A STRUCTURAL STUDY
of the
MOINE THRUST ZONE IN SUTHERLAND

BY

ANDREW J. McLEISH, B.Sc.

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SECTION I:

INTRODUCTION

1. General Statement

Although there is now considerable evidence to show the existence of polyphase deformation in the Moine Thrust Zone of the North-West Highlands of Scotland there are still many uncertainties concerning the interpretation of the structures. Again, there is very little information regarding the amount of strain in the deformed rocks of the region. This thesis presents data that have a bearing on these problems.

Firstly, it presents the results of detailed structural analyses carried out in three areas - at Kempie (Loch Eriboll), Glen Coul and Durness - lying in the Moine Thrust Zone. The structural history of the Moine Nappe at Glen Coul is treated in particular detail in an attempt to throw new light on the proposal by Christie (1956, 1963) that the Moine Thrust is really a strike-slip fault.

Secondly, it presents quantitative analyses of the strain of the deformed Pipe Rock at Kempie and Glen Coul. Such analyses help to clarify the natures of certain planar and linear structures. For example, analysis of pipe strain in mylonitised Pipe Rock in the Moine Nappe at Glen Coul has proved to be of significance in considering the problem of the origin of mylonites.

Thirdly/
Thirdly, the Durness Moines, being klippen of the Moine Nappe, offer evidence of the amount (and perhaps the direction) of slip on the Moine Thrust-plane.

2. The areas studied: locations, topography and exposure

The locations of the areas are shown in Fig. 1.

Area I: Kempie, Loch Eriboll.

Area I is situated on the east side of Loch Eriboll between Ard Neackie and Inbhirean; it extends inland for about half-a-mile.

There are no distinctive topographical features; the ground rises steadily from the shore of the Loch to attain a maximum height in the area of 625 feet about 700 yards south of Kempie.

Exposures are generally abundant.

Area II: Glen Coul.

Area II is situated at the head of Loch GlenCoul. It is a strip of country extending from the lower reaches of the Fionn Allt north-west to the stack of GlenCoul, thence northwards to Lochain Feith an Leothaid.

From the Fionn Allt, the ground rises to the rounded knoll of Cnoc an Fhuarain Bhaain (1,282 ft.) and continues north-west as a broad undulating ridge between Loch an Eircill and Loch nan Coarach to the Stack of Glencoul (1,620 ft.). Between the Stack and the hummocky plateau in the north of the area is the narrow cleft of Glen Coul.

Exposures/
Figure 1

Outline map of the extreme north-west of Scotland showing the locations of the three areas studied.
Cape Wrath 10 mi
10 km.

Fig 1.

Faraid Head
Durness
Loch Eriboll
Loch Hope

Kinlochbervie
Rhiconich
Loch Laxford
Scourie

Point of Stoer
L. Glendhu
L. Glencoul
Loch Assynt
Lochinver
Inchnadamph

Cape Wrath

-58° 30'N

10 miles
10 km.
Exposures are abundant, except between the Fionn Allt and Loch an Eircill where much of the ground is peat covered.

Area III: Durness.

Area III lies ten miles east of Cape Wrath and includes the peninsula of An Pharaid and the coast-line from Creag Thaibhe to the south-east margin of Sango Bay. From Sango Bay the area extends inland, in a strip one-third of a mile wide, almost to Loch Culadail.

The coast-line consists, for the most part, of a narrow rocky fore:shore backed by cliffs which, near Faraid Head, attain a maximum height of 300 feet.

Coastal exposure is excellent. Inland, the ground is mainly rough pastureland and exposures are rare.

The Kempie and Durness areas are on the Ordnance Survey "One-inch" map of Cape Wrath (Sheet 9: 1959). The Glen Coul area is on the Loch Inver and Loch Assynt map (Sheet 13: 1959).

The Kempie area is on Ordnance Survey "Six-inch" sheets NC 45 NW and NC 45 NE (1961); the Durness area on sheets NC37 SE, NC 36 NE and NC 46 NW (1962); and the Glen Coul area on sheets NC22NE, NC 23 SE, NC 32 NW and NC 32 SW (1963).

3. Regional Geology

In the North-West Highlands of Scotland the Caledonian Mountain Belt is separated from the foreland to the west by a marginal thrust zone -
Table I: Summary of the geology of the North-West Highlands.

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<td>Durine Group</td>
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<td>Crois-a-phuill Group</td>
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<tr>
<td>Balnaskiel Group</td>
<td>Limestone and dolomite 4,000 feet</td>
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<td>Sangomore Group</td>
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<td></td>
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<td>Sailmhor Group</td>
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<td>Eilan Dubh Group</td>
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<td>Grudaith Group</td>
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<tr>
<td>Serpulite Grit</td>
<td>Quartzite, sandstone, dolomite 40 - 100 feet</td>
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<tr>
<td>Fucoid Beds</td>
<td>Limestone, mudstone, sandstone, dolomite 250 - 300 feet</td>
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<tr>
<td>Pipe Rock</td>
<td>Orthoquartzite Numerous Skolithos burrows</td>
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<tr>
<td>Basal Quartzite</td>
<td>Orthoquartzite 150 - 350 feet</td>
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<td>unconformity</td>
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<tr>
<td>Torridonian Series</td>
<td>Arkoses 900 million years Moines 12,000 feet Metamorphism post-Cambrian</td>
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<td>Pre-Cambrian</td>
<td>Gneisses metasediments igneous rocks 2,600 - 1,200 million years migmatites</td>
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<td>Glencoul Nappe</td>
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<td>&quot;Sole&quot; Thrust</td>
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the Moine Thrust Zone.

The dominant rocks within the Mountain Belt belong to the Moine Series but, in addition to the Moinian Psammites, Schists and Gneisses, Lewisian Gneiss is present as autochthonous or allochthonous basement.

The foreland rocks are Lewisian Gneiss of the Scourian and Laxfordian complexes, Torridonian sediments - largely sandstones and arkoses - and Cambro-ordovician sediments which are dominantly quartzites and carbonates. The Torridonian unconformably overlies the Lewisian; the Cambro-Ordovician lies unconformably on both.

The narrow marginal thrust zone stretches 120 miles from Eriboll to Skye and reaches a maximum width of about 12 miles in Skye. In general, the thrust zone consists of a sequence of nappes separated by easterly dipping thrust planes, the highest of which is the Moine Thrust-plane. The nappes beneath the Moine Nappe consist of Lewisian Gneiss and Torridonian (south of Loch Glen Coul) and Cambro-Ordovician sediments.

The lithology and stratigraphic relationships of the rocks of the North-West Highlands are summarised in Table I. The main geological features of the extreme north-west of Scotland are shown in Fig. 2

1. The Geological Settings of the Areas Studied.

Area I: Kempie, Loch Eriboll

The stratigraphic and general structural relationships of the Eriboll and Durness areas were established through the work of Nicol (1961), Lapworth (1883 and 1885), Callaway (1883) and Peach and Horne (in Peach et al. (1907)).
Map illustrating the general geology of the extreme north-west of Scotland. [After Geological Survey $\frac{1}{2}$ inch Sheet 5 (1948) and Johnson (1965) Fig. 3.1]

A - Lewisian Gneiss ($A_1$ - Scourian Complex; $A_2$ - Laxfordian Complex; and $A_m$ - Hornblende rocks of Lewisian type occurring within the Moines)

M - Moines - largely psammites and pelites

t - Torridonian ($t_1$ - Diabaig Group; $t_2$ - Applecross Group; $t_3$ - Aultbea Group; and $t$ - undifferentiated)

a - Cambro-Ordovician ($a_1$ - Basal Quartzite, Pipe Rock, Fucoid Beds and Serpulite Grit; and $a_2$ - Durness Limestone)

The major thrusts are numbered as follows: 1. Sole Thrust; 2. Arnaboll Thrust; 3. Glencoil Thrust; 4, 4' and 5. Ben More Thrust; and 6. Moine Thrust. Christie (1963) considered "3" and "4" ("the Assynt Thrust") to be equivalent.
At Kempe, the basal major thrust is the Arnaboll Thrust which brings folded and faulted Iaxfordian Gneiss and Cambro-Ordovician sediments (Basal Quartzite to Eilan Dubh Limestone) to rest with striking discordance on the much faulted, but generally easterly dipping, Cambro-Ordovician of the foreland (See Peach et al. (1907) pp. 480-481; and Geological Survey "One-inch"Sheet 114 (1980)).

According to Peach et al. (loc. cit) the Arnaboll Nappe is overlain by the Moine Nappe but Wilkinson (1955) redefined the Moine Thrust-plane of Peach et al. (loc. cit) as the "Eriboll Thrust-plane"; he considered the Moine Nappe to overlie the Eriboll Nappe.

The present work is a study of the folded and faulted sediments of part of the Arnaboll Nappe. Particular attention has been devoted to the analysis of strain in the deformed Pipe Rock.

Peach and Horne (in Peach et al. (loc. cit)) and Wilson (1965) noted the existence of deformed pipes on Ben Arnaboll and Whiten Head, respectively, but no previous attempts have been made at quantitative strain analysis.

Area II: Glen Coul

The early work on the geology of this area has been fully summarised by Christie (1956 and 1963).

In the vicinity of Glen Coul, the Lewisian Gneiss of the Glen Coul Nappe is overlain by Cambro-Ordovician sediments (Basal Quartzite to Chrudaich Limestone/
South of the Stack of Glen Coul, the Glen Coul Nappe is overlain by the Cambro-Ordovician of the Ben More Nappe. The mylonites, schists and psammites of the Moine Nappe overlie both the Ben More and Glen Coul Nappes. At Loch nan Coarach the Moine Nappe "oversteps" the Ben More Nappe and rests directly on the Glen Coul Nappe (but see Christie, 1963).

In the Glen Coul Nappe, study has been made of the structures developed in the Cambro-Ordovician sediments between Lochain Feith an Leothaid and Loch nan Coarach. As at Kempie, the deformation of the Pipe Rock has been specially considered.

The Ben More Nappe has not been studied but a detailed structural analysis of part of the Moine Nappe is presented.

Area III: Durness

The Moinian of Durness and An Fharaid are klippen separated, by seven miles, from comparable Moinian successions (Peach et al. 1907) pp. 478 - 480) on the east side of Loch Eriboll. The existence of these klippen was interpreted by Peach and Horne - in Peach et al. (op. cit.) - as showing that the Moine Nappe had "been driven westwards for a distance of ten miles from the hill-slopes on the east side of Loch Eriboll" (p.469).

The Moinian meta-sediments on the western extremity of An Fharaid are overlain by a sheet of Lewisian Gneiss which can be traced north-south from Faraid Head to A'Chleit. The Lewisian is, in turn, overlain by Moinian psammites which extend from Faraid Head to Geodha Brat.

The An Fharaid Moine and Lewisian is separated from the Moine and Lewisian/
Lewisian at Durness by a major fault which runs west-north-west from Creag Thairbe to the southern margin of Balnakeil Bay.

South of Creag Thairbe the Moine Nappe consists of mylonite and schists, underlain by mylonitic Cambrian Quartzite. The Nappe rests on Durine Limestone of the foreland.

Lewisian Gneiss is exposed in the east of Sango Bay; its relationships to the Moines are not clear.

The present work is a study of the structures developed within the Moine Nappe. The evidence indicative of the amount and direction of displacement of the Moine Nappe has been re-examined.

5. The use of symbols in describing time relationships among structures.

(a) Introduction

An integral part of structural analysis is the recognition of time relationships among structures. Structures may be arranged in order of development by examination of their mutual interference.

It is now common practice among structural geologists to designate symbols to structures, components of structures and structural processes and to indicate time relationships by numerical subscripts.

There are at present two systems of symbolic nomenclature designed specifically for use in describing structural histories.

The first of these is due to Rast (1958 and 1963). In the Dalradian of Perthshire, Rast (1958) found "four systems of minor folds" (p. 73). The processes giving rise to the fold systems were variously defined as "sets of movements", "stages of deformation", "movements", "episodes"/
"episodes of deformation" - Rast (1958) p. 33 - "episodes of folding" - Rast (1967) p. 126 - and "episodes of deformation" - op. cit. p. 135. The "stages of deformation" were symbolised $F_{1-5}$ where the subscripts indicate time sequence.

In description, the symbols were used largely as prefixes to the structures and structural processes of any stage of deformation. Thus, Rast described: "$F_4$ movements", "$F_3$ episode of deformation", "$F_2$ folds", "$F_1$ times", "$F_2$ structures", "$F_2$ folding", "$F_2$ age", "$F_2$ axes", "$F_1$ strike", "$F_2$ trend", "the effects of $F_1$, $F_2$, and $F_3$", "folds which were produced by $F_2$", - Rast (1958) pp. 34-42 - "$F_1$ microfabric", "$F_1$ and $F_2$ directions of folding", "$F_2$ micro-folds", "$F_3$ down bend", and "$F_1$ episode of folding" - Rast (1963) pp. 127-134.

Rast (op. cit.) p. 139, also introduced the symbols $M_{1-3}$ to represent "stages of metamorphism". $M_1$ began "probably during the $F_1$ movements and terminated at the $F_2$ episode"; $M_2$ "is entirely post-$F_2$ movements; and $M_3$ is "associated with the $F_3$ movements". (loc. cit.).

Johnson (1965) p. 145, in a discussion of Dalradian regional metamorphism, distinguished four "structural events", $F_1 - F_4$ and three "metamorphic events", $M_1 - M_3$.

In the Moine Thrust Zone, Johnson (1960) distinguished six phases (Phase 1 etc.) of structure development. During phases 1-4 folds $F_1 - F_4$ were formed; there was no folding during Phase 5 so that the $F_5$ folds developed during Phase 6.

Johnson/
Johnson (1961) redefined $F_{1-4}$ as "four movement episodes" (p. 418) and as "metamorphic episodes" (pp. 419-429). As in Rast (1958 and 1963), $F_{1-4}$ were used as prefixes to structures and structural processes.

In the Caledonides of North-West Scotland Ramsay (1963) pp. 162-167, defined $F_1-F_4$ as "first folding" "second folding" "third folding" and "fourth folds", respectively. In addition, Ramsay (op. cit.) pp.168-170 described $F_1-F_4$ "metamorphic events" and evaluated "The relationships between metamorphic events and the phases of folding ....".

The second system of symbolic nomenclature is due to Turner and Weiss (1963) p.131. Adopting, to some degree, the symbols proposed by Sander (1930 and 1948) structures and their components were given separate symbols. Thus, a planar structure is $S_1$, a fold axis $B$, and a lineation, $L$. The sequence of the development of structures is indicated by numerical subscripts; thus, $S_1$ predates $S_2$ which, in turn, predates $S_3$.

Folds have no special symbol but fold axes are distinguished by use of sub and superscripts which are, respectively, the folded surface and the axial surface of the fold. "Thus $\beta_{S_1}S_2$ is the axis of a fold in $S_1$, the axial surface of which is $S_2$." - Turner and Weiss (1963) p.131.

The author has developed a system of symbolic nomenclature which will be presented, then discussed and compared with the systems of Rast (1958 and 1963) and Turner and Weiss (1963).

(b) Set Notation

Use is made of the Boolean concept of sets.

A set is any collection of objects or abstractions. Sets are composed/
composed of elements.

In this study, an element is defined as any structure or group of similar, probably genetically related structures. A set is all the structures forming what the observer considers to be a distinct group.

**Elements**

The elements of a set are enclosed in brackets and are denoted by lower-case letters. Table II shows the letters chosen to symbolise structures.

**Sets**

Sets are denoted by Roman numerals such that a time sequence is inferred; that is, Set I predates Set II.

Element symbols are suffixed by the number of the set to which they belong; thus, $f_I$ are the folds of Set I.

If a set contains two or more elements of similar type which may be separated in time, a second numerical suffix indicates the relationship; thus, $l_{I_1}$ predates $l_{I_2}$. Where such similar structures cannot be separated in time but may be differentiated in type, they are distinguished by using a letter as second suffix; for example, $l_{Ia}$ may be a grain-elongation lineation and $l_{Ib}$ a cleavage-bedding intersection lineation.

Further differentiation in type or age may be made by using additional suffixes; for example $l_{Ia}$ predates $l_{Ia2}$.

An element may appear in only one set.

**Special sets.**

**Set 0**

Set 0 is that set of structures which predates the structural marker/
Table II

**Set Elements.**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Structure(s) or use</th>
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<tr>
<td>b</td>
<td>bedding</td>
</tr>
<tr>
<td>d</td>
<td>mineral fabrics</td>
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<tr>
<td>f</td>
<td>folds</td>
</tr>
<tr>
<td>g</td>
<td>clastic particles, crystals</td>
</tr>
<tr>
<td>h</td>
<td>faults</td>
</tr>
<tr>
<td>k</td>
<td>kink bands</td>
</tr>
<tr>
<td>l</td>
<td>lineation</td>
</tr>
<tr>
<td>p</td>
<td>pipes</td>
</tr>
<tr>
<td>s</td>
<td>cleavage, schistosity, foliation</td>
</tr>
<tr>
<td>w</td>
<td>structures, undiscovered by the observer, which have been described by previous workers.</td>
</tr>
<tr>
<td>x</td>
<td>structures whose nature is undecided</td>
</tr>
<tr>
<td>y</td>
<td>structures which the observer cannot assign, or has not assigned, to a set.</td>
</tr>
<tr>
<td>z</td>
<td>structures not discovered or not considered by the observer. z is an element of every set.</td>
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marker which is determined, or chosen, to be the earliest element of Set I. The elements of Set 0 are thus, pre-"first" structures; all sedimentary, organic and diagenetic structures are elements of Set 0. In this study, structures of Lesician age are included in Set 0.

Set U

By definition, the elements of any set are superimposed on the elements of all preceding sets. Where structures are developed whose time relationships are not known (through lack of evidence of superimposition) they are included in Set U. Set U holds a tentative position in any time sequence.

The origins of structural sets

The process (or processes) by which a structural set develops is called set generation. The agencies of set development are set generators.

(c) Discussion

It is clear from the writings of Rast (1958 and 1963), Johnson (1960 and 1961) and Ramsay (1963) that the symbol letter "F" has distinct connotations with "folds" and "folding". The author considers that only under certain circumstances - for example, where folds are the only structures, or where folds are undoubtedly dominant (as in $F_1$ of the southern Moine Thrust Zone and $F_1-F_3$ of the Perthshire Dalradian) - can such an emphasis of folds be justified. Where folds, and particularly minor folds, are only one of many types of structure belonging to a synchronous group the/
group the author can see little reason for considering the folds to be all important and for regarding the group of structures to be the result of a "phase of folding". Lineation and foliation frequently develop synchronously with folds, yet, as far as the author is aware, no structural geologist has described "phases of lineating" or "phases of foliating".

Emphasis on folding carries with it subtle genetic implications in that those structures associated with folds are automatically ascribed to a "phase of folding" and the mechanisms of folding become, in consequence, an apparently integral part of their modes of formation. By way of illustration Barber (1965) p.225, has stated: "Where actual folds are absent the effects of the episode of folding are indicated by ......lineation.....". (With respect to F₃ of the Moine Thrust Zone). This statement implies that the lineation is the result of folding; but can linear (and planar) structures derive from folding? By definition, it would appear that only folds can be the product of a phase or an episode of folding.

The author considers that the symbolism due to Turner and Weiss (1963) is defective in that it is too complex, since:

(1) Although the subscripts of planar structures (S₁, S₂, S₃, etc.) denote relative age relationships, the subscripts of lineations (L₁, L₂, L₃, etc.) carry "no necessary connotation of relative age ...." (op. cit. p.131) This is confusing.

and (2) The use of both sub and superscripts to denote fold axes is unwieldy; synchronous axes could be designated Bₛ¹₅, Bₛ²₅, Bₛ³₅, and Bₛ⁴₅. Any fold with axial surface S₅ must be capable of folding S₁-S₄; it/
it is hardly necessary to use four symbols to show this.

In conclusion the author considers the advantages of set notation to be as follows:

(1) In common with the system due to Rast (1958), set notation is simple. The system of Turner and Weiss (op. cit.) is defective in this respect.

(2) In common with the symbolism of Turner and Weiss (op. cit) set notation is entirely lacking in genetic implications. Rast's (op. cit) system is not entirely free of such implications (see above).

(3) Set notation may be applied to any structural history, whether or not folds have developed, without the necessity of introducing new symbols such as "M" (Rast (1963)) for "metamorphism".

(4) The phrase "set generation" includes within its meaning all those processes by which a structural set develops. Thus, "set generation" encompasses such terms as "phase of folding", "episode of deformation", "set of movements" and "movement episode" which, in consequence, become unnecessary.

(5) In set notation the numerical subscripts always imply time sequence; this is not the case with \( L_1, L_2, L_3 \) etc. of Turner and Weiss (op. cit.).

(6) The symbolism of set notation places no particular emphasis on any one type of developed structure; this is not the case with the "F" notation of Rast (1958) (see above) and

(7) Set notation is completely comprehensive since the observer can formulate a symbol for every type of developed structure. Table III gives an imaginary/
imaginary structural history and the symbolisms of Rast (op. cit.), Turner and Weiss (op. cit.) and the author which could be applied to the history. Set notation is the only system which can fully symbolise the sequence of structures.

Finally, any system of symbolic nomenclature should be simple, unambiguous, concise, devoid of genetic implications and comprehensive. Since the systems due to Rast (op. cit.) and Turner and Weiss (op. cit.) are defective in certain respects, set notation has been evolved in an attempt to satisfy the above named requirements.

6. Field Work

Field work was carried out during the summers of 1962-1966. As a general rule, detailed mapping of major rock boundaries was not undertaken and the boundaries shown in the author's geological and structural maps are essentially those mapped by the Officers of the Geological Survey. Modifications to the survey maps have occasionally been necessary; these have been noted in the text.
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<tbody>
<tr>
<td>Sedimentary sequence</td>
<td>( S_1 )</td>
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<td>( S_1, L_1 )</td>
<td>( S_1 = (b_o, g_o, z_o) )</td>
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<tr>
<td>Folds, cleavage, cleavage-bedding intersection lineation</td>
<td>( F_1, F_2 ) folds etc.</td>
<td>( S_2, B_2, L_2 )</td>
<td>( I_1 = (f_1, s_1, l_1, z_1) )</td>
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<td>Cleavage, intersection lineations with bedding and earlier cleavage</td>
<td>( ? )</td>
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<td>Thrusts</td>
<td>( ? )</td>
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<td>( S_3, L_3 )</td>
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<tr>
<td>Folds</td>
<td>( F_2 )</td>
<td>( B_2, B_5, B_5, B_5, B_5 )</td>
<td>( S_4 = (b_4, g_4, z_4) )</td>
<td>( S_4 = (b_4, g_4, z_4) )</td>
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<td>Foliation, lineation in foliation, quartz microfabrics, intersection lineations with pre-existing planar structures.</td>
<td>( M )</td>
<td>( S_6, L_6 )</td>
<td>( S_5 = (b_5, g_5, z_5) )</td>
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<tr>
<td>Folds</td>
<td>( F_3 )</td>
<td>( B_6, B_6, B_6 )</td>
<td>( S_7, L_7 )</td>
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SECTION II:

**STRAIN ANALYSIS OF DEFORMED PIPE ROCK**

1. Introduction

This section deals with the theory of the strain analysis of states of planar, homogeneous strain and its application to the calculation of strain and shear parameters in deformed Pipe Rock.

In unstrained Pipe Rock, the pipes (worm burrows) are normal to the bedding (Peach et. al., (1907) p. 366; Hallam and Swett, (1966) p. 102).

If the pipes and the bedding are treated as linear and planar elements respectively, then, in the strained state, all that may be measured is the change of angle (shear) between them and complete strain analysis is not possible. To permit strain analysis the strains of the originally orthogonal elements must be known. The strains of the pipes and bedding may be found by considering the pipes to be cylindrical. The values of the pipe and bedding strains, in conjunction with the magnitude of the modified pipe-bedding angle, may be used, by methods described below, in the analysis of planar, homogeneous strain. It is assumed that the pipes lie in a principal plane of the deformation; throughout this work, analysis is described in terms of the plane containing the maximal and minimal principal strains.

In/
In the Moine Thrust Zone, recorded strain analyses are very rare and have been accomplished in deformed conglomerates (Kanungo, (1956) pp. 105-109 and 120-122: Ramsay (1963) p. 147).

In a discussion of the variation of deformation within the rocks of the North West Caledonides, Ramsay, op.cit., noted the extreme rarity of "Objects of known pre-deformation shape" and concluded that "it is very difficult to obtain any quantitative estimates of the amount of local deformation and that it is probably impossible to obtain any exact information about the variation of regional deformation or of crustal shortening" (p.146).

Since Pipe Rock occurs throughout the Moine Thrust Zone, strain analysis of deformed Pipe Rock may in future prove useful in helping understanding of the natures and mechanisms of formation of the structures within the region.

2. "Pipes":

"Pipes" are trace fossils of the genus Skolithus; Haldeman, 1840. Skolithus is described by Hallam and Swett (1966) p. 102 as follows:

"Straight, subcylindrical, sediment-plugged tubes or pipes oriented normal to the bedding. The diameter, constant for a given tube, ranges from 3 to 15 mm. and the length may exceed 1 metre ... very slight mineralogical differences (exist) between the material of the pipe and of the inter-pipe matrix. A slightly lower sericite content within the pipes is sometimes discernible with a petrographic microscope. This slight mineralogical difference is, however, often impossible to detect petrographically."

3.

In this section the principles of strain analysis are set out. Throughout, analysis is considered in terms of planar homogeneous strain and is developed for the plane containing the maximal \( (\varepsilon_1) \) and minimal \( (\varepsilon_3) \) principal strains.

(a) Strain components. (see Nadai, 1950)

If a line of initial length \( l_0 \) is strained such that its length becomes \( l \), then the change of length \( \Delta l \) is \( l - l_0 \).

\[ \varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0} = \frac{l}{l_0} - 1 \]

\( \varepsilon \) is positive or negative depending, respectively, on whether \( l \gt l_0 \) or \( l_0 \gt l \).

The quadratic elongation, \( \lambda \), of the strained line is:

\[ \lambda = \frac{l^2}{l_0^2} = (\varepsilon + 1)^2 \]

If a plane \( p_0 \) and its normal \( n_0 \) are sheared to become \( p \) and \( n \), then \( p \cdot n \neq 90^\circ \). (For "p · n" read "the angle between p and n.") If the normal to \( p \) is \( n_1 \) then let \( n \cdot n_1 = \psi \). The unit shear, \( \gamma \), of the plane and its normal, is:
its normal is:  
\[ \gamma = \tan \psi \]

Where  \( p-n = \omega \ (90^\circ, \omega) \):
\[ \gamma = \cot \omega \]

In planar strain where originally perpendicular lines \( l_0 \) and \( l_0'' \) become \( l' \) and \( l'' \) then, where \( l' - l'' = \omega \ (90^\circ, \omega) \), the unit shear of these lines is:
\[ \gamma = \cot \omega \]

(b) **Principal strains**

(see Nadai, 1950)

The principal strains may be denoted:
\[ \varepsilon_1', \varepsilon_2', \varepsilon_3' \], where \( \varepsilon_1', \varepsilon_2', \varepsilon_3' \)
or \( \lambda_1, \lambda_2, \lambda_3 \), where \( \lambda_1, \lambda_2, \lambda_3 \)

In general strains with no volume change it may be shown that:
\[ (\varepsilon_1 + 1)(\varepsilon_2 + 1)(\varepsilon_3 + 1) = 1 \]
and \( \lambda_1, \lambda_2, \lambda_3 = 1 \)

In planar strain:
\[ \varepsilon_2 = 0 \quad \text{and} \quad \lambda_2 = 1. \]
and \( (\varepsilon_1 + 1)(\varepsilon_3 + 1) = 1 \); \quad \text{and} \quad \lambda_1, \lambda_3 = 1. \]

In this study, the semi-axes of the strain ellipsoid are \( X, Y \) and \( Z \)
where \( X, Y, Z \).

(c) The strain of the pipes and bedding in the plane of deformation

The symbols used in the following text are defined in Table IV.

In Fig. 3 \( P_1 \) and \( B_1 \) become, with strain, \( P_2 \) and \( B_2 \).

