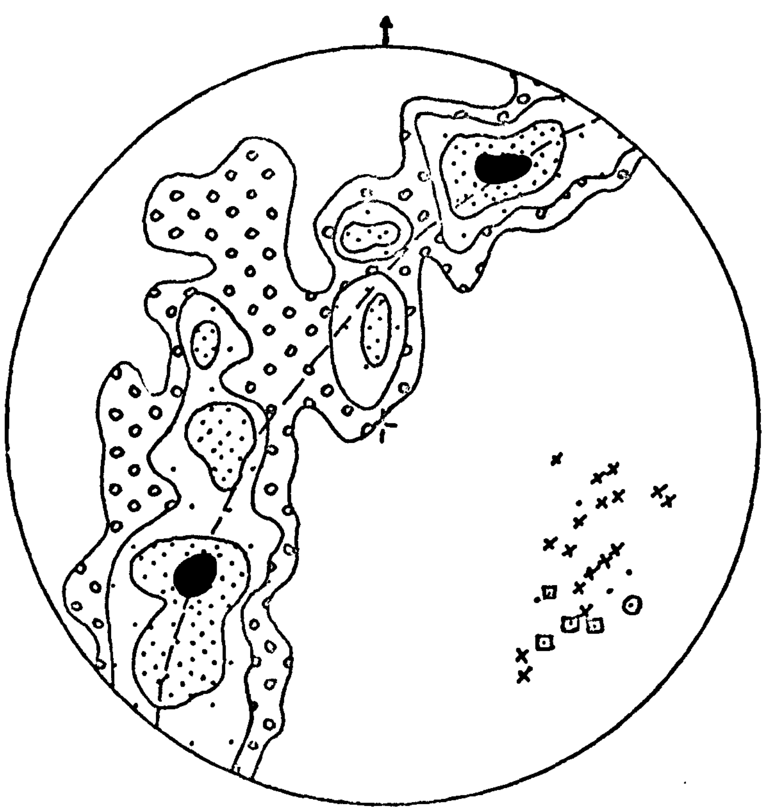
In these diagrams (⊖) F_5 major fold axes, (X) L_4 lineation, (◻) L_5 lineation and (·) L_8 lineations are shown.



a



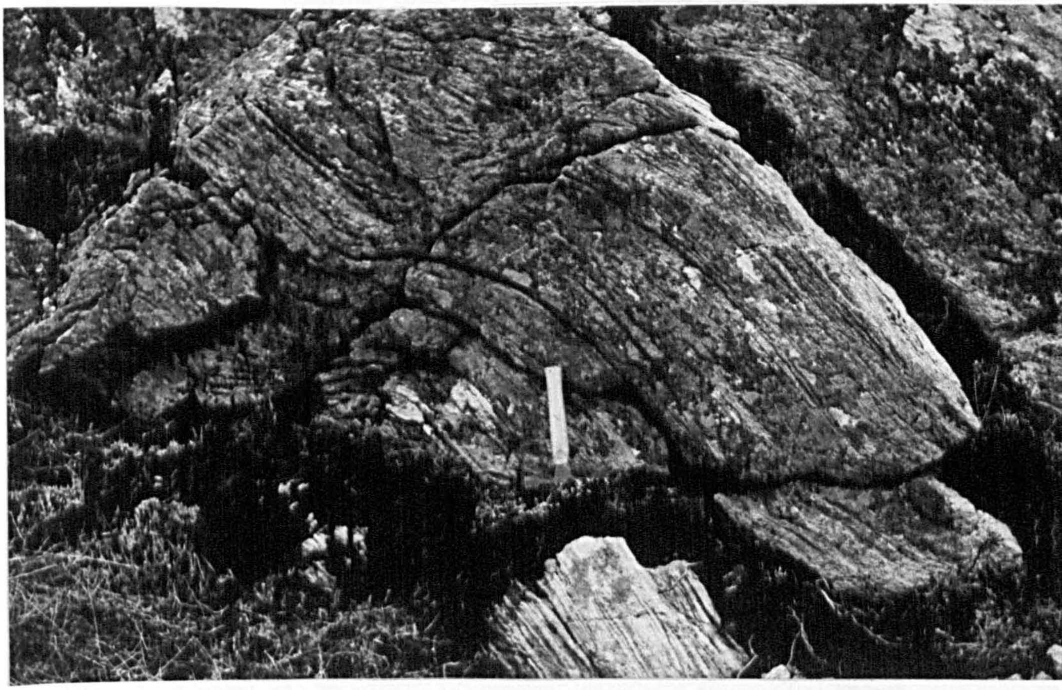
b



c

Plate V-14a. F_5 open fold; 50 metres south of Loch na Beiste (82305847).

Plate V-14b. F_5 minor folds affecting gneisses at the summit of Meall Ceann na Creige (80505975).



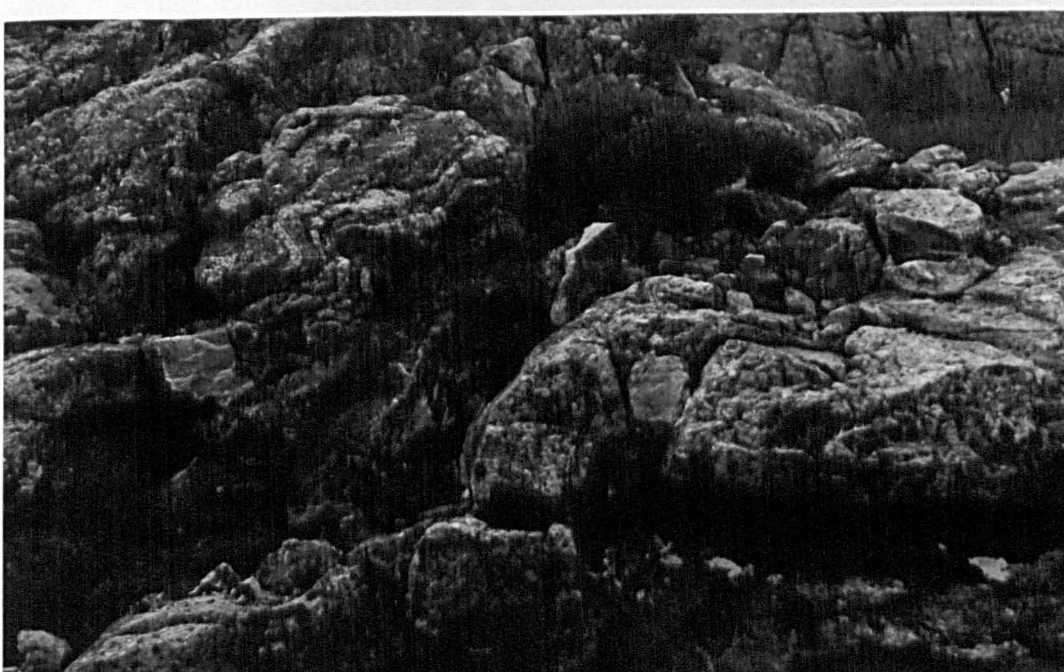


Fig.V-16. F_5 interference structures produced by superposition of F_5 (dash lines) and F_4 folds (dash-dotted lines). Traced from photograph taken in the belt of gneisses, 200 metres west of Creag an Fhraoich (80705905).

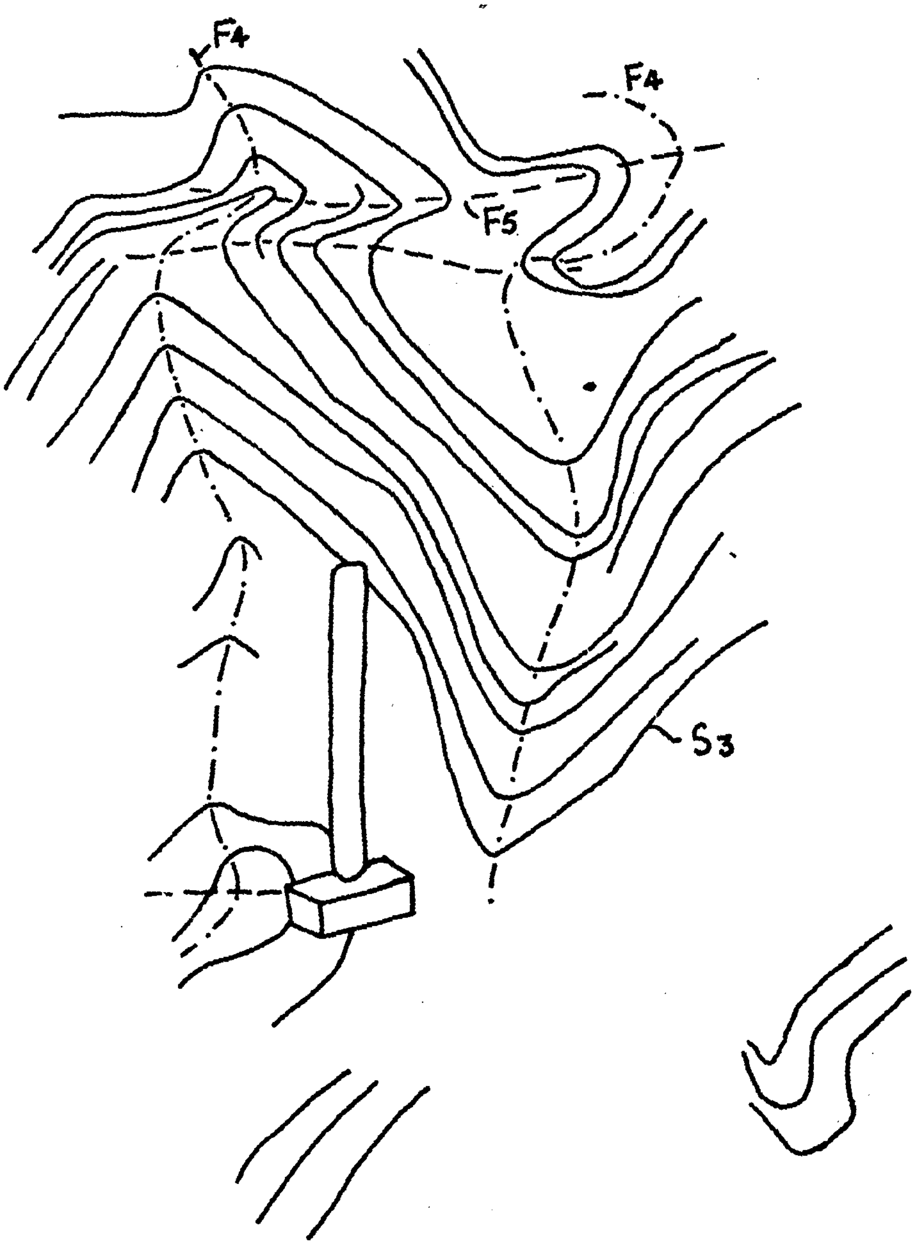
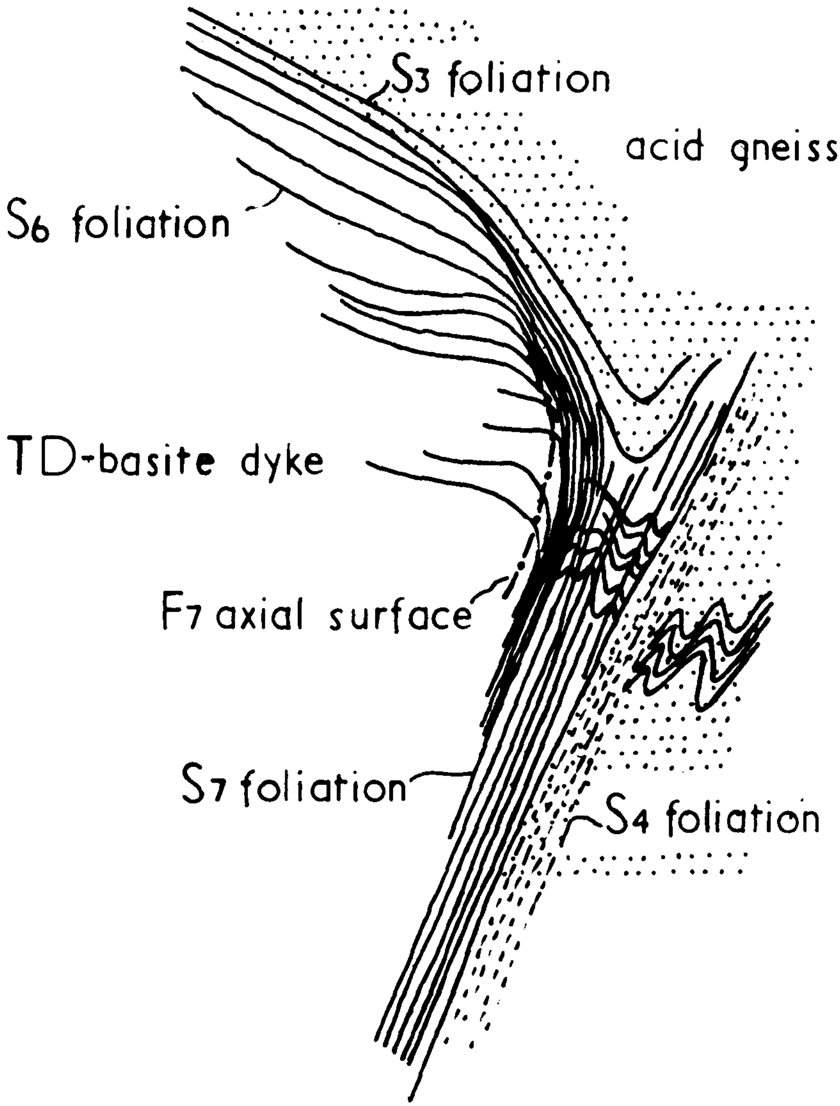

F4
F4
F5
S3

Fig.V-17. F_7 folds affecting S_6 foliation in type-TD basite dyke, south-west of Loch Airidh Eachainn (82606074).


S3 foliation
acid gneiss
S6 foliation
TD-basite dyke
F7 axial surface
S7 foliation
S4 foliation

folded and transposed into an axial-planar S_7 foliation. When the irregular margin is followed, the S_7 and F_7 fold axial surfaces are seen to bend round in concordance with the margin until it becomes confluent with the S_6 foliation.

Where evidence of folds of the S_6 foliation are lacking, it is impossible to decide whether the foliation in a dyke is S_6 or S_7 since they have a similar attitude, parallel to the dyke margin.

The D_7 Structures

The D_7 fold movements, since they are co-axial and co-planar to the D_4 fold movements are generally only recognized with certainty in the dykes. In the majority of dykes there is very little evidence of macroscopic folding of the dyke margins in such a way as to affect their outcrop pattern. However, in two instances where dyke margins have been folded, at the most south-westerly point of Rudha na h-Airidh (78755924) and in the dyke B8 (83045985) (see Plate V-15a), the folds are never more than 10 metres in wavelength and are generally tight and angular, with a small hinge-zone. The general lack of folded margins is presumably due to the intrusion of the dykes parallel to S_4 and thus in attitude unfavourable for the production of folds in D_7.

Although oblique folding of the dyke margins is uncommon, there is abundant evidence of F_7 minor folding in the dykes. These folds affect gneissic xenoliths, discordant pegmatites (see Fig.V-18) and the S_6 foliation. The folds are generally tight to isoclinal (see Plate V-15b) with thinned limbs and thickened hinge-zones and generally have an associated foliation S_7. In Plate V-16a the S_7 foliation shows slight differences from the typical axial-planar foliation in that the foliation at the hinge-zone becomes sub-parallel to the pegmatite band. In some examples, the S_7 foliation is parallel to the NE dipping limb of the F_7 folds (see Plate V-16b) which is sub-parallel to the axial surface of the fold.

In almost all the dykes examined in the Loch Torridon area, the S_7 foliation is parallel to the margins. The dykes are schistose at

Fig.V-18. F_7 minor fold affecting pegmatite vein in type-TD basite; from the coastal section, south of Diabaig (79985945).

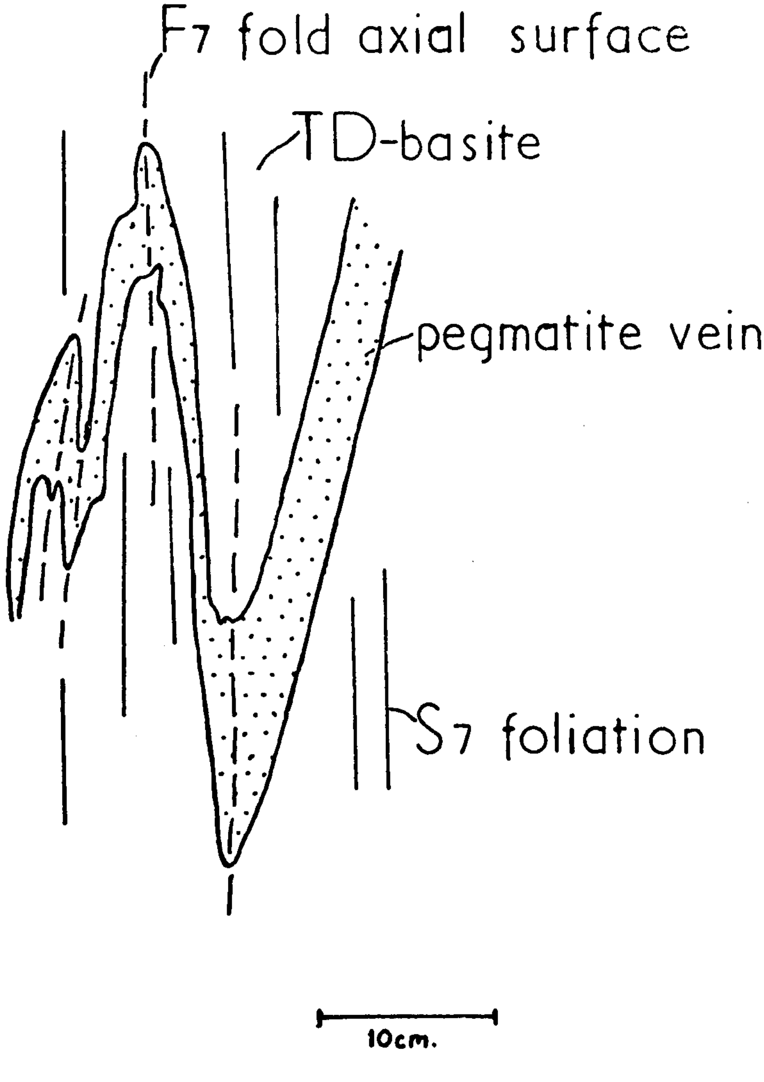
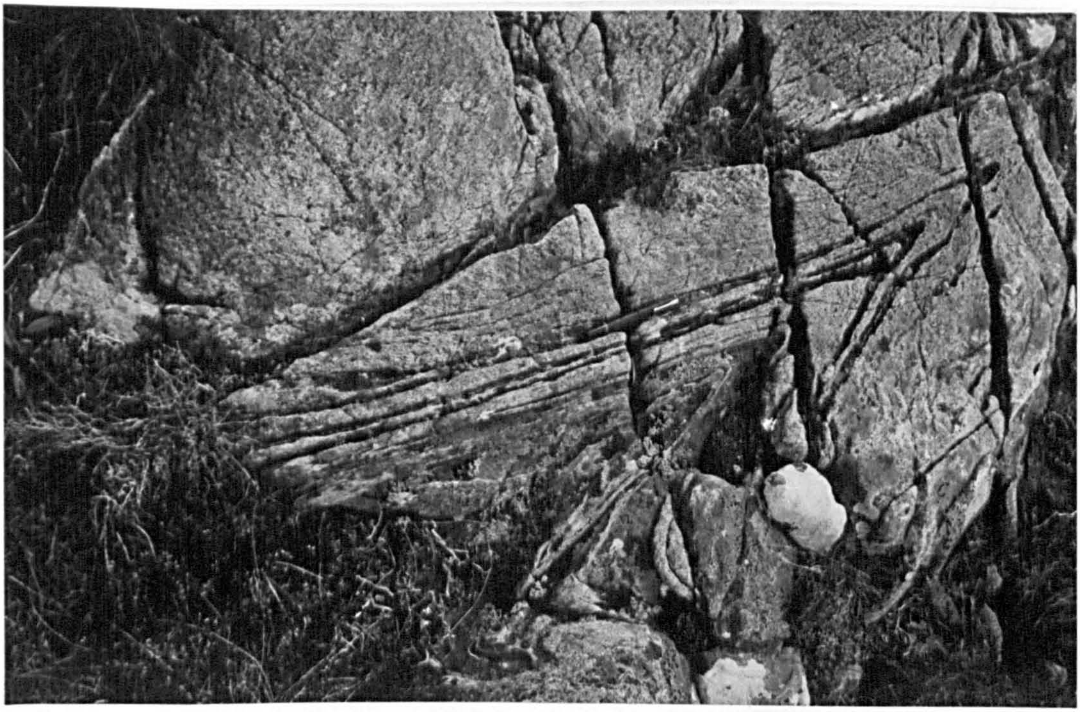

F7 fold axial surface
TD-basite
pegmatite vein
S7 foliation
10cm.

