UNIVERSITY OF EDINBURGH
GEOLOGICAL CLASS
LIBRARY

STRUCTURE AND METAMORPHISM

of the

KISHORN-LOCHCARRON REGION IN ROSS-SHIRE

oOo

PRADIP K. GANGOPADHYAY, M.Sc. (Calcutta)

Thesis submitted to the University of Edinburgh

for the Degree of Doctor of Philosophy.

1961

EX BIBL UNIV EDINBURGEN

CONTENTS

Page

SECTION I. INTRODUCTION

A. General Introduction 1
B. Review of Previous Work 3
C. Scope of the Thesis and Outline of Results 27

SECTION II. THE ROCK TYPES

A. General Statement 32
B. Rocks lying above the Kishorn thrust plane 33

(1) The Lewisian Gneisses 33
(a) Ultrabasic Hornblendite ... 40
(b) Amphibolite and Hornblende-schist 42
(c) Intermediate and Acid Gneisses 53
(d) Pink Quartzo-felspathic Gneiss 59
(e) Banded Gneisses 60
(f) Quartzo-felspathic veins and Pegmatites 61

(2) The Torridonian (Diabaig Group) Rocks 61
(a) Epidotic Grits 65
(b) Loch na Dal Beds 68
(c) Beinn na Seamraig Grits ... 70

(3) The Torridonian-Lewisian Contact 71

(4) Metamorphic Episodes in the Lewisian and Torridonian (Daibaig Group) Rocks 75

C. Rocks lying below the Kishorn thrust plane 77

(1) General Statement 77
(2) Applecross Group 78
(3) Cambro-Ordovician Rocks 79

SECTION III. MEGASCOPIC STRUCTURAL DATA

A. General Statement 84
B. Megascopic Structures above the Kishorn thrust plane ... 88
(1) The Structures of the First Generation 91
(2) The Structures of the Second Generation 99
(3) The Structures of the Third Generation 109
(4) The Structures of Uncertain Age ... 112

C O N T E N T S (Continued)

		Page
C.	Megascopic Structures below the Kishorn thrust plane	114
	(1) The Structure of the area between Meall an Daimh and Coille Dhubh ...	117
	(2) The Structure of the area between Coille Dhubh and Loch Kishorn ...	127
D.	The Kishorn Thrust	130
SECTION IV.	MICROSCOPIC STRUCTURAL DATA	
A.	General Statement	138
B.	Quartz Orientation in Rocks above the Kishorn thrust plane	138
	(1) The Quartz Microfabric of the First Movement Phase	140
	(2) The Quartz Microfabric of the Second Movement Phase	152
	(3) Conclusions	158
C.	Quartz Orientation in Rocks below the Kishorn thrust plane	159
D.	Comparison of Microfabric data with those reported by other workers in the thrust belt	163
SECTION V.	SUMMARY OF CONCLUSIONS AND DISCUSSION ...	167
SECTION VI.	ACKNOWLEDGEMENTS	187
SECTION VII.	LIST OF WORKS TO WHICH REFERENCE IS MADE	188

LIST OF FIGURES

Figure 1. Location of the area studied.

" 2. Ultrabasic pods in acid gneiss.

" 3. Sketch showing inclusions in garnet and hornblende.

" 4. Profile of fold structure formed by slumping in Torridonian (Diabaig) rock.

" 5. Diagram showing the main structural units of the Kishorn-Lochcarron area.

" 6. Structural analysis of sub-areas above the Kishorn thrust.

" 7. 1500 poles to foliation and bedding planes in rocks above the Kishorn thrust.

" 8. Plots of linear structures in Lewisian and Diabaig rocks.

" 9. Poles to the axial planes of minor folds in rocks above the Kishorn thrust.

" 10. First folds in Lewisian and Diabaig rocks.

" 11. Second folds in Lewisian and Diabaig rocks.

" 12. Location of outcrops selected to demonstrate the relationship between the first and second linear structures.

" 13. Structural analysis of an outcrop of Lewisian rocks at Torr na h-Iolaire, illustrating the relationship between the first and second linear structures.

" 14. Structural analysis of an outcrop of Lewisian rock northeast of Glas Bheinn, illustrating the relationship between the first and second linear structures.

" 15 /

Figure 15. Third folds in Lewisian and Diabaig rocks.

" 16. Kinematic interpretation of the Conjugate Folds.

" 17. Folds of Uncertain Age in Lewisian rocks.

" 18. Plots of axes and poles to axial planes of minor folds in Cambrian quartzites and Torridonian (Applecross) grits.

" 19. Orientations of the thrust planes in the zone of dislocation.

" 20. Plots of poles to axial planes and axes of minor folds in Cambro-Ordovician limestones in Coille Dhubh area.

" 21. β - diagram showing the calculated axis of warping of the Kishorn thrust.

" 22. Exposed section of the Kishorn thrust north-east of Tornapress.

" 23. Exposed section of the Kishorn thrust north-east of Glas Bheinn.

" 24. Localities of the specimens of quartz-bearing rocks which have been used for petrofabric analysis.

" 25. (a,b,c,d,e,f,g,). - Quartz orientation diagrams in deformed Torridonian (Diabaig) rocks.

Figure 26. (a,b,c,d,e,f,g,h). Quartz orientation diagrams in a mylonitized Lewisian rocks

Figure 27. (a,b,c,). Quartz orientation diagrams in Lewisian rocks.

Figure 27d. Synoptic diagram showing the orientation of the maxima of quartz c-axes in some Lewisian and Torridonian (Diabaig) rocks.

Figure /

Figure 28 (a,b,)	Quartz orientation diagrams from a second fold in a Lewisian rock (Specimen A 2).
" 29 (a,b,c,d,)	Quartz orientation diagrams from a second fold in a Lewisian rock (Specimen A.3).
" 30	Diagram to show early rotation of first girdle followed by the transposition of the girdle during the later Shear folding.
Figure 31 (a,b,c,d,e,	Quartz orientation diagrams in rocks lying below the Kishorn thrust plane.

LIST OF PLATES

Plate I.

a. Kishorn thrust outcrop: Lewisian gneiss lying above the Cambrian quartzite.

b. Kishorn thrust outcrop: Lewisian gneiss lying above the Cambro-Ordovician limestones.

Plate II.

a. Outcrop of the Glen More Fault between Loch Carron and Loch Kishorn.

b. Repetition of the outcrops of Applecross grit and Cambrian quartzite by thrusting.

Plate III.

a,b. Isoclinal folds (First Folds) in Lewisian gneiss.

Plate IV. a. Long limbed isoclinal first fold in Lewisian gneiss.

b. Isoclinal microfold in Lewisian gneiss, showing stretching of constituent minerals along axial plane.

Plate V. a. Isocline (First Fold) refolded on the Second Fold axis. Lewisian gneiss.

b. First linear structure (b_1) cut across by the second cleavage (S_2). Lewisian gneiss.

Plate VI. a. Second Fold (a microfold) in Lewisian gneiss.

b. Second Fold (a microfold) and associated axial plane cleavage. Lewisian gneiss.

c. Magnified view of stretched quartz grains on the limb of microfold in Plate VI a.

Plate VII/

Plate V11 a,b. Examples of folds which have been classified as the "Structures of Uncertain Age".

Plate V11 c. Refolding of the limbs and axial plane of an isoclinal fold (First Fold) by a fold of uncertain age.

Plate V111 a,b. Examples of N.N.E. - S.S.W. trending asymmetrical folds in Cambrian quartzite.

Plate 1X a,b. Minor folds in Cambro-Ordovician (Eilean Dubh Group) limestone.

Plate X a. Photomicrograph of undeformed ultrabasic hornblendite with coarse granular texture.

b. Photomicrograph of deformed and schistose ultrabasic rock.

Plate X1 a. Hornblende-schist (Lewisian) with porphyroblastic garnet.

b. Sheared basic rock (Lewisian) from near the inverted Lewisian-Torridonian contact at the Cearcall Dubh area.

c. Example to show the relative resistance to deformation of the basic rocks compared to the acid rocks.

Plate X11.a. Sheared basic rock showing fibrous tremolitic amphiboles growing from hornblende. Section normal to the foliation (S_1) and the lineation (b_1).

b. Same. Section normal to the foliation (S_1) and parallel to the lineation (b_1).

c. Hornblende-schist with bluish green hornblende. Section normal to the foliation and the lineation.

d. Same. Section normal to the foliation and parallel to the lineation.

Plate X111.a,b,c. Examples of sheared Lewisian acid gneisses.

Plate X1V a. Lewisian acid gneiss showing clusters of recrystallized quartz grains. Section normal to the foliation (S_1) and the lineation (b_1)

b. Same. Section normal to the foliation (S_1) and parallel to the lineation (b_1).

Plate XV/

Plate XV, a,b. Mylonite. Lewisian gneiss.

c. Blasto-mylonite. Lewisian gneiss.

d. Conglomerate-like rock.

Torridonian-Lewisian contact.

Plate XVl, a,b. Cataclasite. Torridonian (Diabaig) rock.

c. Cataclasite. Lewisian gneiss.

Plate XVlla. Mechanically deformed Torridonian (Diabaig) grit. Section normal to the schistosity (S_1) and the lineation (b_1).

b. Same. Section normal to the schistosity (S_1) and parallel to the lineation (b_1).

c,d. Partially recrystallized Torridonian (Diabaig) grit.

Plate XVlll a. Undeformed Torridonian (Applecross) grit.

b. Deformed Torridonian (Applecross) grit.

Plate XlX a. Undeformed Cambrian quartzite with granular texture.

b. Cataclastically moderately deformed Cambrian quartzite.

c. Cataclastically strongly deformed Cambrian quartzite.

==========

M A P S

Map. 1. Geological map of Lochcarron - Wester Ross.

Map 2. Structural map of Lochcarron - Wester Ross.

==========

SECTION I - INTRODUCTION

A. General Introduction

The area investigated by the author is about 21 square miles in extent and is situated in Ross-shire, about 40 miles W.S.W. of Dingwall (Fig.I). The village of Lochcarron is situated about ¼ mile to the south of the area, on the main road leading from Inverness to Skye. The area is bounded on the south and south-east by the valley of Glen More and Glen Carron, on the north and north-east by the high escarpments of the hills of An Ruadh-stac and Fuar Tholl, on the west by Loch Kishorn and the River Kishorn.

The Kishorn-Lochcarron area may be described as a denuded, rather uneven mountain plateau. Notable features of the surface relief are two valleys which run in a nearly E-W direction. The most southerly of these valleys follows the trend of the Glen More fault (Plate IIa). North of this narrow valley the ground, which is occupied by the Lewisian gneisses, rises and forms the dip slope of the steep escarpments of Sgurr a'Gharaidh (2,395 ft.) and Glas Bheinn (2,330 ft.). North of these escarpments, /

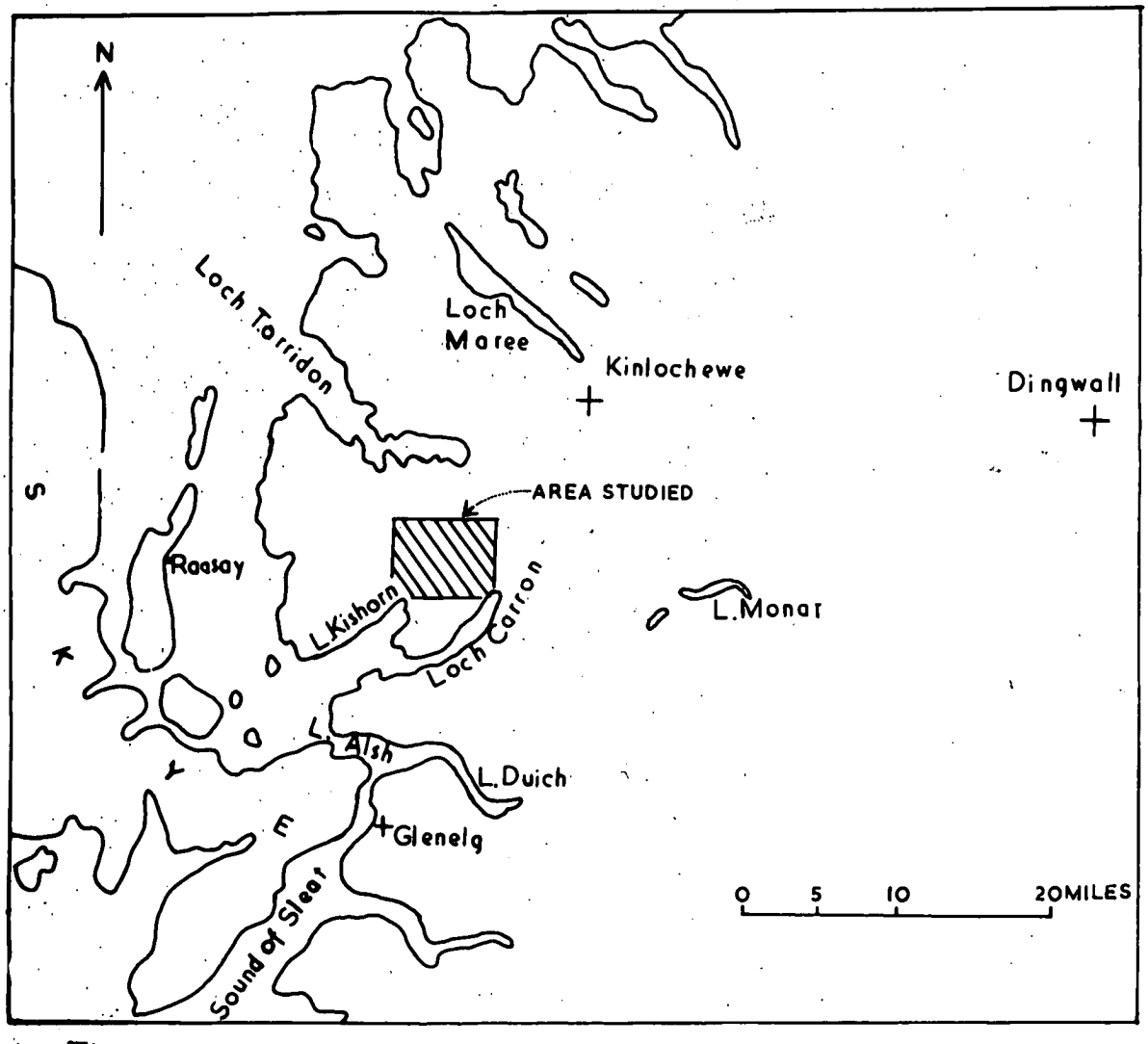


Figure 1. Map showing location of area studied.

escarpments, the second valley follows the outcrop of the Kishorn thrust and is a conspicuous feature in the landscape (Plate I a). North of this valley the ground level rises steadily to the peak of An Ruadh-stac (2,919 ft.) which is situated on the northern boundary of the area.

Glacial action in the area is evidenced by the patches of morainic drift on the lower hill slopes, by the deposits of glacial and fluvio-glacial materials on the boundaries of some lochs and by the lateral and terminal moraines in the valleys and corries. Prominent glacial striae, trending E-W, are present on weathered surfaces of rocks throughout the area.

There are numerous streams fed by smaller tributaries, in the area. Most of them, including the Amhainn Bhuachaig which occupies a large fluvio-glacial valley between Glas Bheinn and Tòrr na h-Iolaire, flow south-eastwards into Loch Carron. Of the few streams that flow westwards into Loch Kishorn, the most prominent is the Allt Mòr, which along part of its course occupies a deep gorge in which outcrops the Kishorn thrust.

Besides the two sea lochs, Loch Kishorn and Loch Carron there are, throughout the area, many fresh water lochs and lochans of which the larger are Loch an Lòin, /

Lòin, An Gorm Loch, Loch Cadh' an Eididh, Loch a' Mhuilinn and Loch na Caillich.

The Kishorn-Lochcarron area is almost uninhabited, the small population being chiefly confined to the village of Lochcarron and the crofting hamlets of Strathcarron and Glen More, together with a few widely scattered lodges and shepherd's houses. Agriculture is carried on in isolated patches along the lower ground near Loch Carron. The vegetation on the hill slopes and valleys is mainly coarse grass which provides pasture for the numerous sheep. There are scattered patches of peat which is cut to provide fuel for the local populace.

The rocks are well exposed throughout most parts of the area. Locally, notably in the Torridonian outcrop east of Courthill House, in the Lewisian outcrop north-east of Tullich and in the Cambro-Ordovician outcrop between Loch Cadh' an Eididh and Glas Bheinn, the rocks are partly concealed beneath the fluvio-glacial drift and peat.

B. Review of Previous Work

The North-West Highlands of Scotland display many features that are of outstanding geological interest and have attracted the attention of numerous geologists since the beginning of the nineteenth century. The Kishorn /

Kishorn-Lochcarron area has been regarded as a key area in the elucidation of the problems of the Caledonian thrust belt. In this section a review is presented of the previous work dealing with the part of the Caledonian thrust belt within the area under discussion and also of some literature which has a bearing on the problems of the thrust belt in the N.W. Highlands in general.

The earliest geological study of the Kishorn-Lochcarron region was undertaken in 1891 by Peach, Horne, Hinxman and others for the Geological Survey. The results of their work are shown on Geological Survey 1" sheets 81 and 82, published in 1896 and 1913 respectively. Later the geology of the region, as well as that of other parts of the North-West Highlands was described in two memoirs - the N.W.Highlands Memoir (1907) and the Central Ross-shire Memoir (1913).

The Memoir on "Geological Structure of the North-West Highlands of Scotland" (1907) was edited by Geikie and it contained contributions from Peach, Horne, Clough, Hinxman and Teall. The Memoir which describes the complex structure of the Caledonian thrust belt must rank as an outstanding text on structural geology. In the Kishorn-Lochcarron region two major thrust planes were recognised : the /

the Kishorn thrust, which has brought Torridonian and Lewisian rocks above the Cambro-Ordovician and Torridonian (Applecross) rocks of the Foreland, and the Moine thrust, which occurs above the Kishorn thrust and separates the overlying Moine rocks from the underlying Torridonian and Lewisian rocks. The Moine thrust and the rocks that occur above it are outside the limits of the area investigated by the present author. The structure of the area lying below the Kishorn thrust was described mainly by Hinxman (Mem.1907, pp.558-565) and that of the area above the thrust by Peach and Horne (Mem.1907, pp.565-566).

The area lying structurally below the Kishorn thrust plane is mostly occupied by parallel strips of Cambro-Ordovician and Torridonian (Applecross) rocks, the outcrops of which trend N.N.E. - S.S.W. The Cambro-Ordovician and Torridonian strata are repeated by thrusting and folding. Hinxman (op.cit.) traced the outcrop of two major N.N.E. trending thrust planes into the present ground from areas situated to the north of An Ruadh-stac. The more westerly outcropping of the two thrusts (the "Sole Thrust") occurs to the west of An Gorm Loch & North of the present area the effect of the Sole thrust is to carry Torridonian (Applecross) rocks upon themselves. "Near

An /

An Gorm Loch, about a mile and a half south-west of An Ruadh-stac, the thrust passes entirely into the Cambrian strata, bringing forward the pipe-rock upon itself along the slopes above Allt Ghiubhais as far as the Coille Dhubh (Sheet 81). From this point westwards to Kishorn, the Middle Cambrian Series is thrown against the undisturbed serpulite-grit along the outcrop of the thrust" (Hinxman, op.cit.pp.558-559).

The more easterly outcropping of two major thrusts is located about three quarters of a mile to the east of, and follows a somewhat sinuous course nearly parallel to, the Sole thrust. North of An Ruadh-stac the thrust carries, for the most part, Torridonian rocks upon themselves. In the present area, this thrust has brought forward the Torridonian grits and sandstones and has carried them over the folded Cambrian quartzites. The stratigraphical sequence throughout the region is often inverted by major or minor thrusting and "sharp inverted folding" (Hinxman, op.cit.,p.561). A section (op.cit., fig. 53) drawn across the district just north of An Ruadh-stac illustrates the structure.

South of An Ruadh-stac, the structure is illustrated by a section (Hinxman, op.cit., fig.54) drawn in a south-easterly direction from the valley of Strath a'Bhathaich, across/

across the ridge of Glas Bheinn to Loch Carron at Kirkton. Part of the explanation of the section is reproduced below -

"South of the Gorm Loch, above the major thrust-planes, a considerable area round the upper part of the Allt a'Ghiubhais glen and the pass that leads through to Strath Carron is occupied by repetitions of the fucoid-beds, serpulite-grit, and basal limestone, folded and driven together in great complexity. On the south side of that glen this mass of piled-up material is soon overlain by limestones belonging to the Ghrudaidh and Eilean Dubh groups. These have been carried forward by a thrust which traverses the southern slopes of the Kishorn valley, and gradually descends to the roadside at Rassal, where it is cut off by the Fasagh fault. A belt of ground, five miles in length and nearly three quarters of a mile in breadth, is occupied by these limestones, which, though inclined at very high angles, are made to spread over so large an area by being incessantly repeated by folds and reversed faults.

A short distance west of the Allt a'Ghiubhais pass the limestones are themselves overlapped by another thrust-plane on which the quartzite has been carried westward. On the watershed at the head of the pass the pipe rock dips at a high angle beneath the basal quartzite, which in turn is followed in inverse order by Torridonian grits, these again /

again being overlain in a similar manner by Lewisian gneiss. The double unconformity is thus represented here in inverted order. Owing, however, to folding and crushing, the boundary lines of the different rocks are considerably involved ....

..... On the south side of the pass rise the steep craggy side of Glas Bheinn, a mass of Lewisian gneiss which has been brought forward by a powerful dislocation (Kishorn thrust). ..... The materials driven forward upon its sole consist of Lewisian gneiss (A) and portions of the lowest Torridonian group (Ba). The two formations preserve their normal unconformable relations, but in inverted order ....." (Hinxman, op.cit., pp.562-563).

The structure of part of the present area which occurs above the Kishorn thrust was briefly described by Peach and Horne (op.cit., pp.565-566) as follows :-

"The most striking feature of the belt of complication..... is the stupendous inversion of the Torridon Sandstone and Lewisian rocks above the Kishorn thrust-plane. The overturned gneissic floor, lying at a gentle angle on the inverted epidotic grits, black shales, and sandstones of the lowest Torridon division, forms a bold and conspicuous escarpment to the north and south of the entrance to Loch Carron. The boundary line between the /

the two formations has been traced from the western slope of Cearcall Dubh, north-east of Kishorn, southwards to a point in Loch Carron about a mile west of North Strome....." A section (op.cit., fig.55), drawn in a south-easterly direction from Loch Kishorn to Loch Carron, shows Lewisian and Torridonian rocks occurring in inverted order and forming part of the upper limb of a recumbent synclinal fold (known as the Loch Alsh Syncline). Commenting on this structural section and others drawn just south of the present area, Horne (op.cit., p.467) wrote - "The horizontal sections (Figs. 55, 56, 57) show that this inversion forms part of a great fold which has been driven westward along the Kishorn thrust-plane."

Referring to the inverted Torridonian and Lewisian rocks between Loch Kishorn and Loch Alsh, Peach and Horne (op.cit., pp.565-566) stated -

"Within the belt of complication in this district a high grade of metamorphism is observable among the lowest Torridonian strata usually at or near their inverted base line. This alteration may be studied with advantage at Fernaig in the conglomerate which crops out there. This rock is traceable only for a limited distance, but when it is absent its place is taken by epidotic grits and shales /

shales ..... Considerable differential movement has taken place in some parts of the Lewisian rocks and underlying epidotic grits. New divisional planes have consequently arisen, which are inclined at gentle angles to E.S.E."

Teall (Mem. 1907, pp.278-290) showed that the inverted Lower Torridonian rocks of Skye and Loch Carron have undergone considerable mineralogical and textural changes. In the sandstones, grits and shales new minerals, such as sericitic micas, magnetite and chlorite have developed. In many cases the original quartz and felspar grains are crushed and the sedimentary texture is replaced by a "secondary microcrystalline mosaic" which has "all the distinctive characters of a true schist". A special section on "The Dynamic Metamorphism of Torridonian Rocks" (Teall, op.cit., pp. 288-290) contains details of these changes.

In the Kishorn-Lochcarron region, crushing and mylonitization of the Lewisian rocks, which consist mainly of biotite and hornblende gneisses with bands of hornblende-schist and pink pegmatites, have been mentioned by Peach and Horne (1907, pp.262 - 263, p.470, pp.565-573). The gneisses, "in places, have been much sheared by the post-Cambrian movements ..... A fine flaser structure has not /

not infrequently been developed, and the felspars then form augen in a mylonised matrix" (op.cit., p.263). In a later publication (Mem.1913), the deformed nature of the Lewisian gneisses lying above the Kishorn thrust near the hills of Glas Bheinn and Tòrr na h-Iòlaire was briefly described by Peach (op.cit., pp.12-14) and Hinxman (op.cit., p.14). An extract from the description of these rocks by Peach (op.cit.) is given below -

"The chief characteristic of this rock, which was originally a hornblendic and micaceous gneiss, is the intense cataclastic action to which it has been subjected. The evidence of this deformation is strongly apparent in the first few feet above the thrust plane, where the rock is completely drawn out into platy mylonite, independently of the nature of the gneiss."

Hinxman (op.cit.) also noted that in many places near the Kishorn thrust "the (Lewisian) rock is in the condition of a green flaggy mylonite."

Peach (Mem.1913, p.13) noticed "mylonites" which are not confined to the vicinity of the Kishorn thrust plane in Lewisian gneisses and commented as follows -

"Along certain planes of movement which dip south-east in a direction parallel to the underlying Kishorn /

Kishorn thrust plane, the rocks are drawn out into mylonites similar to those near that plane .... the intermittent bands of mylonised rocks within the mass are produced by the dynamic force being transmitted through more stable portions to successive layers of weakness.

The deformation of these mylonites, although for the most part destructive, is not wholly so, granulitization of the quartz and felspar having taken place to a considerable extent, accompanied by the setting up of small individuals of secondary mica....."

It was believed (Horne, Mem.1907, pp.466-471; Peach, Mem. 1913, p.28) that thrusting was a long continued process in the North-West Highlands and that the rocks lying above the major thrusts (such as the Kishorn thrust and the Moine thrust) were driven west-north-westwards. Horne (op.cit., p.471) noted in this connection - "Fine parallel lines, trending generally E.S.E. and W.N.W., appear on the new divisional planes, in accordance with the general direction of the post-Cambrian movements." E.S.E - trending linear structures in "mylonised rocks in advance of Moine thrust" and in Moine schists, have been recorded from the ground just south of the present area (Geol. Survey sheet No.82).

It may be noted here that Clough, working in Sleat

of Skye, recorded minor folds and "direction of stretching" (i.e. lineation) in inverted Torridonian rocks which occupy a similar structural position to the Torridonian (Diabaig) rocks investigated by the present author. Clough's lineation map was published in a paper by Bailey (1955, fig.6) many years later. In Skye, Clough (Mem.1907, fig.59) also noted that on the inverted limb of the Loch Alsh Syncline, pelitic rocks of the Torridonian show a cleavage which dips towards east at higher angles than bedding.

Ever since the discovery of the Moine thrust and the belt of thrusting and folding to the west of it, the structural and metamorphic features of the N.W. Highlands have been the subjects of many controversies, notably those on the age of the Moine folding and regional metamorphism. The concept of thrusting implied the operation of powerful dynamic forces in the North-West Highlands. Influenced by this concept, Lapworth, as early as 1883-4, suggested that the Moine schists may be a metamorphic compound formed by the recrystallization of a mechanically crushed mixture of Cambrian, Torridonian and Lewisian rocks. In 1885, Lapworth noted the occurrence along the great thrust planes of a distinctive rock type, which he termed "mylonite" (Gr. mylon, a mill). The rock is "composed of shattered fragments of the original crystals of the rock set in a cement /

cement of secondary quartz, the lamination being defined by minute inosculating lines (fluxion lines) of kaolin or chlorite material and secondary crystals of micaceous mineral. Whatever rock rests immediately upon a thrust plane whether Archaean, igneous or Palaeozoic, it is similarly treated, the resulting mylonite varying in colour and composition according to the material from which it is formed .... The mylonites may be described as microscopic pressure-breccias with fluxion structure, in which the interstitial dusty, siliceous, and kaolinitic paste has only crystallized in part; the augen-schists are pressure-breccias, with fluxion structure, in which the whole of the interstitial paste has crystallized out. The mylonites were formed along the thrust planes, where the two superposed rock systems moved over each other as solid masses; the augen-schists were probably formed where the all-surrounding weight and pressure forced the rock to yield somewhat like a plastic body. Between the augen-schists there appears to be every gradation, on the one hand to the mylonites, and on the other to the typical mica-schist composed of quartz and mica" (Lapworth, op.cit., p.559).

Favouring the dynamic origin of the Moine schists, Geikie (1899, p.23 and 1894, p. 264) suggested that various groups /

groups of rocks, notably the Torridonian and possibly Cambrian or even later sediments, "underwent the same conversion to a foliated condition" during the thrusting (cf. Lapworth, 1884, p.438).

In 1892 Peach observed evidence near Loch Carron that the Torridonian had been converted into "granulitic" flagstones, like the so-called Moine schists". The same view was expressed by Peach in "Chapters on the Geology of Scotland" which was published posthumously (Peach and Horne, 1930, p.200) -

"the clean-cut thrust planes, the deformation of the Torridon Sandstone, the regional metamorphism of the Moine Series ..... were produced by the same set of movements in the post-Cambrian time".

Horne, however, did not agree with Peach's view that the metamorphism and folding of the Moine schists was of post-Cambrian date and connected with the thrusting (see Geikie, 1899, p.15). He contrasted the lithology of the Torridonian with that of the Moine and regarded "the Moine series as consisting mainly of sedimentary schists of pre-Torridonian age, modified by post-Cambrian movements, which developed, along the outcrop of the Moine thrust, a complex of Mylonites, green schists, phyllites, lenticles of Cambrian quartzite /

quartzite, of schistose Torridon Sandstone, ... and deformed Moine schists, with common planes of schistosity determined by these movements" (Peach and Horne, 1930, pp.200-1).

Phemister (1926) concluded, like Horne, that the general Moine metamorphism was earlier than, and distinct from, the post-Cambrian thrust-movements. Horne's hypothesis was developed by Read (1931), after he had made an investigation of the Moine schists near the Moine thrust in Central Sutherland. He observed that in a broad belt adjacent to the Moine thrust outcrop the schists had undergone a "marked dislocation metamorphism". Close to the thrust, in a zone varying in width from a few feet to almost a mile, the schists are converted into mylonites, but the dislocation effects, notably granulation of minerals and development of "slickensides", are recognizable in a zone up to three miles wide.

In 1934, Read made a brief review of the various ideas on the origin and metamorphic history of the Moine schists and discussed the evidence bearing on the problem. He pointed out that the resemblance in texture and mineralogical composition between the Moine schists near the thrust and the sheared Torridonian rocks (as noted by Peach) was due to "metamorphic convergence", whereby rocks of differing /

differing texture and metamorphic grade but similar bulk chemical composition may, in zones of dislocation metamorph-:ism, give rise to similar sheared derivatives. Read concluded that the Moine Series, and its general metamorphism, are of a pre-Torridonian, probably Lewisian age.

Bailey (1939) in a review of the structure and metamorphism of the thrust belt between Lochcarron and Skye suggested that the difference in crystallinity between the slightly metamorphosed Torridonian rocks and the Moine schists is one of degree and not kind. Bailey again expressed his complete agreement with Peach's views in a later paper (Bailey, 1955, p.107). He (op.cit.,p.134) reported the occurrence of "greenish-brown biotites" in deformed inverted Torridonian (Diabaig) rocks at Skye and Loch Carron. Thus part of the Diabaig outcrop in the present area is within the "biotite-zone" as delimited by Bailey (op.cit., fig.I).

Subsequent to the initial work carried out by the Geological Survey new techniques were developed for the study of rock fabrics (i.e., textures and structures on all scales) and principles have been evolved for the interpretation of these fabrics. In recent years the Universal Stage has been widely used to study the optical orientation of minerals in rocks. F. C. Phillips, who was the /

the first geologist to apply methods of petrofabric analysis to the rocks of the Scottish Highlands, undertook a regional study of the microfabric of Moine schists and of Torridonian and Cambrian rocks from the Moine thrust belt and the Foreland, which comprises the unmoved rocks lying to the west of the thrust belt (Phillips, 1937). The optic axes of quartz in specimens of Moine schists, which were collected over a large region, lie in a partial or complete girdle when plotted on a stereonet. The plots of cleavage (001) poles of micas usually cluster in a strong maximum which is situated normal to the trace on the net of the foliation of the Moine rocks. In some of Phillips' diagrams the mica cleavage poles show an incipient or complete girdle, which has a similar orientation to the quartz girdle. The plane of the mica and quartz girdles trends N.E.-S.W. Phillips noted that the axes (known as b-axes) normal to the plane of the girdles are parallel to megascopic linear structures such as lineation, fold axis, rodding, mullions, all of which plunge towards the south-east. Sometimes, in the quartz fabric diagrams Phillips found that the optic axes form not a single girdle, but intersecting girdles. Phillips suggested that such patterns might be produced by, either /

either (a) a "crossed strain" causing rotation in a plane normal to the first girdle, or (b) the influence of later movements on an earlier, single, girdle. After discussing the principles governing the production of microfabric girdle, Phillips concluded that "b-axes ..... over a given area ..... have a similar significance to fold axes, and it can safely be asserted that the deformation ..... has acted in a plane more or less perpendicular to them" (op.cit., p.591). Phillips considered that the fabric evidence indicated that the "Moine schists were brought to their present state of regional metamorphism by a deformation acting along approximately south-west and north-east lines ..... prior to the dislocation phase of the Caledonian movements" (op.cit., p.603). Phillips examined the effects of "dislocation metamorphism" in Moine schists near the Moine thrust and found that the thrust movements had very little, if any, constructive effect on the schist micro-fabric. The Cambro-Ordovician and Torridonian rocks of the Foreland and within the thrust belt, show little evidence of any preferred orientation of quartz (Phillips, op.cit., figs.D.27, D.28, Plate XXV). Rarely, quartz c-axes in Cambrian quartzites and Torridonian sandstones collected from the thrust belt, show an incipient girdle /

girdle pattern. The plane of the girdle trends N.W. - SE., "normal to the outcrop of the (Moine) thrust, with its b-axis perpendicular to the direction of movement in the post-Cambrian dislocations" (op.cit., p.603).

Two years later, Phillips (1939) published further fabric diagrams of sheared Torridonian sandstones collected from within the thrust belt. Quartz optic axes are seen to form a diffuse but recognisable girdle which trends N.W. - S.E. (op.cit., figs. 15 and 16, p.236).

In order to test the homogeneity of the preferred orientation of quartz c-axes over a wide area of the N.W. Highlands, Phillips (1945) selected 50 quartz orientation diagrams from widely scattered localities. The diagrams were rotated to their true geographical orientation and then combined to give a composite diagram (op.cit., fig.I.). The diagram shows that the quartz c-axes in the Moine schists form a girdle pattern trending N.E.-S.W. In contrast, the composite geographically oriented diagram (op.cit., fig. 4) for quartz c-axes in the Torridonian and Cambrian rocks below the Moine thrust and within the thrust belt yield a weak girdle with a N.W. - S.E. trend. Phillips suggested from this evidence that the regional girdle fabric of the schists was not produced during the thrust movements and that the "crossed-girdle" patterns in the Moine schists are /

are possibly due to the "overprinting" of a thrust fabric upon the regionally developed girdle.

Phillips (1951) noted that there are certain similarities between Moine and Lewisian fabrics. Like the Moines the Lewisian gneisses of the Foreland show a lineation plunging to the south-east. The quartz and mica fabrics in some Lewisian rocks form N.E. - S.W. trending girdle patterns which resemble those in the Moine schists. Phillips cautiously suggested that such an "apparent coincidence" seemed to favour the hypothesis that the general Moine metamorphism was of Lewisian age.

McIntyre (1954) has ably summarised and discussed the problem of age relationship between Moine folding and thrusting in the North-West Highlands. He stated that there are reasons for believing that the folding and the thrusting represent two tectonic events, which were separated by an unknown but probably considerable, time-inter-:val.

Recently several parts of the thrust belt in the North-West Highlands have been re-investigated with a view to establish the time sequence of events in this belt.

Christie (in McIntyre, 1954; 1955; 1956, Ph.D. Thesis; 1960), working in Assynt, found that during the post /

post-Cambrian movements there has been "a single penetrative movement about a common B-axis" in the Moine schists, the mylonitic rocks above the Moine thrust and the deformed Lewisian, Torridonian and Cambrian rocks below. This common B-axis (defined by megascopic fabric elements, such as, lineation, fold axis etc.) plunges to the E.S.E.. Microfabric analysis showed that the symmetry of the fabric of both the Moine schists and the "rocks intimately associated with the (Moine) thrust" seems to be nearly orthorhombic (i.e. fabric diagrams show two or more planes of symmetry).

Christie (1956,1960) also pointed out that laminated rocks mapped as "mylonite" by the Survey geologists do not always strictly conform to Lapworth's definition. Many show marked recrystallization and are more accurately described as augen-schists (Lapworth,1885) and blastomylonites (Sander, 1912 and Knopf, 1931). These rocks, which Christie referred to as "Primary Mylonitic Rocks" occupy a zone along the horizon mapped as the Moine thrust and grade upwards, with increasing crystallinity, into low grade Moine schists. Locally the "Primary Mylonitic Rocks" and the Moine schists have been affected by the secondary deformation of a post-crystalline nature. As a result of the latter deformation the well laminated pelitic /

pelitic rocks were converted to phyllonites and the more massive rocks were converted to kakirite and cataclasite. These are grouped as "Secondary Mylonitic Rocks" by Christie.

In the area around Loch Eireboll, Wilkinson (1955) noted the presence of prominent linear structures which occur in Moine schists and "in rocks below the Moine thrust", plunging E.S.E. Wilkinson suggested that the evidence points to the post-Cambrian origin for the lineation and possibly for the general metamorphism of the Moine schists.

Crampton (1955), working in the thrust belt region bordering Sutherland and Ross, reported that quartz fabric diagrams for Moine schists show transitions from a regional girdle disposed in a N.E.-S.W. plane, through various types of crossed girdles, to a girdle disposed S.E.-N.W. The latter "exceptional quartz fabric can sometimes be shown to correspond to modification of the pre-existing regional fabric during overthrusting". Quartz fabric in Cambrian rocks immediately below the thrusts usually consist of two girdles; at greater distances from the thrust there is either no preferred orientation or a pattern of sedimentary type.

At a meeting of the London Geological Society in 1958, Crampton presented the results of some fabric analyses of Moine and Cambrian quartzites of the North-West/

West Highlands. The regional Moine fabric is characterised by a "homotactic girdle preferred orientation, partial to complete, of quartz, muscovite, biotite and epidote vertical axes, disposed vertically S.W.-N.E., normal to the south-easterly plunging lineation". The fabric of the Cambrian quartzites below the Moine thrust plane was considered to have originated prior to the thrusting and consists of quartz (0001) axes aligned parallel to the bedding. Both the regional fabrics, i.e. that above the Moine thrust plane in Moine of metamorphic origin and that below in Cambrian of sedimentary origin, have been strongly modified by the thrust movements. "New preferred orientations of quartz (0001) axes are developed, including crossed girdles, the girdle intersection being directed parallel to the regional lineation, and rarely, simple girdles parallel to lineation" (op. cit.).

Johnson (1955, 1957) re-investigated the thrust belt near Loch Carron and Coulin Forest in Ross-shire and reported the occurrence of two sets of minor structures (lineation, minor folds, etc.) in Torridonian, Lewisian and Moine rocks affected by post-Cambrian movements. All these rocks, where affected by thrust movements, are seen to have developed quartz and mica fabrics which are orthorhombic /

orthorhombic in symmetry. These fabrics are "overprinted" on the monoclinic fabric of the regionally metamorphosed Moine rocks.

It is interesting to note that Johnson (1956) recorded "conjugate folds" in the thrust zone in the Lochcarron and Coulin Forest areas. The axial planes of these folds are inclined towards the north or south so that no regional directional translation of the rocks can be postulated from these structures, whose symmetry as a whole is orthorhombic. The folds were considered to have resulted from local lateral extension and concomitant compression of laminated rocks involved in the thrusting.

Johnson (1960) discussed the structural history of the Moine thrust zone at Loch Carron, in the ground immediately to the south that mapped by the present author. From a study of the minor structures found in rocks, Johnson concluded -

(a) that the Torridonian and Lewisian rocks lying in inverted order between the Kishorn thrust and the Moine thrust, and Moine rocks, lying above the Moine thrust, showed a remarkable parallelism in structure.

(b) that there developed three sets of minor structures in the Torridonian, Lewisian and Moine formations during /

during the Caledonian movements. At least two of these three sets pre-date the Moine thrust movements. The mylonites which are not restricted to the vicinity of the Moine thrust outcrop, belong to an earlier phase of movement than these minor structures and are not directly connected with the clean-cut thrust-movements (cf. Barber, mentioned in Johnson, 1960)

(c) that the inversion of the rocks to the west of the Moine thrust (i.e., in the "Kishorn Nappe", see Bailey, 1939) occurred before the formation of the minor structures mentioned above.

(d) that the plastic, para-crystalline style of the earlier deformation contrasts markedly with the post-crystalline brittle style of the latter deformations.

It may be mentioned in this connection that Barber (in discussion of Sutton and Watson, 1959, p.256) who has recently investigated the mylonitic rocks near the Moine thrust at Loch Alsh (about 15 miles S.W. of Loch Carron) reported, in the mylonites, the occurrence of two sets of minor structures which may pre-date the thrust movement.

C. Scope of the Thesis and Outline of Results.

The Kishorn-Lochcarron area forms part of the thrust belt in the North-West Highlands. The large-scale structural features, such as the thrusts and folds of the area have been described in detail in Geological Survey Memoirs (Peach, et al, Mem. 1907; Peach, et al, Mem. 1913). The Kishorn and Moine thrusts attracted special attention from the Survey workers(Op.cit.). It has been implied in the Survey Memoirs (op.cit.) that thrusting in the Lochcarron region (and in the N.W. Highlands as a whole) was a long continued process and that many of the structural features of rocks in the thrust belt had a causal connection with thrusting. As mentioned in the previous section, in recent years several parts of the thrust belt in the N.W. Highlands have been re-investigated, particular attention being given to the minor structures(Christie, 1955, 1956, 1960; Wilkinson, 1955; Crampton, 1955,1958; Johnson, 1955, 1957, 1960; Barber, in Sutton and Watson, 1959 and in Johnson, 1960). The results of these investigations have thrown new light upon the movement histories of the rocks of the Caledonian thrust belt.

The area selected for the present investigation occurs below the Moine thrust. It is structurally divided into two units : one consists of Lewisian and Torridonian rocks/

rocks lying above the Kishorn thrust and the other consists of Cambro-Ordovician and Torridonian rocks lying below the Kishorn thrust. The rocks of the latter unit are separated from the undisturbed Foreland, of which a small part is included in the area, by the Sole thrust plane. The primary purpose of the investigation is to elucidate and compare the structural histories of the rocks above and below the Kishorn thrust. The main topics to be discussed are -

(i) The style and orientation of small-scale folds and linear structures and their mutual relations in Torridonian and Lewisian rocks above the Kishorn thrust.