Since there is no area change:

\[
P_1 \cdot 2r = P_2 \cdot 2b
\]

\[
\frac{P_2}{P_1} = \frac{r}{b} = \frac{a}{b} \quad (a = r)
\]

\[
\lambda_P = \frac{(a)}{(b)}^2 \quad (1)
\]

\[
\frac{B_2}{B_1} = \frac{d}{2r}
\]

\[
= \frac{2b}{2r \sin \omega} \quad (d = \frac{2b}{\sin \omega})
\]

\[
= \frac{b}{a \sin \omega} \quad (a = r)
\]

\[
\lambda_B = \left( \frac{b}{a \sin \omega} \right)^2 \quad (2)
\]

(d) Algebraic strain analysis in the plane of a planar homogeneous strain, are given by Brace (1961) p. 1065, equations/
Symbol Use and relationships

pipe: longitudinal dimension of pipe
pipe before and after strain
radius of section of \( P \): \( P \cdot r = 90^\circ \)
semi-axes of section of \( P \): \( P \cdot a = P \cdot b = 90^\circ \)
\( a \cdot \varepsilon_2 = 0^\circ \). In planar shear, since \( \varepsilon_2 = 0.0 \), \( a = r \)
\( P \) and \( b \) lie in the \( \lambda_1 \lambda_3 \) plane.
bedding: trace of bedding in \( \lambda_1 \lambda_3 \) plane.
bedding before and after strain.
pole to \( B \): \( b \cdot P = 0^\circ \).
pole to \( B \)
bedding thicknesses before and after strain, i.e. of \( B \) and \( B_2 \)

quadratic elongations of pipes and bedding in \( \lambda_1 \lambda_3 \) plane.

\[
\begin{align*}
\rho_p' &= \lambda_1 \cdot P_2 \\
\rho_B' &= \lambda_1 \cdot B_2 \\
\rho_p' &= \lambda_1 \cdot P_2 \\
\rho_B' &= \lambda_1 \cdot B_2 \\
\omega &= P_2 \cdot B_2 \\
\omega &< 90^\circ \\
\end{align*}
\]

unit shears of pipes and bedding. Since \( B \cdot P = 90^\circ \),

\[ \gamma_p = \gamma_B. \]

angle of shear in simple shear

\[ \gamma_s = \tan \alpha \]

"plane" of simple shear (also circular section of strain ellipsoid)

\[
\begin{align*}
P_1' &= S \cdot \varepsilon_1 \\
P_2' &= S \cdot \varepsilon_3 \\
\theta_{P_1} &= P_1 \cdot S \\
\theta_{P_2} &= P_2 \cdot S \\
\theta_{B_1} &= B_1 \cdot S \\
\theta_{B_2} &= B_2 \cdot S \\
n &= \text{number of ratios measured at a position in the field} \\
\end{align*}
\]
geometric mean of n ratios
Figure 3
For explanation see text.
equations (7) and (8)):

\[ \lambda' = \frac{\lambda_1' + \lambda_3'}{2} + \frac{\lambda_1' - \lambda_3'}{2} \cdot \cos 2\phi_1' \]  
\[ \Rightarrow \frac{1}{\lambda_1} = \frac{\lambda_3 + \lambda_1}{2} + \frac{\lambda_3 - \lambda_1}{2} \cdot \cos 2\phi_1' \]  

and

\[ \gamma' = -\frac{(\lambda_1' - \lambda_3')}{2} \cdot \sin 2\phi_1' \]  
\[ \Rightarrow \frac{\gamma_1}{\lambda_1} = -\frac{(\lambda_3' - \lambda_1')}{2} \cdot \sin 2\phi_1' \]

In the notation used by Brace:

\[ \lambda_1' = \frac{1}{\lambda_1} \]  
\[ \gamma_1' = \frac{\gamma_1}{\lambda_1} \]  
\[ \lambda_1' = \frac{1}{\lambda_1} = \lambda_3 \]  
and

\[ \lambda_3' = \frac{1}{\lambda_3} = \lambda_1 \]  
(p. 1065)

Thus (1) and (2) may be rewritten as:

\[ \frac{1}{\lambda_1} = \frac{\lambda_3 + \lambda_1}{2} + \frac{\lambda_3 - \lambda_1}{2} \cdot \cos 2\phi_1' \]  
\[ \Rightarrow \frac{\gamma_1}{\lambda_1} = -\frac{(\lambda_3' - \lambda_1')}{2} \cdot \sin 2\phi_1' \]
For deformed Pipe Rock (2) may be written (where $\phi'_B = \phi'_1$):

For bedding strain and shear:

$$\frac{\gamma_B}{\lambda_B} = -\left(\frac{\lambda_3 - \lambda_1}{2}\right) \cdot \sin 2\phi'_B \quad (5)$$

For pipe strain and shear:

$$\frac{\gamma_P}{\lambda_P} = -\left(\frac{\lambda_3 - \lambda_1}{2}\right) \cdot \sin 2(\omega - \phi'_B) \quad (6) \quad [\text{See Fig 3b}]$$

Dividing (6) by (5)

$$\frac{\gamma_P, \lambda_B}{\lambda_P, \gamma_B} = \left(-\frac{1}{2}\right) \left(\frac{\lambda_3 - \lambda_1}{\lambda_3 - \lambda_1}\right) \cdot \frac{\sin 2(\omega - \phi'_B)}{\sin 2\phi'_B}$$

Since $\rho_1 = \rho_1 = 90$ their unit shears are equal (p18), that is, $\gamma_B = \gamma_P$.

$$\therefore \frac{\lambda_B}{\lambda_P} = \frac{\sin 2(\omega - \phi'_B)}{\sin 2\phi'_B}$$

Simplifying:

$$\frac{\lambda_B}{\lambda_P} = \frac{\sin 2\omega}{\tan 2\phi'_B} - \cos 2\omega$$

Solving/
Solving for $2 \phi_B'$:

$$\tan 2 \phi_B' = \frac{\sin 2 \omega}{\frac{\Delta B}{\lambda_p} + \cos 2 \omega}$$

(7)

Since $P_1 = \phi_1 = 90^\circ$, it may be shown that

$$\tan \phi_B' \cdot \tan \phi_p' = \frac{\lambda_3}{\lambda_1}$$

(loc. cit. p. 1071)

$$\tan \phi_B' \cdot \tan (\omega - \phi_B') = \lambda_3^2 \left[ \frac{\lambda_1}{3} \right]$$

(8)

(e) Measurement of shear

In a planar homogeneous strain the maximum unit shear is:

$$\gamma_{\text{max}} = \frac{\lambda_1 - \lambda_3}{2}$$

(loc. cit. p. 1067)

In simple shear $\gamma_s = \tan \alpha$ and:

$$\gamma_s = \varepsilon_1 - \varepsilon_3$$

(Nadai (1950) p. 147)

In Fig 4a:

$$\tan 2 \beta_1' = \tan 2 \beta_2' = \frac{2}{\gamma_s} \quad [\text{loc. cit. pp. 147-148}]$$

and:

$$\tan \beta_1' = -\frac{\varepsilon_3}{\varepsilon_1}$$

and:

$$\tan \beta_2' = \frac{\varepsilon_1}{\varepsilon_3}$$
In analysis, if the values and orientations of $\varepsilon_1$ and $\varepsilon_3$ are known the orientations of the "shear planes" may be found. Since $\beta_1'$ may be measured on either side of $\varepsilon_1$, the attitude of the "shear planes" cannot be found unambiguously.

(f) **Calculation of pipe and bedding rotation in the $\lambda_1\lambda_3$ plane:**

1. Rotation in the $\lambda_1\lambda_3$ plane of pure shear

Slight modification of equations given by Brace (1961) p. 1071 gives:

$$\tan \phi_B = \lambda_1 \tan \phi'_B$$

and

$$\tan \phi_P = \lambda_1 \tan \phi'_P$$

The rotation of the bedding is $\phi'_B - \phi_B$ and of the pipes is $\phi'_P - \phi_P$ (Fig. 3(b))

2. Rotation in the $\lambda_1\lambda_3$ plane of simple shear

In Fig. 4 (b):

$$\tan \theta_{P_2} = \frac{k}{OB} = \frac{k}{OA + d}$$

$$= \frac{k}{\frac{k}{\tan \theta_{P_1}} + k \tan \alpha}$$

$$OA = \frac{k}{\tan \theta_{P_1}}$$

$$d = k \tan \alpha$$

$$\cot \theta_{P_1} = \cot \theta_{P_2} - \gamma_s$$

Similarly /
Figure 4.

For explanation see text.
Similarly:
\[ \cot \theta_{B_1} = \cot \theta_{B_2} - y_s \]

Since the "shear planes" may have either of two orientations (p. 23), the rotations of the pipes, \( \theta_{P_1} - \theta_{P_2} \) and bedding, \( \theta_{B_1} - \theta_{B_2} \), and, thus, their orientations before shear cannot be found unambiguously.

(g) Change of bedding thickness

In Fig 5a:

\( B_1 \) and \( t_1 \) become \( B_2 \) and \( t_2' \) with strain.

\( t_2 \) is the thickness of \( B_2 \). Since there is no area change:

\[ B_1 \frac{t_1}{t_2} = B_2 \]

\[ \therefore \quad \frac{t_2}{t_1} = \frac{B_1}{B_2} = \frac{1}{\sqrt{\lambda_B}} \]

(h) "Planes" of simple shear

In the \( \lambda_1, \lambda_3 \) plane of simple shear, rectangular coordinates \( x \) and \( z \) may be chosen such that, during deformation, points follow paths of type \( z = c \), where \( c \) is a constant; the displacement parallel to \( x \) is proportional to \( z \).
During deformation, $x$ and $z$ remain constantly oriented but $\lambda_1$ and $\lambda_3$ rotate; $x$ and $z$ are never parallel to $\lambda_1$ and $\lambda_3$ (unless, that is, strain is infinite).

Where $\gamma = \theta = 0^\circ$, it is common practice among structural geologists to call the $xy$ plane "the plane of simple shear". To be theoretically precise, there is no such thing as a "plane of simple shear". Consideration of simple shear as the slip of planes parallel to $xy$ - the "card-deck model" of simple shear - is merely a convenient analogue of simple shear; in simple shear there is no slip on, or between, discrete planes.

It may be shown that a simple shear is equivalent to a pure shear plus a pure rotation, and that "planes of simple shear" are planes in which no deformation occurs (Jaeger (1964) pp 32-33). Thus, the "planes of simple shear" are parallel to one of the circular sections of the strain ellipsoid. Since the strain ellipsoid has two circular sections it follows that in strain analysis, two possible orientations of the "planes of simple shear" may be calculated ($S_1$ and $S_2$ in this study).

Simple shear could, then, be described as that particular type of homogeneous, planar strain in which one of the circular sections of the strain ellipsoid remains constantly oriented. Since it does remain constantly oriented, it is a useful reference plane for algebraic strain analysis.

In conclusion, because it is convenient, the phrase, "planes of simple shear" will be used throughout this work, with the qualifications that: (a) these planes are abstract geometric - not actual - planes; (b) they are not/
not planes of discrete slip; and (c) in the strained state they represent planes in which there has been no strain (that is, they are parallel to one of the circular sections of the strain ellipsoid).

4. Treatment of sectional ratios measured in deformed Pipe Rock

Most undeformed pipes are not truly cylindrical. Since no quantitative estimates have been made by the author it is necessary to make certain assumptions regarding the population distribution of the sectional ratios of undeformed pipes.

It is assumed that, if any line, \( L_o \), of indefinite length be drawn on a bedding plane of undeformed Pipe Rock then, considering only those sections with a semi-axis parallel to \( L_o \), for every ratio \( \frac{a_o}{b_o} \) there is a corresponding reciprocal value.

(Fig. 5b)

Thus:

\[
G_o = n \sqrt{\frac{a_o}{b_o_1}} \times \frac{a_o}{b_o_2} \times \ldots \frac{a_o}{b_o_n}
\]

\[
= \text{antilog} \left[ \frac{\log \frac{a_o}{b_o}}{n} \right]
\]

\[
= 1.0
\]

It is further assumed that the frequency distribution of \( \log \frac{a_o}{b_o} \) is normal, with arithmetic mean, \( \mu_o = 0.0 \) and standard deviation, \( \sigma_o \).

(With deformation, the distribution of \( \log \frac{a}{b} \) remains normal with arithmetic mean/)
mean $\mu = 0.0$ and $\sigma = \sigma_o$). Identical distributions are assumed to exist in all orientations of $L_o$.

Let $L_o$ be the trace of the $E_1E_3$ plane on the bedding when $E_1 = E_2 = E_3 = 0.0$. Let $L_o$ become $L$ as a result of planar homogeneous strain. Thus, $L$ is the trace of the $E_1E_3$ plane in the bedding when $E_1, E_2, E_3$. (Fig 5b).

$a_o$ is parallel to $E_2$; with shear its value remains unchanged. Thus $a_o = a$.

In the general case $b_o$ is parallel to neither $E_1$ nor $E_3$. Thus, with strain, there is a geometric change of length of $b_o$ to $b$.

Let $b = \frac{b_o}{k}$. Thus: $\frac{a}{b} = k \frac{a_o}{b_o} \quad [a_o = a]$

With strain, the ratios on $L_o$ become those on $L$ (Fig 5b).

Thus:

$$\left(\frac{a_o}{b_o}\right)_1 \rightarrow \left(\frac{a}{b}\right)_1 = k \left(\frac{a_o}{b_o}\right)_1 = k \left(\frac{b_o}{b}\right)_1$$

Sim: $(a) \_2 = k$, and $(a) \_3 = ku$

From this, $G = k$, which is the sectional ratio of an originally cylindrical pipe.

In treating the data the geometric means of the sample ratios have been taken, as these are apparently the best approximations of the sectional ratios of originally cylindrical pipes. This computation does not, however, take into/
Figure 5

For explanation see text.
Fig 5

(a)

B₁

(b)

B₂

t₁

L₀

(a₀/b₀)₃ = u

(a₀/b₀)₂ = 1

(a₀/b₀)₁ = 1/u

G = 1

(a₀/b₀) = w

(a₀/b₀) = 1/w

L

(a) = ku

(a)₂ = k

(a)₁ = k/u

G = k
into account the possible (unknown) effects of measuring sections with no semi-axis in the $\varepsilon_1\varepsilon_3$ plane (as $w$ and $\frac{1}{w}$ in Fig 5b).

5. Collection and treatment of data from the Pipe Rock

Because of the scarcity of outcrops at which deformed pipes could be measured, stations were not distributed according to any sampling plan.

From outcrops, the following data were recorded:

(1) The mean strike and dip of the bedding ($B_2$)
(2) The mean direction and plunge of the pipes ($P_2$)
(3) The angle (acute) between the pipes and the bedding; $P_2 - B_2 = \omega$.

If $\omega$ cannot be determined in the field it is found either by stereographic construction, or from:

$$\sin \theta = \sin \alpha \cdot \sin \beta$$

(4) As many readings as possible of $\frac{a}{b}$ ratios, $n = 30$ is desirable sample size (see Appendix I) but, unfortunately, this size of sample was only once attained. The geometric mean ($G$) of the $\frac{a}{b}$ ratios is calculated.

From these measurements assuming:

1. Deformation by planar homogeneous strain; and
2. The $Pb$ plane is the $\lambda_1\lambda_3$ plane;

calculations of strain and shear parameters were made. Most of the data were
were calculated by computer, but a specimen numerical calculation is given in Appendix II.

6. Sources of error in calculation.

Errors may arise in the following ways:

1. Errors may have been made by observer in taking field measurements. In those parts of the calculation not done by computer (specified in Appendix II) arithmetic errors may have been made.

2. Strain may have been neither planar nor homogeneous. In the areas studied, the presence of folds in the deformed Pipe Rock is clear evidence of at least local inhomogeneous strain synchronous with pipe deformation.

3. The deformed pipes may not lie in the $\lambda_1 \lambda_3$ plane of strain.

4. In the field it was not generally possible to determine the precise orientations of the a and b semi-axes of the pipe sections. As far as the author could judge, the a semi-axes were generally horizontal; in consequence, the a semi-axes were always taken as being horizontal. Thus, it has been assumed that the $P_2 b$ (and the $\lambda_1 \lambda_3$) planes are vertical. Consequently, the $P_2 b_2$ planes ($b_2 = 90^\circ$) should be vertical; this is not strictly true (Figs. 11c & 29c).

5. An error of unknown significance has been introduced by measuring pipe sections with their $b$ semi-axes oblique to the $\lambda_1 \lambda_3$ planes (see p. 28).

6. It was assumed that $P_1 - B_1 = 90^\circ$. In the relatively incompetent layers between massive bedding units $P_1 - B_1$ may have had a variety of values (see Appendix III).

7. Sample parameters are estimates of population parameters. Since the/
the samples of \( a \) ratios are small the calculated values of \( G \) may be markedly
different from the population \( G \) values (see Appendix I).

8. Strain may vary over short distances. Single samples of \( b \) ratios
may include ratios from domains of differing strain.

9. Calculations are valid only if the pipes and their matrix are
physically identical. In the relatively incompetent margins of bedding units
the pipes are stronger than their matrix; pipes and matrix appear to approach
physical identity towards the centres of bedding units (See Appendix III).

10. In calculating the orientations of \( P_1 \) and \( B_1 \) only simple and pure
shear are considered. The actual strain may have been planar and homogeneous,
yet neither of these two types.

Components of pure rotation (perhaps a result of folding) contributing
to the final strained state, cannot be calculated.

The described sources of error may be considered as falling into
two categories:

Firstly, there are those sources of error whose significance cannot
be estimated; for example, the effects of errors made in sampling and taking
field measurements, and the possible role of pure rotation in contributing to
deformation, cannot be exactly evaluated.

Secondly, in the specific examples of Pipe Rock deformation considered
below, field evidence exists which permits some qualitative judgment regarding
the significance of certain of the possible sources of error. Further discussion
is presented later, but at this point, it may be noted that, at both Kempie
and Glen Coul, strain may have been approximately planar and that the deformed
pipes/
pipes may well lie in the $\lambda_1 \lambda_3$ plane of deformation. It has also proved possible to make a semi-quantitative evaluation of the effects of strength differences existing between the pipes and their matrix during strain (pp60-63).

SECTION III, IV AND V

Structural Analyses

Introduction

In Sections III, IV and V structural analyses of the three areas under consideration - at Kempie (Loch Eriboll), Glen Coul and Durness - are presented.

Throughout, the symbolism of set notation (see above pp9-14) is used. Structural sets are first defined and described, then their modes of origin (generations) considered.

At Kempie and in the Glen Coul Nappe particular attention has been devoted to strain analysis of the deformed pipe rock using the methods described in Section II (pp15-31).

The minor structures within the Moine Nappe at Glen Coul and Durness are considered in detail. At Glen Coul the position of the Moine Thrust plane has been redefined and the origins of the mylonites and the dominant east-south-east lineation are considered. At Durness folds have been discovered beneath the Moine Thrust-plane. The geometrics of these folds may indicate the direction of displacement on the Thrust-plane.
SECTION III

Area I: Kempie, Loch Eriboll

1. Introduction

The folded and faulted Cambro-Ordovician sediments of this area constitute part of the Arnaboll Nappe. Quartzite—particularly Basal Quartzite and Pipe Rock—is the dominant rock type but, in the south of the area, limestones, dolostones, siltstones and sandstones are well represented.

The sediments lie in major folds, with north-south trending axes, cut in the south of the area by north-south striking faults.

The Lewisian Gneiss within the area was not examined.

Figs 6 (a) and (b) are geological and structural maps of the area.

2. Structural Sets

The structures have been grouped into the following sets:

Set $O = \{b_o, g_o, p_o, z_o\}$

Set $I = \{w_I, f_{Ia,b}, s_{Ia,b,c}, t_{Ia,b,c}, g_I, h_I, t_I, z_I\}$

Set $II = \{t_{II}, z_{II}\}$

3. Descriptions of structural elements

Set $O$:

The elements of this set will not be described.

Set $I$:

$w_I$: /
Set I:

$\mathcal{W}_I$

The isoclinal folds — described by Peach et al. (1907) p. 463 — on the hillside above Kempie, were not observed. In the author's opinion these folds do not exist.

$f_{Ia}$:

The sediments have been folded into major and minor folds ($f_{Ia}$). Fold profiles are shown in Fig. 7; the forms of the major folds are shown in Fig. 8. The variability of bedding dip in the eastern limb of the major $f_{Ia}$ syncline (Fig. 8) is due to the presence of subsidiary (often large scale and sideways-closing) apparently contemporaneous folds.

The poles to the bedding ($b_0$) are shown in Fig 9a; they apparently lie in a girdle indicating that, within the area, the $f_{Ia}$ folds are cylindroidal. The girdle pole, which is the statistically defined axis of folding, plunges at a low angle to the south-south-west.

The $f_{Ia}$ axes have a general north-south trend (Fig. 9(b); the axial planes dip generally eastwards (Fig. 9c).

The $f_{Ia}$ folds are evidently concentric folds. Individual beds apparently retain constant thicknesses throughout the folds (Fig. 7).

$f_{Ib}$:

The $f_{Ib}$ folds are folded pipes ($p_0$). Two types of $f_{Ib}$ fold were observed:

(a) The $P$ and $b$ pipe dimensions (see Table IV) are coplanar within the fold profile but their orientations within the plane are variable/
Figure 7.
Kempie, Loch Eriboll
Profiles of $f_{\text{In}}$ folds
Figure 8.

Diagram showing, in a very simplified manner, the general form of the major $f_{la}$ folds, Kempie.
Figure 9
Kempie: structural data.

(a) 302 poles to bedding ($b_o$). Contours 5%, 3%, 1%, 0.33% per 1% area.

(b) 21 axes of $f_{la}$ folds.

(c) 20 poles to axial planes of $f_{la}$ folds.

(d) 69 poles to $s_1$ planar structures.
Figure 10.
Kempie, Loch Eriboll

a and e. Diagramatic representations of folded pipes with, respectively, b and $P_2$ and a and $P_2$ coplanar.

b - d. Folded pipes with coplanar a and $P_2$ dimensions.

f and g. Folded pipes with b and $P_2$ coplanar.
variable (Fig 10a). These folds are commonly developed. and

(b) The P and a pipe dimensions are coplanar within the fold profile and, as in (a), their orientations within the profile are variable (Fig. 10a). These folds were only rarely observed.

\[ s_{Ia}, b, c: \]

- \( s_{Ia} \) is foliation defined by the planar alignment of the a, b semi-axes (a b c) of deformed clastic particles (\( g_o \)).
- \( s_{Ib} \) is fracture cleavage.
- \( s_{Ic} \) is crenulation foliation - Whitten (1966) p.232.

Crenulation foliation is equivalent to "strain-slip cleavage" - Bonney (1986) - and "crenulation cleavage" - Knill (1960).

Because of the nature and environment - it appears to be restricted to finely bedded limestones - of the developed crenulation foliation, \( s_{Ic} \), its presence may only be detected microscopically. The crenulation foliation lies in the axial planes, of very small scale \( f_{Ia} \) folds (see Plate III h).

The foliation \( s_{Ia} \) is particularly well developed in the relatively incompetent partings between the massive bedding units of the quartzites. In general, \( s_{Ia} \) appears to approach parallelism with either the bedding or the axial planes of the \( f_{Ia} \) folds.

The fracture cleavage, \( s_{Ib} \), does not appear to be strictly synchronous with the foliations \( s_{Ia} \) and \( s_{Ic} \). Where the fracture cleavage interferes with the foliations it is seen to be the later structure (see Plates II d and f).

\( s_{Ib} \) is tentatively included in Set I because it appears to be genetically related to the \( f_{Ia} \) folds and to have developed as a late-stage effect. The fracture cleavage/
cleavage is, in general parallel to pre-existing planar structures - bedding (b₀) and foliations (s₁a and s₁c) - see Plates II d and f.

The s₁ structures exhibit various relationships with the deformed pipes. The P₂ and a dimensions of the pipes often lie in s₁ planes; very rarely the P₂ and b dimensions lie in s₁ planes. Where the pipes are folded (f₁b folds) the P₂ and a dimensions of parts of the pipes may lie in s₁ planes (Fig. ).

The s₁ structures are common and they are variably oriented; they have a general north-north-east-south-south-west strike and, for the most part they dip to the east-south-east (Fig. 9d)

I₁a, b, c:
I₁a is the most commonly developed lineation; it lies in the plane of s₁a and is defined by the preferred orientation of elongate clastic particles. (s₁a is defined by the planar alignment of the a, b semi-axes of deformed grains (g₀); I₁a is defined by the linear alignment of the a semi-axes (a > b > c))

Since s₁a is generally confined to relatively incompetent partings in the quartzites it follows that I₁a is similarly confined. I₁a is often apparently parallel to the bedding (b₀) and to the deformed pipes when P₂ = 0°.

I₁a plunges generally at a low angle to the east and east-south-east (Fig. 11). It is therefore approximately normal to the axes of the major folds (f₁a) since these have a general north-south trend (Fig 9b).

I₁b is the lineation defined by the intersection of s₁ with the bedding/
Figure 11.

Kempie, Loch Eriboll. Structural data.

a. 47 plots (•) of the grain elongation lineation, ′La; 5 plots (x) of the cleavage - bedding intersection lineation, ′Lb; and 3 plots (O) of the streaking lineation, ′Lc.

b. Orientations of deformed pipes (46 readings)

c. Poles to the P₂ b₂ planes. In calculation these planes were taken as being vertical.

d. Plots of P₂ and poles (b₂) to B₂ (see Table V)
bedding, b_o.

I_b generally plunges at a low angle to the south-west (Fig. 11a). I_b is, thus, inclined at a high angle to I_a and at a low angle to the f_a axes. Very rarely it may be observed to be parallel to f_a axes.

I_b is not commonly developed.

I_c is a faint streaking lineation very rarely found on the fracture cleavage, s_I_b. I_c may be slickenside lineation originated by slight slip on the cleavage planes.

I_c has a steep easterly dip (Fig. 11a). Its orientation is roughly coincidental with that of the grain elongation lineation I_a.

During Set I generation the inter-granular fraction of the quartzites recrystallised to chlorite, white mica and quartz. The chlorite and white mica crystals may be aligned in the plane of s_I_a. In the massive relatively unstrained beds the mica and chlorite are interstitial to the quartz and felspar clastic grains.

The effects of Set I generation on the mineralogy of the carbonate rocks have not been studied.

h_I:

A fault surface, separating Fucoid Beds from Pipe Rock, is exposed at the road-side about 150 yards east of Kempie.

The fault plane strikes generally north-south and has a steep westerly dip; it is a reverse fault.
A thrust-plane (Strike 206°; dip 24°E) exposed on the shore at Kempie, separates Fucoid Beds from underlying Ghruaidh Limestone. About 300 yards south of Kempie, this fault surface appears to be nearly vertical.

The described fault surfaces ($h_1$ and $t_1$) cut the major $f_a$ folds; they may, therefore, post-date Set I generation. Folding, (and, in particular, concentric folding) and faulting may, however, be genetically related, synchronous phenomena (See, for example, De Sitter (1964) pp 132-212; and the experiments of Hubbert (1951)). The author tentatively considers the formation of $h_1$ and $t_1$ to have been the result of those processes (Set I generators) also responsible for $f_a$ folding. The possible genetic relationships will be discussed later. (pp 80-81).

Set II

No new work was done on either the Arnaboll or Moine Thrust planes. The author can, therefore, only reiterate the conclusions of Peach et al. (1907) pp 430 - 486.

Within the area studied the Arnaboll Thrust-plane is not exposed. In east-west sections through the area Peach et al. (loc. cit.) show the Thrust plane as a gently curving surface with a general low easterly dip. In addition, faults (as $h_1$ above) within the Arnaboll Nappe are shown as terminating against the Arnaboll Thrust-plane; of this there is no evidence within the area studied.

The Arnaboll Nappe is separated from the overlying Moine Nappe by the Moine Thrust-plane. (But note, that Wilkinson (1955) redefined the Moine Thrust of Peach et al (loc. cit) as the Eriboll Thrust. The discussion of the problem/
problem of thrust-plane nomenclature in the Durness area (below pp.159-164) deals, in
detail, with Wilkinson's work) Peach et al. (loc. cit.) show the Moine Thrust
plane dipping at a low angle to the east.

4. Set generation

In this section it is intended to analyse described structure with
a view to determining their mechanisms of formation. Evidence useful in the
kinematic interpretation of set generation may be obtained by examination of
(i) the effects of set generators on the elements of pre-existing
structural sets, and

(ii) the structures (such as folds, lineations and cleavages)
developed by set generators.

(a) The generation of the Set I elements

(i) the deformation of the Set O elements by the Set I generators.

(ii) Deformation of bedding (b). The bedding has been folded by Set I generators; it has, thus,
been rotated and strained.

Where clastic particles (g) are apparently unstrained, then

Where clastic particles (g) are apparently unstrained, then

\[ \varepsilon_B = 0.0 \]

and the bedding has suffered pure rotation. The positions at

which \[ \varepsilon_B = 0.0 \] are shown in Fig.

In the Pipe Rock, bedding strain may be calculated in conjunction

with pipe strain (see Table V)

(ii) Deformation of clastic particles (g)

Throughout the area, the shapes of the unstrained grains are

so irregular that no quantitative estimates of strain may be made from their

strained counterparts.

Qualitatively,
Qualitatively, it is obvious that the grains defining $s_{Ia}$ have been strained (see Plate II d) and that the grains in the relatively incompetent bedding margins are more strongly deformed than those in the massive interiors of the bedding units (compare Plates II b and c).

(iii) Deformation of Pipe Rock

The localities at which data were collected are shown in Fig. 12. The data, and the information calculated from these are shown in Table V. The calculated orientations of the principal strains are shown in Fig. 14 b; the orientations and magnitudes of $\varepsilon_1$, are shown in Fig. 13.

(a) Discussion of results.

1. Sources of error.

As noted (p 23) strain was assumed to have been homogeneous. Inhomogeneity of strain is, however, shown by the presence of folds.

The major $f_{Ia}$ folds shown that strain was inhomogeneous on a large scale. Though areas of homogeneous strain may exist within major folds, local inhomogeneity is shown by the presence of minor $f_{Ia}$ folds and of folded pipes, $f_{Ib}$.