Plate V-15a. F_7 folds affecting type-TD basite dyke margin; 500 metres north of Loch nan Tri-eileanan (82786048).

Plate V-15b. Tight F_7 folds affecting acid gneiss band in type-TD basite dyke; 400 metres east of Loch nan Tri-eileanan (83045985).



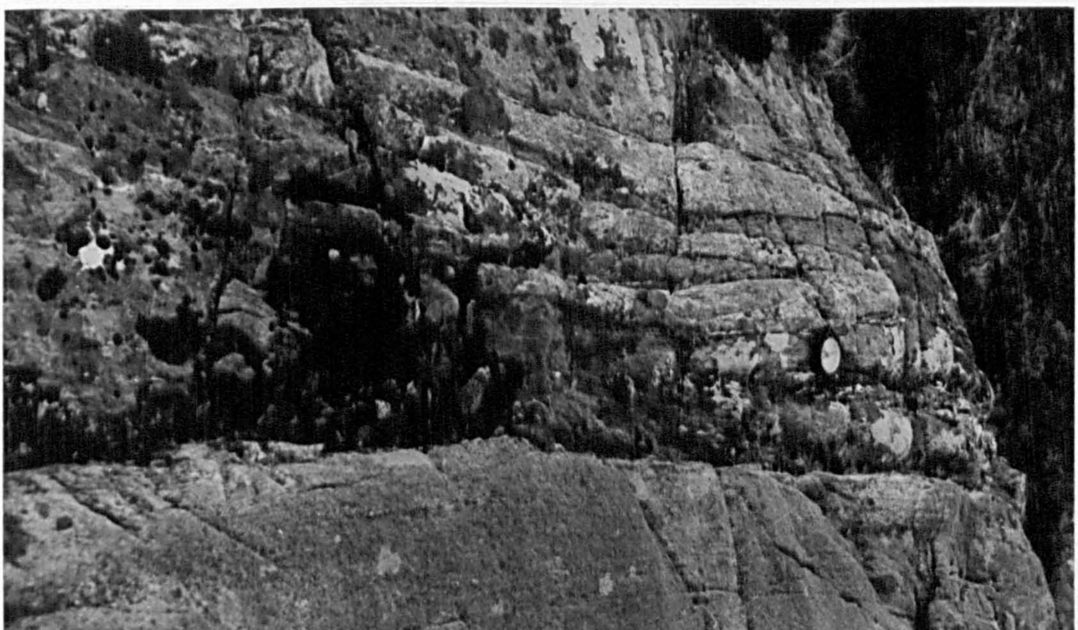
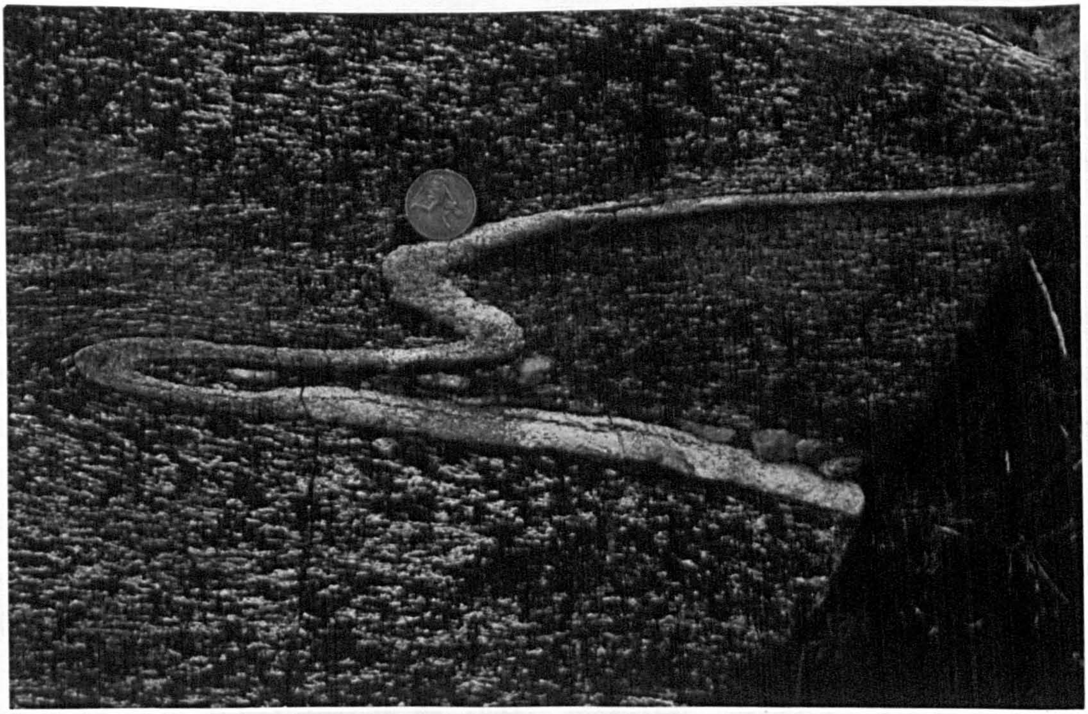


Plate V-16a. F_7 minor fold and S_7 axial planar foliation formed in type-TD basite dyke; south-east of Lochan Dharach (82725892).

Plate V-16b. F_7 fold of S_6 foliation in type-TD basite. S_7 foliation is formed parallel to one of the limbs; 300 metres west-south-west of Meall na h-Airde (78785884).



the margins but towards the centre the foliation becomes less penetrative and is in general absent in the wider dykes. In the deformed multiple dykes, the foliation is parallel to the margin between the separate intrusions (see Plate V-17a), the finer grained later intrusion being more schistose than the coarser grained earlier one.

The variation in expression of foliation in the dykes in different parts of the area has already been discussed in Chapter III. B1. The dykes in the south are normally foliated throughout, whereas further north the foliation is absent in the dyke centres, and in the vicinity of An Ruadh Mheallan many dykes are completely massive and undeformed. There are also more local variations in deformation in the dykes which appear to be related to the structures in the adjacent gneisses. Thus, where the dykes have been emplaced parallel to the S_4 foliation, they are more deformed than where they were emplaced discordantly irrespective of their location.

1. F_7 superposed folds

Interference structures of F_7 folds with earlier folded surfaces are very uncommon, although their presence would be expected. The main reasons for their scarcity appears to be:- (i) the widespread occurrence of S_4 and the co-axial and co-planar relationship of S_7 to S_4, and (ii) the lack of earlier folded surfaces in the dykes, which are generally the only bodies in which S_7 can be conclusively identified.

In a small early basite, 150 metres south of Loch na Leirg, interference patterns produced by the superposition of F_3, F_4 and F_7 folds are found (see Fig.V-19). The interference patterns which are formed in the D_7 fold movements (see Fig.V-20) involve the earlier folds F_4 of Fig.V-20 and are of class 1 of Ramsay (1962). Since the S_4 and S_7 foliations are in general co-planar, the interférence patterns produced by the interaction of F_7 and F_4 involve no refolding of earlier fold axial surfaces and would be expected to be of the dome-and-basin type. The most characteristic feature of these interference patterns is the variable attitude of the fold axis within the common axial surface of the two phases of folds. The F_4 fold axes are represented by the trend a-b. As a result of flattening perpendicular to the axial surfaces of the F_4 folds, the fold axes become rotated into the trend b-c producing elongate basin and dome structures. Increased flattening produces further rotation of the fold axes until they all have a similar trend (d-e), parallel to the penetrative mineral lineation (g-h) in the rock.

It would seem, therefore, that increasing co-planar flattening of F_4 folds results in rotation of the initially formed fold axes into parallelism with the mineral lineation of the rock, and since recrystallization has occurred in the M_7 metamorphism, the movements appear to be related to the D_7 deformation.

2. <u>Relationship between S_7 foliation, L_7 mineral lineation and F_7 fold axes</u>

The first effects of the D_7 deformation episode is to produce a rock having a lineated appearance produced by the alignment of hornblende laths and with increased deformation, the dykes also develop a foliation (see Chapter III.B1). A well developed mineral and fabric lineation, the former represented by aligned hornblende laths and the latter by drawn out aggregates of plagioclase and quartz, is formed in the plane of the foliation. The L_7 lineation is always found to be parallel to the F_7 fold axes and is, therefore, a b-lineation. The drawing out of felsic aggregates into the direction of the lineation in the dykes suggests that this lineation represents the direction of maximum elongation in the rock, which is confirmed by the presence of elongated ellipsoidal garnets with their maximum elongation parallel to the mineral lineation.

3. <u>The D_7 quartz fabric</u>

Investigations of the D_7 quartz fabric has revealed that the quartz c-axis forms a girdle whose plane lies normal to the foliation and whose axis isparallelto the b-lineation in the rock (see Figs.V-21a-b). The

Fig.V-19. Superposed fold formed as a result of interference of F_3, F_4 and F_7 folds; from the belt of gneisses 150 metres south of Loch na Leirg (81185876).


F3 fold axial surface
F4 —— " —— " ——
F7 —— " —— " ——

Fig.V-20. "Eye" shaped interference structures produced by the superposition of F_7 on F_4 folds; from the belt of gneisses 100 metres south of Loch na Leirg (81185876).

a-b is the initial trend of F_4 fold axes.

e-d is the trend of re-oriented F_4 fold axes which are parallel to the L_7 mineral lineation direction (g-h).

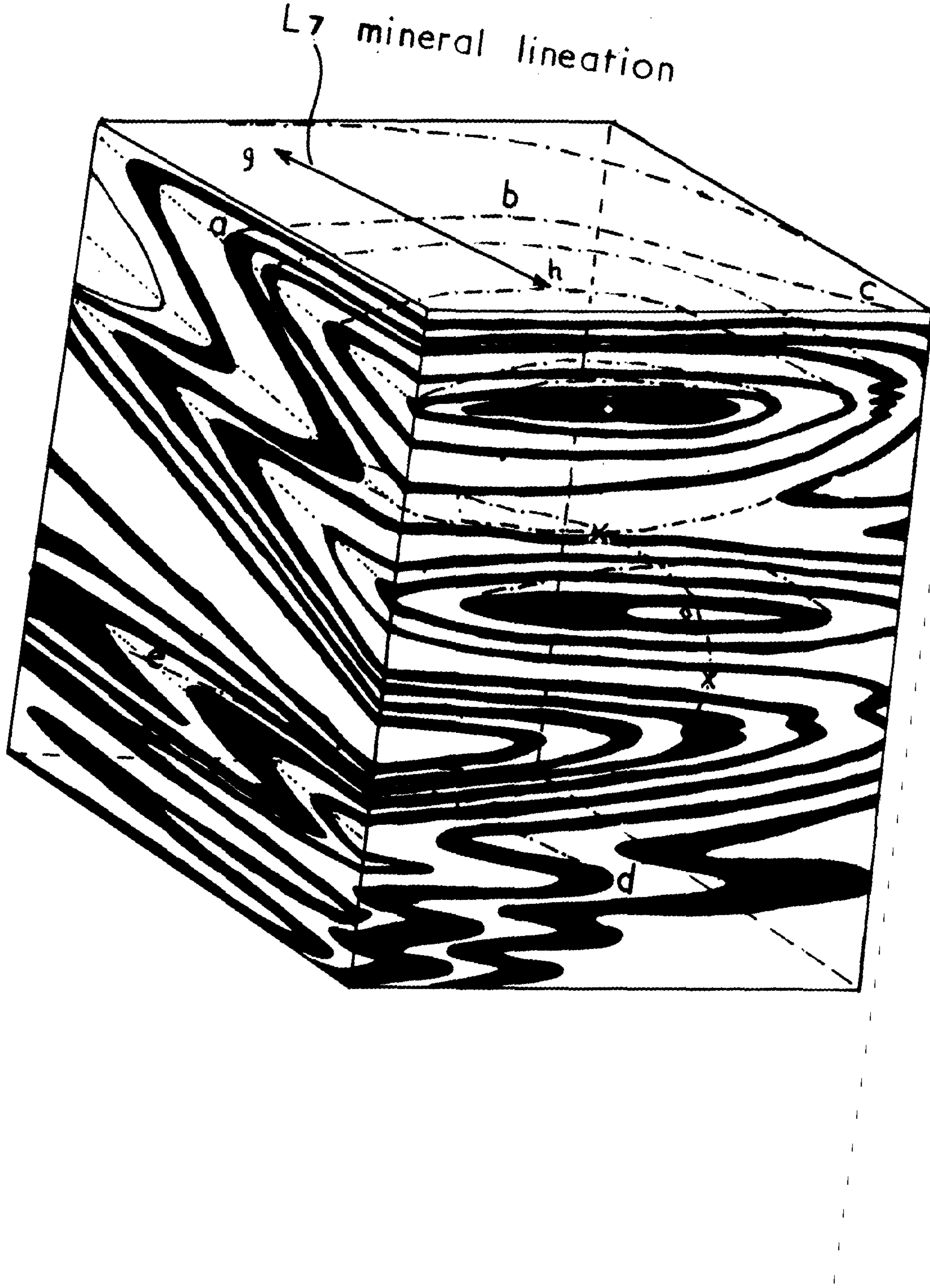
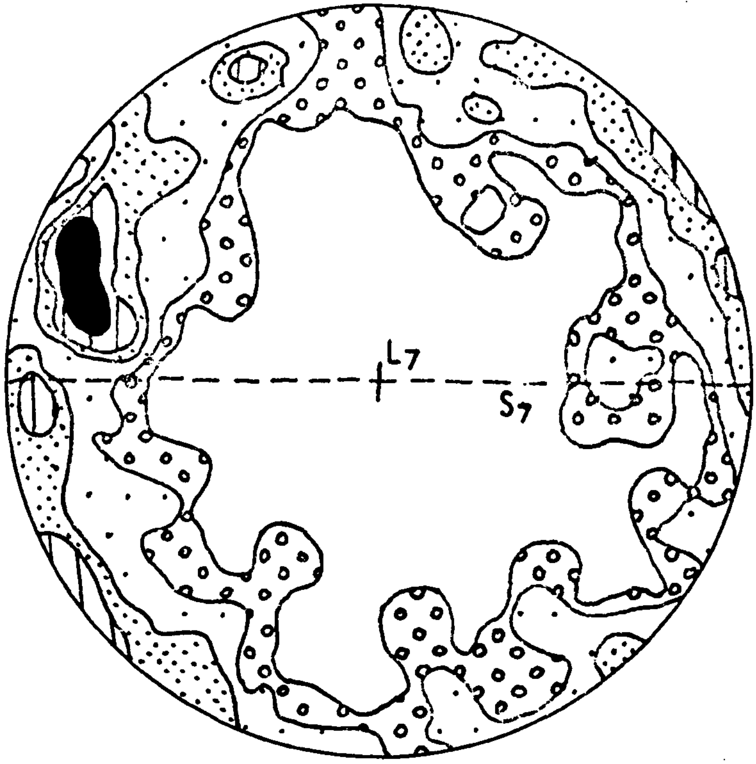
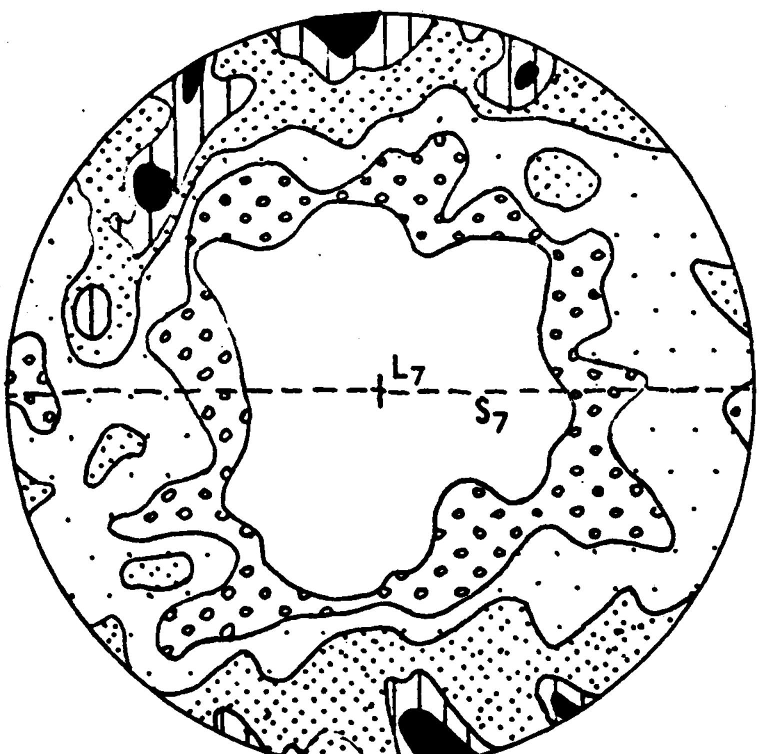

L7 mineral lineation
g
a
b
h
c
e
d

Fig.V-21a-b. Orientation diagram for (0001) in quartz; monoclinic symmetry. Contoured at intervals of $\frac{1}{2}$, 1, 2, 3 and 4%.



a



b

fabric is therefore monoclinic and homotactic, the girdle forming the plane of symmetry. In the more perfect quartz fabric (Fig.V-21a) there is one maximum which lies on the girdle, approximately 20° out of the plane of the foliation, the significance of the maximum being unknown.

The attitude of the S_7 foliation and L_7 lineation

Figs.V-22a-c show the variation in attitude of the S_7 foliation poles and L_7 lineation over the complex. By comparing Figs.V-22a and b with Figs.V-9c and 9f, which are from identical domains, it can be seen that S_7 in the dykes coincides with the S_4 distribution in the acid gneisses, which demonstrates the co-planar nature of the foliations. Similarly, the comparison between Fig.III-2e and Fig.V-23c demonstrates the concordance that is found between the dyke margins and S_7 foliation. The spread observed in the L_7 lineation (see Fig.V-22c) is probably a result of both the variation in S_7 and the attitude of the S_6 foliation in the dykes, since it is the latter foliation which is folded and S_7 is a b-lineation caused by the intersection of S_6 and S_7 foliations.