(ii) The style and orientation of small-scale and large-scale folds in Cambro-Ordovician and Torridonian rocks below the Kishorn thrust and their relation to the major thrust faults.

(iii) The relation of structural elements in rocks above the Kishorn thrust with those in rocks below this thrust.

(iv) The age of thrusting in the structural history as revealed by the minor structures.

(v) The metamorphism of the cataclastically deformed rocks and its relation to the structural events.

(vi) /

(vi) The grain orientation in rocks above and below the Kishorn thrust.

The area, which is covered by Ordnance Survey 6" = 1 mile maps (sheet nos. C111, C1V, CX, CX1, second editions, 1907), has been geologically remapped, the location of the various rock types and the orientations of structural elements being recorded on field slips. From the field-maps, two maps have been prepared - one lithological (Map 1) and another structural (Map 2).

The part of the area above the Kishorn thrust plane has been divided into fourteen sub-areas and the structural elements (foliation, bedding planes, minor folds, cleavage) in these sub-areas have been studied in detail. Some outcrops, where the relationship between structures of different generations is clearly displayed, have been mapped on a large scale.

Petrofabric analyses of quartz-bearing Lewisian, Torridonian and Cambrian rocks have been made. The studied rocks include quartzites and grits from the Foreland and from the disturbed region between the Sole and Kishorn thrusts, and gneisses and grits from above the Kishorn thrust. Rocks have been selected for analysis on the basis of the examination of the visible structures and from localities where the relation between different sets of structures is known.

For /

For convenience in the presentation of the data the megascopic and microscopic data are described separately, but the final conclusions are based on the consideration of the fabric on all scales, as well as on the metamorphic characters of the rocks.

The author has followed the standard procedures described by Ingerson (in Knopf and Ingerson, 1938, pp.211-262) and Fairbairn (1949, pp. 241-292) in operations involving the measurement of megascopic and microscopic fabric data, the collection of oriented specimens, the preparation and examination of thin sections and the presentation of data. Orientations of structural data are plotted on the lower hemisphere of an equal-area projection.

Outline of Results

The study suggests a sequence of Caledonian movements and metamorphic episodes in the thrust belt.

The rocks above the Kishorn thrust have undergone at least three phases of movements, during each of which a set of minor structures developed. The style of the earlier deformations was plastic and quartz microfabrics developed during two phases of metamorphism. The style of later deformation was brittle and the rocks suffered cataclasis.

The rocks below the Kishorn thrust have mainly undergone a single phase of movement. There is no evidence /

evidence in these rocks of a quartz microfabric related to the tectonic structures (major folds and thrust planes). The relatively simple structure of the rocks below the thrust markedly contrasts with the complex structure (and metamorphic history) of the rocks above the Kishorn thrust.

The clean-cut thrusting along the Kishorn thrust plane took place at a late stage in the Caledonian movement history.

SECTION II - THE ROCK TYPES

A. General Statement

The petrography of the rocks occurring above the Kishorn thrust plane and that of the rocks below the thrust will be described separately in this section, emphasis being placed on the discussion of the Caledonian deformation and metamorphism of the rocks as evidenced by their mineralogical and textural features.

The Lewisian and Torridonian (Diabaig Group) rocks, lying above the Kishorn thrust plane have undergone granulitization and mylonitization which possibly occurred prior to and also during the isoclinal first fold movements. Recrystallization, possibly affected the rocks during the later phases of the isoclinal folding. During the second fold movements there is evidence of considerable post-crystalline deformation and some recrystallization. An interesting aspect of this study is that the deformed gneisses and sediments of the area provide an example of the behaviour of the different rock types undergoing the same movements. During the later stages of the structural history the rocks were subjected to cataclasis notably in the immediate vicinity of the Kishorn thrust.

The Cambro-Ordovician and Torridonian (Applecross Group) rocks, lying below the Kishorn thrust, are very slightly /

slightly deformed despite the presence of major folds and thrusts. The style of deformation is cataclastic, the effects of which are borne only by rocks near the thrust planes, particularly the Kishorn thrust. There is no evidence of constructive metamorphism in these rocks.

B. Rocks lying above the Kishorn thrust plane.

(1) The Lewisian Gneisses

The Lewisian gneisses occupy an area about 9 sq. miles and their outcrop extends from north-east of Loch Kishorn to Torr na h-Iolaire (Map 1). The gneisses, which lie as a sheet, some 1,700 feet thick, structurally above the Kishorn thrust plane, form lofty escarpments on the northern slopes of Sgurr a'Gharaidh and Glas Bheinn.

The gneissic complex consists dominantly of a foliated hornblende-bearing acid gneiss and numerous concordant bodies of amphibolite and hornblende-schist. Both the acid and basic rocks contain coarse grained, pink-coloured pegmatites which are possibly late injections into the complex, though they possess a foliation which is parallel to that of the acid and basic gneisses.

It has been recognised by previous workers in the North-West Highlands that the Lewisian rocks within the /

the thrust belt have undergone "intense cataclastic action" during the post-Cambrian movements, with the partial or complete obliteration of the original features of the gneisses (Peach, Mem.1913, pp.12-14). The present work suggests three reasons for believing that the modifications are more extensive than previously supposed. Firstly, the structural events described later show that the Lewisian gneisses, along with the Torridonian rocks, have been involved at least three phases of Caledonian movements. Secondly, there have been notable metamorphic changes whereby the original gneisses have been reconstituted during these movements, the most important modifications being produced by granulitization and mylonitization but in addition there has occurred recrystallization and the overprinting of Caledonian microfabrics upon the modified gneisses. Zones of intense shearing are found within the Lewisian outcrop, especially along the contact of different rock types. This is evidenced by the narrow shear zones of laminated mylonites (Lapworth, 1885) and partly recrystallised blasto-mylonites (Sander, 1912 and Knopf, 1931). Outside the shear zones the Lewisians are only slightly deformed. Thirdly, there is evidence of late cataclasis of the mylonitic gneisses in the immediate vicinity of the Kishorn thrust plane.

On the bases of differences in mineralogical composition and texture the relatively undeformed Lewisian gneisses of the area can be divided into the following groups -

I - Rocks composed entirely of hornblende; ultrabasic in composition; often massive or only slightly schistose; occurring as small nodules or pods, not more than a few feet across, within other gneisses.

II - Rocks in which hornblende is the dominant ferromagnesian mineral; felspar always present.

A Without quartz or containing very little quartz; rocks basic in composition:

(1) Rocks massive or slightly foliated :

(a) Epidote (Zoisite) - amphibolite.

(b) Garnet - amphibolite

(c) Amphibolite without garnet or zoisite.

(2) Rocks foliated:

(a) Hornblende-schist

(b) Garnetiferous hornblende-schist.

B With quartz; rocks intermediate or acid in composition; foliation usually distinct, but in some cases weakly developed; constituent minerals often show a granular arrangement with respect /

respect to each other; the rock is grey in colour and is referred to as "grey hornblende gneiss".

III - Acid quartzo-felspathic gneiss with prominent pink potash felspar and referred to as "Pink Gneiss".

IV - Banded gneiss, the individual acid and basic bands varying in thickness from a fraction of an inch to several feet. Within this category are included some migmatitic variants where acid and basic components are not separated into distinct folia. Some migmatitic types show large augens of pink potash felspar.

V - Quartzo-felspathic veins and pegmatitic sheets, some of which contain coarse grains of pink potash felspar.

No attempt has been made to classify the basic rocks (Type IIA) into "Newer" and "Older" categories (cf. Sutton and Watson, 1951). Peach and Horne (1907,pp.262-263), however, made such a distinction in the present area and stated -

"On Glas Bheinn and Sgòrr a'Gharaidh the rock's consist of biotite-and hornblende-gneiss with bands of hornblende-schist, which evidently represent the basic dykes /

dykes in the unmodified areas of Lewisian gneiss in Ross and Sutherland, ... for many of them still show intrusive junctions. They also include a considerable development of early basic material, composed largely of garnet-amphibolite, and traversed by massive pink pegmatites, which are well seen on the hill-slope about a mile west of Slumbay and south of Sgòrr a'Gharaidh.

An important feature of this displaced mass is the occurrence in it of a massive sill of hornblende-schist, ... This type has been traced continuously from Cearcall Dubh, north-east of Loch Kishorn, south by An Sgòrr to Kyle Strome, and beyond Stromeferry to Gleannan Dorch, south of Duncraig."

The present author could not find any basic rock which showed "intrusive junctions" - such as chilled margins or discordant boundaries. The basic rocks, which occur as concordant sheets and lenses, share a foliation with the surrounding gneisses. Felspathisation is not confined to any particular type of basic rocks. The "massive sill" mentioned by Peach and Horne (op.cit.), part of which occurs in the present area, is garnetiferous, foliated and intruded by small bodies of pink pegmatite. The texture of this and the other basic rocks is metamorphic and no relic igneous texture could be detected in them.

Among /

Among the rock types listed above as forming the gneissic complex, the acid grey hornblendic gneisses (type II B) occupy the largest outcrop area. Pink quartzo-felspathic gneiss (type III) occurs in thin bands throughout the area, the largest exposure being just north-west of Drochaid a' Chadha. Banded and migmatitic rocks (type IV) are not common. They have been observed more frequently in localities north and south of Cearcall Dubh than in any other part of the gneissic outcrop. There are numerous sheets, lenses and pods of amphibolites and hornblende-schists scattered over the whole area. The largest basic body, the "massive sill" of Peach and Horne (op.cit.) represented by garnetiferous hornblende-schist, is about ½ mile long 150 yards wide and occurs just west of Loch na Caillich. There is every transition from one variety of rock to another in this gneissic complex. For example, the onset of migmatization of basic rocks is marked by the introduction of acid materials, the appearance of augen and lit-par-lit structures which gradually increase so that banded rocks result. This is possibly one of the processes responsible for the origin of banded rocks in the complex.

Most of the gneissic rocks are deformed. The acid and basic gneisses and their migmatitic variants show every transition to fine-grained, platy mylonites through /

through intermediate stages of laminated augen mylonites and mylonite gneiss which preserve part of the original gneissose textures. There have been several periods of cataclasis in the area, some of which possibly pre-date the isoclinal first folding, and some may be comtemporaneous with it (see page 97.). For example, some mylonitic rocks have formed at the cores of isoclines due to intense differential slip along axial plane. Some bands of mylonitic rocks have first linear (b_1) and planer(S_1) structures superimposed upon them and were, presumably, formed prior to the isoclinal fold episode. There is also evidence of strong differential slip, which possibly occurred before the period of isoclinal folding, along the Torridonian and Lewisian contact.

A notable metamorphic feature of the gneisses is the partial recrystallization and new mineral growth which followed granulitization. This constructive metamorphism, which also affects in varying degrees the Torridonian rocks, belongs to the same general phase as the first fold movements described later. Further, there is evidence of post-crystalline deformation, followed by partial recrystallization during the period of second folding.

The /

The petrographical features of the different members of the gneissic complex are presented in the following section.

(a) Ultrabasic Hornblendite (I)

The ultrabasic rocks form only a small proportion of the Lewisian complex in the area. They are monomineralic aggregates, composed entirely of hornblende and occur as small pods within the acid and basic gneisses (Fig.2.). The largest pod observed measures about 15 ft. x 8 ft., the maximum thickness being 5 ft.

The ultrabasic rocks are massive, with the hornblende crystals arranged haphazardly, or they have a rude foliation which is parallel to that of the surrounding gneiss. The hornblende crystals are usually very coarse (2 mm. x 1·5 mm.) and are free from inclusions. They show the following optical properties -

Pleochroic Scheme	Extinction Angle	R.I.
X = pale yellowish green		N_X = 1·656 ±·002
Y = green	$Z \wedge C = 22^\circ$	
Z = deep green		N_Z = 1·678± ·002
X < Y < Z		

The ultrabasic masses are sometimes injected by acid /

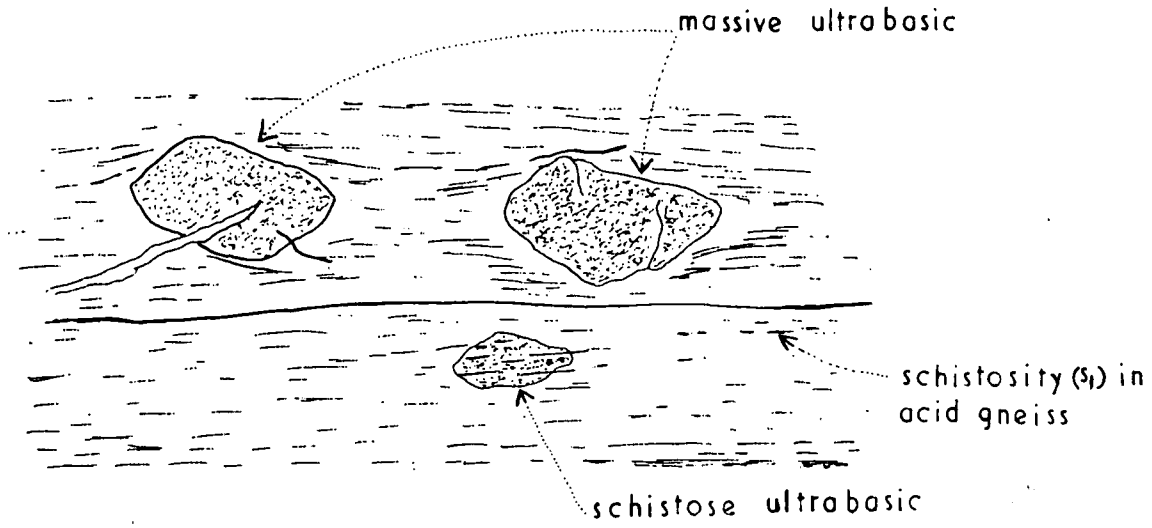


Figure 2. Ultrabasic pods in acid gneiss

acid quartzo-felspathic and pegmatitic veins. With increasing felspathisation a rock which approaches amphibolite in mineral composition is produced.

It has been often observed that the ultrabasic masses remain practically unmodified by the Caledonian shearing while the surrounding gneisses, particularly the acid varieties, are strongly deformed by differential slip. An excellent example of this phenomenon has been observed in an outcrop south of Sgùrr a'Gharaidh, where considerable differential movement has taken place along the contact between a lenticular ultrabasic mass, about 5 ft. in its thickest part, and the surrounding acid gneiss. The acid gneiss (c.f;- Plate XIII b,c) has been highly sheared while the ultrabasic rock shows no sign of deformation (Plate Xa), except that a few hornblende crystals may disclose slight undulose extinction.

The degree of deformation of the ultrabasic masses depends, to some extent, on their size. Some of the smaller bodies (about one foot or less in thickness) take up the stresses by the development of widely spaced, undulating shear planes which are usually coated with brownish limonitic materials. The coarse hornblendes become fractured and twisted and exhibit strained extinction. In some rocks a dimensional parallelism of deformed hornblende crystals /

crystals has been induced and indicates a schistose arrangement. This change in texture is accompanied by the development of a fibrous amphibole which has the same optical properties as the coarse hornblende from which it is derived (Plate Xb). The small fibrous amphiboles differ from the coarse stumpy hornblende in their slender prismatic habit. The schistosity of these ultrabasic rocks can be traced into the neighbouring acid and basic gneisses (type IIA and IIB) and is seen to be parallel to the axial plane of the isoclinal folds in the latter rocks. Small grains of secondary epidote, quartz and opaque ores are occasionally formed as a result of the partial breakdown of the coarse hornblende.

(b) Amphibolite and Hornblende-schist (IIA)

The basic hornblende-plagioclase rocks have been divided, according to structure, into two types namely, amphibolites, which are massive or only slightly schistose and hornblende-schists, which are distinctly schistose. The two types are often intimately associated and a basic body may be partly an amphibolite and partly a hornblende-schist.

The following mineralogical assemblages have been noted in the basic rocks -

(a)/

(a) Hornblende-plagioclase (oligoclase-andesine)-(quartz)

(b) Hornblende-plagioclase (oligo.-and.) - almandine-(quartz)

(c) Hornblende - plagioclase (oligo.-and.) - zoisite - (quartz).

Quartz may form a very small proportion of each of the above constituents or it may be absent.

The assemblages suggest that the rocks belong to the Amphibolite facies (Turner and Verhoogen, 1951, p.446). The rocks, when deformed, sometimes but not always contain unstable assemblages, such as, -

(1) Hornblende - tremolite - plagioclase - quartz

(2) Hornblende - almandine - Chlorite (after almandine) - plagioclase - quartz

(3) Hornblende - chlorite (after almandine) - plagioclase - quartz.

The common rock type is an amphibolite or hornblende-schist with hornblende, oligoclase-andesine felspar with or without a small proportion of quartz. Hornblende, the dominant constituent, occurs in very coarse prismatic grains about 2 mm. x 1·2 mm. in size. The optical properties of hornblende are as follows -

Scheme of Pleochroism	Extinction Angle	R.I.
X = pale yellowish green Y = green Z = deep green X < Y < Z	$Z \wedge C = 21^{\circ}$	$N_X = 1{\cdot}655 \pm {\cdot}002$ $N_Z = 1{\cdot}675 \pm {\cdot}002$

Hornblende /

Hornblende grains are idiomorphic, with ragged terminations and they may contain inclusions of quartz and sphene. Rarely, when the inclusions are numerous, the hornblende crystals exhibit "sieve structure" (Fig.3.). Plagioclase is usually cloudy in appearance and is frequently altered into a saussuritic aggregate of felspar and epidote or zoisite. The secondary epidotes occur as small needle-like crystals with a criss-cross or radiating arrangement within the altered plagioclase crystals. The presence of saussuritic patches impart a speckled appearance to some of the basic rocks. Plagioclase, when least altered, has been identified, on the following properties, as the oligoclase-andesine variety (cf:- Winchell, part I, 1956, p.262) -

Sp.No.	R.I.			Species of Felspar
	α	β	γ	
A.31	1·548	1·552	1·554	Acid andesine (An_{35})
A.87	1·545	1·550	1·553	Acid andesine (An_{32})
A.103	1·541	1·545	1·548	Oligoclase (An_{20})

Values of refractive indices(R.I.) are subject to a correction of ± ·001

Quartz, in small irregular grains, occurs in the interstitial spaces between other grains such as hornblende and /

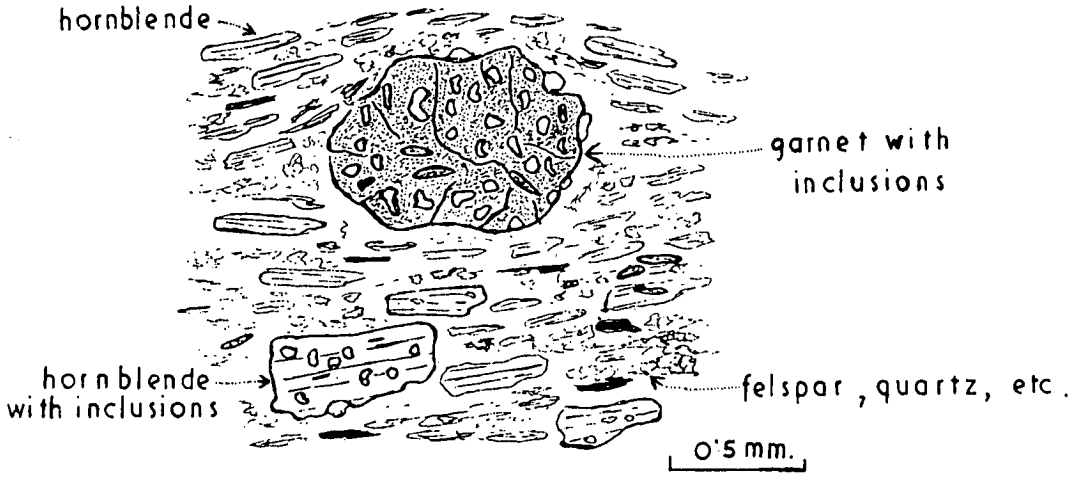


Figure 3. Occurence of inclusions of minerals (mainly felspars, quartz and sphene) in garnet and hornblende, simulating sieve structure. The rock is a hornblende-schist.

and plagioclase. Sphene, in lozenge-shaped stout crystals, is usually scattered in distribution. Iron ores are irregular in shape and in reflected light, some show silver-white leucoxinic alteration, suggesting that at least some ores are titaniferous. The proportion of sphene to that of iron ore varies inversely. The iron-ore is rare when sphene is frequent and vice versa.

Some basic rocks contain almandine garnet in addition to hornblende and plagioclase. The idiomorphic garnets are round in shape and are usually large in size - sometimes about 2 mm. in diameter. A few garnets exhibit porphyroblastic habit and also "sieve structure", due to the presence of numerous inclusions of quartz and sphene (Fig.3). The distribution of garnet in the rocks is irregular, the same basic body being garnetiferous in some parts but lacking the mineral in others.

Epidote - amphibolites are not common. In these rocks, epidote or zoisite occurs as stout prismatic crystals, which are sometimes intergrown with hornblende. Zoisite exhibits an ultrablue interference colour. The epidotes and zoisites are distinct from the secondary needle-like epidotes occurring in saussurites formed as a result of the alteration of plagioclases.

The /

The basic rocks are either schistose or coarse granular in texture (Plate Xl,a.). No relic igneous texture, such as blastophitic, has been observed in any of the rocks.

Most of the basic rocks have been subjected to processes of granulitization and mylonitization. Plate Xlb shows a highly sheared garnetferous basic rock collected from near the inverted Torridonian and Lewisian contact. The hornblendes are pulverized and reduced to a very fine grain size; garnets are remarkably flattened in appearance. The rock possesses a close-spaced platy lamination. It is possible that the highly sheared state of the rock is due to sliding connected with inversion.

The basic rocks, where involved in the first isoclinal folding, have undergone shearing along the axial planes of these folds. At the initial stages the shearing is indicated by the occurrence of coarse irregular shear planes subparallel to the axial planes of isoclines. The shear planes, which are usually coated with reddish-brown limonite, show a tendency to intersect with one another and thus to dissect the rock into lenticular segments. Hornblende grains are slightly bent and show moderate strained extinction. With increasing differential slip

along /

along shear planes the hornblendes are markedly twisted and fractured; cleavage planes are bent and strained extinction develops. Some deformed hornblendes are dragged into parallelism with the axial planes of the folds, while others occur with their longer dimension and parallel traces of prismatic cleavages at any angle to the axial plane. Both hornblende and felspar, notably the latter, show marginal granulation. Garnet is fractured and sometimes flattened in appearance. Felspars are usually altered into saussuritic aggregates of albite and epidotes. Narrow rims of pleochroic brown biotite appear around deformed hornblendes and also along cracks traversing the mineral.

The basic rocks, though showing effects of shearing, acted more resistantly to the deforming stresses than did the neighbouring acid gneisses. In a thin section (Plate XI,c), prepared from a specimen containing acid and basic bands, which are respectively 1 cm. in thickness, the contact betwen the two bands is denoted by a shear plane deeply coated with brownish limonitic material. The acid band has been converted into fine grained platy mylonite with a close spaced planar structure. The basic band, however, still retains its identity. It is traversed by a number of shear planes parallel to the mylonitic /

mylonitic banding in the adjacent acid band. The quartzo-felspathic constituents in the basic band have been completely mylonitized. The hornblendes are twisted and fractured, but still occur as recognizable stout crystals. Their prismatic cleavage traces may be disposed at any angle to the shear planes.

Rarely, a pale tremolitic amphibole which is distinct from the original deep green hornblendes in the basic rocks has developed in the sheared derivatives. A specimen of sheared basic rock, collected south of Glas Bheinn, shows a close-spaced schistosity and mineral lineation formed by the parallelism of prismatic amphiboles. The schistosity is parallel to the axial plane schistosity (S_1) of the adjacent acid gneiss and can be traced continuously from one rock type into the other. The mineral lineation is parallel to the fine striation lineation (b_1, - see p. 94) associated with the isoclines in the neighbouring acid gneiss. Though the narrow band of basic rock from which the specimen was collected does not show any minor isoclines, it is likely that their planar and linear arrangement, as in the acid rocks, has been produced during the phase of isoclinal folding. In the rock (Plate XII, a,b), tremolite needles are distinct from the coarse hornblende and the textural relationship suggests that tremolite has developed from hornblende.

The /

The two minerals have been identified by the following properties -

Scheme of Pleochroism	$Z \wedge C$	R. I.	Species
X = pale green Y = green Z = deep green	22°	N_x = 1·654 N_z = 1·676	Hornblende
X = very pale yellow (nearly colourless) Y = pale green Z = bluish green	16°	N_x = 1·600 N_z = 1·624	Tremolitic Amphibole

(Values of refractive indices are subject to a correction of ±·002)

Two sections cut perpendicular and parallel to the megascopic lineation suggest that the lineation is due to the parallelism of slender prismatic tremolitic amphiboles. The original green hornblendes, have been dragged subparallel to the tremolitic amphiboles to emphasize the lineation.

A linear alignment of long axis of bluish-green hornblende has been observed in an isolated outcrop of hornblende-schist south-west of Cearcall Dubh. The rock is essentially composed of hornblende, with minor amounts of plagioclase. The optical properties of the hornblende is /

is as follows :-

Pleochroic Scheme	Extinction Angle	R. I.
X = pale yellow Y = green Z = bluish green X < Y < Z	$Z \wedge C = 20^{\circ}$	$N_x = 1{\cdot}654 \pm {\cdot}002$ $N_z = 1{\cdot}675 \pm {\cdot}002$

A strong linear alignment, denoted by parallelism of prismatic crystals of unstrained hornblende, is visible. Two mutually perpendicular sections have been prepared from the rock. In the section (Plate XII, c) normal to the visible lineation most of the hornblendes exhibit their characteristic two sets of cleavages at 124° and in the section (Plate XII, d) parallel to lineation, elongate hornblendes show cleavage traces parallel to prismatic faces. The orientation is, therefore, optical as well as dimensional. The relationship between the structural events in the area and the period of formation of this particular hornblende lineation is not known. The hornblende-schist does not show any minor folds nor is there any exposure of other gneissic varieties in the immediate vicinity, which might have indicated some possible clue to the origin of this lineation /

lineation. Two possibilities, however, may be considered -

(1) The hornblende lineation is unrelated to the minor folds in the area and possibly pre-dates them. The long dimensions of the hornblendes are aligned E.S.E. parallel to the trend of the first linear structure in the Cearcall Dubh area. The parallelism may be due to a coincidence in trend of two unrelated structures. Alternatively the hornblende-schist bands containing the oriented amphiboles might have been rotated so that the hornblende lineation now parallels the trend of the first linear structure.

(2) The hornblende lineation formed during the period of first folding. The properties of the mineral indicate that though the refractive indices approach those of common hornblende, the absorption colours are much paler than those of deep green hornblendes which are common in other basic rocks in the area. It is possible that in restricted zones, temperature and pressure conditions have been appropriate to facilitate the growth of some bluish-green hornblendes during the phase of first folding.

Basic rocks involved in one or more phases of folding that post-date the first folds bear imprints of retrogressive action. This has been observed in basic bands occurring near Sgùrr a' Gharaidh and east of Cearcall Dubh/

UNIVERSITY OF EDINBURGH EX BIBL

Dubh. Hornblende is partially replaced by irregular patches of brown biotite and green chlorite, which develop along cleavages and cracks in the hornblende crystals. Chlorite also develops along cracks traversing garnets which it partially replaces. Rarely, the replacement is complete and a pseudomorph of chlorite after garnet is produced, which retains the oval shape and porphyroblastic habit of garnet. A few sphenes are present, in the manner of inclusions in the original garnet, in some pseudo morphs. The felspars in these rocks are much altered and their optical properties are difficult to determine. In a few thin sections a comparison of refractive indices of least altered felspars with that of Canada Balsam were made by Becke Test (cf:- Winchell, part I, 1949, p.78) as shown below -

Sp. No.	Comparison of R.I. with that of Canada Balsam (1·54).
A .175	R.I.< R.I. of Canada Balsam in both vibration directions.
A .169	Do.
A .11	Do.

The observations suggest that the felspars are albitic in composition. The mineralogical assemblages of the basic rocks, therefore, show every transition from Amphibolite /

Amphibolite facies to Green-schist facies through the intermediate stage of Epidote-Amphibolite facies (Turner and Verhoogen, 1951, p.433).

(C) Intermediate and Acid Gneisses (II B)

A grey coloured gneiss, usually containing some hornblende, is the dominant type of rock in the Lewisians in the area. Depending on the proportion of quartz, some of these rocks may be termed intermediate (quartz 40-60%) and others acid (quartz > 60%): There is every transition between these two varieties. The essential mineral constituents are quartz and felspar. Opaque iron ores and sphene are accessory. Hornblende, which is usually presemt in small proportion, is coarse (1·5 x 1 mm.), compact, and shows the following properties -

Scheme of Pleochroism	Extinction Angle	R.I.
X = pale yellowish green Y = green Z = deep green X < Y < Z	$Z \wedge C = 21^{\circ}$	$N_x = 1{\cdot}654 \pm {\cdot}002$ $N_z = 1{\cdot}676 \pm {\cdot}002$

The dominant felspar is oligoclase and it usually occurs in coarse grains (1-2mm.). A few coarse, pink-coloured K-felspars/

K-felspars (orthoclase or microcline or both) are present, especially in localities where pegmatitic sheets occur in the gneiss. Epidote, when present, occurs as stout idiomorphic crystals (·5 - ·8mm.) or as grains with irregular shape. These epidotes are quite distinct from small needle-like or granular epidotes produced by saussuritization of plagioclases. The rocks possess a schistosity which may vary from a vague planar orientation of mineral components to a well-defined close-spaced planar arrangement of the constituent minerals. The schistosity is parallel to the axial planes of isoclinal folds.

The acid and intermediate gneisses have been modified by strong differential movement within zones (shear belts) wherein the rocks have undergone mylonitization and granulitization. Outside these zones, the rocks are much less sheared. The changes undergone by the acid and intermediate rocks during mylonitization and granulitization can be divided into several stages and can be studied in a series of specimens as described below. It is to be noted, however, that the classification made is entirely descriptive and does not imply any time sequence.

Stage I - In the least deformed rocks the constituent minerals show a coarse granular arrangement. Gently curved planar structures are present, along /

along which tiny sericitic flakes occur (Plate XIII, a). Hornblende is slightly fractured and may be slightly strained. Felspars are slightly flattened in shape, with little or no marginal granulation. Quartz grains are broken into fragments, usually in the shape of elongate slivers which show strained extinction.

Stage II - In a more advanced stage of breaking down the more resistant hornblende and felspars assume a lenticular or "eye"-like shape and are set in a much finer grained matrix composed mainly of quartz (Plate XIII, b, c). Sericitic micas, indicative of neo-mineralization, frequently grow along the slightly curved planar structure (parallel to the axial plane of isoclines) which encloses the "eyes" of felspars and hornblende. Hornblende is fractured, its cleavage bent and the grains show undulose extinction. Patches of chlorite, biotite and granular epidote occur as alteration products along cracks traversing the hornblende grains. Felspars exhibit strong strained extinction, twisted twin lanellae and sometimes marginal granulation. Sometimes felspars /

felspars are altered into saussuritic aggregates of albitic plagioclase and needle-like epidotes. The matrix, which is composed of light coloured quartzo-felspathic materials, is reduced to a very fine size.

Stage III- Uncrushed relics, mostly felspars, occur as lenticular porphyroclasts in the comminuted matrix. The finely crushed quartzo-felspathic matrix has partly recrystallized to form an aggregate and clusters of interlocking grains, mostly quartz, with sutured margins. Sericitic micas occur in narrow bands which alternate with the recrystallized quartzose layers and define a close-spaced schistosity parallel to the axial planes of isoclinal folds. Elongate porphyroclasts of felspars and hornblende also emphasize this schistosity.

The recrystallized quartzes, which form elongate clusters (Plate XlV, a,b), define a fine striation lineation (first linear strudture, b_1, see page 94). Further, it has been observed in thin sections of isoclinal microfolds that recrystallized quartzes and newly developed sericites occur on the hinges as well as on the limbs of the folds - a feature which suggests that either these minerals /

minerals crystallized contemporaneously with the formation of isoclines or they developed mimetically after the isoclines were produced. The results of the microfabric analysis, which have been stated later (page 143), indicate that recrystallization of quartz occurred mainly during the phase of isoclinal folding.

Stage IV. This stage is represented by mylonites which are found in narrow zones within the Lewisian complex. In the mylonites most of the materials in the matrix have been finely comminuted and a few relatively large augens of felspars survive (Plate XV, a, b). The rock is platy, laminated and conforms to the description of "mylonite" by Lapworth (1885, p.559).

In some mylonitic rocks the finely comminuted quartzo-felspathic matrix has partially recrystallized (Plate XV, c.). Signs of the mechanical crushing to which the rock was subjected are borne by lenticular porphyroclasts of felspar which exhibit undulose extinction. Cataclastic rocks in which recrystallization has obscured the effects of mechanical deformation have been termed blasto-mylonite by Sander in 1912. (See Knopf, 1931, pp.12-13; also wee Waters and Campbell, 1935, pp.477-481). Mylonitic /

Mylonitic rocks in which recrystallization of the comminuted paste is practically complete have also been described as "Augen-schist" by Lapworth (1885) or as "Mylonite-gneiss" by Quensel (1916). The present author has used the term "blasto-mylonite" (cf. Knopf, op.cit.) for partially recrystallized mylonites of the area.

The exact period of formation of the mylonitic rocks in the area is not known. However, the possible timings of mylonite formation may be briefly discussed here on the basis of the results of structural analysis (see Sections III and IV). The mylonitic bands are folded by the second and third folds and must pre-date these folds in age. The widespread occurrence of planar (S_1) and linear b_1) structures of the first generation in the bands of mylonites in the Lewisian gneisses suggest that at least some mylonites existed before the phase of isoclinal first folding. As a rule, the mylonitic banding is parallel to the axial plane schistosity (S_1) of the gneissic rocks. From the south of the present area, Johnson (1960, p.149) has obtained evidence which suggests that some mylonites occurring in narrow zones have been affected by isoclinal folding and that the mylonitic banding has been transposed parallel to the axial planes of isoclines. The present author's observations (page 97), combined /

combined with Johnson's (op.cit.) account of the structure of the ground immediately to the south of the present area suggests that some mylonites in the area possibly existed prior to the isoclinal folding. Rarely, the present author has observed partially recrystallized blasto-mylonite in the core of isoclinal micro-folds, which may belong to the phase of isoclinal folding.

The Acid and Intermediate gneisses underwent some textural change during the second fold movements. Quartz grains have been stretched and dimensionally re-oriented in the axial plane cleavage, S_2, associated with the second folds (Plate V1). Some of the stretched grains show strained extinction, while others are recrystallized and disclose no sign of strain.

During the period of monoclinal and conjugate folding the gneisses suffered local cataclasis. In the immediate vicinity of the Kishorn thrust, it has been observed that the sheared gneisses have suffered a late cataclasis connected with thrusting (see page 134).

(d) Pink Quartzo-felspathic Gneiss (III)

The pink coloured quartzo-felspathic gneiss, unlike the grey acid and intermediate gneiss (type II B) described above, contains a considerable proportion of pink potash felspars (orthoclase and microcline). With the decrease /

decrease in amount of potash felspars, the pink gneiss grades into the acid grey gneiss. The pink gneiss also shares the schistosity of the grey acid gneiss into which it grades.

The pink gneiss has been deformed by differential slip and the stages of the deformation are similar to those described in connection with the grey acid and intermediate gneisses.

(e) Banded Gneisses (1V)

Banded gneisses, which include some migmatitic types, occur as bands, which measure from a few inches to several yards in thickness, within the grey and pink acid gneisses (types IIA and III). The gneissic banding of the rock, which is indicated by the alternate dark hornblende-rich layers and white quartzo-felspathic layers, is parallel to the foliation of the surrounding acid gneisses of more uniform composition. The migmatitic types have been commonly observed when the basic layers contain lit-par-lit veins and augen, most of which are pink K-felspar and perthite. Sometimes myrmekitic structure is present in the migmatitic rocks.

The features of deformation of the banded gneisses are similar to those described in connection with the basic (type IIA) and acid (type IIB) rocks.

(f)/

(f) Quartzo-felspathic veins and pegmatites (V)

Concordant quartzo-felspathic veins and lenses together with pegmatitic sheets, which possibly represent acid materials introduced into the complex, occur throughout the area. The pegmatites contain very coarse pink K-felspars, some plagioclase and quartz and, rarely, patches of green chlorite. Many of the pegmatites show evidence of deformation, including crushing of quartz and felspar grains. The stretched, eye-like felspars exhibit marked strained extinction. Some narrow (less than ½" thick) quartzo-felspathic veins are seen to be isoclinally folded and others are broken up by axial plane slip so as to form rods parallel to the axes of isoclines (Fig.10 d.).

Some quartzo-felspathic veins run discordantly through the rocks. The age of these veins is not certain.

(2) The Torridonian (Diabaig Group) Rocks

The Torridonian rocks under discussion occupy a roughly triangular area, approximately 3 square miles in extent, situated to the north-east of Loch Kishorn (Map 1). These rocks belong to the Diabaig group which represents the lowest number of the Torridonian succession as established in Skye, (Clough, Mem. 1907, p.349; and also Phemister, 1948, p.41). They consist of felspathic /

felspathic sandstones, grits (some of which are arkosic : felspar > 25%), dark shaly rocks, and few sandy shale bands. Gritty and shaly rocks near the overturned base of the Torridonian strata occasionally contain calcareous lenticles. The area contains three of four of the divisions of the Diabaig Group that were recognized by Clough (op.cit.); these are, the "Epidotic Grits", "Loch na Dal Beds" and "Beinn na Seamraig Grits".

The strata are inverted and dip gently eastwards beneath the Lewisian Gneisses. There is a close parallelism between the bedding planes of the Torridonian and the foliation of the gneisses, especially near the inverted junction between the formations, which is exposed at Cearcall Dubh. Westwards from this place and ascending the stratigraphical succession, the Beinn na Seamraig Grits dip eastwards in inverted order beneath the basal Epidotic Grits and Loch na Dal Beds. As is shown in Sections III and IV of this thesis, the Diabaig sediments, along with the Lewisian gneisses, have undergone at least three phases of movement subsequent to their inversion. The Torridonian sediments bear evidence of mechanical granulation and partial recrystallization (cf. Teall in Peach and others, Mem.1907, pp.278-290). In the following discussion of the Torridonian rocks emphasis has been given to the textural and mineralogical modifications of the sediments.

Part /

Part of the ground, from Cearcall Dubh westwards for a distance of up to ½ mile, has been included by Bailey (1955, fig.1) within the "biotite zone" of regional metamorphism in the N.W. Highlands. This zone, according to Bailey, represents the grade of metamorphism in inverted Torridonians in the Skye-Lochcarron region. Bailey (op.cit., p.143) reported the occurrence of greenish-brown biotites in deformed Diabaig rocks at Fernaig, which is about 5 miles south of the present area. The author has not observed greenish-brown biotites in the present area, in which the only metamorphic index mineral is chlorite.

Peach and Horne (Mem 1907, pp.342-347), adopting the classification of Diabaig Group by Clough (in Peach and others, Mem.1907, p.349), described the distribution and general petrographical features of the members of this Group in the region, which includes the present area, between Kishorn and Loch Alsh. Following the classification accepted by the Survey workers (Clough, op.cit.; Peach and Horne, op.cit.), the three sub-divisions of the Diabaig Group, which occur in the area, have been listed by the present author in their normal stratigraphical order in the following table

Table /

TABLE I.

- Succession interrupted by the Kishorn thrust.

3. BEINN NA SEAMRAIG GRITS

Grey and buff-coloured grits, sandstones (some are arkosic) and flags. Rare shale bands are impersistent. Thickness 1100 ft.

2 LOCH NA DAL BEDS

Dark greenish grey shales and grits with rare calcareous lenticles. Thickness. 330 ft.

1. EPIDOTIC GRITS

Greenish-grey or green epidotic grits. Thickness 50 ft.

? Basal Conglomerate.

The total thickness of the Diabaig rocks in the present outcrop, calculated geometrically, is about 1500 ft. which corresponds very closely to the aggregate thickness of the Epidotic Grits, Loch na Dal Beds, and Beinn na Seamraig Grits as estimated by Peach and Horne (Mem.1907, p.342) for the area between Kishorn and Loch Alsh. The author, however, considers that the thickness of the sediments is only apparent and does not represent their original thickness. The structural analysis (Section /

(Section III) of the present area, combined with the results of the recent investigation by Johnson (1960) in the adjoining area to the south, suggests that the inverted Torridonian rocks have been isoclinally folded. The strata, therefore, may have been tectonically much thickened.

The nature of the contact between the Torridonian and Lewisian formations is interesting. Peach and Horne (Mem.1907, p.343) have interpreted this contact as a substantially unmodified unconformity. The present author has observed highly sheared and mylonised rocks along the inverted contact which possibly has acted as a plane of differential movement and sliding. These differing views on the nature of the contact between the Torridonian and Lewisian formations will be discussed in more detail at the end of the present section.

The distribution and some aspects of petrographic features of the Diabaig rocks are described below.

(a) Epidotic Grits

The Epidotic Grits, which are apparently about 50 ft. thick, are exposed along a crag extending from Drochaid a' Chadha to Cearcall Dubh. The bedding of the sediments, which is indicated by compositional colour banding /

banding, dips eastwards at low angles (18° - 25°) beneath the Lewisian gneisses. The prominent megascopic planar structure of the grits is, however, a flaggy parting. The microscopic features described below suggest that the megascopic parting is a schistosity (S_1). Throughout the area, the parting is parallel to bedding. Mineralogically, the rocks are composed mainly of felspars, quartz and epidote. The proportion of felspars does not exceed 25%, both K-felspar (microcline and orthoclase) and plagioclase (oligoclasic) being present.

The grits bear the imprints of mechanical deformation (due to differential slip along axial planes of isoclines) and partial recrystallization. A close-spaced schistosity, the features of which are described later, is denoted by the alignment of the stretched out quartzo-felspathic constituents and by parallel narrow bands along which secondary sericitic micas have developed. The felspars, which are relatively large (1 mm. x .5mm.), are lenticular and they exhibit strained extinction and sometimes marginal granulation. The twin lamellae of plagioclase and microcline crystals are distorted. The stout epidotes (0·8mm.), which are scattered throughout the rock, are sometimes seen to be traversed by cracks and fracture planes and to display a strained extinction.

In /

In contrast to the felspars, the quartz grains seem to have yielded readily to deforming forces. The stages in the deformation and granulation of quartz grains can be studied in some rocks. In the initial stages of deformation, the quartz grains display strong strained extinction. Subsequently the grains break into slivers which result from a stretching of quartz crystals along the axial planes of isoclinal folds. The dimensional parallelism of the slivers and the development of platy sericitic micas (Plate XVll, a.b.) indicates the initiation of a widespread schistose structure, which is megascopically visible as a parting. Further, the alignment of the longest dimensions of slivers (Plate XVll, a,b.) produces a prominent striation lineation (b_1, see page 94) parallel to the axes of isoclinal folds. In some rocks tiny quartz grains, which have been affected by intense crushing and marginal granulation, are scattered through the matrix. The crushed quartz grains, acting as seed crystals, recrystallize and form aggregates of clear, unstrained, small (·05 - ·1mm.) quartzes. The individual grains in these aggregates have sutured margins. When recrystallization is advanced, the grain boundaries are straight and a secondary micro-crystalline mosaic of quartz grains has resulted. The narrow bands of micro-crystalline aggregates of quartz and parallel flaky sericites usually wind round eye-like prophyroclasts of relatively /

relatively large felspars and emphasize the schistose structure of the rock (Plate XVll, c,d.). Rarely idiomorphic crystals of magnetite occur, the porphyroblastic habit of which suggests that they are possibly secondary (cf:- Teall, 1907, p.286). A few secondary chloritic patches occur along the schistosity.