To permit the calculation of strain and shear parameters strain was assumed to have been planar. The existence of at least local non-planar strain in the bedding is shown by the presence of very small scale $f_{Ia}$ folds, developed, in deformed Pipe Rock, with their axes lying in the assumed plane of deformation (Fig. 20 b). There must have been some straining normal to the plane containing the long dimensions of the pipes (assumed $\lambda_1\lambda_3$ plane) for such/
Table V

Calculated strain and shear parameters: Pipe Rock, Kempie
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<th>G</th>
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Figure 12.

Kempie, Loch Eriboll. Map showing the positions (I etc.) in the Pipe Rock for which strain and shear data have been calculated (see Table V).

\[ a_1 \] - Basal Quartzite. \[ a_2 \] - Pipe Rock. \[ a_3 \] - Fucoid Beds.
\[ a_4 \] - Serpulite Grit. \[ a_5 \] - Durness Limestone. \[ a \] - Undifferentiated Cambro-Ordovician. \[ g \] - Rocks of the Moine Nappe. M.T.P. - Moine Thrust-plane. A.T.P. - Arnaboll Thrust-plane. These symbols have also been used in Figure 13.
Figure 13.

Map showing the calculated directions, plunges and values of $\varepsilon_1$ in the Pipe Rock, Kempie.

At those positions marked "9" the rocks were qualitatively judged to be unstrained.
such folds to have developed. The forms of the fold profiles (Fig 20b) indicate that shortening normal to the assumed $\lambda_1 \lambda_3$ plane was slight.

The long dimensions of the pipes were assumed to lie in the $\lambda_1 \lambda_3$ plane of deformation.

Fig. 11 b shows the plunges of the deformed pipes. In general, they plunge steeply to the east and east-south-east. The distributions of the plunges of the pipes and of the grain-elongation lineation ($l_{\text{La}}$) are almost identical. (Compare Figs 11 a and b.) As noted (p 38), deformed clastic grains could not be used to give quantitative estimates of strain; nevertheless, it is possible that the orientations of the a, b and c semi-axes (a < b < c) of deformed grains may roughly define the orientations of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$, respectively. If such a correlation holds, the distribution of the lineation $l_{\text{La}}$ (defined by the a semi-axes of deformed grains) would roughly correspond to the distribution of $\varepsilon_1$ and the poles to $s_{\text{La}}$ (defined by the planar alignment of grain a, b semi-axes) would approximately define the distribution of $\varepsilon_3$.

(The $s_{\text{La}}$ poles are shown in Fig 9 d).

On the above reasoning the combined distributions of the $l_{\text{La}}$ plunges and the $s_{\text{La}}$ poles should approximately define the $\varepsilon_1 \varepsilon_3$ plane. In Fig. 14 a the $l_{\text{La}}$ plunges and the $s_{\text{La}}$ poles are shown together. The points approximately define a plane striking west-north-west - east-south-east and dipping steeply to the north-north-east. If this plane is the $\varepsilon_1 \varepsilon_3$ ($\lambda_1 \lambda_3$) plane of deformation then $\varepsilon_2$ plunges at a low angle to the south-south-west and the deformed pipes, since their distribution is closely comparable to the distribution of the grain-elongation lineation ($l_{\text{La}}$), lie approximately within/
Fig. 14

Kempie: Structural data.

a. Composite plot of the grain-elongation lineation, \( \text{Ia} \), and the poles to \( a_i \).

b. Calculated orientations of the principal strains in the Pipe Rock. (See Table V).
within the $E_1E_3$ plane.

Calculations of the orientations of the principal strains, simple shear planes and pipes and bedding before strain were based on the assumption that the planes containing the deformed pipes and the poles to the strained bedding ($P_2b_2$ planes) were vertical. The distributions of $P_2$ and the poles ($b_2$) to $B_2$ are shown in Fig. 11d; the poles of the $P_2b_2$ planes are shown in Fig. 11c. The approach of the $P_2b_2$ poles to verticality indicates that the assumption does not introduce a great error.

All samples of $\frac{a}{b}$ ratios are smaller than the desirable sample of $n = 30$.

The characteristics of the rock containing the pipes largely determine the amount of available data. Deformed pipes are best seen (often only seen) in relatively incompetent layers. In the massive beds the pipes and their matrix approach physical identity and the pipes are generally not sufficiently "weathered out" for their orientations and sectional ratios to be measured. Collected data is then, not representative of the Pipe Rock as a whole.

As noted (p. 29 and see Appendix III) pipes before deformation are not invariably normal to the bedding. Positions VIa and VIb are on the same stratigraphic horizon and only a few yards apart, yet in VIa the deformed pipes plunge at 45° to the east-south-east, while in VIb the pipes plunge east-south-east at 80° (see Table V). Such marked variation in the pipe plunge within a short lateral distance may indicate that the unstrained pipes were variably oriented with respect to the bedding.
Data measured on a specimen (III sp; see Fig 20) collected at position III were found to differ significantly from the data collected in the field (see Table V: Field-data are $G = 3.21$ and $\omega = 63^\circ$; specimen data are $G = 2.04$ and $\omega = 30^\circ$.)

The differences in these data may be due to the fact that when collecting field data $\frac{a}{b}$ ratios may be inadvertently taken from domains of differing strain and the angle ($\omega$) between the pipes and the bedding may be measured in only one of these strain domains. Thus, pipes taken to be at $\omega$ to the bedding may not, in fact, be so inclined.

In conclusion, the $E_1E_3$ plane suggested by analysis of the orientations of the grain-elongation lineation $l_a$ and the poles to the foliation $s_a$, is in approximate concordance with the profile plane of the major $f_{la}$ folds. Thus $E_2$ is approximately parallel to the axes of the $f_{la}$ folds. The fold profile may be considered to consist of small areas of near homogeneous strain - overall strain is inhomogeneous - and it is for such domains that strain and shear parameters have been calculated. Sources of error are such, however, that calculated parameters may only be considered to approximate actual parameters.

2. Possible mechanisms of deformation.

(i) Discussion of deformation mechanics is limited by the following restrictions:

(a) In calculating strain and shear parameters, strain was assumed to have been planar and homogeneous. It follows, therefore, that these parameters may not be used in discussing any other types of strain.

(b)/
(b) Geometrically identical states of planar strain may be the result of markedly differing processes - see Jaeger (1964) pp 32-33.

(c) Calculated strains are those of folded rocks. Deformation by irrotational strain is unlikely. In pure shear $\sigma_1 - \varepsilon_3 = 0$. It is most unlikely that the principal stresses would have remained constantly oriented during folding. Pure shear may, however, have contributed to the total strain as a "flattening" component - see Ramsay (1962) and

(d) Since the deformed Pipe Rock is contained within major folds its deformation must be considered in conjunction with the mechanisms of folding. It is therefore necessary to establish some relationships between pipe strain and fold geometry.

(ii) Pipe strain and fold geometry.

In unstrained Pipe Rock the pipes are normal to the bedding and their geometric relationships to the bedding after folding may be employed to determine folding mechanisms. It is intended to study pipe geometry in the profiles of idealised fold types because the profiles of the $f_{la}$ folds are apparently the $\varepsilon_1$ $\varepsilon_3$ planes of deformation.

(a) Flexural folds

See Ramsay (1961) pp 92-96

Fig 15(a) shows a block of length, $l$, and thickness, $t$.

Fig 15(b) shows the block $\{l\}$ folded to become part of a concentric fold.

In Fig 15(b):

arc/
Figure 15.

For explanation see text.
\[ \text{arc } EC = \theta (r+t) \quad (\theta \text{ in radians}) \]
\[ \text{arc } DA = \frac{\pi}{2} r \]

But \[ EC = DA = 1 \]

\[ \therefore \theta (r+t) = \frac{\pi}{2} r \]

\[ \therefore \theta = \frac{\pi r}{2(r+t)} \quad (1) \]

alternatively:

\[ \theta = \frac{\pi 1}{nt + 21} \quad (2) \quad (r = \frac{21}{n}) \]

\[ \tan \alpha_{\text{max}} = \frac{BC}{AB} = \frac{BC}{OB-OA} \]

\[ = \frac{\cos \theta (r+t)}{\sin \theta (r+t) - r} \quad (3) \quad (BC = OC \cos \theta) \]
\[ (OB = OC \sin \theta) \]

alternatively:

\[ \tan \alpha_{\text{max}} = \frac{\cos \theta \left( \frac{21}{n} + t \right)}{\sin \theta \left( \frac{21}{n} + t \right) - \frac{21}{n}} \quad (4) \]

Let the coordinates of \( F \) be \( x_1, y_1 \) and of \( G \) be \( x_2, y_2 \).

\[ \sin \psi = \frac{x_1}{r} \quad \therefore x_1 = r \sin \psi \quad (5) \]
\[ \cos \psi = \frac{y_1}{r} \quad \therefore y_1 = r \cos \psi \quad (6) \]

Similarly/
Similarly

\[ x_2 = (r + t) \sin \mu \]
\[ y_2 = (r + t) \cos \mu \]

Where angles are in radians:

\[ \frac{DF}{r} = \psi \]
\[ \frac{EG}{(r + t)} = \psi \]

But \[ DF = EG = k \]

\[ r = (r + t) \mu \]
\[ \mu = \frac{r}{r + t} \]
\[ x_2 = (r + t) \sin \frac{\psi r}{r + t} \quad (7) \]

and \[ y_2 = (r + t) \cos \frac{\psi r}{r + t} \quad (8) \]

\[ \tan \phi = \frac{y_2 - y_1}{x_2 - x_1} \]

and from trigonometry:

\[ \tan \theta = \frac{\tan \phi - \tan (90 - \psi)}{1 + \tan \phi \tan (90 - \psi)} \]
\[ = \frac{\tan \phi - \cot \psi}{1 + \tan \phi \cot \psi} \quad (9) \]

Ramsay/
Ramsay (op. cit.) p. 95 has given an expression for the angle shown as $\omega$ in Fig.

$$\omega + \alpha = 90^\circ; \text{ thus } \cot \omega = \tan \alpha.$$  

The relative displacement between EG and DF is equal to GH.

$$EH = \psi (r + t) = k + GH$$  

$$DF = \psi r = k$$  

$$\therefore \psi (r + t) = \psi r + d$$  

(where $d = GH$)

$$\therefore d = \psi t \quad (10)$$

If it be supposed that block it is Pipe Rock then let:

$$FH = P_1 \text{ and } FG = P_2$$

In triangle OFG, from the cosine rule:

$$GF^2 = P_2^2 = OF^2 + OG^2 - 2 OF \cdot OG \cos \eta = r^2 + (r + t)^2 - 2r(r + t) \cos \eta$$

But $\eta = \psi - \mu = \psi - \frac{r}{r + t}$

$$\therefore P_2^2 = r^2 + (r + t)^2 - 2r(r + t) \cos \psi (1 - \frac{r}{r + t})$$

See Ramsay, loc. cit)

Since $P_1 = t$

$=$/
\[ \lambda_P = \frac{r^2 + (r + t)^2 - 2r(r + t) \cos \psi (1 - \frac{r}{r + t})}{t^2} \]  

(11)

Where EC and DA represent bedding:

\[ \lambda_B = 1.0 \]

If \( r + t \), the radius of curvature of EC, is sufficiently great, then the curvature of GH may be neglected, and:

\[ d = t \tan \alpha = P_1 \tan \alpha = P_2 \sin \alpha \]
and

\[ \frac{P_2}{P_1} = \sec \alpha = \cosec \omega \]

\[ \therefore \lambda_P = \sec^2 \alpha = \cosec^2 \omega \]

and

\[ \varepsilon_P = \sec \alpha - 1 = \cosec \omega - 1 \]

If the folding of the block it is considered to have taken place by slip on concentric "shear planes" deformation may then be considered to have approximated to simple shear in type. The smaller the area considered within the fold profile the more closely does the deformation approach simple shear because, for small areas, the curvatures of EC and DA, and, thus, the shear planes, may be neglected. For areas of infinitesimal size:

\[ \tan \alpha = \gamma_s \]

(see page 23)

\[ = \varepsilon_1 - \varepsilon_3 \]

and/
and
\[ \tan (1^\circ E_1) = -\frac{E_3}{E_1} \]
and
\[ \tan (1^\circ E_3) = \frac{E_1}{E_3} \]

Thus the orientations and magnitudes of the principal strains may be fixed at any point in the fold profile.

Flexural slip folding of thick units (Fig. 15c) results in rupture between the units and \( \rho \cdot B_1 = \rho_2 \cdot B_2 = 90^\circ \). Pipes and bedding are both unstrained; \( \lambda_p = 1.0 \) and \( \lambda_B = 1.0 \).

Massive, competent bedding units may slip on relatively incompetent beds. In Figs. 15d and e, unit I (incompetent) becomes \( I' \) with folding. \( I' \) may show the strain relationships deduced above for the folding of block I on (Figs. 15a and b), while in the competent beds (C and C'; Figs. 15d and e) both pipes and bedding are unstrained. Pipes passing from competent to incompetent beds are folded (Fig. 15e).

(b) Similar folds.

In discussing similar folds it will be assumed that they develop either by differential simple shear (see Turner and Weiss (1963) pp 450 - 482) or by differential flattening (see Ramsay (1962) a).

(1) Folds formed by differential simple shear in the fold axial planes.

Where "S" represents the planes of simple shear, folds developed such/
such that \( R_1 \cdot S = 90^\circ \), \( P_1 \cdot S = 0^\circ \) and \( E_2 \cdot \text{fold axis} = 0^\circ \) (Fig 16a) have the following characteristics:

1. The pipes retain their original orientations; they are parallel to the trace of the axial plane in the fold profile; their cross-sectional ratios are unchanged; and \( \lambda_p = 1.0 \) (\( \lambda_B > 1.0 \))

and

ii. where \( \alpha \) is the angle of simple shear

\[
\alpha = B_1 \cdot B_2
\]

\[
= 90^\circ - \omega \quad (\omega = P_2 \cdot B_2)
\]

Where the simple shear planes are oblique to the bedding before strain and \( E_2 \cdot \text{fold axis} = 0^\circ \), the deformed pipes are folded about the fold hinges (Fig 16b)

(2) Folds formed by differential flattening.

(Ramsay op.cit.)

Where \( \varepsilon_1' \), \( \varepsilon_2' \), and \( \varepsilon_3' \) are the principal strains of only the flattening component of the total strain and where \( P_1 \cdot E_1 = 0^\circ \), \( B_1 \cdot E_3 = 0^\circ \) and \( E_2' \cdot \text{fold axis} = 0^\circ \), then, in the developed fold (Fig 16c), the pipes have a relatively constant orientation subparallel to the trace of the axial plane in the fold profile. The pipes are flattened; for an originally cylindrical pipe:

\[
(a)^2 = \lambda_p = \lambda_1
\]

Where the pipes and bedding before strain are oblique to and/
Figure 16.
For explanation see text.
and the pipes are oblique to the axial plane trace in the fold profile.
(Fig 16d). If domains of differential strain exist sub-parallel to the axial plane the pipes are folded as they pass from one domain to another (Fig 16e).

(c) Pipe-fold relationships at Kempie.

In the folded Pipe Rock at Kempie the following relationships have been established:

i In general, the pipes are normal to the bedding ($P_2 \perp B_2 = 90^\circ$) but, in incompetent layers, $P_2 \perp B_2 < 90^\circ$ and, occasionally, $P_2 \perp B_2 = 0^\circ$. As the pipes traverse bedding units they are often sigmoidally folded ($f_{Ib}$ folds); the angle $P_2 \perp B_2$, increases from the bedding margins towards the competent bedding interiors (see Fig 10).

ii Where $P_2 \perp B_2 < 90^\circ$ the pipes are strained; $\lambda_P$ frequently (at positions I - V and VIII - X; see Table V) approaches $\lambda_1$ in value. Since $\lambda_P$ is always $> 1.0$ the pipes are invariably elongated.

$\lambda_B$ is always $< \lambda_P$. Only at two localities (VIa and b; Table V) have the beds been elongated ($\lambda_B > 1.0$); in every other locality the beds have been shortened and at localities I, III - V and VIII, $\lambda_B$ approaches $\lambda_3$ in value. In III sp. and at position VIb the bedding has suffered very little strain ($\lambda_B \approx 1.0$).

and iii The deformed pipes are invariably inclined at low angles to the maximum principal strains ($P_2 \perp \lambda_1 = \varphi_P = 5.95^\circ$ max. at position VIa; Table V). The bedding is generally inclined at a high angle to $\lambda_1$ ($B_2 \perp \lambda_1 = \varphi_B = 11.05^\circ$ min. at VIa; Table V).
If the above relationships are compared with the theoretical relationships deduced for similar folds it is evident for the following reasons that the Pipe Rock has not been folded by the mechanism of similar folding and, in consequence, that the \( f_{\text{Ia}} \) folds are not similar folds:

i. Where similar folds are formed by differential simple shear in the fold axial planes the bedding is generally elongated; that is \( \lambda_B \) generally exceeds 1.0. In the Kempie Pipe Rock only at Position VIIb is \( \lambda_B' = 1.0 \) (\( \lambda_B = 1.09 \)).

ii. In similar folds formed by differential flattening, the pipes within any domain of homogeneous flattening, are constant in orientation. No such zones of constantly oriented pipes exist in the Kempie Pipe Rock.

In similar folds in which the pipes are parallel to the axial plane (Fig. 16c) it was shown that \( \lambda_P = \lambda_1 \) (p 49). At Kempie, \( \lambda_P \) often does approach \( \lambda_1 \) in value, but the pipes are very variable in orientation and are not all approximately parallel to the axial planes of the \( f_{\text{Ia}} \) folds.

iii. A distinctive feature of similar folds is that the folded layers attain their maximal thicknesses in the fold hinges and are attenuated in the fold limbs. As noted (p 33) there is no field evidence to suggest that the beds within the \( f_{\text{Ia}} \) folds vary in thickness throughout the fold profiles.

Since the \( f_{\text{Ia}} \) folds are not similar in style it is evident that they are flexural folds. This conclusion is supported by the following:

i. As noted, the pipes are often normal to the bedding. Where
competent beds are folded by flexural-slip folding, the pipes remain normal to
the bedding (Fig. 15c) and

The presence of sigmoidally folded pipes ($f_{Ib}$ folds) may
indicate slip of competent bedding units on less competent layers (see Fig. 10).

In ideal flexure folds the folded layers are unstrained. Thus,
if the $f_{Ia}$ folds were ideally of this type, $\lambda_B$ would equal 1.0. Since $\lambda_B = 1.0$ at only two localities (III sp and VIIb; Table V) it is clear that the
$f_{Ia}$ folds are not ideal flexure folds.

It was shown (p. 47) that ideal flexural slip folding may conveniently
be considered as simple shear deformation with the shear planes parallel to the
folded surfaces and that (p. 44; and see Fig. 15b):

$$ \theta = \frac{\pi r}{2(r + t)} $$

and

$$ \tan \alpha_{\text{max}} = \frac{\cos \theta (r + t)}{\sin \theta (r + t) - r} $$

Let $t$ be expressed as a ratio of $r$; that is let $t = jr$;
then

$$ \theta = \frac{\pi}{2(1 + j)} $$

and

$$ \tan \alpha_{\text{max}} = \frac{\cos \theta}{\sin \theta - \frac{1}{1+j}} $$

In III sp (Table V), $\lambda_B = 0.96$ and $\tan \alpha = 1.80$; in VIIb, $\lambda_B = 1.09$ and $\tan \alpha = 1.96$. By graphical solution, when $\tan \alpha = 1.80$, $j = 0.14$ and when $\tan \alpha =$
\[ \tan \alpha = 1.96, \quad j = 0.225, \] where these values of \( \tan \alpha \) are assumed to be maximal. Thus, in III sp. and VI b respectively, \( t = 0.14 \) \( r \) and 0.225\( r \), where \( t \) is the thickness of the folded layer in which \( \alpha \) was ascertained. The \( f_{Ia} \) folds at Kempie are, for the most part, major folds; thus, the radius of curvature of the folded beds must be generally of considerable magnitude. Since the Basal Quartzites have been folded and since they are of the order of 250 feet thick (See Swett, 1965) it follows that, at an absolute minimum, \( r = 250 \) feet. Thus, at localities III and VI, respectively, \( t = 35 \) feet and 56 feet. These results are clearly absurd since the Pipe Rock bedding units rarely exceed 3 feet in thickness. Calculations indicate, therefore, that even where \( \lambda_B = 1.0 \) (III sp and VI b), folding has not been by ideal flexural slip and that the \( f_{Ia} \) folds are modified flexural folds. Since this is the case it is necessary to consider those factors which may have been responsible for modifying the fold forms:

1. The \( f_{Ia} \) folds may have been modified by flattening - see Ramsay (1962)a - such that the bedding may have been thickened in the fold hinges and thinned in the fold limbs.

Such modification has been detected in a minor \( f_{Ia} \) fold and is described below (see p 58 and Fig. 18); 20% shortening, normal to the axial plane was calculated. It is important to notice that this fold was found in the Fucoid Beds. Conclusions drawn from the analysis of folds within the incompetent Fucoid Beds need not apply to folds within the competent/
Modification of an ideal concentric fold by flattening results in a fold whose folded surfaces are parts of concentric ellipses. A fold profile resulting from the flattening of concentrically folded Pipe Rock is shown in Fig. 17b. The flattening component in this fold could be calculated:

(i) by methods given by Ramsay (loc. cit)

(ii) from examinations of flattened, unrotated pipes in the fold hinge (in these \( \frac{a}{b} = \lambda_1 = \lambda_1 \) : p 49); and

(iii) by the algebraic analysis (by methods given in Section II) of those beds (D' and F' in Fig. 17b) unstrained during folding but strained during flattening (compare layers D and D' and F and F' in Fig. 17b).

The effects of flattening are:

(a) The bedding is strained. Where the bedding is thinner than it was originally then \( \lambda_B > 1.0 \); where the bedding is thickened then \( \lambda_B < 1.0 \).

(b) Sigmoidal folds (\( f_{ib} \)) in the pipes are either opened or tightened depending on their orientations with respect to the principal strains (compare Figs 17 a & b).

Strength differences within the rock may affect the response to flattening. In general, in the Pipe Rock the bedding margins are weaker than the massive interiors of the beds. If a massive beds M in Fig 17c responded largely by pure rotation the incompetent bed, I, would accommodate to/
With flattening fold "a" becomes fold "b". The fold in $P_1$ is opened to become $P_2$. The fold in $P_3$ is tightened where $P_4$ passes from $E'$ to $F'$.

C. For explanation see text.
to their buckling perhaps by flowing into the fold cores, such that the profile of Fig. 17c would result.

ii The pure rotation of massive bedding units may deform intermediate incompetent material and such deformation may have contributed to pipe strain (the theory of this type of deformation is developed below (pp. 60-62)). The strain due to this mechanism cannot be quantitatively assessed because it is not possible to calculate the pure rotation of a bed unless its original orientation is known. The rotations calculated algebraically (see Table V) are not pure rotations. The derived orientations of the pipes and bedding before strain - P, and B, must be considered at best to be only approximations of their actual orientations since, as noted, the amount of pure rotation is unknown.

iii The emplacement of the Arnaboll and Moine Nappes (Set II structures) may, in addition to truncating them, have considerably modified the Set I structural elements. It is possible that the weight of the Moine Nappe acting vertically downwards, may have modified the folds within the Arnaboll Nappe and induced additional strain in the Pipe Rock so that the total strain is the composite effect of the Set I and Set II generators.

iv The strain and shear parameters in Table V were generally calculated for layers which are less competent than the massive bedding units. Slip between the massive layers during folding may have induced strain mechanisms in the incompetent layers which were either not of simple shear type or of simple shear type with the shear planes oblique to the bedding. In both cases, $\lambda_B = 1.0$. /
and v. The calculated values of $\lambda_B$ are, except at localities VIa and b, less than one. Since $\frac{t_2}{t_1} = \frac{1}{\sqrt{\lambda_B}}$ (p. 24), calculations show that, in general, the bedding has been thickened (see Table V).

Geological sections through the area normal to the $f_{Ia}$ axes (see Peach et. al (1907), pp 182 and 185) indicate that the "intensity" of the folding decreases from east towards west. In the east the $f_{Ia}$ folds are asymmetrical and are overturned towards the west; in the west the folds are symmetrical and the bedding is not inverted.

Hubbert (1951) has theoretically analysed such asymmetric fold systems and noted that "the folds are unidirectionally overturned and accompanied by reverse faulting with ...... the direction of the relative displacement of the upper block with respect to the lower – in the same sense as the overturning of the folds" (p. 368).

The rapid lateral decrease in deformation away from the "active thrust" was shown by Hubbert (op. cit.) to be due to the lateral decrease in the component of compressive stress (op. cit.; see Fig. 14 p. 369, in which $\sigma_{x_1} > \sigma_{x_2}$).

Hubbert (op. cit) did not discuss the effects of "one sided push" on the thicknesses of the folded and faulted layers but it is evident from his experimental work (op. cit. see Plate 2 facing p. 357) on loose sand that the layers nearest the "one-sided push" are thickened much more than those remote from the "push" (Such thickening was shown qualitatively by Hubbert, op. cit.; Fig. ...
Folds formed under conditions of lateral compressive "push" from an "active area" cannot be ideally concentric \( \lambda_B = 1.0 \) in type since all of the folded layers cannot be of constant thickness \( \lambda_B \neq 1.0 \).

Qualitatively, competent beds may be expected to be less strained than relatively incompetent beds. In consequence, the incompetent beds may show greater increases in thickening. At Kempie, the massive beds of quartzite frequently show little or no evidence of strain, whereas the relatively incompetent bands, from which, in general, the data on deformed pipes were collected are often significantly strained.

In conclusion, the calculated bedding thickening may have, in part, been the result of unequal thickening of the sedimentary pile under the action of compressive stresses decreasing in value from east towards west. All of the localities at which data were collected lie on the generally inverted, easterly limb of the major \( f_{\text{Ia}} \) syncline. The bedding within this limb may have been undergoing thinning in the later stages of folding since, as the bedding approached verticality as it was being inverted, it would approach the orientation of \( E_1 \) and hence suffer elongation.

(d) Conclusions.

On the assumption that the Pipe Rock deformation and the \( f_{\text{Ia}} \) folds are genetically related, it has been shown that, although the \( f_{\text{Ia}} \) folds may, in general terms, be considered to be flexural folds they are far from being of ideal flexure type. Several mechanisms have been suggested by which the fold forms/
forms may have been modified; their significance will be discussed below (p.85-88).

2. Genetic consideration of the Set I elements

   (1) The Set I folds

   a. $f_{Ia}$:

   1. An $f_{Ia}$ fold with conjugate axial planes (Plate I d) was observed. Johnson (1956) and Ramsay (1962)b have suggested that during the formation of conjugate folds, the principal stresses of the generating stress system bear fixed relationships to the orientations of the conjugate axial planes; the orientation of $\sigma_2$ is defined by the intersection of the axial planes while $\sigma_1$ and $\sigma_3$ bisect the angles between the planes ($\sigma_1 > \sigma_2 > \sigma_3$).

   If these relationships hold, the following orientations of the principal stresses operative while the above mentioned $f_{Ia}$ fold was forming are indicated:

   $\sigma_1 \quad 80^\circ \quad 0^\circ$

   $\sigma_2 \quad 175^\circ \quad 10^\circ S$

   $\sigma_3 \quad 355 \quad 80^\circ N$

   2. For the most part, the $f_{Ia}$ folds are major folds; only three hand specimens of major $f_{Ia}$ folds could be collected. Of these, only one proved suitable for geometric analysis by methods given by Ramsay (1962)a. This fold is of concentric or flexure type. Marked thickening of the bedding units in the fold hinge (shown by measuring thicknesses normal to bedding) may indicate that the fold has been modified by flattening such that there has been about 20% homogeneous shortening (in addition to shortening by flexuring)/
Figure 13.

Quantitative analysis of the profile of a minor $f_{La}$ fold, Fucoid Beds, Kempie.

$t$ - Thickness normal to bedding.

$d$ - Distance along bedding.

$T$ - Thickness parallel to axial plane trace.

$D$ - Distance normal to axial plane trace.

A.P. - Axial plane trace.

Thickening of the bedding in the hinge indicates that the fold is of modified concentric type. (See Ramsay, 1962, a).
carbonate veining
flexuring) normal to the axial plane (see Fig. 18).

Ramsay (op. cit.) p. 313 defined flattening as resulting "in contraction in a direction parallel to that of the principal compressive stress and in expansion at right angles to this in the direction of minimum stress". This is simply the definition of pure shear; in pure shear \( \sigma_1 \land E_3 = 0^\circ \) and \( \sigma_3 \land E_1 = 0^\circ \).