G. The D_8 Structures

The D_8 deformation episode produces structures which are markedly different from those produced in earlier fold movements. Although they are found throughout the area, they occur more commonly towards the shore of Loch Torridon.

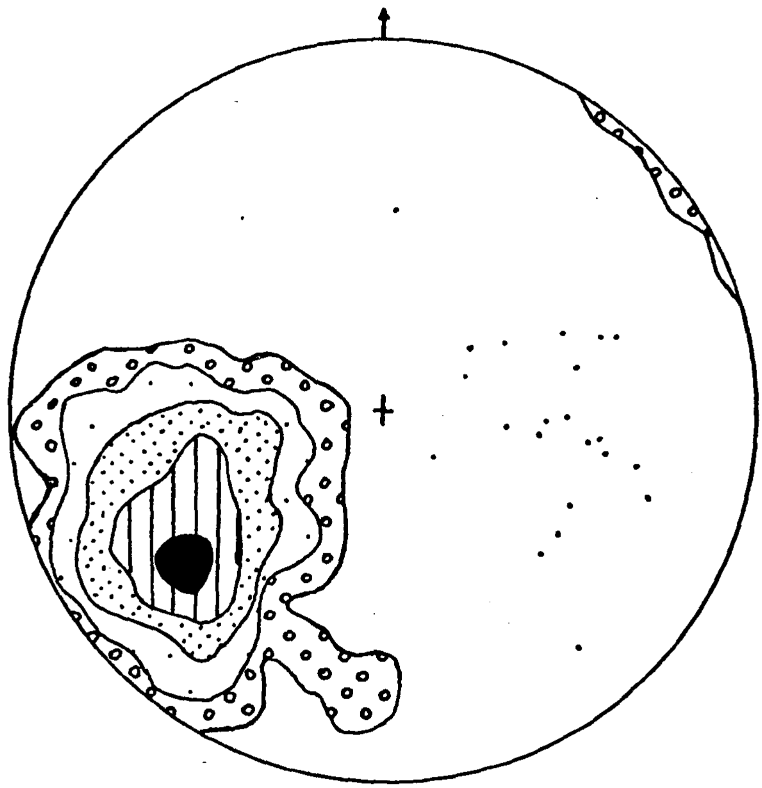
The fold style shows considerable variation through fairly open (Plate V-17b) to close (Plate V-18a) and fairly tight profiles. The hinge-zones may be broad (Plate V-17b) producing curved profiles or extremely narrow producing angular folds. The folds are generally asymmetric (see Plate V-18b) and often die out parallel to their axial surfaces (see Plate V-19a). In some examples of F_8 folds the axial surface is found to bifurcate producing a disharmonic fold. In Plate V-18a the disharmonic fold probably reflects the difference of competence between the alternating layers.

Observations of the orientation of F_8 fold axes in relation to both L_4 and L_7 in the gneisses indicate that F_8 fold axes are in the

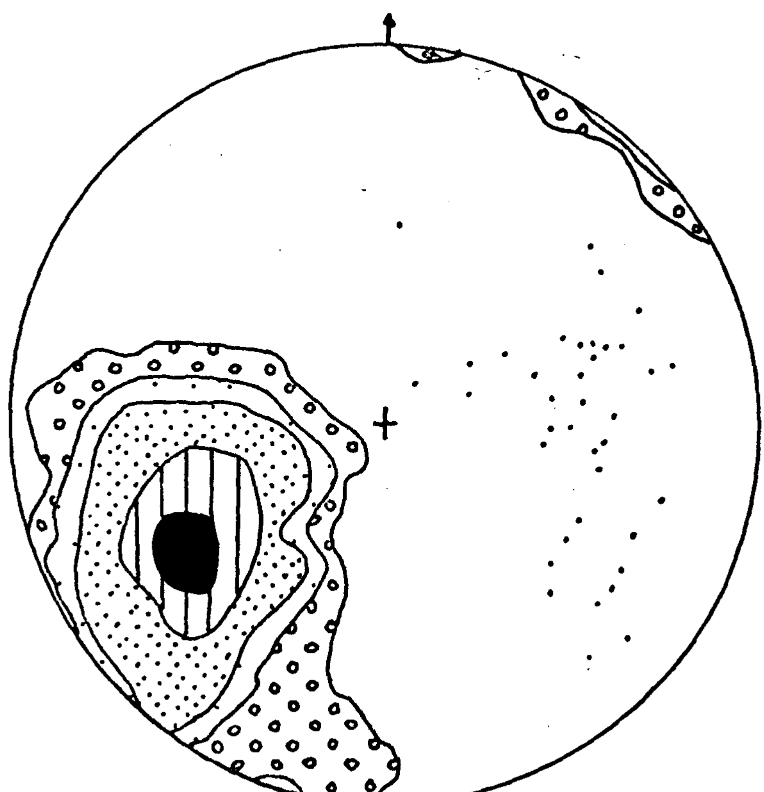
Fig.22a-c. S_7 foliation poles (contoured) and L_7 lineation (·) in the dykes (a) from domains 1, 2, 3, 4 and 5; 126 poles contoured at intervals of ½, 2, 4, 8 and 15%.

(b) from domains 8 and 9; 40 poles contoured at intervals of 1, 6, 12½ and 14%.

(c) for the whole area; 212 poles contoured at intervals of ½, 1, 2½, 7 and 12%.



a



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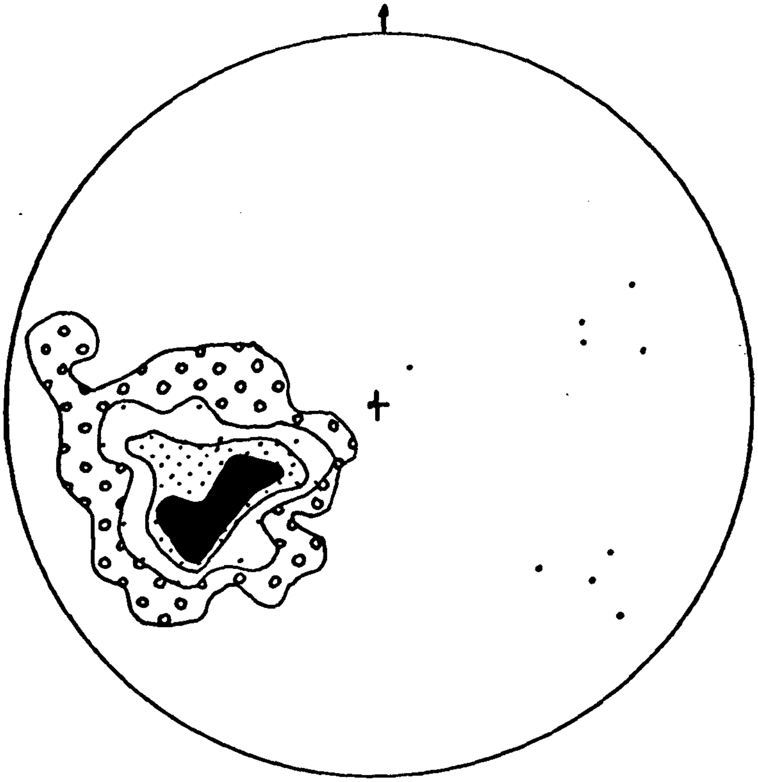


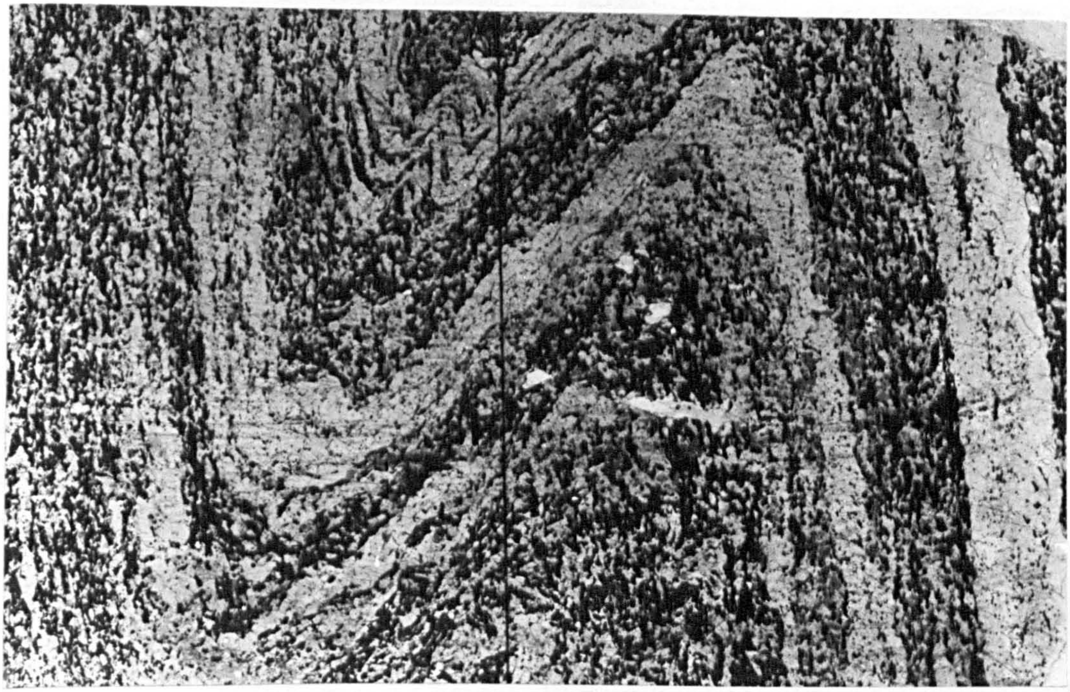
b

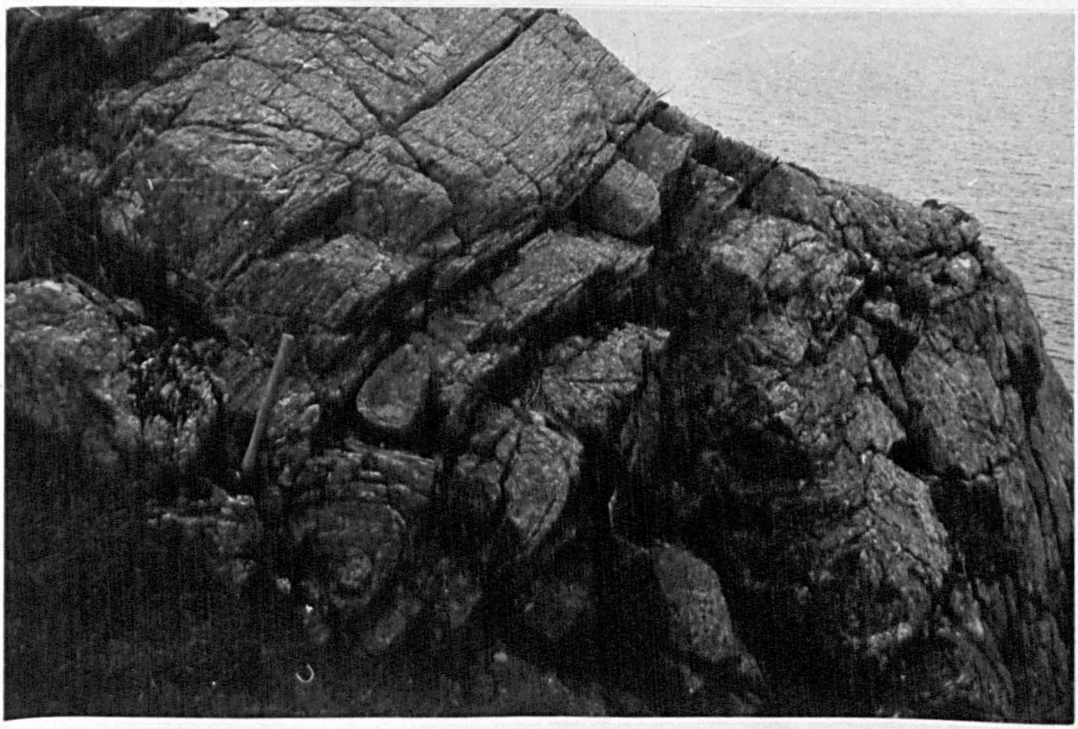
Plate V-17a. S_7 foliation formed parallel to contact between dykes in a multiple type-TD basite dyke; 450 metres east-north-east of Loch nan Tri-eileanan (83126010).

Plate V-17b. F_8 minor folds affecting S_7 foliation in type-TD basite; 300 metres west of Loch a'Choin Dubh (81265797).

Plate V-18a. V-shaped F_8 minor fold affecting S_7 in type-TD basite; 350 metres west of Lochan Dharach (82105910).

Plate V-18b. Tight F_8 fold affecting S_4 banded gneisses; 300 metres south of Lochan Duibh (79755778).





majority of cases co-axial to these earlier linear structures, although occasional refolded L_4 and L_7 lineations are found. Fig.V-23 illustrates the relationship between L_8 and L_7 lineations in the belt of gneisses on the shore of Loch Diabaig, 250 metres south-south-west of Diabaig. It is apparent that L_8 duplicates the attitude of L_4 and it would seem that the orientation of L_4 and L_7 lineations represent a weakness in the gneisses which has initiated a rotation axis for F_8 folds.

Where earlier lineations are observed to be refolded by F_8 folds (see Plate V-19b) the disposition of these lineations fall on a small circle (see Fig.V-24) which suggests that the folding mechanism was buckling (see Ramsay 1963) and that the fold axis is the b-kinematic axis. The buckling mechanism of folding is further indicated by the parallel nature of the layering in the fold (i.e. constant orthogonal thickness). However, not all F_8 folds have a constant layer thickness, but show thickening in the region of the hinge-zone.

Fig.V-25a illustrates the spread in F_8 fold axes for the area. This broad spread of F_8 fold axes may be explained by:-

(i) the variable attitude of S_4 (see Fig.V-10a)

(ii) the variation in attitude of F_8 fold axial surfaces (see Fig.V-25b)

(iii) the co-axial nature of F_8 folds to L_4 and L_7, the latter lineations showing a considerable variation in their attitude.

A thin foliated type-TD basite, 550 metres south-east of Diabaig (80015932) shows pinch-and-swell structure affecting the S_7 foliation which indicates that the type-TD basite has undergone extension in the plane of the foliation. Fig.V-26a illustrates the variation in attitude of the basite margin, which forms a girdle whose axis plunges south-east slightly steeper than the F_8 folds in the vicinity. The attitude of the pinch-and-swell structure can be used to determine the components of strain parallel to the S_7 foliation within this belt. Fig.V-26b shows the axes of minimum Z, intermediate Y and maximum strains X in the structure computed from the plunge of the structure and the attitude of the S_7 foliation.

Fig.V-23. Relationship between L_4 lineation (·) and L_8 lineation (⊙) from the coastal section, 600 metres south of Diabaig. Tie lines (broken lines) joining associated L_4 and L_8 lineations.

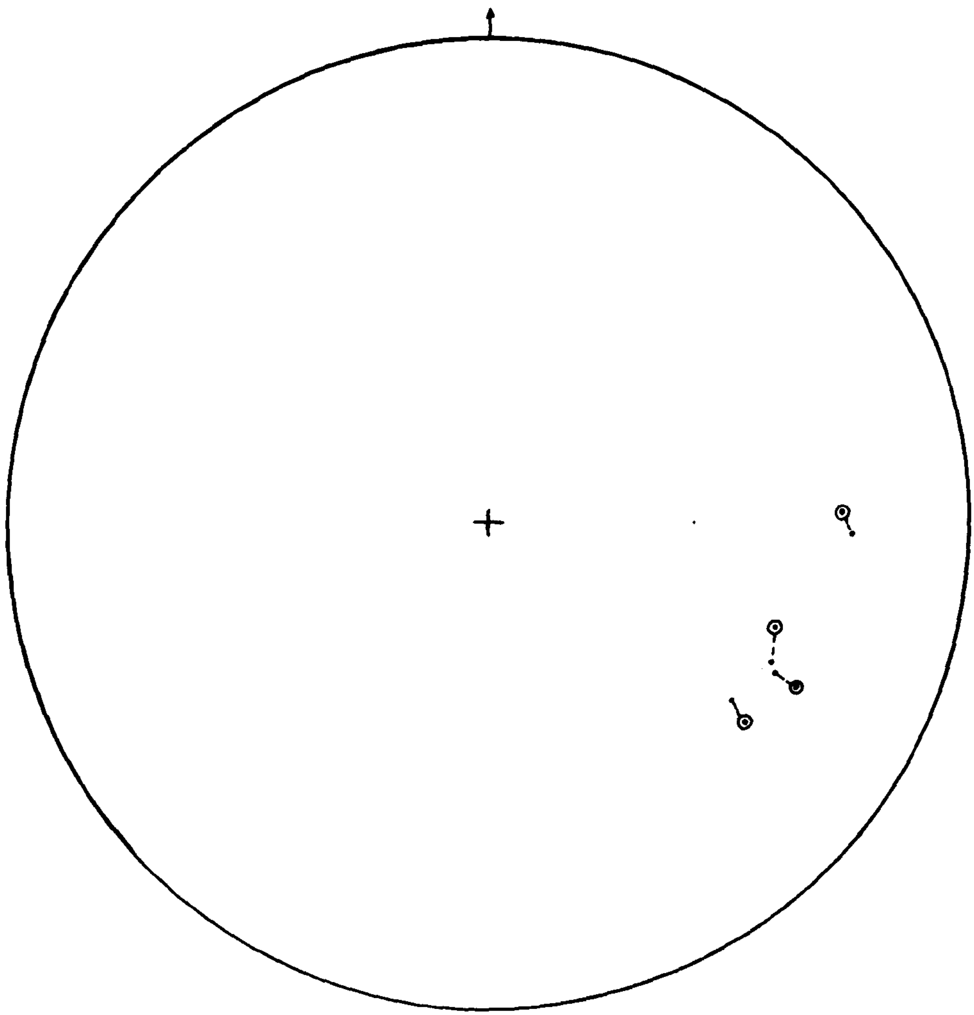


Plate V-19a. F_8 minor folds affecting type-TD basite; 200 metres south of Loch na Leirg (81135865).

Plate V-19b. L_7 lineation being refolded by F_8 fold; 200 metres south of Creag an Fhraoich (80855858).