Near the contact with the overlying Lewisians, the Epidotic Grits are highly sheared and have a platy mylonitic appearance. All the constituent minerals, including the felspars, have been reduced to a very fine grain size. Likewise the Lewisian rocks immediately above the grits are extremely sheared and, particularly when they are epidote-bearing, the mylonitized gneisses are difficult to distinguish from the schistose grits.

(b) Loch na Dal Beds

The rocks of this sub-division dip eastwards below the Epidotic Grits along the crag extending from Drochaid a'Chadha to Cearcall Dubh. From Cearcall Dubh northwards, the Epidotic Grits are absent and the Loch na Dal Beds are in contact with the Lewisian gneisses.

The Loch na Dal Beds consist of grey and dark green shaly rocks and subordinate greyish felspathic sandstones and pebbly grits. The presence of thick shaly layers, the smaller amount of epidote and the occasional patches of carbonates /

carbonates distinguish the Loch na Dal Beds from the Epidotic Grits. Rarely, current bedding has been observed in the gritty bands which alternate with shaly rocks. The bedding and current-bedded layers are, however, distorted by folding and the original attitude of the current bedding could not be determined.

The rocks are deformed and schistose in appearance. The schistosity, like that in the Epidotic Grits, is defined by the parallel alignment of secondary sericitic micas and by bands of finely recrystallized quartz grains, as well as by the alignment of slivers of quartz. A few patchy chlorites occur along the schistosity. The clastic felspar grains (plagioclase, microcline and perthitic felspars), which are lenticular in shape, bear the imprints of mechanical deformation. A few randomly scattered muscovite flakes, which are distinct from the felted sericites, exhibit bent cleavage and strong undulose extinction and are possibly clastic grains of the sediments. Quartz grains are usually ruptured into elongate slivers, the longest dimensions of which are aligned parallel to a magascopic lineation (b_1). With the advance of recrystallization the quartz is found in small clusters which are elongated parallel to the visible lineation.

Near the contact with the Lewisian gneisses, the Loch /

Loch na Dal shales are much sheared and are platy, laminated in appearance. In some crushed rocks, individual mineral grains are difficult to distinguish.

(c) Beinn na Seamraig Grits

The Beinn na Seamraig Grits outcrop in the ground between the Allt Mòr and the Allt an t-Sratha Fhuair, below the crags at Cearcall Dubh. South of the Allt an t-Sratha Fhuair, the rocks are mostly concealed by fluvio-glacial drift. Near Tornapress, the rocks of this division are terminated by the Kishorn thrust, the outcrop of which follows the Allt Mòr. The bedding planes, which dip gently eastwards, are indicated by compositional colour banding as well as by narrow (less than 1" thick) bands of heavy minerals (irregular clastic grains of opaque ores, epidote, sphene). The rocks of this division rarely exhibit tightly appressed sedimentary folds formed due to intraformational slumping (Fig. 4.). It is interesting to note that in the example cited the orientation of the slump structure with respect to bedding suggests that the strata are inverted.

The rocks bear imprints of strong mechanical deformation. The felspars exhibit undulose extinction and twisted twin lamellae. The quartz grains show strained extinction /

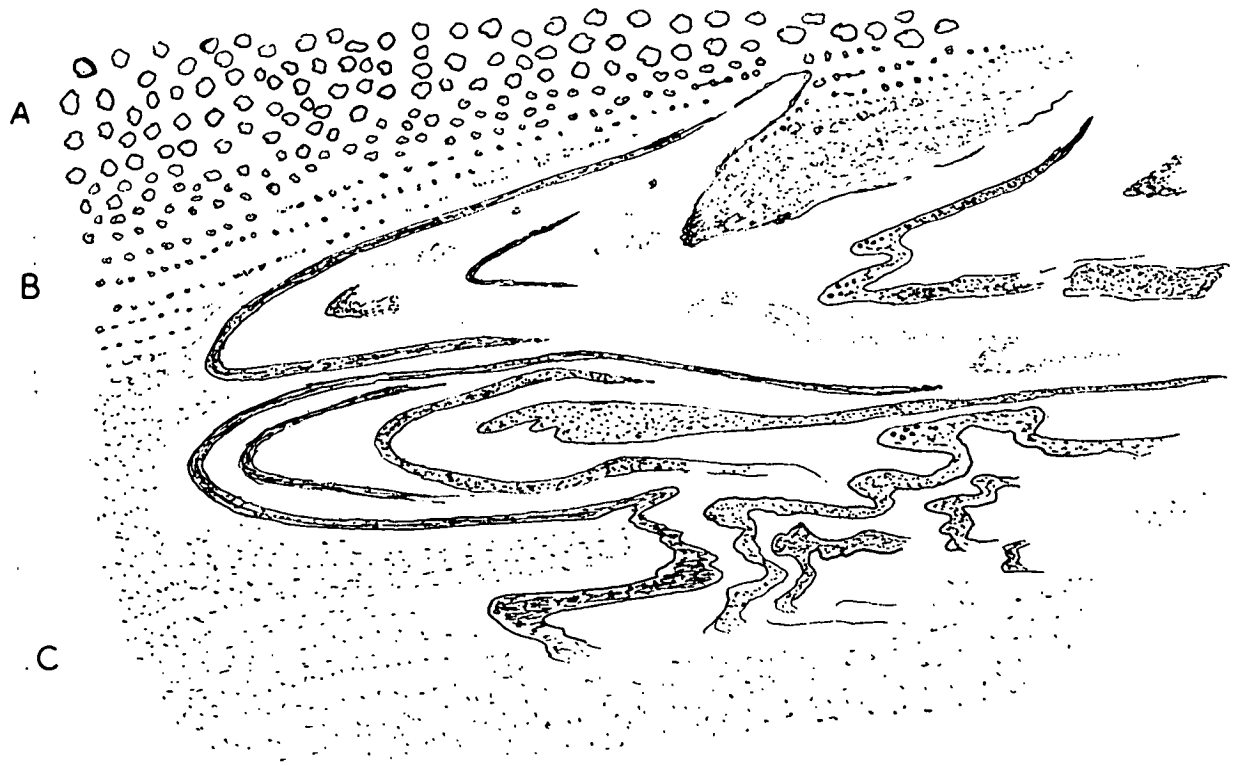


Figure 4. Profile of fold structure formed by slumping in Torridonian rock.

A- coarse grained layer

B- medium grained layer

C- fine grained layer

extinction, and may have broken into elongate slivers. Secondary thin felts of sericites occur in narrow bands and together with the stretched quartzo-felspathic materials emphasize a schistose arrangement.

North-east of Tornapress, just above the Kishorn thrust, the grits are highly crushed and transformed into cataclasite, and are profusely stained with haematite (page 133).

(3) The Torridonian-Lewisian Contact

The nature of the Torridonian-Lewisian contact calls for some discussion. Peach and Horne (Mem.1907, p.343) regarded this contact as a substantially unmodified unconformity. They observed that in the ground north of Loch Carron the lower beds of the Diabaig Group (the Basal Conglomerate and Epidotic Grits) are frequently absent and in consequence the Loch na Dal Beds are in contact with the Lewisian gneisses. The Basal Conglomerate, which is sheared and partially recrystallized, is well developed and easily recognizable at Fernaig, about 5 miles south of the present area. Regarding the present area, Peach and Horne (op.cit.) made the following statement -

"In Glenmore, about two miles east of Courthill House, Kishorn, a small exposure of epidotic grit is visible /

visible at the roadside ..... Northwards. the dark shales (Loch na Dal) are in contact with the Lewisian gneiss, and at Cearcall Dubh a local conglomerate appears in that position, the epidotic grits and Loch na Dal shales both being absent."

Peach and Horne (Mem. 1907, p.343) attributed the non-appearance of the basal rocks of the Diabaig Group over most of the ground north of Loch Carron to the unevenness of the Lewisian floor on which the Torridonian sediments were laid down. They considered that the general parallelism of the planar structure between the Torridonian and Lewisian rocks was produced by the development of new divisional planes in the Lewisians (Peach and Horne, op. cit., p.471 and p.566). Johnson (1960, p.145), however, suggested a different interpretation for the same contact and stated as follows -

"..... the general parallelism of structure was produced by the rotation and dragging into alignment of the originally discordant bedding and foliation planes. This is supported by the fact that it is the <u>compositional</u> banding of the Lewisian rocks that lies parallel to the Torridonian bedding. Furthermore, the intensely sheared condition of the Lewisian rocks near their contact with the Torridonian rocks indicates considerable differential slip movement which may have locally obliterated the original unconformity /

unconformity. The Basal Conglomerate and Epidotic Grits may have been sheared out in the process."

The evidence obtained in the present area strongly favours the interpretation suggested by Johnson (op.cit.). It has already been mentioned that the Epidotic Grits and Loch na Dal rocks are highly sheared and reduced to a very fine grain size near this contact. These highly sheared Torridonians do not exceed 15 ft. in thickness at any place, but are present throughout the exposed contact. The Lewisian gneisses in the immediate vicinity (within about 10 ft.) of the contact are also very highly sheared. Two specimens of sheared gneiss may be cited here. The first is a platy, laminated basic rock, collected at the contact, in which most of the constituents are reduced to a fine pulverized state and the garnets are remarkably stretched (Plate XI,b). The second is a laminated augen-gneiss which was collected at the contact on Cearcall Dubh. In this rock the only recognizable constituents are porphyro-:clasts of felspar and epidote; the rest of the constituents of the rock have been completely rolled out to a rock flour (Plate XV a,b.).

A point of further interest is that the present author could not identify the "local conglomerate" recorded by Peach and Horne (Mem.1907, p.343) at Cearcall Dubh. It is known (cf. Teall in Peach and others, Mem.1907,p.273; Horne/

Horne, Mem. 1907, p.343) that the Torridonian basal conglomerates in the N.W. Highlands usually contain pebbles of various types of the nearby epidotic Lewisian gneiss. When a conglomerate, composed largely of gneissic materials, is subjected to strong shearing the metamorphosed product may be virtually indistinguishable from the parent gneissic rocks which are undergoing the same changes. At Cearcall Dubh, the only rock that bears some resemblance to a "conglomerate", occurs in an isolated outcrop (10 ft. x 3 ft.) which is situated near the line of contact. No recognizable grits or gneisses are exposed in its immediate vicinity. The highly sheared and partially recrystallized rock contains a few eye-like grains of quartz and felspar (Plate XV.,d), the largest of which measure about ½" along its longest dimension; no rock fragments could be recognized. The texture of the rock is schistose. Whether the quartz and felspar grains represent original pebbles now occurring as "porphyroclasts" in a metamorphosed sediment is problematical. Sheared and partially recrystallized augen-gneisses (the identities of which are beyond doubt because they can be traced continuously into less deformed gneisses) /

gneisses) are exactly similar in texture and mineralogy to the rock described above. For example, Plate XV,c depicts a modified augen-gneiss, collected near Loch na Caillich, about ¼ mile east of Cearcall Dubh from within the Lewisian outcrop which is remarkably similar to the so-called conglomerate.

(4) Metamorphic Episodes in the Lewisian and Torridonian Rocks.

The metamorphic episodes in the Lewisian and Torridonian rocks described in the previous sections have been summarised in the following table in which an attempt has been made to correlate these episodes with the structural events which are discussed later.

TABLE /

TABLE II

Rock Types	? Early Phase of differential slip	Period of 1st Folding	Period of 2nd Folding	Period of 3rd Folding
Ultrabasic rocks	no evidence	Granulation of hornblendes. ? Growth of fibrous amphibole from hornblende	no evidence	no evidence
Amphibolite and Hornblende-schist	?Mylonitization	Granulation of hornblende, felspar, garnet. Tremolite developed from green hornblende. ? Development of some bluish green hornblende	no evidence	cataclasis; chloritization of garnet; formation of chlorite and biotite from hornblende
Intermediate Acid grey gneisses; Pink quartzo-felspathic gneiss: Pegmatites	?Mylonitization	Mylonitization; subsequent partial recrystallization of quartz; development of sericite; secondary epidotes formed by break-down of felspars	Post-crystalline straining of quartz and its subsequent recrystallization.	cataclasis of previously recrystallized quartz.
Torridonian (Diabaig) rocks	?Mylonitization	Granulation of quartz, felspar and epidotes; partial recrystallization of quartz; development of sericite, chlorite, and few magnetites	Post-crystalline straining of quartz. No evidence of recrystallization	cataclasis.

C. Rocks lying below the Kishorn thrust plane.

(1) General Statement -

The outcrops of the Torridonian (Applecross Group) and Cambro-Ordovician sediments that lie structurally below the Kishorn thrust stretch from Loch Kishorn northeastwards to Meall an Daimh (Map 1). West of the An Gorm Loch a narrow strip of strata, which consist of Applecross grits overlain by Cambrian quartzites, lie below the Sole thrust and belong to the unmoved Foreland. The Torridonian (Applecross) and Cambro-Ordovician rocks occurring between the Sole and Kishorn thrusts have been involved in folding and thrust-faulting during the post-Cambrian movements. East of the outcrop of the Sole thrust, the stratigraphic relation of the Cambro-Ordovician and Torridonian strata is often no longer normal. A succession of thrust planes and folds, with a general N.N.E. - trend, repeat the outcrops of the two formations and give rise to a rapid alternation of parallel bands of Cambrian and Torridonian rocks.

Despite the large scale folding and thrusting the rocks between the Sole and Kishorn thrusts have suffered very little internal deformation. Their mineralogical and textural features are usually unaltered and are like those of the sediments belonging to the unmoved /

unmoved Foreland. It is only in the immediate vicinity of the thrust planes, particularly the Kishorn thrust, that the sediments have undergone some textural modification due to mechanical granulation.

The detailed petrographic and palaeontological features of the Applecross and Cambro-Ordovician sediments have been described by the Survey geologists (Hinxman, Mem. 1907, pp.269-277 and pp.334-339; Peach and Horne, Mem. 1907, pp.363-387) and for the present discussion it is only necessary to give a brief account of the different rock types and to comment on their deformation.

(2) Applecross Group

The Applecross Group constitutes the middle sub-division of the Torridonian formation, the upper and lower sub-divisions being the Aultbea and Diabaig Groups (cf:- Mem. 1907, p.274).

The Applecross rocks in the present area are composed of medium to coarse grained (·8 - ·2mm.) chocolate and red arkoses, sandstones and grits, with pebbles of quartzite, quartzo-felspathic rocks, jaspers etc. Their red colour is due to the occurrence of thin rims of iron-oxide coating the individual quartz and felspar grains. The principal mineral constituents of the rocks are sub-angular grains /

grains of quartz, alkali-felspars (orthoclase and microcline) and plagioclase (oligoclase-albite) which are set in fine matrix. A few muscovite flakes occur.

The sediments have suffered mechanical deformation near the N.N.E. trending major thrusts and minor faults. A thin section of a rock collected just north-west Loch Cadh' an Eididh and below a major thrust, showed that the felspar and more especially the quartz, grains exhibit strained extinction and rarely, marginal granulation (Plate XVlll,b). The twin lamellae of microcline and plagioclase felspars are slightly distorted. Along microscopic fracture planes some red iron materials have penetrated into the rock. Another specimen from the same grit band and about 10 ft. above the clean-cut thrust plane is entirely undeformed (Plate XVlll,a.).

(3) Cambro-Ordovician Rocks

Except for a narrow band of quartzites below the Sole thrust, the Cambro-Ordovician rocks of the area have been involved in folding and thrusting. Strata have been repeated and frequently the normal order of succession of the members of the Cambro-Ordovician formation has been reversed. Although no complete and undisrupted succession of these rocks can be traced in the present area, the members /

members of the formation, with notes on their main features are listed below in their normal order, as established by the Survey geologists (cf:-Horne, 1907, pp.365-366) in the undisturbed areas in the N.W.Highlands.

T A B L E III

Rock Types	Chief Features	Distribution
Eilean Dubh Group	Fine-grained, white and lilac flaggy limestones. Some are dolomitic and effer-:vesce very feebly with dil H Cl.(25%). Sp.Gr.ranges from 1·72 - 1·81. Thin bands of sandy materials occur and stand out as ridges on weathered surfaces. Some-:times cherty bands, varying in thickness from a few inches to one foot, occur within limestones. Chief minerals of lime-:stone rocks are carbonates, some quartzo-felspathic materials and a small proportion of white micas.	The Eilean Dubh and Ghrudaidh limestones occupy an area about 4 miles long, ¾ miles wide between Loch Kishorn and Coille Dubh.
Ghrudaidh Group	Fine-grained dark limestones, some of which are dolomitic and effervesce feebly on treatment with dil. H Cl (25%). Sp.Gr. ranges from 1·82 - 1·85. Mainly composed of carbonates which are dotted with dark inclusions and few quartz and felspars. Narrow cherty bands sometimes occur	

TABLE /

TABLE III(Continued)

Rock Types	Chief Features	Distribution
Serpulite Grits	Quartzites and grits, grading upwards into dolomitic grit. Sometimes contain worm-casts and burrows at high angles to bedding.	Serpulite Grits and Fucoid Beds occur in narrow bands, often repeated, north of Torr na h-Iolaire. Glas Bheinn and Sgùrr a' Gharaidh. Other exposures are near Courthill House and Rassal
Fucoid Beds	Dolomitic shales, mudstones weathering with a rusty colour. The limy bands effervesce strongly with dil. HCl (25%). Frequently contains worm-casts which resemble fucoidal markings and appear flattened on bedding plane.	
Pipe Rock	Medium to coarse grained, compact quartzites often containing some felspars. Exhibit vertical worm-casts and burrows ("pipes").	A narrow undisturbed band of Basal quartzite overlain by Pipe Rock occurs below the Sole Thrust west of An Gorm Loch and Meall an Daimh to the east, several N.N.E. trending outcrops of quartzite alternate with those of Applecross Grits. Bands of Quartzites are exposed north of Sgùrr a'Gharaidh and Glas Bheinn. A narrow outcrop occurs ½ mile east of Courthill House.
Basal Quartzite	Medium to coarse grained quartzites, usually false-bedded. Composed mainly of quartz and subordinate felspars. Rarely, flaggy grits, not more than 2 ft. in thickness, alternate with quartzites. Near the base (as seen in the undisturbed area below the Sole thrust) the quartzite is coarse, conglomeratic with Sub-angular pebbles of quartz and felspars.	

The /

The Cambro-Ordovician rocks, though involved in folding and thrusting, are unmodified sediments except in the immediate vicinity of the thrusts, where the style of deformation is cataclastic, with evidence of crushing and incipient shearing. Strong cataclasis has affected the rocks occurring just below the Kishorn thrust.

The unmodified quartzites of the area are composed of an equigranular, medium-sized mosaic (0·5 - 0·8mm.) of quartz grains, with subordinate felspars (microcline and others) and some randomly scattered white mica flakes. The shape of the quartz grains vary from nearly oval to irregular and angular (Plate XlX,a). The onset of cataclasis, which is shown by a rock (Plate XlX,b) collected about 10 ft. below the Kishorn thrust north of Glas Bheinn, is marked by the flattening of grains and their strained extinction. A few grains show deformation lamellae (Fairbairn, 1949, pp.13-17) which are denoted by parallel rows of cavities that are sometimes filled in by opaque inclusions. The wave of strained extinction passes nearly normal to the trace of the lamellae. There is some granulation along grain boundaries and along narrow zones (·5 - 1mm.) that cut the rock. A more advanced degree of crushing is evidenced by a specimen of quartzite (Plate XlX,c) collected immediately below an exposure /

exposure of the clean-cut Kishorn thrust in a stream north-east of Glas Bheinn. In section the rock discloses intense ruptural breakdown and granulation of the quartz and felspar grains which have been mostly rendered so fine by crushing that frequently the individual crystals cannot be distinguished. A few clusters of coarser grains occur; they are highly strained. The rock is traversed by narrow vein-like strings of carbonates and reddish iron staining occurs along irregular cracks.

Features of mechanical deformation, similar to those described above, have been observed in Serpulite Grits that are exposed below the Kishorn thrust. The Fucoid Beds and the Eilean Dubh and Ghrudaidh limestones are traversed by narrow, intersecting joints and fracture planes which are now filled in with carbonates and quartz.

SECTION III - MEGASCOPIC STRUCTURAL DATA

A. General Statement

Structurally the area can be divided into two main units (cf. Fig. 5):-

(1) Lewisian and Torridonian (Diabaig Group) lying above the Kishorn thrust plane.

(2) Torridonian (Applecross Group) and Cambro-Ordovician rocks, occurring below the Kishorn thrust plane. A section of these rocks, situated below the Sole thrust, which structurally underlies the Kishorn thrust, belongs to the Foreland undisturbed by the post-Cambrian movements. The rocks that occur between the Sole and Kishorn thrusts have been affected by the post-Cambrian movements and constitute a zone of dislocation.

Above the Kishorn thrust plane, the Torridonian and Lewisian rocks occur in inverted stratigraphical sequence and there is a remarkable parallelism between the foliation of the Lewisian gneisses and the bedding planes of the Torridonian sediments, which dip at moderate angles to the E.S.E. A study of the Geological Survey maps (sheet/

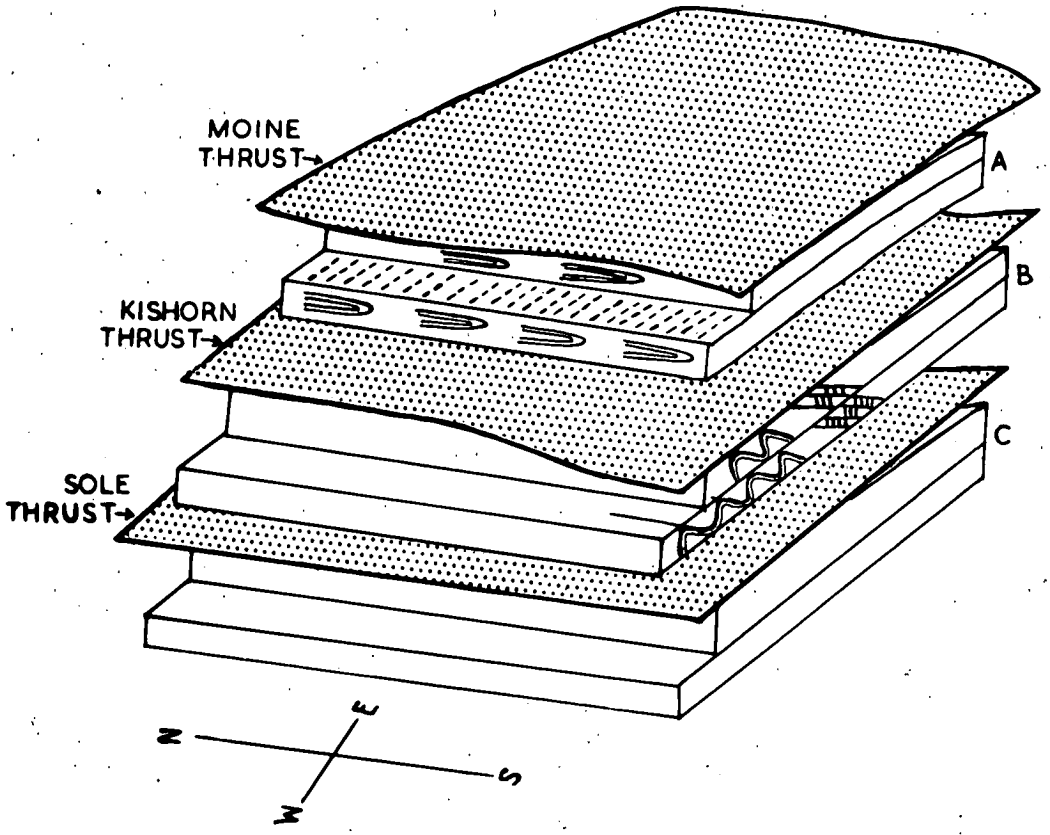


Figure 5. Diagram showing the main structural units of the Kishorn–Lochcarron area.

A. Lewisian and Torridonian (Diabaig) rocks.

B. Torridonian (Applecross) and Cambro–Ordovician rocks.

C. Undisturbed Foreland.

(sheet nos. 81,82 and 71) shows that the stratigraphical inversion of the Torridonian and Lewisian rocks extends southwards from Lochcarron to the eastern part of Skye and forms the inverted limb of a major fold,"the Loch Alsh Syncline" (Peach, et al, Mem. 1907; Bailey,1955). The fold with a N.N.E. - S.S.W. axial trend, is thought to close to the south-east (Bailey, op. cit). The normal uninverted limb of the fold can be well observed at Loch Alsh but northwards, at Lochcarron, the rocks outcropping belong entirely to the overturned limb. It is possible that the general parallelism of structure at Lochcarron was produced by the rotation and dragging into parallel alignment of the originally discordant bedding of sediments and foliation of basement rocks during the formation of Loch Alsh syncline. It is significant to note in this connection that there is evidence of strong differential movement at the contact region between the Torridonian and Lewisian rocks (see page 73). Johnson (1960), working just south of the present area made a similar observation and suggested that two possible types of movement may produce the parallelism of foliation in the formations: "Firstly, the Lewisian and Torridonian rocks underwent a phase of folding, the Lewisian rocks occupying/

occupying an anticlinal fold core. Secondly, the Lewisian represents a thrust slice which has been driven over the Torridonian rocks" (op. cit., p. 145). The parallelism may be a combined effect of the two processes suggested above, because it is well known that a fold may pass into a thrust fault and vice versa.

While the consideration of foliation and bedding planes of the Lewisian and Torridonian rocks gives the impression of a relatively simple structure, the minor structures (that is, minor folds, lineation, axial planes of minor folds, cleavage, etc.) in these rocks disclose a complex structural history. Four sets of minor folds and their associated structures, have been recognized by their distinct style, orientation and by their mutual relationships. Their history of development indicates that the rocks above the Kishorn thrust place have undergone at least three phases of movement, each phase probably being separated from the following one by some time interval. Further, it can be suggested that the style of early deformations was plastic and para-crystalline, whereas that of the later deformations was mainly brittle and post-crystalline.

In the area below the Kishorn thrust, there are several thrust planes which dip at moderately steep angles /

angles to the E.S.E. The most westerly of these N.N.E.-S.S.W. trending thrust planes (and, therefore, structurally the lowermost member) is the Sole thrust (Maps 1 and 2). The rocks outcropping west of the trace of the Sole trust have not been disturbed by the post-Cambrian movements and belong to the Foreland. The small section of the unmoved Foreland which has been mapped by the present author consists of Torridonian (Applecross) grit succeeded unconformably by the Cambrian quartzites; the rocks of both formations dip gently to the E.S.E. The Torridonian (Applecross) grits and Cambro-Ordovician quartzites, grits, mudstones and limestones which outcrop between the Sole thrust and the Kishorn thrust have been involved in the post-Cambrian movements. In this region, termed the 'zone of dislocation', the rocks usually dip at moderate angles to the S.E. and have been repeated by folding and thrusting on a large scale. The major folds have a N.N.E.-S.S.W. axial trend and the thrust planes dip moderately steeply to the E.S.E. Minor folds, though not common, have been recorded. The mutual relationships of the major folds, the thrusts and the minor folds have been investigated. The textural characters of the rocks in the zone of dislocation suggest that they have suffered local cataclastic deformation, especially in the immediate vicinity of thrust planes.

The /

The Kishorn thrust which is a major structural feature in the area is well exposed as a clean-cut fracture at several localities. The nature of the thrust plane and that of the rocks in the immediate vicinity is described in a later part of this section.

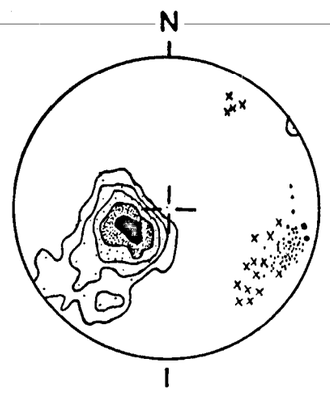
B. Megascopic Structures above the Kishorn thrust plane

The structural investigation of the rocks lying above the Kishorn thrust plane is based on the mapping of the main rock types and the measurement of the orientation of foliation, bedding planes, linear structures, cleavage and axial planes of minor folds. For detailed analysis the area has been divided into 14 sub-areas, for each of which the foliation, fold axes and associated linear structures have been plotted separately (Fig.6).

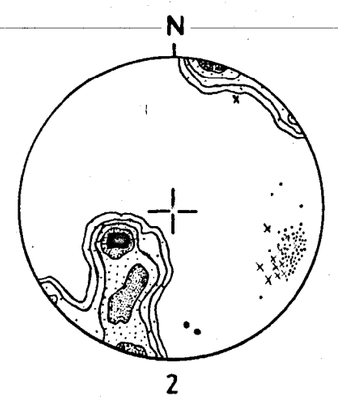
The predominantly gentle E.S.E. dip of foliation and bedding planes over the area is shown on a stereonet by the strong concentration of their poles (Fig.7). In addition some foliation and bedding plane poles are spread to form a girdle whose axis plunges at moderate angles to the E.S.E./S.E.

The attitude of the foliation planes can be assessed in more detail by considering the diagrams which show/

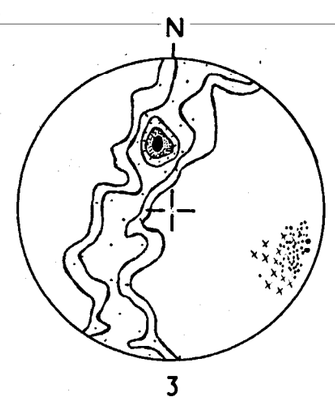
STRUCTURAL ANALYSIS: DIAGRAMS OF POLES TO FOLIATION PLANES, FOLD AXES AND LINEATIONS



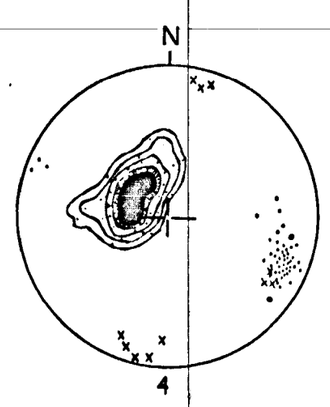
1



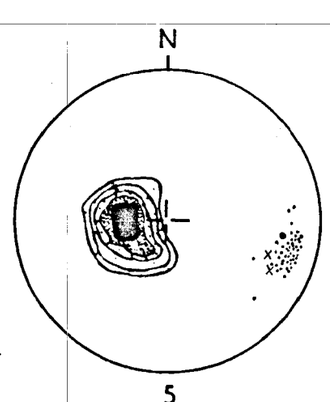
2



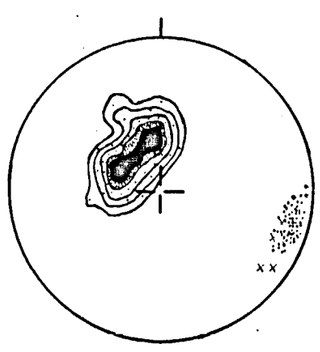
3

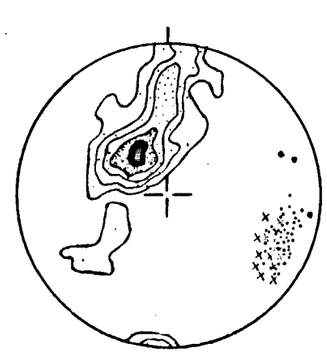


4

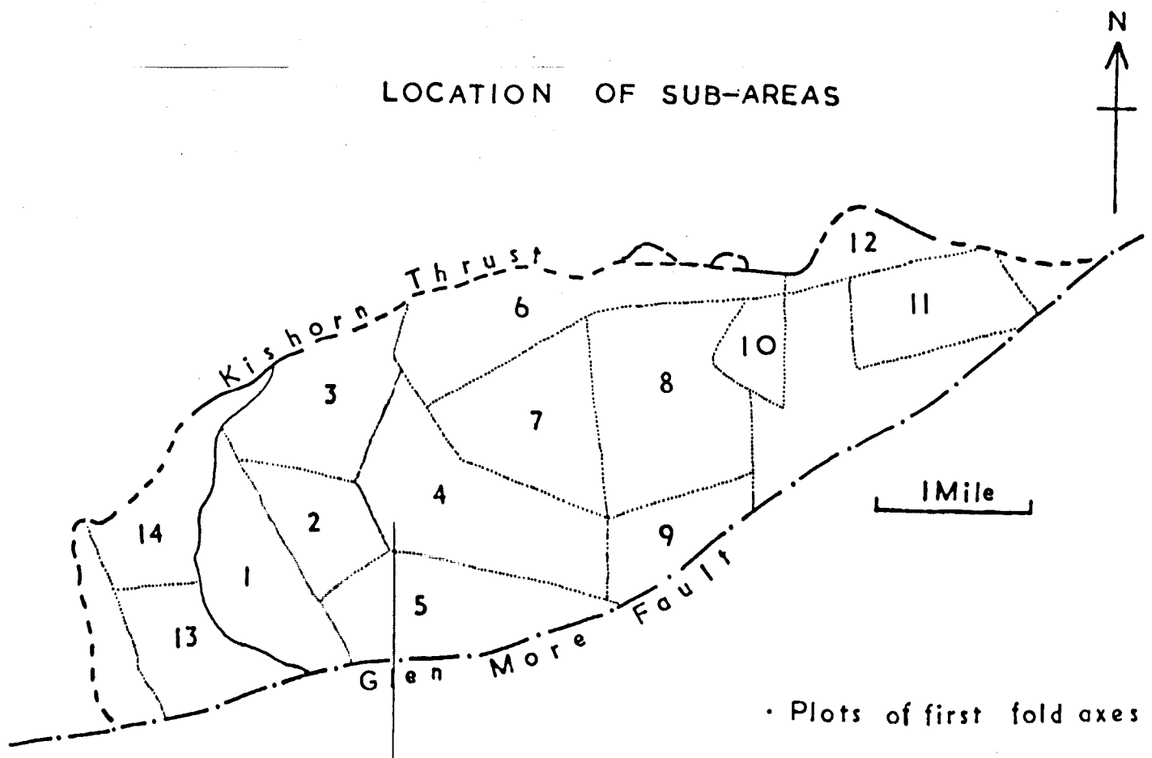


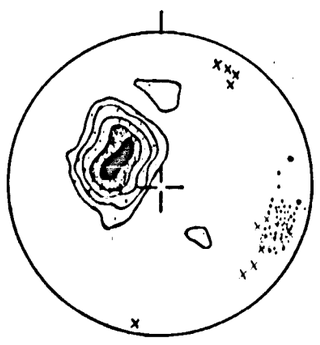
5

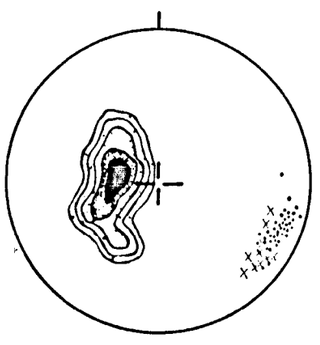

6


7

LOCATION OF SUB-AREAS

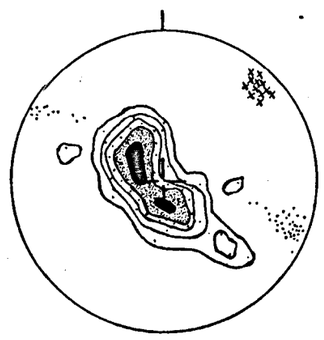


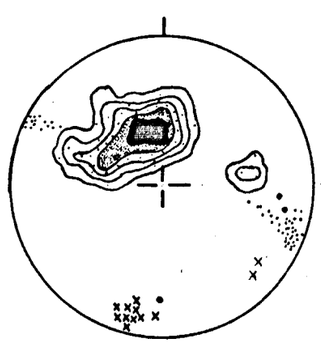

8

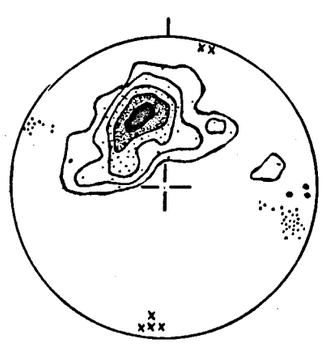

9

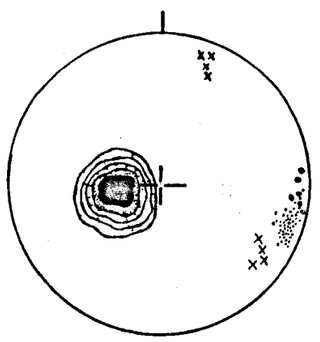
- Plots of first fold axes and lineations
x Plots of second fold axes and lineations
• Plots of third fold axes
x Plots of fold axes and lineations of uncertain age

Poles to foliation planes contoured
Contours at 1-3-6-9-15%


10


11


12


13

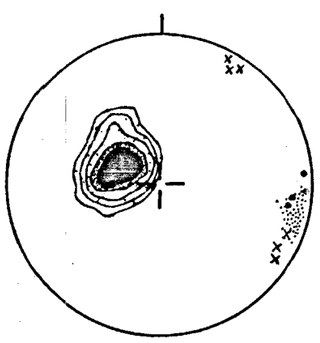

14

FIGURE. 6.

show the structural geometry of the sub-areas (Fig.6). In sub-areas 4,5, 8, 9, 13 and 14 (op. cit). the gentle eastward dip of the foliation and bedding is emphasised by the strong maximum in the diagrams. As will be shown later the regular dip of the foliation corresponds to the dip of the limbs and axial planes of the first isoclinal folds which are numerous in these sub-areas. In a few sub-areas (1,2,3,10,11,12 in Fig.6) in the Lewisian outcrop the poles to the foliation scatter to form partial or complete girdles. The rocks in these sub-areas have been affected by the second or third folds or by the "folds of uncertain age" which have been super-:imposed on the first isoclinal structure. These features will be further discussed while considering the different minor fold systems.

The minor structures can be grouped, on the following criteria, into distinct generations -

(a) structures of similar style and pattern of orientation are likely to be of the same generation.

(b) structures of one style and one pattern of orientation overprint and distort structures of another style and another pattern of orientation.

(c) structures belonging to different sets may have similar/

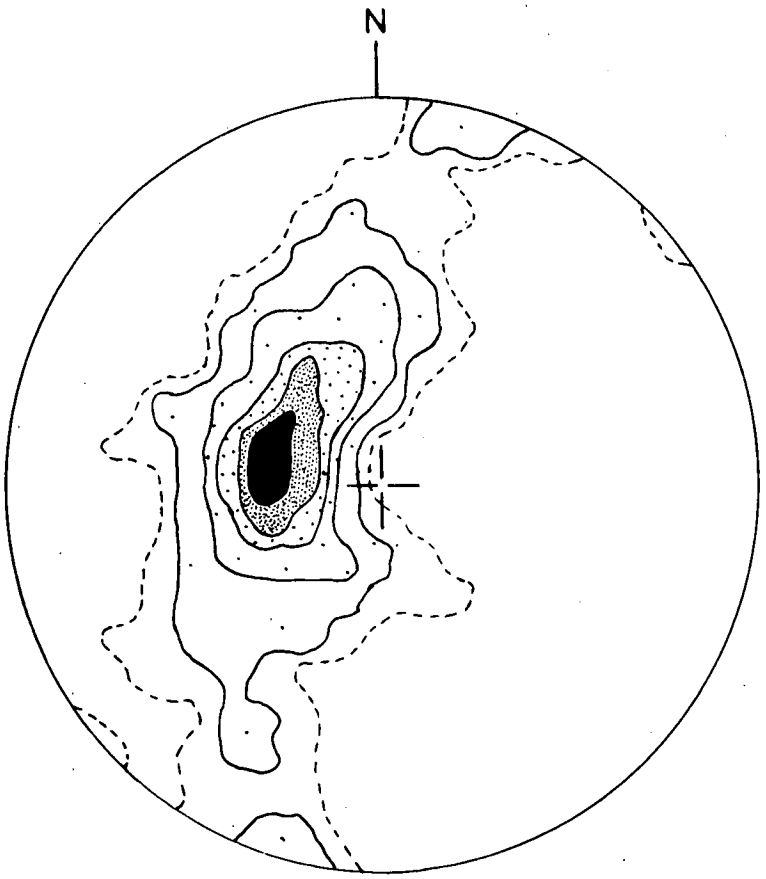


Figure 7. 1500 poles to foliation and bedding planes in rocks above the Kishorn thrust.

Contours at (½)-1-3-6-9-15 per cent.

similar pattern of orientation (such as two co-axial but different fold systems) but they differ in style.

Four sets of minor structures, which differ in their style or orientation or both, have been recognised in the Torridonian and Lewisian rocks. Of these, three sets can be arranged in their relative order of development and they have been termed structures of the first, second and third generations respectively. Another set, which possesses a distinct style and orientation, is certainly later than the first set of structures, but its relationship with the second and third sets is not apparent. The structures belonging to this set have been termed "Structures of Uncertain Age". Consideration of the minor structures suggest that the Torridonian and Lewisian rocks, together with the mylonitic rocks derived from them, have undergone at least three phases of movement.

When all the minor fold axes and their associated linear structures measured over the whole area are plotted collectively on a stereonet they form a strong maximum which plunges to the E.S.E. down the dip of the foliation of the rocks (Fig.8, e,f.). A sub-maximum trends N.N.E.-S.S.W. The remaining poles to linear structures form a girdle, the plane of which dips gently to the E.S.E. sub-parallel to/

Figure 8. Plots of linear structures in Lewisian and Torridonian (Diabaig) rocks.

a. 350 first linear structures.

b. 100 second linear structures.

c. 200 third linear structures.

d. 250 linear structures of uncertain age.

e. Collective diagram of 900 linear structures.

f. Synoptic diagram showing the regional dip of foliation and the maxima of linear structures (I, II, III and IV) derived from a, b, c, and d.

Contours at 1-3-6-9-15%.