Ramsay's technique (op. cit. pp 314-315) measures "flattening" perpendicular to the axial planes of modified flexure folds. Thus, since "flattening" and pure shear are identical, it follows that \( E_3 \) and \( \sigma_1 \) are normal to the fold axial plane while \( E_1 \) and \( \sigma_3 \) lie in the trace of the axial plane in the fold profile. In consequence, Ramsay's method (op. cit.) may be employed to calculate the orientations of the principal stresses operative during flattening, and to calculate the principal strains of the pure shear component of deformation. For the fold under consideration the deduced orientations and values are:

\[
E_1, \sigma_3, E_2, \sigma_2, E_3, \sigma_1
\]

(parallel to fold axis)

\[
290,46W, 185,15E, 81,40E
\]

\[
E_1 = 0.25, E_2 = 0.0, E_3 = -0.2
\]

3. Very small \( f_{la} \) folds were found to exist in the bedding of a specimen.
of deformed Pipe Rock (III sp. Table V; and see Fig 20). Despite the
small size of the folds it may be observed that they are disharmonic and of
modified concentric type (Fig 20); the fold axes are approximately parallel
to the dimensions of the pipes. The pipes in the specimen are not perfectly
straight but they are not folded in the manner described.

Thin section examination of the rock has shown the pipes to be, in
general, coarser grained and more quartzose than their matrix. The author
would infer that the pipes are stronger than the matrix. Such a strength
difference may have been an important factor in determining the strain reaction
of the rock when stressed. It is possible to analyse, to some degree, the possible
effects of strength differences where strain is assumed to have been planar.

During deformation the pipes may either:

i. have behaved perfectly rigidly so that only the bedding suffered
   strain (λ_p = 1.0; λ_B < 1.0) or

ii. by virtue of their greater strengths, have suffered relatively
   less strain than the bedding.

Considering "i", two limiting conditions are likely:

(a) Perfectly free slip may take place between the pipes and their
   matrix. and

(b) No slip may take place between the pipes and the matrix.

If free slip occurs between the pipes and the bedding,
deformation of the bedding is homogeneous. Where strain is planar the area of
the/
the bedding does not change; in Fig. 19(a) \( A_1 = A_2 \).

In Fig. 19(b) \( \delta \) is the angle of rotation of the pipes; \( r \) is the pipe radius; \( d \) is the vertical distance between the pipes after rotation; and \( \omega = \frac{p_2}{\lambda} \).

\[
\cos \delta = \frac{d + 2r}{B_1 + 2r} = \frac{B_2 \sin \omega + 2r}{B_1 + 2r} \quad (d = B_2 \sin \omega)
\]

\[
\cdots \cdots \cos \delta B_1 + \cos \delta 2r = B_2 \sin \omega + 2r
\]

\[
\cdots \cdots \cos \delta B_1 - \sin \omega B_2 = 2r (\cos \delta + 1)
\]

Dividing through by \( B_2 \):

\[
\frac{B_1 \cos \delta - \sin \omega}{B_2} = \frac{2r (\cos \delta + 1)}{B_2} \quad (\frac{B_2}{B_1} = \frac{d}{\sin \omega})
\]

\[
\cdots \cdots \frac{B_1}{B_2} = \frac{1}{\cos \delta} \left[ \frac{\sin \omega \frac{2r (\cos \delta + 1)}{d} + \sin \omega}{\frac{2r (\cos \delta + 1)}{d} + 1} \right] = m
\]

\[
\cdots \cdots \frac{B_2}{B_1} = \frac{\cos \delta}{\sin \omega \left[ \frac{2r (\cos \delta + 1)}{d} + 1 \right]} = \lambda
\]

and \( \lambda_B = m^2 \)

Where/
Where $t_1$ and $t_2$ are the thicknesses of $B_1$ and $B_2$ respectively and, since there is no change of area:

\[ B_1 t_1 = B_2 t_2 \]
\[ t_1 = m t_2 \]
\[ (t_2' = \sin \theta t_1') \]

\[ (t_1') \text{ is the strained equivalent of } t_1 \]

\[ \frac{t_1'}{t_1} = \frac{1}{m \sin \omega} \]
\[ = \sin \omega \left( \frac{2r}{d} (\cos \delta + 1) + 1 \right) \]
\[ \cos \delta \sin \omega \]
\[ \frac{1}{\cos \delta} \left[ \frac{2r}{d} (\cos \delta + 1) + 1 \right] = n \] (2)

and $\lambda_t = n^2$

(b) Where the bedding in contact with the pipes is not strained, ($\lambda_t = 1.0$), strain parallel to the bedding must be inhomogeneous so that the requirement $A_1 = A_2$ is satisfied; in other words, folds develop. (as for example, in Fig.19(c) ii.)

Where folding is disharmonic (Fig.19(c) i and iii - for simplicity the pipes are treated as linear, not cylindrical elements) $B_1 < B_2$ but $B_3 < B_4$. Thus, the bedding thickness cannot remain constant and the resultant folds (Fig.19 (c) iii) have the forms of modified concentric or even similar folds.

The author has produced folds experimentally be deforming layered plasticene/
Figure 19.

For explanation see text.
Figure 20.

Kempie, Loch Eriboll

a, b. Details of specimen III sp (see Table V)

c-g. Folds in bedding enlarged from "a".
h-j. Folds produced in layered plasticene deformed between rotated plates.
plasticene between plates suffering pure rotation. The resultant fold profiles are shown in Fig 20. The folds are strongly disharmonic and characteristically of modified concentric type - (Ramsay (1962) a.)

Where the pipes are stronger than the bedding matrix but are not perfectly rigid (\( \lambda_p < 1.0 \)) algebraic strain analysis of deformed Pipe Rock may not be valid. The strain of the pipes may still be calculated -

\[
\lambda_p = \left( \frac{a}{b} \right)^2
\]

but the relationship \( \lambda_B = \left( \frac{b}{a \sin \omega} \right)^2 \) may not hold, because the magnitude of the angle \( \omega \) \((= p_2 - B_2)\) may not be entirely due to rotation induced by strain but may contain an unknown component of pure rotation. Thus,

\[
\omega_{\text{observed}} = \omega_{\text{from strain}} + \delta_{\text{from pure rotation}}
\]

and calculated \( \lambda_B \) values exceed actual \( \lambda_B \) values.

Where the pipes and bedding are physically distinct they may form separate domains of homogeneous strain. If this is the case the domains must be bounded by fractures; thus, fracturing must take place between the pipes and their matrix. If fracturing does not take place strain must be inhomogeneous; that is, folds develop within the bedding.

The possible effects of the deformation of incompetent bedding layers strained between rigid beds suffering pure rotation during folding has already been briefly mentioned (p 55) with respect to pipe strain.

Where the incompetent layer is deformed by planar homogeneous shear, fracturing/
fracturing occurs between the rigid and plastic beds and:

\[ \lambda_p = m^2 \] (see eq. (1) p 61)

and \[ \lambda_B = n^2 \] (eq (2) p 62)

In these cases \(2r\) is the thickness of the rigid beds and \(d\) is the perpendicular distance between the rigid beds after rotation. (See Fig. 21).

Where the incompetent layer in contact with the rigid layer is unstrained then the strain throughout the rest of the incompetent layer is inhomogeneous, the pipes are folded, \(\lambda_B\) is variable in value, and fractures do not develop parallel to the bedding (Fig. 21c).

Returning to the very small scale \(f_{ia}\) folds under discussion it would appear that they may have originated by one of two possible mechanisms:

1. The folds are "parasitic" to the major \(f_{ia}\) syncline, and
2. The folds were induced in the bedding as it was "squeezed" between rotating, more rigid pipes.

(1) According to Whitten (1966):

"On a regional scale any sequence of sedimentary rocks includes some more and some less competent units, and regional deformation tends to involve flexural-slip folding. Characteristically, when a region is folded multitudes of folds of every possible size develop. The thick competent units are thrown into broad synclines and anticlines, while the thinly bedded and other less-competent units develop smaller folds. The relatively small folds have commonly been/"
Figure 21.

a. Massive bedding units in Pipe Rock with intermediate incompetent layer.

b. Massive beds rotated; incompetent layer deformed homogeneously. Fracturing takes place parallel to bedding $A_1 = A_2$.

c. No fracturing between rotated beds. Incompetent layer deformed inhomogeneously.
been called "drag folds" because it was thought that slip of the competent members dragged the intervening less-competent units into small folds" (p. 165).

The very small $f_{Ia}$ folds have the following characteristics of parasitic or "drag" folds.

i. They are developed in the relatively incompetent rock between massive competent beds and

ii. The small $f_{Ia}$ folds lie in the inverted, easterly limb of the major $f_{Ia}$ syncline. Flexural slip folding would have induced bedding slip in this limb such that the older beds would move relatively downwards. The movement would be generally from west towards east.

The vergences of the small $f_{Ia}$ folds are in accord with such relative slip (see Fig. 20).

(2.) The following factors suggest that the small $f_{Ia}$ folds formed by deformation of the bedding between rotating stronger pipes:

i. On the assumption that the strains calculated for the specimen in question (III sp - See Table V and Fig 20) were the result of planar, homogeneous shear, $\lambda_B = 0.96$. Such a compressive strain component may have resulted by deformation of the bedding between rotating, stronger pipes.

(But note that Ramberg (1963) showed that a component of compressive strain parallel to the layering (in this case, bedding) was necessary for the development of drag folds. Inspection of Plates VIII and IX (op. cit.) shows that the strains parallel to the layering of experimentally folded rubber sheets approach $\lambda_3$ in value. In III sp., the bedding has suffered only slight compression ($\lambda_B = 0.96$) and the minimal principal strain ($\lambda_3 = 0.20$) is inclined at a high angle to the bedding).
It is unlikely that slip between competent units would have induced thickening of the bedding \( \left( \frac{t_2}{s_1} = 1.04 \right) \) in the intermediate incompetent layer.

ii The forms of the small \( f_{Ia} \) folds have been imitated fairly closely by deforming plasticene between rotating plates (see Fig. 20). Parasitic folds often reflect the geometries of the associated major folds - Hills (1965) p. 284; the very small \( f_{Ia} \) folds are quite unlike the major \( f_{Ia} \) folds, and

iii The pipes have not behaved perfectly rigidly (\( \lambda_p = 4.16 \)) but they are apparently stronger than their matrix (see p. 60). Unless there is free slip between the pipes and the bedding, rotating stronger pipes must induce inhomogenous strain in the bedding. For free slip, fracturing must occur between the pipes and their matrix. In III sp. there is no evidence of fracturing and, if strain was planar, folding of the bedding is a necessity of deformation.

In conclusion, the author considers that the very small \( f_{Ia} \) folds of III sp. are at least in part, a result of the bedding having been "squeezed" between rotating stronger pipes. Those folds may, however, be a secondary effect of interbedding slip, since such slip may have caused the pipes to rotate.

4. De Sitter (1964) pp 175-176, maintained that, in regional folding, \( \sigma_1 \) (compressive) is horizontal and normal to the axes of the developing folds (\( \sigma_2 \) is parallel to the fold axes; \( \sigma_3 \) is vertical).

If this is the case then, during the development of the \( f_{Ia} \) folds, \( \sigma_1 \) would have been horizontal and oriented generally east-west. \( \sigma_2 \) would have been horizontal and trending north-south.

b \( f_{Ib} \) (folded pipes);
b. \( f_{Ib} \) (folded pipes)

1. The \( f_{Ib} \) folds in which the P and b pipe dimensions are coplanar within the fold profile are characteristically of sigmoidal form (Fig. 10). As the pipes traverse bedding units the angle \( (P_2 \cdot B_2) \) between the pipes and bedding varies. In the relatively incompetent bedding margins \( P_2 \cdot B_2 < 90^\circ \) (sometimes \( P_2 \cdot B_2 = 0^\circ \)) but in the competent interiors of the beds \( P_2 \cdot B_2 = 90^\circ \). These folds clearly show that the strains in the massive bedding units are significantly less than those in the incompetent layers.

Folds of this type may have developed by any one of a number of different mechanisms of planar shear (to simplify discussion, sharp discontinuities are assumed to exist between the competent and incompetent layers).

As noted (p 43) the various mechanisms of planar shear result in geometrically identical states of strain. Since this is the case all mechanisms - but note that simple shear with shear planes parallel to bedding, \( S \cdot B = 0^\circ \), (see p.47) has certain unique features - produce strained states which have the following common characteristics:

(1) The pipes and the bedding may be strained, or rotated or both strained and rotated.

(2) The thickness of the incompetent band does not remain constant.

(3) Since the competent beds are less strained than the incompetent beds, the domains of homogeneous strain are bounded by fractures; the fractures are/
are parallel to the bedding of the competent beds. Thus, no individual pipe may be traced from one competent bed to another.

(4) The bedding in the incompetent bed may not be parallel to the bedding in the competent beds.

Unless deformation was by simple shear, the mechanism of shear may not be uniquely determined. Nevertheless, the following comments may be made:

(a) It is probable that the \( f_{ib} \) folds developed during \( f_{ia} \) folding. The \( f_{ia} \) folds are apparently flexural-slip folds. It is unlikely that relative slip between competent bedding units would have caused irrotational (pure shear) strain in the intermediate incompetent layers.

and (b) Deformation of the incompetent layers by simple shear, with the shear planes oblique to the bedding, may have taken place either such that the sense of simple shear was the same as or opposed to bedding slip. The deformed pipes are "overturned" in the direction of slip deduced for the fold limb in which the deformed pipes lie (see Fig 10 b). Thus, if deformation was by simple shear then the senses of shear and bedding slip were the same. (It is important to remember that simple shear is only one of an infinite number of possible rotational, homogeneous, planar shears. Thus, the preclusion of pure shear as the strain mechanism does not, of necessity, mean that deformation was by simple shear).

Till now, the formation of the \( f_{ib} \) folds has been considered in terms of homogeneous strain. But, inhomogeneity of strain within the relatively incompetent beds is shown by the following:

i. There is no sharp discordance between the competent and relatively/
relatively incompetent beds. The angle between the pipes and the bedding generally increases gradually from the margins towards the interiors of the beds, and

ii As noted (p 62) strength differences between the pipes and their matrix cause inhomogeneous strain. Fig. 10c shows \( f_{ib} \) folds in which the pipes in one limb of the folds are in contact; the bedding matrix has apparently been completely "squeezed out" from between the rotating stronger pipes (Thus, \( \lambda_B = \infty \)).

In conclusion, the author considers that the \( f_{ia} \) and the \( f_{ib} \) folds (with \( P_2 \) and \( b \) coplanar in the fold profile) are contemporaneous and genetically related. The basic mechanism of pipe folding has been deformation of relatively incompetent beds between competent beds sliding relative to each other during flexural slip folding. Shear in the incompetent beds has apparently been rotational but not necessarily of simple shear type. The direction of "overturning" of the deformed pipes indicates the sense of bedding slip.

2. As noted (p 34) the \( f_{ib} \) folds in which the \( P \) and \( a \) pipe dimensions are coplanar within the fold profile were only rarely observed. They were seen in situ at only one locality - about 200 yards west-north-west of Kempie - where they lie in the core of a major \( f_{ia} \) anticline. They were also seen in a loose block on the hillside above Eriboll House. (Fig 10f)

It is a matter of some significance that these folded pipes lie within the foliation \( s_{ia} \). Thus, they show that the \( s_{ia} \) planes are not, of necessity, planes of homogeneous strain.

Folds of this type are evidently the result of three dimensional, inhomogeneous strain involving
(i) a compressive strain component normal to the fold profile and
(ii) variable shear within the profile plane.

The possible process of fold development is shown in Fig. 22

The shearing component in the \( f_{\text{Ib}} \) folds west-north-west of Kempie may
have been induced by inter-bedding slip during \( f_{\text{Ia}} \) folding. If this is the case,
these folds indicate that the upper beds slid relatively from north-north-east
towards south-south-west - that is, approximately parallel to the axis of the
major \( f_{\text{Ia}} \) anticline in whose core the \( f_{\text{Ib}} \) folds lie. As far as the author is
aware, bedding slip parallel to the axes of flexural-slip folds has never been
reported; but if slip in the fold limbs was not exactly perpendicular to the fold
axis, there is a necessary component of slip in the hinge, parallel to the axis
(see Fig. 23).

(ii) The Set I planar and linear structures:

(a) Fracture cleavage, \( s_{\text{Ib}} \), and bedding - \( s_{\text{I}} \) intersection lineation

For the following reason, the author finds that he can draw no positive
conclusions regarding the origin of the cleavage, \( s_{\text{Ib}} \).

1. The fractures are developed in an anisotropic rock mass.

Application of any existing fracture theory (for discussion of fracture
theories, see Jaeger (1964), pp 72-86) to anisotropic rock is of very doubtful
value. Serafin (1964) considered that: "For stratified or schistose rocks, Mohr's
theory of rupture must be abandoned". (p 643) and Donath (1964) stated: "It
would ...... seem important, if not essential, that the effects of anisotropy
be evaluated before attempting ...... theoretical analysis of stress in rocks of the
earth's crust ...." (p 296).
Figure 22

Mechanism by which $f_{1b}$ folds (P2 and a coplanar in the fold profile) may develop.

a. Unstrained Pipe Rock.

b. Pipe Rock of "a" deformed by compression (C) and variable shear (S). The bedding, $B_2$, is strained but unfolded.
Figure 23.

Diagram illustrating that slip in the fold limbs oblique to the axis of a flexural-slip fold causes inter-bedding slip parallel to the axis.
In deformation experiments with slate, Donath (op. cit.) found that the differential stress (Differential stress equals axial stress applied to a specimen in compression, minus the confining pressure) required to produce failure was a function of the orientation of the slaty cleavage with respect to the principal stresses. Failure tended to occur parallel to the cleavage when the cleavage was inclined at from 15 to 60° to the direction of axial compression; only when the cleavage was normal to the compression did the anisotropy have no effect on the orientation of the developed shear fractures (op. cit. - Fig. 12).

As far as the author is aware the effects of anisotropy on fractures developed under conditions of tensile stress have not been evaluated. Since planar structures, such as stratification or foliation may constitute planes of relative weakness it may be qualitatively expected that, as in compression, fractures will tend to follow pre-existing planar elements, except when tension is applied parallel to the planes.

In the area under consideration the fracture cleavage is very often parallel to the foliations, $s_{Ia}$ and $s_{Ic}$, and to the bedding, $b_0$. Such relationships indicate that its development was controlled to a marked extent by the pre-existing planar anisotropy and that its orientation bears no predictable relationship to the generating stress system.

There is no positive evidence as to whether the forces which generated the fracture cleavage were compressive or tensile in nature. It would appear that the fracture cleavage is a late-stage phenomenon associated with folding. Thus, it may be suggested that the cleavage owes its development partly to compression during the later stages of folding and partly to tension induced on cessation.
cessation of compression by the relaxation of residual stress "stored" during folding. (Tensile fractures formed on removal of compressive stress from experimentally deformed rock, formed during what Griggs (1936) p. 565 called "elastic after-working" or "elastic return" have been termed "release fractures" by Billings (1960) p. 97).

2. The fractures are developed in folded rocks.

If folding took place during the development of the fracture cleavage the principal stress orientations cannot be deduced from the cleavage orientation since, during folding, strain was almost certainly rotational. and

3. Lineations defined by the intersections of planar structures need bear no predictable relationships to the orientations of the principal stresses, since the orientations of the lineations are, in part, dependent on the attitudes of those planes in existence before the onset of stress.

(b) Foliation, \( s_{Ia} \), and grain elongation lineation, \( l_{Ia} \).

In analysing the origins of these structures the following factors must be considered:

1. The foliation, \( s_{Ia} \), and the lineation \( l_{Ia} \), are very probably genetically related to the \( f_{Ia} \) folds. The \( f_{Ia} \) folds appear to be generally of flexural-slip type.

2. \( s_{Ia} \) and \( l_{Ia} \) are generally restricted to relatively incompetent bands between the massive bedding units. and

3. \( l_{Ia} \) is approximately normal to the axes of the \( f_{Ia} \) folds (see Figs. 9b and 11a ). The poles to \( s_I \) lie approximately within the profile plane of the \( f_{Ia} \) folds (see Fig 9d ).
It was suggested (p. 40), in connection with Pipe Rock deformation, that the foliation, $s_{Ia}$, may define the approximate orientation of the $\varepsilon_1 \varepsilon_3$ plane ($\varepsilon_3 \wedge s_{Ia} = 90^\circ$) while $l_{Ia}$ may define the orientation of $\varepsilon_1$.

The author considers these relationships to be largely the result of flexural-slip folding such that relative slip of competent beds approximately normal to the fold axes has induced strain in the relatively incompetent bedding margins. The plane of slip (the fold profile) is the $\varepsilon_1 \varepsilon_3$ plane. $\varepsilon_2$ is thus approximately parallel to the $f_{Ia}$ fold axes. Since strain was almost certainly rotational the attitudes of the principal stresses may not be derived; but, if strain was planar, $\sigma_2 \wedge \varepsilon_2 = 0^\circ$.

Since strains could not be calculated from the deformed clastic grains it has not been possible to apply any quantitative test to the above suggestions.

(c) Crenulation foliation, $s_{Io}$ (see plates II f, g and h).

The crenulation foliation is oblique, not to an earlier foliation but to the bedding, $b_0$. According to Whitten (1966) p. 254; "As pointed out ...... crenulation foliation appears to develop only at the expense of an earlier $S$-surface but, contrary to the majority of reports, the earlier $S$-surface need not be of tectonic origin. Original bedding $S_0$-surfaces ... can commonly be affected by crenulation structures ......".

As noted (p 34) the crenulation foliation is parallel to the axial planes of very small scale $f_{Ia}$ folds. The folds and the foliation are evidently genetically related.

The following relationships may have some bearing on interpreting the origin of the foliation.

1. /
1. The bedding (defined by thin chart bands) were unfolded, is inclined, generally at about $30^\circ$ to the foliation.

2. The bedding has apparently suffered tensile strain. This is indicated by:
   
   (i) The chert bands have been boudinéed, and
   (ii) Where the chert bands have not been boudinéed the quartz crystals within them are elongate parallel to the bedding (see Plates IIg and h).

3. The long dimensions of the carbonate crystals in adjacent microlithons are often conjugately inclined to each other so that, in their section, the rock has the "herring-bone" texture characteristic of crenulation foliation.

4. The bedding has been transposed along the surfaces separating the microlithons. In opposite fold limbs the senses of slip are opposed. The thicker, relatively competent chert bands, though folded, are not transposed.

5. Bedding within the microlithons is often folded. This may indicate compressive strain normal to the microlithons and

6. A folded, boudinéed chart band shows the following features:
   
   (i) The folds are step-like in profile (Fig. 24a), and
   (ii) Where the chert band approaches parallelism with the foliation it is generally thicker than where it is approximately normal to the foliation. Thus, the chert band often, attains its minimal thicknesses in the cores of the $f_{1a}$ micro-folds (Fig. 24a).

Turner and Weiss (1963) have noted that: "The evolution of strain-slip cleavage (crenulation foliation) is not a simple process and is still not fully/
a. Details of folded chert bands in dolomite cut by crenulation foliation, S_{10}, Kempie. (See also Plate II). The chart bands are frequently thinner in the fold hinges than in the fold limbs.

b. Diagram illustrating how flattening accentuates thickness variation. With pure shear C becomes C'.

c. Diagram showing how a band of variable thickness may first be compressed then buckled about axes situated in the thinnest parts of the band.
fully understood" (p. 465). In essence, however, they subscribed to the views of Hoeppener (1956) and concluded that crenulation foliation developed, initially, oblique to $\sigma_1$, then, with further compression the foliation is flattened and rotated towards $\sigma_3$.

As a general rule, the author considers deformation at Kempie to have been the result of rotational strain. If the crenulation foliation, $S_{ic}$, formed under such conditions, its development cannot be analysed in terms of flattening and its relationship to the principal stresses cannot be ascertained.

The simplest form of rotational shear is simple shear and the following analysis has been developed in terms of this type of shear.

Under simple shear deformation, the suggestion that crenulation foliation is normal to $\sigma_1$ (see above) would require to be reinterpreted as: crenulation foliation is normal to $\varepsilon_3$.

For simplicity, let $\varepsilon_2$ lie in the plane of the foliation. If the initial development of the foliation is oblique to $\varepsilon_1$, then under flattening (pure shear) infinite strain is required for the foliation to come to lie in the $\varepsilon_1\varepsilon_3$ plane. Under simple shear, however, the foliation may, by a simple process, come to contain $\varepsilon_1$ and $\varepsilon_2$.

In Fig 25 fractures or slip surfaces, $f$, (the first stage in the development of the crenulation foliation) are assumed to have developed at the onset of strain such that $f \cdot S = 0$. With simple shear, $f$ becomes $f'$ and $\theta$ becomes $\theta'$.

From page 23:

$$\cot \theta = \cot \theta' - \gamma_5$$

From page 22:

$$\tan/$$
\[
\tan \beta' = -\frac{E_3}{E_1} \quad (\beta' = \sin \varepsilon_1)
\]
\[
\cot \beta' = \frac{E_1}{E_3}
\]

\(f'\) and \(\varepsilon_1\) are coincident when \(\theta' = \beta'\), that is, when:

\[
\cot \theta' = \cot \beta'
\]
and:

\[
\cot \theta + \gamma_s = -\frac{E_1}{E_3}
\]
and:

\[
\frac{E_1}{E_3} + \gamma_s = \cot \theta \quad (1)
\]

From page 22:

\[
\gamma_s = \varepsilon_1 - \varepsilon_3
\]
\[
\therefore -\cot \theta = \frac{E_1}{E_3} + \varepsilon_1 - \varepsilon_3 \quad (2)
\]

In simple shear:

\[
(E_1 + 1) (E_3 + 1) = 1 \quad (p. 18)
\]

From which:

\[
E_3 = \frac{-E_1}{E_1 + 1}
\]

Substituting in (2):

\[
-\cot \theta = \frac{E_1(E_1 + 1)}{-E_1} + E_1 + \frac{E_1}{E_1 + 1}
\]

\[
= \frac{-1}{E_1 + 1}
\]

\[\therefore \cot \theta = \frac{1}{E_1 + 1}
\]

\[\therefore \tan \theta = \frac{\varepsilon_1 + 1}{(3)}
\]

for \(f' \cdot \varepsilon_1 = 0^\circ\)

Since \(\varepsilon_1 + 1 > 1, 90^\circ > \theta > 45^\circ\).

If fracturing takes place during simple shear and \(f' \cdot \varepsilon_1 = 0^\circ\)
then/
Figure 25

For explanation see text.
then from (1):

\[ -\cot \theta = \frac{\varepsilon_1}{\varepsilon_3} + \gamma_s' \]

Where \( \gamma_s' \) is that part of the simple shear responsible for the rotation of \( f \) (\( \gamma_s > \gamma_s' \)).

It should be noted that, strictly speaking, the above type of deformation should not be called "simple shear" since, in simple shear, fracturing does not occur. The fractures are, however, considered as purely passive elements deformed by simple shear.

From the above relationships it may be shown, for example, that when \( \varepsilon_1 = 0.25 \) and \( \varepsilon_3 = -0.20 \) then for \( f' : \varepsilon_1 = 0^o, \theta = 51^o \) (and \( \beta' = 39^o; \gamma_s = 0.45 \)).

For simplicity the above analysis was made in terms of homogeneous strain. It is obvious, however, that the planes of any crenulation foliation constitute planes of strain discontinuity within the strained rock and that folding within the microlithons is clear evidence of inhomogeneous strain.

Evaluation of such inhomogeneities and discontinuities can only be made using largely qualitative methods.

Let it be supposed that the vertical distances between the initial planar structures from which the crenulation foliation develops are equal to \( d \) (Fig. 25d). With homogeneous, planar shear \( d \), becomes \( d_2 \). Since there is no area change:

\[ f \cdot d = f'd_2. \]

Since \( f' > f \), \( d_i > d_2 \).

The following factors may cause inhomogeneity:

(1)/
(1) If the planar surfaces, \( f \), behave as planes of perfect slip the microlithons may suffer only pure rotation; that is, \( f = f' \) and \( d_1 = d_2 \) (Fig. 25c).

(2) The microlithons may not have identical physical properties; that is, \( \frac{d_2}{d_1} \neq k \), where \( k \) is a constant. When \( \frac{d_2}{d_1} \neq k \) differential slip must take place between the microlithons (Fig. 25d).

(3) The geometric shortening \( d_1 \to d_2 \) may not take place homogeneously. In this case, folds develop within the microlithons and the planar structures, \( f' \), may not be parallel (Fig. 25e), and

(4) \( d_1 \) may not be constant and the initial planar structures, \( f \), may be discontinuous. Slip on the discontinuous planes would transmit shear stress to, and cause folding in, the microlithons in which \( f' \) peters out. (Fig. 25g).

Developed folds may be disharmonic. \( f' \) lies in the axial planes of the folds.

As noted, the foliation lies in the axial planes of very small \( f_{la} \) folds. This relationship may have been the result of either:

(a) Development of \( s_{lc} \) as a late stage phenomenon so that it was superimposed on previously formed folds or

(b) The synchronous development of \( s_{lc} \) and the \( f_{la} \) folds.

(a) If an ideal concentric fold with its axis parallel to \( \varepsilon_2 \) is modified by planar, homogeneous strain, the fold profile becomes elliptical and \( \varepsilon_1 \) and \( \varepsilon_2 \) lie in the fold axial plane.