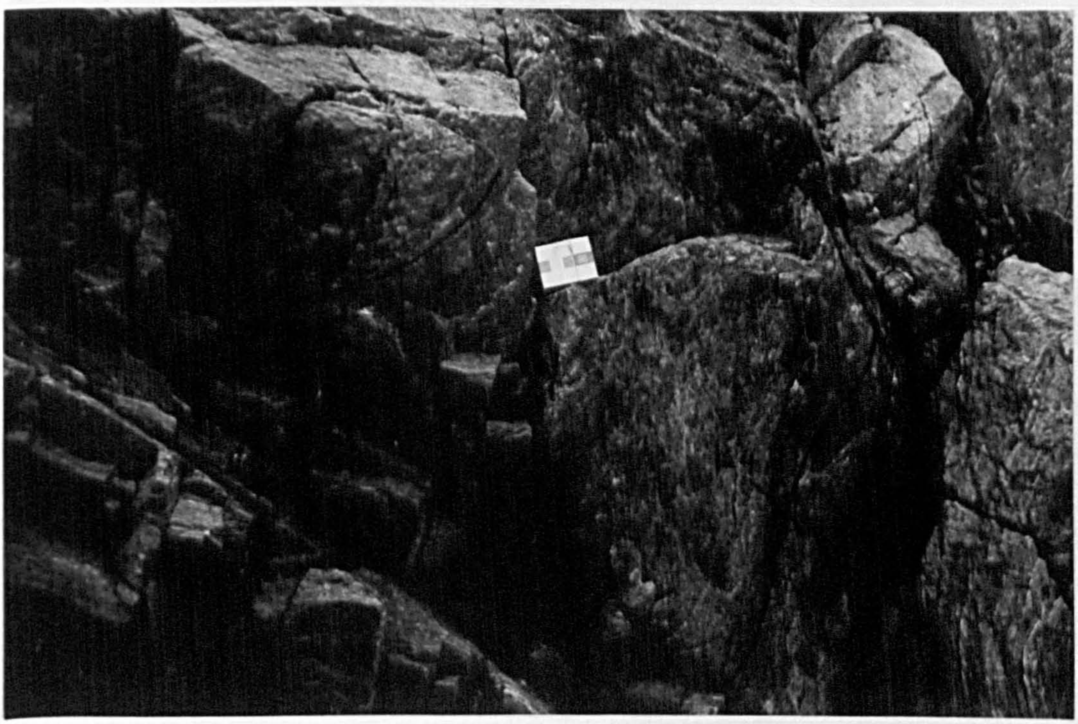


Fig.V-24. Small circle disposition of L_4 lineations (·) as a result of F_8 folding of S_4 (great circles). From belt of gneisses, 100 metres south of Creag an Fhraoich (80885864).

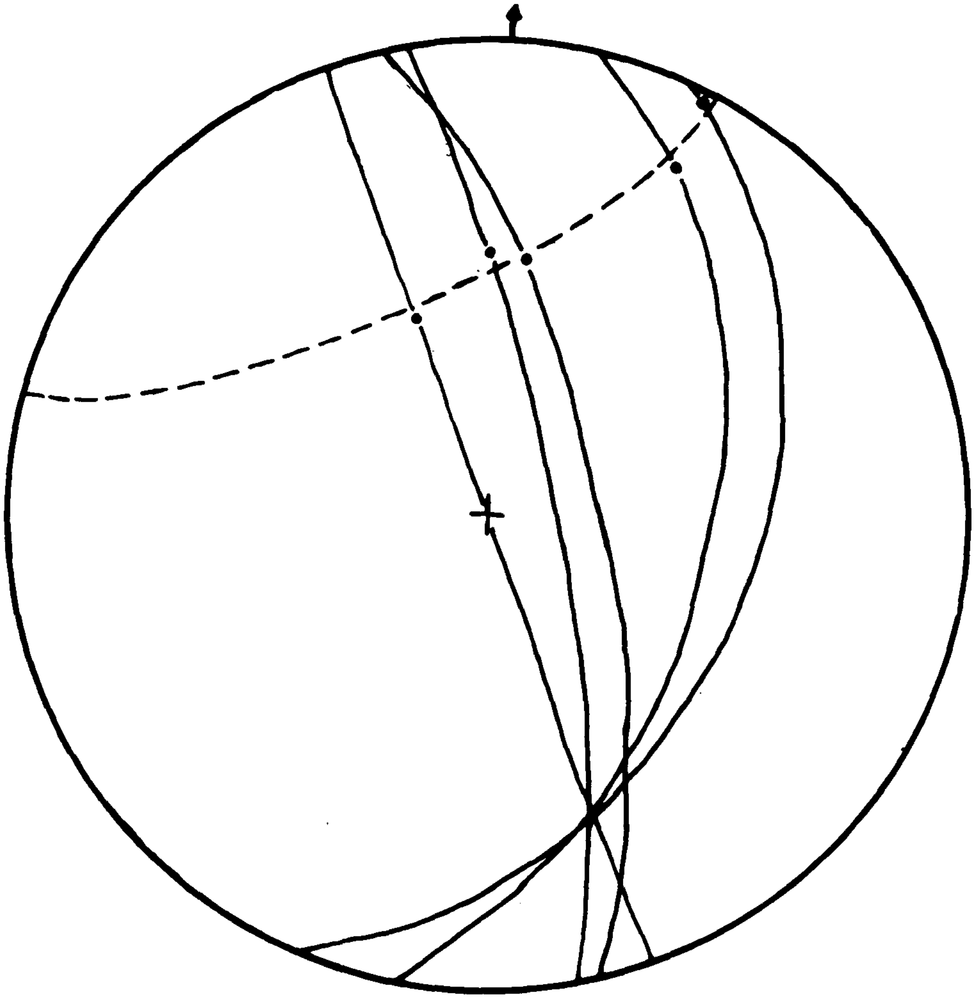
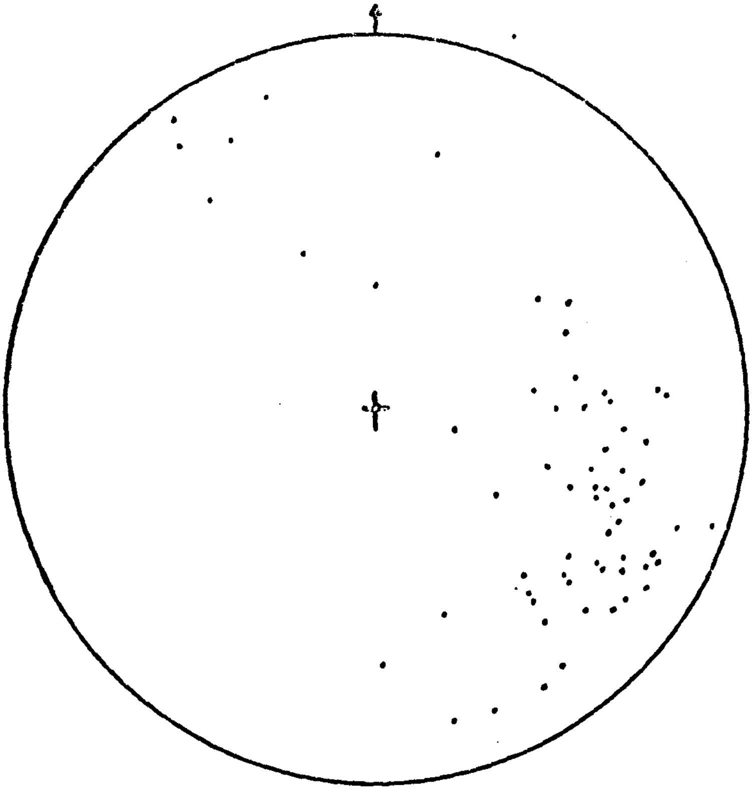


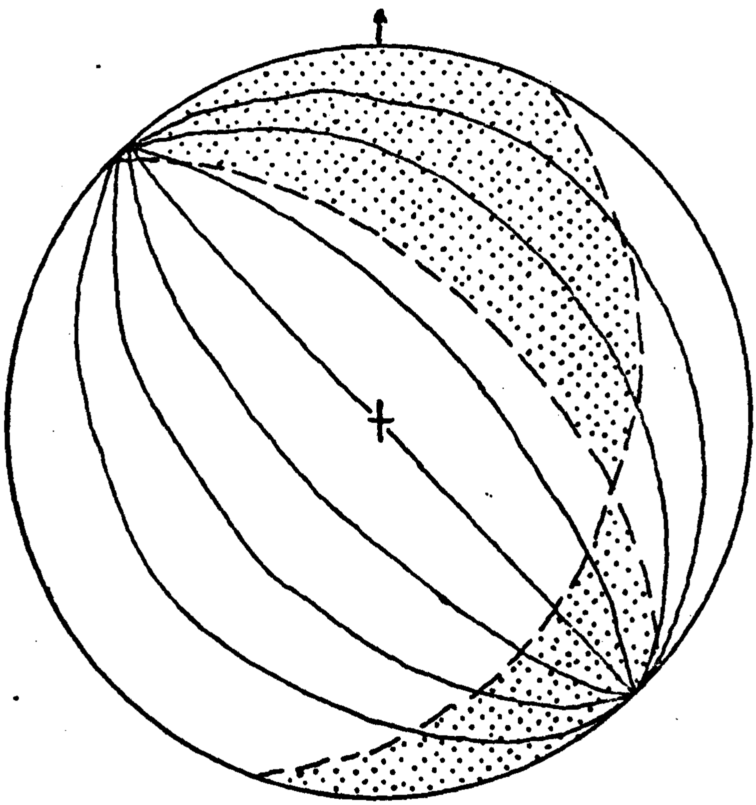
Fig.V-25a-b. Actual and expected L_8 lineation plot for the area.

(a) Actual variation in L_8 lineation.

(b) Expected variation of L_8 (shaded area) obtained from the limits in attitude of F_8 fold axial surfaces (dash lines) and the variable attitude of the S_4 foliation (full lines) over the area.



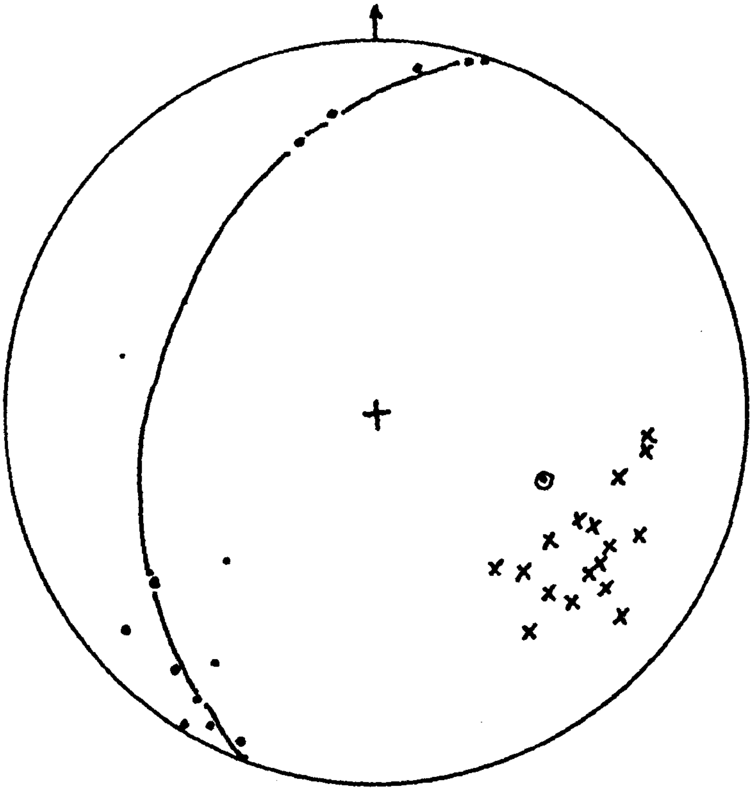
a



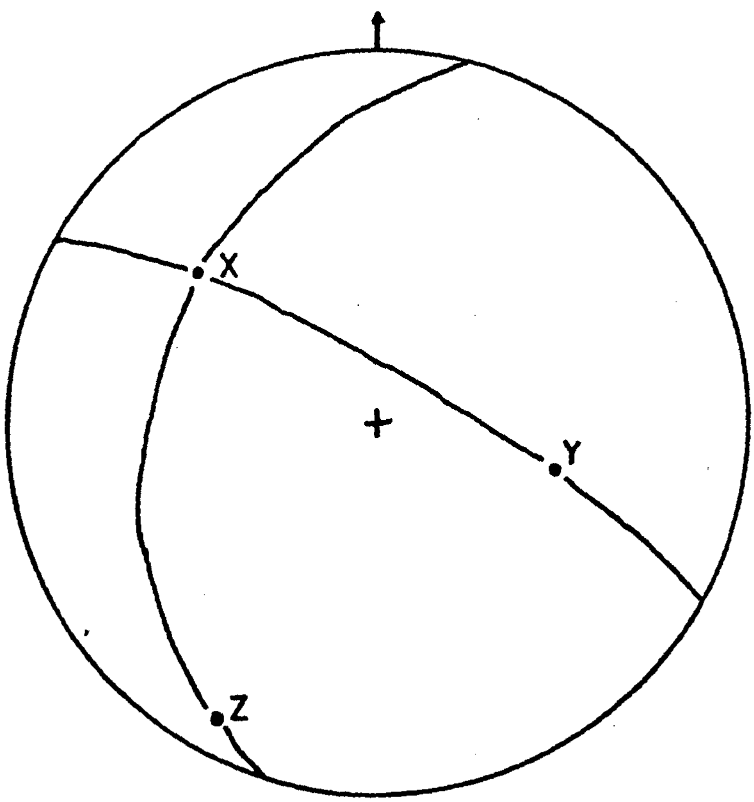
b

Fig.V-26a. Girdle distribution of poles (·) to the margin of the D_8 pinch-and-swell structure in dyke; from the coastal section south of Diabaig. Associated L_8 lineations (X) inserted. (80015932).

Fig.V-26b. Computed X, Y and Z attitudes in the D_8 pinch-and-swell structure.



a



b

Structures which can be assigned to Ramsay's class 3 interference patterns have been found in the dykes and are a result of superposition of F_8 folds upon F_7 folds (see Plate V-20a). In the belt of gneisses 450 metres south-south-east of Diabaig (79955954) is an interference pattern of class 3 (cf. Ramsay op.cit.) sufficiently large to enable statistical data to be obtained. Fig.V-27a illustrates the form of the interference structure. The F_4 fold has been refolded about an F_8 axis plunging approximately 45°E. Further F_8 folding has produced folds (F_8A) that appear to have formed as a result of slip along the S_3A limb of the F_4 fold, such that the axial surfaces of these folds are parallel to the F_4 fold axial surface S_4B. From Fig.V-27b it is apparent that as a result of the refolding of the F_4 fold, the F_8A fold axes and F_8 fold axis of the refolded fold all fall in the same plane (ie. the F_8A axial surface which is parallel to the refolded F_4 axial surface S_4B).

1. Quartz fabric associated with F_8 fold belts

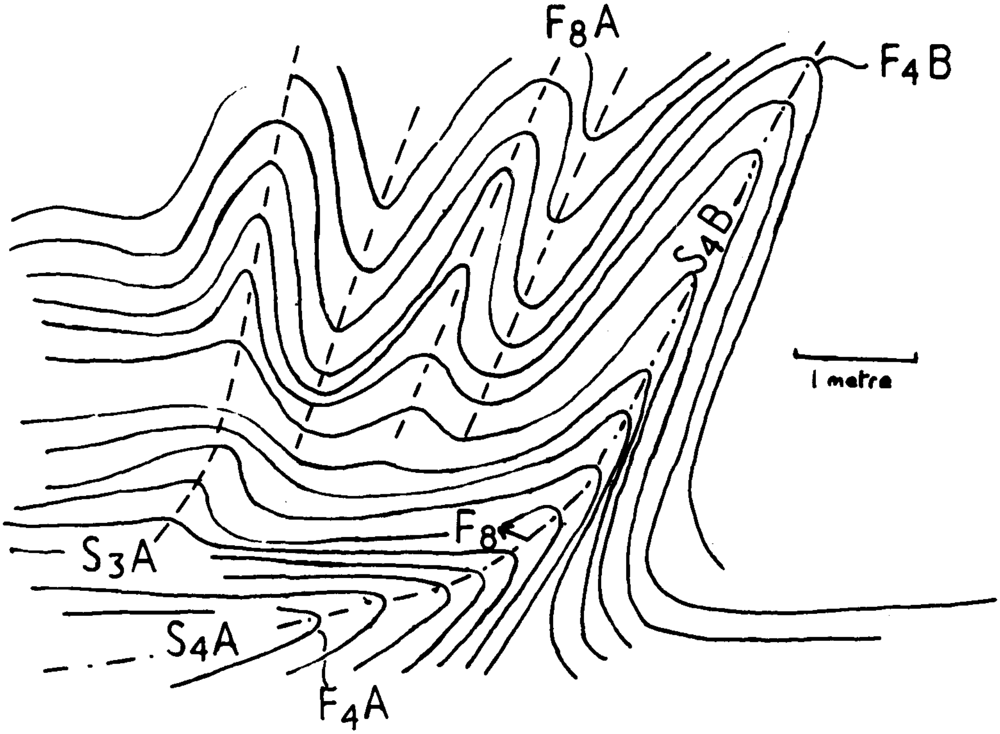
A complete determination of the behaviour of quartz in the D_8 fold movements has not been possible owing to a lack of suitable material. However, two rocks were studied, one of which was from an F_8 fold (Fig. V-28a), the other from a belt of rocks where gneisses were intensely affected by D_8 fold movements (Fig.V-28b). An interesting feature of these petrofabric diagrams is that they still reflect imperfectly the girdle pattern of the F_7 quartz fabric, but the widespread development of maxima and the breadth of the girdle indicate that the earlier fabric has in part been recrystallized (cf. Phillips 1960) - whether syntectonically or post-tectonically cannot be determined. Partial recrystallization of quartz during the post-D_8 metamorphism has been suggested in Chapter III.B2., which the writer suggests is responsible for the adjustment to the quartz girdle pattern.

H. The D_9 Structures

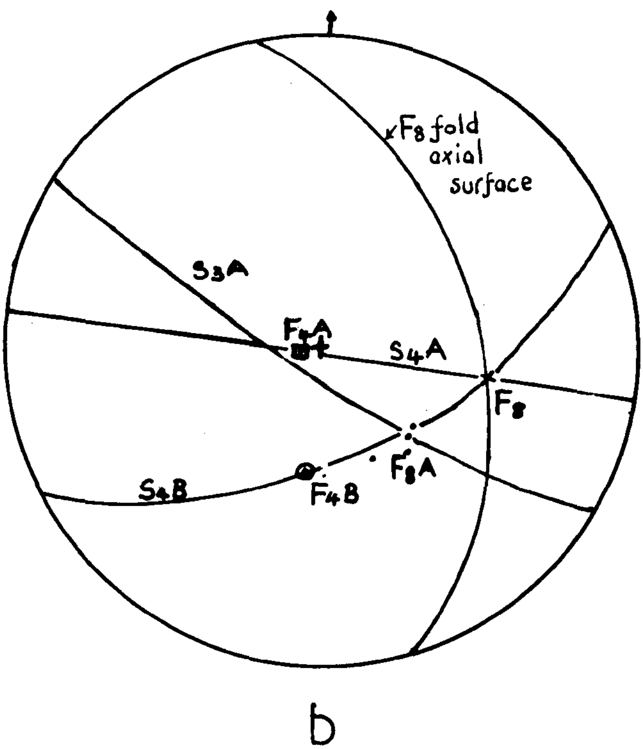
The D_9 deformation episode results in the formation of brittle structures in the gneisses and dykes of the area. These brittle structures vary in the extent of cataclasis they exhibit from mylonites and ultramylonites to rocks whose minerals show undulose extinction.

Fig.V-27a. Superposed fold produced by interference between F_4 and F_8 folds from the coastal section south of Diabaig (79955954).

Fig.V-27b. Relationship between F_8 and F_4 folds in Fig.V-28a.