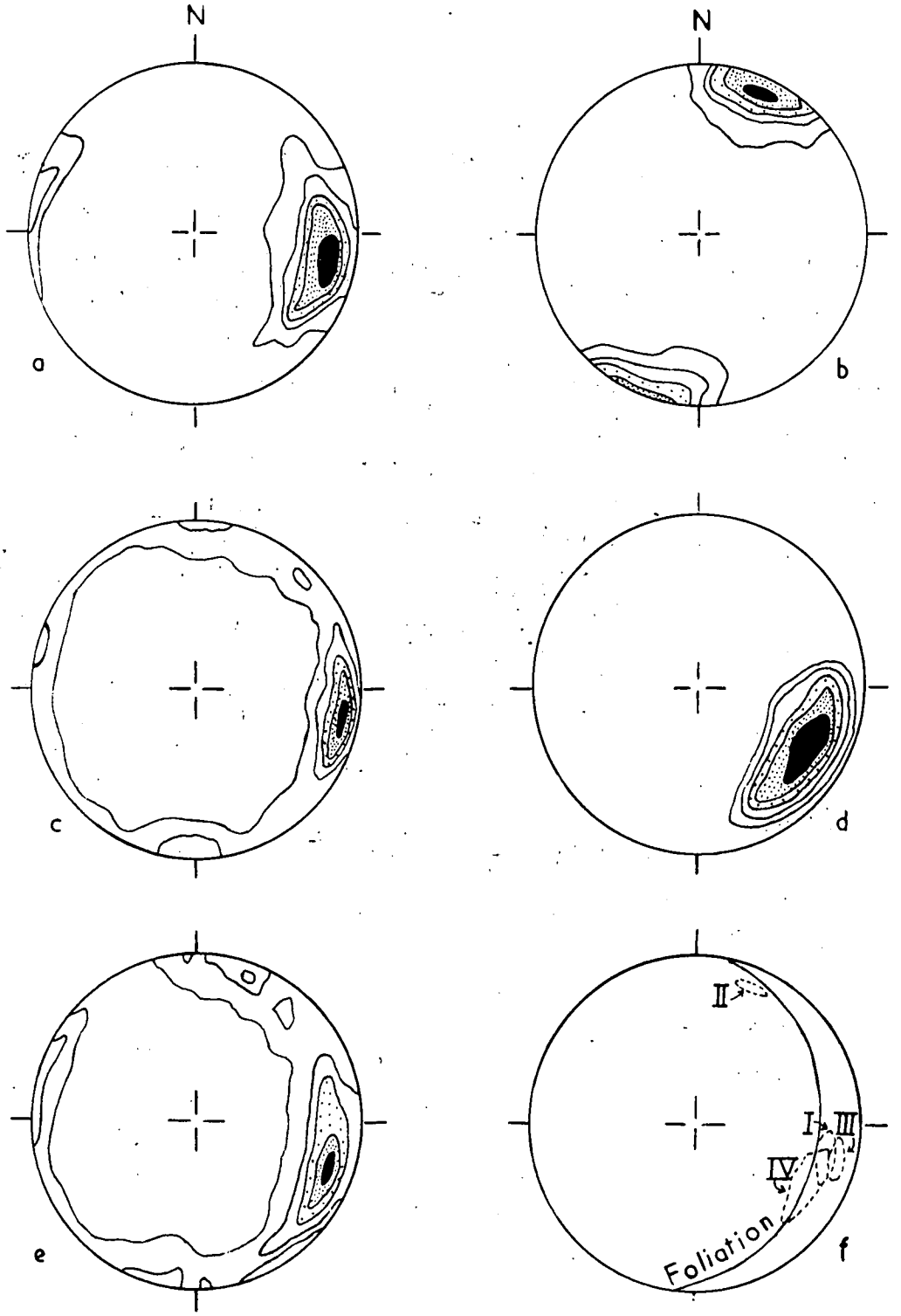


Figure 8.

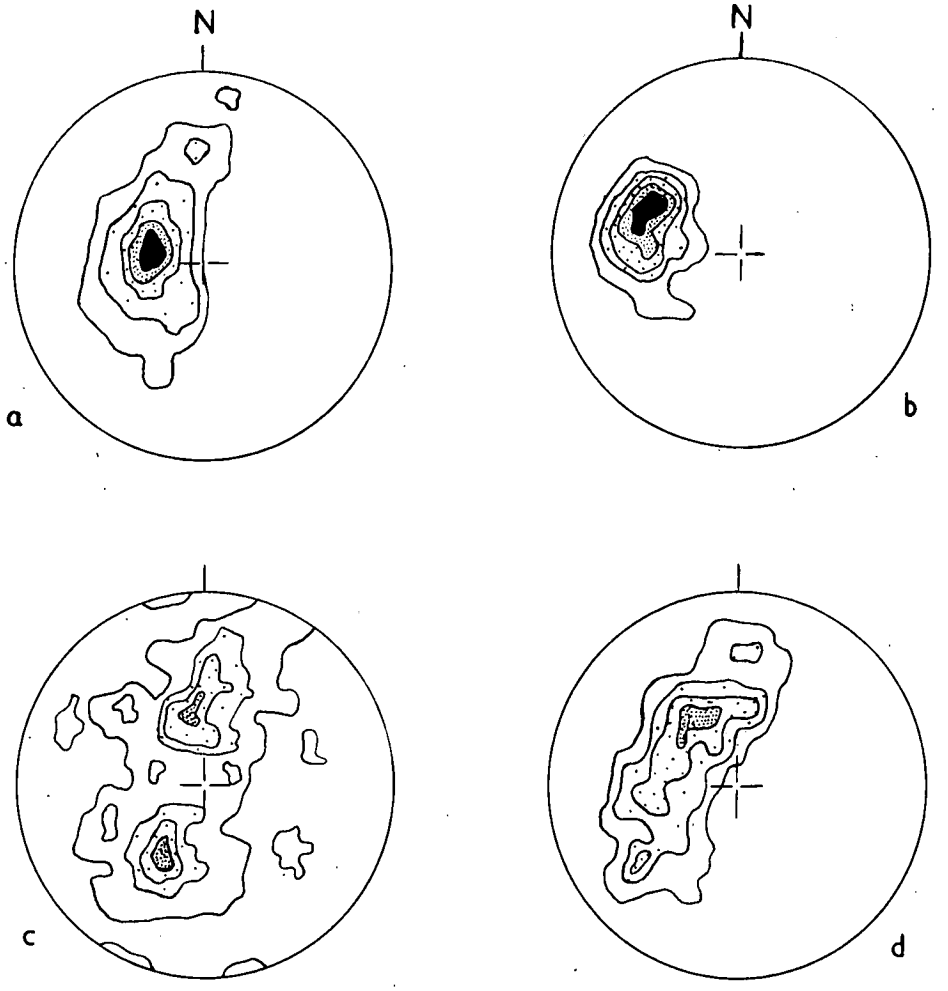


Figure 9. Poles to axial planes of minor folds in rocks above the Kishorn thrust:

a. first folds
b. second folds
c third folds
d folds of uncertain age

Contours at 1-3-6-9-15%

to the dominant dip of foliation. The arrangement of minor fold axes and other linear structures, all of which lie on the foliation, suggests that their orientations have been controlled by the attitude of the E.S.E. dipping planes.

In the following section the style and orientation of the minor structures will be described, their development traced in different rock types and the possible movement responsible for their generation discussed.

(1) The Structures of the First Generation

The structures of the first generation are -

- (a) Minor folds (First Folds) which are generally long limbed and very tightly appressed or isoclinal in shape (Fig. 10; Plates III and IV)
- (b) Schistosity s_1, parallel to the axial planes of minor folds.
- (c) Linear structures b_1, parallel to the axes of minor folds.

The minor folds, which are usually tightly appressed, exhibit thinning of the limbs and thickening of the crestal parts. The axes of the first folds and the associated parallel linear structures, unless affected by the structures of later generations, plunge at gentle angles to the E.S.E. (Fig. 8a and Map 2.). The axial /

axial planes of the tight folds and isoclines and the axial plane schistosity (S_1) are nearly parallel or sub-parallel to the foliation or bedding planes of the rocks. The first axial plane schistosity (S_1), both in the Torridonian and in the Lewisian rocks, dips at gentle angles to the E.S.E. except in areas where this plane has been contorted by folds of later generations (Fig.9a and Map 2). Since, as a rule, the gentle dip of the foliation and bedding in the rocks corresponds to the dip of the limbs and axial planes of the isoclines, the style of folding can be described as "reclined" (cf. Johnson 1960,p.147).

The presence of isoclines in the Torridonian rocks, together with the metamorphic texture and well developed microfabric in these rocks (see page 140) suggests that the Torridonian sediments suffered considerable internal deformation during this fold episode. The axial plane schistosity (S_1) of the first folds gives the rocks a prominent flaggy parting. It is only at the apices of the tight folds that the schistosity is clearly seen to cut across the bedding planes (Fig. 10a). An appreciable thickening of the crestal part of a fold is noted when schistosity is strongly developed. The schistosity (S_1) is usually coated with sericitic micas of secondary origin. A fine/

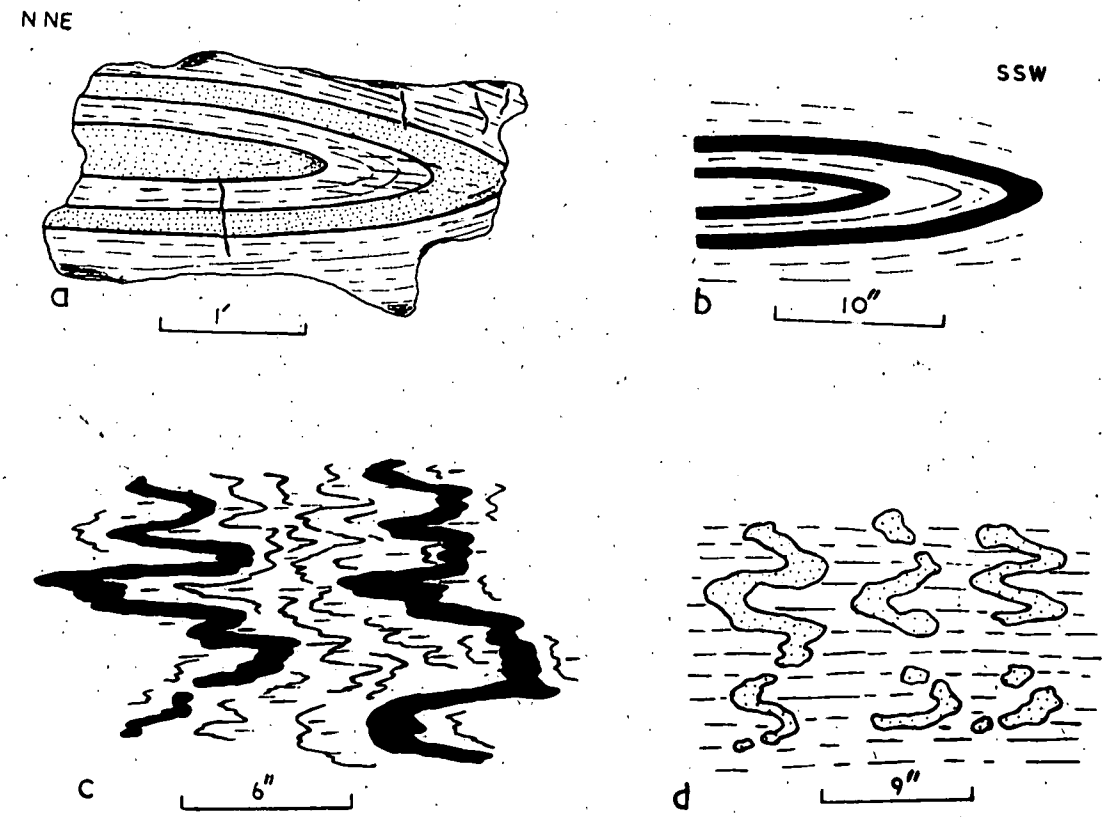


Figure 10. Profiles of first folds:
a. in Torridonian (Diabaig)
b. in Lewisian
c in Lewisian
d in Lewisian (folds are marked by quartz veins)

fine striation lineation parallels the axes of minor folds and is determined by the parallelism of longer dimensions of quartz slivers or elongate clusters of partially recrystallized quartz (see page 67). It is to be noted in this connection that in the Torridonian sediments there are a few tight folds of sedimentary origin, possibly formed by intraformational slumping (Fig. 4., see page 70). These structures simulate in style the isoclinal folds of tectonic origin, but differ from them in being less regular in form and orientation. Further the absence of axial plane schistosity and axial lineations separates the sedimentary folds from the tectonic folds. The origin of a limited number of folds, however, cannot be ascertained due to the absence of definite criteria as mentioned above and these have not been considered in the present analysis (cf. - Sutton and Watson 1959, p.247).

Long limbed, tightly appressed first folds have been recorded throughout the Lewisian outcrop. The crestal parts of these folds are much thicker than the limbs. The prominent parting in these rocks, as in the Torridonians, is a close-spaced schistosity (S_1) parallel to the axial plane of the folds. Where the folds/

folds occur in the banded gneiss, the foliation or compositional banding (denoted by alternate dark basic and white acid layers) is seen to be parallel to the axial plane schistosity (S_1) on the limbs and it is only at the crests of the tight folds that the axial plane schistosity (S_1) cuts across the compositional colour banding. Over most of the area the original banding of the gneiss has been completely transposed by shear slip parallel to the axial plane schistosity (S_1) (Fig. 10,c.). The textural and mineralogical changes that have taken place during the development of S1 have been described in a previous section (page 32).

A set of linear structures parallel to the first minor fold axes have been traced over the whole area. These will be collectively referred to as the linear structures of the first generation (b_1). A common type is a fine regular striation formed by an alignment of minerals such as quartz, felspar or amphibole. Other types of linear structures are quartz rodding and elongated felspathic augen. Striation lineation (defined by quartz) and rodding are common in the Torridonian and striation lineation (defined by quartz, felspar or amphibole), rodding and felspathic augen are frequent in the Lewisians.

While/

While reporting the occurrence of post-Torridonian isoclines and associated structures in Lewisians from the Lochcarron area, Johnson (1960, p.149) remarked -

> "The banded Lewisian rocks exhibit long-limbed flow folds which seem to have been produced during the pre-Torridonian migmatization. It is not unusual to find that the axes and axial planes of these folds are parallel to structures in the nearby Torridonian sediments ..... It is possible, therefore, that some considerable rotation of the original Lewisian structures has taken place in the Caledonian movements, presumably by means of strong differential slip movements."

In the present area it has not been possible to detect any folds that can be attributed with certainty to a pre-Torridonian movement phase in the Lewisians. In considering the possibility that some such structures did exist in the gneisses prior to the Caledonian movements, it has to be admitted that either they have been totally obliterated or they must have been rotated during the Caledonian movements in such a manner that they are now indistinguishable from the post-Torridonian structures.

It /

It has already been mentioned that in the Lewisian gneisses the original gneissic banding (denoted by alternate dark and white layers) is sheared through by slip along axial plane schistosity (S_1). Some folds bear other evidence of shear movement. A specimen of Lewisian gneiss (Fig. 10.c.) shows several small near-isoclinal folds. The folds are such that the limbs are thinned and the crests relatively much thickened. In section the grains in folded quartzose layers are seen to be strongly flattened and are aligned with their long axes parallel or sub-parallel to the axial plane (Plate IV, b.). The quartz microfabric prepared from the limbs and cores of the individual folds are essentially the same and cannot be unrolled about the fold axis - a feature which suggests that the folding has been achieved by shear movement along axial plane (see page 144).

A close-spaced planar structure parallel to the axial plane schistosity (S_1) of the gneisses is conspicuous in some mylonite zones occurring within the Lewisian outcrop. As a rule the mylonitic banding is parallel to S_1. No isoclinal folds could be recognized in the mylonites, but a strong penetrative striation lineation is present. The lineation, which can be traced/

traced continuously from the mylonitic bands into the surrounding gneisses without any change in its orientation is probably identical with the linear structures of the first generation (b_1) in the gneisses. The widespread occurrence in the mylonitic rocks of planar and linear structures, which are similar to those of the first generation in their nature and orientation, suggests that at least some mylonitic rocks existed prior to the first fold episode (cf. Johnson, 1960, p.149). There is also a possibility that some mylonites might have formed by slip movement along the axial plane schistosity (S_1) because, rarely, mylonitic rocks have been observed at the core of small first folds.

Discussion of movement :-

The constancy of arrangement of the axes and axial planes of the first folds suggests that there are no major folds of this generation in the present area. The Lewisian rocks are, therefore, unlikely to represent a fold core of this generation and the inversion of the basement presumably preceded this phase of movement (cf. - Johnson, 1960, p. 147).

The officers of the Geological Survey noted linear structures with E.S.E. trend in several parts of the Moine thrust belt (cf. - Horne, Mem.1907, p.471 and Geological/

Geological Survey one-inch sheet nos. 71, 82, 108). Horne (op. cit.) considered that the linear structures (termed "fine parallel lines") were formed by the W.N.W. movements on the thrust planes. This view has been supported by Phillips (1937, p. 603) in recent years.

It seems likely that the E.S.E. linear structures referred to by Horne and others (Mem. 1907, op. cit. and one inch sheet 82) are equivalent to the first linear structure in the present area. But the geometry of the isoclinal first folds and their associated fine striation does not suggest that a W.N.W. movement plan was responsible for their generation. The shape of the first folds is such that their limbs are thinned and crests relatively much thickened. This feature suggests that shear slip along axial plane (S_1) has played an important part in their production (cf. - de Sitter, 1956, p. 183). There is ample microscopic evidence of shear movement along axial plane (see page 144). Since the first folds are very tight, the direction of shear which is responsible for the generation of the folds must be at high angles to the fold axes though not necessarily normal to them. The axial planes of the folds dip at gentle angles to the E.S.E. and the fold axes plunge at low angles in the same direction. The shear movement/

movement along axial planes, therefore, must have been directed on a nearly N.N.E.-S.S.W. trend. This movement plan does not correspond to the W.N.W. movement on the thrust planes as suggested in the 1907 Memoir (cf. Horne 1907, p.471) and the structures of the first generation are considered to be unrelated to the Kishorn thrust in the present area. It is possibly significant that the first linear structure disappears in the cataclastic rocks immediately above the Kishorn thrust plane. This has been observed at several well exposed sections of the thrust and will be described separately in a later section (pages 134-5).

(2) The Structures of the Second Generation

Two main types of structures belong to this generation -

(a) Minor folds (second folds) with N.N.E.-S.S.W. axial trends. The axes of these folds and their associated linear structures plunge at gentle angles either to the N.N.E. or to the S.S.W. (Fig. 8,b.).

(b) A set of cleavage planes (S_2) which strike N.N.E.-S.S.W. and are parallel to the axial planes of the second folds.

The first and second folds can be easily distinguished by their differing styles as well as by their widely different orientations. The first folds are/

are long limbed near-isoclinal while the second folds have a moderately appressed asymmetrical shape.

The axial planes and axial plane cleavages (S_2) of the second folds strike N.N.E. and dip at moderately steep angles (40° - 55°) to the E.S.E. (Fig. 9,b). They cut across the first axial plane schistosity, S_1 and the first linear structure, b_1 (Plate V and Fig. 11,d). The cleavage is much better developed in the incompetent rocks than in competent rocks (Plate VI,b). The shape of the folds is such that the limbs are thinned and the crests relatively much thickened (Fig. 11 and Plate VI, a).

The second folds and associated axial plane cleavages (S_2), which are not common in the Torridonian rocks, are better developed in the shaly bands than in the gritty rocks. A lineation, produced by the intersection of cleavage (S_2) with the bedding runs parallel to the axis of the second folds. The cleavage dips at a steeper angle than the inverted bedding.

The second folds are found intermittently over the area occupied by the Lewisian gneisses. As a rule, minor structures of the first generation are much more widespread than the second structures which do, however, dominate /

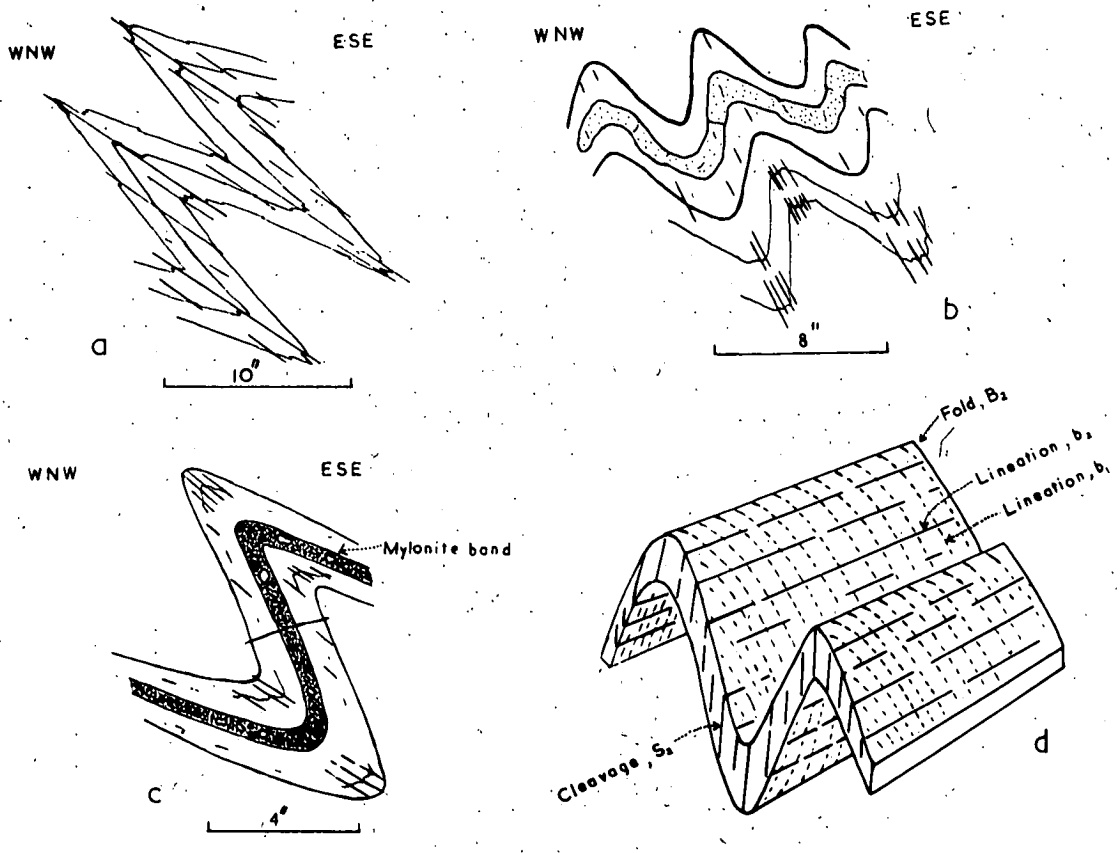


Figure II

a. Profile of second fold in Lewisian
b. Profile of second fold in Torridonian (Diabaig).
c. Mylonite band folded by second fold. Lewisian.
d. First lineation(b_1) folded by second fold(B_2) and cut across by second cleavage(S_2) Second lineation(b_2) is superimposed on first lineation(b_1). Lewisian.

dominate in a few localities where the usual E.S.E. dip of the foliation is contorted on the second fold axes. For example, in sub-areas 10 and 11, the poles to foliation spread on partial girdles trending W.N.W.-E.S.E. (Fig. 6.). The N.N.E. trending axes of the girdles coincide with the axes of the second folds occurring in these sub-areas. The moderately tight asymmetrical second folds refold the isoclines (Plate V, a). The axial plane cleavage (S_2) belonging to the second folds, dips rather steeply (40° - 55°) to the E.S.E. It cuts across the first linear structure (Plate V, b) and intersects the foliation to give a coarse crinkling lineation which runs parallel to the second fold axes. The girdle pattern of the foliation poles is, therefore, a result of superimposition of the second folds on the first ones.

Some mylonitic rocks within the Lewisian have been folded by the second folds (Fig. 11,c.) and are thought to have been formed prior to the second fold episode.

(i) Deformation of first linear structures by second folds.

During the second episode of folding the minor structures formed during the first fold movements were /

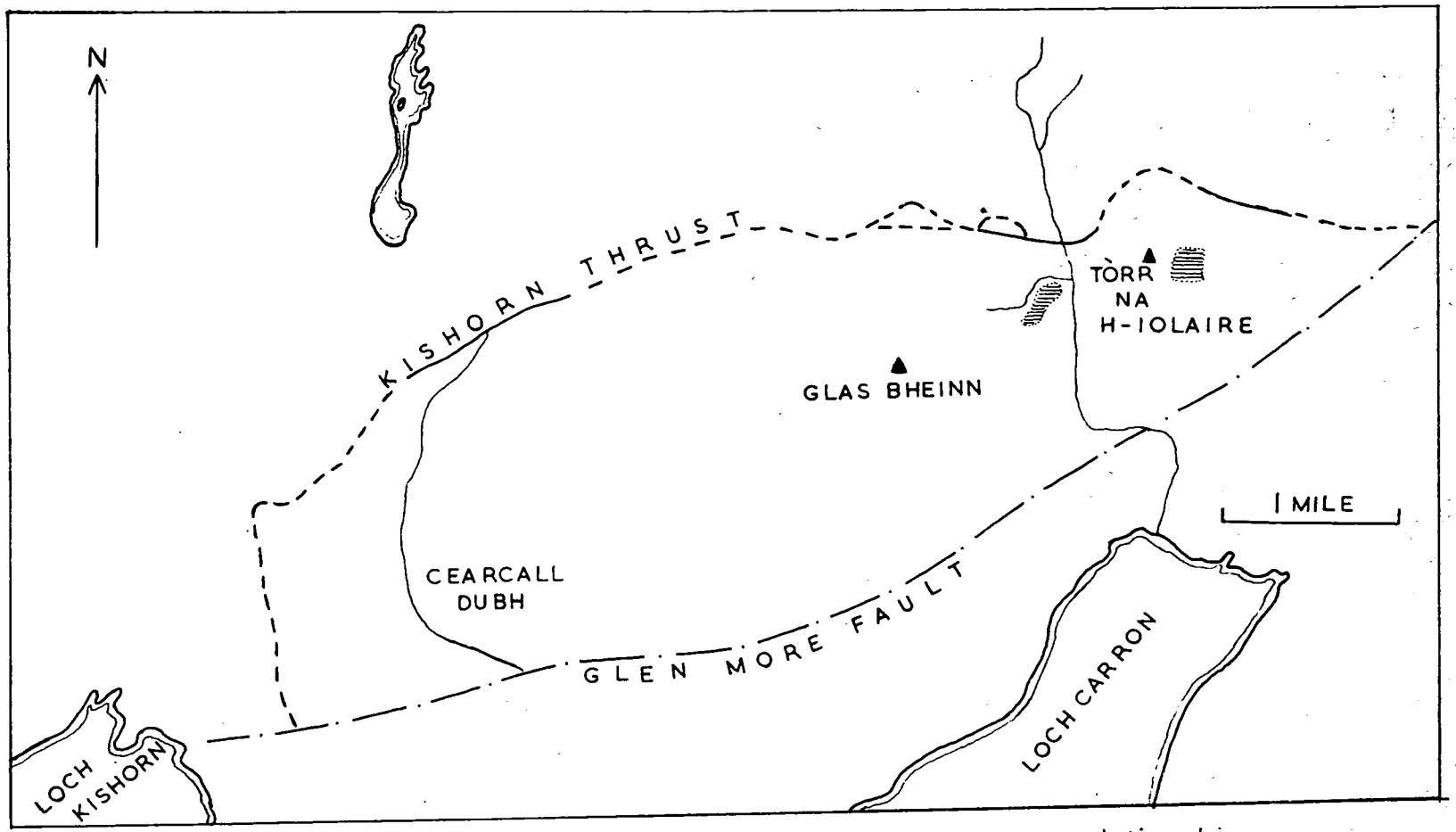


Figure 12. Location of outcrops selected to demonstrate relationship between the first and second linear structures.

were deformed. The limbs and axial planes of the first folds were refolded (Plate V, a.) and the first linear structures were distorted as the axial plane schistosity (S_1) was folded on new axes. The early striation and quartzo-felspathic rods have been cut across by the second axial plane cleavage, S_2, and at places are nearly obliterated (Plate V, b.). The early linear structures may retain their original elongate form, but have superimposed upon them the second coarse crinkling lineation.

The geometrical relationship between the second and first linear structures may be illustrated by considering two outcrops in the Lewisians, where the relationship can be studied in detail. The locations of these outcrops, which have been mapped on a large scale, are indicated on a sketch map (Fig. 12.).

In the first outcrop, which is an approximately rectangular area about 200 feet wide and 250 feet long and is situated near the hill of Tòrr na h-Iolaire, the rock type is hornblende-bearing quartzo-felspathic gneiss (Fig. 13a). There are several minor second folds of the magnitude of a few feet in amplitude. An axial plane cleavage is associated with these folds. The /

Figure 13. Structural analysis of an outcrop in Lewisian gneiss at Torr na h-Iolaire area, illustrating the relationship between the first (b_1) and second (b_2) linear structures.

a. Map showing the orientations of the first and second linear structures, foliation and second axial plane (S_2).

b,c,d. Orientations of first linear structures on three second minor folds. Plots of first linear structures are indicated by crosses and those of second fold axes by dots on the stereonet.

e. Plots of foliation planes which intersect to give the β-axis.

f. Plots of β-axis (open circle), the first linear structures (crosses) and the second fold axes (dots) measured in the outcrop.

The trace of great circle through the plots of first linear structures intersects the second axial plane (S_2) to give the $\underline{a}$-axis in Figs. 13, b,c,d,f.

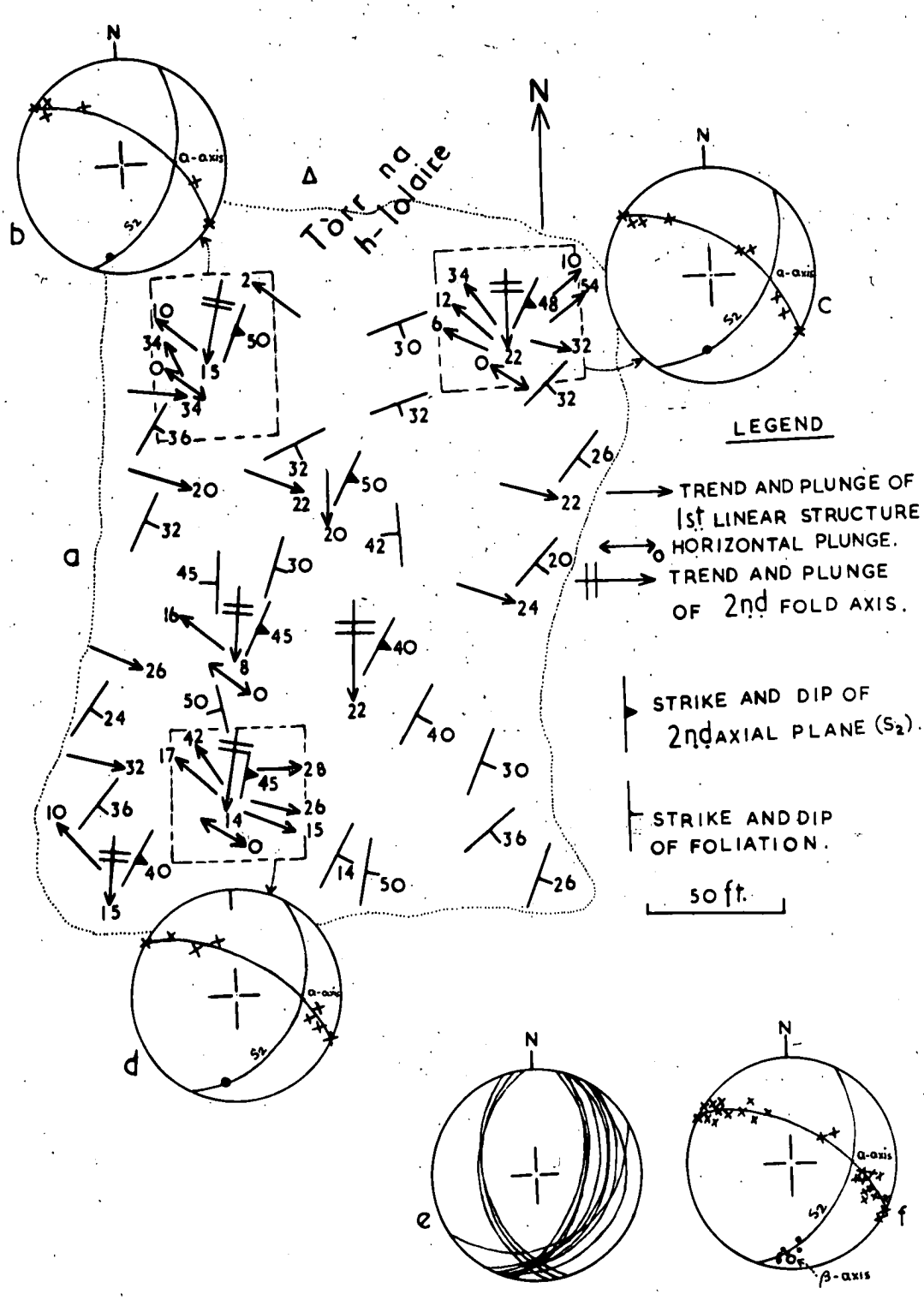

N
a-axis
S2
b
Tòrr na h-Iolaire
c
a
d
e
f
β-axis
LEGEND
TREND AND PLUNGE OF 1st LINEAR STRUCTURE.
HORIZONTAL PLUNGE.
TREND AND PLUNGE OF 2nd FOLD AXIS.
STRIKE AND DIP OF 2nd AXIAL PLANE (S2).
STRIKE AND DIP OF FOLIATION.
50 ft.

Figure 13.

The first linear structure, which is a fine striation, shows variable trend and plunge. The cyclographic projections of all the foliation planes measured within this outcrop intersect to give a β-axis (cf:- Weiss, 1954), which plunges at low angles to the S.S.W. (fig. 13, e). The projected poles of the second minor folds cluster around this β-axis (fig. 13, f). Three second folds, which are seen to refold the early striation, have been studied separately (figs. 13, b,c,d). The angle between the second fold axis and the first linear structure varies systematically over each of these folds, being high (approx. 80°) on the limbs of the second folds and gradually decreasing to a minimum value (approx. 55°) as the crestal part is approached. In each of these folds, the poles of the first linear structure, when plotted on a stereonet, spread along a great circle. The geometrical relationship, just outlined, between the first and second linear structures is found to be valid for the entire outcrop, as is seen when all the data from this outcrop are plotted together (fig. 13, f).

The second outcrop is situated on the northern slopes of Glas Bheinn and about 200 yards S.S.W. of the intersection of the Allt Dubh and the Amhainn Bhuachaig north of Tullich. The outcrop which is roughly elliptical in /

Figure 14. Structural analysis of an outcrop in Lewisian gneiss north-east of Glas Bheinn, illustrating the relationship between the first (b_1) and second (b_2) linear structures.

a. Map showing the orientations of the first and second linear structures, foliation and second axial plane (S_2).

b. Plots of foliation planes which intersect to give the β-axis.

c. Plots of β-axis (open circle), the first linear structures (crosses) and the second fold axes (dots) measured in the outcrop. The trace of the great circle through the plots of the first linear structures intersects the second axial plane (S_2) to give the $\hat{a}$-axis.

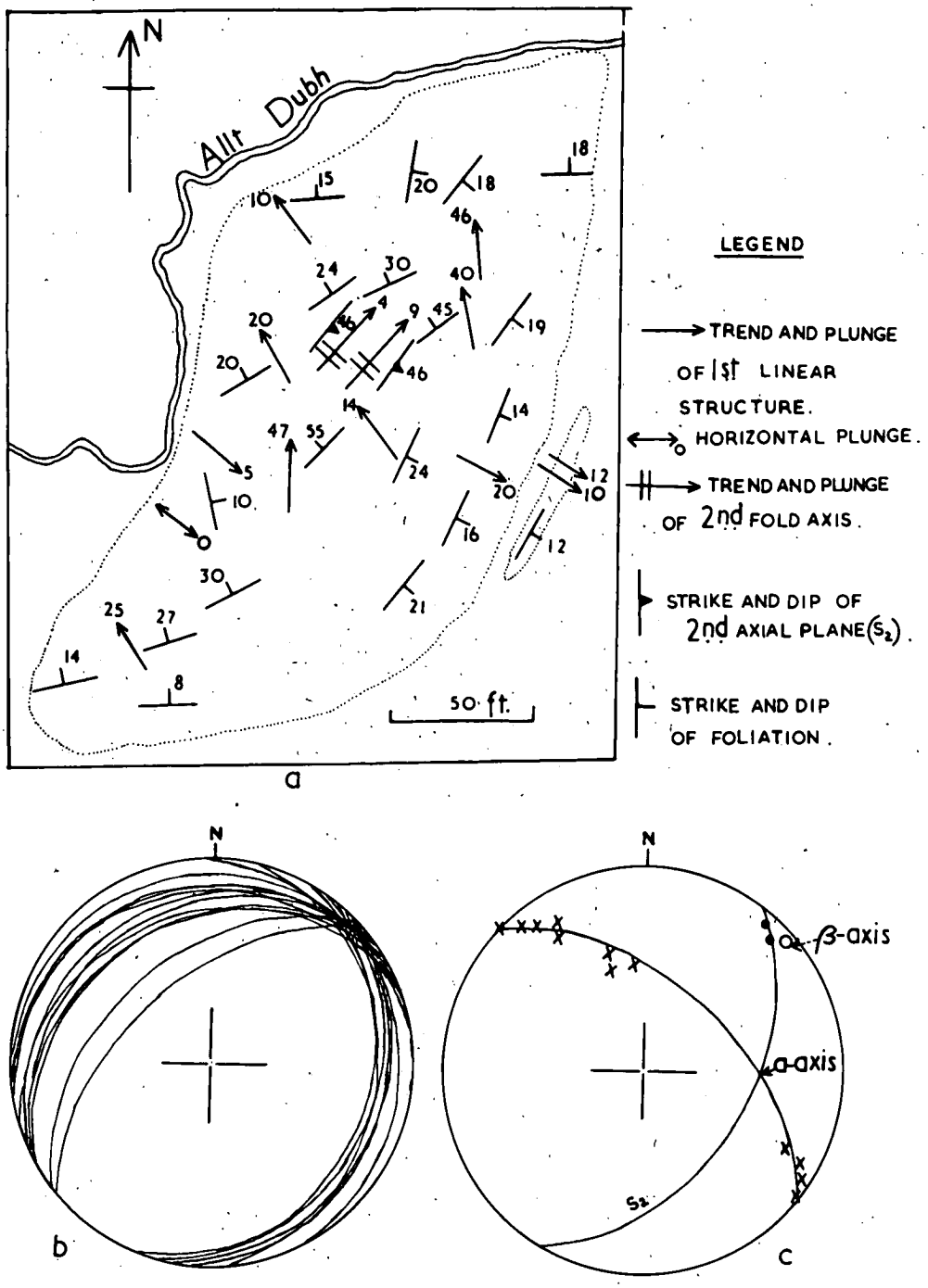

N
Allt Dubh
LEGEND
TREND AND PLUNGE OF 1st LINEAR STRUCTURE.
HORIZONTAL PLUNGE.
TREND AND PLUNGE OF 2nd FOLD AXIS.
STRIKE AND DIP OF 2nd AXIAL PLANE(S2).
STRIKE AND DIP OF FOLIATION.
50 ft.
a
N
b
N
β-axis
α-axis
S2
c

Figure 14.

in shape is about 125 ft. at the widest and 350 ft. long (fig. 14, a). The foliation of the hornblende-bearing quartzo-felspathic gneiss in the outcrop is folded on a N.N.E.-trending axis. The traces of foliation intersect on a stereonet to give a β-axis plunging at low angles to the N.N.E. (fig. 14, b,). The axes of the two minor folds of the second generation that have been recorded in the outcrop plot very close to the B-axis, which lies in the projected axial planes of the minor second folds (fig. 14, c,). The first linear structures, which are found all over the outcrop, vary in plunge and trend. On the stereonet (fig. 14, c,), the poles of the first linear structures, though having a limited range of scatter, show a definite tendency to spread along a great circular arc. The significance of the geometrical relationship between the first and second structures which has been elucidated in the two outcrops described above will be discussed in the following pages.

Discussion of movement:- The style of the second folds is such that the limbs are thinned and the crestal parts relatively much thickened. This feature, together with the occurrence of strong axial plane cleavage, suggests that the folds are of similar type (de Sitter, 1956, p.183).

Similar /

Similar folds originate by shear which takes place either along axial plane cleavage or on invisible shear surfaces parallel to axial plane. This contrasts with the mechan-:ism of flexural slip or Concentric folding, wherein slip occurs along bedding planes. The similar style of the second folds is borne out by the microscopic evidence of the extension of quartz crystals along axial plane cleav-:age (plate VI) and also by the geometrical relation-:ship between the first and second linear structures, which has been described previously. The relationship can be used to establish the direction of movement, along axial plane surfaces responsible for the generation of the second folds. The principles underlying the procedure have been described by Ramsay (1960) and Weiss (1959) and may be briefly set out below.

Linear structures lying on a surface which is deformed by Concentric folding have their locus on a partial cone (stereogram plots show a small circle pattern), whereas those lying on a surface folded in a Similar manner have their locus on a plane (stereogram plots show a great circle pattern). In Concentric folding, the angle between the refolded linear structure and the axial direction of folding always remains constant no matter where the linear structure /

structure is situated on the fold, whereas in Similar folding, the angle between the refolded linear structure and the axial direction of the fold is variable. Ramsay (op. cit.) describes the method of determining the actual direction of movement (or $\underline{a}$-kinematic axis) of particles during Similar folding. Since the nature of Similar folding is such that the angles between the refolded linear structure and the axial trend of a Similar fold vary sys-:tematically and the linear structures are so arranged that they are all contained in one plane, which is repres-:ented as a great circle on stereonet, it is possible to deduce the orientation of $\underline{a}$- (or movement) axis in rocks deformed by Similar folding from the following facts -

(i) The fold axial plane (deformation plane) contains the $\underline{a}$-axis.

(ii) The plane containing the variably oriented early linear structure (i.e., great circle trace on stereonet) is controlled by the $\underline{a}$-axis and by the initial orientation of the linear structure.

Therefore, the intersection of these two planes represents $\underline{a}$ (Ramsay, op. cit., p.89). An important fact that emerges from Ramsay's study is that the fold axis may not be at right angles to the movement direction $\underline{a}$. In areas /

areas of multiple folding the fold axes may form at any angle to the direction of transport.

In the two outcrops where the geometrical re-:lationship of the first and second structures has been studied in detail the second axial planes (S_2) and the great circle trace which can be drawn through the poles of refolded first linear structure, intersect in a line which is constant in orientation and plunges at 40°-45° to the east (see figs. 13, b,c,d,f and 14, c). The megascopic analysis, therefore, suggests that the second folds were produced by movement on planes (axial plane surfaces) which dip at moderately steep angles (40°-55°) to the E.S.E., the direction of movement (a-axis) being parallel to a line plunging 40°-45° to the east. Further evidence of movement on the axial plane surfaces is pro-:vided by the microscopic structures of rocks folded in a Similar manner at Tòrr na h-Iolaire (see p.152). It has been found from a study of these rocks that strong axial plane shear has controlled the dimensional and optical orientation of quartz grains. In one of the specimens of folded rocks in which grain orientation has been studied, it has been concluded that slight flexural slip might have taken place at an initial stage of folding but /

but axial plane shear was the dominant movement mechanism (p. 156).

(ii). Relation of Second folds to Loch Alsh Syncline and Kishorn Thrust.

The axial plane cleavage (S_2) dips more steeply than the inverted bedding planes of the Torridonians and this raises the question of the relation of the second fold to the Loch Alsh Syncline which is thought to be responsible for the stratigraphic inversion in the area. If the cleavage had been produced as a result of Loch Alsh fold movements, it should dip less steeply than the inverted bedding (cf:- Wilson, 1946). Hence the second folds and their associated cleavage (S_2) are not related to the geometry of the Loch Alsh Syncline and they presumably post-date the inversion (cf:- Sutton and Watson, 1959, p.247; Johnson, 1960, p.153).