If modification were by simple shear, then superimposed crenulation foliation would lie in the fold axial plane after shear when:

\[
\tan \theta = \varepsilon_1 + 1 \quad (\text{see p. 76}).
\]

(b) The \( f_{la} \) folds with \( s_{lc} \) in their axial planes are folds in chert bands.
bands which are presumably much more competent than their matrix of carbonate.

It may be suggested, that either the development of the folds has controlled the development of the foliation or the folds are "by products" of foliation formation. The fact that the foliation is present where the chert bands are unfolded indicates that the latter suggestion is the more probable.

The author would suggest that the development of folds in the chert bands is due to the greater competency of the chert; where strain is compressive the chert bands respond by buckling; where strain is tensile the chert bands are boudined. During homogeneous strain any line, if suitably oriented with respect to the principal strains, may be shortened then lengthened, but no line may be lengthened then shortened. Thus, even where strain is inhomogeneous, it may be expected that, during a single phase of deformation, folds may be boudined but boudins will not be folded. De Sitter (1958) has discussed these relationships in terms of flattening. Where \( E_3 \) is a line undergoing pure shear, then where \( E_3 \cdot l < 45^0 \), \( E_l < 0.0 \), and where \( E_3 \cdot l > 45^0 \), \( E_l > 0.0 \). De Sitter (op. cit.) called these fields of shortening and stretching "respectively the field of parasitic folds and the field of boudinage". (p. 281)

An interesting feature of some of the \( f_{Ia} \) microfolds associated with \( S_{Ic} \) is that the folded chert bands are often thinner in the fold cores than in the fold limbs. The author can only suggest that in a competent layer of variable thickness, boudin-like structures may form under compression. Thickness variations are accentuated during compression (Fig. 24b) and folding may then take place about axes situated in the thinnest parts of the strained layer. On being boudined, such folds would tend to separate at the hinges, and the relationships exhibited/
exhibited by the chert band described above (p 74) may be attained.

In conclusion although the mechanism of formation of the crenulation foliation, $^{5}$\textsubscript{Ic}, is unknown the author considers that its origin and development should be discussed, not in terms of flattening, but in terms of rotational strain.

d. Streaking lineation, \textit{\textsuperscript{1}Ic}.

\textit{\textsuperscript{1}Ic} is very rarely developed. Lack of data requires that its mechanism of formation cannot be analysed. \textit{\textsuperscript{1}Ic} may possibly indicate directions of incipient slip on either the fracture cleavage, $^{5}$\textsubscript{Ib}, or the crenulation foliation, $^{5}$\textsubscript{Ic}. This interpretation of its significance must, however, be regarded as being highly tenuous.

e. Crystallisation of the Set I minerals ($\varepsilon_{\text{I}}$).

The growth of chlorite and white mica during Set I generation indicates that deformation took place under conditions of greenschist facies metamorphism (quartz-albite-muscovite-chlorite subfacies) at a temperature of about 300\textdegree C (see Turner and Verhoogen (1960) pp 534-537).

No petrofabric work was done on $\varepsilon_{\text{I}}$ so that the relationships of $\varepsilon_{\text{I}}$ with the Set 0 and other Set I structures have not been statistically evaluated.

f. The Set I thrust (t\textsubscript{I}) and reverse fault (h\textsubscript{I})

Hafner (1951) has theoretically analysed possible relationships between faulting and systems of planar stress. He assumed that fracture took place on conjugate planes inclined at about 30\textdegree to $\sigma_{\text{i}}$. In stress systems induced by horizontal pressure on a homogeneous block Hafner (op. cit.) showed that the trajectories of $\sigma_{\text{i}}$ curved downwards away from the "active push" so that the proposed conjugate fractures were not simply inclined at 30\textdegree to the horizontal, but were themselves/
themselves curved surfaces. The senses of displacement on the deduced fractures were always upper over lower. Thus, Hafner (op. cit.) considered that a conjugate system of thrust and reverse faults could develop from horizontal "one-sided push".

The attitudes and relative directions of displacement on the Set I thrust and reverse faults conform, in a very general way, to the theoretical attitudes and displacements deduced by Hafner (op. cit.). This may suggest that during the formation of $h_1$ and $t_1$, $\sigma_1$ and $\sigma_3$ lay approximately in an east-west striking vertical plane and that $\sigma_1$ was nearly horizontal while $\sigma_3$ approached verticality.

It should be noted that Hafner's (op. cit.) stress analysis may be of only limited application to the situation at Kempie. Hafner (op. cit.) considered stresses only in homogeneous bodies and he took no account of stress redistribution on fracturing. In addition, it may be noted that Hubbert (1951) deformed loose sand under conditions of "one-sided push" and found that slip occurred on only the thrust fault system of fractures. These results may indicate that only $t_1$ developed during folding and that $h_1$ is a later structure.

(3) Set I generation: discussion

Genetic interpretation of the Set I structures has been based largely on the geometries of individual structures and on the geometric relationships existing between structures. In this discussion, an attempt will be made to evaluate the procedures employed in, and the results obtained from, genetic analysis.

(i) The analysis of principal stress orientations from geological structures.

Stress analysis is, of necessity, based on the assumption that some component/
component (or components) of the developed structure bears some particular relationship to the orientation of the principal stresses of the generating stress system.

a. Stress analysis from folds

The orientations of the principal stresses given in analysis of the "flattened" minor $f_{\text{la}}$ fold (p. 59) were deduced by assuming that the fold profile was modified by pure shear deformation. Stress analysis is invalid either if $E_2$ was not parallel to the fold axis or, if strain was rotational.

As noted (p. 66) De Sitter (1964) maintained that, in the development of major folds, $\sigma_1$ is horizontal and normal to the fold axes, $\sigma_2$ is parallel to the fold axes, and $\sigma_3$ is vertical. Turner and Weiss (1963) p. 524, have suggested that the orientations of the principal stresses are related to the symmetry of the fold. The $f_{\text{la}}$ folds in the area studied have a single plane of symmetry normal to the fold axes, for such folds, Turner and Weiss (loc. cit.) suggested that "one axis of principal stress is normal to the symmetry plane ..... (in the $f_{\text{la}}$ folds this axis would be $\sigma_2$). The directions of the other two stress axes are indeterminate".

Bell and Currie (1964) performed folding experiments with layered photo-elastic media such as gelatin and cellulose acetate. The folds produced were symmetrical about their axial planes; $\sigma_3$ was parallel to the fold axes. They showed that the patterns of the trajectories of $\sigma_1$ and $\sigma_3$ within the fold profiles were exceedingly complex. Their results suggest that analysis of principal stress orientations from fold structures is at best a highly tenuous procedure. It is to be expected that the patterns of principal stress trajectories will change continuously with folding. De Sitters' (op. cit) argument can hold only on a regional basis, in which the surface of the earth "is by far the most important plane of/
plane of discontinuity that enters into the stress field" (op. cit. p. 175)

The uncertainty of relationship between fold components and principal stresses has been noted by Turner and Weiss (1963) p. 525 who state: "The ground on which we stand is firmer when our interpretation of folds and fold systems is framed in terms of strain and the movement picture of deformation".

b. Stress analysis from planes of failure.

Where planes of failure intersect it is assumed in stress analysis, that their intersection defines the orientation of $\sigma_2^e$, and that $\sigma_1$ and $\sigma_3$ bisect the angles between the planes. The analysis appears to have its basis in the Coulomb-Navier and Mohr theories of fracture (see Jaeger (1964) pp 75-83.) Both theories assume $\sigma_2$ to lie in the planes of failure.

The above relationships of principal stresses and planes of failure, assumed (p 58 and pp 80-81) in the analysis of the $f_{La}$ conjugate fold and the Set I fault and thrust ($h_1$ and $t_1$) are open to the following criticisms:

1. The possibly significant effects of rock anisotropy have not been evaluated; it is very doubtful if the Coulomb-Navier and Mohr fracture theories are applicable to anisotropic rock. As noted (p 70) Serafim (1964) considered that Mohr's theory should be abandoned for layered rock.

In deformation experiments with anisotropic rock, Jaeger (1964) b found that $\sigma_2$ did not lie in the plane of failure. The plane of failure passed "through the intersection of the plane of foliation and the plane perpendicular to $\cdots \sigma_1$" (op. cit. p. 298) and

2. Argument from theoretical to actual situations, as done in considering the origins of $h_1$ and $t_1$ has been criticised by Jaeger (1964) a. The apparent
apparent relationship between the planes of failure predicted by Hafner (1951) and patterns of thrusts and faults may not exist, "since in practice when failure takes place at a point there will be a redistribution of the stress system before further fracture occurs and it is this redistributed stress system which determines the direction of the next failure". (Jaeger op. cit., p. 178).

In conclusion, the author considers that the analysis of principal stress orientations from structures is a process of questionable value. Where deformation has been by pure strain, and is recognisably so, then the principal stresses are parallel to the principal strains. Under all other conditions of deformation it is doubtful if the orientations of $\sigma_1$, $\sigma_2$, and $\sigma_3$ may be accurately determined.

(ii) Strain analysis from geological structures.

Strain analysis in tectonites may be a most useful procedure in that it may permit the exact determination of the nature of a structure; for example, a lineation may be shown to be a direction of elongation or a foliation may be shown to be the $E_1E_2$ plane of deformation.

Analysis is, however, limited in value by the following factors:

(a) The determination of strains and shears does not permit unique identification of the mechanism of strain. Identical states of strain may result from various processes. In the present study because strains were calculated in folded rocks, strain is thought to have been rotational; such a conclusion could not have been drawn solely from the calculated data and

(b) To make calculation possible it is generally necessary to make certain/
certain assumptions regarding the state of strain. Here, strain was assumed to have been planar and homogeneous. Such assumptions may introduce significant errors.

In this study, strain analysis was most useful when considered in relationship to the mechanisms of development of the major folds. Pipe-bedding relationships showed that folding was basically of flexural-slip type, but strain analysis showed that the folds could not be considered to be of ideal flexure type.

4. **Set I generation: conclusions**

The dominant Set I structures are the major $f_{Ia}$ folds. These folds are, in essence, of flexural-slip type; that they are not ideal flexural-slip folds is shown by the fact that the bedding has, in places, been strained.

It is probable that inter-bedding slip approximately normal to the $f_{Ia}$ axes was instrumental in causing strain in relatively incompetent beds and in forming $f_{Ib}$ folds (folded pipes) $l_{Ia}$ (grain elongation lineation) and $s_{Ia}$ (foliation).

The fact that factors, in addition to inter-bedding slip, have contributed to deformation is shown by the existence of strain in massive quartzites, the presence of crenulation foliation in the carbonate rocks, and evidence that the $f_{Ia}$ folds may have been modified by flattening. Strain calculations in the deformed Pipe Rock indicate that the bedding may have been significantly thickened. Such thickening could have been caused by compression at the onset of folding resulting in unequal thickening of the sedimentary pile.

The major $f_{Ia}$ folds show that, on a large scale, strain was inhomogeneous. Inhomogeneity on a small scale is shown by the existence of minor and microscopic/
scopic $f_{Ia}$ folds and of folded pipes. It was suggested that local inhomogeneity may often result from strength differences between adjacent structures; for example, between the pipes and their matrix. It is probable that the effects of anisotropy were significant throughout Set I generation and it is possible that the attitude of the fracture cleavage, $^s_{Ib}$, was largely controlled by pre-existing planar anisotropy.

The author considers strains developed during $f_{Ia}$ folding to be largely of rotational type. If strain was rotational it would follow that the origin and development of the crenulation foliation, $^{s}_{Ic}$, could not be considered in terms of flattening. The author has suggested a model of crenulation foliation development in terms of simple shear. Since simple shear is the simplest type of rotational strain it is to be expected, however, that the actual mechanism of formation of crenulation foliation is rather more complex.

In view of the above considerations the author would tentatively suggest that the following processes and sequence of events were responsible for the formation of the Set I structures:

It is thought that, in general, deformation took place under the action of forces acting generally east-west, and decreasing in magnitude from east to west.

During initial compression the sedimentary pile may have been thickened such that thickening decreased from east to west. With continued compression, buckling took place and the major $f_{Ia}$ folds began to form essentially as flexural slip folds. Since compressive forces were greatest in the east the developed folds were asymmetric in profile and were overturned towards the west.
Inter-bedding slip, approximately normal to the $f_{Ia}$ axes, during flexural-slip folding was largely responsible for pipe deformation and pipe folding ($f_{Ib}$ folds) and for the development of the foliation, $s_{Ia}$ and the lineation, $l_{Ia}$. (The deformed pipes, the grain elongation lineation, $l_{Ia}$ and the poles to $s_{Ia}$, all lie approximately normal to the $f_{Ia}$ fold axes).

The $f_{Ia}$ fold profiles may define the $\varepsilon_1 \varepsilon_3$ planes of deformation; thus, $\varepsilon_2$ may be parallel to the fold axes. In the fold profile it is thought that $l_{Ia}$ approximately defines the orientation of $\varepsilon_1$ while $s_{Ia}$ approximately defines the $\varepsilon_1 \varepsilon_2$ plane ($\varepsilon_3 - s_{Ia} = 90^\circ$).

During Set I generation, failure, besides taking place by folding, also took place by fracturing; faulting ($h_I$) and thrusting ($t_I$) occurred. The fracture cleavage, $s_{Ib}$, is generally parallel to pre-existing planar structures—bedding and foliation—and apparently developed during the later stages of folding. The cleavage may have formed on the release of the compressive forces.

The origin of the crenulation foliation, $s_{Ic}$, is enigmatic, and its relationships with all of the other Set I structurally elements are not fully known. In common with the other Set I structures it is thought, however, to have been the result of rotational and not flattening, strain.

It has been shown—for instance, by the presence of bedding strain—that the $f_{Ia}$ folds are not of ideal flexural type. Within the broad framework of flexural-slip folding there exist "side-effects"—strains and structures—whose origins cannot be simply considered in terms of flexural slip. For example, a component of apparently homogeneous shortening was detected normal to the axial plane of a minor $f_{Ia}$ fold (Fig 18), and minor $f_{Ia}$ folds developed between deformed pipes/
pipes (Fig 20b) are thought to have resulted by "squeezing" of the bedding matrix between rotating, more rigid pipes.

It may be concluded that, in general, the Set I structures are the result of complex processes induced within an anisotropic rock mass under the action of compressive forces. The role of anisotropy in determining the mechanics of deformation has been of considerable significance; it is most obvious in considering the development of the major folds - flexural slip folding is only possible in layered media - but in the analysis of small scale structures and local strains though probably important, it is most difficult to evaluate.

(b) Set II generation

As noted, the Set II structures are the major Arnaboll and Moine Thrust planes.

It is not intended to analyse the possible mechanisms of thrust formation and nappe emplacement.

Although major thrusting might be expected to have modified the Set I and Set II structures no such modifications have been recognised other than the truncation of Set I folds by thrusts.

5. General conclusions regarding the structural history of the Arnaboll Nappe

The tectonic structures of the area studied fall into two distinct groups which, in general terms, may be described as major folds post-dated by major thrusts.

Attention has been concentrated on the major folds and their associated structures (Set I structures). Algebraic strain analysis in Pipe Rock involved
in folding has been attempted and the geometric relationships of the deformed pipes with the fold geometry were found to be of value in determining the mechanism of folding. It was concluded that folding was basically but not ideally, of flexural-slip type.

It may be stated that, as a general rule in the analysis of deformation mechanics, the author has erected theoretical, ideal models of known geometric relationships, and compared these with the actual structural relationships. Such a procedure was of value in this study because the pipes are convenient "structural markers". Although this method of approach may not lead to precise identification of the mechanism of deformation it may allow certain mechanisms to be eliminated from discussion. For example, it was shown that simple shear, with shear planes parallel to the bedding, did not occur during flexural-slip folding.

In conclusion, the structural history of the Arnaboll Nappe, though apparently simple, has been found to be complex. The description of, and the determination of relationships between developed structures now play a minor, but important part in structural analysis; this study has been primarily concerned with the analysis, using strain data, of the mechanics of formation of the developed structures.

Section IV
Section IV

Area II: Glen Coul

1. Introduction

The major structural features in the area studied are the Glen Coul, Ben More and Moine Nappes. This section deals with the structural histories of parts of the Glen Coul and Moine Nappes.

In the Cambro-Ordovician of the Glen Coul Nappe structures have been described and their possible mechanisms of formation analysed. In the deformed Pipe Rock, the algebraic techniques described in Section II have been used in strain calculation.

The structural history of the Moine Nappe has been treated in detail. Previously unrecognised Lewisian Gneiss found within the Moines provides evidence of the existence of fundamental "first" structures within the area. Such structures have, for instance, been described by Johnson (1960) and Ramsay (1963) as F, structures.

Analysis of deformed Pipe Rock at the base of the Moine Nappe has been found to be of some significance in considering the origins of the mylonites and of the dominant east-south-east plunging lineation.

The results of Christie's (1956 and 1963) structural analysis have been critically reviewed.

2. The position of the Moine Thrust-plane

Since part of this study deals with the Moine Nappe it is important that the position of the Moine Thrust-plane be clearly defined.

The Geological Survey "One-inch" Map of the Assynt District (1923) shows the rocks of the Moine Nappe - "Eastern Schists" or "Rocks of Moine Type" - to be "Undifferentiated" Eastern Schist (psammites), Quartz Schist and Mylonised Rocks ("μ-rock"). On the map all of the "μ-rock" is quite clearly shown as lying within the/
the Moine Nappe. In general, north of the Fionn Allt, the base of the Nappe is composed of mylonite. In the vicinity of the Stack of Glen Coul, two bands of "μ-rock" are shown; the Moine Thrust underlies the lower of these.

Despite the relationships shown in the map, the accompanying geological section (from Loch Glendhu south-east to the Stack) shows the Moine Thrust-plane at the Stack as overlying the lower "μ-rock". The lower "μ-rock" is shown as separated from the Glen Coul Nappe by an un-named thrust. The relationships of the upper "μ-rock" with the Moine Thrust are not shown.

The positioning of the Moine Thrust-plane above the lower "μ-rock" is due to Clough (in Peach et. al. (1907) pp 500-503) who stated that "sheared Lewisian gneiss ("μ-rock") and schist of the Moine series have been brought forward by different thrusts" (loc. cit. pp 500 - 501); and that at the Stack of Glen Coul, there are two thrusts: "The lowest of these has carried forward a thin band of greatly-sheared rock - apparently Lewisian gneiss - while the highest or Moine Thrust ..... has brought on a fine grained puckered schist ..." (loc. cit. pp 502-503).

Christie (1956 and 1963), in identifying the Moine Thrust-plane, followed the usage of the Geological Survey maps; that is, he considered it to underlie the "μ-rock".

At the stack of Glen Coul and between Loch an Eircill and the Fionn Allt the Moines (including "μ-rock") are separated from the Ben More and Glen Coul Nappes by Torridonian and Cambrian sediments. Elsewhere, Moinian psammites, schists and "μ-rock" rest directly on the underlying nappes. Christie (1963) has shown, from the similarity of minor structures and quartz fabrics, that the Moinian/
Moine psammites, schists and mylonites, and the Torridonian and Cambrian sediments mentioned above, "all belong to a single structural unit" (loc. cit. p. 381). He therefore concluded that "the Moine thrust is merely a lithological boundary" (loc. cit.)

The latter statement is true only in those areas where Cambrian and Torridonian intervene between the Moines and the Ben More and Glen Coul Nappes; elsewhere the Moine Thrust cannot possibly be considered to be a lithological boundary.

That the Moine Thrust is, in fact, a distinct structural break is, perhaps most clearly seen to be the case on Lochan Feith an Leothaid, where hornblende Lewisian Gneiss - mapped as "μ-rock" - rests directly on the Cambro-Ordovician of the Glen Coul Nappe.

The present author considers the Cambrian and Torridonian between the Moines and the Ben More and Glen Coul Nappes to constitute part of the Moine Nappe. Thus, the "single structural unit" of Christie (loc. cit.) is simply the Moine Nappe, and the Moine Thrust-plane is redefined as underlying the Cambrian and Torridonian in question.

The position of the redefined Moine Thrust is shown in Fig. 26; it is clearly a well-marked fault surface which brings Cambrian and Torridonian sediments, mylonites ("μ-rock") Moine schists and psammites, and Lewisian Gneiss to lie, with striking discordance, on the underlying Ben More and Glen Coul Nappes.

3. Structural analysis of the Cambro-Ordovician of the Glen Coul Nappe

(a) Introduction.

The sediments under consideration run in a narrow strip from the headwaters/
headwaters of the Allt Feith an Leothaid to the north-west end of Lochnan Coarach (Fig 26). Basal Quartzite and Pipe Rock are the dominant rock types but thin slices of Fucoid Beds, Serpulite Grit and Ghrudaidh Limestone are present on An Sniomh and west of the Stack of Glencoul felsite sills and sheets are common in the quartzites.

(b) Structural sets

The structures developed within the area have been grouped into the following sets:

Set 0 = \((b_0, s_0, p_0, e_0, z_0)\)

Set I = \((f_I, s_{Ia}, b, s_{Ib}, c, e_I, z_I)\)

Set \(U_a\) = \((f_{Ua}, Z_{Ua})\) Set \(U_b\) = \((h_{Ub}, Z_{Ub})\)

Set \(II\) = \((t_{II}, Z_{II})\) Set \(III\) = \((f_{III}, Z_{III})\)

Set \(IV\) = \((t_{IV}, Z_{IV})\) Set \(V\) = \((h_V, Z_V)\)

It is known that Set \(U_a\) post-dates Set I and that Set \(U_b\) predates Set \(II\). No definite time relationship could be established between Sets \(U_a\) and \(U_b\).

(c) Descriptions of structural sets.

Set 0:

\(b_0\):

Bedding poles are shown in Fig.

The bedding dips generally eastwards.

The other Set 0 elements will not be described.

Set I:

\(f_I\)
Figure 27.

Glencoul Nappe, Glen Coul. Structural data.

a. 79 poles to the bedding (b_0)

b. 6 axes (o) and 6 poles (0) to the axial planes of the f_I folds.

c. Orientations of the grain elongation lineation, \( L_a \) (•) (29 readings) and the cleavage – bedding intersection lineation, \( L_b \) (0) (3 readings)

d. Orientations of 54 deformed pipes
Profiles of $f_I$ folds are shown in Fig. 28. The orientations of their axes and axial planes are shown in Fig. 27b. In general, they have near-horizontal axes, and easterly dipping axial planes. $f_I$ folds are not common.

The $f_I$ folds are not major folds but, at the same time, they are not small enough to collect as hard specimens. Thus, they have not been quantitatively classified — see Ramsay (1962)a. They are developed in highly competent quart-zites and the absence of any clearly defined thickness variation in the folded layers suggests that they are some form of flexure folds.

$l_{1a}$:

$l_{1a}$ is the lineation defined by the preferred orientation of the $a$ semi-axes ($a > b > c$) of elongate, deformed clastic particles ($g_o$).

$l_{1a}$ plunges generally at a low angle to the south-east (Fig. 27c). It is therefore inclined at a high angle to the $f_{1a}$ fold axes.

$l_{1b}$:

$l_{1b}$ is the rare lineation defined by the intersection of the cleavage ($s_{1b}$) and the bedding ($b_o$).

Its orientation could only be measured at three localities where it plunges at low angles, either to the south or to the north-east (Fig. 27c).

$s_I$:

The following types of Set I planar structures have been recognised:

$s_{1a}$: Foliation defined by the planar alignment of the $a$ and $b$ semi-axes.
Figure 28
Glencoul Nappe, Glen Coul.

a-k. Profiles of $f_I$ folds.
i-n Profiles of $f_{wa}$ folds.
axes \((a \succ b \succ c)\) of deformed sedimentary grains \((g_0)\). The lineation \(l_{Ia}\) lies in \(s_{Ia}\).

\(s_{Ia}\) is best developed in their relatively incompetent zones within and between the massive quartzite bedding units. As far as can be determined, \(s_{Ia}\) is parallel to the bedding \((b_0)\) but slight angular discordance may pass undetected in the field. \(l_{Ia}\) was always measured on bedding planes. Thus \(l_{Ia}\) may be an "apparent lineation" - den Tex (1953) - defined by the intersection of the bedding with ellipsoidal, deformed grains.

\(s_{Ib}\): Cleavage.

\(s_{Ib}\) is fracture cleavage developed in the quartzites. Its orientation is shown in Fig 29a; it has a general easterly dip.

\(s_{Ic}\): Incipient foliation developed in felsite. It is defined by the planar alignment of chlorite and white mica crystals \((g_1)\). It can only be seen microscopically.

\(s_{Ib}\) and \(s_{Ic}\) are sub-parallel to the axial planes of the \(f_1\) folds (see Fig 28). Though \(s_{Ia}\) and \(s_{Ib}\) are included in Set I they do not appear to be synchronous. Where they interfere, the fracture cleavage, \(s_{Ib}\), is seen to cut (and, thus, to post-date) the foliation, \(s_{Ia}\). Since \(s_{Ib}\) post dates \(s_{Ia}\) it follows that \(l_{Ib}\) post dates \(l_{Ia}\). In the author's opinion \(s_{Ib}\) and \(l_{Ib}\) developed late in Set I generation.

\(g_1\):

During Set I generation, chlorite and white mica crystallised in the sediments and felsites. In the sediments the \(g_1\) crystals are generally aligned.
Glencoul Nappe: Structural data.

a. 9 poles to the foliation, $s_1$.

b. Poles (o) to the bedding, $B_2$, and orientations (.) of the deformed pipes, $P_2^*$. (See Table VI).

c. Poles to the $P_2 b_2$ planes.

d. Calculated orientations of the principal strain axes in the Pipe Rock.
aligned in the foliation $s_{1a}$; in the felsites the $g_1$ crystals are aligned in $s_{1o}$. These relationships may indicate that $s_{1a}$ and $s_{1o}$ are genetically related and differ in character because they have been developed in rocks of differing lithology and competency.

Quartz recrystallisation, though extensive, has nowhere resulted in complete recrystallisation of the quartzites. As a rule, the $g_1$ quartz crystals are small and of bladed habit; they are aligned in the plane of the foliation, $s_{1a}$. Thus, though $s_{1a}$ is normally defined by the planar alignment of deformed clastic grains it may locally be defined by bladed $g_1$ crystals.

Set $U_a$:

\[ f_{ua} \]

The $f_{ua}$ folds were found at only one locality - about 300 yards north of An Sniush. $f_{ua}$ profiles are shown in Fig 28; the folds are small scale and monoclinal in form. They post-date Set I because they fold pipes ($p_o$) which have been strained during Set I generation.

Set $U_b$:

\[ h_{ub} \]

Just north of An Sniush the quartzites are cut by a north-east-south-west striking fault. It is apparently a normal fault downthrowing to the south-east. The fault is truncated by the Moine Thrust-plane, which is, with reference to the structures developed within the Glencoul Nappe, a Set IV structure.

Set II:

\[ t_{II} \]

Between Glen Coul and Loch Nan Coarach the Cambro-Ordovician sediments/
sediments are much interrupted by thrusts which, in general, strike north-south and dip to the east; the thrusts are often parallel to the bedding. On An Sniomh a thin thrust mass, in which all rock types of the Cambro-Ordovician of the area are represented, oversteps the underlying Basal Quartzite on to the Lewisian Gneiss.

Set III:

\[ t_{III} \]

The Set II thrust-planes have been weakly folded on axes which apparently trend north-south (see Peach et. al (1907) p. 503).

Set IV:

\[ t_{IV} \]

With reference to the structures developed in the Cambro-Ordovician of the Glencoul Nappe, the Moine Thrust-plane \( t_{IV} \) is apparently a Set IV structure.

North of Glen Coul, the Moine Thrust is, in general, parallel to the bedding of Pipe Rock and Basal Quartzite. Between the Glencoul River and Loch Nan Coarach, however, comparisons of strike directions above and below the Thrust, show it to be discordant to the rocks of the Glencoul Nappe. (see map - Fig 26).

Set IV:

\[ h_{IV} \]

On Lochan Feith an Leothaid is a north-west-south-east striking fault; it is apparently normal with a downthrow to the north.

(a) Set Generation

(i) The generation of the Set I structures.

Evidence of the nature of the Set I generators may be obtained by examination.
examination of:

(a) the deformation of the Set 0 structures,

and (b) the geometric relationships of the Set I structures.

(i) The effects of the Set I generators on the Set 0 structures.

(a) The deformation of sedimentary grains \( (g_0) \)

Throughout the area, the shapes of the undeformed clastic particles are so irregular that no strain analysis could be made from their deformed counterparts.

(b) The deformation of the bedding \( (b_0) \).

Bedding strains have been calculated in conjunction with pipe strain (see below pp. 18-102). The existence of folds in the bedding \( (f_1) \) folds shows that, at least locally, bedding strain has been inhomogeneous and that, in places, the bedding has suffered pure rotation in addition to strain.

(c) Pipe Rock deformation

The positions at which data were collected are shown in Fig. 30. Calculated strain and shear parameters are given in Table VI.

The orientations of the deformed pipes are shown in Fig. 27d; they have a general south-easterly plunge. The orientations of the undeformed pipes are represented by the poles to the bedding, \( b_0 \) (Fig. 27a).

1. Discussion of results.

i Sources of error.