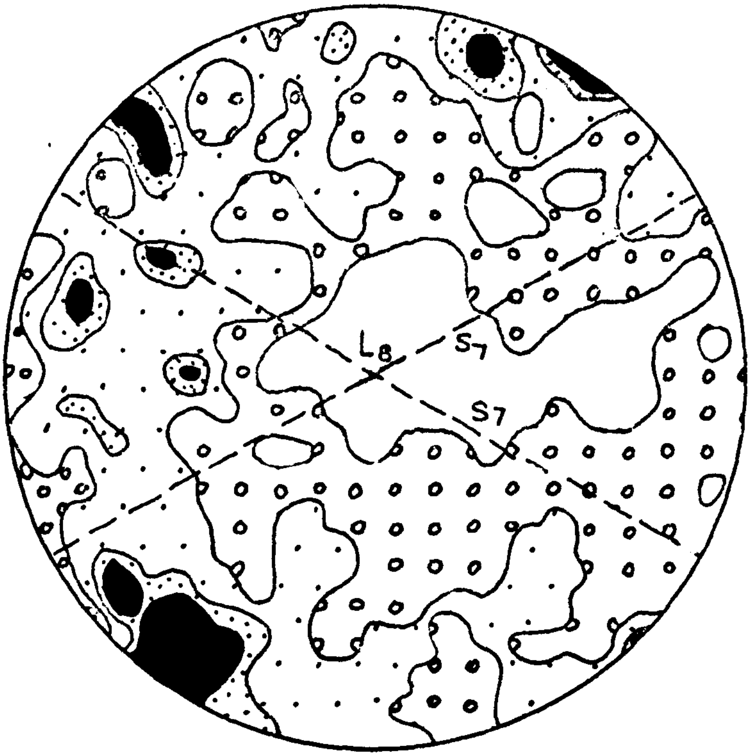

F8A
F4B
S4B
1 metre
F8
S3A
S4A
F4A

a

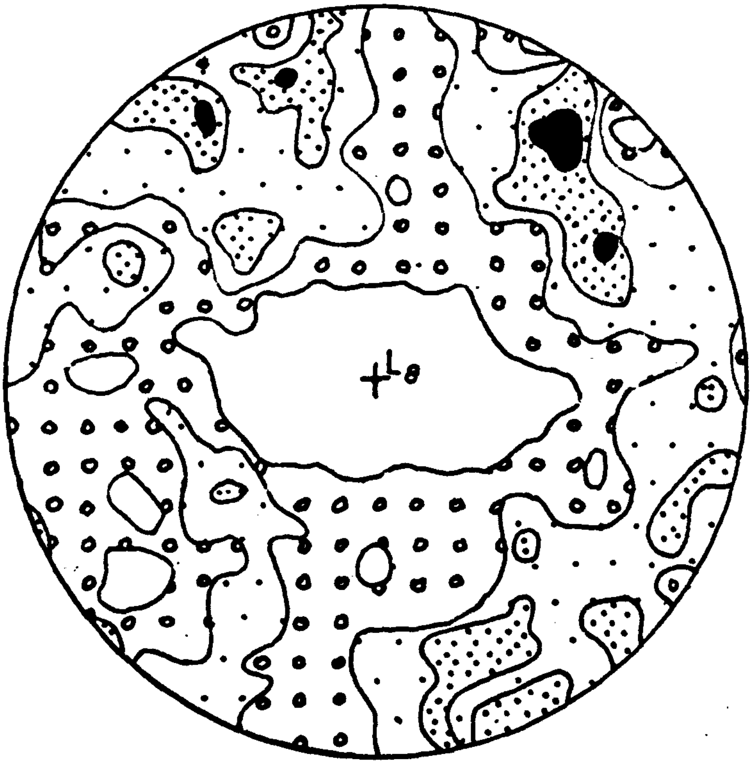

F8 fold
axial
surface
S3A
F4A
S4A
F8
F8A
S4B
F4B

b

Fig.V-28a-b. Orientation diagram for (0001) in quartz, contoured at intervals of ½, 1, 2 and 2½%.



a



b

The effects of the D_9 deformation episode in the principal minerals are:- kinks and allied structures in micas; undulose extinction, strain shadows, boehm lamellae, deformation bands and granulation in quartz, and undulose extinction, fractures and granulation in feldspars. Rocks which have completely resisted the effects of the D_9 deformation episode are rare, and most specimens show weak undulose extinction at least. There are two distinct NW-SE-striking belts of gneisses where intensely cataclastic rocks are found (cf. Sutton and Watson 1951A). These are approximately 100 metres wide and occur in the vicinity of Lochan Dharach and west of Loch na Beiste and Loch na Leirg (see Fig. V-29).

1. Cataclasites

The most characteristic feature exhibited by the mylonites is the S_9 mylonite-banding which has generally been found parallel to the earlier foliation in the gneisses and dykes. For instance, Plate V-20b shows a mylonite which has been extensively granulitized along certain bands parallel to the earlier foliation in the acid gneiss. Where mesoscopic folds can be examined in the acid gneisses, the mylonitic-banding is often found to be parallel to their NW-SE-striking axial surfaces. It is uncertain whether these folds were generated in the D_4, D_7 or D_9 deformation episodes because all these deformations produce folds having parallel axial surfaces. Plate V-21a illustrates such a fold in acid gneiss at the margin of a metadolerite dyke. The fabric of the metadolerite and acid gneiss has been converted to a mylonitic-banding which is parallel to the margin of the metadolerite and to the axial surface of the fold. The disruption and transposition of the earlier banding in the acid gneiss into the mylonitic-banding can be observed towards the dyke margin in Plate V-21a.

The mylonites are formed by granulation of an earlier mineral assemblage and consists of a very dark, near-isotropic powder with lenticular inclusions of uncrushed quartz and feldspar, the elongation of these grains being parallel to the S_9 banding in the highly granulitized material (see Plate V-21b). In Plate V-22a although the

Fig.V-29. Distribution of mylonite belts.

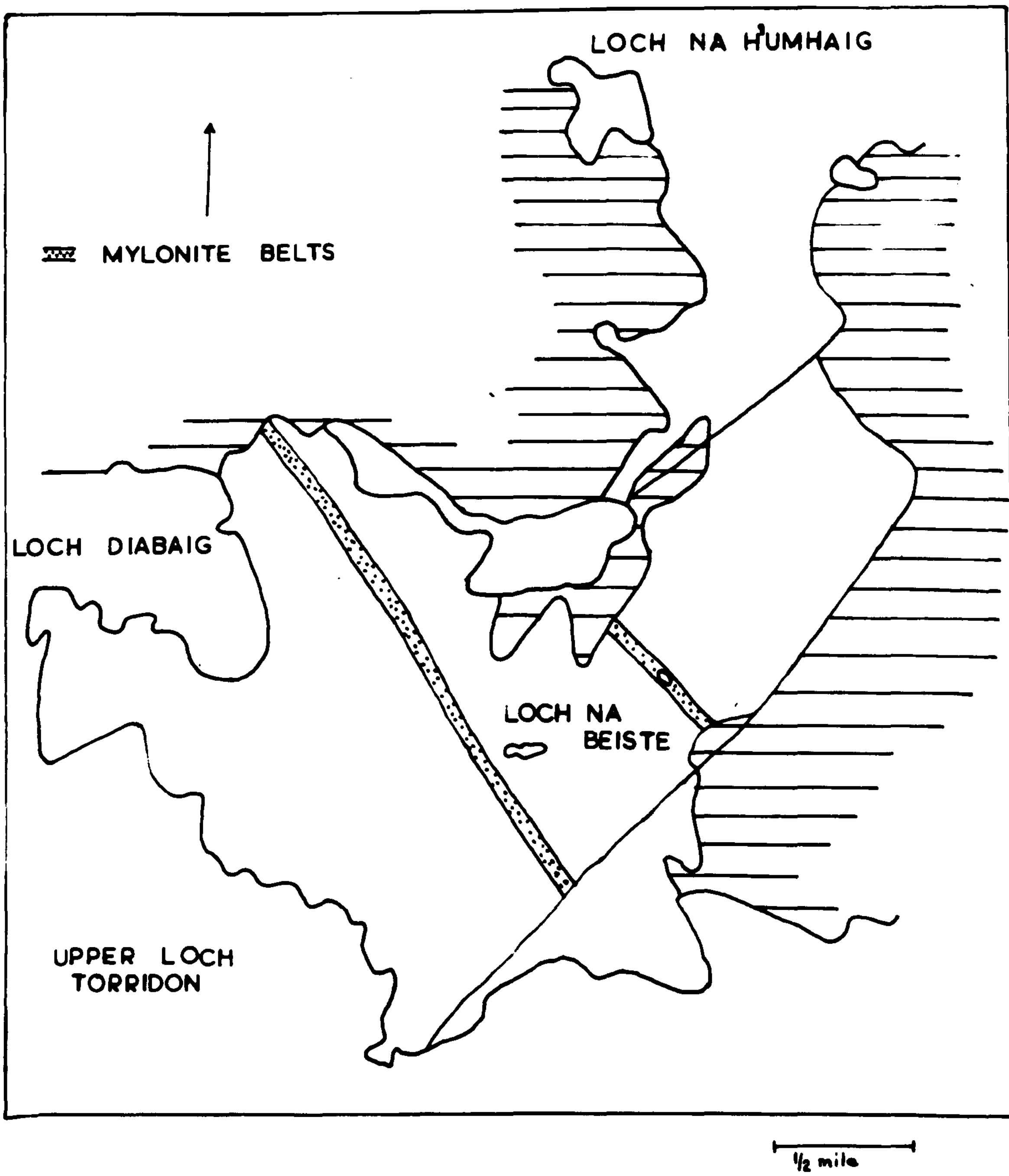
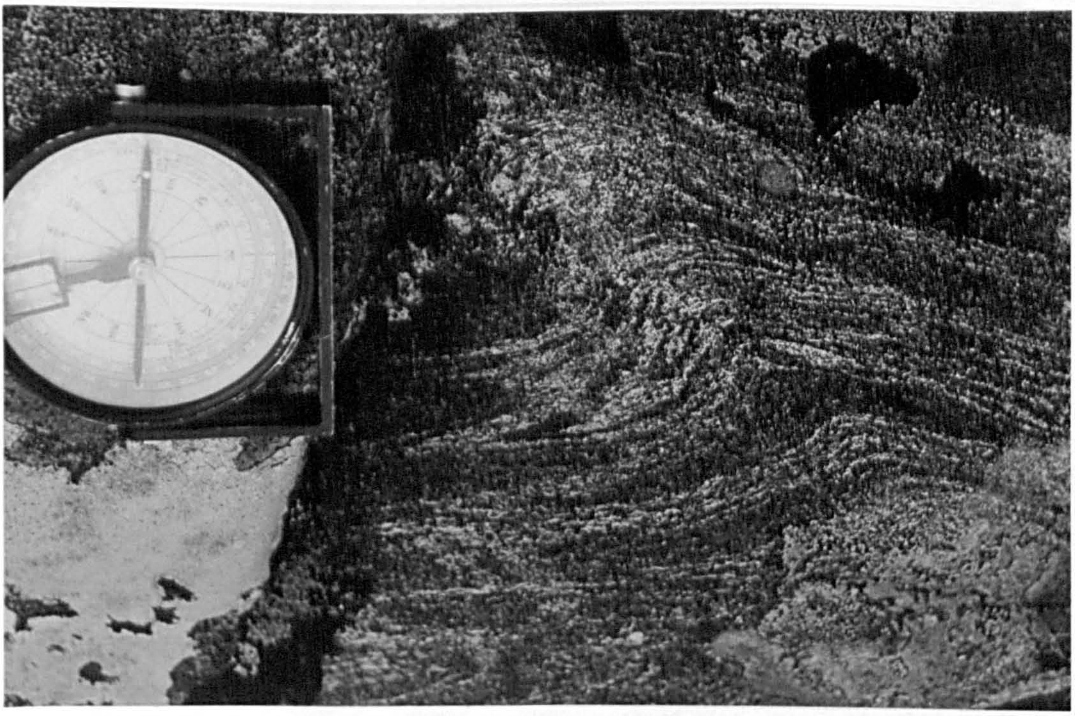

LOCH NA H'UMHAIG
MYLONITE BELTS
LOCH DIABAIG
LOCH NA BEISTE
UPPER LOCH TORRIDON
1/2 mile

Plate V-20a. D_8 interference structure produced by F_8 folding of F_7 fold in type-TD basite; 200 metres south of Loch na Leirg (80135865).

Plate V-20b. Mylonite.



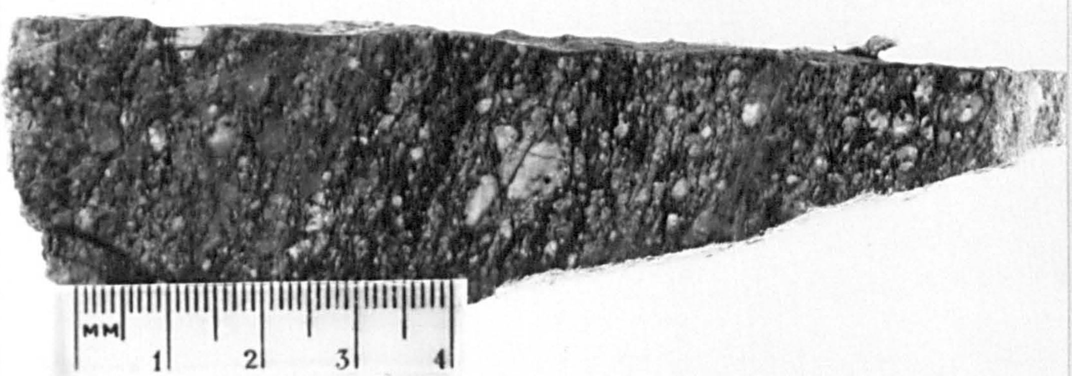
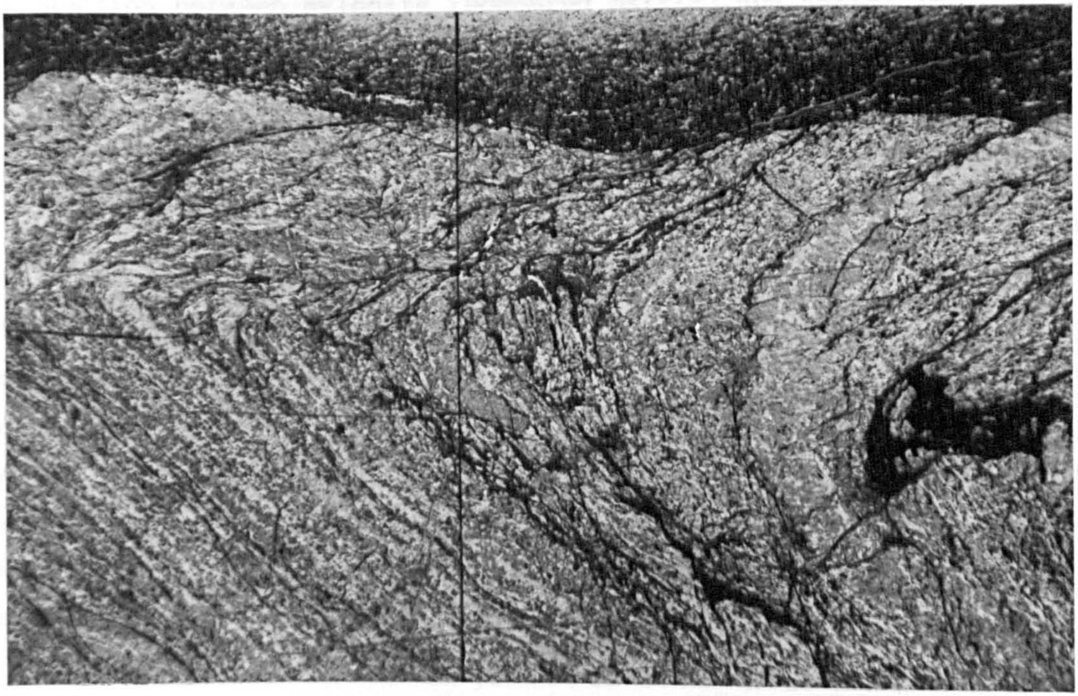

MM
1
2
3
4

Plate V-21a. S_9 mylonite banding formed parallel to type-TD basite dyke margin and axial plane of fold in acid gneiss(x5).

Plate V-21b. Mylonite(x5).



mylonite-banding is parallel to the earlier foliation in the gneisses, the junction between mylonite (powdered matrix) and gneiss is discordant to the mylonitic and gneissic banding.

2. Effects on minerals

(a) Quartz

Quartz is the first mineral to respond to the brittle deformation with development of undulose extinction. Increased deformation intensifies the undulose extinction until the strain effects are concentrated into deformation bands in the quartz; at this stage, biotite and plagioclase are usually unaffected by the deformation (see Plate V-22b). According to Carter, Christie and Griggs (1964) deformation bands are developed parallel to 0001 in quartz. Further deformation produces boehm lamellae in quartz, which form approximately at right angles to the deformation bands (see Plate V-23a). At this stage, biotite responds by flexuring (see Plate V-23a).

The formation of strain shadows, undulose extinction, deformation bands and boehm lamellae are the products of ductile strain in quartz. Further deformation results in the formation of visible fractures parallel to the deformation bands (see Plate V-23b) producing long, slender splinters which are in turn destroyed by granulation (see Plate V-24a). The strain effects at quartz grain boundaries produce suturing followed by granulation, and finally mortar structre.

(b) Feldspar

Feldspars resist the first effects of the D_9 deformation episode and thus do not register undulose extinction as early as quartz. The sequence - undulose extinction, fractures (see Plate V-24b) and granulation of feldspar occurs with increasing deformation. The production of fractures in the feldspars is not accomplished until the quartz has undergone intense granulation (see Plate V-24a), the pattern of brittle deformation in quartz appearing to be controlled by the feldspar grain shapes.

Plate V-22a. Mylonite

Plate V-22b. Deformation bands affecting quartz (x25 X.P.L.).

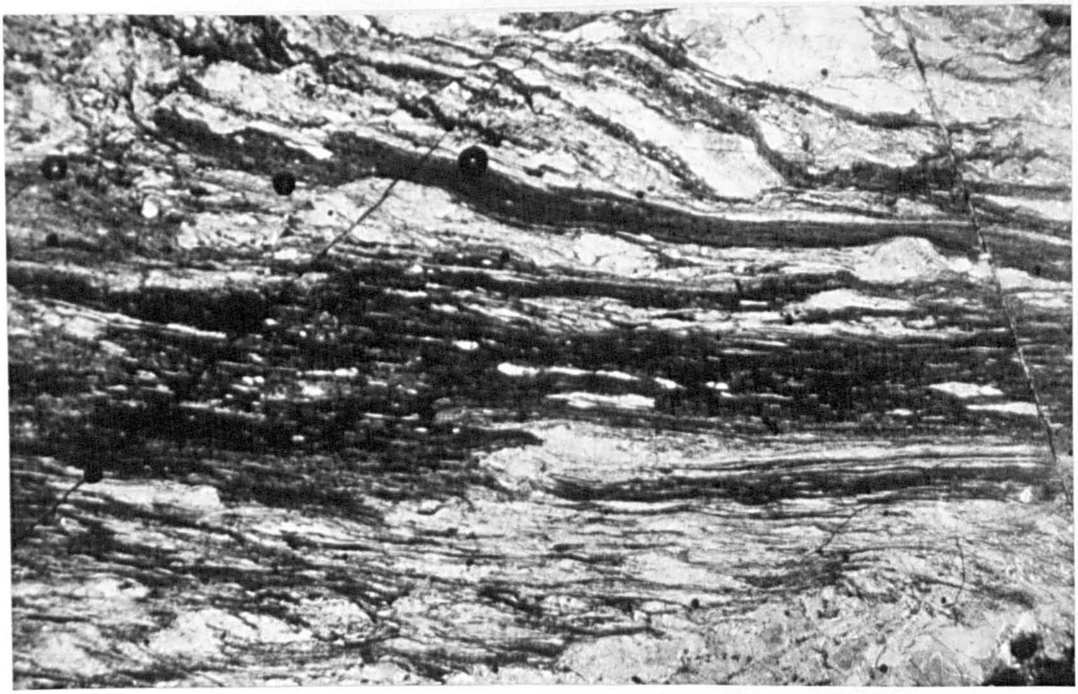


Plate V-23a. Deformation bands and fine boehm lamellae in quartz (qu) (x100 X.P.L.).