The relationship of the second folds with the period of thrusting along the Kishorn thrust is not certain. Three possible relationships are mentioned here, the assessment of which is the more likely being deferred until the closing sections of this thesis -

(a) The second set of structures pre-date the period of thrusting. Minor structures (third generation), which are thought to be contemporaneous with thrusting, /

thrusting, refold structures of the second generation. The folds of the third generation are more brittle in style than the second folds.

(b) The second set of structures are due to the agency of thrusting. The axial plane of the second minor folds dip consistently to the E.S.E. at a moderate angle (40°-55°), but the amount and direction of dip of the Kishorn thrust plane as shown later (p. 131) vary considerably throughout its outcrop over a wide area. It is difficult to postulate a movement plan on the Kishorn thrust, which is a warped surface, to account for the generation of the second folds.

(c) The second set of structures largely ante-date the thrusting but there was an overlap of events and the movement responsible for the generation of second structures culminated in a phase of clean-cut thrust-:ing.

There is no evidence to suggest that the second folds originated after thrusting.

(3) <u>The Structures of the Third Generation</u>

A set of small scale monoclines and conjugate folds (third folds) has been superimposed on the first and second structures. The occurrence of conjugate folds in the /

the thrust belt was first reported by Johnson (1956) from Lochcarron and Coulin Forest, Ross-shire.

The third folds, which have a brittle style with straight limbs and sharp hinges (fig. 15), differ markedly from the folds of the preceding sets. They arise as small "kink zones" on the foliation and subsequently develop by stages into small "steps" or monoclines. In conjugate folds paired shear planes may develop parallel to the mutually inclined axial planes. Small scale brecciation of rocks has been noticed along these shear planes. An individual monocline is one of the paired conjugate folds, whose axial planes are mutually inclined and may intersect in a line parallel to the gently plunging fold axis.

Considered over the area, the axes and axial planes of the third folds have a variable orientation (figs. 8, c, and 9, c.) but a majority of the third fold axes trend in the E.-W. direction. The projections of the third fold axes on a stereonet form a girdle which overlaps the areas of projection of the first and second linear structure described previously (see figs. 8, a,b,c).

There are no lineations associated with the third folds.

The third folds are best developed in flaggy mylonite /

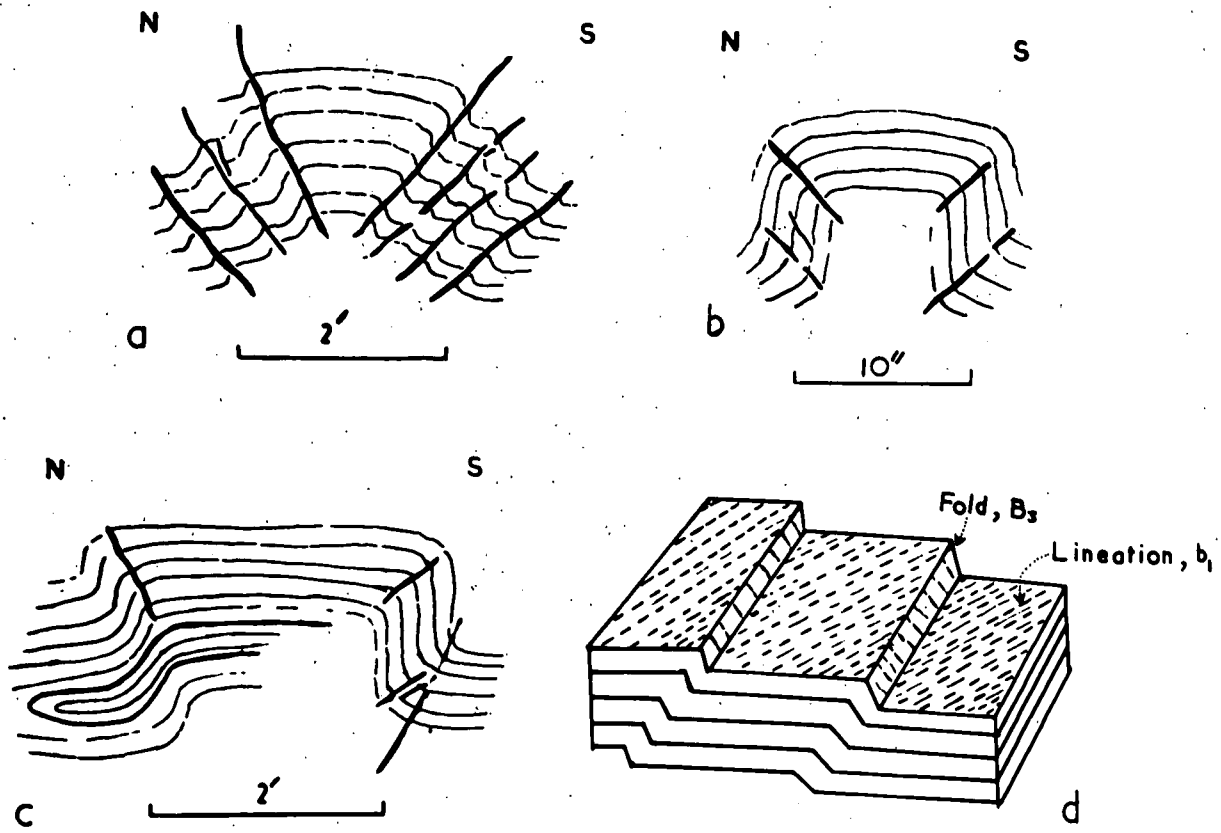


Figure 15

a. Profile of third (conjugate) fold in Lewisian.
b Profile of third (conjugate) fold in Torridonian (Diabaig).
c. First fold (isocline) refolded by third fold. Lewisian.
d First lineation (b_1) distorted at the hinge of third fold (B_3) Lewisian.

mylonite rocks, where the E.S.E. dipping parting planes are contorted on the third fold axis.

The third folds generally twist and deflect the first and second linear structures. Some third folds may be nearly co-axial with the E.S.E.-trending first linear structures. But the open monoclinal or conjugate third folds contrast markedly with the tightly appressed and isoclinal style of the first folds. Further, the axial planes of the isoclines are visibly refolded by the third folds (fig. 15,c).

Discussion of movement:- The style and orientation of the third folds suggest that they have been produced by local irregular compressive stresses, which were constant neither in direction nor in sense. The irregular stresses may have been induced in rocks by the thrust movements, with which the third folds are probably associated. It has been found (see p. 131) that the Kishorn and Moine thrusts are warped and the rock masses involved in thrusting have, therefore, been tectonically thickened at places. It is possible that the brittle conjugate folds developed in the thickened rock masses during the phase of thrusting, or shortly afterwards. Fig. 16 shows the possible mode of formation of these folds by local vertical extension and concomitant lateral compression /

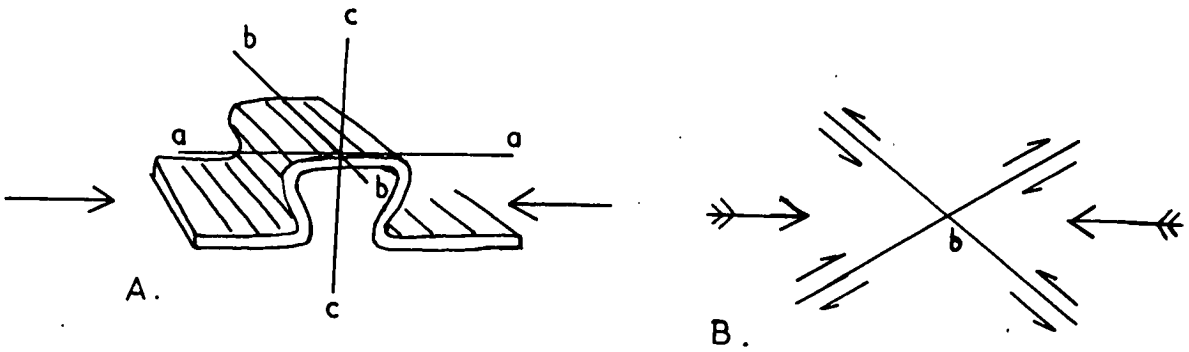


Figure 16. Kinematic interpretation of the Conjugate Folds. (after Johnson, 1956, p.348.)

A. Development of a conjugate fold by compressive stress(a). Note relief of the fold in the direction c.

B. Sense of movement along the slip planes which occur in some conjugate folds. The maximum compressive stress producing the slip movements is shown by arrows with barbs.

compression of laminated rocks. The style of the conjugate folds suggests that they developed during a period of move-:ment when transport was restricted so that the rocks, when subject to lateral compression, found relief mainly in a near-vertical direction.

(4) The Structures of Uncertain Age.

A set of structures, distinct from the three sets previously described has been recognized in the area. They consist of a set of minor folds and their associated, local, cleavage and lineation. These have been classified as "structures of uncertain age". Field evidence, described later, suggests that the "minor folds of uncertain age" are later than the first isoclinal folds. The age relationship between the structures of the second and third generations and those of uncertain age is not apparent in the present area. The open folds of uncertain age are, however, dis-:tinct in style and orientation from the moderately tight N.N.E.-trending second folds. The third, conjugate and monoclinal folds, some of which trend E.S.E., may be co-axial with the open asymmetrical folds of uncertain age, but their brittle style serves to distinguish them from the latter.

The folds of uncertain age, which attain a larger size /

size than those belonging to the other fold systems, are asymmetrical in shape, the angle between the limbs being usually more than 50° (plate VII, a, and fig. 17). Some have a variable style and are disharmonic or box-like (plate VII, b).

The observed fold axes plunge at moderate angles (20°-40°) towards S.E./E.S.E. (fig. 8,d). The axes of larger folds which measure several yards from crest to crest, can be calculated from the dips of contorted foli-:ation.

Some folds show a coarsely developed cleavage parallel to their axial planes. The intersection of the axial plane cleavage with the foliation produces a corru-:gation lineation.

In a few outcrops, the folds of the present set are nearly co-axial with the first linear structures. But the isoclinal folds and their associated fine striation can be readily distinguished from the later open asymmet-:rical folds and coarse lineation. The open folds refold the limbs and axial planes of the first isoclinal folds (fig. 17, c, and plate VII, c; also see plate IV, a). The coarsely developed cleavage associated with the open folds cuts across the axial plane schistosity (S_1).

The /

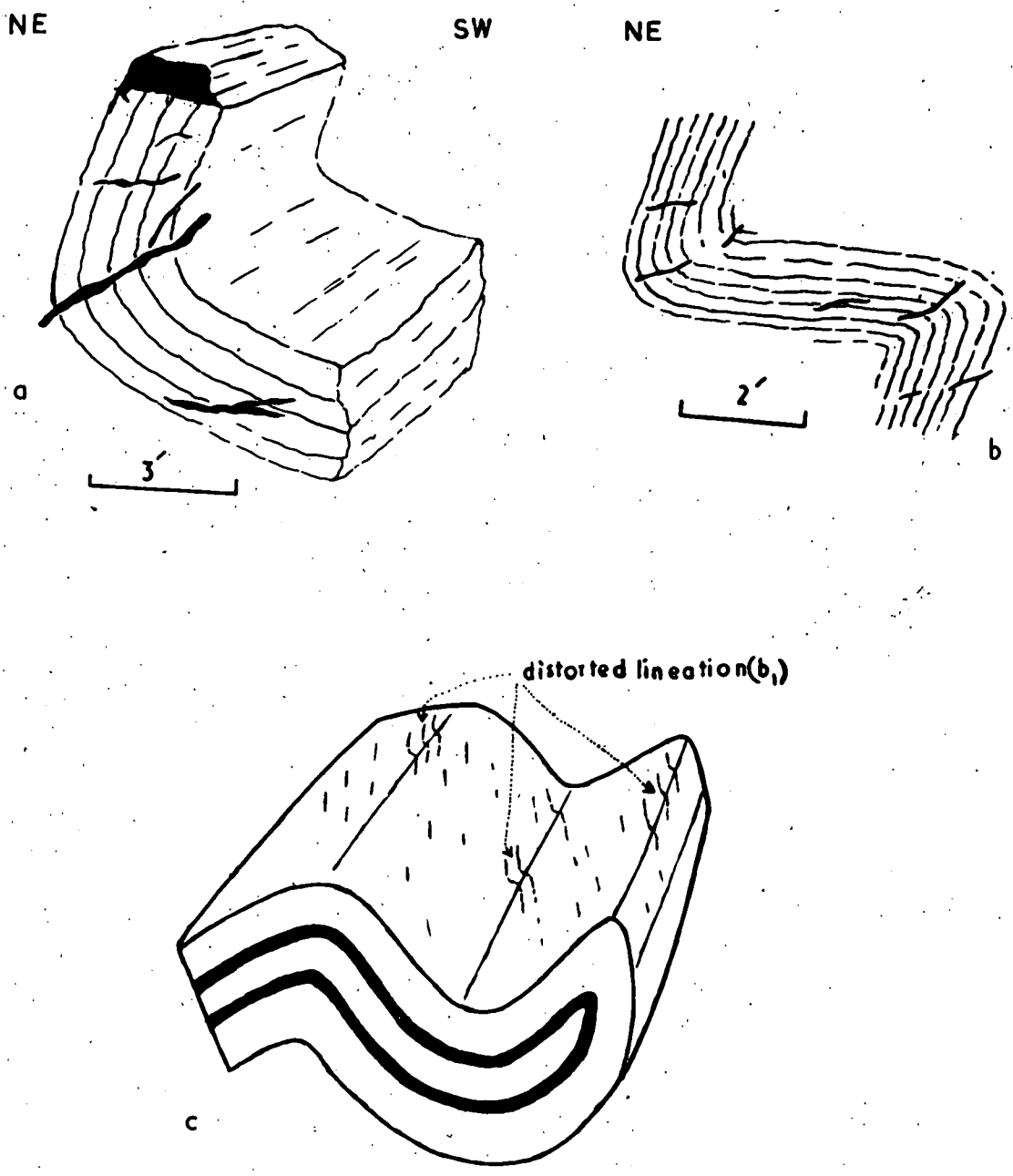


Figure 17

a and b. Profiles of open asymmetrical folds of uncertain age in Lewisian.

c. Refolding of first (isoclinal) fold and distortion of first lineation (b_1) by an asymmetrical fold of uncertain age. Lewisian.

The open minor folds of uncertain age and their associated structures occur both in the Torridonians and Lewisians. They are more frequent in Lewisians and have been recorded from most parts of the gneissic outcrop. In places (such as, sub-areas 1,2 and 3 in fig. 6) where the folds are well developed the foliation plane poles spread into a partial or complete girdle, striking N.N.E., which reflects the open folds. The weak maxima in the girdle patterns indicate the dominantly easterly dip of foliation. The E.S.E./S.E.-trending axis of the girdle corresponds to the axes of the numerous open folds which refold the early isoclines in these sub-areas.

C. Megascopic Structures below the Kishorn thrust plane

General Statement

The area under consideration in this section extends from Loch Kishorn north-eastwards to the south-eastern slopes of An Ruadh-stac (Map. 1). For convenience in describing the structures, this large area has been divided into two parts: a north-eastern part /

part lying between Meall an Daimh (about ½ mile south of An Ruadh-stac) and Coille Dubh and a south-western part lying between Coille Dubh and Loch Kishorn.

The north-eastern part, extending from Meall an Daimh to Coille Dubh, is occupied by the Cambrian quartzites (Basal Quartzite and Pipe Rock), grits and mudstones (Serpulite Grit and Fucoid Bed) and Torridonian (Applecross Group) grits, the outcrops of which trend N.N.E.-S.S.W. At the westerly limit of this part, west of An Gorm Loch, a narrow strip of Foreland rocks, consisting of Applecross grits and Cambrian quartzites undisturbed by the post-Cambrian movements, has been mapped. The Foreland rocks are structurally overlain by the Cambro-Ordovician and the Torridonian (Applecross) rocks which occur above the Sole thrust. The outcrop of the Sole thrust which trends N.N.E.-S.S.W. has been traced just west of An Gorm Loch.

In the south-western part of the area, between Coille /

Coille Dubh and Loch Kishorn, the rocks outcropping are entirely of Cambro-Ordovician age and they occur structurally above the Sole thrust. The Ghrudaidh and Eilean Dubh limestones occupy most of this ground and rest on a thrust plane which has overlapped the Sole thrust at Coille Dhubh. Between Coille Dhubh and Loch Kishorn, the Sole thrust does not outcrop because a normal fault, the Fasagh Fault (cf. Mem. 1907, p. 328), has thrown down the Sole thrust and has brought the disturbed Cambro-Ordovician rocks into contact with the unmoved Torridonians of the Foreland. The outcrop of the Fasagh Fault, trending N.E.-S.W. has been traced from a point near Loch an Lòin south-westwards to Loch Kishorn (Map 1 and Map 2).

Below the Kishorn thrust, the rocks affected by the post-Cambrian movements have been folded and thrusted on a large scale (cf. Hinxman, Mem. 1907, pp. 558-565). The major folds have a N.N.E.-S.S.W. axial trend and the major thrust planes are moderately steeply inclined to the E.S.E. Above the major thrust planes, at /

at several structural levels, are zones of imbricate structure formed by parallel sets of minor reverse faults which dip steeply to the E.S.E. Minor folds, which are not common, have been recorded and apparently belong to two sets.

The relationship between the major and minor folds and that between the thrusts and folds will be discussed in this section.

(1) <u>The Structures of the area between Meall an Daimh and Coille Dhubh</u>

(a) <u>Major Structures</u> :- The Cambro-Ordovician and Torridonian rocks, over this area, usually dip at low angles (15° - 25°), through near thrust planes the angle of dip may be high (40° - 90°). In general the strike of the strata trends consistently N.N.E.-S.S.W., but locally it may be deviated into a N.N.W. or E.N.E. trend, a feature which suggests gentle warpings of the bedding planes on a N.W.-S.E. axis. A study of the Geological Survey maps (sheet Nos. 81 and 82) shows that a gentle warping of bedding plane on the same axis is present north of the limits of the present area.

A remarkable geological feature in the zone of dislocation is the occurrence of repeated bands of white /

white Cambrian quartzite and chocolate-red Applecross grits. The Cambrian and Torridonian strata have been repeated, individually and en bloc, by thrusting and folding. Of the two major thrusts, both of which dip to the E.S.E, that are found in this area the more westerly outcropping and therefore that occupying the lower structural level, is the Sole thrust which is seen in outcrop west of the An Gorm Loch. The dip of the Sole thrust cannot be measured directly in the present area, but as calculated by drawing stratum contours on its trace on the one-inch Geological Survey maps (sheet nos. 81 and 82) it is 45° to the E.S.E. North of An Gorm Loch and beyond the limit of the present area, the effect of the Sole thrust is to thrust the Torridonian rocks upon themselves. In the present area, a wedge of Cambrian strata (quartzites), which form part of the unmoved Foreland, appears beneath the Sole thrust plane so that the disturbed Torridonian grits, overlying that plane, rest on the unmoved Torridonian in some localities and on the Basal Quartzite and Pipe Rock in others. The unmoved Foreland rocks dip at low angles (10° - 20°) to the S.E. with the Cambrian quartzites lying unconformably above the Torridonian grits. Near the Sole thrust, the Foreland rocks sometimes dip steeply (40° - 70°). South-west of An Gorm Loch, the Sole thrust is entirely within /

within the Cambrian strata and along the slopes above the Allt Ghuibhais, it brings forward the Pipe Rock upon itself. Near Coille Dhubh, the Sole thrust is overlapped by another thrust, termed the Rassal thrust by the present author, which has brought forward the Eilean Dubh and Ghrudaidh limestones of Glen Kishorn (Map 1.).

The trace of outcrop of the second and more easterly thrust, termed the Cadh'an Eididh thrust by the present author, runs N.N.E. from near Loch Cadh' an Eididh, parallel to that of the Sole thrust (Map 1.). The Cadh' an Eididh thrust, which is clean-cut and well exposed (Plate II, b), dips 60° to the E.S.E. and, throughout the entire length of its outcrop in the present area, the thrust has brought the Applecross grit upon Cambrian quartzite (Map 1). South of Loch Cadh' an Eididh, the thrust is overlapped by a zone of imbrication composed of Fucoid Beds and Serpulite Grit.

A major anticlinal fold, involving the Applecross grits, Basal Quartzite and Pipe Rock, has been recognised near the crescent-shaped Loch Cadh' an Eididh which occurs at the hinge of the fold (Map 2). Just south of the Loch the strata assume a nearly E.W. trend. The /

The fold axis plunges southwards at a gentle angle and the axial plane trends N.N.E.-S.S.W. On the eastern limb of the fold Applecross grit, Basal Quartzite and Pipe Rock dip to the S.E. in their normal stratigraphical sequence. The western limb of the fold is, however, cut by the Cadh' an Eididh thrust (Map 1 and Map 2).

At Meall an Daimh and eastwards from the major fold described above, the Pipe Rock lies beneath the south-easterly dipping Basal Quartzite which is, in its turn followed to the south-east in upward sequence by the Applecross grit. Both the Cambrian quartzites and the Applecross grit are inclined at moderate angles (15° - 35°) to the S.E. and the rocks, therefore, occur in inverted stratigraphical order. The inverted junction between the Basal Quartzite and the Applecross grit usually trends N.N.E.-S.S.W. but just south of Meall an Daimh, near Loch a Mhuilinn, the outcrop of the junction curves eastwards and the Applecross grit is succeeded in normal stratigraphical order by south-easterly dipping Basal Quartzite. The cause of the inversion of stratigraph-:ical sequence at Meall an Daimh is not clear. On the evidence available in the present area, two possi-:bilities may be considered :-

a. The inversion is caused by thrust-faulting, which has brought the Applecross grit above the Cambrian quartzites/

quartzites at Meall an Daimh. The junction between the chocolate-red grits and the white quartzites is exposed at several places; but there is no evidence of crushing (such as, fault-breccia) along this junction.

b. The inversion is caused by overfolding. Hinxman (Mem.1907, fig. 53 and pp. 560-561) attributed the inversion at Meall an Daimh to overfolding on a N.N.E. axial trend and claimed that the folded unconformable junction between the Applecross grit and the Basal Quartzite, on the inverted western limb of a major fold, is well displayed on the northern slopes of An Ruadh-stac, which is about ½ mile north of the limit of the present area. It is interesting to note in this connec-:tion that the grits and the quartzites intertongue with one another just north of Loch a' Mhuilinn, where the trend of outcrop of the boundary between the two rock groups changes from a N.N.E.-S.S.W. trend to the east (Map 1.).

The observations made by the present author combined with Hinxman's (op. cit) account of the structure north of Meall an Daimh, strongly suggest that the structure at Meall an Daimh is a fold, over-:turned to the west and with a N.N.E.-S.S.W. trending axial /

axial plane. Since the bedding planes have the same dip on the inverted and normal limbs of the fold the exact attitude of the fold axis could not be determined. If the fold is tightly compressed, as Hinxman's section (op. cit.) drawn north of Meall an Daimh shows, then there are two possible attitudes for its axis:

either, (1) a horizontal or a very gently plunging N.N.E-S.S.W. axis,

or, (2) an axis plunging steeply to the S.E.

Imbricate Structure:

On the northern side of Glas Bheinn, Sgurr a' Gharaidh and Torr na h-Iolaire narrow N.N.E.-trending bands of Serpulite Grit and Fucoid Beds are repeated and piled-up by parallel sets of reverse faults which dip steeply to the E.S.E. (cf:- Hinxman, Mem. 1907, fig. 54, p. 563). The imbricate structure ("schuppen struktur", Hinxman, op. cit.) has formed at successively higher levels above the Sole thrust. The zone of imbrication north of Sgurr a' Gharaidh and Glas Bheinn structurally occurs between the Sole and Cadh' an Eididh thrusts and that north of Torr na h-Iolaire occurs above the Cadh' an Eididh thrust (map 1 and map 2).

A successful imitation of the formation of imbricate structures was made by Cadell (1888) in the laboratory. /

laboratory. His study suggests that steeply dipping reverse faults can form by overall transport of a rock-pile along a gently inclined basal or Sole thrust. The movement on the Sole can cause an initial buckling of the overlying strata and eventually the stress is released by the development of parallel sets of steeply inclined reverse faults, which meet the Sole at a moderate angle. Once the process of imbrication has been initiated, the the structures can form at successively higher horizons above the basal or Sole thrust.

(b) Minor folds:- A few minor folds, which are found mainly in the Cambrian quartzites and rarely in the Applecross grits, have been recorded in this area (map 2). The chief features of the folds, which range in size from a few feet to about 30 ft., are as follows -

(1) The folds are open asymmetrical in shape (plate VIII), and are consistently overturned towards the west. The folding is concentric in type, that is, it has been achieved by shortening of strata by slip along bedding planes. The thickness of the strata as measured perpendicular to bedding planes, remains constant throughout the fold.

(2) The axes of the folds plunge at moderately low angles /

angles to the south, south-south-west or south-south-east (fig. 18).

(3) The axial planes of the folds dip steeply (50°-86°) eastwards or are vertical (fig. 18).

There is no lineation associated with these folds.

Some of the minor folds mentioned above occur in the quartzites on the eastern limb of the major fold north of Loch Cadh' an Eididh. Although the greater part of the western limb of this major fold has been truncated by the Cadh' an Eididh thrust, it can be deduced from the attitude of bedding planes that the fold is a moderately open anticline plunging at a low angle to the south, its axial plane being inclined moderately steeply to the E.S.E. The minor folds conform in their open style; axial plunge and orientation of their axial planes to the geometry of the major fold (map 2 and fig. 18). Further, the sense of movement indicated by the asymmetrical minor folds conform to the anticlinal structure. Other N.N.E.-S.S.W.-trending minor folds, which occur outside the limit of this major fold are considered, because of similarity in style and orientation, to be of the same set as the major and minor folds at Loch Cadh' an Eididh.

(c) /

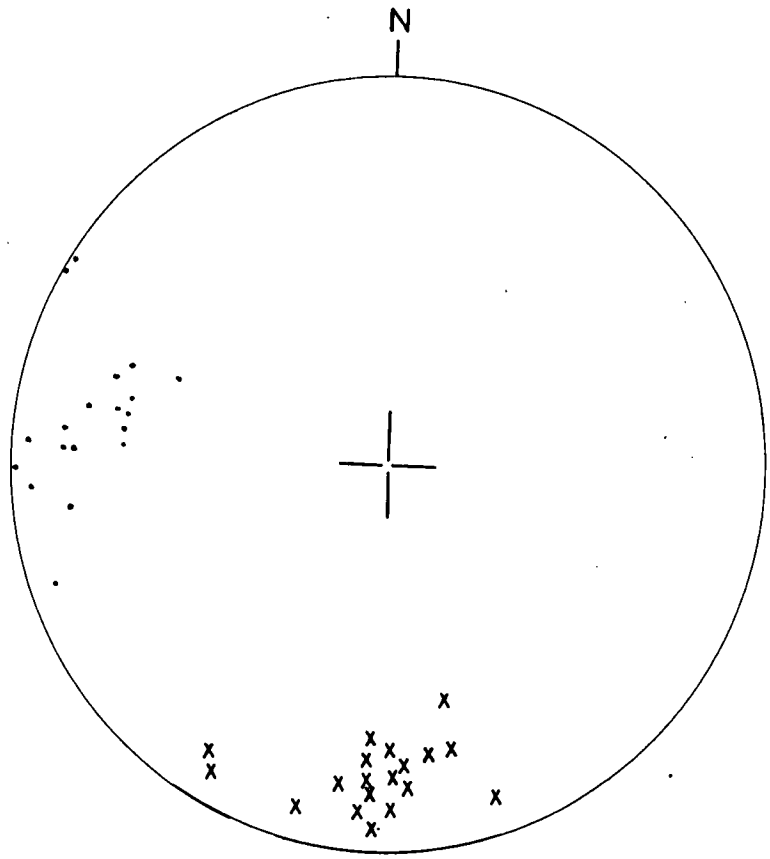


Figure 18. Plots of axes (crosses) and poles to axial planes (dots) of minor folds in Cambrian quartzites and Torridonian (Applecross Group) grits below the Kishorn thrust.

(c) Relationship of folds and thrusts: An apparent relationship between folding and thrusting is suggested by the sub-parallelism between the axial planes of the folds and the thrust planes. Hinxman's (1907, pp. 558-565) account of the structure of the area implies that folding and thrusting belong to the same movement episode. In order to calculate the attitudes of the major thrusts that occur beneath the Kishorn thrust, stratum contours have been constructed using their traces on the one inch Geological Survey sheet nos. 81 and 82 (fig. 19). The dips of the two major thrusts, namely, the Sole and the Cadh' an Eididh thrusts and those of other thrusts occurring north of the limit of this area, have been determined at several stations between Loch Kishorn and Kinlochewe. The measurements show that the thrust planes dip to the E.S.E. at moderately steep angles (45°-68°).* The sub-parallelism of the fold axial planes and /

---

* The term "thrust" generally denotes a reverse fault with low inclination; that is, it is equivalent to the term "overthrust" in the system recommended by the Committee on the Nomenclature of Faults (Reid, et al, 1913). The term "thrust" has been used to denote any reverse fault, without regard to its inclination (op. cit., p.179). The present writer has retained the term "thrust" for these planes, which are, strictly speaking, reverse faults in order to avoid confusion that may arise by changing the terminology because the term "thrust" has been consistently used by previous workers (Peach, et al, Mem. 1907) to designate these planes in the N.W. Highlands.

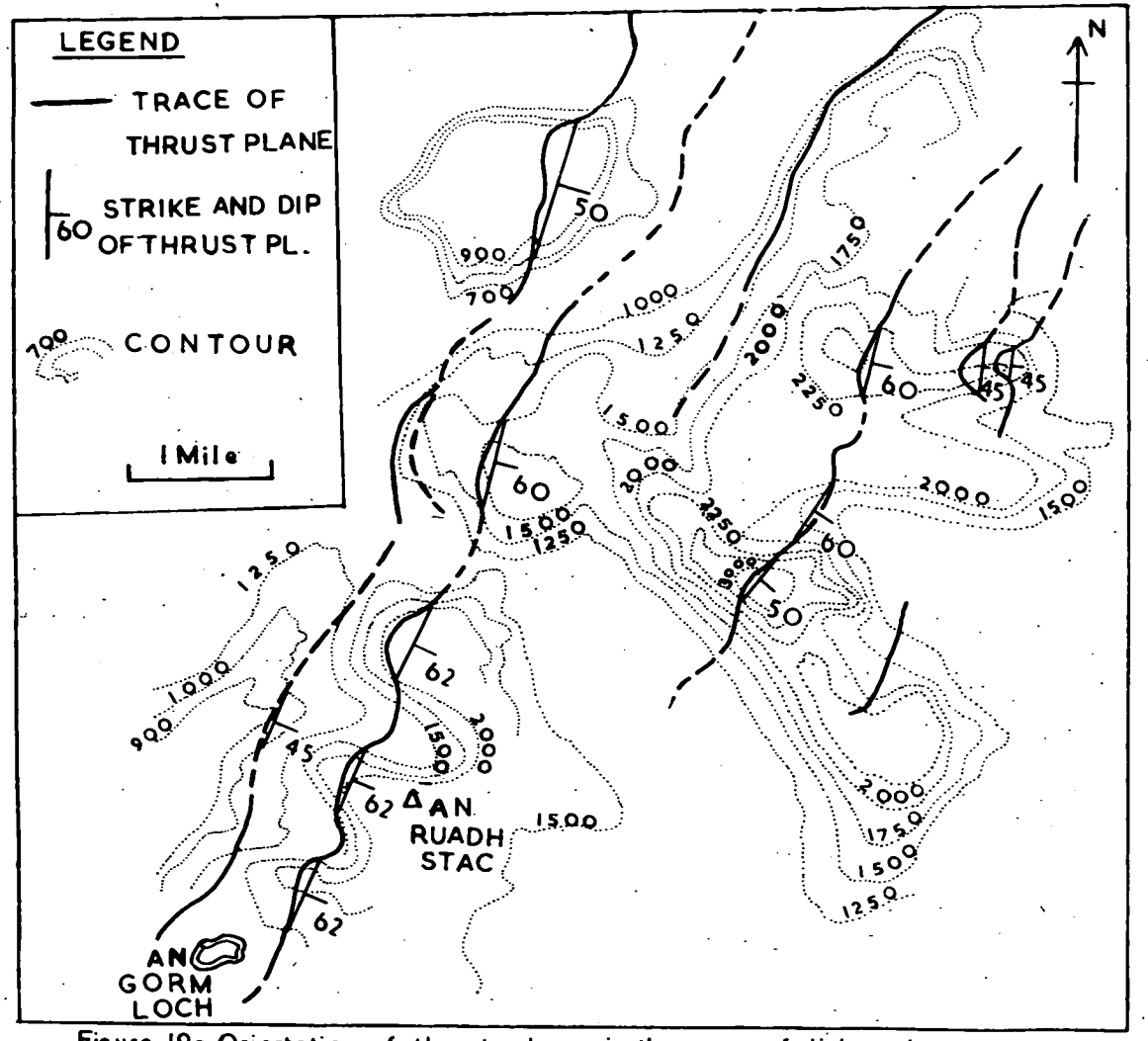


Figure 19a. Orientation of thrust planes in the zone of dislocation.

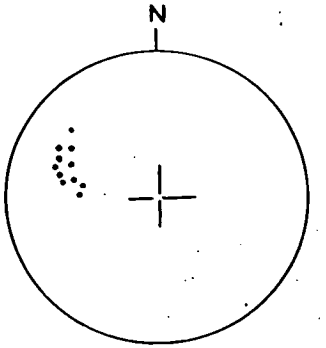


Figure 19b. Plots of poles to thrust planes.

and the thrust planes (figs. 18 and 19) suggest that the folds and the thrusts may be genetically related and from their attitude it can be inferred that both these structures have formed by movement directed on an E.-W. trend. Although these structures may be genetically connected, there is evidence to suggest that thrusting possibly post-dates the folding. It has been stated previously that one limb of a major fold, to which some of the minor folds are related, has been truncated by the Cadh' an Eididh thrust. A study of Hinxman's (1907, pp. 561-562 and fig. 53) section drawn just north of the present area, shows that the axial planes of the N.N.E.-trending folds are always more steeply dipping than the thrusts. In the present area it has been observed that though the axial planes of the N.N.E.-trending minor and major folds are apparently sub-parallel to the thrust planes, the axial planes are actually inclined at slightly higher angles than the thrusts. Further, the present author's observations combined with Hinxman's (op. cit) account of the structure of the area lead to the conclusion that thrust planes may occur in any position on the limbs or crestal region of a major fold. While not disputing Hinxman's postulated genetical relationship between folding and thrusting, it may be pointed out that the above /

above discussion suggests that thrusting post-dates folding, at least slightly, in the area considered.

(2) The Structure of the area between Coille Dhubh and Loch Kishorn.

(a) Major Structures: The rocks outcropping from Coille Dhubh to Loch Kishorn belong entirely to the Cambro-Ordovician formations and structurally occur above the Sole thrust. The Eilean Dubh and Ghrudaidh limestones occupy most of the ground and have been brought forward along a thrust plane, termed the Rassal thrust, which, near Coille Dhubh, has overlapped the Sole thrust. The outcrop of the Rassal thrust, on which the limestones rest, has been traced from Coille Dhubh south-westwards to Rassal where it descends to the road-side (Map 1.). Below this thrust, outcrop of the Basal Quartzite, Pipe Rock, Serpulite Grit and Fucoid Bed occupy a narrow zone, the rocks dipping at low angles to the S.E. This Cambro-Ordovician succession is separated from the Torridonian (Applecross) grits of the undisturbed Foreland by the Fasagh fault. It appears that the Sole thrust has been cut off by the Fasagh fault and part or all of the Cambro-Ordovician succession mentioned above has been brought to its present position by faulting. South-eastwards from the narrow outcrop of Cambro-Ordovician rocks mentioned above /

above and separated from them by the Rassal thrust, the Ghrudaidh and Eilean Dhubh limestones dip steeply (50°-90°) to the E.S.E. and, as a result of folding and thrust-:ing, occupy an area above four miles long and ¾ mile wide. The repetition of these two groups of limestones and the intertonguing of their outcrops at Coille Dhubh, suggests large-scale folding on a N.N.E.-S.S.W. axial trend.

About ½ mile east of Courthill House the Cambro-Ordovician rocks, comprising the Basal Quartzite, Fucoid Beds, Serpulite Grit, Eilean Dubh and Ghrudaidh Lime-:stones, are repeated by a parallel set of reverse faults dipping steeply to the E.S.E. and so form a zone of imbricate structure just below the Kishorn thrust plane (cf:- Peach and Horne, Mem. 1907, fig. 55). The large scale structural features in the S.W. part of the area below the Kishorn thrust are, therefore, similar to those in the N.E. part described previously and indicate movement directed on an E.-W. trend.

(b) Minor Folds: A few minor folds, varying in size from a few feet to about twenty feet, have been noticed in the incompetent dolomitic limestones. The minor folds, which are open asymmetrical structures (plate IX, a), are emphasized by thin quartzose layers that stand out /

out from the more readily weathered limestones. At the crestal parts of some folds, the rock has developed conjugate-like puckers with sharp hinges and paired axial planes, (plate IX, b) parallel to which are coarse shear planes.

The moderately plunging fold axes vary in trend from the E.S.E. to S.E. (fig. 20). The axial planes of folds dip either to the N.E. or to the S.W. The paired axial planes of the conjugate-like puckers intersect in a line which is parallel to the axes of the folds.

The relationship between these S.E.-trending minor folds and the major N.N.E.-trending folds in the area is not apparent. The style and orientation of the minor folds in the limestones suggest that they have been generated by movement directed on a N.N.E.-S.S.W. or N.E.-S.W. trend, whereas the major structures, as noted previously, have developed by movement on a nearly E.-W. trend.

D. /

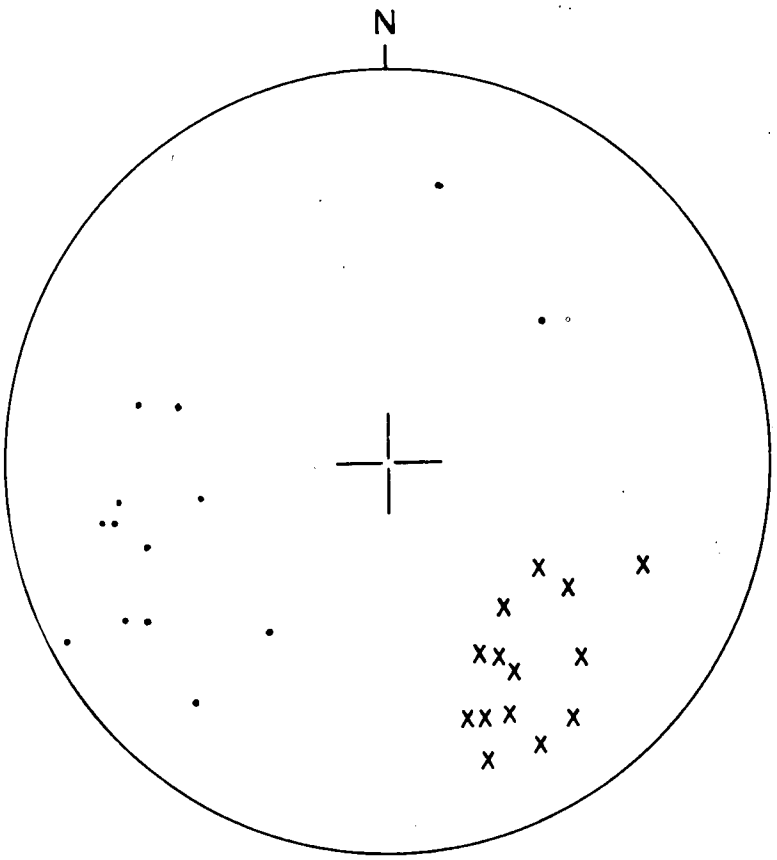


Figure 20.

Plots of poles to axial planes (dots) and axes (crosses) of minor folds in Cambro-Ordovician limestones in Coille Dhubh area.

D. The Kishorn Thrust

The Kishorn thrust, which outcrops to the west of the Moine thrust, is one of the major planes of disruption in the thrust belt of the N.W. Highlands of Scotland. The thrust, which of course derives its name from Loch Kishorn in the present area, has been traced by the Survey Geolo-:gists from Loch Kishorn, northwards to Kinlochewe (sheet nos. 81 and 82) and beyond and southwards to Skye (sheet no. 71). The Kinlochewe, Ben More (in Assynt) and Ben Suardal (in Skye) thrusts, all of which outcrop to the west of and are overlain structurally by, the Moine thrust are considered to be equivalent to the Kishorn thrust by Horne (Mem. 1907, p.466). The Kishorn thrust plane divides the present area into two structural units, the features of which have been described in the previous sections. In the following pages some data have been assembled to give an idea of the nature of the thrust plane itself.

It is apparent from a study of the Geological Survey one inch maps (sheet nos. 81 and 82) that the Kishorn thrust, though trending in its general N.N.E. direction over part of the area between Kinlochewe and Loch Carron, actually follows a somewhat curved course, exhibiting a broad swing in outcrop immediately north of

Glen /

Glen Carron. In order to determine the geometrical form of the Kishorn thrust plane its dip has been calculated at a number of stations between Loch Kishorn and Kinlochewe. The dips at these stations have been calculated by stratum contours, which were drawn on Geological Survey maps (op. cit.) The cyclographic projections of the various attitudes of the thrust planes intersect and show a S.E.-axis of warping (fig. 21). Johnson (1957, p.261), from a similar method of analysis, found that both the Kishorn and Moine thrusts, in the Lochcarron and Coulin Forest region, have been broadly warped on a south-easterly axis. "That this warping is not the result of folding after the development of the thrust belt is shown by the fact that upwarps in the Moine thrust tend to occur vertically above downwarps in the Kishorn thrust." (Johnson, op. cit., p.261). The warping of the thrust planes has caused, locally, a tectonic thickening of the rocks involved in thrusting.