As noted (p. 28), the calculation of strain and shear parameters was based on the assumption that strain was both homogeneous and planar. Although the existence of the \( f_1 \) folds is clear evidence of inhomogeneous strain the folds are not/
Table VI

Calculated strain and shear parameters: Pipe Rock, Glen Coul and Moine Nappes
<table>
<thead>
<tr>
<th>Position</th>
<th>$B_2$</th>
<th>$P_2$</th>
<th>n</th>
<th>G</th>
<th>$\omega$</th>
<th>$\lambda_p$</th>
<th>$\lambda_B$</th>
<th>$t_2/t_1$</th>
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Figure 30.

Map showing the positions within the Glenooul and Moine Nappes for which strain data have been calculated (see Table VI).
A - Lewisian Gneiss. \( a_1 \) - Basal Quartzite. \( a_2 \) - Pipe Rock.
\( a \) - Undifferentiated Cambro-Ordovician. M - Rocks of the Moine Nappe. M.T.P. - Moine Thrust-plane. B.T.P. - Ben More Thrust-plane. These symbols are also those of Figure 31.
Figure 31

Map showing the calculated directions, plunges and values of $\varepsilon_1$ within the Glencoul and Moine Nappes.

In the Glencoul Nappe the values for positions IV, V, VIII and XII have been excluded. Positions XIV and XV are within the Moine Nappe.
not widespread. Thus, the \( f_1 \) folds may represent local inhomogeneities in an overall near-homogeneous strain pattern. That strain was, at least locally, non-planar is shown by the presence of very small-scale folds, with their axes parallel to the \( P_2^{-b_2} \) planes, in the bedding between deformed pipes (Fig 32).

Differences in physical properties, occurring for instance, between the pipes and their matrix and between bedding margins and interiors, are instrumental in causing inhomogeneous strain. Inhomogeneities induced by the straining of adjacent physically different rock components have been analysed above (pp 60-64).

It would appear that the major effect of such inhomogeneity is that strains in the relatively incompetent bedding margins are often greatly in excess of those in the competent bedding interiors.

The long dimensions of the pipes were assumed to lie in the plane of deformation.

The grain elongation lineation, \( l_{1a} \), and the deformed pipes both have a general south-easterly plunge (compare Figs 27c and d). As noted (p 98), the deformed clastic grains (g') could not be used to give estimates of strain. If, however, the a, b and c semi-axes (a > b > c) of the deformed grains may be roughly correlated with the X, Y and Z semi-axes of the strain ellipsoid, then it could be concluded that \( E_1 \) has a low plunge to the east-south-east, \( E_3 \) plunges steeply to the west-north-west and \( E_2 \) is near horizontal and trends north-east-south-south-west. Thus, the \( E_1 E_3 \) plane may have a general east-north-east-west-north-west strike and may approach verticality. Fig 27d shows that many of the deformed pipes lie within the possible range of the \( E_1 E_3 \) planes (for further discussion)
At locality IX (see Fig 30) it was found that the intersections of the deformed pipes and the $^{1}_{\text{Ina}}$ plane were elliptical and that $^{1}_{\text{Ina}}$ was exactly parallel to the long-axes of the ellipses (Fig 32). The long-axes of the ellipses are the intersections of the $P^b_2$ planes with the foliation, $s_{\text{Ina}}$. Thus, $^{1}_{\text{Ina}}$ lies in the $P^b_2$ planes. If $^{1}_{\text{Ina}}$ defines the orientation of $\varepsilon_1$, then $\varepsilon_1$ lies in the $P^b_2$ planes; if $s_{\text{Ina}}$ defines the $\varepsilon_1\varepsilon_2$ plane then $\varepsilon_3$ also lies in the $P^b_2$ planes.

In conclusion, although it cannot be definitely shown that the long dimensions ($P_2$) of the deformed pipes lie in the $\varepsilon_1\varepsilon_3$ plane of deformation, the author, nevertheless, considers that the $P^b_2$ and $\varepsilon_1\varepsilon_3$ planes are in approximate concordance.

It was assumed, in calculating the orientations of the principal strains, planes of simple shear and pipes and bedding before strain, that the planes containing the poles to the strained bedding and the pipe long dimensions ($P^b_2$ planes) were vertical. The approach of these planes to verticality (Fig 29c) indicates that the assumption does not introduce a great error.

Only once, at position XIII, was the desirable sample size of $n = 30$ attained. Thus, and particularly where samples are very small, the calculated parameters may approach only very approximately the actual parameters.

Samples cannot be considered to be representative of the Pipe Rock as a whole. As noted (p 41), pipe sectional ratios and pipe-bedding angles are most easily measured in the relatively incompetent layers, since, in these layers, the pipes weather out more readily than they do in the massive bedding units.

In conclusion, most of the possible sources of error (p 29) cannot be even approximately evaluated. The author would consider, however, that locally, strain may have been approximately homogeneous and that, as suggested by their relationships to/
Figure 32

Glencoul Nappe.

a. Position IX (see Fig. 30). Intersection of deformed pipes, $P_2$, on the foliation, $s_{1a}$. The grain elongation lineation, $l_{1a}$, is parallel to the long axes of the elliptical $P_2 / s_{1a}$ intersections.

b. and c. Evidence of strain inhomogeneity from position X.

b. Three sections of deformed pipes. One pipe has been folded about its long axis.

c. Weak folds in the bedding with their axes parallel to the long axes of the pipes.
to the foliation ($s_{1a}$) and lineation ($l_{1a}$), the pipes may lie in the plane of deformation. On the whole, however, sources of error are such that the calculated parameters may only be considered to be approximations of actual parameters.

ii The mechanics of deformation.

Some of the difficulties inherent in the analysis of strain mechanics are as follows:

(a) Identical states of strain may develop by different mechanisms - see Jaeger (1964) pp 32 - 33. Thus, calculated strain and shear parameters give no indication of the mechanism by which strain developed.

(b) Since strain was assumed to be both planar and homogeneous, calculated results cannot be used in discussing any other strain mechanisms.

(c) It is not possible in the Glencoul Nappe to relate the strains and shears to the geometry of any major structure. At Kempie, the relationships of the strains and shears to the major folds proved helpful in analysing fold and strain mechanics; in the Glencoul Nappe a similar analysis is not possible.

and (d) Strain analysis takes no account of possibly significant pure rotation. Pure rotation has undoubtedly taken place about the north-south trending $f_1$ fold axes; such rotation may have been more than a purely local feature. Calculated orientations of the pipes and bedding before strain may, therefore, bear little relationship to the actual orientations. Thus, comparisons of the pipe and bedding pole distributions before and after strain cannot be used as an aid to analysis.

In addition, the orientations of $P$, and $B$, were calculated only for the special cases of pure and simple shear.

The above considerations unfortunately decree that no positive assertions, regarding/
regarding the mechanism of deformation of the Pipe Rock, can be made.

(ii) Genetic consideration of the Set I elements.

\[ f_I^a \ \ |_{lb'} \ \ |_{lb^s} \]

Examination of these structures yields little pertinent information.

The \( f_I \) folds are apparently of flexural-slip type (see p 94). Thus, the folded bedding planes were kinematically active during folding. The folds are not, however, widespread and it is not possible to evaluate the role of inter-bedding slip in the deformation of the Pipe Rock.

\[ I_{la'} \ \ |_{la^s} \]

The possible significance of these structures has been suggested above (pp 99-100). It is thought that the lineation, \( I_{la} \) is approximately parallel to and that the foliation, \( s_{la} \), approximately defines the \( \varepsilon_1, \varepsilon_2 \) plane of deformation.

Since in the field, \( s_{la} \) often appears to be approximately parallel to the bedding, \( b_0 \), the bedding poles approximately define the orientations of the poles to \( s_{la} \). Thus, the poles to \( b_0 \) approximately define the orientation of \( \varepsilon_3 \).

If it be assumed, therefore, that \( I_{la} \ \cdot \varepsilon_1 = 0^\circ \), and that the poles to \( b_0 \) are parallel to \( \varepsilon_3 \) the orientations of the principal strains may be deduced in a very approximate manner. In general terms, has a low plunge to the east-south-east, \( \varepsilon_2 \) is near horizontal and trends south-south-west - north-north-east and \( \varepsilon_3 \) plunges steeply to the west-north-west.

The deduced \( \varepsilon_1, \varepsilon_3 \) plane lies very approximately in the profiles if the \( f_I \) folds and, in consequence \( \varepsilon_2 \) is nearly parallel to the \( f_I \) axes. In the field the author found no evidence of strain parallel to the fold axes; this may indicate that/
that strain was planar.

It is not possible to deduce the strain mechanism by which $l_{1a}$ and $s_{1a}$ developed.

$s_{1c}, f_{1}$:

The chlorite and white mica crystals ($s_1$) which define the foliation, $s_{1c}$, indicate that Set I generation took place under conditions of greenschist facies metamorphism (quartz-albite-muscovite-chlorite subfacies) at temperatures in the vicinity of 300°C. (see Turner and Verhoogen (1960) pp 524-537).

(iii) Set I generation: Tentative conclusions.

Although strain inhomogeneity is shown by the presence of folds, and throughout the Pipe Rock by the variation of calculated strains, the relatively constant orientation of the grainelongation lineation, $l_{1a}$ indicates that, overall, strain may have approached homogeneity.

It has not been possible to determine the mechanism of deformation. But it may be noted that during folding, the principal stresses do not remain constantly oriented (see Bell and Currie (1964)). The existence of the $f_1$ folds would therefore indicate that rotational strain occurred during Set I generation. Since the folds are of restricted development it may not follow that rotational strain was operative when the Pipe Rock was deformed.

Conclusions regarding the orientations of the forces operative during Set I generation must be tentative. The facts that the $f_1$ axes trend north-south and that the $f_1$ folds are apparently buckle-folds, would suggest that folding/
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folding was induced by compressive forces acting, generally, within an east-west striking near-vertical plane.

(2) The generation of Sets $U_a$ to $V$.

It is not intended to consider the mechanics of development of these structures but it may be noted that the generators of Sets $U_a$ to $V$ may have modified the Set $O$ structures. That is, the calculated strain and shear parameters given in Table VI, may not be the result of Set I generation alone; all "movement phases" post-dating the Set $O$ structures may have contributed to their deformation. In particular, the thrust movements may have modified the Set $O$ structures.

It has not been possible to assess the effects of the emplacement of the Moine Nappe. There is no positive evidence that Moine Thrusting ($t_{IV}$) has induced deformation within the Glencoul Nappe or that strains within the Pipe Rock increase upwards towards the Moine Thrust.

(e) The Glencoul Nappe: General conclusions.

The present study of the Cambro-Ordovician of part of the Glencoul Nappe has been primarily concerned with strain analysis within the deformed Pipe Rock.

Pipe Rock deformation is considered to have occurred during Set I generations. On the whole, the rarity of folds and the constancy of orientations of the lineation, $l_{Ia}$, suggest that strain approached homogeneity. It has not been possible to determine the mechanism of deformation but the existence of the Set I folds ($f_{I}$) may indicate that strain was rotational. The $f_{I}$ folds appear/
appear to be flexural-slip folds; thus active bedding slip may have been a component of deformation.

Since the present analysis is confined to a small area it is difficult to make comparisons with Christie's (1963) structural analysis of the dislocation zone of Assynt. Of the three groups of folds described by Christie (op. cit.) pp 382-389, only those with north-south trending axes could possibly be equivalent to the folds \( f_I \) described by the present author. The correlation is not, however, a good one since the folds described by Christie (op. cit.) are all major folds whereas the \( f_I \) folds are not.

4. Structural analysis of the Moine Nappe

(a) Introduction.

In this section a detailed structural analysis of the rocks of the Moine Nappe, between the Fionn Allt and Lochain Faith an Leothaid is presented. The Moine Nappe is separated from the underlying Ben More and Glencoul Nappes by the Moine Thrust-plane.

In the extreme south of the area the base of the Moine Nappe consists of Torridonian sediments overlain by Basal Cambrian Quartzite. The Basal Quartzite is, in turn, overlain by Pipe Rock which extends north-west to the southwest side of Loch an Eircill. Basal Quartzite reappears, lying above the Pipe Rock in a small wedge 300 yards from the south-east end of Loch an Eircill. Pipe Rock again forms the base of the Nappe at the Stack of Glencoul.

The maps published by the Geological Survey - c.f. the "One-inch" map of the Assynt District (1923) show "Mylonised Rocks" (\( \mu \)-rock) at the base of the Moine/
Moine Nappe, between the Stack of Glencoul and Lochain Feith an Leothaid. Clough – in Peach et al. (1967) – refers to the "μ-rock" of Lochain Feith an Leothaid as "sheared Lewisian gneiss" (op. cit. p. 500) and to the "μ-rock" at the base of the Stack as "greatly-sheared rock – apparently Lewisian gneiss" (op. cit. p. 502) and as "sheared gneiss" (op. cit. p. 505). These statements indicate that Clough mapped both the mylonites and the Lewisian Gneiss of the Moine Nappe as "μ-rock" and that he considered the gneiss to be the parent rock of the mylonite.

In addition to the "μ-rock" at the base of the Nappe, Clough mapped a band of "μ-rock" within the Moines. It runs in a Z shaped outcrop from north of Glen Coul to within about 200 yards of the east side of Loch nan Coarach.

Re-examination of the "μ-rock" within the area has shown not only, as Clough stated, that Lewisian Gneiss forms the base of the Moine Nappe on Lochain Feith an Leothaid, but that the upper "μ-rock" is also Lewisian Gneiss.

As far as the author is aware, Clough has never discussed either the lithology or the structural relationships of the upper "μ-rock". Peach (in a diagram on Clough's "six-inch" field map) and Christie (1963) considered the lower and upper "μ-rock" in the vicinity of the Stack of Glencoul to be the same band. Peach thought that the "μ-rock" had been repeated by folding; Christie considered it to have been repeated by movement on the Ben More Thrust post-dating emplacement of the Moine Nappe.

At the Stack of Glencoul the "μ-rock" at the base of the Moine Nappe is overlain by chloritic schists which Clough – in Peach et al. (op. cit.) p. 505 – described/
- described as "Stack-schist". The "Stack-schist" is apparently overlain by the upper, Lewisian "μ-rock" and it, in turn, is overlain by Moinian psammites. The "Stack-schists" do not appear to have been derived from Lewisian Gneiss.

(b) Petrography.

The dominant rock types in the Moine Nappe include mylonites, schists, psammites, gneiss and quartzite. The petrography of all these rocks, with the exception of the gneiss, has been described in detail by Christie (1956) pp 54-68; 175-180; and 182-184: (1960) pp 87-89: and (1968) pp 397-400.

The mylonites are fine grained and well laminated. They consist of quartz and felspar with chlorite, white mica, biotite, epidote and lesser amounts of sphene, ores and calcite. The mineral assemblages are characteristic of the greenschist facies of metamorphism.

The Moine schists contain the same mineral assemblages as the mylonites but they lack the distinct lamination of the mylonites and are coarser grained. In places the schists consist almost entirely of chlorite.

The psammites are metamorphosed siliceous sediments. They consist predominantly of quartz with lesser muscovite, biotite, epidote, sphene, garnet, and ore minerals.

The Lewisian Gneiss at the base of the Moine Nappe in the extreme north of the area is only slightly modified by the deformation and metamorphism which affected the Moines. In the basic bands, hornblende, partially retrograded to chlorite, is the dominant mineral; in the quartzo-felspathic layers chlorite is the/
the dominant felsic. The original Lewisian foliation is distinct and quartz rods may be recognised. Plate IIIf is a photomicrograph of Lewisian Gneiss from Lochain Feith an Leothaid.

The Lewisian Gneiss of the upper "μ-rock" (Plates IIIg and h) has been significantly modified by Moinian metamorphism and deformation. No hornblende was found within this gneiss; chlorite is the dominant felsic. The foliation of the gneiss is locally mylonitic and is concordant with the Moinian layering above and below. The rock is, nevertheless, recognisable Lewisian Gneiss, particularly in hand specimen where the often pegmatitic nature of the original gneiss is evident. In places, quartz rods have been preserved.

(o) Structural sets.

Fig. 26 is a structural map of the area. The following structural sets have been recognised:

Set 0 = (b₀, e₀,₂, g₀, p₀, f₀, z₀)
Set I = (t₁, x₁, z₁)
Set II = (aⅡa,b, lⅡa,b, fⅡ, dⅡ, gⅡ, zⅡ)
Set III = (aⅢa,b, fⅢ, lⅢa,b, gⅢ, kⅢ, wⅢ, zⅢ)
Set IV = (fIVA,b, kIV, gIV, zIV)
Set V = (tV, zV)
Set VI = (fVI, zVI)
Set VII = (hVII, zVII)

(a)/
(d) Descriptions of structural sets.

Set 0:

\[ b_0 : \]

Bedding may be readily distinguished in the Cambrian and Torridonian
The dominant layering of the Moine Psammites is bedding.

\[ s_{01} : \]

\[ s_{01} \] is the foliation of the Lewisian of Lochain Feith an Leothaid and
of the upper "μ-rock".

In the extreme north of the area the Lewisian has been only slightly
modified by post-Lewisian deformation and the foliation is clearly defined by
quartzofelspathic and hornblendic bands. There appears to be a gradual transition
southwards from Lewisian Gneiss to mylonite. In the extreme north, mylonitic
foliation (fine colour banding - \[ s_{02} \] below) is only locally developed within the
Lewisian; southward the mylonitic banding comes to supercede the gneissose
foliation.

\[ s_{02} : \]

\[ s_{02} \] is the well defined colour layering (as distinct from mineral
lamination) of the mylonites. The laminae are variously coloured (typically
cream, black and shades of green) and of variable thickness (up to about twelve
distinct layers may occur in a thickness of one inch). The variable colours
reflect the differing mineralogies of the laminae; cream coloured layers are
quartzose, black layers are rich in ore minerals and the green layers are
chloritic.
chloritic.

The mylonitic layering is tentatively considered to be \( b \) and \( s \), so modified by Set II generators that the parent rock is generally unrecognisable.

It is probable however that mylonitised quartzites which occur in thin bands in the north of the area, in Glen Coul, and above the upper Lewisian "\( \mu \)rock" at the extreme southerly end of its outcrop, are derived from Cambrian quartzite. Mylonitised Pipe Rock forms the base of the Moine Nappe at the Stack of Glencoul.

On Lochain Feith an Leothaid the mylonites have been derived from Lewisian Gneiss. South of this locality, the parent rock of the mylonite is unknown, though on An Snicmh, thin pegmatite bands within the mylonites suggest derivation from gneiss.

Set I:

The Set I structures are evidently major structures which have been so modified by subsequent deformation and metamorphism that their true characteristics are difficult to recognise.

Set I:

The contact between the Moines and the Cambro-Ordovician above the Moine Thrust at the Stack of Glencoul and south east of Loch an Eircill is considered to be a thrust contact.

Where Pipe Rock is in contact with the Moines it is evident that part of the Cambro-Ordovician succession, as found in the thrust slices, is absent. In addition/
addition, the Moines are discordant to the underlying Cambro-Ordovician; in
the Pionn Allt the Moines rest on Basal Quartzite but a few hundred yards to
the north-west they rest on Pipe Rock; and between Loch an Eircill and Loch
nan Coarach the Moines truncate a felsite dyke in the Pipe Rock and overstep
from Pipe Rock on to Basal Quartzite.

x
The nature of the Lewisian-Moine contacts is unknown; the Lewisian of
the upper "\$\mu\$-rock" could be either a thrust slice or an isoclinical fold core;
the contact on Lochan Feith an Leothaid is not clearly defined - the Moines
may be separated by a thrust-plane or an unconformity from the Lewisian. (If
the bands of quartzite in this locality are Cambro-Ordovician then the contact
of Moines and Lewisian is not an unconformity because, in places, the quartzite
can be seen to overlie the gneiss).  

Between Loch an Eircill and Loch nan Coarach the Basal Quartzite rests
on Pipe Rock. Thus, the Cambro-Ordovician sequence has been inverted; the
inversion is apparently due to Set I generators. The nature of the contact
between the Basal Quartzite and the Pipe Rock is unknown so that inversion may
have been the result of either thrusting or folding.

Set II:

Set II generation is equivalent to the "primary deformation" described by
Christie (1963). The primary structures were produced by two distinct, but
related, types of movement.

The first set of movements had monoclinic symmetry and, during these
movements the primary mylonites were formed. ("Primary" mylonites are laminated
mylonites, augen schists and blastomylonites - see Christie (1960). They are
broadly/
broadly equivalent to the "μ-rock" of the Geological Survey). The primary folds (B-folds) plunge consistently to the east-south-east and they have a strong penetrative lineation parallel to their axes. The B-folds are flexural-slip folds; they are often intra folial isoclines and they were formed during mylonitisation by the mechanism of "glide-folding" - Kienow (1953). Approximately 75% of the B-folds are overturned towards the south-south-west. During the formation of the primary mylonites the Moine Nappe was emplaced by movement within the mylonites normal to B; that is the Nappe was transported towards the south-south-west.

The second set of primary movements had orthorhombic symmetry. Flattening took place in a vertical east-south-east - west-north-west striking plane of deformation; the maximum principal strain was parallel to B; the minimum principal strain (normal to B) plunged steeply to the west-north-west. During flattening, the orthorhombic quartz microfabrics were induced and the B folds were appressed.

\( S_{IIa} : \)

\( S_{IIa} \) is the dominant schistosity of the area; it is defined by the planar alignment of disc -, blade -, and ribbon - shaped grains (\( s_0 \) and \( s_{II} \)).

\( S_{IIa} \) is generally parallel to the Set 0 planar structures. It was only observed to be oblique to \( s_{02} \) (mylonitic colour banding) in the hinges of the \( f_{II} \) folds. \( S_{IIa} \) is only rarely oblique to \( b_0 \) and \( s_0 \), where these are unfolded.

Where \( S_{IIa} \) and \( f_{II} \) are developed in association, \( S_{IIa} \) generally lies in the fold axial planes.

\( S_{IIIb} : \)

\( S_{IIIb} \) is cleavage developed in the Pipe Rock south-east of Loch nan Coarach.
It lies in the axial plane of the large scale fold \( f^{I} \) or \( f^{II} \)? shown in Plate IVa. It is apparently parallel to the foliation of the overlying Moines. It is tentatively included in Set II.

The orientations of \( b_0 \), \( s_0 \), and \( s^{II} \) are shown collectively in Fig. 33a. They dip generally eastwards at low angles.

\( l^{IIa} \):

\( l^{IIa} \) is the dominant lineation of the area. It is a penetrative lineation defined by the preferred orientation of blade- and ribbon-like grains \( g_0 \) and \( g^{II} \) and grain clusters.

\( l^{IIa} \) lies in \( s^{II} \) (the dominant foliation). It plunges generally at a low angle to the east-south-east (Fig 33b); it is not consistently parallel to the axes of the \( f^{II} \) folds.

\( l^{IIb} \):

\( l^{IIb} \) is defined by the intersection of \( b_0 \) and \( s_0 \) with \( s^{II} \). It occurs only in the hinges of the \( f^{II} \) folds and is parallel to the fold axes.

\( f^{II} \):

The \( f^{II} \) folds are minor folds. Fold profiles are very variable in form (Fig. 34). Analysis by methods given by Ramsay (1962)a shows that the \( f^{II} \) folds are dominantly of modified concentric type but that occasionally they approach true similar form (Fig. 35).

The orientations of the fold axes and axial planes are shown in Fig. 33. The axes are variable in orientation but plunge generally eastwards at low angles; the axial planes are generally parallel to \( b_0 \), \( s_0 \) and \( s^{II} \).

The relationships between \( f^{II} \) and \( l^{IIa} \) are complex. (As noted, \( l^{IIb} \) is parallel to the axes).

Inspection/
Figure 33.

Moine Nappe, Glen Coul. Structural data:

a. 213 poles to the layering (including b₀, s₀ and s₁₁) of the nappe rocks. Contours 20%, 10%, 5%, 1%, 0.47% per 1% area.

b. 356 plots of the lineation, t₁₁a. Contours 20%, 10%, 5%, 1%, 0.28% per 1% area.

c. 123 axes of f₁₁ folds.

d. 88 poles to the axial planes of the f₁₁ folds.
Figure 34

Moine Nappe, Glen Coul.

Profiles of $f_{II}$ folds.

Scale lines: Solid - 2.5 cm. Dashed - 30 cm.
Figure 35.
Quantitative analysis of the profiles of three \( f_{II} \) folds, Moine Nappe, Glen Coul. The scale lines are 5 cm.

- \( t \) - Thickness normal to layering
- \( d \) - Distance along layering
- \( T \) - Thickness parallel to axial plane trace
- \( D \) - Distance normal to axial plane
- \( A_P \) - Trace of axial plane

Measurements indicate that "a" is near similar and that "b" and "c" are modified concentric folds. (See Ramsay 1962a).
Inspection of the orientations of $l_{\text{IIa}}$ and the $f_{\text{II}}$ axes (see Figs. 33b and c) shows that the lineation is much less variable in plunge direction and that, although the lineation and fold axes are often parallel, they are not consistently so; the lineation may be inclined at up to $90^\circ$ to the fold axes.

Where the $l_{\text{IIa}}$ lineation is at an angle to the fold axes it is folded. In the fold hinges, $l_{\text{IIa}}$ may have been obliterated by the development of $l_{\text{IIb}}$.

$d_{\text{II}}$:

No new petrofabric work was undertaken. Christie (1963) found that the quartz fabric throughout the area is characteristically of orthorhombic symmetry. A symmetry axis of the fabric is parallel to the dominant lineation, $l_{\text{IIa}}$.

$g_{\text{II}}$:

The most common minerals to crystallise during Set II generation were quartz, chlorite, biotite, muscovite and garnet with accessory white micas (sericite?) sphene, epidote and ore minerals.

The grade of metamorphism appears to grade upwards into the Moine Nappe. At the base of the Nappe, chlorite is the dominant felsic mineral and only partial recrystallisation of the matrix of the parent rocks has occurred. In the Moine Psammites, biotite is the dominant felsic and no Set 0 structures besides bedding, $b_0$, are recognisable.

For the most part, the $g_{\text{II}}$ crystals are blade-or disc-shaped; they are aligned in the foliation, $s_{\text{IIa}}$.

Set III:

Set III generation is equivalent to the "Secondary deformation" described by Christie (1963). Christie (op. cit.) in general, considered the lower and upper "μ-rock"/
"μ-rock" to be primary mylonite and considered the secondary mylonites to occupy the intermediate zone. The secondary structures are found only within the secondary mylonites. The secondary folds (Bn-folds) are flexural-slip folds with axial planes dipping invariably to the east. A faint lineation is, sometimes developed normal to the axes of the Bn-folds. The primary lineation, B, is folded about the Bn-axes. In places within the secondary mylonites a new s-surface (S') is developed at a high angle to the s-surface (S) of the primary mylonites.

The present author's field mapping has shown (see map - Fig 26) that, although the Set III structures are sporadically developed over the area, they are certainly not restricted in the manner described by Christie (op. cit.):

\[ S_{IIIa} \]
\[ S_{IIIa} \] is crenulation foliation (strain-slip cleavage) - see Plate VIb. It is commonly developed; it has a general north-south strike and it dips steeply to the east. (Fig. 36a). \[ S_{IIIa} \] lies in the axial planes of the f_{III} folds.

\[ S_{IIIb} \]
\[ S_{IIIb} \] is foliation defined by the alignment of \( \sigma_{III} \) chlorite and quartz crystals. \[ S_{IIIb} \] is developed both in the axial planes of the f_{III} folds and approximately parallel to the Set 0 and Set II layering. Both habits of \[ S_{IIIb} \] are illustrated in Plate VIA.

The chlorite crystals which define \[ S_{IIIb} \] often lie in pod- or lens-shaped clusters (Plate VIb). Where well developed, \[ S_{IIIb} \] obliterates all pre-existing structures and the rock resulting from crystallisation of the \( \sigma_{III} \) chlorite is a dark-green or black schist. This schist is apparently what Peach et al. (1907) described as "frilled schist" (p.478) and as "oyster-shell rock" (p. 598) and which Clough/
Clough (in Peach et al. op. cit) described as "Stack schist" (p. 502). (For further discussion of "Stack schist" see Christie (op. cit.) pp 364-365).

\( f_{III} \):

The \( f_{III} \) folds are all minor folds. They have monoclinic symmetry with the single plane of symmetry normal to the fold axes. The folds are almost invariably overturned to the west; the axes are near horizontal and trend generally north-south; the axial planes dip generally to the east (see Figs 36c and 37). As noted, \( s_{IIIa} \); and sometimes \( s_{IIIb} \); lie in the axial planes.

The fold profiles are variable in form (see Fig 37). Analysis by the methods given by Ramsay (1962) has shown that the \( f_{III} \) folds are largely of modified concentric type. (Fig 38)

\( l_{IIIa} \):

\( l_{IIIa} \) is the most commonly developed Set III structure. It is defined both by the intersection of \( s_{III} \) with, and by wrinkles and crenulations on, the Set 0 and Set II planar structures.

In general, \( l_{IIIa} \) has a near-horizontal north-south trend (Fig 36d); it is parallel to the \( f_{III} \) fold axes.