Plate V-23b. Fracturing along deformation lamellae in quartz (x100 X.P.L.).


qu

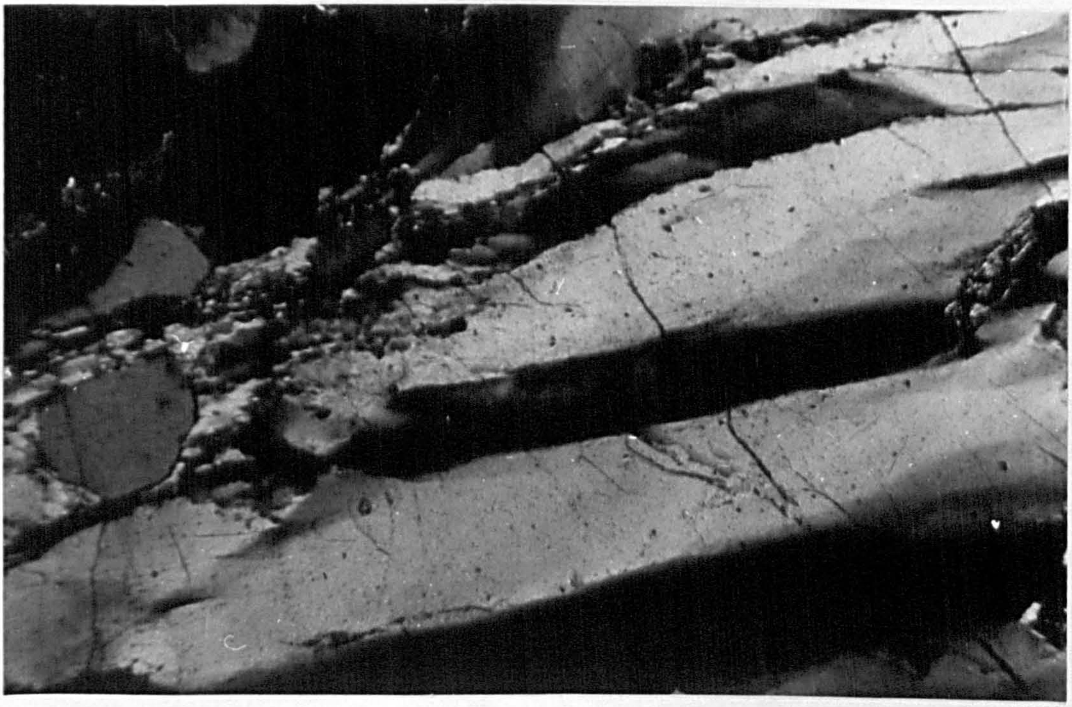
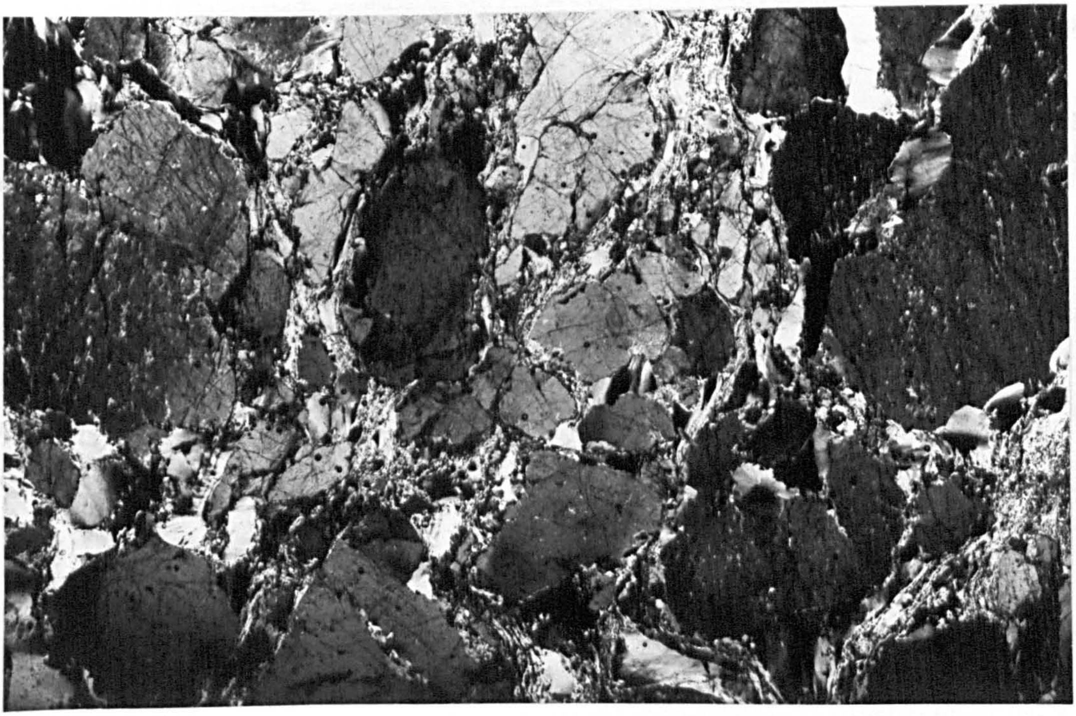


Plate V-24a. Intense fracturing in quartz, whilst microclines do not register **same** degree of deformation.

Plate V-24b. Displacement of albite twin lamellae along fracture in plagioclase (x500 X.P.L.).



(c) Micas

The micas appear to be more sensitive to the F_9 deformation episode than feldspars but not as sensitive as quartz, since the latter is affected by fairly intense ductile strain before the micas are affected. The strain in the micas has produced open flexure folds, conjugate folds, bend glides, chevron folds (see Plate V-25a) and shredded flakes in increasing order of deformation. An interesting feature of these structures is the occurrence of narrow fold hinges producing an angular shape to the folds. The chevron folding occurs along curved axial surfaces which often converge. In almost all the examples of shredded flakes, the biotite has been retrogressed to chlorite.

3. Origin of mylonite-banding

There are two essentially contrasting views as to the origin of mylonite-banding, the classical view involving the rolling out or milling produced by differential movement of material, or the recent explanation by Johnson (1967) who suggests that mylonite-banding developed approximately perpendicular to the maximum compressive stress σ_1.

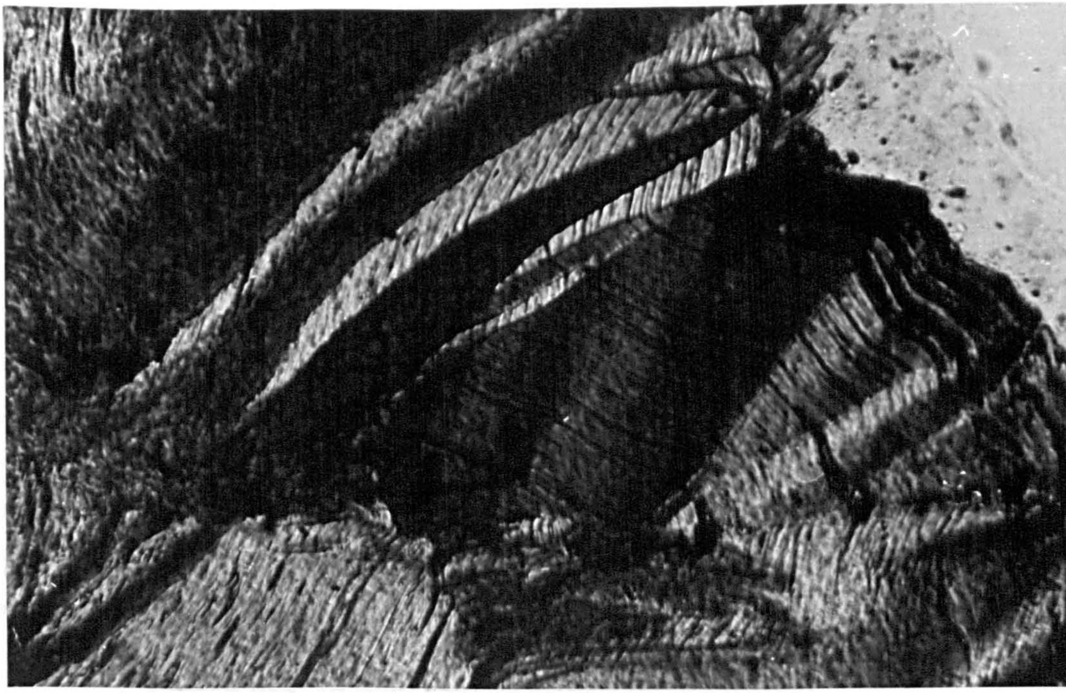
The main difference between the two views is that the classical interpretation requires [redacted] resolvable shearing stress parallel to the mylonite-banding, whereas that of Johnson requires that the mylonite banding be parallel to a surface of low resolvable shearing stress.

The writer favours Johnson's interpretation because the lenses of ungranulatized material are ovoidal or lenticular in shape and lie parallel to the S_9 banding suggesting that flattening occurred parallel to the banding. Since the margin between mylonitized material and gneiss is often found to be discordant to the S_9 banding, it would suggest that no resolvable differential movement has taken place parallel to the banding, although it does not raise any objection to Johnson's interpretation. That fold movements took place after the formation of the S_9 banding is indicated by the folded nature of the banding in Plate V-25b.

The possible occurrence of pseudotachylite in the area is suggested by the presence of rocks which are veined by a black flinty-looking material which has a dark isotropic unresolvable nature in thin section (see Plate V-25b). The occurrence of this fine-grained material as discordant veins in the gneisses suggests that it was mobile at some stage. However, since devitrified groundmass or spherulites have not been found in these rocks the suggestion that the mobility of the material was due to it occurring as a melt remains tentative.

Plate V-25a. Kink-banding in biotite (x500 P.P.L.).

Plate V-25b. Ultramylonite veining acid gneiss. The ultramylonite banding shows fold form (x25 P.P.L.).



VI. DISCUSSION AND CONCLUSIONS

A. Origin of the gneisses

1. Acid gneisses

The Geological Survey (Peach et al. 1907) ascribed an igneous origin to the majority of the Lewisian basement gneisses, but regarded the belt of rocks around Loch Maree as metamorphosed sediments. More recently, Sutton and Watson (1951A) regarded the basement gneisses of Loch Torridon as migmatitic derivatives of sediments. In the Outer Hebrides the occurrence of paragneiss in South Harris has been recorded by Craig and Jehu (1934) and Dearnley (1964). Park 1963 (Ph.D. thesis) and Inglis (Ph.D. thesis 1966) from petrological and geochemical studies of the gneiss complex around Gairloch and Laxford Bay respectively, believed that the origin of the acid gneisses lay in the alteration of a parent greywacke.

In the present investigation it was possible to distinguish a variety of gneiss types of which ultrabasite, basite, massive and banded gneisses are the most important (see Chapter IIA-B). Field evidence has yielded little information as to the origin of the gneisses in the absence of diagnostic sedimentary or igneous structures preserved in the acid gneisses. The scanty field evidence together with the mineralogical composition of the acid gneisses appears to be the only available means by which a determination of their origin may be made. Sutton (in Sutton and Watson op.cit.) argued that certain rock types in the complex, whose mineral composition was akin to rocks derived from sediments, represented paragneisses which have been altered to varying degrees by metamorphism and migmatization. However, the present work has revealed little evidence to substantiate Sutton's views and many of the supposed sedimentary derivatives need not represent original sediments.

For instance, the semi-pelitic granulites of Sutton (see Chapter II.A4) may be produced by deforming and recrystallizing a variety of igneous rocks ranging in composition from diorites to granites. Rocks which are more akin to paragneisses, such as flaggy-quartz-epidote-rock and quartzites may also owe their origin to metamorphism and migmatization of rocks other than sediments. Thus quartzites may represent deformed and recrystallized quartz veins, and flaggy-quartz-epidote rocks probably [redacted] represent the metamorphic derivatives of early basites. It was found (see Chapter II.B.3) that during the M_4 metamorphism the initial mineralogy of the early basites undergoes adjustments involving the replacement of hornblende by epidote producing rocks with a quartz-epidote assemblage. Furthermore, flaggy-quartz-epidote rocks are consistently associated with early basites.

The writer, therefore, concludes that the supposed sedimentary derivatives found in the complex may equally likely represent products of migmatization and metamorphism of igneous rocks.

The massive and banded biotite gneisses make up almost all the acid gneisses of the early complex, the main differences between the two groups being related to the proportion of mafic minerals present, banded gneisses being more mafic. Field evidence has revealed that the junction between the two groups is very sharp and appears to represent an initial boundary between two rock types. The boundary does not seem to be the result of migmatitic and metamorphic effects but could represent a junction between contrasting sedimentary and/or igneous rocks.

In other belts of biotite gneisses (Harme 1959, Simonen 1953, Gavelin 1960, Engel and Engel 1953 and Crowder 1959) it has been demonstrated that these gneisses have been derived by migmatization and metasomatism of rocks ranging from arkoses to greywacke in composition.

Because of the lack of conclusive evidence the writer is uncertain whether the acid gneisses represent transformed sediments or igneous rocks.

2. <u>Early Ultrabasites and Basites</u>

The early ultrabasites and basites found in the complex are concordant sheet-like bodies which show a degree of deformation, metamorphism and migmatization equivalent to that exhibited by the acid gneisses.

The writer considers that the early ultrabasite bodies are of igneous origin and closely akin to the zoned ultrabasite complexes found in orogenic belts throughout the world (Wyllie 1967). This conclusion was suggested by:-

(a) The presence of the mineral assemblage olivine-hypersthene-tremolite-spinel-iron ore in the centres of ultrabasic bodies, where metamorphism and migmatization is least, which is characteristic of zoned ultrabasic igneous rocks.

(b) The presence of a mineral banding in the least altered ultrabasites similar to that of other zoned ultrabasite bodies.

(c) The occurrence of zoning with a centre consisting of olivine-tremolite-hypersthene and margin of hornblende-biotite (chlorite), although this zoning may primarily be an igneous effect. Most zoned ultrabasite pods in the complex appear to have formed by migmatization and metamorphism resulting in a transference of material between the pods and host acid gneisses (see Chapter II.B2.b). Matthews (1967) has recorded zoned Lewisian ultrabasite pods in thrust sheets in the Moine Thrust and interpreted them as metasomatic derivatives of an initially dolomitic sediment.

The early basites are amphibolites having a mineral assemblage consisting of hornblende, epidote, sphene, plagioclase, magnetite and quartz. Amphibolites may result from the metamorphism of either basic igneous rocks or marly sediments (cf. Evans and Leake 1960, Walker et al. 1960). Since neither igneous minerals nor igneous texture have been found in the early basites, and since insufficient geochemical data are available, their origin remains uncertain. However, since early basite and ultrabasite bodies are closely associated in the field, the writer favours an igneous origin for both.

B. The Pre-Dyke Migmatitic and Metamorphic changes in the complex

There are at least four pre-dyke migmatitic events that affect the complex. These are:-

(a) The pre-D_3 migmatites

(b) The post-D_3, pre-D_4 migmatites

(c) The D_4 syntectonic and post-tectonic migmatites

(d) The D_5 migmatites

Only one metamorphism (M_4) can be identified in the pre-dyke complex and it is associated with the D_4 deformation episode.

Since Pre-D_3 structures are very rare in the area, little can be determined of the nature of the pre-D_3 migmatization except that it produced pegmatite bodies in the gneisses.

1. The Post-D_3, Pre-D_4 Migmatites

The post-D_3, pre-D_4 migmatization has produced trondhjemitic pegmatites and feldspar augen in the acid gneisses, whereas early basite bodies have been converted into agmatites. The concordant pegmatite sheets have clearly been intruded into the acid gneisses, whereas the augen, since they overgrow the pre-existing fabric in the rock, are thought to have grown by metasomatism probably by permeation of fluids from the pegmatite sheets into low pressure areas where growth took place. It is considered that the pegmatites were intruded as a trondhjemitic magma parallel to the S_3 banding in the gneisses, and that incorporation and part digestion of the gneisses has produced embrechites (see Chapter II.C.3). The absence of chilled margins in the pegmatites suggests that intrusion of magma took place into hot country rock.

The pegmatites in the acid gneisses are quartz-plagioclase (An_{22}) - biotite-sphene assemblages, whilst the plagioclase augen have an identical composition to the plagioclase in the pegmatites. In the agmatites, the plagioclase of the pegmatite fractions is more calcic (An_{22-29}) than that associated with the acid gneisses which suggests that reaction between early basite and trondhjemitic magma took place.

2. The M_4 metamorphism

The M_4 metamorphism is the earliest recognizable metamorphic event, and [redacted] the relationship of the minerals to the mesoscopic structures in the gneisses, indicate that the metamorphism was syntectonic. Since the metamorphism was associated with a syntectonic migmatization in the south-west, the effects of M_4 are clearer for the rocks around An Ruadh Mheallan where the metamorphism and migmatization form two separate events.

The gneisses in the neighbourhood of An Ruadh Mheallan have the following M_4 mineral assemblages:-

Ultrabasites:	serpentine-talc-chlorite-calcite-magnetite
Early basites:	hornblende-plagioclase (An_{28-33})-sphene
Massive gneisses:	biotite-muscovite-plagioclase (An_{22-24})-quartz
Banded gneisses:	biotite-epidote-muscovite-plagioclase (An_{22-27})-quartz$\pm$hornblende

These mineral assemblages indicate that the facies of the M_4 metamorphism was almandine-amphibolite (Turner and Verhoogen (1960).

3. The D_4 syntectonic and post-tectonic migmatization

The D_4 syntectonic and post-tectonic migmatites occur throughout the area and exhibit varying characteristics from north to south. They can be subdivided into two phases, an earlier phase of granitization and a later phase of pegmatite formation.

In the south of the area, the migmatization is syntectonic with D_4 and has produced no recognizable changes in the mineral assemblage of the acid gneisses, whereas in the early basites considerable effects were registered. Thus the initial amphibolite mineral assemblage of the early basites is now represented by a dioritic assemblage. The granitization of the early basites resulted in an increase in plagioclase, introduction of quartz and breakdown of hornblende to biotite and epidote. The granitizing medium appears to have been granitic in composition, thus having little recognizable mineralogical effects on the acid gneisses except for an increase in grain size as compared with similar gneisses in the north-east.

Northwards, these migmatitic effects become progressively less pronounced and increasingly lag behind the M_4 metamorphism in such a way that in the north-east they are post-tectonic to D_4. There is also a variation in the mineral assemblages that the migmatization produces. Thus, towards the north biotite, quartz and plagioclase occur in decreasing proportions in the early basites. However, in the acid gneisses, the migmatitic effects are more evident than those in the south. The post-tectonic nature of the granitization is exhibited by the overprinting of M_4 metamorphic fabric and D_4 mesoscopic structures producing the series: S_4 banded gneisses-embrechites-massive trondhjemitic rocks, with increasing granitization.