In the present area, the Kishorn thrust outcrop which is usually marked by a topographic feature (plate I, a and b) has been traced for a total distance of nearly nine miles. Between Kishorn and Tornapress, a /

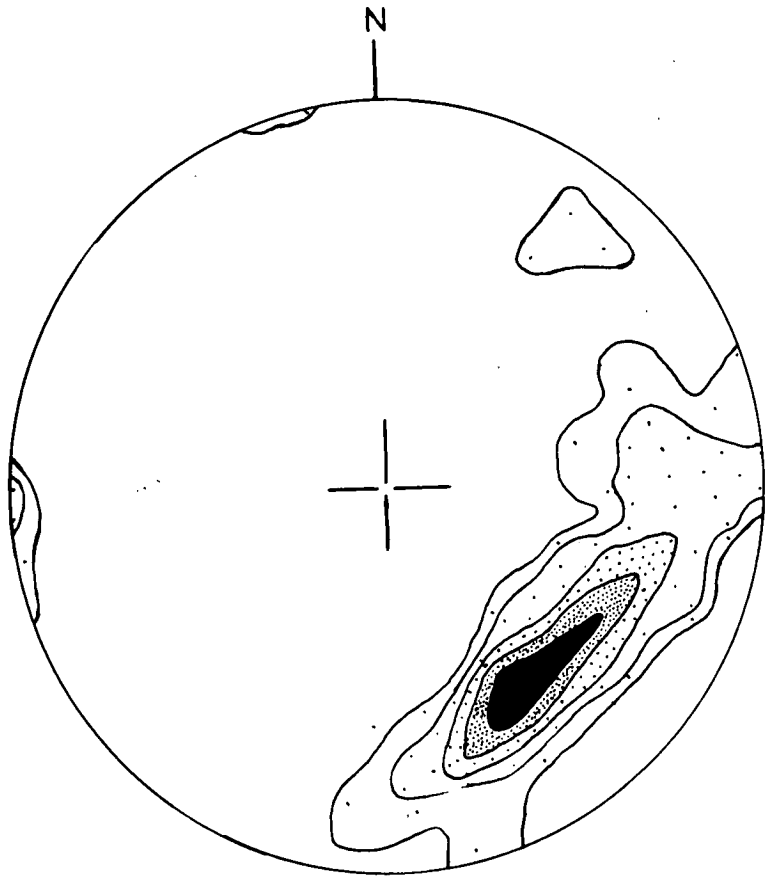


Figure 21. β-diagram showing the calculated axis of warping of the Kishorn thrust.

Contours at 1-2-4-6-8%

a distance of 1½ miles, the thrust strikes N.N.E; thence the thrust takes a N.E. strike, following the course of the Allt Mór and then, assuming an E.N.E. strike, it sweeps round the high escarpments north of Sgurr a' Gharaidh, Glas Bheinn and Tòrr na h-Iolaire and finally descends to the roadside near Cnoc na h-Atha in Glen Carron (Map 1). The thrust has brought Torridonian (Diabaig Group) and Lewisian rocks into contact with different members of the Cambro-Ordovician formation, which outcrops beneath this plane. The thrust is clean-cut and excellent exposures of it have been observed in the gorge occupied by the river Allt Mór northeast of Tornapress, in the stream sections north-east of Glas Bheinn and on the northern slopes of Tòrr na h-Iolaire. The actual measurements of the dip (35°- 55°) of the thrust plane at these places correspond to the moderately steep south-easterly dip which has been calculated indirectly (see above) using the Survey maps for part of the Lochcarron-Kishorn region. Two exposures, which are typical of the numerous others at which the Kishorn thrust may be examined, are described below.

The thrust is well exposed in the deep gorge cut by the Allt Mór about 1½ miles north-east of Tornapress /

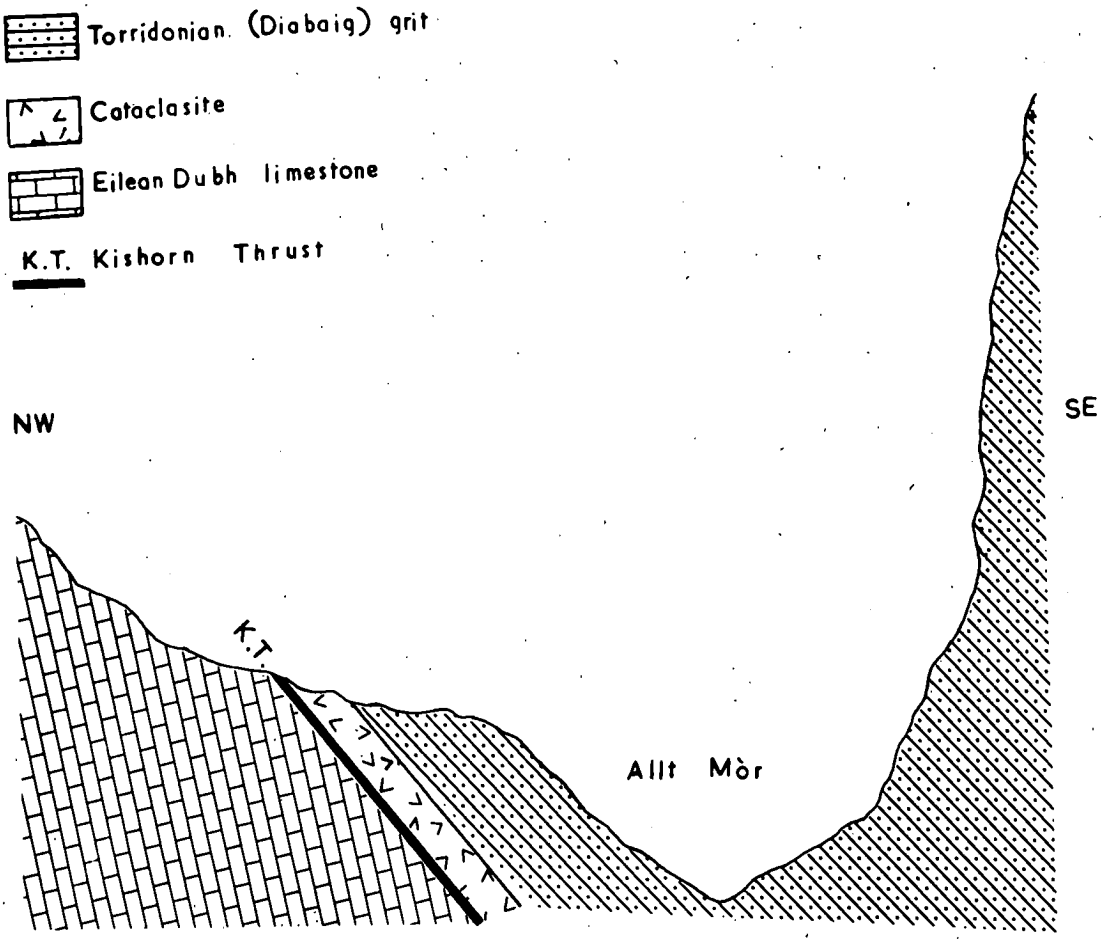


Figure 22. Exposed section of the Kishorn thrust in a gorge cut by the Allt Mòr north-east of Tornapress.

Tornapress (Fig. 22). The clean-cut thrust plane separates the underlying steeply dipping (70° - 80°), shattered, Eilean Dubh limestones from the overlying Diabaig grits. The thrust plane dips at an angle of 50° to the South-east. Just above the thrust plane there occurs a zone, about 2 feet thick, of extremely fine-grained highly crushed rubbly rock, possibly derived by crushing and pulverisation of the overlying grits. A few irregular, angular fragments of grits are seen in the crushed rock, which may be termed a cataclasite (Plate XVI, a). It may be mentioned here that the term "cataclasite" was originally used by Grubenmann and Niggli (1924 ; also see Knopf, 1931, Waters and Campbell, 1935 and Christie, 1960) for a "structureless cataclastic rock" which differs from a mylonite (Lapworth, 1885) in the absence of fluxion structure or parallel platy lamination. The term cataclasite has been used for the present rock which conforms to the above description. The zone of cataclasite is succeeded to the S.E. by the flaggy sheared Torridonian grits (Fig. 22). The Cambro-Ordovician limestones and the Torridonian grits in the vicinity /

vicinity of the thrust are stained with red haematite and are sometimes traversed by small carbonate veins. No linear structures have been observed in the rocks occurring immediately above and below the thrust plane in this section.

The second exposure of the Kishorn thrust to be described is located about 1 mile north of Tullich, on the course of the Amhainn Bhuachaig, where mechanically shatter-:ed and closely jointed Cambrian quartzite is exposed just below the clean-cut thrust plane, which dips at an angle of 35° to the S.E. (Fig. 23). Immediately above the thrust there occurs a two feet thick zone of rubbly cataclasite, which is almost powdery at places and im-:pregnated with carbonates and red haematite. A few lenticles of gneissic rocks and coarse felspars are visible in the cataclasite which is devoid of parallel lamination (Plate XVI, c.). Succeeding this zone is a hornblende-bearing acid Lewisian gneiss, with foliation parallel to the thrust plane. For a thickness of about 2½ feet above the zone of cataclasite, the gneiss is extremely sheared and flaggy but at greater distances from the zone the gneiss bears very little impression of cataclasis. A fine striation lineation plunging to the E.S.E. (1st linear structure /

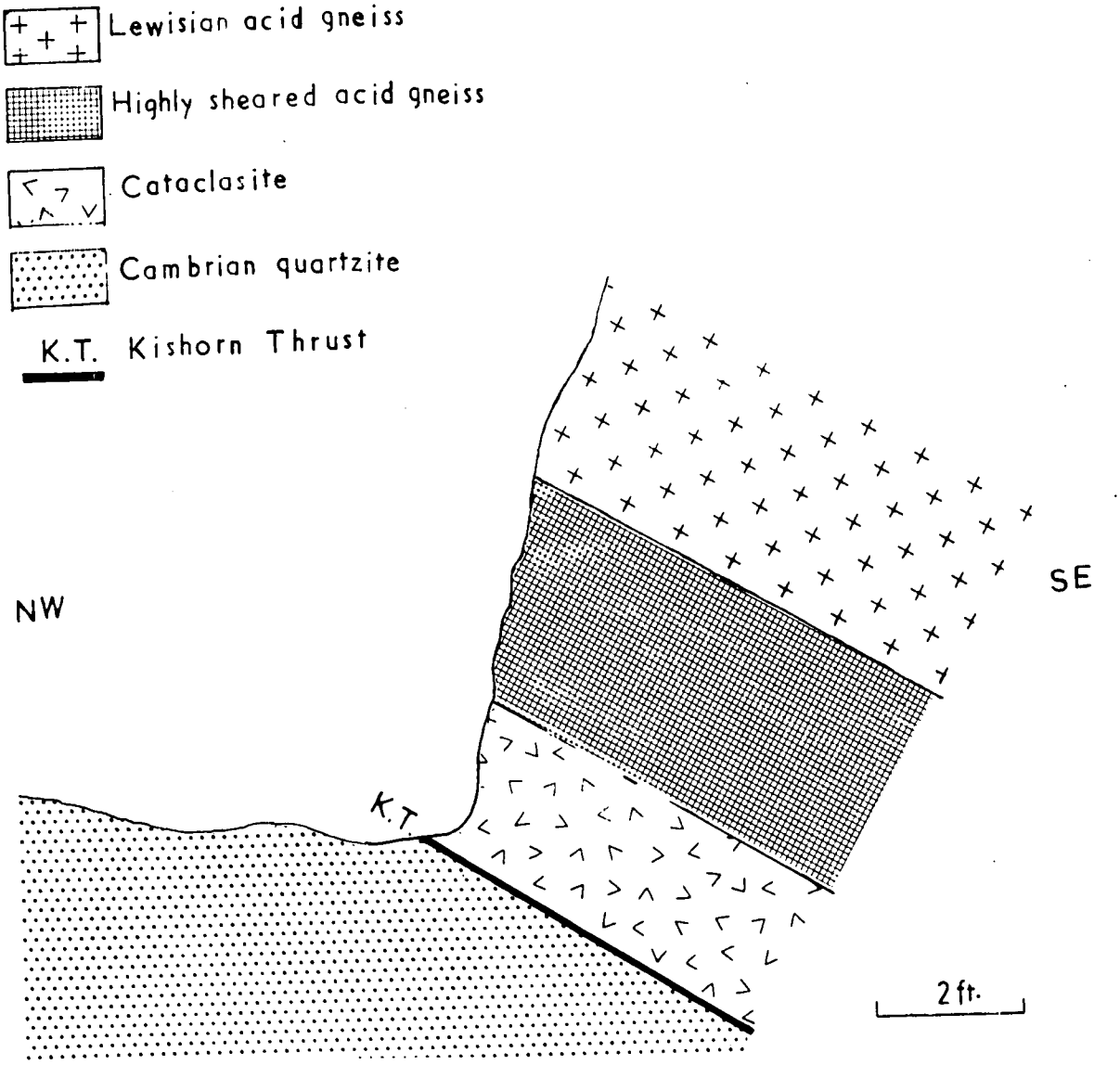


Figure 23. Exposed section of the Kishorn thrust north-east of Glas Bheinn.

structure, see page 94) is present in the topmost band of Lewisian rocks in Fig. 23. On approaching the thrust, the lineation can be traced into the upper part of the flaggy, sheared hornblende-bearing acid gneiss, but beneath this, in the zone of cataclasite, just above the thrust plane, the lineation cannot be detected. There is no linear structure in the Cambrian quartzite below the thrust. The quartzite is strongly deformed by mechanical granulation but exhibits no sign of constructive metamophism. It may also be mentioned here that the cataclasite occurring just above the thrust, is different in character from the flaggy, banded, mylonites and partially recrystallized blasto-mylonites recorded from within the Lewisian outcrop away from the Kishorn thrust.

On the basis of the foregoing discussions, some aspects of the Kishorn thrust are summarized below :-

(a) The Kishorn thrust is clean-cut and dips, for part of its outcrop, moderately steeply to the south-east. The study of the Geological Survey maps (sheet nos. 81 and 82), however, suggests that the Kishorn thrust is not a plane surface, but is flexed on a S.E. axis, which has resulted in broad embayments of /

of the thrust outcrop as seen between Kishorn and Kinlochewe.

(b) The transgressive nature of the thrust is shown by the fact that it has brought the overlying Torridonian and Lewisian rocks into contact with different members of the Cambro-Ordovician formation. Irrespective of the nature of the rocks that have been brought into contact (such as grit and limestone; grit and quartzite; gneiss and quartzite; gneiss and mudstone etc.) the thrust is always a sharply defined plane.

(c) The cataclasites occurring just above the Kishorn thrust are about 2 feet in thickness and are formed by mechanical granulation of overlying rocks. The cataclasites, which lack any close-spaced planar structure, differ in character from the platy, laminated mylonites and blasto-mylonites in the Lewisians away from the Kishorn thrust.

(d) The trace of the E.S.E. trending first striation lineation, which is present in Lewisian and Torridonian (Diabaig) rocks above the Kishorn thrust, is lost in the vicinity of the 2 feet thick cataclasite which occurs just /

just above the thrust and no linear structure can be traced continuously from the rocks above the Kishorn thrust to those below it. The Cambro-Ordovician rocks just below the thrust are mechanically shattered and lack any linear structure.

(e) The extent of horizontal displacement along the Kishorn thrust cannot be ascertained on the evidence available in the area. It may be mentioned, however, that the normal uninverted limb of the Loch Alsh Syncline, which is well observed at Loch Alsh and in eastern Skye, cannot be traced northwards from Loch Alsh into the present area (cf. Geological Survey sheets nos. 81, 82 and 71) and presumably this limb as well as part of the inverted limb has been truncated by the Kishorn thrust (cf. Mem. 1907, fig.55). From a consideration of the width of outcrops of the Torridonian rocks at Loch Alsh and at Loch Carron (sheet nos. 81, 82 and 71), it may be suggested that Torridonian rocks, at least 3 - 4 miles wide, have been cut out along the Kishorn thrust plane north of Loch Carron.

SECTION IV - MICROSCOPIC STRUCTURAL DATA

A. General Statement.

The pattern of the megascopic structures having been established, it is proposed now to describe the results of a petrofabric analysis, which has been carried out on rocks occurring above and below the Kishorn thrust plane. The rocks analysed consist of Cambrian quartzites, Torri-:donian grits and Lewisian gneisses and their mylonitic derivatives. The specimens for analysis were collected at localities shown on the sketch map, fig. 24. Quartz has been selected for microfabric analysis because it is common in the different rock types and hence useful for comparative study.

Petrofabric analysis has been carried out with two objectives, firstly, to compare the microfabrics of rocks of the different formations occurring above and below the Kishorn thrust plane and secondly, to study the relations of microfabrics to the visible structures.

B. Quartz Orientation in Rocks above the Kishorn thrust plane.

The analysed specimens consist of Torridonian (Diabaig) grits and Lewisian acid gneisses and their mylonitic derivatives. The deformation and metamorphism of /

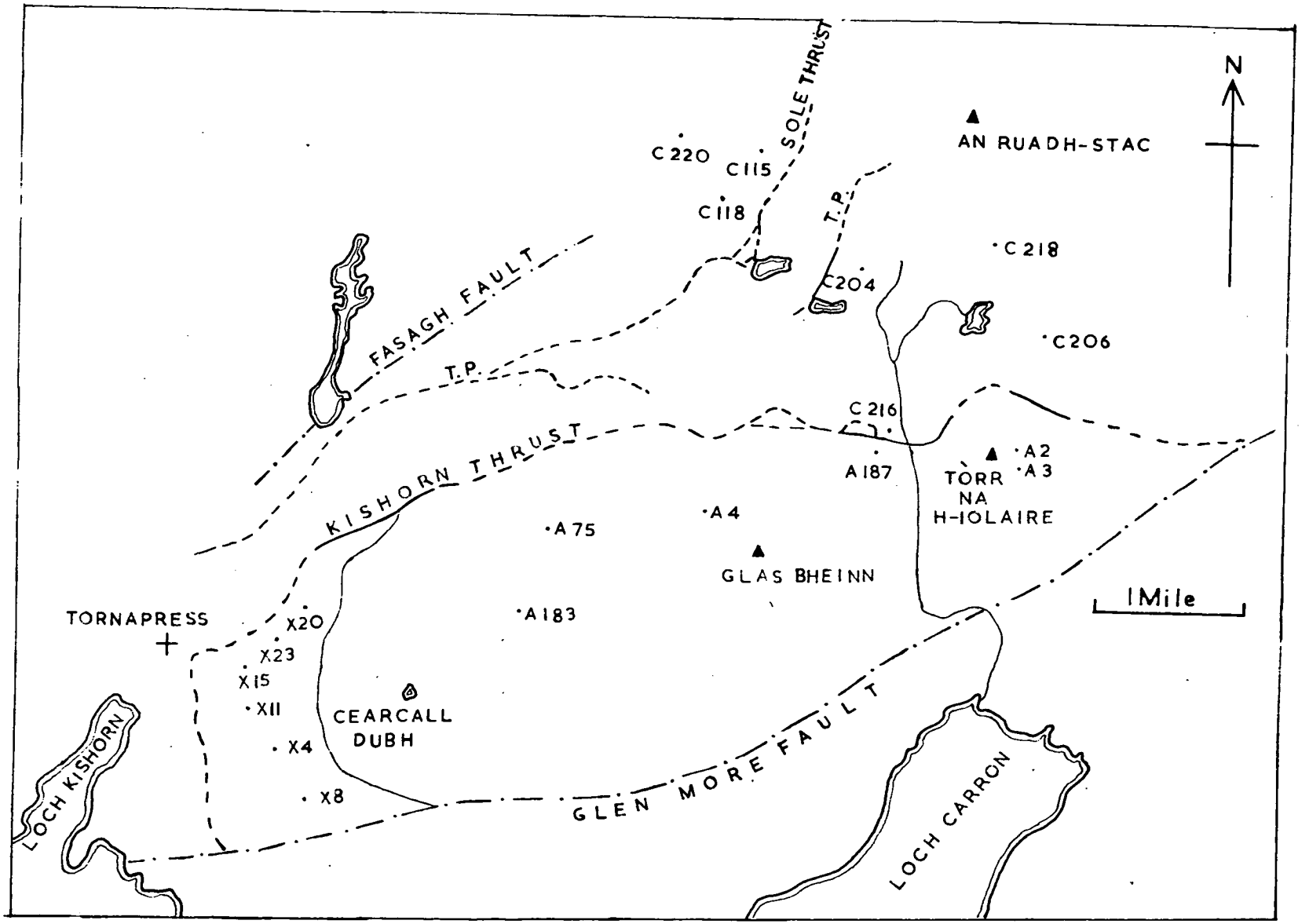


Figure 24. Map showing localities of the analysed specimens of quartz-bearing rocks.

of the rocks has already been discussed (Sections II and III). In the majority of the specimens the C-axes of quartz have been measured in a single section cut normal to the foliation and to the visible linear structure. The quartz C-axes may be measured no matter what their orientation in a section but errors may arise due to the omission or underselection of grains in which the C-axis is normal to the plane of the section and which, therefore, remain in extinction during rotation about the vertical axis of the Universal Stage. In all the fabric diagrams prepared from Lewisian and Torridonian (Diabaig) rocks the megascopic structures, such as, foliation, cleavage and lineation have been plotted so as to serve as co-ordinates when the diagrams are compared with one another. In two specimens - one each from the Torridonian (specimen no. X.8, fig. 25e) and Lewisian (specimen no. A.187, fig. 27a) rocks - C-axes were measured in two sections cut at right angles to each other. The pattern obtained in one section was then rotated (cf:- Knopf and Ingerson, 1938) into the plane of the other section and the rotated fabric was found to be essentially similar to that obtained by independent measurements made from the other section. This observation suggests that the quartz fabric is homo-:geneous in these rocks. It has to be noted, however, that /

that in the deformed Torridonian rocks, the diagrams are selective because some crushed quartz grains are too small to be measured. In one of the several Lewisian microfolds studied, the fabric has been found to be inhomogeneous on the scale of that single fold.

Microfabric analysis of these rocks indicates that the quartz crystals acquired a preferred orientation during two movement phases. The fabric of the first phase is developed in Lewisian and Torridonian rocks. Overprinting of fabric of the second phase upon that of the first can be best studied in some Lewisian rocks.

(1) The Quartz Microfabric of the First Movement Phase.

(a) Torridonian (Diabaig) Rocks

Six specimens, each containing the first linear structure (b1), have been studied (fig. 25). Three of these specimens show effects of strong mechanical granu-:lation and little recrystallization, while the other three rocks exhibit evidence of a greater degree of recrystallization. The tectonic quartzes measured in these rocks belong to two categories:-

(i) Elongate slivers formed by the stretching and mechanical granulation of quartz (plate XVII a,b). The slivers are flattened in the schistosity (S1) and /

and have their longer dimensions parallel to megascopic lineation (b1). The quartz crystals show undulose extinction and the orientation of the C-axis varies, in some cases quite considerably, over a single grain. For those grains in which the variation was slight, the mean C-axis orientation of the grain was recorded, but where the variation was great, the orientations of the C-axes at different parts of a single grain were separately recorded. Weiss (1954, p.62) has observed that this is a satisfactory method of presenting a representative picture of the optical orientation of highly strained quartzes.

(ii) Recrystallized small, granular quartzes which usually occur in lenticular clusters, the longer dimensions of which are parallel to the megascopic lineation (b1) (see plate XVII c,d). The individual grains in the clusters are clear, free from strained extinction and have straight or slightly crenulate margins.

Figs. 25, a,b,c, show the orientation of the C-axes of "sliver-like" quartzes. The pattern is either a partial girdle, the axis of which is parallel to the megascopic lineation, or crossed-girdles with the girdles being /

Figure 25. Quartz orientation diagrams in deformed Torridonian (Diabaig) rocks.

a. 280 c-axes in specimen X.15. Quartz slivers. Contours at 1-2-4-6-8% per 1% area.

b. 300 c-axes in specimen X.23. Quartz slivers. Contours at 1-2-4-6-8% per 1% area.

c. 250 c-axes in specimen X.20. Quartz slivers. Contours at 1-2-3-4-6% per 1% area.

d. 300 c-axes in specimen X.4. Recrystallized quartz. Contours at 1-2-3-4% per 1% area.

e. 250 c-axes in specimen X.8. Recrystallized quartz. Contours at 1-2-4-5% per 1% area.

f. 150 c-axes in specimen X.8. Quartz slivers. Contours at 1-2-3-4% per 1% area.

g. 250 c-axes in specimen X.11. Recrystallized quartz. Contours at 1-2-4-5-6% per 1% area.

h. 150 c-axes in specimen X.11. Quartz slivers. Contours at 1-2-3-4% per 1% area.

b_1 - first linear structure.

S_1 - schistosity parallel to axial planes of the first folds.

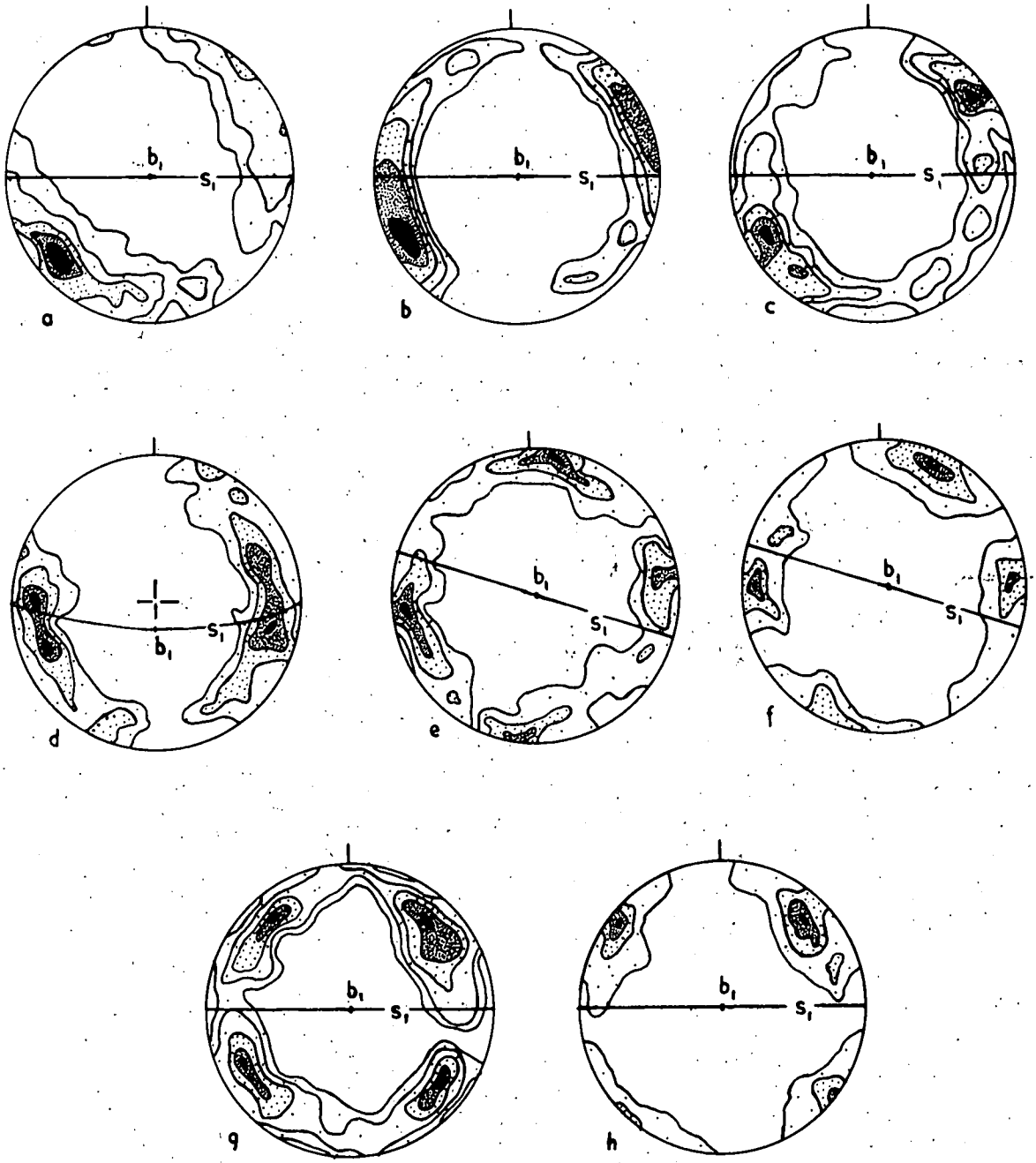


Figure 25

being inclined at low angles to each other and intersecting in a line nearly perpendicular to the lineation (b_1). Both patterns show strong maxima which are situated 30°-40° from the trace of schistosity (S_1) and 70° from the projected pole of the lineation. Since the megascopic lineation is due to the parallelism of longer dimensions of the elongate slivers, the C-axes of these quartzes are, therefore, at high angles to their elongation. The symmetry of the diagrams is monoclinic.

Figs. 25, d,e,g, are the orientation patterns of the C-axes of recrystallized granular quartzes. The C-axes are arranged in crossed-girdle fashion with scattered sub-maxima, the girdles intersecting in a line normal to the megascopic lineation. A pair of relatively stronger maxima occur 30°-40° from the trace of schistosity and about 70° from the pole of the megascopic lineation. In fig. 25, d, the stronger maxima lie close to the schistosity (S_1).

An interesting feature in these crossed-girdle patterns, particularly in fig. 25, e, and fig. 25, g, is that they approach orthorhombic symmetry. This symmetry is not perfect because only one of the ideal, paired maxima is developed in a single diagram. When the diagrams are considered together with the megascopic schistosity /

:tosity (S_1) and lineation (b_1), the symmetry of one diagram (fig. 25,e) becomes monoclinic, while the near-orthorhomic symmetry of the other (fig. 25,g) remains unaffected.

The specimens from which figures 25,e, and 25,g, have been prepared contain some sliver quartzes in addition to the recrystallized granular quartzes which have been measured. The orientation of the C-axes of the slivers have been determined (figs. 25,f, and 25,h) by selective measurement from the same thin sections used for figs. 25,e, and 25,g. The patterns are essentially similar to those derived by measurement of recrystallized grains.

(b) Lewisian Rocks

The Lewisian gneisses are usually more recry-:stallized than the Torridonian rocks. Evidence of mechanical deformation is borne by the porphyroclasts of felspars but most of the quartzes have recrystallized. The data presented below have been obtained from rocks which show the effects of the first fold movements only.

Petrofabric diagrams (fig. 26) have been prepared from a specimen of mylonitized Lewisian containing several near-isoclinal first folds. The folds are such that the limbs are thinned and the crests are thickened. In sec-:tion the rock consists of bands of very fine-grained sericitic /

Figure 26. Quartz orientation diagrams in a mylonitized Lewisian rock (specimen A4).

a. first fold showing concordant quartz veins (in black).

b. showing fields in which quartz c-axes were measured.

c. thinning of fold limbs and sliding of one fold over another. Cf. - Warren Carey. 1954.

d. 200 c-axes in field 1.

e. 200 c-axes in field 11.

f. 200 c-axes in field 111.

g. 200 c-axes in fine grained slivers.

b_1 - fold axis, parallel to first lineation.

A.P. - axial plane, parallel to first axial plane schistosity (S_1).

Contours at 1-4-6-8-10-16% per 1% area.

h. Synoptic diagram of quartz maxima from different parts of the specimen (A4).

Full lines - maxima of 8% and more.

Dotted lines - maxima of 6% and more.

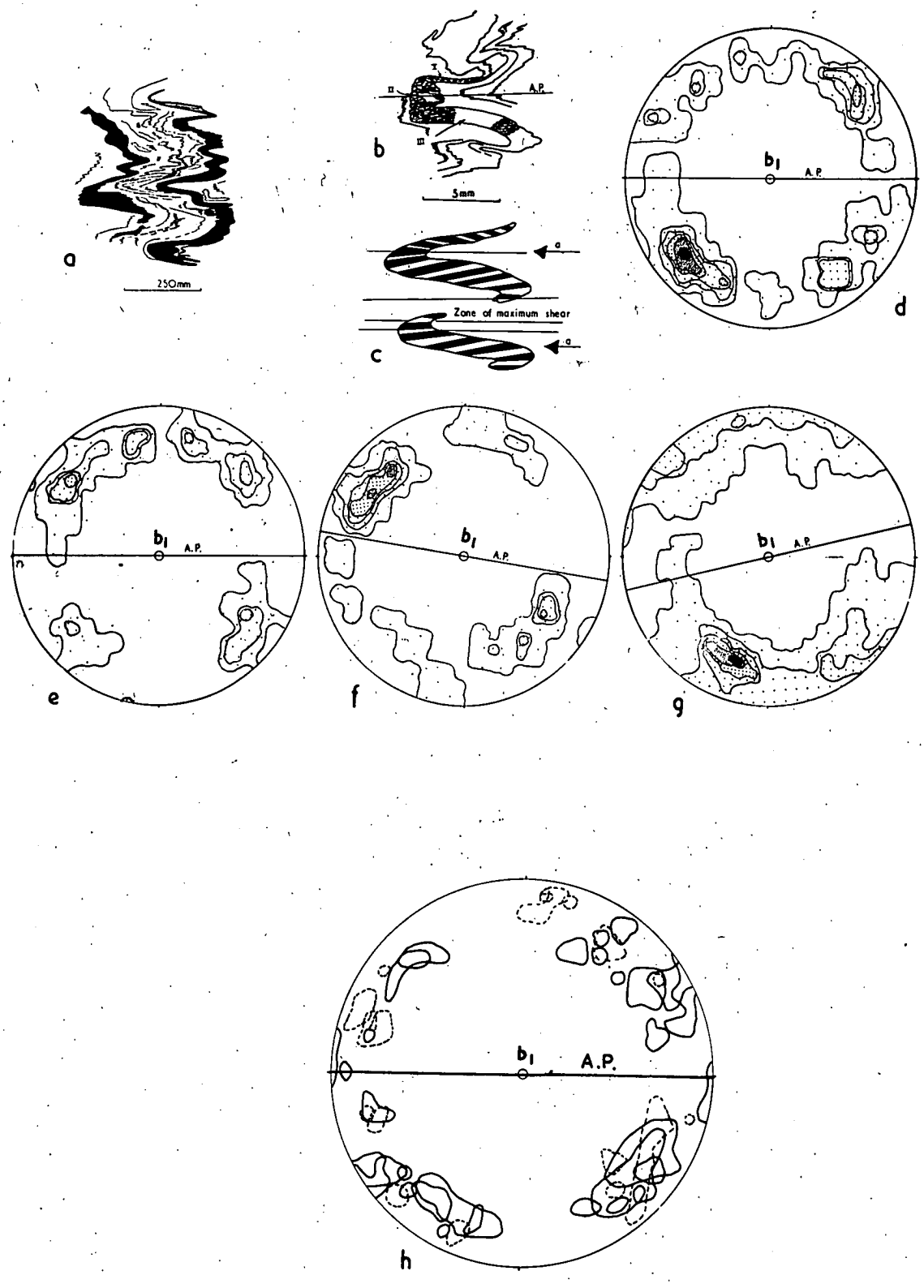

a
250mm
b
II
I
III
A.P.
5mm
c
a
Zone of maximum shear
a
d
b1
A.P.
e
b1
A.P.
f
b1
A.P.
g
b1
A.P.
h
b1
A.P.

Figure 26

sericitic material and concordant bands of quartzose material. In individual folds the quartz grains are commonly dimensionally aligned either with their long axes parallel to the axial plane or with them arranged in a fan around the hinge. Some folds have a rather different arrangement to this: on one limb the quartz grains are relatively large and are less flattened than usual in the rock, while on the other limb the grains are much smaller and are greatly flattened. In these folds the former limb is thickened and the latter is thinned so that it presumably represents a zone of maximum shear (see Carey, 1954) along which the fold as a whole has moved. The diagrams (fig. 26, d,e,f.) prepared from the limbs and the cores of the folds in the specimen are essentially the same and consist of prominent maxima that are arranged approximately symmetrically around the axial plane. The maxima lie in two girdles which intersect in a line that makes a high angle to the fold axis. The symmetry of the quartz fabric is near-orthorhombic as seen by plotting the maxima from different diagrams in a synoptic diagram (fig. 26, h.). In one of the folds showing strong attenuation of one limb, it was found that the fabric is homogeneous on the scale of a single fold. Thus /

Thus of the paired maxima mentioned above, one is strongly developed on one limb and the other is prominent on the other limb.

Figures 27, a, b and c have been prepared from specimens which show a fine striation lineation (b_1). The quartzes are small recrystallized grains and they occur in clusters which are elongated in the direction of mega-:scopic lineation. Figures 27a and 27b show partial girdle patterns with maxima at 30°-40° to the schistosity (S_1) and 70° to the projected pole of lineation (b_1). The girdle axis is parallel to b_1. Fig. 27c shows a double-girdle or crossed-girdle pattern, in which the scattered sub-maxima are arranged in a roughly symmetrical manner about the trace of the schistosity. The relatively stronger maxima occur at 40° to the schistosity (S_1) and at high angles to the lineation (b_1). The girdles are moderately inclined to each other and intersect in a line nearly normal to the lineation. The diagram, considered together with the megascopic schistosity and lineation, approaches orthorhombic symmetry.

(c) Summary of data on the microfabric of the first movement phase.

The microfabric data obtained from the Torri-:donian and Lewisian rocks are summarised below:-

(a) The Torridonian and Lewisian rocks share similar patterns of quartz microfabric. In the range of specimens /

Figure 27.
(a, b, c.) Quartz orientation diagrams in Lewisian rocks.

a. 250 c-axes in specimen A 187.
Contours at 1-2-4-6-8% per 1% area.

b. 250 c-axes in specimen A 75.
Contours at 1-2-4-6-8% per 1% area.

c. 250 c-axes in specimen A 183.
Contours at 1-2-4-6% per 1% area.

S_1 - foliation parallel to axial plane of first folds.

b_1 - first linear structure.

Figure 27. d.

Synoptic diagram showing the orientation of the maxima of quartz c-axes in Torridonian (Fig. 25, e, f, g, h,) and Lewisian (Figs. 26 and 27, c) rocks with "crossed-girdle" pattern. Maxima 4% or more.

S_1, b_1 as in Figs. 25, 26.

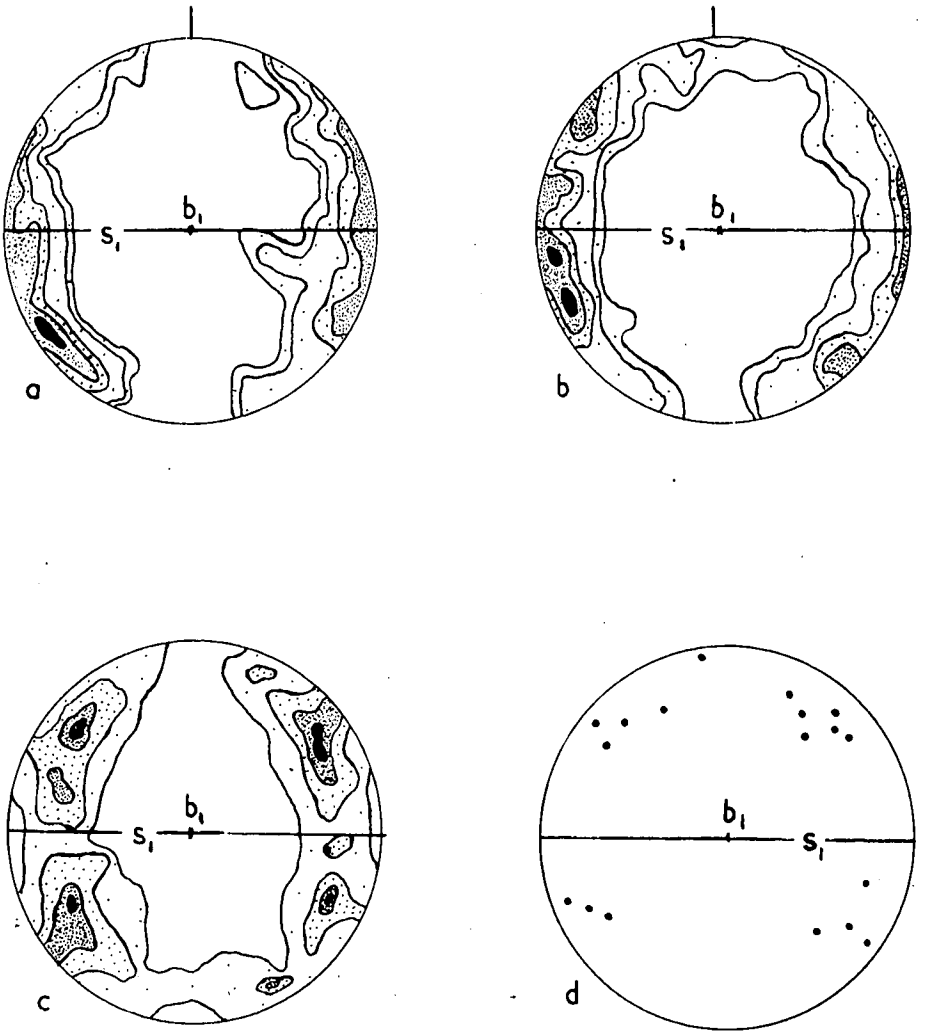


Figure 27

specimens considered, a notable feature is that the fabric patterns in rocks which show advanced recrystallization are essentially similar to those in rocks which are weakly recrystallized. In the specimens analysed there is no evidence of tectonic structures and textures other than those related to the first fold movement.

(b) The pattern of the microfabric is either a partial girdle with an axis trending W.N.W.-E.S.E., parallel to the visible first linear structure (b_1) or double girdles which are inclined at a low angle to one another and intersect in a line perpendicular to the first linear structure (cf:- Johnson and Gangopadhyay, in press).

(c) Some diagrams with double-girdle or crossed-girdle patterns approach orthorhombic symmetry. In some cases, including the Lewisian specimen containing first folds (fig. 26), the near-orthorhombic symmetry is not disturbed when the megascopic structures (S_1 and b_1) are inserted in the fabric diagrams. In other cases, notably in fig. 25e, the trace of schistosity and the pole of lineation do not coincide with the trace of a symmetry plane and the pole of a symmetry /

:metry axis respectively. When the megascopic struc-:tures are plotted in this fabric diagram, the near-orthorhombic symmetry of the diagram is reduced to monoclinic.

The "crossed-girdle" patterns with near-orthor-:hombic symmetry are problematical and raise the question of relationship of such fabrics with the first folds, which posses a monoclinic symmetry. In the case of Lewis-:ian folds analysed (fig. 26) it has been noticed that the microfabric is identical on the limbs and core of the folds and cannot be unrolled about the fold axis. The orienta-:tion of the quartz C-axes has, therefore, taken place during or after the generation of these folds. The fold geometry and texture of the rock suggests considerable transport along the axial planes and consequently, the movement plan responsible for the generation of first folds is likely to be monoclinic in symmetry. An appar-:ently orthorhomic fabric, however, indicates little or no transport.

Quartz microfabrics with orthorhombic symmetry, especially of the crossed-girdle type, have been reported from many parts of the world. They have been described from the granulites of Saxony (Sander, [illegible] 1930, 1934), the /

the Finnish granulites (Sahama, 1936), the Finnish quartz-:ites (Hietanen, 1938) and the quartz-tectonites in the Appalachians (Balk, 1952). [Some of the fabric patterns in the Moine Schist (Phillips 1937) have crossed-girdle pattern with near-orthorhomic symmetry]. Christie (1956, Ph.D. thesis) in Assynt, Johnson (1957, 1960), Johnson and Gangopadhyay (in press) in Ross-shire, have noted the occurrence of orthorhomic crossed-girdle quartz fabrics in rocks from the thrust belt. Patterns of crossed-girdle type have also been recorded in Dalradian quartzites (Weiss, McIntyre and Kürsten, 1955). The pattern is so common that it is likely that it represents a special kind of quartz fabric as has been suggested by most workers (Sander, 1930, 1934; Turner, 1948; Fairbairn, 1949).