\( l_{IIIb} \):

Christie (op. cit.) p. 364, stated that:

"Lineations are not common in the phyllonites ("Stack schist") but in some there is a faint streaking on the \( s \)-surfaces, resembling slickensides. This lineation is approximately normal to the axes of \( Bn \)-folds; that is, it is an \( a \)-lineation", and p. 361, "A faint \( a \)-lineation (slickensides) is ... present ... in some of the phyllonitised rocks near the (Moine) thrust; (it) plunges at low angles to the east and the east-southeast".

This/
Figure 36

Moine Nappe, Glen Coul. Structural data: Set III structures.

a. 31 poles to the foliation, $s_{\text{III}}$.
b. 106 axes of the $f_{\text{III}}$ folds.
c. 89 poles to the axial planes of the $f_{\text{III}}$ folds.
d. 80 plots of the lineation, $l_{\text{III}}$. 
Figure 37

Meine Nappe, Glen Coul.

Profiles of $f_{III}$ folds.

Scale lines: Solid - 2.5 cm.  Dashed - 30 cm.
Figure 38

Quantitative analysis of three f. III folds, Moine Nappe, Glen Coul.

- **t** - Thickness normal to layering.
- **d** - Distance along layering.
- **T** - Thickness parallel to axial plane trace.
- **D** - Distance normal to axial plane trace.
- **A.P.** - Trace of axial plane in fold profile.

"a" and "c" are evidently modified concentric folds; "b" is a near ideal concentric fold. (See Ramsay, 1962, a).
This faint lineation in the "Stack schists" is, in the author's symbolism, \( I_{IIIb} \):

\( g_{III} \):
The dominant minerals to crystallise during Set III generation were chlorite, white mica and quartz (Plate VI). The Set III crystals are aligned in, and define, the foliation \( s_{IIIb} \):

\( k_{III} \):
Kink bands are very rare. Their forms are shown in Fig. 39. The kink bands are developed in association with the crenulation foliation, \( s_{IIIa} \):

\( W_{III} \):
Christie (op. cit.) considered secondary deformation (equivalent to Set III generation) to have resulted from displacement of the Moine Nappe on the Ben More Thrust. The problem of whether or not movement did take place on the Ben More Thrust after the Moine Nappe had been emplaced, will be discussed below when the origins of the Set III structures are considered (pp143-148). It is only intended to note at this point that the present author can find no evidence of such a displacement.

Set IV:

The Set IV structures, which include monoclines, conjugate folds and kink bands, are apparently equivalent to the structures (east-plunging folds and kink zones) ascribed to Deformation Phase Ic by Christie (op. cit.) p. 411. Christie (1965) noted that he found no interference relationships between the Phase Ic and the Phase II (secondary) structures. He showed, however, that the Ic structures post-dated the primary mylonites. Christie (op. cit.) assigned the east/
Figure 39

Set III kink structures, $k_{\text{III}}$. Scale lines are 2.5 cm.
Figure 40

Moine Nappe, Glen Coul.

\( f_{II} \) folds post-dated by Set III structures. Scale lines are 2.5 cm.

a, b, c, f, g - \( f_{II} \) isoclines refolded by \( f_{III} \) folds

d, e - \( s_{III} \) oblique to \( f_{II} \) folds.
east-plunging folds and kink zones to the end of primary deformation because the Ic fold axes approach parallelism with the axes of the B-folds.

The Set IV structures described below have been classified into distinct types. The structures are, however, intergradational; monoclines with oppositely dipping axial planes can occasionally be seen to converge to form conjugate folds and monoclines and conjugate folds often exhibit kinking in their axial planes.

f<sub>IVa</sub>: Monoclines are the most common type of Set IV fold. The monoclines are best developed in the psammites. The scales on which the monoclines are developed are variable; the fold amplitudes are generally less than about 3 feet but one monocline was observed with an amplitude in excess of 30 feet (see Fig 43).

The monoclinal fold axes are variable in orientation though easterly plunging axes are predominant (Fig 41a). The axial planes are very variable in orientation (Fig 41b); for the most part, they dip either to the south-east or to the north west.

f<sub>IVb</sub>: f<sub>IVb</sub> are conjugate folds. They are mostly developed on a small scale (Fig 43). The fold axes plunge, at low angles, in various directions; the axial planes show no apparent preferred orientation (Figs 42a and b).

k<sub>IV</sub>: The Set IV kinks are very common. They are best developed in the finely layered mylonites and schists but are not entirely absent in the psammites. As noted, kinking often occurs in the axial planes of the monoclines and conjugate folds (Fig 43). The kink-bands are generally less than one inch thick but they may locally exceed six inches in thickness (Fig 43).
Moine Nappe, Glen Coul. Structural data:—Orientations of Set IV structures.

a. 75 axes of monoclines, $f_{IVa}$

b. 64 poles to axial planes of monoclines, $f_{IVa}$

c. 56 poles to kink planes, $k_{IV}$
Figure 4.2

Moine Nappe, Glen Coul. Structural data.

a. 19 axes of conjugate folds, $f_{IVb}$.

b. 29 poles to the axial planes of the conjugate folds, $f_{IVb}$.

c. Orientations of the principal stresses (14 plots of each) existing during the formation of the $f_{IVb}$ folds (see Ramsay, 1962, b.)
Figure 43.

Monte Nappe, Glen Coul.

Set IV structures: monoclinal, conjugate folds and kink bands. Scale lines:
- Solid - 2.5 cm.
- Dashed - 30 cm.
- Dot-dash (in W) 1 m.
Figure 44

Maine Nappe, Glen Coal. Diagrams illustrating the superimposition of Set IV structures on Set II and Set III structures. The scale lines are 2.5 cm.

a. c. d. f. g. $f_{II}$ folds modified.
b. $s_{III}$ foliation cut by kink-band, $k_{IV}$.
c. $f_{III}$ fold and $s_{III}$ foliation apparently post-dated by conjugate fold, $f_{IVb}$. 
As a general rule, the kink folds are angular. In the terminology of Dewey (1965) p. 460 the $k_{IV}$ structures are, almost entirely, reverse kink-bands.

The kink-planes (bounding surfaces of the kink-bands) are very variable in orientation (Fig. 41c). For the most part the planes dip either to the south-west or to the north-east.

$\xi_{IV}$:
Quartz veins are commonly present in kink bands and in fold axial planes.

Set V:
$t_{V}$:
Emplacement of the Moine Nappe took place along the Moine Thrust-plane ($t_{V}$). The Thrust-plane is mostly parallel to the layering of the Nappe rocks and it dips generally to the east at about 20\°.

The nature of the Moine Thrust-plane has already been discussed (pp 90-92). It was concluded that the Thrust-plane is, throughout the area, a distinct fracture surface which separates the structural unit of the Moine Nappe from the underlying Ben More and Glencoul Nappes.

Since the Moine Thrust is never exposed definite relationships with other structures cannot be established. Thrusting is however, tentatively considered to post-date the Set IV structures. At national grid reference NC 297276 the layering (apparently $b_{0}$) of the Nappe rocks is locally vertical as a result of $f_{IV}$ folding. The underlying Thrust-plane is here apparently oblique to and thus apparently later than, the Set IV folds.

Set VI
$f_{VI}$:
The Moine Thrust-plane is not exactly planar (see Peach et. al. 1907 p. 505).
This suggests that either the Moine Nappe was emplaced on a curved surface or the thrust-plane was weakly folded after the Nappe had been emplaced.

Set VII

The Moine thrust-plane has been faulted at Lochain Feith an Leothaid, in Glen Coul, and to the east of Loch nan Coarach (See Fig 26).

Interference relationships among some of the described structures are illustrated in Figs. 40 and 44.

(e) Set generation.

In this section the described structural elements are analysed with a view to determining their modes of formation. Evidence as to the nature of the set generators may be obtained by examining both the structural elements of a set and the effects of set generation on the structures of existing sets.

(1) Set I generation.

As noted, the Set I structures include major (?) thrusts and, perhaps, major folds. It was also noted that the Set I structures have been significantly modified by later deformation and metamorphism; hence, it is not possible to deduce the "movement picture" or mechanism of formation of the Set I structures.

(2) Set II generation.

(i) The deformation of the Set I elements by the Set II generators.

Analysis of the effects of the Set II generators on the Set I elements is complicated by the fact that the contribution of the Set I generators to deformation is unknown. Thus, strains and shears attributed to Set II, may have been partly the result of Set I deformation.

(a) Deformation of the Pipe Rock.

1. Pipe Rock at the Stack of Glencoul
1. Introduction.

Clough - in Peach et. al. (1907) p. 504 - considered the band of mylonitised Pipe Rock at the base of the Stack of Glencoul to be part of Sub-zone IV. Sub-zone IV of the Pipe Rock is characterised by the presence of very numerous "ordinary pipes" (op. cit. p. 373).

The deformed Pipe Rock is banded-black and various shades of green - and is typically mylonitic in appearance (Fig 45). The pipes lie "with perfect parallel alignment in the plane of the foliation" - Christie (1963) p. 400. They have elliptical sections and the dominant lineation, $l_{IIIa}$, is exactly parallel to their lengths. The pipes are themselves lineated. $l_{IIIa}$ is defined by the preferred orientation of the a semi-axes (a > b > c) of ribbon-like and blade shaped quartz grains (op. cit. Plate 9). The foliation, $S_{IIla}$, defined by the planar alignment of the a and b semi-axes of the quartz grains is parallel to the mylonitic colour banding ($S_{02}$).

As far as can be seen, the deformed pipes are straight; this indicates that they were strained by some mechanism of homogeneous strain.

ii. Pipe strain.

If it be assumed that the volumes of the pipes remained constant during deformation:

$$v_1 = v_2$$

(where $v_1$ and $v_2$ are the volumes of a pipe before and after strain)

If the unstrained pipes were elliptical in section then the volume of an unstrained pipe is

$$v_1 = a_1 b_1 P_1$$

(where $a_1$, and $b_1$ are the semi-axes of the pipe section before strain and $a_2$, and $b_2$ are the semi-axes after strain.)

but

$$v_2 = a_2 b_2 P_2$$

$$\therefore a, b, P,$$
Figure 45.

Sketch of mylonitised Pipe Rock from above the Moine Thrust-plane,

Stack of Glencoul.
\[ \therefore \pi a_i b_i P_i = \pi a_2 b_2 P_2 \]

\[ \therefore \frac{P_2}{P_i} = \frac{a_i b_i}{a_2 b_2} \]

and \[ \varepsilon_p = \frac{a_i b_i}{a_2 b_2} - 1 \] (1)

Forty pipe sections were measured on a specimen of unstrained foreland Eriboll Pipe Rock, kindly lent by Dr. K. Swett. The mean semi-axes of these "ordinary" pipes were

\[ a_i = 4.75 \text{ mm and } b_i = 3.71 \text{ mm.} \]

Twenty five pipe sections measured on a specimen of mylonitized Pipe Rock from the stack of Glencoul gave an average \( a_2 b_2 \) product of 1.66 mm2.

Substituting the mean values in (1):

\[ \varepsilon_p = \frac{4.75 \times 3.71}{1.66} - 1 \]

\[ = 9.62 \]

\( \varepsilon_a \) and \( \varepsilon_b \) may only be calculated if the pipes did not rotate during deformation lines because, with rotation during strain, those which are \( a_2 \) and \( b_2 \) after strain were not \( a_i \) and \( b_i \) before strain. If the assumption be made that no rotation took place, then \( P_2, a_2 \) and \( b_2 \) are parallel to the principal strains. Then, since there has been considerable extension parallel to the lengths of the pipes and since \( a_2 > b_2 \) the most likely relationships among \( P_2, a_2 \) and \( b_2 \) and \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) are:

\[ P_2 \cdot \varepsilon_1 = 0^\circ; \quad \varepsilon_p = \varepsilon_1 \]

\[ a_2 \cdot \varepsilon_2 = 0^\circ; \quad \varepsilon_a = \varepsilon_2 \]

\[ b_2 \cdot \varepsilon_3 = 0^\circ; \quad \varepsilon_b = \varepsilon_3 \]
To calculate $\varepsilon_a$ and $\varepsilon_b$, the undeformed pipes must be considered as having been perfectly cylindrical.

The volume of unit length of an undeformed cylindrical pipe is:

$$V_i = \pi r^2$$

(where $r$ is the radius of the pipe section)

The mean volume of unit length of an undeformed pipe of elliptical section is:

$$V_i = \pi \left( \frac{a_1}{n} \right) \left( \frac{b_1}{n} \right)$$

(where $n$ is the number of readings of $a_1$ and $b_1$)

If $V_i = V$:

$$r = \sqrt{\frac{a_1}{n} \left( \frac{b_1}{n} \right)}$$

If the $a_1$ and $b_1$ readings from the Eriboll Pipe Rock be used to calculate $r$:

$$r = \sqrt{4.75 \times 3.71}$$

$$r = 4.2 \text{ mm}$$

In the mylonitised Pipe Rock:

$$\frac{a_2}{n} = 3.06 \text{ mm}$$

and

$$\frac{b_2}{n} = 0.56 \text{ mm}$$

The strains parallel to $a_2$ and $b_2$ are

$$\varepsilon_a = \frac{a_2}{r} - 1 \quad \text{and} \quad \varepsilon_b = \frac{b_2}{r} - 1$$

Substituting for $r$, $a_2$ and $b_2$:

$$\varepsilon_a = -0.27 \quad \text{and} \quad \varepsilon_b = -0.87$$

and
\[ \varepsilon_1 = \varepsilon_p = 9.62 \]
\[ \varepsilon_2 = \varepsilon_a = -0.27 \]
\[ \varepsilon_3 = \varepsilon_b = -0.87 \]

The ratios of the semi-axes of the strain ellipsoid are:

\[ X:Y:Z = 14.55: 1: 0.32 \]

If the pipes rotated during straining they may have been oblique to all of the principal planes or they may have rotated within a principal plane. In the latter case, the strain of the pipe dimension normal to the plane is equal to a principal strain (The pipe dimension does not rotate). Therefore, one of \( \varepsilon_p \), \( \varepsilon_a \) and \( \varepsilon_b \) may, in fact, be equal to the principal strain with which it was equated.

Throughout strain analysis, the assumption has been made that the pipes have rotated in the \( \varepsilon_1, \varepsilon_3 \) plane (that is, \( P \) and \( b \) lie in this plane) while \( a \) has been assumed to be parallel to \( \varepsilon_2 \). If this assumption is valid in the case of the pipes under consideration, then \( \varepsilon_a = \varepsilon_2 = -0.27 \), and, since in planar shear, \( \varepsilon_2 = 0.0 \) this result indicates that strain may have been approximately planar.

iii Conclusions.

Study of the mylonitized Pipe Rock at the base of the Stack of Glencoul has shown (a) the pipes have suffered considerable positive (\( \varepsilon_p > 0.0 \)) strain. The fact that the pipes are straight indicates that strain was homogeneous.

The lineation, \( l_{IIa} \), is parallel to the lengths of the pipes (that is, \( l_{IIa} \)
\[ P_2 = 0^\circ \). Thus, at least in this locality, \( l_{IIa} \) defines a direction of significant positive strain.

(b) As noted, the foliation \( s_{IIa} \) is parallel to the mylonitic colour banding.
so2. The P2 pipe dimensions lie within these planes. Thus, significant strain has occurred within so2 and sIIa.

The pipes are ribbon-like in form and b2 is normal to so2 and sIIa. It is most probable that there has been considerable negative strain normal to so2 and sIIa.

The mylonitic colour layering was considered (p110) to be Set 0 bedding and foliation greatly attenuated during mylonitisation. Thus, the colour banding was considered to be a Set 0 structure and it was designated "so2".

In the mylonitised Pipe Rock, the parallelism of P2 and so2 would appear to preclude the possibility of the colour banding (so2) being attenuated bedding (b0); since P1 \cdot B1 = 90°, infinite strain would appear to be necessary for parallelism (P2 \cdot B2 = 0°) to result.

However, infinite strain is only necessary if the pipes and their bedding matrix are physically identical. Where strength differences exist between pipes and matrix an unknown element of inhomogeneity is introduced into the strain and the pipes and bedding may suffer pure rotation in addition to the rotation induced by homogeneous strain. In consequence, and particularly where strains are of large magnitude, parallelism of pipes and bedding may result.

(c) Mylonitisation does not obliterate all pre-existing structures.

Since the pipes have retained their identity it follows that other pre-mylonitic structures may have survived.

and (d) This study of the mylonitised Pipe Rock is of some significance in considering the nature of the mylonites as a whole. However, discussion of the mylonites has been deferred (pp138-142) so that the evidence from study of the Set II/
II elements may also be considered.

2. Pipe Rock between Loch an Eircill and Loch nan Coarach.

The pipe rock at the base of the Moine Nappe between Loch an Eircill and the Fionn Allt is only locally mylonitic. Bedding (b_o) is distinct throughout and, in consequence, the methods of strain analysis described in Section II may be applied.

The data calculated for two stations (XIV and XV, Fig. 30) are given in Table V.

Assuming, as always, deformation by planar, homogeneous strain, the values of ε_1 are 8.23 (position XIV) and 3.40 (position XV). In both localities X has a low plunge to the east, while Z plunges steeply to the west.

In both positions, the pipes have suffered significant elongation (at XIV, \( \lambda_p = 11.09 \); at XV, \( \lambda_p = 14.90 \)). Since \( P_2 \cdot l_{IIa} = 0^\circ \) the calculations indicate that \( l_{IIa} \) defines a direction of considerable positive strain. In the mylonitised Pipe Rock at the base of the Stack of Glencoul \( \lambda_p = 112.78 (= \lambda_1?) \) This indicates that the strains within the mylonites are greatly in excess of those developed within the non-mylonitic tectonites.

At position XIV, \( \omega = P_2 \cdot B_2 = 2^\circ \) is very small. Where \( \omega \) is of such magnitude slight errors in its measurement result in significant errors in calculated strain and shear parameters. Thus, the data calculated for position XIV must be considered to be only approximations of actual parameters.

(ii) Genetic consideration of the Set II elements.

\( s_{IIa}, l_{IIa}, d_{II} \);

In combination, the elements \( s_{IIa}, l_{IIa} \) and \( d_{II} \) give the Set II fabric an approximate/
approximate homotactic orthorhombic symmetry.

Turner and Weiss (1963) pp 4.54-4.55 state that "Symmetry argument supports correlation of homotactic orthorhombic fabrics with geometrically concordant orthorhombic systems of pure strain and of stress .... \( \sigma_1 \) is much more likely to be normal than parallel to \( S \) (foliation) so that \( S \) could also be defined as the AB plane (XY plane in this study) of the strain ellipsoid".

In addition they note that, within the plane of the foliation, either \( \sigma_2 \) or \( \sigma_3 \) must be parallel to the lineation. \( \sigma_1 \) is always normal to the lineation.

Study of the deformed Pipe Rock within the Moine Nappe has shown that \( l_{IIa} \) \( (p_2 \cdot l_{IIa} = 0^\circ) \) defines a direction of significant positive strain. The author would infer that, throughout the Nappe in this area, there has been positive strain in \( l_{IIa} \). Further to this, the constancy of orientation of \( l_{IIa} \) (see Fig. 33b) indicates that strain approached homogeneity.

Since there has apparently been considerable strain parallel to \( l_{IIa} \) it may be concluded, if the symmetry argument holds, that \( \sigma_3 \cdot l_{IIa} = 0^\circ \). \( \sigma_2 \) then lay in \( s_{IIa} \) and was normal to \( l_{IIa} \).

The deduced orientations of the Set II principal stresses and strains are, from symmetry argument, approximately as follows:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Plunge</th>
<th>(In pure strain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_1 ) and ( \sigma_3 )</td>
<td>100(^\circ)</td>
<td>15-20(^\circ) E.S.E.</td>
</tr>
<tr>
<td>( \varepsilon_2 ) and ( \sigma_2 )</td>
<td>10(^\circ)</td>
<td>0(^\circ)</td>
</tr>
<tr>
<td>( \varepsilon_3 ) and ( \sigma_1 )</td>
<td>280(^\circ)</td>
<td>70-75(^\circ) W.N.W.</td>
</tr>
</tbody>
</table>

In the particular case of the mylonitised Pipe Rock at the base of the Stack/
Stack of Glencoul, the symmetry of the quartz fabric "is perfectly orthorhombic" (Christie (1963) p. 401; and Fig 23 = D_2 and D_3). Symmetry argument suggests the following relationships:

\[
P_0 \{ E_1, \sigma_3 \} = 0^\circ
\]

\[
P_0 \{ E_2, \sigma_2 \} \rightleftharpoons \{ E_1, \sigma_2 \} \rightleftharpoons \{ E_2, \sigma_3 \} = 0^\circ
\]

\[
P_0 \{ E_3, \sigma_1 \} = 90^\circ
\]

\[
P_0 \{ E_3, \sigma_1 \} \rightleftharpoons \{ E_2, \sigma_2 \} \rightleftharpoons \{ E_1, \sigma_3 \} = 90^\circ
\]

Flinn (1965) p. 39 has classified tectonites as L-tectonites ("linear rocks") S-tectonites ("schistose non-lineated rocks") and L-S tectonites ("schistose lineated rocks"). These tectonites are "referred to collectively as the L-S fabric system".

Study of the L-S fabric system led Flinn (op. cit.) to conclude that: "it is reasonable to assume that rocks containing the L-S system of fabrics have been deformed by homogeneous deformation" (p. 40) and that: "L-tectonites are to be associated with prolate deformation ellipsoids, S-tectonites with oblate deformation ellipsoids and L-S tectonites with appropriately shaped orthorhombic ellipsoids all oriented so that the longest axes of the ellipsoids lie parallel to the lineation in the fabric and the longest and intermediate axes to the schistosity" (p. 41).

In Flinn's (op. cit.) terminology the Set II fabric is that of an L-S tectonite/
teotonite. The evidence from Flinn's (op. cit.) analysis suggests the following relationships:

Where \( X > Y > Z \) (\( \varepsilon_1 \wedge X = 0^\circ \), \( \varepsilon_2 \wedge Y = 0^\circ \), \( \varepsilon_3 \wedge Z = 0^\circ \))

\[
XY \wedge s_{IIa} = 0^\circ; \quad X \wedge l_{IIa} = 0^\circ \quad \text{and} \quad Z \wedge s_{IIa} = 90^\circ.
\]

In conclusion, study of the Set II foliation and lineation (\( s_{IIa} \) and \( l_{IIa} \)) and the quartz microfabric (\( d_{II} \)) suggests that the Set II fabric is the result of homogeneous strain (perhaps pure strain) such that \( \varepsilon_3 \) is normal to the foliation \( \varepsilon_1 \), and \( \varepsilon_2 \) lie in the foliation, and \( \varepsilon_3 \) is parallel to the lineation.

\( \varepsilon_{II} \) (and \( \varepsilon_{00} \)):

Christie (1963) pp 397 - 399 described the quartzites of the Moine Nappe as being of two types -I and II.

According to Christie (loc. cit.) the textures of the Type I quartzites are the result of mylonitisation. The grains are ribbon-like in form and they have a strong dimensional orientation (Defining \( l_{IIa} \)).

The mylonitised Pipe Rock at the base of the Stack of Glencoul is of Type I. "The ratio of the (relict) grain dimensions is of the order of 1: 10: 100, the shortest axis being normal to the foliation and the longest parallel to the lineation" (loc. cit. p. 397; and see Plate 9).

It may be that the grain dimensions reflect, the dimensions of the strain ellipsoid. On this very tenuous basis:

\( X: Y: Z = 10.0: 1: 0.1 \)

If the unstrained grains approached sphericity then:

\( \varepsilon_1 = 9.0; \quad \varepsilon_2 = 0.0; \quad \text{and} \quad \varepsilon_3 = -0.9 \)

Since/
Since the deformed grains are elongate in the lineation \((l_{IIa})\) and flat in the foliation \((s_{IIa})\) it may be that:

\[
\begin{align*}
\varepsilon_1 \cdot l_{IIa} &= 0^\circ; & \varepsilon_2 \cdot l_{IIa} &= 90^\circ; & \varepsilon_3 \cdot s_{IIa} &= 90^\circ.
\end{align*}
\]

In addition, since in planar strain \(\varepsilon_2 = 0.0\), the values of the principal strains given above may indicate that strain was approximately planar.

In the Type II quartzites, "the mylonitic textures are obliterated by recrystallisation; the rocks consist of an equigranular (granoblastic) aggregate of quartz grains which, though small, show no trace of ruptural strain. The dimensional orientation in these rocks is weak compared with that in the Type I quartzites ..... but the grains are slightly flattened in the foliation and elongate parallel to the lineation \((l_{IIa})\)" (loc. cit. p. 397)

Despite the textural differences existing between the Type I and II quartzites Christie (op. cit.) p. 402, showed that "there can be no doubt that the quartz orientation \((d_{II})\) in the quartzites, the primary mylonitic rocks and the Moine schists was induced during the same phase of deformation".

The deformation during which the quartz fabrics were induced was thought by Christie (op. cit.) to have been flattening (pure shear) in a plane of deformation striking east-south-east with the maximum principal strain parallel to B and with the minimum principal strain plunging steeply to the west-north-west. In terms of the symbolism used in this study these relationships are

\[
\begin{align*}
\varepsilon_1 \cdot l_{IIa} &= 0^\circ; & \varepsilon_2 \cdot l_{IIa} &= 90^\circ; & \varepsilon_3 \cdot s_{IIa} &= 90^\circ.
\end{align*}
\]

The flattening was thought to have occurred as the final orthorhombic imprint of the monoclinic movements which produced the B folds.

The/
The textures of the Moinian psammites are similar to those described by Christie (op. cit.) in the Type II quartzites; that is, complete recrystallisation has taken place and the quartz grains show only weak dimensional orientation.

The author considers that the textural differences between the mylonites and psammites and Type II quartzites are largely due to variation in strain. The tectonites are all of the L-S type (Flinn, 1965). In the mylonites where the quartz grains are ribbon-like, X is much greater than Y; both are much greater than Z. In the psammites it would appear that the strain ellipsoid, though orthorhombic, approaches an oblate form; that is, X is slightly greater than Y which, in turn, is slightly greater than Z.

Christie (1963) considered the geometries and orientations of the B-folds (I in this study) to be of fundamental importance in deriving the movement-picture of the primary deformation.

Christie (op. cit.) regarded the B-folds as flexural-slip folds formed by "glide folding" (Kienow, 1953) at the same time as the primary mylonites. He considered the closely appressed nature of the B-folds to be due to the late flattening which induced the quartz fabrics (d). The primary mylonites represent a zone of distributed movement between two relatively stable blocks. Movements within this zone was normal to the axes of the B-folds. The B-folds plunge consistently to the east-south-east and have monoclinic symmetry such that approximately 75% of them are overturned towards the south-south-west. Thus, the Moine Nappe was transported, on the movement zone, towards the south-south-west. The B-folds which are overturned towards the north-north-west are the result of local inhomogeneities in the main movement pattern or of slight later movements/
movements towards the north-north-west.

Christie (Op. cit.) conclusions regarding the significance of the B-folds are open to serious objection because recent theoretical studies have shown that fold geometries need bear little relationship to the geometries of the stress and strain patterns under which the folds developed. Flinn (1962) has stated that: "Neither fold-axes nor axial planes need bear any special relation to the axes of the deformation ellipsoid. When they are observed to be parallel to one or more of these axes during or after deformation, it is because they were parallel to them before the deformation. Fold-axes and axial planes are therefore useless as indicators of movement directions or directions of flow in rocks. To use them is to assume that at the start of deformation the layering had a special orientation relative to the future pattern of flow, which is thereby fixed in direction quite arbitrarily".

Examination of the true significance of the \( f_{II} \) folds must take the following factors into consideration:

I. The fold axes are variable in orientation (see Fig. 33c) they are not consistently parallel to the lineation \( I_{IIa} \).

2. It has been shown in the study of mylonitised Pipe Rock that mylonitisation does not obliterate all pre-existing structures. Thus, some of the folds designated \( f_{II} \) may be modified \( f_{o} \) or \( f_{I} \) folds.

3. As noted, fold geometry need bear little relationship to strain geometry.

Strains calculated for the deformed Pipe Rock within the Moine Nappe show that \( I_{IIa} \) is, very probably, a direction of significant positive strain. The constancy of orientation of \( I_{IIa} \) indicated that strain approached homogeneity. As noted, symmetry argument suggests that Set \( II \) deformation was pure strain with \( I_{IIa} \).
$l_{II}a = 0^\circ, \varepsilon_2 l_{II}a = 90^\circ$ and $\varepsilon_3 l_{II}a = 90^\circ$. For simplicity, strain will be assumed to have been planar; that is, it will be assumed to have been pure shear. (That strain may in fact have been approximately planar is indicated by strain calculations in the mylonitised Pipe Rock at the Stack of Glencoul; here $\varepsilon_a = -0.27$)

It is intended to examine the $f_{II}$ folds in relation to pure shear deformation with $\lambda_1 l_{II}a = 0^\circ$ and $\lambda_3 l_{II}a = 90^\circ$. $\lambda_2$ is taken to be horizontal and to trend north-north-east - south-south-west.