In the neighbourhood of An Ruadh Mheallan where the migmatitic effects are very mild, post-tectonic pegmatite veins formed parallel to F_4 fold axial planes are the only products in the acid gneisses, whereas in the early basites the replacement of hornblende by epidote has produced quartz-epidote rocks.

The acid gneisses of the south-west appear to be more basic than those of the north-east, and show an increase in biotite and in the An-content of the plagioclase (An_{22-33}). This change in composition of the plagioclase does not occur in the early basites. There appear to be three possible causes for these variations:-

(a) Introduction of the Fe, Mg, Ca and Al necessary for the formation of biotite and anorthite, during the migmatitic event.

(b) Increase in M_4 metamorphic grade towards the south-west.

(c) Pre-D_4 variation in composition of the gneisses from the north-east to the south-west.

It would seem unlikely that the first two possibilities were the cause of the variation since the early basites would be expected to show similar changes. The cause would seem to be due to a Pre-D_4 variation in composition of the acid gneisses from north-east to south-west.

Mineralogical changes associated with the migmatization

The following mineral transformations have occurred in the early basites and in the ultrabasic pods:-

(a) In the north-east, hornblende is replaced by epidote and small amounts of sphene.

(b) In the south-west, hornblende is replaced by biotite and epidote, and quartz and plagioclase are introduced.

The replacement of hornblende by biotite and epidote has been recorded from other rocks (Sutton and Watson 1951A, Cheng 1943, Hietanen 1947 and Harme 1958) and is thought to be a result of potash metasomatism. The reaction may be represented by equation (1).

(1) $2.2\ CaO\ .3\ (MgFe)\ C.2\ Al_2O_3\ .6\ SiO_2 . H_2O + K_2O + H_2O$
Hornblende

$= K_2O\ .6\ (MgFe)\ O.Al_2O_3\ 6\ SiO_2.\ 2\ H_2O$
Biotite

$+ 4\ CaO.\ 3\ Al_2O_3.\ 6\ SiO_2.\ H_2O$
Epidote

Potassium must be available for this reaction to take place, since hornblende does not contain enough potassium to produce sufficient biotite (Harme op.cit.). Potassium must originate either in the early basites, from the host acid gneisses or from an external source connected with the migmatization.

The first possibility is dismissed since in the zoned ultrabasite pods (see Chapter II.B.2b) a biotite sheath is formed at the pod margin against acid gneiss, suggesting that potassium was introduced through or from the host acid gneisses. Of the remaining possibilities an extraneous source for potassium is favoured because of the replacement features exhibited by the early basites in the north-east. Here hornblende has been replaced by epidote and sphene (cf. Soen 1962) without the development of biotite, indicating that there was no introduction of potassium. If the host gneisses were responsible for the introduction of potassium, the early basites in the north-east should contain biotite, which is not the case.

4. The D_5 granitization

The D_5 granitization has only produced localized effects such as the pegmatite secretions around early basite boudins. These secretions are believed to develop in the pressure shadows of the relatively rigid early basite-ultrabasite pods.

C. The Dykes

In the period separating the D_5 and D_6 deformation episodes, a NW-SE trending swarm of dykes ranging from basic to ultrabasic in composition were intruded into the complex. It is possible to recognize at least three separate intrusion episodes within the dyke swarm producing the following sequence of rocks:-

(1) Type-TD basites
(2) Type-TB basites
(3) Ultrabasites

The Type-TD basites form by far the largest proportion of the swarm, there being four type-TB basite and ultrabasite dykes. Relict textures of the type-TD basites indicate that they are doleritic with an ophitic texture, whereas in the ultrabasite and type-TB dykes no mineralogical evidence relating to the nature of the intrusions has been found. The type-TD dykes occasionally form multiple intrusions, whereas the ultrabasite and type-TB dykes are either composite or separate intrusions. In all the dykes, chilled margins are developed against the country rocks or adjacent dykes. There is no evidence to suggest that the dykes were intruded into hot country rock (cf. O'Hara 1961).

The least altered type-TD basites have two-pyroxene (hypersthene-augite)-biotite-ilmenite-plagioclase-quartz assemblages with the mesostasis filled either by a quartz-alkali feldspar intergrowth or by quartz. The mineral assemblage of these dykes indicates that they have tholeiitic affinities.

The mineral assemblage of the type-TB basites and ultrabasites poses a problem of interpretation, for it is uncertain whether it is metamorphic or igneous. In the least altered ultrabasite dykes the assemblage amphibole-biotite-chlorite-magnetite occurs, whereas in the type-TB basites the assemblage is amphibole-biotite-chlorite-rutile-plagioclase. It is not clear at what stage these dykes have been affected by the post-dyke metamorphic effects - the plagioclase feldspar in some cases has certainly not been recrystallized. There is thus doubt whether the ultrabasite and type-TB basite mineral assemblages are in part igneous or represent a metamorphically recrystallized assemblage.

Banding of alternating felsic and mafic layers occurs in its original attitude in one of the type-TB basites and is steeply dipping and sub-parallel to the margin. Since there are no relict minerals, the origin of this banding is in doubt. Because of the attitude of the banding it seems unlikely that it could have been produced by gravity differentiation. A mechanism of flow differentiation seems more likely since it is considered that some of the ultrabasite bodies were emplaced as a crystal mush and underwent flow differentiation which is believed to be responsible for the presence of chilled margins in these bodies (see Chapter III.E6).

1. <u>Structural controls which affected dyke intrusion</u>

The pre-dyke structure of the complex appears to have controlled the strike and dip of the dykes; their thickness, separation and degree of deformation, and their overall form. Four distinct domains, exhibiting differences in kind and degree of structural control, have been established in the complex (see Chapter III.B1). Thus, ~~dykes~~ in areas where the pre-dyke foliation is discordant (ie. in belts of dominant S_3 foliation) the dykes are generally thick, widely separated, undeformed and often bifurcated and interconnected. In areas where the pre-dyke foliation is concordant to the dykes (ie. in belts of S_4 foliation) the dykes are thin, closely spaced and considerably deformed. These characteristics indicate that dykes were more easily emplaced where the associated gneisses have a concordant foliation than where this foliation is discordant.

2. Geochemistry

25 geochemical analyses of the dyke rocks were made, 17 of type-TD basites, 2 of ultrabasites, 5 of type-TB basites and an early basite body which resembled the TD basites.

The catanorms of the type-TD basites when considered in terms of the classification of Yoder and Tilley (1962) fall in the fields of olivine tholeiites, tholeiites and alkali basalts, whereas those of the type-TB basites and ultrabasites fall in the fields of olivine tholeiites and alkali basalts (see Chapter III.E2). The mineral assemblage and chemistry of the type-TD basites suggest affinities more closely allied with tholeiites.

From a consideration of the chemical analyses of the type-TD basites, it is believed that they represent a suite produced by a normal differentiation trend, with high iron concentration, in which olivine and pyroxene separated from a parent tholeiite magma. They also show a similar compositional field as the basites in the Gairloch area (Park 1966) which suggests that they were formed from the same parent magma. The catanorms of the type-TB basites and ultrabasites and their field within an alkali-silica-diagram (Tilley 1950) indicate a tholeiitic composition and the element variations suggest that they belong to a single igneous series formed as a result of the magmatic differentiation of a tholeiitic parent magma. However, the variation trends of certain elements differ from those produced in a normal differentiation series (cf. Wager and Mitchell 1950) - in particular the ultrabasites are considerably richer in iron and titanium than the basites, there being no appreciable differences in magnesium.

To account for these anomalies it is necessary to imply that magmatic differentiation involved [redacted] the fractionation of iron-titanium-rich phase(s) early in the series and their concentration in the ultrabasite fraction, followed by gravity separation of olivines and pyroxenes responsible for the element variations in the series.

The mineral likely to have produced such a differentiation series is amphibole (cf. Watterson 1968) and the writer has suggested (see Chapter III.E.4b) that the crystallization and gravity separation of an amphibole varying in composition from barkevikite to kaersutite with increasing fractionation has produced the igneous series. The ultrabasites are thought to be cumulative amphibole fractions of the tholeiite magma, and were intruded as a mixed crystal-liquid phase in which a mechanism of flow differentiation was thought to be responsible for the formation of chilled margins.

In conclusion, the writer considers that the dyke swarm owes its origin to the magmatic differentiation of two parent tholeiitic magmas whose diversity in fractionation has resulted in the variety of dyke rocks.

3. Correlations with other dykes of the mainland

The importance of dykes as stratigraphic marker horizons in Lewisian chronology has already been emphasized (see Chapter I.B and III.A).

Observations from other parts of the Lewisian (Peach et al. 1903, Sutton and Watson 1951A, O'Hara 1962 and Tarney 1963) have revealed a broad intrusion sequence of dolerite followed by norites and peridotites which appears to correspond to that present in the dykes at Loch Torridon. Further evidence lies in the NW-SE trend of these dykes and the similarity in chemical composition of the type-TD basites to the type Scourie dykes (O'Hara 1961, Burns, 1966, Park 1966). It is, therefore, reasonable to assume that the correlation of the Loch Torridon type-TD basite suite with the Scourie dyke swarm of further north is justified.

D. The Post-Dyke Petrological Changes Affecting the Complex

The post-dyke petrological changes affecting the complex have been found to involve the following events:-

(a) The M_6 metamorphism

(b) The M_7 metamorphism

(c) The intrusion of pegmatites and a granite sheet

(d) The post-D_8 retrogressive metamorphism accompanied by a phase of potassium metasomatism.

1. The M_6 and M_7 metamorphisms of the dykes

The identification of the M_6 and M_7 metamorphic events resulted from an examination of the structure and petrology of the dykes and by a correlation of similar features in the gneisses.

a. M_6 metamorphism

The M_6 metamorphism in the dykes appears to have produced two contrasting rock types - at the dyke margins, where the D_7 deformation episode has produced the S_7 foliation and in the undeformed dyke centres where igneous texture is still preserved. The new mineral assemblage in both is represented by garnet-amphibolite, but there is a difference in the textural relationships of the minerals. These differences are reflected in the corona-like arrangement of minerals (see Chapter III. B . 2) in which garnet appears to play the dominant role. The uralitization of the igneous pyroxenes in the undeformed dyke centres, which is associated with these garnets, is only partial, producing a narrow rim of amphibole about the pyroxenes. The garnets in the foliated dyke margins are xenoblastic, whereas those in the centres are more widespread and form idioblastic dodecahedra. Rast (1962) has observed similar development of garnets in metamorphosed basic igneous rocks in the Dalradian. Since all the least altered type-TD basites possess garnets, it is believed that the M_6 metamorphism was far more thorough than the later M_7 metamorphism. Garnet is more widespread and amphibole is less widespread in the dyke centres than in the margins suggesting a different M_6 metamorphic environment in margins and centres.

The formation of amphibole would be expected to depend partly upon the availability of water during metamorphism. Since hornblende is widespread at the dyke margins, it would appear that here water was more abundant than at the centres, where uralitization of pyroxene was incomplete. The variability of water concentration may have also affected the development of garnet in the dykes.

Yoder (1955) has shown that at 1 atmosphere PH_2O almandine is stable below 785°C. In the presence of wate: as a free phase, almandine is stable only below 785°C and above the stability range of hydrous minerals such as hornblende and biotite, but in water-deficient regions it is stable also at low temperatures. Thus, it would appear that the genesis of the garnet has been affected by the availability of water which appears to have promoted recrystallization of pyroxene into amphibole at the margins. It would also seem likely that water would be more concentrated in the dyke margins since the adjacent gneisses probably promoted water migration, and the S_6 foliation also offers a convenient route for the migration of water. Conversely, the undeformed dyke centres would be expected to offer a greater resistance to water migration.

The occurrence of clouded plagioclase feldspars in these undeformed dykes and the disappearance of clouding in the dyke affected by M_7 metamorphism suggests that clouding, possibly due to the presence of minute garnets, is related to the M_6 metamorphism and is thus of regional metamorphic origin (cf. Poldervaart 1953, Carsten 1955, Murthy 1958, Bhose 1961, Reynolds and Frederickson 1962). It has been suggested by these authors that clouding requires a medium, probably water-rich, for transportation of the necessary ions to the sites of clouding.

The metamorphic facies suggested by the M_6 mineral assemblage is almandine-amphibolite (Turner and Verhoogen 1960).

b. <u>M_7 metamorphism</u>

The M_7 metamorphism has been responsible for much of the recrystallization found in the dykes. The M_7 metamorphic fabric (see Chapter V.F) indicates that the metamorphism was syntectonic. It retrogresses the M_6 mineral assemblage, although this can only be recognized by the replacement of garnet by a biotite-magnetite-epidote assemblage, suggesting that it was effectively more hydrous than M_6. From observations of the minerals and textures developed across the dykes, the following progressive stages of the M_7 metamorphism can be seen:

(i) Loss of garnet; pyroxenes have been transformed into hornblende and sphene develops as a rim around ilmenite.

(ii) Igneous lath-like plagioclase has been recrystallized into reverse-zoned polygonal grains, with loss of clouding.

(iii) Formation of S_7 schistosity. Progressive recrystallization has produced a mineral assemblage hornblende-sphene-biotite-magnetite-plagioclase±quartz.

The above sub-divisions correspond to steps 2-3, step 4 and step 5 respectively of Sutton (1951A) and to the stage 1, 2 and 3 dykes (Sutton op.cit.). The stage 4 dykes of Sutton which occur in the area mapped by the writer were found to be early basite bodies migmatized in pre-dyke migmatitic events.

2. The M_7 metamorphism of the gneisses

The M_7 metamorphism has produced equidimensional, reverse-zoned, polygonal grains of plagioclase feldspar by recrystallization of the M_4 xenoblastic plagioclase. Widespread recrystallization has not occurred except where gneisses have a fine S_4 foliation. However, there is a general increase in the extent of M_7 recrystallization towards the south-east.

Two possible explanations are put forward for the origin of reverse-zoning (see Chapter IV. A1):-

(i) Growth of a new feldspar in a changing metamorphic environment.

(ii) Adjustment of recrystallized plagioclase by a later process.

The writer prefers the second alternative (for discussion see Chapter IV.A.2b) and considers that reverse-zoning in plagioclase is the result of a post-growth, grade-dependent process in which addition of Ca^{2+} and Al^{3+} ions and removal of Na^{+} and Si^{4} ions occurred at plagioclase grain boundaries. The latter may be the result of the reaction relations between co-existing plagioclase and hornblende (or epidote) or of the action of an extraneous fluid, rich in Ca^{2+} and Al^{3+} ions, on the plagioclase involving the removal of Na^{+} and Si^{4+} from the borders of the plagioclase grains. Such a fluid, provided that the environmental conditions were such that the temperature was 400-600°C and pressure 750-3500 Bars, could be capable of removing Na^+ and Si^{4+} (albite) in the order of 2% by weight (Currie 1968).

The M_7 metamorphism with assemblages of quartz-plagioclase (oligoclase-andesine)-biotite-epidote-muscovite in the acid gneisses and hornblende-sphene-biotite-plagioclase (oligoclase-labradorite)± quartz in the dolerites is of the almandine-amphibolite facies (Turner and Verhoogen 1960). This is confirmed by the nature of the hornblende which is a blue-green variety (Engel and Engel 1963) and the mineral assemblage of the stage (iii) dykes which corresponds to the garnet- and kyanite-zone epidiorites of the South-West Highlands (Wiseman 1934).

3. Origin of the post-D_8 pegmatite dykes and granite sheet

A granite sheet and pegmatite dykes which were intruded after D_8 and before D_9 have been found in the complex (see Chapter III.B.). The granite and pegmatites are plagioclase-quartz-muscovite-microcline-epidote assemblages. The microcline, muscovite and epidote are considered to have formed later than the rest of this assemblage (see Chapter IV.C4) indicating that the initial rock was trondhjemitic. The granite has discordant, sharp margins with host gneisses, whereas the pegmatite dykes are usually concordant. From the discordant margins of the granite, and since the granite has a graphic texture, it is thought that it represents an intrusion of trondhjemitic magma. The pegmatites are also considered to be intrusions of trondhjemitic magma since the granite sheet feeds associated pegmatites.

4. The post-D_8 retrogressive metamorphism and associated alkali-metasomatism

The post-D_8 retrogressive metamorphism and associated alkali-metasomatism has resulted in biotite being replaced by chlorite, muscovite overgrowing plagioclase and quartz, microcline replacing plagioclase and in the introduction of quartz.

The positive correlation revealed by the occurrence of muscovite, microcline and chlorite suggests that they developed contemporaneously.

Chlorite is most widespread, followed by microcline then muscovite.

The association of alkali rims around plagioclase and of quartz-plagioclase myrmekites with microcline suggests that these features were formed by some process related to microclinitization. Since alkali rims are always associated with microcline perthites it would seem that microcline is the source of albite for these rims (Marmo 1962) although Rogers (1961) believes that similar albites in granites were formed synchronously with k-feldspar and were a product of direct crystallization during late stages of magmatic solidification. Textural relations in the granite sheet and pegmatite dykes indicate that microcline and plagioclase recrystallized at different times.

The occurrence of quartz-plagioclase myrmekite in some of the plagioclases which are being replaced by microcline is more difficult to explain. Shelley (1964) considered myrmekite to be due to the incorporation of recrystallizing quartz in growing albite that has been exsolved from orthoclase. However, the absence of myrmekite from alkali rims around plagioclase in these rocks seems to deny such an origin. The myrmekite texture tends to indicate that either quartz was overgrown by plagioclase in a pre-metasomatic phase or that quartz was introduced into the plagioclase during the metasomatic event, but prior to the development of the alkali rims. Since myrmekites are always formed at microcline-rich sites, the latter suggestion seems more likely.

In considering the replacement of a plagioclase in the range of oligoclase-andesine, the essential chemical components required are potassium and silicon (see equations (1), (2) and (3)).

1. $NaAlSi_3O_8 + K^+ = Na^+ + KAlSi_3O_8$
2. $CaAl_2Si_2O_8 + 2K^+ + 4SiO_2 = Ca^{2+} + 2KAlSi_3O_8$
3. $2CaAl_2Si_2O_8 + K^+ = 2Ca^{2+} + KAlSi_3O_8 + 3Al^{3+} + Si^{4+} + 4O_2$

Evidence of introduction of quartz during the metasomatic phase is offered by the replacement of chlorite by quartz in metasomatized type-TD basites. Since the metasomatic phase is presumably rich in $Si^{4+} + K^+$

ions to produce microcline, then it could be expected that this phase is also responsible for the introduction of quartz into plagioclase to produce microcline (Drescher-Kaden 1948).

A further feature exhibited by rocks rich in microcline is the occurrence of epidote grains found at adjacent microcline grain boundaries, suggesting that its genesis may be related to the metasomatism (Harme 1958 and Marmo 1962). From a consideration of the equations 2 and 3 which represent likely reactions during potash metasomatism, it is found that an excess of Ca^{2+}, Al^{3+} and Si^{4+} ions are produced in the formation of microcline. Since these three ions are the essential components for epidote minerals, it is inferred that this mineral is a by-product of potash metasomatism (see equation 4).