Sander (op. cit.) interpreted the orthorhombic fabric in terms of a "flattening" (plättung) achieved by slip on two equivalent hol slip planes, combined with yielding on okl planes. Whereas the orthorhombic symmetry of the fabric indicates little tectonic transport while the fabric was produced, Sander considered that the quartz fabric reflected the final imprint of deformation, which may have been preceded by translative movements of con-:siderable /

:siderable magnitude. Sahama (1936) considered that the orthorhombic crossed-girdle fabric was an overprint due to a late flattening type of deformation on a pre-existing megascopic fabric. Christie (1956) concluded that the quartz orientation was induced by the final (orthorhombic) imprint of the deformation which produced the near-isoclinal folding in rocks - the earlier monoclinic and the later orthorhombic movement episodes being genetically related. The near-isoclinal folds were produced by bed-:ding slip at an early stage of deformation, while the microfabric was induced by pure shear on intersecting planes, which are inclined to the axial plane of folds, at a late stage of deformation when bedding slip became passive. Johnson (1960), Johnson and Gangopadhyay (in press) considered that the orthorhombic crossed-girdle fabric was related to the same episode of movement as the first fold movements recognized in the Lochcarron area.

It is suggested here that some caution is necessary when attempting to interpret the symmetry of fabric in terms of symmetry of movement. It has been suggested by many authors (cf:- Sander, 1930; Turner, 1948; Fairbairn, 1949; Knopf and Ingerson, 1938) that the symmetry of fabric reflects the symmetry of movement and the hypo-:thesis /

:thesis has been applied in many cases. There are, however, exceptions (cf:- Anderson, 1948, p.121; Kvale, 1946-47, p.194 and 1953, pp. 52-53; Weiss, 1955) and care has to be taken to assess the nature of the fold movement before interpreting the symmetry of fabric (cf:- Weiss, 1956, D.Sc. thesis, p.102). In case of shear folds, the mechanism of fabric formation may be complex (cf:- Carey, 1954). Ball (1960, p.276), investigating folds of com-:plex nature observed that the symmetry of the microfabric did not reflect the symmetry of fold though the micro-:fabric and fold were genetically related. In the iso-:clinal folds investigated in the present area, there is abundant evidence of flowage along axial planes. The quartz microfabric suggests a movement plan higher in symmetry (near-orthorhombic) than that required to explain the generation of the folds with monoclinic symmetry. It is possible that the mechanisms responsible for the quartz microfabric in some folds, which show evidence of axial plane shear and flowage, may be more complex than commonly understood at the present time. There is considerable difference in opinion among geologists as to the mechanisms by which quartz acquires a preferred orientation (Fairbairn, 1949, pp. 117-133). The high symmetry and crossed-girdle patterns /

patterns of microfabrics may, therefore, be misleading in some cases.

The close relationship between the microfabric and the megascopic structures has already been noted in previous pages of this section. The single girdle patterns with monoclinic symmetry can be interpreted in terms of the first fold movements. The orthorhombic symmetry of the crossed girdle pattern is not perfect. The insertion of megascopic structural data (S_1 and b_1) in individual diagrams may or may not reduce the near-orthorhombic symmetry. A synoptic diagram (fig. 27d), prepared by plotting the positions of maxima from all the fabric diagrams with crossed-girdle patterns, shows that the maxima maintain a symmetrical relationship with the regional megascopic structures (S_1 and b_1). Statistically, therefore, there is a significant angular relationship between the megascopic structures of the first generation and the quartz microfabric. The orthorhombic microfabric, even if imprinted slightly later than the first folds, is genetically related to the phase of first fold movement. Further, the specimens analysed show no effect of any movement phase other than the first phase and the microfabric is essentially the same in weakly recrystallized Torridonian and in the well-recrystallized Lewisian rocks. It /

It is concluded, therefore, that the quartz microfabrics both the single and crossed-girdle types, are genetically related to the first fold movements. Whether some fabrics of high symmetry have been imprinted slightly later in the same movement phase (cf:- Sahama, 1936; Christie, 1956) is considered to be debatable because of the complex nature of some folds.

(2) The Quartz Microfabric of the Second Movement Phase.

In certain localities within the Lewisian out-:crop the second folds occur with a well-developed axial plane cleavage. In specimens collected from these locali-:ties a quartz microfabric related to the second folds has been found to be overprinted on the first girdle fabric.

The second folds, which have axes (b_2) trending N.N.E.-S.S.W. and axial planes (S_2) dipping 40°-55° to the E.S.E., are such that their limbs are thinned and cores relatively much thickened. It has been shown previously (p.107) that these folds have been generated by strong shear movement along axial plane surfaces, the direction of movement (a-axis) being parallel to a line plunging moderately (40°) to the E.S.E. The quartz fabric that is related to the second folds is described below.

Two specimens for analysis have been collected from /

from Tòrr no h-Iolaire (maps 1 and 2), where the second folds are strongly developed and the megascopic structures of the first generation (S_1 and b_1) are distorted by those of the second (S_2 and b_2) (see p.102 and plate V). Micro-:scopic examination of the rocks provides evidence of extension along axial plane surfaces. Quartz grains, which occur in concordant bands, exhibit a marked dimen-:sional orientation and their long axes lie sub-parallel to the second axial plane cleavage, S_2 (plate VI). The grains show, at most, only slight strained extinction and the intergranular boundaries are smooth. The fine serici-:tic matrix between the quartzose bands is minutely corru-:gated.

In the first specimen, the first linear struc-:ture (b_1) is cut by a close-spaced cleavage (S_2) and is nearly obliterated. Two fabric diagrams, one from the limb and one from the crestal part of a second fold, have been prepared (fig. 28). The patterns obtained in these diagrams are similar and most of the quartz C-axes are concentrated in a maximum which is situated near the axial plane (S_2), the trace of which has been plotted on the diagram. This maximum is stronger in the diagram pre-:pared from the limb than in that prepared from the crestal part, /

Figure 28. Quartz orientation diagrams from a second fold in a Lewisian rock (specimen A2).

a. 350 c-axes from field 1 of a second fold.

b. 200 c-axes from field 11 of a second fold.

b_1 - first linear structure.

b_2 - second fold axis.

S_1 - foliation parallel to axial plane of first folds.

S_2 - second axial plane.

Contours in (a) at 1-2-3-4-5% per 1% area.

Contours in (b) at 1-2-3-4-8-9% per 1% area.

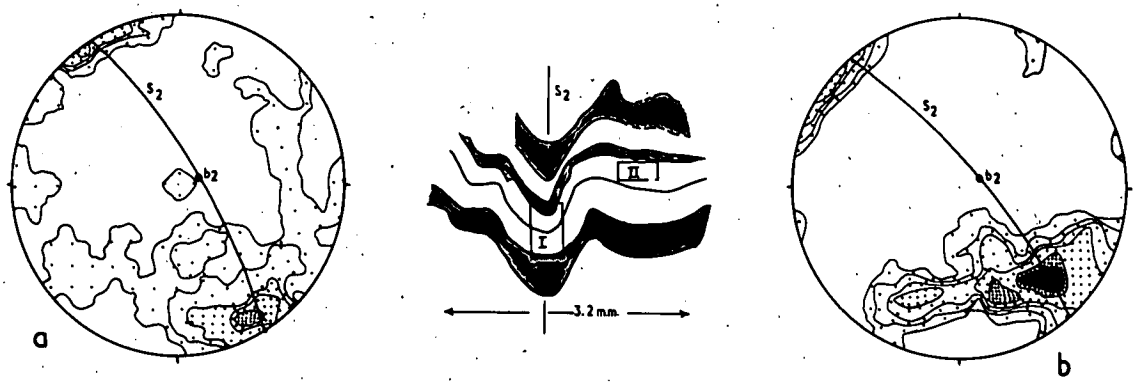


Figure 28

part, where the quartz grains are less flattened. The preferred orientation is so strong throughout the rock that it can be easily recognised by using a sensitive tint, which shows that the majority of grains are simultaneously in extinction. The position of the maximum in relation to the axial plane in the diagrams (fig. 28,a,b) suggests that the C-axes of the quartzes contributing to the maximum are sub-parallel to the a-axis of axial plane slip, which has been calculated by methods described by Ramsay (1960). The pattern of the quartz microfabric is essentially the same whether measured on the crestal region or on the limbs of folds and cannot be unrolled about the fold axis. These facts, together with the textural evidence, suggest that strong shear-slip along axial plane surfaces was responsible for the generation of the microfabric. The second folds and the quartz microfabric which is homogeneous throughout these folds are, therefore, contemporaneous.

In the fabric diagrams described above, the maxima are easily recognizable features; but the optic axes of some quartzes lie outside the maxima and their pattern of arrangement tends towards a partial girdle. It /

It is likely that the optic axes of these grains have been only partially reoriented from their positions in the first fabric, which probably existed in the specimen prior to the second fold movements. Another possible explanation of the partial girdle pattern is that it is evolving from the strong maximum during the second fold movements.

The modification and obliteration of the first microfabric can be studied in diagrams (fig. 29) prepared from a second specimen, in which the first linear structure is well preserved and the quartz grains are less flattened in shape than in the first specimen. In this specimen, the orientation of quartz C-axes has been measured from several parts of a moderately open second fold (fig. 29,). Two fabric patterns have been recognized in the diagrams (fig. 29, a,b,c.) prepared from this specimen. Throughout the fold the C-axes are concentrated in a maximum which is situated close to the axial plane, as in the first specimen. In addition, the optic axes of some quartzes form a girdle, the axis of which parallels the first linear structure (b_1). As the latter is deflected, the weak girdle correspondingly changes its attitude. On the crestal part of the fold the maximum and /

Figure 29. Quartz orientation diagrams from a second fold in a Lewisian rock (specimen A3).

a. 300 c-axes from field 1.

b. 300 c-axes from field 11.

c. 300 c-axes from field 111.

S_1, b_1, S_2, b_2, as in Fig. 28.

d. A.V.A. diagram showing the distribution of quartz grains of the first and second fabrics in field 111 of Fig. 29 c.

Contours at 1-2-3-6-8% per 1% area.

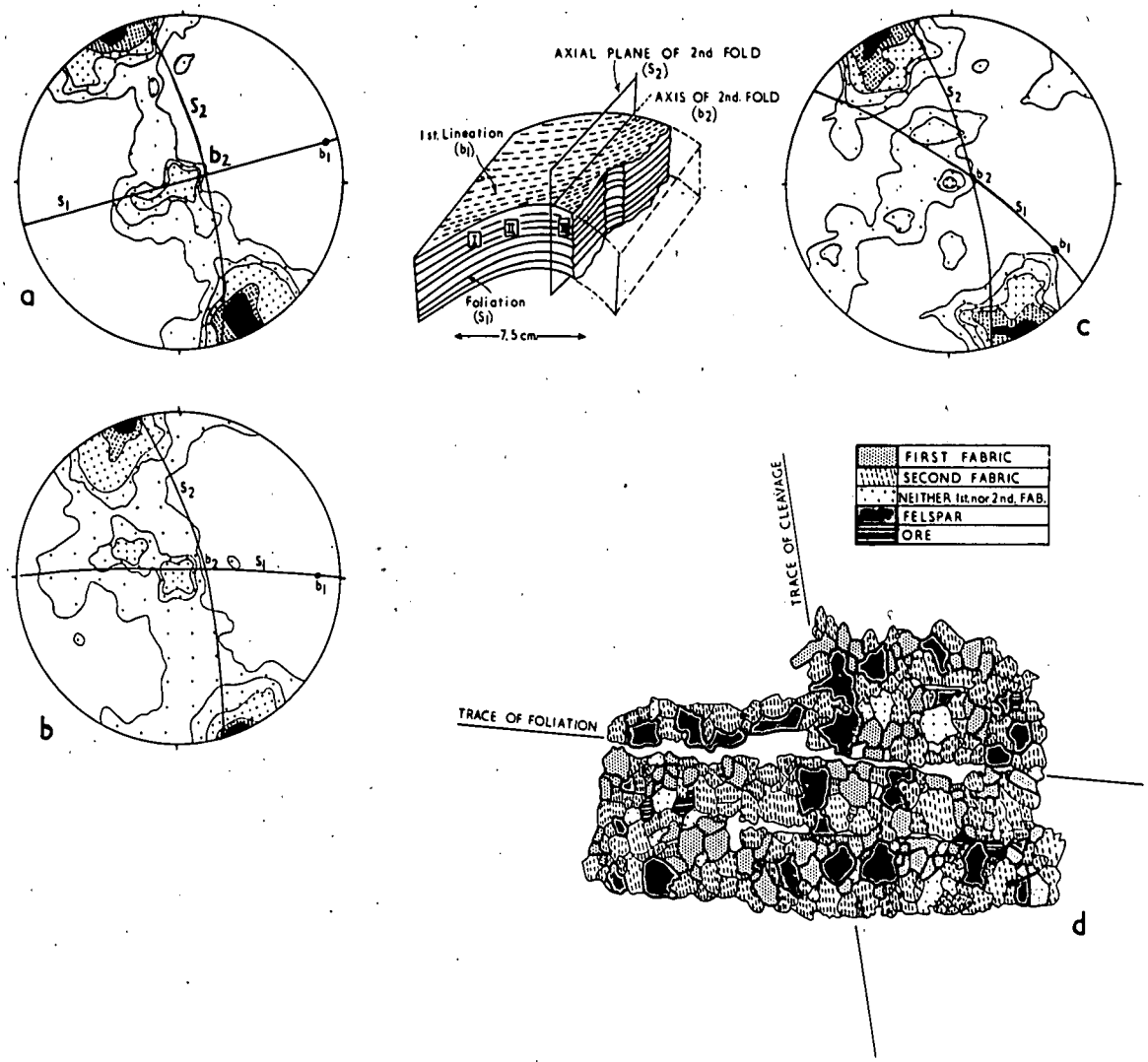

a
S_2
b_2
b_1
S_1
AXIAL PLANE OF 2nd FOLD
(S_2)
AXIS OF 2nd. FOLD
(b_2)
1st. Lineation
(b_1)
Foliation
(S_1)
7.5 cm
c
b
FIRST FABRIC
SECOND FABRIC
NEITHER 1st nor 2nd. FAB.
FELSPAR
ORE
TRACE OF CLEAVAGE
TRACE OF FOLIATION
d

Figure 29

and the girdle are distinct (fig. 29, c) - the strong maximum lies near the second axial plane (S_2) and the weak girdle lies nearly normal to the first lineation (b_1). On the limb (fig. 29, a, b.), however, the girdle has taken up a position nearly parallel to the second axial plane and so the strong maximum of the second fabric occurs within the first girdle. In the specimen studied, the angle between the first linear structure and the second fold axis varies from 55° on the crest to 80° on the limbs and the poles of the first lineation occur on a great circle around the second fold axis. In addition, the poles to the various positions of the first girdle also fall on a great circle about the same axis. This evidence (cf:- Ramsay, 1960) suggests that the first linear structure and the accompanying quartz-girdle have been distorted by shear folding. The fan-like arrangement of the first girdle around the second fold cannot be attributed entirely to shear folding. It is possible that the main shear slip was preceded by a weak phase of flexural-slip which de-:flected the early girdle into a "fan" before a stronger phase of transposition along the axial plane surfaces (cf:- de Sitter, 1958). Fig. 30 is a diagrammatic re-:presentation of the sequence suggested above.

The /

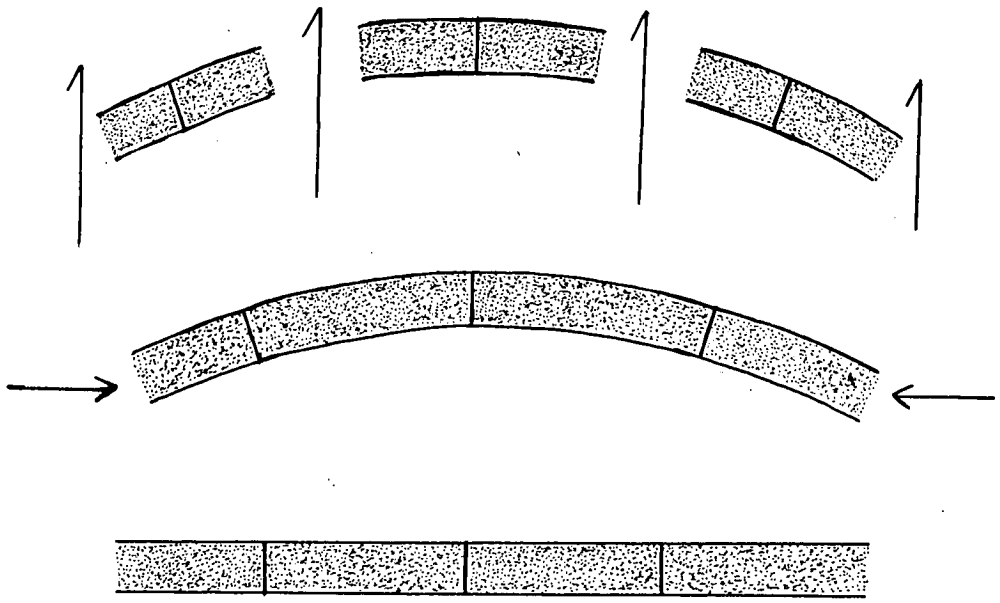


Figure 30. Diagram to show early flexural slip and rotation of first girdle followed by the transposition of the resulting positions of the girdle along axial plane surfaces in the later Shear folding.

The survival of the relic fabric is remarkable in view of the fact that most of the quartzes in the rock have been texturally rearranged by strong axial plane shear during the second fold movement. An optic axial plane map (A.V.A. or Achsenverteilungsanalysen, cf:- Sander, 1950; Weiss, 1954; Harris and Rast, 1960) shows the distribution of the grains that are oriented in each of the two fabrics found in the rock (fig. 29,d.). The grains that are oriented in the first (girdle) fabric occur in small patches of a relatively few grains that are dispersed among the larger patches of quartzes whose axes contribute to the second (strong maximum) fabric. The survival of the first linear structure (striation lineation) is due to the fact that it is defined, not by the elongation of individual quartz grains in recrystallized matrix but by elongate clusters of grains. Some of these clusters, although possibly reduced in size, have survived the later shearing. In other clusters the majority of the grains have been stretched and re-oriented in the second axial plane (S_2). The survival of the relic fabric in patches and its gradual obliteration by the second movement phase, indicates that the quartz micro-fabric in these rocks is inhomogeneous. In the specimens studied /

studied the scale of inhomogeneity is that of part or all of a thin section, but larger scale inhomogeneity may be expected, with specimens from some localities or areas showing one fabric and those from other places showing the other fabric. . The A.V.A. study points to the interesting possibility that if the patches in which the first fabric is preserved happen to be unusually large, the second microfabric may not even be traced by selective measurement and vice versa.

(3) Conclusions.

The results of the microfabric analysis bring out the difference in style between the first lineation, which is a penetrative mineral lineation and the second lineation which is defined by planar intersection. Since the second folds are localized it can be suggested that the amount of recrystallization decreased between the first and the second fold movements in the area. While the first movements are largely para-crystalline, the second movements happen to be largely post-crystalline.

In view of the diversity of the opinions on the mechanism by which quartz acquires a preferred orientation (Fairbairn, 1949, pp. 117-133) no attempt will be made to account for the behaviour of quartz in the orientation patterns /

patterns obtained. It is interesting to note, however, that in the case of some Torridonian rocks that show the first fabric, elongate "slivers" of quartz are so oriented that their C-axes lie at high angles to the longest grain dimensions, whereas the elongate quartzes in Lewisian rocks, which contribute to the second fabric, have their C-axes sub-parallel to elongation. It seems, at least in these two cases, that quartz is likely to yield along planes which are either sub-parallel or nearly normal to the C-axis. The question whether these are rational crystallographic planes (Griggs and Bell, 1938) or only statistically defined surfaces (Hietanen, 1938) cannot be decided on the present evidence.

C. Quartz Orientation in Rocks below the Kishorn thrust plane.

The orientation of C-axes of quartzes have been measured in seven specimens of Cambrian quartzites and Applecross (Torridonian) grits (fig. 31). Three of these specimens (figs. 31, a,b,c) have been collected from the undisturbed Foreland, west of the Sole thrust and four (figs. 31, d,e,f,g) from the zone of dislocation east of the Sole thrust. The latter specimens though involved in the post-Cambrian movements, show very little sign of deformation except in the immediate vicinity of thrust planes. /

Figure 31. Quartz orientation diagrams in rocks lying below the Kishorn thrust plane.

a. Applecross grit from the Foreland. 300 c-axes in specimen C 220. Section parallel to bedding plane which dips 16° to the E.S.E.

b. Cambrian quartzite (Basal Quartzite) from the Foreland. 250 c-axes in specimen C 115. Section parallel to bedding plane which dips 18° to the E.S.E.

c. Cambrian quartzite (Current-bedded Basal Quartzite) from the Foreland. 250 c-axes in specimen C 118. Section parallel to bedding plane which dips 18° to the E.S.E. Trace of foreset beds shown by solid great circle trace and the trend of current direction (N.N.W.-S.S.E.) by arrow. Contours at 1-2-3-4% per 1% area.

d. Applecross grit from the zone of dislocation. 270 c-axes in specimen C 218. Section normal to the strike of bedding plane which dips at 25° to the E.S.E.

e. Cambrian quartzite (Basal Quartzite) from the zone of dislocation. 300 c-axes in specimen C 204. Section parallel to bedding plane which dips at 25° to the S.E.

f. Cambrian quartzite (Current-bedded Basal Quartzite) from the zone of dislocation. 250 c-axes in specimen C 206. Section parallel to bedding plane which dips 25° to the S.E. Trace of foreset beds shown by solid great circle trace and the trend of current direction (N.N.W.-S.S.E.) by arrow. Contours at 1-2-3-4% per 1% area.

g. Cambrian quartzite (Basal Quartzite). 225 c-axes in specimen C 216 which has been collected just below the Kishorn thrust northeast of Glas Bheinn. Section normal to strike of bedding plane dipping at 30° to the S.E.

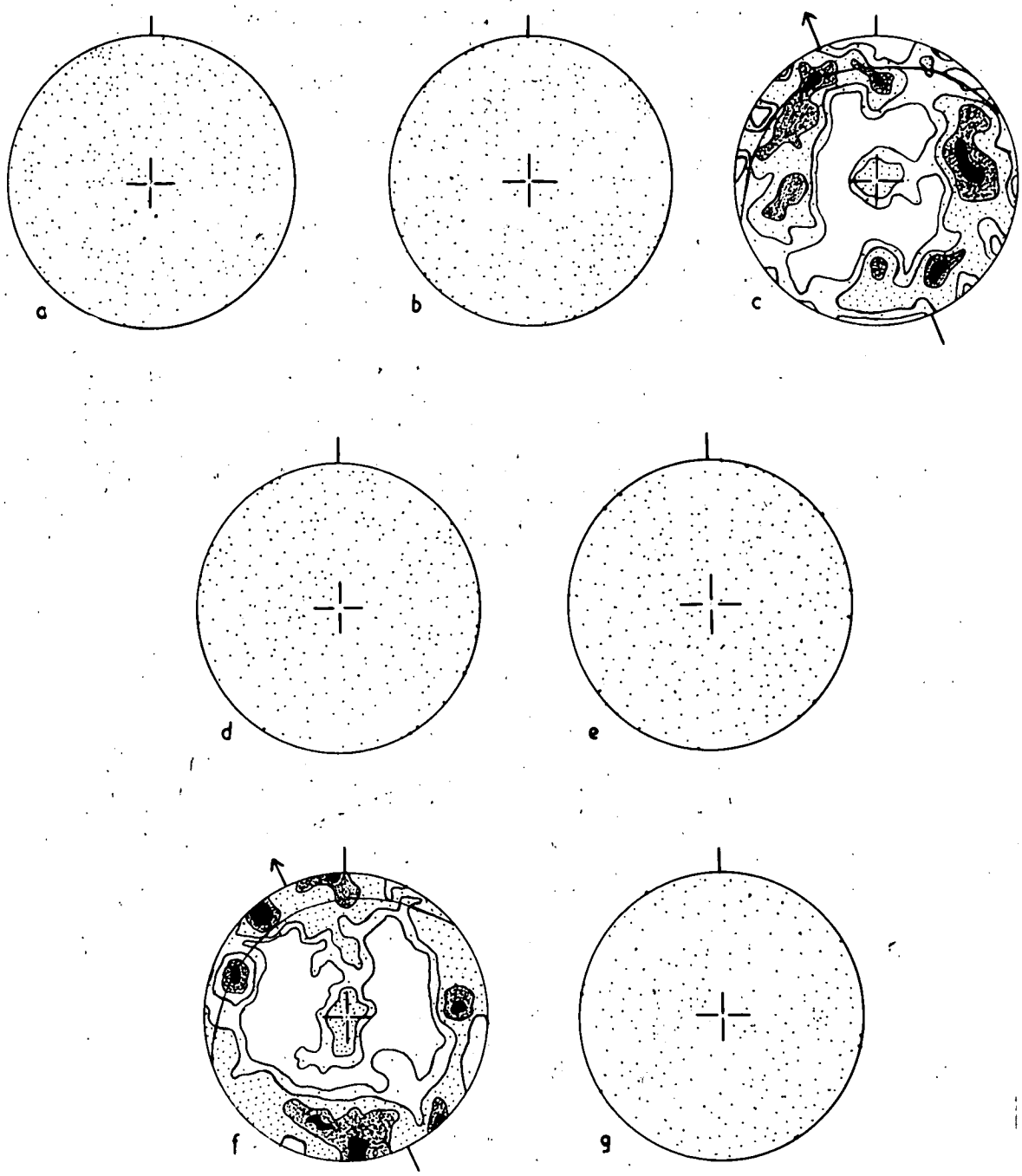


Figure 31

planes. The sedimentary textures of the Applecross grits are well preserved (plate XVIII, a,). The Cambrian quartzites, which have recrystallized under sedimentary conditions like the quartzites of the Foreland, are com-:posed of coarse, granular quartzes (plate XIX,a). Some quartzites exhibit effects of mechanical deformation - the grains are slightly flattened and exhibit moderately strained extinction (plate XIX, b). It is only just below the Kishorn thrust plane that the quartzites show intense mechanical granulation. These deformed quartzites are breccia-like rocks and they do not show any sign of constructive metamorphism (plate XIX, c).

Sections for fabric analysis have been cut either parallel to the bedding plane or perpendicular to the strike of the bedding plane.

Figs. 31, a and b, show the arrangement of C-axes of quartz grains in specimens of Applecross grit and Basal Quartzite collected from the undisturbed Foreland. Both diagrams indicate that the C-axes have a random scatter and accordingly they have not been contoured.

Fig. 31 c has been prepared from a specimen of false bedded Basal Quartzite which was also collected from the undisturbed Foreland. The orientation diagram of quartz /

quartz C-axes, measured from a section parallel to the bedding plane, reveals a very complex girdle pattern. Maxima are scattered, though most of them show a tendency to be close to the current direction as determined in the field, by measurement of the current bedding, or at high angles to it. Texturally, the rock is coarse-grained and granular with no shape orientation of quartzes. It is possible that a shape orientation was present at one stage and has been destroyed by sedimentary recrystallization. The fabric in the grits and quartzites of the Foreland is, therefore, either a random scatter of C-axes or a very complex girdle pattern in the bedding plane.

Figs. 31, d,e,f and g show results obtained from rocks occurring east of Sole thrust (i.e., in the zone of dislocation). A specimen of Applecross grit, collected from Meall an Dairmh, shows clastic quartz grains which exhibit moderately strained extinction. Measurements of C-axes reveal no preferred arrangement (fig. 31d). Similar haphazard arrangement of C-axes of quartz has been noted in a Cambrian quartzite (fig. 31e) that was collected from the zone of dislocation in which the rocks have been affected by folding on a N.N.E.-S.S.W. axis.

In some of the quartzites from the zone of dis-:location a very complex fabric, in the bedding plane, which /

which is similar to that obtained in quartzites of the Foreland and likewise is presumed to be sedimentary in origin. Fig. 31,f shows this complex pattern obtained in a specimen of quartzite which shows current-bedding. The maxima are scattered, though there is a tendency for them to show a preferred orientation either close to the current direction or at high angles to it. Texturally, the rock is coarse, granular and the quartzes exhibit no shape orientation.

Fig. 31,g has been prepared from a specimen of quartzite collected just below the Kishorn thrust in a locality situated about one mile north of Tullich where the thrust is well exposed (see p. 134). The specimen has suffered intense mechanical granulation and parts of it are so fine grained that individual grains cannot be distinguished. A few relatively coarser grains, showing strained extinction, are either scattered in a fine matrix or occur in clusters. The measurement of C-axes of the coarse quartzes reveals no preferred orientation.

The microfabrics of the quartz-bearing rocks below the Kishorn thrust plane contrast markedly with the microfabrics found in rocks above this thrust. Whereas the rocks above the thrust show two tectonic phases of quartz /

quartz fabric formation, those below the thrust show either no preferred orientation or a complex sedimentary fabric.

D. Comparison of Microfabric data with those reported by other workers in the thrust belt.

The fabric data obtained in the present area is briefly compared here with those found by other workers in the thrust belt.

In some respects the results differ considerably from those stated by Phillips in his pioneer petrofabric studies of the Moines and some associated rocks in the thrust belt. Phillips (1937) found only a slight constructive effect of the post-Cambrian movements on the rocks of the thrust belt. He found that the rocks of the Foreland, as well as most rocks within the "zone of imbrication" below the Moine thrust have no preferred orientation of quartz C-axes (op.cit., figs. D.27, 28). In a few cases, Torridonian and Cambrian rocks below the Moine thrust showed the beginning of formation of a girdle trending N.W.-S.E. (op.cit., p.603). Later Phillips (1939, figs. 15 and 16; 1945, fig. 4) published fabric diagrams which showed a weak fabric in a number of Torridonian and Cambrian rocks from the thrust belt. The fabric, which was attributed to the Moine thrust movements, was also found in near-thrust Moines and was thought to have /

have been overprinted on the regional N.E.-S.W. girdle which Phillips found in the Moine schists away from the thrust belt. He suggested that the weak N.W.-S.E. girdles, which were typical of the rocks within the thrust belt, contrast with the strong N.E.-S.W. girdles found in the Moines away from the Moine thrust. In some Moine schists occurring in the thrust belt, the "revised" N.E.-S.W. girdle survives as a relic (cf:- Phillips, 1951, table I, p. 234). In the present area, which structur-:ally occurs below the Moine thrust, it has been found that the Torridonian and Lewisian rocks between the Kishorn and Moine thrusts show evidence of constructive metamorphism and they exhibit well developed microfabrics. It is only in rocks below the Kishorn thrust plane that the constructive effects of metamorphism and the micro-:fabrics of tectonic origin are absent. In the Lewisian and Torridonian rocks lying between the Kishorn thrust and the Moine thrust in the present area there have been two phases of quartz orientation. The fabric of the first phase, a girdle pattern, is widespread and has an axis parallel to the well-developed E.S.E.-plunging megascopic lineation. The girdle is nearly parallel to the "revised" N.E.-S.W. girdle that Phillips (1951, table /

table I, p. 234) interpreted as a relic fabric in the Moinesin thrust belt. According to Phillips the "revised" N.E.-S.W. girdle pattern is absent in the thrust Torridonians which only possess a weak "orthodox" N.W.-S.E. girdle (op. cit.). But the presence of girdles with "revised" orientation in the Torridonians of the present area conflicts with Phillips' interpretation that any N.E.-S.W. girdle in the thrust belt is a relic. The fabric of the second phase in the present area is essentially a very strong maximum which may spread into a weak N.W.-S.E. partial girdle.

In recent years Christie (1955, 1956), Wilkinson (1955) and Johnson (1955, 1957, 1960) have reported the occurrence of widespread lineations, fold axes and quartz-girdle axes that plunge to the E.S.E. from different parts of the thrust belt. Johnson (op.cit.) showed that there are two periods of microfabric formation in the thrust belt in Ross-shire. The two phases differ in character and intensity - the earlier fabric consisting of girdle patterns with an E.S.E.-axis; the latter fabric is localized in areas of intense movement where the quartz grains are flattened and aligned in the axial planes of folds. The microfabric results obtained by the present author /

author from rocks above the Kishorn thrust plane agree with these observations.

Fabric results obtained from the Cambrian quartzites occurring below the Kishorn thrust differ markedly from those reached by Christie (1955, 1956) in quartzites below the Moine thrust in Assynt area. The quartzites of Assynt show a megascopic lineation trending E.S.E. and the C-axes of quartz grains form a girdle pattern normal to the lineation. In the present area, the quartzites, which are devoid of any constructive metamorphism, show either no preferred orientation of quartzes or a very complex pattern related to sedimenta-:tion. No microfabrics of tectonic origin are found in the rocks below the Kishorn thrust. It is interesting to note that Crampton (1955) stated that "Cambrian rocks immediately below the thrusts usually consist of various combinations of two girdles; at greater distances from the thrusts there is either no preferred orientation or a pattern of sedimentary type (an apposition fabric)".

SECTION V

SUMMARY OF CONCLUSIONS AND DISCUSSION

The structural and metamorphic events undergone by rocks lying above and below the Kishorn thrust plane are summarised in the following table. The proposed correlation, set out in this table, between the structures above the Kishorn thrust and those below the thrust will be discussed later in this section.

TABLE IV

(Structural and metamorphic events)

Above the Kishorn thrust	Below the Kishorn thrust
(Lewisian and Diabaig rocks)	(Applecross and Cambro-Ordovician rocks)
? a. Loch Alsh folding and inversion of strata. Possible formation of some mylonites	———
b. <u>The Structures of the First Generation</u> Minor isoclinal folds, plunging gently to the E.S.E.; associated axial plane schistosity (S_1) and lineation (b_1); mylonitization and granulitization followed by partial recrystallization; formation of quartz girdle microfabric.	———
c./	

TABLE IV (Continued)

(Structural and metamorphic events)

Above the Kishorn thrust	Below the Kishorn thrust
(Lewisian and Diabaig rocks)	(Applecross and Cambro-Ordovician rocks)
c. The Structures of the Second Generation Minor asymmetrical folds trending N.N.E.-S.S.W.; associated axial plane cleavage (S_2) and lineation (b_2). Post-crystalline deformation and partial recrystallization; formation of quartz maxima microfabric.	1.(i) Formation of N.N.E.-S.S.W. Folds. Large scale folds and associated minor asymmetrical folds. No lineation or microfabric. Local cataclasis (ii) Formation of N.N.E.-S.S.W. thrusts and reverse faults.
d. The Structures of the Third Generation Minor monoclinal and conjugate folds with generally variable axial trends. A large number of folds, however, plunge to the E.S.E. Local cataclasis.	? Formation of minor conjugate folds and associated asymmetrical folds plunging to the S.E./E.S.E.
? The Structures of Uncertain Age Minor open asymmetrical folds and disharmonic folds, plunging to the S.E./E.S.E. Later than the first isoclines, but relation with other structures unknown.	

It may be pointed out that the term "the Structures of the First Generation" has been retained for the minor isoclinal /

isoclinal folds, although in the table these structures have been placed second in the list of events. The reason for this is that the Loch Alsh Fold, which is a major structural feature in the Skye-Lochcarron region and is thought to be responsible for the inversion of strata, is considered to have formed prior to the generation of the isoclines. None of the minor structures in the area correspond to the geometry of the Loch Alsh Fold and there is no evidence that the minor structures have been distorted by the inversion of strata having taken place after the formation of these structures.

The main object of the present work is to elucidate the structural history of the area and, in the light of the evidence thus obtained, to study the Kishorn thrust: its nature, tectonic significance and relative age in the structural history of the Kishorn-Lochcarron region. The status of the Kishorn thrust is now discussed by considering four topics :

(a) the correlation of structures across the Kishorn thrust.

(b) the evolution of tectonic styles above the Kishorn thrust.

(c) the movement plans of structures in the area.

(d) the age of the mylonitic rocks.

Finally /

Finally, the results of the present research are briefly compared with recent work done by other investigators in the thrust belt of the Skye-Lochcarron region.

(a) The correlation of structures across the Kishorn thrust.

The Kishorn thrust, which is clean-cut, has brought into contact rocks belonging to different stratigraphic horizons (i.e., the older, Lewisian and Torridonian (Diabaig) rocks, now structurally overlie the younger, Torridonian (Applecross) and Cambro-Ordovician, rocks). Further, the thrust has approximated rocks of different metamorphic conditions and different structural histories. The Lewisian and Diabaig rocks lying above the Kishorn thrust have undergone at least three phases of movement subsequent to their inversion and have a polymetamorphic history. The Applecross and Cambro-Ordovician rocks lying below the Kishorn thrust have undergone a single main phase of movement and possibly one additional minor phase, evidence of which is restricted to the Cambro-Ordovician limestones. The complex structural and metamorphic history above the Kishorn thrust, therefore, contrasts to a great extent with the relatively simple structural history below the thrust.

In the Applecross and Cambro-Ordovician rocks, belonging to the zone of dislocation below the Kishorn thrust, there is no evidence of any movement phase that can be /

be correlated with the period of inversion (Loch Alsh Folding) above the thrust. The first isoclinal minor folds and their associated structures found above the Kishorn thrust, have not been recognized below it. The phase of recrystallization and constructive metamorphism that has affected the Lewisian gneisses and Torridonian (Diabaig) sediments during the period of isoclinal folding, is not reflected in the Cambro-Ordovician and Torridonian (Applecross) rocks.

The axes of the second minor folds (the structure of the second generation) above the Kishorn thrust are parallel to the axes of the N.N.E. - trending folds below the thrust, (Table IV). These folds, above and below the thrust, are overturned to the W.N.W. : the axial planes of the second folds dip at moderately high (40° - 55°) angles to the E.S.E., while those of the N.N.E. trending folds dip more steeply (60° - 85°) in the same direction. The sub-parallelism in axial trends of these two sets of structures (cf:- Figs. 8b, 9b and 18) possibly suggests that they are of the same generation. There is, however, an important difference in style between the second folds and the N.N.E. - folds . While the second folds are Similar, that is produced by axial plane shear, the N.N.E. folds are Concentric and have developed by slip along bedding planes. The phase of recrystallization and textural reconstitution /

reconstitution that has taken place during the second fold movements in Lewisian rocks has not been observed in Cambro-Ordovician and Applecross rocks deformed by the N.N.E. folds. This difference in style and in metamorphic conditions possibly suggests that the second folds formed in rocks which behaved somewhat plastically, being aided by partial recrystallization, whereas the N.N.E. folds developed in rocks which behaved rather rigidly, being devoid of recrystallization. It is possible that the second folds and the N.N.E. folds are of the same age but have formed at widely separated places and have been later approximated by transport on the Kishorn thrust.

A third phase of movement in the rocks above the Kishorn thrust is indicated by the brittle monoclinal and conjugate folds. The conjugate folds in the Cambro-Ordovician limestones strongly resemble these structures in style. The conjugate structures, which plunge to the E.S.E., in the limestones are, unlike those occurring above the Kishorn thrust, associated with minor open asymmetrical folds and are sometimes seen to occur at the hinges of the latter folds. The conjugate structures above the Kishorn thrust vary in their axial trends, although a majority of these folds do plunge to the E.S.E.. Therefore, it is not certain whether the conjugate folds above and below the thrust /

thrust can be correlated with each other despite their resemblance to one another.

No attempt has been made to correlate the "Structures of Uncertain Age" above the Kishorn thrust with any of the structures below it.

The debatable correlation of structures across the Kishorn thrust, together with the evidence that a considerable thickness of strata has been cut out along the thrust, emphasizes the tectonic significance of the Kishorn thrust and suggests that the thrust has brought a complex structural unit of older rocks close to a relatively simple structural unit of younger rocks at a late stage in the Caledonian orogeny.

(b) The evolution of tectonic styles above the Kishorn thrust

A notable feature of the present analysis is the recognition of a sequence of discontinuous movements, which produced structures of varying styles, in the thrust belt. The first isoclinal fold movement was largely para-crystalline and the rocks behaved plastically. Penetrative movements induced a strong striation lineation (mainly defined by quartz, mica and amphiboles), which was strongly developed in the Lewisian gneisses as well as in the Diabaig sediments. The second fold movement, which produced /

produced structures that were locally superimposed on those of the first generation, was largely post-crystalline. The phase of the second folding affected the rocks only locally. Microfabrics of the rocks deformed by the second folds suggest that some quartz grains recrystallized during the second folding. The micas and amphiboles were cataclastically deformed and no recrystallization of these minerals took place. Whereas the first lineation (b_1) is a mineral orientation, the second lineation (b_2) is a cleavage-bedding intersection. The evidence suggests that the amount of crystallization appreciably decreased in the area between the first and second fold movements. The third fold movement was entirely post-crystalline and produced structures with a brittle style. This sequence of differing tectonic and metamorphic events may be interpreted as indicating the changing conditions of deformation in the Kishorn-Lochcarron area. The apparent increase in rigidity and brittleness of the rocks with time seems to suggest that the discontinuous movements have culminated in a final phase of clean-cut thrusting.

In this connection some of the observations made by Peach (Mem. 1913, pp.27-28) regarding the nature of movement on the Moine thrust may be briefly discussed here. Peach (op.cit., p.27) stated -

"A/

"A study of the rocks above and to the east of the Moine thrust-plane, shows that they have been subjected to the same great movements of the earth's crust to which the tectonic structures of the region to the west of that line of dislocation are due. .... In this eastern region they were, however, exerted in a different layer of the crust, where the load was sufficient to prevent disruptive and cataclastic action..... the phenomena of the belt of thrusting are but a marginal phase, produced under less load, of the fold and consequent deformation that prevailed over the whole of the area of metamorphic rocks to the east of that belt."

Peach (op.cit., p.28) admitted that there is evidence of crushing of some of the "Moine" structures along the Moine thrust west of Loch Carron and stated -

"The structures impressed upon the rocks from their subjection to different conditions during the <u>one continuous movement</u> might easily account for the late breaking down of structures produced at a rather earlier time during the movements. This is on the supposition that the movements were continuous both as to rate and time, which may not have been the case..... ..... The temperature of the masses may have been considerably/

considerably raised by movement. If this movement was intermittent there may have been time for the loss of temperature through several causes - conductivity, change in molecular structure, or in chemical action. On movement being resumed the rocks would be more rigid, and crushing would take place." The idea of discontinuous movement implicit in this latter statement by Peach is significant. In the present area, the changing styles of structures and metamorphic conditions in different episodes of movement indicate, as shown previously, a gradual decrease in temperature. It is thought, however, that the clean-cut thrusting along the Kishorn thrust plane is a late stage event. It cannot be suggested that there was movement along the thrust plane prior to the clean-cut thrusting.

(c) The movement plans of structures

Horne (Mem. 1907, pp.463-476) and Peach (Mem.1913, pp.27-28) considered that the movement on the Moine and associated major thrusts such as the Kishorn thrust, was towards the W.N.W. and that the thrusts, particularly the Moine had a long life history. The rocks "in advance of the major thrusts" were reduplicated by thrusting and folding and the prominent E.S.E. trending linear structures in rocks associated with thrusting marked the "direction of stretching" parallel to the thrust movement. The linear structures /

structures (Horne, op.cit., p.471) were later interpreted by Read (1931) as superficial slickensides - a view which was subsequently supported by Phillips (1937, p.603).