4. $2CaAl_2Si_2O_8 + K^+ + 2SiO_2 + H_2O = Ca_2Al_3Si_3O_{12}{}^{OH} + KAlSi_3O_8 + H^+$

The late muscovite-quartz symplectites which are regularly associated with microcline may have their origin in the action of the potash metasomatism. Since it overgrows plagioclase the two equations below may express the reactions that have occurred (Barth 1952 and Marmo 1962).

5. $2NaAlSi_3O_8 + K_2O + 2H_2O + 2Al_2O_3 = 2KAl_3Si_3O_{10}(OH)_2 + Na_2O$
6. $CaAl_2Si_2O_8 + K_2O + 2H_2O + 2Al_2O_3 + 4SiO_2 = 2KAAl_3Si_3O_{10}(OH)_2 + CaO$

Another effect associated with the potash metasomatism is the formation of hematite from magnetite and chlorite. The formation of hematite from chlorite appears to be associated with the replacement of chlorite by quartz. The formation of hematite from magnetite involves oxidation and suggests that potash-metasomatism has taken place under strong oxidizing conditions.

a. Source of the potash-metasomatic fluids

There is abundant textural evidence that metasomatism has taken place in these rocks resulting in the formation of microcline and muscovite and that the foliation planes in the gneisses have facilitated movement of a potash-rich fluid since microcline is concentrated along the foliation planes (cf. Scotford 1956 and Inglis 1966. Ph.D. Thesis).

This potash- and silica-rich fluid may have been derived from the host rock (cf. Hietenan (1963) or an extraneous source (cf. Hietenan op.cit.) or the magma responsible for the granite sheet or pegmatite dykes. The only minerals in the rocks that are likely to contain sufficient potassium are micas (biotite) and plagioclase feldspar. However, biotite is not developed in sufficient quantity to be the sole source of potassium (cf. Harme 1958). It would seem unlikely that plagioclase (oligoclase-andesine) in these rocks contains sufficient potassium to produce microcline in the quantities observed. It would therefore seem unlikely that the host rocks were a source of potassium.

Eskola (1956) considered that crystallization of granites must continue within the hydrothermal range and that certain late kinematic granites are more K-rich than eutectic systems. This may indicate that a K-silicate will separate out as a liquid phase remaining in the rocks as a pore solution producing replacing potassium feldspars. Since some of the type-TD basites adjacent to late pegmatites have been metasomatized, the latter may constitute the required potash-source. However, there are not enough late pegmatites to account for all the metasomatic features in the complex. The writer, however, considers that the occurrence of a large granite source at depth may be responsible for the pegmatites and metasomatic features of the complex.

The mineral assemblage produced in the post-D_8 retrogressive metamorphism and alkali metasomatism suggests that the metamorphism was of greenschist facies (Turner and Verhoogen 1960).

E. The Structure of the Complex

At least nine deformation episodes, D_1-D_9, have been identified in the complex. The determination of the sequence of structures has depended primarily upon the use of dykes as stratigraphic marker horizons. Two conditions must be satisfied to justify their use (see Chapter III.A):-

(i) The age relations between individual dykes must be established.

(ii) The structures exhibited by the dykes must be carefully analysed so that they may be fitted into the general structural sequence.

An analysis of the dykes along these lines strongly suggests that they were all intruded in the period between the D_5 and D_6 deformation episodes.

1. The Pre-Dyke Structures

a. The Pre-D_4 structures

The earliest widespread pre-dyke structure is the S_3 foliation, dominant in the north-east of the area, which is an axial-planar foliation to the F_3 folds. The F_3 fold axes show variable plunges since F_3 involves either folds of S_1 and S_2 or interference structures produced by the interaction of S_1 and S_2. From the nature of the D_3 interference structures the attitude of S_2 can be extrapolated and is found to be a NW-SE striking, steeply dipping foliation. The initial attitude of S_1 is unknown. The formation of S_3 was followed by a phase of migmatization, which was in turn followed by a flattening phase D_3A which has produced boudinage and pinch-and-swell structure in competent layers of the gneisses.

The variability in attitude of the S_3 foliation indicates that S_3 has undergone large-scale folding, D_3B, prior to F_4 minor folding and probably after the D_3A flattening phase. As a result of the variable dip of S_3, the D_3B fold movements have produced variably plunging major folds.

b. <u>The D_4 structures</u>

The most widespread structures belong to the D_4 deformation which has produced a penetrative S_4 foliation, F_4 folds, dislocation augen, quartz rods and L_4 mineral lineations. The D_4 structures vary in style, scale and attitude, which is believed to be, in part, due to a related syntectonic and post-tectonic migmatization. Thus, F_4 plastic flow folds are associated with syntectonic migmatites, whereas more brittle F_4 folds are associated with post-tectonic migmatites. A variety of F_4 fold profiles have been produced ranging from open asymmetric to tight symmetric folds as well as occasional box-like and disharmonic folds. The least deformed F_4 folds have a parallel style, whereas the more severely deformed folds have a similar style.

Towards the south-west the folds increase in wavelength and appear to have been formed under increasingly plastic conditions in contrast with [redacted] those of the north which show features more akin to brittle deformation. This variation is thought to be related to the migmatitic phase which is syntectonic in the south-west and post-tectonic in the north-east.

As a result of the superposition of the F_4 folds on the F_3 folds, a variety of interference patterns ranging from "mushroom" to "eye" shaped structures were formed.

The F_4 folds are generally cut by an axial-planar foliation (S_4) which is poorly developed in the north of the area, but becomes increasingly more penetrative south-westwards. In the north, S_4 occurs in narrow belts which increase in thickness south-westwards, such that, in the extreme south, belts of penetrative S_4 100 metres wide alternate with belts of untransposed F_4 folds.

The S_4 foliation varies regularly in attitude over the area: in the north-east, S_4 is steep to vertical and becomes progressively less steep until it is sub-horizontal in the neighbourhood of Meall Ceann na Creige and Loch na Beiste. Further south, the same pattern is repeated. The overall form of S_4 gives the impression of large-scale folds, but this pattern is considered to have been produced by the formation of S_4 in its present attitude without any post-S_4 major folding.

The cause of the variation in attitude of S_4 is not properly understood. Among the possible causes are the effect of a supracrustal group of rocks (cf. Zwart 1963, p.181) or changes in the physical state of the complex such that a particular metamorphic assemblage is also associated with a characteristic fold style and foliation attitude (cf. Hietenan 1961) or a combination of these effects (cf. Noe-Nygaard and Berthelsen 1952).

That changes in the physical state of the system occurred during D_4 is indicated by the occurrence of migmatites believed to be related to a migmatitic "front" coming from the south. However, little is known as to how this "front" could have produced the variable stress system necessary to create the D_4 structural pattern.

Although there is no evidence of the existence of a supracrustal series of rocks at Torridon, Park (1964) has postulated such a series at Gairloch which may have acted as a cover to the gneisses at Torridon and been responsible for the variations in the D_4 structures.

The L_4 lineation pattern has been used in an attempt at finding the relationship between the S_4 foliation and the stresses which have produced it. McBirney and Best (1961) found that the orientation of linear elements was defined by the intersection of layering with the plane normal to the direction of maximum shortening and was independent of the position of Y and Z. Since the L_4 lineation pattern for the gneiss belt around An Ruadh Mheallan is an E-W girdle, then X or the direction of maximum shortening is normal to the lineation girdle and therefore operated in a N-S direction. However, since the lineation pattern for the rest of the area does not conform to this simple pattern, the above explanation may not necessarily satisfy all the D_4 structures.

In fact, since the physical state of the complex varies, the effects of deformation may also have varied throughout the area.

c. The D_5 structures

The D_5 structures are restricted to belts of sub-horizontal S_4 foliation where both major and minor F_5 folds are found. The steep limbs of these major folds are often attenuated with the S_5 foliation occurring parallel to this limb. The folds plunge to the east or south-east at shallow angles and are co-axial to the L_4 lineations in the associated gneisses. The F_5 minor folds have a style varying from parallel to flattened parallel, the latter group showing S_5 axial-planar foliation in the incompetent layers. The occurrence of box folds in these belts is due to interference between F_5 and F_4 minor folds.

Where dykes occur in the belts of sub-horizontal S_4 foliation they are usually intruded parallel to the steep limbs of F_5 major folds.

2. The Post-Dyke Structures

a. The D_6 structures

The D_6 structures are only found in a few dykes, although the spread of L_7 lineations suggests the widespread development of a post-dyke and pre-D_7 planar fabric. When found undeformed, S_6 is seen to be parallel or sub-parallel to the dyke margins.

b. The D_7 structures

The S_7 foliation and L_7 lineation are only recognized with certainty in the dykes, since they are co-axial and co-planar to L_4 and S_4 respectively. However, where thorough M_7 recrystallization has occurred in the gneisses, the foliation, although initially S_4, may be interpreted as S_7.

The F_7 folds are generally tight and V-shaped with narrow hinge-zones, and are cut by the S_7 axial planar foliation. S_7 is always parallel to the dyke margins and is more widespread towards the south-west.

The production of S_7 in the dykes appears to be related to the structures in the adjacent gneisses. Thus, dykes that are parallel to S_4 are more highly deformed than those which were intruded at large angles to the foliation. The L_7 lineation is co-axial to L_4 and L_5 and S_7 is co-planar to S_4 within the same belt of gneisses. The L_7 lineation, from a consideration of ellipsoidal garnets, is thought to represent the direction of maximum elongation in the rock.

The homotactic quartz c-axis fabric indicates that a syntectonic M_7 metamorphism has occurred during D_7.

c. The D_8 structures

The D_8 structures are restricted to belts where intense D_7 fold movements have occurred. It results in the formation of F_8 asymmetric minor folds, although folds of larger scale affecting the outcrop pattern of dykes have been observed. Examination of refolded F_8 lineations indicates that the folding mechanism was by buckling although some folds with slight thickening in their hinge-zones indicate that flattening has operated. Examination of F_8 folds indicates that L_8 is co-axial to L_4, L_5 and L_7. An examination of L_4 and L_7 in small domains reveals that L_7 is dependent upon the attitude of L_4, indicating that a linear direction of weakness in the gneisses has become a rotation axis for F_8 folds.

The co-axial relationship of L_8 to L_4, L_5 and L_7 may indicate either continuous deformation (Watterson 1968 and Wynne-Edwards 1963) or refolding during successive deformation episodes controlled by inherited structures in the gneisses.

Since the D_4 deformation occurred before intrusion of the dyke swarm, and since the dykes show no features that would indicate a syntectonic intrusion, the possibility of continuous deformation for D_5-D_8 structures seems unlikely.

d. The D_9 structures

The D_9 deformation episode has produced NW-SE trending belts of mylonite and ultramylonite. The S_9 mylonite banding in these belts is parallel to the neighbouring S_4 and S_7 foliations and is always associated with belts of finely foliated S_4 gneisses. This seems to indicate that the formation of the mylonite belts has been facilitated by the pre-existing form of the complex. The banding is thought to have originated as a result of flattening by compressive stress normal to the banding (see Johnson 1967) rather than by rolling-out or milling produced by differential movement of material (for discussion; see Chapter V.H).

F. Correlation of the Torridon Lewisian with other areas of the Mainland

Hinxman (in Peach et al., 1903, p.255) considered that the concordant nature of the foliation in the gneisses and dykes and the sill-like appearance of the dykes were the result of secondary structural effects. Hinxman followed other Survey workers in calling this foliation the "second" foliation. The pre-dyke foliation which made up much of the area around An Ruadh Mheallan was the "first" foliation.

Sutton (in Sutton and Watson 1951A, p.257) agreed with this general subdivision of the Torridon Lewisian and likened the dykes during the development of the "second" foliation to "rigid moulds in which the activated gneisses react to the new tectonic forces", [redacted] the dyke attitude being the main factor in forming a NW-SE foliation concordant to their margins.

The writer's views contrast with those of the Survey and Sutton and Watson on the relationship of this second foliation to the dykes. However, it ought to be borne in mind that dyke-country rock relationships may often be ambiguous in regionally metamorphosed terrains (cf. Engel and Engel, 1963 and Gates 1962). Instead of the dykes exerting their influence on the formation of the NW-SE foliation, there is sufficient evidence to indicate that for many of the dykes at least, the foliation (S_4) has controlled the attitude and distribution of the dykes, and is therefore pre-dyke. ~~(i.e. S_4 foliation).~~

The conclusions of the Survey and of Sutton are compared with those of the writer in Table VI-1.

Based on the assumption that all the dykes of the Lewisian mainland are broadly of the same age, Sutton and Watson (op.cit.) subdivided the Lewisian into:-

Survey	Sutton	Writer
Formation of fundamental complex consisting of basic and acid gneisses. Formation of "first" foliation	1. Deposition of a series of sediments	1. Formation of igneous and/or sedimentary host rock perhaps metamorphosed
	2. Intrusion of minor masses of basic and ultrabasic rock. Basic rocks may have crystallized as flows contemporaneous with sedimentation.	2. Formation of early basite and ultrabasite either contemporaneous with to host rocks or later.
	3. First metamorphism: formation of gneissic complex with predominantly NE-SW striking foliation.	3a. Formation of S_1 foliation 3b. Formation of S_2 foliation c. Formation of post-S_2, pre-S_3 migmatites d. Formation of S_3 foliation equivalent to NE striking foliation of Sutton e. Formation of post-D_3, pre-D_4 migmatites f. Formation of S_4 foliation equivalent to NW-SE striking foliation of Sutton. M_4 syntectonic metamorphism equivalent to second metamorphism of Sutton. Formation of syntectonic and post-tectonic migmatites. g. Formation of F_5 folds.
Intrusion of dykes	4. Intrusion of dolerite swarm related to a period of crustal widening.	4. Intrusion of dyke swarm. Sequence of intrusion from type-TD basites through type-TB basites to ultrabasites.
Formation of NW-SE "second" foliation. Metamorphism of dykes.	5. Second metamorphism: formation of NW-SE foliation. Widespread development of microcline-bearing gneisses.	5a. Formation of S_6 foliation. Syntectonic M_6 metamorphism. b. Formation of S_7 foliation equivalent to NW-SE foliation (in dykes) of Sutton. Syntectonic M_7 metamorphism.
	6. Later metamorphism and folding about NW axes.	6. Formation of F_8 folds.
		7. Post-D_8 retrogressive metamorphism with associated potash metasomatism equivalent to the microcline-forming episode of Sutton.
	7. Formation of mylonite.	8. Formation of S_9 mylonitic banding.
	8. Formation of local thrust planes having NW-SE trends.	

Table VI-1.

(i) The Scourian Orogeny

(ii) The Dolerite Dykes

(iii) The Laxfordian Orogeny

The writer has followed Sutton and Watson in regarding all the dykes as being broadly of the same age and intruded in a period when no tectonism occurred. This view is based on the geochemical similarity of the dykes and the lack of any structural evidence that conflicts with it.

Table VI-2 shows the correlation of the Torridon sequence with the chronology of Sutton and Watson.

It is not possible so far to correlate the structures of phases D_{1-3} with structures elsewhere. The most likely correlation of the D_4 deformation and M_4 metamorphism is with the "Inverian" retrogressive metamorphism of almandine-amphibole facies associated with NW-SE foliation recorded from Lochinver and dated at 2200 m.y., prior to the intrusion of basic dykes (Evans and Lambert 1964). The NW-SE foliation and mineral assemblages are similar to those found in the D_4 and M_4 episodes.

The Lewisian rocks of Gairloch have recently been studied by Park (1964) who established the following sequence of events:-

(1) A deformation and granulite-facies metamorphism of (?)Scourian age resulting in the formation of the Ialltaig complex.

(2) Deposition of post-Ialltaig Gairloch sediments and emplacement of the early basic rocks.

(3) Early post-Ialltaig (?Laxfordian) phase of folding accompanied by low-grade metamorphism.

(4) Main phase of folding: major folding followed by minor folding associated with steep axial planar foliation accompanied by almandine-amphibolite facies metamorphism.

(5) Intrusion of South Sithean Mor dyke.

(6) Late phase of folding.

(7) Formation of NW-SE crush belts with pseudotachylite.

Torridonian Sedimentation

	?		D_9 deformation episode: S_9 mylonitic banding.
	1150 m.y.?	Post-M_8 retrogressive metamorphism and alkali metasomatism.	
	?	Intrusion of granites and pegmatites.	
LAXFORDIAN			D_8 deformation episode: F_8 minor folding.
	1500 m.y.?	M_7 almandine-amphibolite facies metamorphism of slightly lower grade than M_6. Reverse-zoned plagioclase.	D_7 deformation episode: S_7 foliation.
	?	M_6 almandine-aphibolite facies metamorphism producing garnet-bearing assemblages in dykes.	D_6 deformation episode: S_6 foliation.
	1950 m.y.?	Intrusion of dyke swarm in order type-TD basites-type-TB basites-Ultrabasites.	
	<2200 m.y.		
	>2200 m.y.	Local syntectonic granitization	D_5 deformation episode: F_5 major and minor folding.
INVERIAN	?	M_4 almandine-amphibolite facies metamorphism, syntectonic and post-tectonic migmatization with potassium metasomatism.	D_4 deformation episode: S_4 foliation.
EARLY SCOURIAN	?	Post-D_3-Pre-D_4 migmatites metamorphism unknown.	D_3 deformation episode: S_3 foliation.
			D_2 deformation episode: S_2 foliation.
	2600 m.y.?		D_1 deformation episode: S_1 foliation.
		Initial complex composed of either greywacke or granite, ultrabasic and basic igneous rocks.	

Table VI-2.

It has already been suggested that the main suite of Gairloch basites (see 2 above) and the Torridon Type-TD basites were formed from the same parent magma since both show very similar chemical variations. If this is a reasonable criterion for correlation, then these basic igneous rocks may be used to correlate the Gairloch and Torridon sequences. Thus:-

(a) The early post-Ialltaig phase of folding and metamorphism is equivalent to the D_6 deformation and M_6 metamorphic episodes at Torridon. The grade of metamorphism in Torridon is higher than was originally suggested by Park (1964), but more recent work in Tollie (Park 1969) and Gairloch indicates that the early phase was in amphibolite facies although heavily retrogressed in Gairloch (Park, personal communication).

(b) The main phase minor folding and accompanying metamorphism at Gairloch would be equivalent to the D_7 and M_7 episodes found at Torridon. The trends of the main phase and D_7 structures are NW-SE and the accompanying metamorphism is the same in both areas.

(c) The late phase of folding at Gairloch would be equivalent to the similar episode (D_8) at Torridon.

(d) The NW-SE crush belts at Gairloch appear to be equivalent to the D_9 brittle structures at Torridon.

The South Sithean Mor dyke is now considered to be pre-main phase (Park, personal communication) and so presents no problems of correlation with Torridon.

Sutton and Watson (op.cit.) did not exclude the possibility that the Gairloch sediments were part post-Scourian in age.

Thus, the metamorphosed dykes of the Torridon area and between Torridon and Gairloch may be related to and equivalent in age with the supracrustal rocks of Gairloch (Gairloch sediments) which were presumably laid unconformably upon a crystalline basement (Torridon gneisses) (cf. Peach and Horne, 1930). As a result of varying deformation, metamorphosed basic dykes can be traced from reactivated basement, in which they are deformed and metamorphosed, into areas where no post-dyke reactivation has taken place (cf. Watterson 1965A).

In conclusion, since the Lewisian rocks range in age from 2600 to 1100 m.y. and since two orogenies, Scourian and Laxfordian, have affected them, the very long and complex structural history shown by the Loch Torridon rocks (see Table VI-2) is not unexpected.

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