When applied to the present area the above interpretation of structures in the thrust belt needs reconsideration. The prominent lineation (first linear structure) running E.S.E., which is widespread in the rocks above the Kishorn thrust in the area is presumably equivalent to the E.S.E. direction of stretching mentioned by Horne (Mem.19 07, p.471; cf:- Sheet 82, Geol.Surv.). The lineation is now seen to be associated with isoclinal folds that have formed by a translative movement on a N.N.E. - S.S.W. trend (see pages97-99of this thesis) and apparently have no relation to the W.N.W. thrust movements (cf:- Christie, 1956; Johnson, 1960). Further the lineation is penetrative and is not a superficial slickenside striation. While not disputing the orthodox view (Horne, Mem. 1907, pp.463 - 476) that the transport on the major thrust planes in the North-West Highlands was towards the W.N.W., the present author wishes to emphasize that the widespread E.S.E. lineation in the present area (and possibly in other parts of the thrust belt) has an entirely different significance from what was previously supposed by Horne /

Horne (1907), Read (1931) and Phillips (1937). The lineation, being unrelated to the thrust movement, does not indicate the direction of transport on the thrust plane. There is evidence of some amount of stretching of particles parallel to this lineation, but the major translative movement, which was responsible for the generation of the lineation and related isoclinal folds, was directed at a high angle to the lineation and the fold axis.

Examples of stretching and elongation of a rock mass perpendicular to the direction of transport have been cited by workers from many other areas. Schmidt (1932) has described triaxial deformation in which extension occurs along the strike (parallel to the regional fold-axis) during deformation. Strand (1944) used this hypothesis to explain "cross-folds" in the Bygdin area of Norway. Balk (1952) discussed elongation of particles perpendicular to the direction of tectonic transport and has drawn an analogy between the phenomenon and the rolling process in metal working. Flinn (1961) has discussed the mechanisms responsible for the elongation of pebbles in some quartz-conglomerates in Shetland and in the Jotunheim area of Norway.

The relation of the second folds (above the Kishorn thrust) and the N.N.E. folds (below the Kishorn thrust) with the thrust movement is not certain. It has been shown, in /

in the previous discussion of the styles of the folds, that the rocks above the Kishorn thrust behaved rigidly after the second folding. There is a possibility that the movements responsible for the generation of the second folds (and the N.N.E. folds) have culminated in thrusting. The Similar second folds have been generated by strong shear movement along axial planes dipping moderately steeply to the E.S.E., the direction of movement being parallel to a line plunging 40° -45° to the east. The Concentric N.N.E. folds occurring beneath the Kishorn thrust suggest a movement on a E.S.E. - W.N.W. trend. The movement plans deduced from the geometry of these folds, occurring above and below the thrust, apparently correspond to the orthodox W.N.W. movement on the Kishorn thrust plane. The structural analysis of the area, however, shows that the folds of the third generation, which are possibly related to the thrust movement, distort the second folds. The second folds (and the N.N.E. folds) may have preceded, at least, slightly the period of thrusting.

It has been noted in Section III D of this thesis that the Kishorn thrust is warped on a S.E. axis as a result of which it shows several broad embayments between Loch Kishorn and Kinlochewe. The Kishorn thrust mapped in the present area forms part of a big warp, which is marked /

marked by the embayment of the thrust outcrop north of Glen Carron, between Loch Kishorn and Coulin Forest. In the ground north of Loch Kishorn (including the present area) the thrust plane dips moderately steeply to the S.E., while near Coulin Forest area it dips gently to the E.N.E. The warping may be due to one of two reasons :

(i) the warping is due to a movement later than thrusting.

(ii) the warping is an inherent feature of thrusting. (cf: - Johnson, 1957, p 261).

In the present area there is no evidence of any movement phase which may account for a warping of the thrust. Johnson (1957, p. 261) observed that down warps of the Kishorn thrust occur below the upwarps of the overlying Moine thrust - a feature which possibly suggests that folding is not responsible for the warping of the thrust planes. Due to warping, which is possibly an inherent feature of thrusting, the rock masses in some areas, such as at Lochcarron and Coulin Forest, have been tectonically thickened. In these areas, the conjugate folds (the t.e Structures of the Third Generation), which are possibly related to the thrust movement, are particularly well developed. The conjugate folds are brittle in style and have been generated by irregular compressive stresses which were constant neither in direction nor in sense. The only constant /

constant feature of these folds is their near vertical relief - a feature which is expected to develop in thickened rock masses subjected to compressive forces.

An important conclusion derived from the present investigation is that thrusting need not necessarily have a causal connection with all the visible structures in the thrust belt and that it represents no more than one of the several phases of movements undergone by the rocks.

(d) The age of the mylonites

In some discussions on the thrust belt it has been assumed that the mylonitization and granulitization to which the rocks have been subjected has a direct causal connection with the thrust movements (Peach, 1913; Read, 1934; MacGregor, 1952). On the other hand, the occurrence of mylonites that possibly formed prior to the Moine thrust movements in the N.W. Highlands has been recently reported by several workers (Christie, 1955,1960; Johnson, 1960; Barber in Sutton and Watson, 1959 and mentioned in Johnson, 1960).

Christie (op.cit.), in Assynt, recognized mylonites and partly recrystallized blasto-mylonites along the Moine thrust and interpreted these rocks as representing a "movement horizon" formed prior to the clean-cut phase of thrusting which brecciated these early mylonitic rocks. Johnson (op.cit.) has recognized three phases of cataclasis in /

in the ground occurring immediately to the south of the present area. The first phase is indicated by narrow zones of mylonites and blasto-mylonites which pre-date the phase of isoclinal folding in the area. The second phase of mylonitization is possibly contemporaneous with the isoclinal folding. The third phase is a late stage cataclasis which brecciated the early mylonites and is related to the clean-cut Moine thrust movement.

In the present area, Peach (Mem. 1913, p.13) noticed "mylonites" in the Lewisian gneisses, which are not confined to the vicinity of the Kishorn thrust. He (op.cit.) considered that these "intermittent bands of mylonites" have been produced by "dynamic forces being transmitted through the more stable portions to successive layers of weakness" and that they are genetically related to the Kishorn thrust movement. The present investigation suggests, however, that there is no obvious relationship between all the mylonitic rocks in the area and the Kishorn thrust, of which there is no evidence prior to the late clean-cut movement phase. The structureless, unlaminated cataclasites, which are confined to the immediate vicinity of the Kishorn thrust and presumably related to the thrust movement, do not conform to Lapworth's definition of a "mylonite" (Lapworth, 1885) and are different in character from /

from the platy, laminated true mylonites and partially recrystallized blasto-mylonites which occur in narrow zones in Lewisian gneisses away from the thrust. The exact period of formation of these mylonitic rocks is difficult to establish. The second and third folds above the thrust contort mylonite bands and must have formed after the production of some mylonites. The widespread occurrence of first linear (b_1) and planar (S_1) structures in some mylonite bands suggests that these rocks possibly existed prior to the formation of first isoclinal folds. The mylonite bands may be interpreted as representing narrow movement zones along which sliding and shearing took place in an early phase of movement history in the area. It is possible that during the period of inversion of strata at Lochcarron, which is presumed to have preceded the first fold movements, considerable sliding and shearing took place and thereby resulting in the production of some mylonites. The evidence of strong shear movement along axial planes of isoclines suggests that some mylonites may belong to the phase of first isoclinal folding.

Comparison of the present work with recent work on neighbouring areas.

The present area, which structurally occurs below the Moine thrust, is a northern continuation of the thrust belt /

belt recently investigated by Johnson (1960). Johnson (op.cit.) reported the occurrence of three sets of minor structures in the inverted Torridonian and Lewisian lying between the Kishorn and Moine thrusts and in the Moine rocks lying above the Moine thrust. These three sets (namely, the first isoclinal, the second asymmetrical and the third conjugate folds and their associated structures) are apparently equivalent to the three similar sets of minor structures which have been recognized in the Torridonian and Lewisian rocks occurring above the Kishorn thrust in the present area. The author has also recognized an additional set of structures (namely, "the Structures of Uncertain Age") in rocks above the Kishorn thrust in the present area. Johnson (op.cit.) established that the rocks above and below the Moine thrust underwent a series of discontinuous movements, the style of deformation changing from an early plastic, paracrystalline to later brittle, post-crystalline type and that the clean-cut Moine thrust movement took place at a late stage. A nearly parallel history emerges from the present area when the structural and metamorphic events only in rocks above the Kishorn thrust are considered. The present work combined with Johnson's (op.cit.) observations, therefore, suggest a remarkable structural continuity above and below the Moine thrust./

thrust. This continuity, however, is disrupted when the rocks below the Kishorn thrust are considered as shown in the present thesis. When the present area and the area to the south of it are considered together, it appears that the major thrusts (Kishorn and Moine) are clean-cut and late phases in a discontinuous complex structural history in the Kishorn - Lochcarron region. Further, the tectonic significance of the Kishorn thrust is emphasized by the fact that it has caused a notable disruption in the stratigraphical as well as structural continuity in this region.

The lateness of the Kishorn and Moine thrust movements at Coulin Forest area has been recently proved by Johnson (1960, p.167). At Coulin Forest the late brittle conjugate structures are abundant and appear to have swamped the early structures, which, in contrast, are well developed at Lochcarron.

The relation of the structures at Kishorn - Lochcarron with those at other neighbouring parts of the thrust belt is not known and any regional correlation must await the examination of a larger area. But it seems probable that complex structures occur to the ground south of Loch Carron and in Sleat of Skye. It has been reported by Barber (in discussion of Sutton and Watson, 1959, p.256; in /

in Johnson, 1960, p.166) that near Loch Alsh fold structures and mylonitic rocks are present, which pre-date the Moine thrust movement.

SECTION VI - ACKNOWLEDGEMENTS

The writer is deeply grateful to Professor F. H. Stewart for a critical reading of the manuscript.

The writer wishes to record his gratitude to Dr. M.R.W. Johnson who suggested the subject of the study and supervised the work. The writer is deeply indebted to him for guidance and encouragement throughout the course of the work.

Thanks are due to Miss J. Tarrant for assis-:tance in preparing the photographs given in the thesis.

The work was carried out with the aid of a post-graduate scholarship awarded in 1957-58 by the Government of West Bengal, India.

SECTION V11 - LIST OF WORKS TO WHICH REFERENCE IS MADE

ANDERSON, E.M., 1948 On Lineation and Petrofabric Structure. Quart.J.Geol.Soc. Lond., Vol. 104, pp.99 - 126

BAILEY, E.B., 1939 Caledonian Tectonics and Metamorphism in Skye. Bull. Geol. Surv. Gt. Brit., No. 2, pp.46-62

- , 1955 Moine Tectonics and Metamorphism in Skye. Trans.Edin.Geol.Soc., Vol.16, pp.93 - 166.

BALK, R., 1952 Fabric of Quartzites near Thrust Faults, Jour.Geol., Vol. 60, pp.415-435

BALL, T.K., 1960 A Petrofabric Analysis of a Fold. Amer.Jour.Sci., Vol. 258, pp.274 - 281.

CADELL, H.M., 1888 Experimental Researches in Mountain-building. Trans.Roy.Soc. Edin., Vol. 35, p.337.

CAREY, S.W., 1954 The Rheid Concept in Geotectonics Geol. Soc. Australia Jour., Vol.1, pp.67 - 117.

CHRISTIE, J.M., 1955 In "Structural Petrology and Problems of the Caledonides". Advanc. Sci. Vol.12, pp.571-578.

- , 1956 Ph.D. Thesis entitled "The post-Cambrian Thrusts of the Assynt Region". University of Edinburgh.

- , 1960 Mylonitic Rocks of the Moine Thrust Zone in the Assynt Region, North-West Scotland. Trans.Edin. Geol.Soc., Vol.18,pp.79-93.

CLOUGH, C.T., 1907 see Peach, B.N., et. al, 1907.

CRAMPTON /

CRAMPTON, C.B., 1955 In "Structural Petrology and Problems of the Caledonides". Advanc.Sci., Vol.12,pp.571-578.

- , 1958 Fabric Analysis of Moine and Cambrian Quartzites of North-West Highlands of Scotland. (communicated by Dr. F.C. Phillips). Meeting of the Geol. Soc.Lond., 10th Dec., 1958

de SITTER, L.U., 1956 Structural Geology. McGraw-Hill Book Co., New York and London

- , 1958 Boudins and Parasitic Folds in Relation to Cleavage and Folding. Geol. en Mijnbouw, Vol. 20, pp.277-286

FAIRBAIRN,H.W., 1949 Structural Petrology of Deformed Rocks. Addison-Wesley Publishing Company, Inc., Cambridge,Mass.

FLINN, D., 1961 On Deformation at Thrust Planes in Shetland and the Jotunheim area of Norway. Geol.Mag. Vol.98,pp.245-256

GEIKIE, J., 1894 Annual Report of the Geol.Surv.Gt. Brit. and the Museum of Practical Geology for year ending 31 Dec.1893.

- , 1899 Ibid for 1898.

GRIGGS, D. and BELL, J.F., 1938 Experiments bearing on the Orientation of Quartz in Deformed Rocks. Bull. Geol.Soc.Amer., Vol.49,pp.1723-1746

GRUBENMANN, U., and NIGGLI, P. 1924 Die Gesteinsmetamorphose.Berlin, pp.219-223.

HARRIS, A.L., and RAST,N. 1960 The Evolution of Quartz Fabrics in the Metamorphic Rocks of Central Perthshire. Trans.Edin.Geol.Soc., Vol.18,pp.51-78

HIETANEN, A., 1938 On the Petrology of the Finnish Quartzites Bull.Comm.Geol.Finl., No.122,pp 1-118

HINXMAN /

HINXMAN, L.W., 1907 See Peach, B.N., et al, 1907.

HORNE, J. 1907 See Peach, B.N., et al, 1907.

JOHNSON, M.R.W., 1955 In "Structural Petrology and Problems of the Caledonides". Advanc.Sci. Vol.12, pp.571-578.

- , 1956 Conjugate Fold Systems in the Moine Thrust Zone in the Lochcarron and Coulin Forest areas of Wester Ross. Geol.Mag., Vol.93, pp.345-350

- , 1957 The Structural Geology of the Moine Thrust Zone in Coulin Forest, Wester Ross. Quart.J.Geol.Soc. Lond. Vol.113, pp.241-270.

- , 1960 The Structural History of the Moine Thrust Zone at Lochcarron, Wester Ross. Trans.Roy.Soc.Edin., Vol. 64, pp.139-168.

JOHNSON, M.R.W., and GANGOPADHYAY, P.K. Quartz Orientation and its Relation to Movement in the Moine Thrust Belt at Loch Carron, Ross-shire. (in press).

KNOPF, E.B., 1931 Retrogressive Metamorphism and Phyllonitization. Amer.Jour.Sci. Vol. 21, pp. 1-29.

KNOPF, E.B., and INGERSON, E., 1938 Structural Petrology. Geol.Soc.Amer. Mem.6, pp. 1-270.

LAPWORTH, C., 1883 The Secret of the Highlands. Geol. Mag., Vol.10, pp.120-8, 193-9, 337-44.

- , 1884 On the Structure and Metamorphism of the Durness-Eriboll District. Proc.Geol.Assoc., Vol.8, pp.438-442.

- , 1885 The Highland Controversy in British Geology, Nature, Vol.32, pp.558-9.

MACGREGOR, A.G., 1952 Metamorphism in the Moine Nappe of Northern Scotland. Trans.Geol. Soc.Edin., Vol.15, pp.241-257.

MCINTYRE, /

MCINTYRE, D.B., 1954 The Moine Thrust - its Discovery, Age and Tectonic Significance. Proc.Geol.Assoc., Vol. 65, pp. 203 - 223.

PEACH, B.N., et al, 1907 The Geological Structure of the North-West Highlands of Scotland. Mem.Geol.Surv.Gt.Brit.

PEACH, B.N., et al, 1913 The Geology of Central Ross-shire. (Explanation of Sheet 82) Mem.Geol. Surv. Scot.

PEACH, B.N., and HORNE, J., 1930 Chapters on the Geology of Scotland. Oxford University Press.pp. 1-232

PHEMISTER, J., 1948 Scotland : The Northern Highlands. 2nd Edition Brit.Regional Geol. Geol.Surv. and Museum.

PHILLIPS, F.C., 1937 A Fabric Study of some Moine Schists and Associated Rocks. Quart.J. Geol.Soc.Lond., Vol.93, pp.581 - 620.

- , 1939 The Microfabric of some Members of the "Tarskavaig - Moine" Series. Geol.Mag.,Vol. 76, pp.229-240.

- , 1945 The Microfabric of the Moine Schists. Geol.Mag., Vol. 82, pp. 205-220.

- , 1951 Apparent Coincidences in the Life History of the Moine Schists. Geol.Mag., Vol. 88,pp.225-235

QUENSEL, P. 1916 Zur Kenntnis der Mylonitbildung, erläutert an material aus dem Kebnekaisegebiet. Bull.Geol. Inst.Univ.Upsala., Vol.15, pp.91 - 116.

RAMSAY, J.G., 1960 The Deformation of Early Linear Structure in Areas of Repeated Folding. Jour.Geol., Vol.68, pp. 75-93

READ, H.H., 1931 The Geology of Central Sutherland. Mem.Geol.Surv. Scotland.

- /

- , 1934 Age Problems of the Moine Series of Scotland, Geol.Mag., Vol.71, pp.302-317.

REID, H.F., et al, 1913 Report of the Committee on the Nomenclature of Faults. Bull.Geol.Soc.Amer., Vol. 24, pp. 163 - 186

SAHAMA, T.G., 1936 Die Regelung von Quartz und Glimmer inden Gesteinen der Finnisch Lapländischen Granulit formation. Bull.Comm.Geol. Finl., Vol.113, pp. 1-119

SANDER, B., 1912 Uber einige Gesteinsgruppen des Tauren - westendes. Geol. Reichsanst. Jahrb., Vol. 62, pp. 249-257.

- , 1930 Gefügekunde der Gesteine. Springer, Vienna.

- , 1934 Petrofabrics (Gefügekunde der Gesteine) and Orogenesis. Amer. Jour.Sci. Vol. 28, pp.37-50.

- , 1950 Einführung in die Gefügekunde der Geologischen Körper. Zweiter Teil. Springer, Vienna - Innsbruck.

SCHMIDT, W., 1932 Tektonik und Verformungslehre, Gerueder Borntraeger, Berlin.

STRAND, T. 1944 Structural Petrology of the Bygdin Conglomerate. Norsk. Geologisk. Tidsskrift, Vol. 24, pp. 14-31.

SUTTON, J. and WATSON, J., 1951 Varying trends in Metamorphism of Dolerites. Geol.Mag., Vol.88, pp.25-35.

- , 1959 Structures in the Caledonides between Loch Duich and Glenelg, North-West Highlands, Quart.J.Geol.Soc.Lond., Vol. 114, pp.231-257.

TEALL, J.J.H., 1907 See Peach, B.N., et al, 1907.

TURNER, F.J., 1948 Evolution of the Metamorphic Rocks. Geol. Soc.Amer.Mem. 30, pp. 1-319

TURNER /

TURNER, F.J., and VERHOOGEN, J., 1951 Igneous and Metamorphic Petrology. McGraw-Hill Book Co., New York, Toronto and London

WATERS, A.C., and CAMPBELL, C.D., 1935 Mylonite from the San Andreas Fault Zone. Amer. Jour. Sci., Vol. 29, pp. 473-503.

WEISS, L.E., 1954 A study of Tectonic Style. California Univ. Dept. Geol. Sci. Pub. Vol. 30, pp. 1-102.

- , 1955 Fabric Analysis of a Triclinic Tectonite and its Bearing on the Geometry of Flow in Rocks. Amer. Jour. Sci., Vol. 253, pp. 225-236.

- , 1956 D.Sc. Thesis entitled "Structural Analysis of Rocks deformed by Flow". University of Edinburgh.

- , 1959 Geometry of Superposed Folding. Bull. Geol. Soc. Amer., Vol. 70 pp. 91-106.

WEISS, L.E., McINTYRE, D.B., and KÜRSTEN, M., 1955 Contrasted Styles of Folding in the Rocks of Ord Ban. Geol. Mag., Vol. 92, pp. 21-36.

WILSON, G., 1946 The Relationship of Slaty Cleavage and Kindred Structures in Tectonites. Proc. Geol. Assoc., Vol. 57, pp. 263-302.

WINCHELL, A.N., 1949 Elements of Optical Mineralogy, Part I. J. Willey & Sons, New York.

- , 1956 _____, Part II., _____.

PLATES

PLATE 1

a. Kishorn thrust outcrop: Lewisian gneiss , which forms the steep escarpment of the hill of Glas Bheinn on the left, is lying above the Cambrian quartzite to the right. Part of the Foreland, composed mainly of the Torridonian (Applecross) rocks, is seen in the background. View from the E.N.E.

b. Kishorn thrust outcrop: Lewisian gneiss , which forms the hill of Sgurr a' Gharaidh to the right, is occurring above the Cambro-Ordovician limestones to the left. View from the S.W.





PLATE 11

a. Narrow valley along the outcrop of the Glen More Fault between Loch Carron and Loch Kishorn. View from the west.

b. Repetition of outcrops of reddish-brown Applecross grit and white Cambrian quartzite by thrusting. The thrust plane (Cadh' An Eididh thrust) dips steeply (60°) to the E.S.E. View from the south.

a

b

PLATE III

a. Isoclinal fold (First Fold) in Lewisian gneiss.

b. Isoclinal fold (First Fold) in Lewisian gneiss. The hinges of some small isoclines have been sheared through by axial plane slip and quartzo-felspathic knots at the core denote the positions of the isoclines.

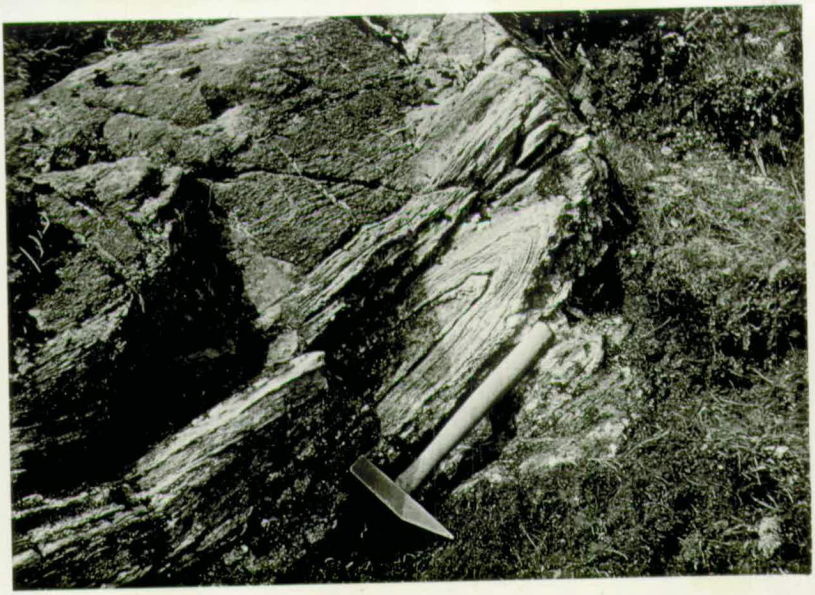




PLATE IV

a. Long limbed isoclinal fold (First Fold) in Lewisian gneiss. The isocline is situated on the limb of an asymmetrical fold of uncertain age. The steep plunge of the axis and the steep dip of the axial plane of the isocline is due to refolding by the latter fold.

b. Isoclinal microfold (First Fold) in Lewisian, showing stretching of the constituent minerals along axial plane. Crossed Nicols. X 25.

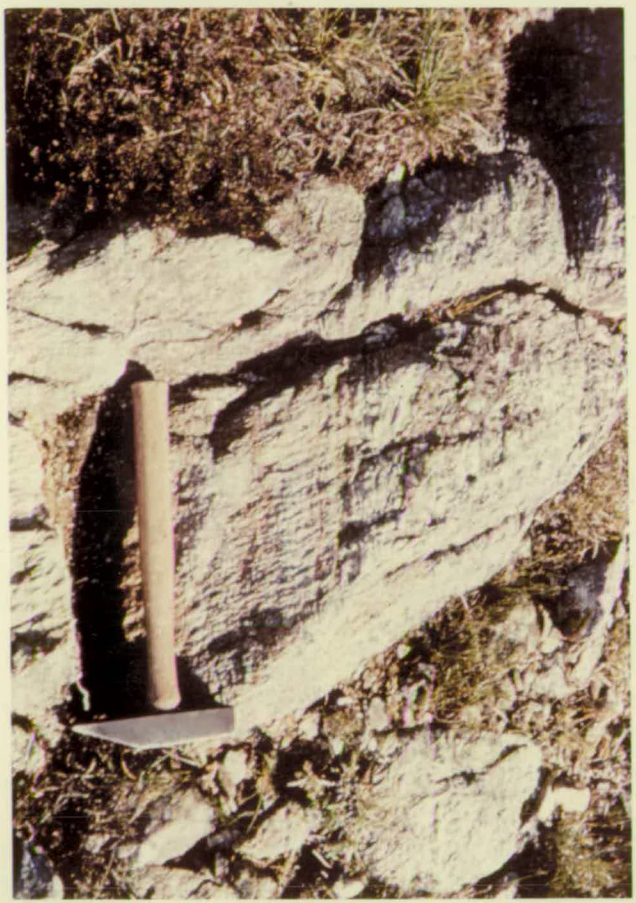
a

b

PLATE V

a. Isocline (First Fold) refolded on the Second Fold axis. Lewisian gneiss.

b. First lineation, b_1, the trend of which is indicated by the handle of the hammer, is cut across by the second axial plane cleavage (S_2). Lewisian gneiss.



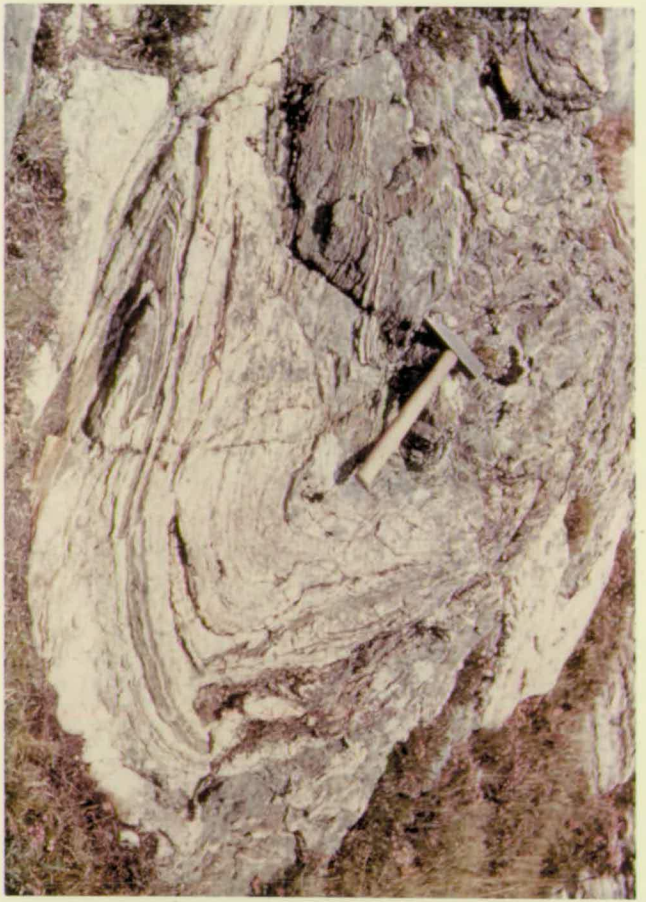


PLATE VI

a. Second Fold (a microfold) in Lewisian gneiss. The thickening of the crests and the relative thinning of the limbs of more micaceous layers is notable. In the quartzose layers, the grains have been stretched by strong axial plane shear. Crossed Nicols. X 35.

b. Second Fold (a microfold) in Lewisian gneiss. The rock shows the development of axial plane cleavage in the more micaceous layers. Crossed Nicols. X 35.

c. Magnified view of stretched quartz grains on the limb of microfold in Plate VI a. Crossed Nicols. X 175.



a



b



c

PLATE V11

Examples of folds which have been classified as belonging to the "Structures of Uncertain Age". These folds are later than the Isoclinal First Folds, but their relationship with other structures in the area is not known. The photographs are from the Lewisian gneisses.

a. South-easterly plunging open-asymmetrical fold.

b. South-easterly plunging "box-like" fold.

c. Refolding of the limbs and the axial plane of an isocline by an open asymmetrical fold of uncertain age. The open fold is nearly co-axial with the isocline.

a



b



c



PLATE V111

a. N.N.E. - S.S.W. trending asymmetrical minor fold in Cambrian quartzite.

b. Part of a N.N.E. - S.S.W. asymmetrical minor fold in Cambrian quartzite.

b

PLATE IX

a. South-easterly plunging open asymmetrical fold in the Cambro-Ordovician (Eilean Dubh Group) limestone. Conjugate puckers have developed at the crest of the fold.

b. The conjugate puckers seen in Plate IX a.



b



PLATE X

a. Photomicrograph of ultrabasic hornblendite with coarse granular texture. Lewisian gneiss. Ordinary light. X 10.

b. Photomicrograph of deformed and schistose ultrabasic rock. Coarse hornblendes exhibit bent cleavages and strained extinction. Fibrous amphiboles, which have developed from the coarse hornblendes, emphasize the schistosity. Lewisian gneiss. Crossed Nicols. X 10.

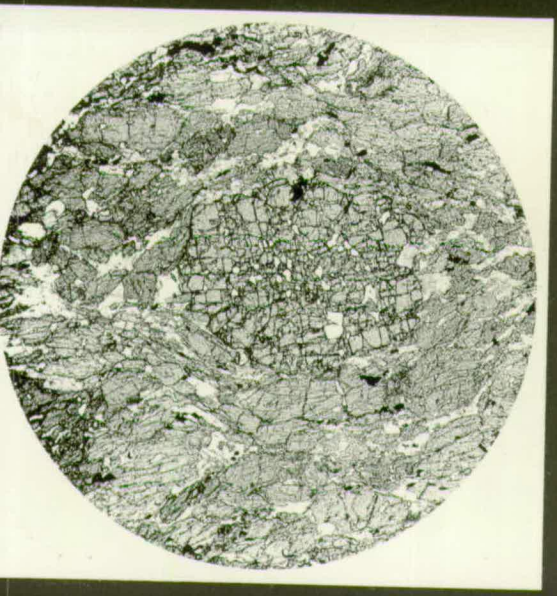
b

PLATE XI

a. Hornblende-schist with porphyroblastic garnet. Lewisian gneiss. Ordinary light. X 35.

b. Sheared basic rock (Lewisian) from near the inverted contact between the Lewisian and Torridonian at Cearcall Dubh area. The hornblende grains have been reduced to a very fine size and the garnet has been remarkably stretched along schistosity. Ordinary light. X 35.

c. Example to show the relative resistance to deformation of the basic rocks compared to the acid rocks. The lower part of the photomicrograph shows the acid rock which has been converted into a platy laminated mylonite by intense differential slip. The basic rock, which is adjacent to the acid rock, contains fractured but still recognizable hornblendes. Slightly undulating shear planes have developed in the basic rock. The presence of a well-developed shear plane at the contact of the acid and basic rocks indicates that strong differential movement has taken place at this contact. Ordinary light. X 10.



a



b



PLATE XII

a. Sheared basic rock (Lewisian). Some fibrous tremolitic amphiboles have developed from the coarse hornblendes. The section is normal to the foliation (S_1) and to the lineation (b_1). Ordinary light. X 35.

b. Same. Section normal to the foliation (S_1) and parallel to the lineation (b_1). Ordinary light. X 35.

c. Hornblende-schist (Lewisian) with bluish-green hornblendes. The section, which is normal to the foliation and the lineation, shows hornblendes with cleavage traces at 124°. Ordinary light. X 25.

d. Same. The section, which is normal to the foliation and parallel to the lineation, shows hornblendes with parallel traces of prismatic cleavages. Ordinary light. X 25.

X

a

b

c

d

PLATE XIII

Examples of sheared Lewisian acid gneisses.

a. Moderately sheared gneiss, showing strained coarse felspars and undulating shear planes along which sericitic micas have developed. Crossed Nicols. X 35.

b. Strongly sheared gneiss, showing eye-like grains of felspars. The rock possesses a slightly undulating planar structure. Ordinary light. X 50.

c. Same field. Crossed Nicols. Recrystallized quartz grains and sericites form narrow bands which wrap round the "eye"-like porphyroclasts of felspars. X 50.

a

PLATE XIV

a. Lewisian acid gneiss, showing clusters of recrystallized quartz grains. Section normal to the foliation (S_1) and the lineation (b1). Crossed Nicols. X 50.

b. Same. Section normal to the foliation (S_1) and parallel to the lineation (b_1). Note the remarkably elongate shape of the clusters of quartz grains. Crossed Nicols. X 50.

PLATE XV

a. Lewisian Mylonite with a few porphyroclastic grains of felspars. Note the platy, laminated character of the rock. Ordinary light. X 50.

b. Same field. Crossed Nicols. Note the extreme granulation of the constituents in the finely laminated matrix. X 50.

c. Lewisian Blasto-mylonite. Platy, laminated mylonitic rock in which most of the constituents in the matrix have recrystallized. Crossed Nicols. X 50.

d. Conglomerate-like rock collected near the inverted Torridonian-Lewisian contact. The rock is partially recrystallized and contains a few large felspar grains. Texturally the rock is indistinguishable from the blasto-mylonite in Plate XV c. Crossed Nicols. X 35.

a

b

c

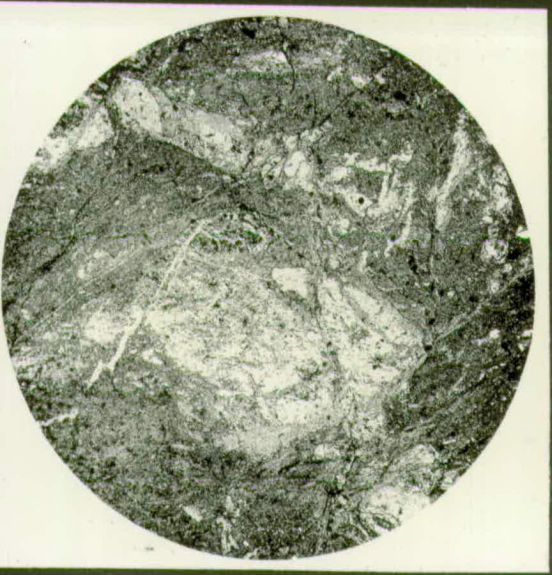
d

PLATE XVI

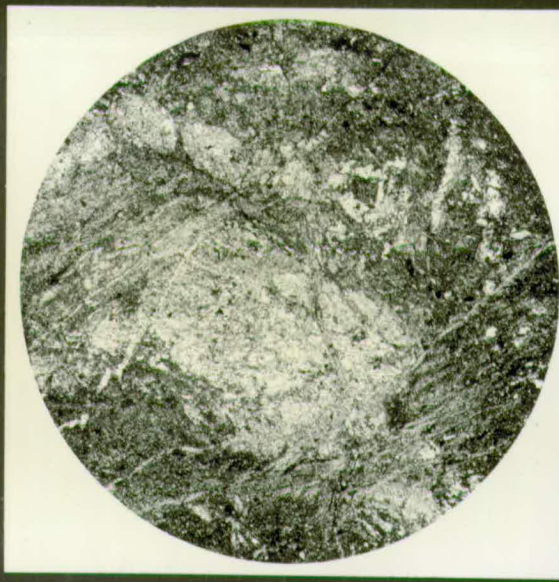
a. Cataclasite collected from just above the Kishorn thrust plane near the All Mo'r. The unlaminated rock consists of crushed fragments of the Torridonian (Diabaig) grit. Ordinary light. X 35.

b. Same field. Crossed Nicols. X 35.

c. Cataclasite collected just above the Kishorn thrust plane north-east of Glas Bheinn. The rock consists of crushed fragments of Lewisian acid gneiss. Carbonates occur along the cracks. Crossed Nicols. X 35.



a



b



c

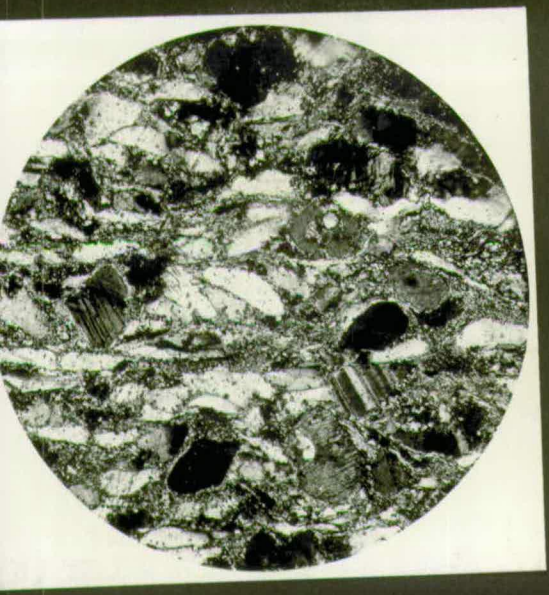
PLATE XVII

a. Torridonian (Diabaig) grit showing effects of mechanical deformation. Quartz grains have been broken into "slivers". Felspars, as well as the quartzes, exhibit strained extinction. Section normal to the schistosity (S_1) and the lineation (b_1). Crossed Nicols. X 35.

b. Same rock. Section normal to the schistosity (S_1) and parallel to the lineation (b_1). Note the elongation of quartz slivers in this section. Crossed Nicols. X 35.

c. Partially recrystallized Torridonian (Diabaig) grit, showing schistose structure. Ordinary light. X 35.

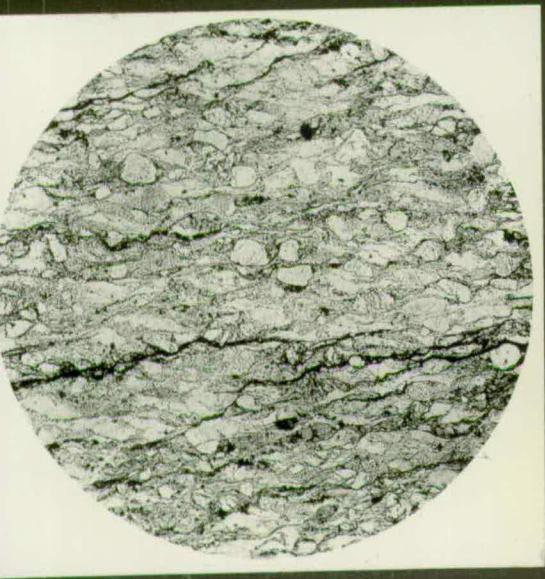
d. Same field. Crossed Nicols. Schistosity (S_1) is emphasized by sericitic micas and clusters of recrystallized quartz grains. Crossed Nicols. X 35.



a



b



c



d

PLATE XVIII

a. Undeformed Torridonian (Applecross) grit collected about 10 ft. below the thrust plane west of Loch Cadh' An Eididh. Crossed Nicols. X 35.

b. Deformed Torridonian (Applecross) grit collected just below the thrust plane west of the Loch Cadh' An Eididh. Felspars and quartz grains exhibit strained extinction. The sedimentary texture of the rock is still preserved. Crossed Nicols. X 35.

PLATE XIX

a. Undeformed Cambrian quartzite with granular texture. Crossed Nicols. X 25.

b. Cataclastically moderately deformed Cambrian quartzite collected about 10 ft. below the Kishorn thrust. The coarse granular texture is partly destroyed. Crushed quartz grains exhibit strained extinction. Crossed Nicols. X 25.

c. Cataclastically strongly deformed Cambrian quartzite collected just below the Kishorn thrust. Most of the quartzose materials have been finely comminuted. A few larger strained grains of quartz and felspar survive in patches. Crossed Nicols. X 35.

a

b

c

STRUCTURAL MAP OF LOCHCARRON — WESTER ROSS

LEGEND

LINEAR STRUCTURES :

ABOVE THE KISHORN THRUST

- 18 TREND AND ANGLE OF PLUNGE OF FIRST LINEAR STRUCTURE .
- 15 TREND AND ANGLE OF PLUNGE OF SECOND LINEAR STRUCTURE .
- 10 TREND AND ANGLE OF PLUNGE OF THIRD LINEAR STRUCTURE .
- 30 TREND AND ANGLE OF PLUNGE OF LINEAR STRUCTURE OF UNCERTAIN AGE .

BELOW THE KISHORN THRUST

- 20 TREND AND ANGLE OF PLUNGE OF LINEAR STRUCTURE

FAULT

THRUST

K.T. KISHORN THRUST

AXIAL TRACE OF MAJOR FOLD

0 ¼ ½ 1 MILE

N

To Stromeferry

Loch Coultrie

Loch an Lòin

Fosgah Fault

RASSAL THRUST

SOLE THRUST

AN RUADH-STAC

An Gorm Loch

CADH' AN EIDIDH THRUST

AXIAL TRACE OF A MAJOR ANTICLINE

MEALL AN DAIMH

Loch Cadh' an Eididh

COILLE DHUBH

K.T.

Rassal

Tornapress

Cnoc nam Broc

SGURR A' GHARAIDH

Loch a' Mhuilinn

Cnoc na h-Àtha

TORR NA H-IOLAIRE

LOCH KISHORN

Courthill House

CEARCALL DUBH

Loch na Cailich

GLAS BHEINN

To Achnashellach

Tullich

Drochaid a' Chadha

GLEN MORE

To Lochcarron

LOCH CARRON

57°34′ 57°30′ 57°28′ 57°26′

MAP I.

GEOLOGICAL MAP OF LOCHCARRON–WESTER ROSS

LEGEND

LEWISIAN
- ACID GNEISS
- AMPHIBOLITE AND HORNBLENDE SCHIST
- PEGMATITE

TORRIDONIAN
- APPLECROSS GROUP
- DIABAIG GROUP

CAMBRO-ORDOVICIAN
- EILEAN DUBH GROUP
- GHRUDAIDH GROUP
- SERPULITE GRIT
- FUCOID BEDS
- PIPE ROCK
- BASAL QUARTZITE

- STRIKE AND DIP OF FOLIATION AND BEDDING
- VERTICAL STRATA
- HORIZONTAL STRATA
- THRUST
- NORMAL FAULT
- K.T. KISHORN THRUST

0 ½ 1 MILE

N

LOCH KISHORN
River Kishorn
Rassal
Tornapress
Courthill House
Allt Mor
Allt an t-Sratha Fhuair
Fasagh Fault
RASSAL THRUST
Loch an Lòin
Loch Coultrie
To Shieldaig
Allt a' Chruibhe
alluvium
COILLE DHUBH
K.T.
Cnoc nam Broc
SGURR A' GHARAIDH
Δ2396
CEARCALL DUBH
Loch na Caillich
Drochaid a' Chadha
GLEN MORE
To Lochcarron
Allt nan Carnan
GLAS BHEINN
Δ2330
SOLE THRUST
CADH' AN EIDIDH THRUST
AN RUADH-STAC
Δ2919
An Gorm Loch
MEALL AN DAIMH
Loch Cadh an Eididh
Loch a' Mhuilinn
Cnoc na h-Àtha
TORR NA H-IOLAIRE
Allt Bhuidhe
Tullich
To Achnashellach
LOCH CARRON
57°34'
57°30'
57°28'
57°26'