In the first place it is necessary to establish some geometric relationships:

1. Strain and rotation of fold axes.

In Fig. 46a, $F_1$ and $F_2$ are a fold axis before and after strain; $P(x,y,z)$ becomes $P'(x',y',z')$.

\[ \alpha = F_1 \cdot \lambda_1 \quad \beta = F_1 \cdot \lambda_2 \quad \gamma = F_1 \cdot \lambda_3 \]

\[ \alpha' = F_2 \cdot \lambda_1 \quad \beta' = F_2 \cdot \lambda_2 \quad \gamma' = F_2 \cdot \lambda_3 \]

\[ \cos^2 \alpha = \frac{x^2}{F_1^2} \quad \text{and} \quad \cos^2 \alpha' = \frac{x'^2}{F_2^2} \]

\[ \therefore \frac{\cos^2 \alpha}{\cos^2 \alpha'} = \frac{x^2}{x'^2} \cdot \frac{F_2^2}{F_1^2} \]

\[ \therefore \cos^2 \alpha = \frac{\lambda_{F}}{\lambda_1} \cdot \cos^2 \alpha' \quad (1) \]

Similarly:

\[ \cos^2 \beta = \lambda_F \cos^2 \beta' \quad (2) \]

And \[ \cos^2 \gamma = \lambda_F \cdot \lambda_1 \cdot \cos^2 \gamma' \quad (3) \]

But:

\[ \cos^2 \gamma' \]
Figure 46.

For explanation see text.
\[ \cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1 \]

\[ \therefore \frac{\lambda}{\lambda_1} \cos^2 \alpha' + \frac{\lambda}{\lambda_1} \cos^2 \beta' + \lambda \lambda_1 \cos^2 \gamma' = 1 \]

\[ \therefore \frac{1}{\lambda} = \frac{\cos^2 \alpha'}{\lambda_1} + \cos^2 \beta' + \lambda_1 \cos^2 \gamma' \]  

(b) Change of orientation of a plane.

In Fig. 46b, ABC becomes A'B'C' with shear. The intercepts of ABC on \( \lambda_1 \lambda_2 \lambda_3 \) are \( x, y \) and \( z \) respectively. The intercepts of A'B'C' are \( x', y \) and \( z' \).

\[ \psi_1 = \lambda_1 \cdot AB \quad \phi_1 = \lambda_3 \cdot BC \]

\[ \psi_2 = \lambda_1 \cdot A'B \quad \phi_2 = \lambda_3 \cdot BC' \]

\[ \tan \psi_1 = \frac{y}{x} \quad \text{and} \quad \tan \psi_2 = \frac{y}{x'} \]

\[ \therefore x \tan \psi_1 = x' \tan \psi_2 \]

\[ \therefore \tan \psi_1 = \frac{x'}{x} \tan \psi_2 \]

\[ \therefore \tan \psi_1 = \sqrt{\frac{\lambda_1}{\lambda}} \tan \psi_2 \]  

Similarly:

\[ \tan \phi_1 = \sqrt{\lambda_3} \tan \phi_2 \]

(c) Change of vertical distance between planes

The geometric change of length normal to a plane may be measured in terms of the ratio of the length of the plane's pole before and after shear: In Fig 46b:

\[ OM \perp ABC \quad \text{ON} \perp A'BC' \]

\[ \omega = M \cdot \lambda_3 \quad \theta = N \cdot \lambda_3 \]

\[ \cos \omega = \frac{OM}{Z} \quad \cos \theta = \frac{ON}{z'} \]

\[ \therefore / \]
\[
\frac{ON}{OM} = \frac{\cos \theta z'}{\cos \omega z}
\]

where
\[
\frac{ON}{OM} = Q
\]

\[Q = \sqrt{3} \frac{\cos \theta}{\cos \omega} \quad (7)
\]

(d) Change in the fold profile

Let a fold before strain be considered to be contained within an orthorhombic or cubic block of sides \(a, b, c\) such that \(a > b > c\). Let \(F_1\) be parallel to \(a\); thus the fold profile lies in \(b\ c\). With shear the block \(a\ b\ c\) becomes a parallelepiped of equal volume such that \(a' \cdot b' \cdot c' = 90^\circ\). \(F_2\) is parallel to \(a'\) (Fig. A3).

Knowing the profile of \(F_2\) the procedure for finding the profile of \(F_1\) is as follows:

1. Calculate the orientation of \(F_1\).
2. Draw in \(b\ c\) \((F_1 \cdot b\ c = 90^\circ)\).
3. Choose orientations of \(a\ b\) and \(a\ c\) such that \(a \cdot b \cdot c = 90^\circ\).
4. Calculate the orientations of \(a'\ b', a'\ c'\) and \(b'\ c'\). Find \(b'\ c'\) and the geometric shortenings perpendicular to \(a'\ b'\) and \(a'\ c'\).
5. Project the \(F_2\) profile on to \(b'\ c'\); project the fold form on \(b'\ c'\) on to \(b\ c\).

The axial plane of \(F_1\) may be found since it contains \(F_1\) and its own trace on \(b\ c\). The use of the formulae set out above is illustrated in Appendix IV.

(d) Further considerations.

1. Section \(b\) (Change of orientation of a plane) may be applied to the axial planes of folds with planar limbs. The section may not be applied to the axial/
axial planes of folds with rounded closures since that plane which is the axial plane of the fold before strain, does not remain the axial plane with strain.

2. Deformed ideal concentric folds with their axes parallel to principal strain axes have certain notable characteristics:

i. Fold axes parallel to \( \lambda_2 \)

Axial plane traces in the \( \lambda_1 \lambda_3 \) plane are parallel to \( \lambda_1 \) and normal to \( \sigma_1 \) (If \( \sigma_1 \) has acted parallel to the axial plane trace, the trace is parallel to \( \lambda_3 \)). Folded units are thickened in the fold hinges and methods given by Ramsay (1962) may be used to calculate strain. More simply where the unmodified folds were ideally concentric:

\[
\lambda_1 = \frac{d''}{d'} \quad \text{and} \quad \lambda_3 = \frac{d'}{d''} \quad (\text{see Fig 47a})
\]

ii. Fold axes parallel to \( \lambda_1 \)

Where the undeformed folds were ideally concentric

\[
\lambda_1 = \left(\frac{e}{d'}\right)^2 \quad \text{and} \quad \lambda_3 = \left(\frac{d'}{e}\right)^2 \quad (\text{see Fig 47b})
\]

iii. Where the axes of deformed concentric folds are oblique to the principal strains Ramsay's (op. cit.) computation may not be applied.

The above relationships provide a method by which the changes taking place in a fold undergoing pure shear deformation may be fully described (see Appendix IV). The more general case of fold modification by pure strain deformation has been described by Flinn (1962). Flinn's conclusions (see, in particular pp 424-425) apply in the case of pure shear with the slight modification that \( \lambda_2 = 1.0 \).

In general terms it may be concluded that (see Flinn, op. cit):

1. All folds/
Figure 47.

Concentric folds deformed by pure shear.

In "a" the fold axis is parallel to
In "b" the axis is parallel to
1. All fold axes which do not lie in the $\lambda_2\lambda_3$ plane are rotated towards $\lambda_1$. Axes which are parallel to $\lambda_1$ were parallel to $\lambda_1$ before strain.

2. All planes, except the $\lambda_2\lambda_3$ plane, rotate towards the $\lambda_1\lambda_2$ plane.

3. Folds may, depending on the attitudes of their limbs, be either opened or closed during strain.

The folds described as $f_{II}$ could be of two types:

1) As noted, some of the $f_{II}$ folds may be deformed Set 0 and Set I folds. Such folds would be in existence before the onset of Set II pure shear and would suffer strain as passive elements.

2) Since no folds may form under conditions of homogeneous strain, $f_{II}$ folds could only have developed from local inhomogeneities in the overall strain pattern. If the Set II pure shear deformation took place over a considerable period of time it is to be expected that $f_{II}$ folds would form at different times. It is also to be expected that the $f_{II}$ folds would form in different orientations; the orientation of the initially developing fold would, perhaps, be controlled to some extent by the anisotropy of the rock. Besides the planar anisotropy inherited from Sets 0 and I the pure shear deformation would have induced planar ($s_{IIa}$) and linear ($l_{IIa}$) anisotropy. It may be, though for this there is no evidence, that developing $f_{II}$ folds would tend to form with their axes approximately parallel to $l_{IIa}$. When the $f_{II}$ folds formed they would be subjected to strain and they would be rotated and deformed. Thus their present orientations are not their original orientations. Christie's (1963) kinematic analysis/
analysis depends on the assumption that the axial orientations of the B-folds \( f_{II} \) are original orientations; that is, he has assumed that the folds have formed in their present positions relative to the lineation, \( l_{IIa} \). If the fold axes have been rotated away from their initial orientations kinematic analysis is invalid, since the present fold attitudes bear no relationship to the "movement pictures" which produced the folds.

In conclusion, as regards the kinematic analysis of the Set II structures, the author would "relegate" the \( f_{II} \) folds to a position of minor importance. He would consider the most important Set II structures (kinematically speaking) to be the foliation, \( s_{IIa} \), and the lineation, \( l_{IIa} \). The \( f_{II} \) folds are thought to have resulted from the development of local inhomogeneities in the overall homogeneous strain system. Kinematic interpretations of the Set II structures are best based on a study of \( s_{IIa} \) and \( l_{IIa} \); the \( f_{II} \) fold geometry has been inherited from original fold forms through the effects of strain and cannot be used as a basis for kinematic analysis.

(iii) The origin of the mylonites

The mylonites of the Moine Thrust Zone have been considered (Johnson (1960) p. 166; (1961) pp. 419-422 and pp 430 - 431; Christie (1960) p. 90; (1963) p. 382; and Barber (1965) pp. 221-222 and p. 232) to have formed in "movement zones" or "movement horizons" or "conform belts" (see Knopf and Ingerson (1938) pp. 33-35).

Shear belts are thought to form between differentially moving resistant blocks. Deformation within shear belts "occurs by differential movement along a large number of closely spaced planes passing through the rock". (Barber (op. cit. p. 222) Slip is "diffused through a considerable thickness of rock. This movement/
movement has produced true mylonites which in section are found to contain slip planes spaced about 0.2 mm. apart ...." (Johnson (op. cit.) p. 419).

According to Turner and Verhoogen (1960) p. 606: "Affine deformation by movement on one set of parallel slip planes ... (sometimes termed simple shear) may be illustrated by equal relative displacement (in a constant direction of slip) of all adjacent cards in a deck" and p. 631; "Mylonites ...... have evolved under the influence of penetrative movement upon one set of parallel or sub-parallel surfaces". Despite the former statement, deformation by movement on slip planes is not simple shear (see pp 24-25). The two mechanisms are, however, analogous in that the "planes" of simple shear (see Jaeger (1964) pp 32-33) and the planes of slip in the "card-deck" model, both represent one of the circular sections of the strain ellipsoid (see Turner and Verhoogen (op. cit.) p. 607); that is, there is no strain within these planes.

In the Moine Thrust Zone, Johnson (op. cit.) Barber (op. cit.) and Wilkinson (1965) considered mylonite formation to be the earliest "structural event" and to predate the formation of the east-south-east plunging lineation and minor folds. In the recent literature only Christie (1963) has considered the mylonites and the east-south-east plunging folds and lineation to have developed synchronously. Christie (op. cit.) considered that the development of "glide-fold" schistosity (Kienow, 1953) during folding about B had played an important role in the production of the mylonitic colour banding.

Johnson (1967) has reconsidered the problem of the origin of mylonites and has concluded (p. 246) that: "mylonitic banding follows a pre-existing compositional layering (foliation in gneisses or bedding in sediments)"; that is, mylonitic colour/
colour layering is attenuated bedding and foliation.

This conclusion is at odds with the general principle stated by Barber (op. cit.) p. 222 that: "All structures observed in rocks which have been mylonitised must be later than the phase of mylonitisation, the pre-existing structures having been obliterated". It has been shown, however, that the pipes in the mylonitised Pipe Rock at the base of the Stack of Glencoul, have retained their identities. Thus, this principle does not hold; compositional layering (foliation and bedding) may, in common with pipes, survive mylonitisation.

Johnson (op. cit.) considered mylonitic foliation ($S_{IIa}$ of this study) to be analagous to slaty cleavage. From the evidence of the shapes of the ellipsoidal porphyroclasts, the orthorhombic symmetry of the quartz fabrics in the mylonites of the Moine Thrust Zone (see Christie (op. cit.) and the forms of the pipes in the mylonitised Pipe Rock at the Stack of Glencoul, Johnson (op. cit.) concluded that mylonitic foliation ($S_{IIa}$) was a plane of flattening which formed normal to $\sigma_1$; that is, mylonites did not form by differential movement on slip planes ("simple shear") but, by pure shear such that the plane of the mylonitic foliation contains $\varepsilon_1$ and $\varepsilon_2$. In those mylonites which are strongly lineated (L-tectonites of Flinn, 1965) the strain ellipsoid is prolate and $\varepsilon_1$ is parallel to the lineation. The mylonites of S-tectonite type (Flinn (op. cit) are not obviously lineated; the strain ellipsoid is oblate - that is $\varepsilon_1=\varepsilon_2$.

The evidence from study of the mylonites of the Moine Nappe at Glencoul is complementary to Johnson’s (op. cit) analysis. It has been shown that:

1. In the mylonitised Pipe Rock, $E_P = 9.62$. Since the P and a pipe dimensions lie in the plane of the mylonitic foliation ($S_{IIa}$) and the plane of the/
the colour banding \( s_{o2} \neq b_0 \) there has been significant strain in these planes \( s_{IIa} \wedge s_{o2} = 0^\circ \). Thus, \( s_{IIa} \) and \( s_{o2} \) are neither planes of simple shear nor planes of differential slip.

In addition there appears to be a significant negative strain normal to the mylonitic foliation and colour banding. In simple shear and in "card-deck" planar slip there is no shortening normal to either the shear planes or the slip planes.

2. Symmetry argument suggests that the foliation \( s_{IIa} \) the lineation \( l_{IIa} \) and the quartz fabrics \( d_{II} \) developed synchronously during pure strain deformation such that \( \sigma_1 \wedge s_{IIa} = 90^\circ, \varepsilon_1 \wedge l_{IIa} = 0^\circ, \varepsilon_2 \wedge s_{IIa} = 0^\circ \) and \( \varepsilon_3 \wedge s_{IIa} = 90^\circ \). 

\( l_{IIa} \) lies in \( s_{IIa} \). Thus, the mylonites of the Glen Coul area are both schistose and lineated; that is, they are L-S tectonites (Flinn op. cit.) In the author's opinion the mylonites originated as L-S tectonites and were not formed (as suggested by Johnson, op. cit., p. 247) by constriction type deformation being imposed on a primary S-tectonite.

3. It is possible that the pure strain deformation indicated approached pure shear (flattening) in type. If the vertical west-north-west - east-south-east striking plane which contains the P and b pipe dimensions, is the \( \varepsilon_1 \varepsilon_3 \) plane of deformation, then \( \varepsilon_a = \varepsilon_2 \). The calculated value of \( \varepsilon_a \) (\( = -0.27; \) p 123) indicates that strain may have been approximately planar (In planar strain \( \varepsilon_2 = 0.0 \)).

It should be noted, in connection with pipe strain, that Johnson's (op. cit.) statement that "The pipes have been rotated nearly parallel with the bedding involving/
involving a rotation through $90^\circ$ (p. 247) is theoretically unsound because it means that the pipes have rotated from $\varepsilon_3$ to the $\varepsilon_1\varepsilon_2$ plane; this is impossible. It is probably more correct to say that both the pipes and the bedding have rotated towards the $\varepsilon_1\varepsilon_2$ plane and that the coincidence of pipes and bedding (if the colour banding is bedding) is due to strain inhomogeneity (see p 125).

Johnson (op. cit.) has noted that "the inferred picture of movement (involving pure compression and extension) for mylonites ...... fails to distinguish between rotational and non-rotational strains" (p. 247).

Identical states of strain may develop by markedly differing processes; rotational strains are simply pure strains plus pure rotations (see Turner and Weiss (1963) pp 270-271). Identification of the plane of mylonitic foliation as the $\varepsilon_1\varepsilon_2$ plane of deformation yields no information as to the strain mechanism; the fact that the colour laminae of mylonites are not "planes" of simple shear does not mean that the mylonites did not develop by simple shear - the "planes" of simple shear may have been oblique to the colour banding. The suggestion that mylonites have formed under conditions of irrotational strain depends on the validity of the symmetry argument.

In conclusion, the author, in agreement with Johnson (op. cit.) considers that the plane of the mylonitic foliation ($s_{IIa}$) may be equated with the XY ($X', Y', Z$) plane of the strain ellipsoid. The lineation, $l_{IIa}$, is thought to be parallel to $X$. The author tentatively considers deformation to have been by pure strain, which may have approached pure shear in type.

(iv) Tentative interpretation of Set II generation.

Symmetry/
Symmetry argument applied to the Set II elements $s_{IIA}$ (foliation), $l_{IIA}$ (lineation) and $d_{II}$ (quartz fabrics) indicates that they developed in response to pure strain. Homogeneity of strain is indicated by the constancy of orientation of $s_{IIA}$ and $l_{IIA}$ and by the fact that the deformed pipes are straight. That strain was not strictly homogeneous is shown by the existence of folds ($f_{II}$) and by the fact that the mylonite bands appear to be zones in which strain reached values in excess of those in the surrounding rocks.

The dominant lineation of the area ($l_{IIA}$) developed parallel to $E_1$ by the strain of Set 0 grains and crystals ($g_0$) and by the growth, under conditions of low grade metamorphism, of similarly aligned Set II crystals ($g_{II}$).

The dominant foliation ($s_{IIA}$) defined by the planar alignment of the $a$ and $b$ semi-axes (a, b, c) of the $g_0$ and $g_{II}$ grains and crystals, developed in the $E_1E_2$ plane of deformation. With deformation the Set 0 planar structures, $b_0$ and $s_0$ were rotated and strained and came to approach parallelism with $s_{IIA}$. With extreme strain, in the mylonite zones, $s_0$ and $b_0$ suffered extreme attenuation and completely lost their identity.

Existing Set 0 and Set I folds would, depending on their orientations to the principal strains be either tightened or opened and completely "smoothed out" (see Flinn, 1962). The axes of surviving folds would rotate towards $E_1$ and the axial planes would rotate towards the $E_1E_2$ plane (see pp136-137).

The Set II folds are considered to have developed at different times throughout Set II generation (see pp137 ) and to have formed by the development of local strain inhomogeneities in the generally homogeneous strain pattern.


Christie/
Christie (1963) considered secondary deformation (equivalent to Set III generation in this thesis) to have been due to movements, post-dating the emplacement of the Moine Nappe, on the Ben More Thrust and its associated reverse faults. His evidence is as follows:

1. Christie (op. cit.) regarded the lower and upper "μ -rocks" as equivalent (op. cit. p. 367; Fig. 9b. Thus, he considered that "the Moine thrust has suffered a reverse displacement of 500 to 1,000 feet above the Ben More thrust and the associated system of faults ....." (p. 365) so that the "μ -rock") was repeated by faulting.

2. Christie (op. cit.) considered that a genetic relationship existed between the Bn- folds and the Ben More Thrust: "The axes of the folds in the secondary mylonitic rocks at the Stack of Glencoul (Bn) ..... are parallel to the intersection of the (Ben More) thrust and the foliation in the primary mylonitic rocks ... This fact confirms the hypothesis that the later folding about approximately north-south axes was contemporaneous with movement on the Ben More thrust and that the folds were formed by kinking of the s-surfaces in the primary mylonitic rocks (s) along surfaces that are parallel to the thrust and its associated reverse faults". (op. cit. pp. 407-408)

and 3. Christie (op. cit. - inset of Fig. 4) considered the secondary structures to be developed in distinct "structural zones" (op. cit. p 365). The distribution of the zones of secondary structures within the Moine Nappe was thought to be related to the underlying Ben More Thrust and its associated faults (op. cit. p. 367; Fig 9b).

Christie's (op. cit.) argument that the Ben More Thrust displaces the Moine Thrust/
Thrust is based principally on the supposed equivalence of the lower and upper "μ-rock". In the author's opinion, the lower and upper "μ-rocks" are not equivalent; the upper "μ-rock" is a band of Lewisian within the Moines; it is quite distinct in appearance from the lower "μ-rock" which, in the immediate vicinity of Glen Coul, is platy mylonite of unknown "parentage".

The author's field-work has shown that the Set III structures (secondary structures of Christie op. cit.) are not restricted in their distribution in the manner described by Christie (op. cit.) The Set III structures are not confined to a zone immediately above the Ben More Thrust. Furthermore, it is unlikely that Set III structures in the extreme north of the area could have any genetic relationship to movement on the Ben More Thrust.

Within the Moine Nappe the author could find no evidence of any faults of the type shown by Christie (op. cit.) p. 367; Fig. 9b which could be in any way related to the Ben More Thrust. Indeed, Christie's field map (op. cit. Fig. 4) shows quite clearly that the Ben More Thrust and its associated reverse faults are truncated by the Moine Thrust. In the inset maps to Fig 4 (op. cit.) Christie shows a reverse fault above the Ben More Thrust cutting the Moine Thrust just to the east of the middle of Loch nan Coarach. Examination of the field relationships in this locality suggests that the juxtaposition of Moinian and Cambrian Quartzite of the Ben More Nappe is due to the presence of a normal, north-east-south-west striking fault (see map Fig 26). The fault downthrows to the north-west and cuts the Moine Thrust and rocks within the Ben More Nappe. The quartzite in question is separated, in the author's opinion, from the Moines to the east by the Moine Thrust-plane and not by the reverse fault shown by Christie (op. cit. Fig. 4).
In conclusion, the author regards Christie's (op. cit.) hypothesis that the Ben More Thrust has displaced the Moine Thrust, as untenable. In consequence he considers Christie's (op. cit.) kinematic analysis of the secondary structures (Set III structures) to be invalid. Christie (op. cit.) thought that the secondary structures formed in response to movements "transmitted" into the Moine Nappe by movement on the Ben More Thrust and its associated reverse faults. Since emplacement of the Moine Nappe post-dated movements on the Ben More Thrust such a mechanism could not have operated.

The author considers that analysis of Set III generation must be based entirely on examination of the forms of the Set III structures. Because of this, conclusions regarding their mechanisms of formation are tenuous. Since this is the case, the author will describe those features of the Set III structures which may be importance in kinematic analysis and will then tentatively suggest how the Set III structures may have developed.

\( f_{III} \)

The \( f_{III} \) folds are essentially flexural-slip folds (see p 116). That flexural slip folding was not the sole mechanism of their formation is shown, however by the presence of axial-plane foliation \( (s_{IIIb}) \) and by the thickening of folded layers in the fold hinges (see Fig 38).

As noted (p 116), the folds have monoclinic symmetry; the symmetry plane is normal to the lineation, \( l_{IIIa} \). The author could find no evidence of strain parallel to \( l_{IIIa} \).

\( s_{III} \)

The apparent parallelism of the \( f_{III} \) axial planes with both the foliation \( (s_{IIIb}) \)
(\(s_{\text{IIIb}}\)) and the crenulation foliation (\(s_{\text{IIIa}}\)) is perplexing. On the one hand, the shapes of the crystals defining the foliation, \(s_{\text{IIIb}}\), suggest that \(s_{\text{IIIb}}\) could be equated with the XY plane of the strain ellipsoid; on the other hand, fracturing within \(s_{\text{IIIa}}\) indicates that it formed at an angle to the principal strain planes.

\(l_{\text{IIIb}}\):

According to Christie (op. cit.) pp 384-385 "The movement during the secondary (Set III) phase of deformation was discontinuous .... The slicken-sides in the phyllonitic rocks ("Stack schist) indicate that the direction of movement was east-west, and the sense of movement given by the (Bn) folds .... is such that the overlying rocks moved to the west".

Christie's (op. cit.) interpretation of the significance of the faint, streaking lineation \(l_{\text{IIIb}}\) is accepted, but very tenuously, by the present author.

Tentative interpretation of Set III generation.

The \(f_{\text{III}}\) folds probably developed initially by the mechanism of simple flexural slip. The author considers the folds to be buckle folds perhaps induced by compressive forces acting generally east-west.

In places, with continued compression, folding by flexural slip ceased and further strain was essentially homogeneous. At this stage the axial plane foliation (\(s_{\text{IIIb}}\)) began to form; it may approximately define the \(\varepsilon_1\varepsilon_2\) plane of strain. The \(f_{\text{II}}\) fold axes may be approximately parallel to \(\varepsilon_2\) (But see Flinn 1962).

Under similar conditions of stress, fracturing occurred and cleavage (the initial stage of the crenulation foliation, \(s_{\text{IIIa}}\)) was formed at some angle to the \(\varepsilon_1\varepsilon_2\)
If the latter homogeneous (?) component of strain was irrotational, near parallelism of crenulation foliation \((s_{IIIa})\) and the \(f_{III}\) axial planes could be attained by rotation of \(s_{IIIa}\) towards the \(\varepsilon_{1}\varepsilon_{2}\) plane.

If the latter strain component was rotational, parallelism of \(s_{IIIa}\) and the \(\varepsilon_{1}\varepsilon_{2}\) plane may have occurred by continuation of straining after the cleavage had formed. The development of such parallelism is the result of the formation of the cleavage in the direction which, after strain, becomes the \(\varepsilon_{1}\varepsilon_{2}\) plane. The mechanism of this process, for the case of simple shear has been described on pp 75-78 with respect to the crenulation foliation developed at Kempie.

In conclusion, the author finds that it is not possible to make any definite assertions regarding the mechanisms of formation of the Set III structures. Set III generation has had no discernible effects on the Pipe Rock of the Moine Nappe. The absence of strain data is a serious handicap to kinematic analysis since determined strains may indicate the true natures of certain structures. Christie (1963) kinematic analysis is considered to be untenable; the author could find no evidence of displacement of the Moine Nappe by the Ben More Thrust and its associated reverse faults.

4. Set IV generation

Johnson (1956), Ramsay (1962)b and Dewey (1965) have discussed the possible orientations of the principal stresses during the formation of conjugate folds and kink bands. They concluded that the intersection of a pair of conjugate planar structures (axial planes and kink bands) defines the orientation of the intermediate principal stress, \(\sigma_2\); the maximum, \(\sigma_1\), and minimum, \(\sigma_3\), principal/
principal stresses bisect the angles between the conjugate planes.

If these relationships hold, then Fig 42c shows the orientations of the principal stresses operative when the conjugate folds \( f_{IV_b} \) developed. (It was assumed in analysis that \( \sigma_1 \) is always nearer to the horizontal than \( \sigma_3 \); that is, \( \sigma_1 \) approaches more closely to the rock layering than does \( \sigma_3 \)). Inspection of Fig. 42c shows that the calculated principal stresses have no discernible preferred orientation.

If it may be assumed that all of the Set IV structures (monoclines, conjugate folds and kink bands) developed under essentially similar conditions, that is, that they reflect the various responses of different rock types to comparable states of stress, then the principal stress directions computed from the conjugate folds may indicate that:

(a) The Set IV structures developed over a long period of time during which stress patterns continuously changed and

(b) If the stress pattern remained relatively constant during Set IV generation then

1. The stress pattern may have been complex and the principal stresses may have varied in orientation from place to place or

2. The geometries of the developed structures may bear no predictable relationship to the geometry of the stress pattern.

The author has already discussed (pp 81-84) the analysis of principal stress orientations from geological structures and, noting comments from the work of Serafim (1964), Donath (1964) and Jaeger (1964)\(a\) and b, concluded that such analysis was of doubtful value. It was noted that only where deformation has been by pure strain/
strain can the orientations of the principal stresses (they are parallel to the principal strains) be calculated.

With particular reference to stress analysis from planes of failure (such as kink planes and the axial planes of conjugate folds) it was noted that the Coulomb-Navier and Mohr theories of fracture (see Jaeger (1964) pp 75-83) very probably cannot be applied to layered rock. Thus the assumption that \( \sigma_2 \) lies in the planes of failure is probably invalid. If \( \sigma_2 \) does not lie in the planes of failure, stress analysis is invalid.

The author concludes that it is not possible to make any definite assertions regarding the modes of formation of the Set IV structures. The extreme variability of orientation of the Set IV structures and the absence of associated metamorphism would, however, suggest that they originated under a highly complex pattern of stress at a relatively low temperature. They may have developed at a high structural level (see Dewey (1965) p. 468).

5. The generations of Sets V, VI and VII.

It is not intended to analyse the generations of these sets in any detail.

In the author's opinion the Moine Nappe was emplaced by movement on a distinct plane of rupture, the Moine Thrust-plane \( (t_\gamma) \): movements were not distributed through a movement zone (c.f. Christie, 1963). The author has found no evidence of either the amount or direction of movement on the Moine Thrust-plane.

(f) The relationship of the present work with other recent work in the Moine Thrust Zone.

Owing largely to the work of Johnson (1955a, 1955b, 1957, 1960a and 1960b), Barber (1965) and Cheeney and Matthews (1965) the structural history of the Moine Thrust/
Thrust Zone south of Kinlochewe is now well known.

The structural history of the northern part of the Thrust Zone is less well known. Christie (1963) has presented a structural analysis of the Moine Thrust Zone of Assynt; and Wilkinson (1965) has outlined the sequence of "structural events" in the Moine Nappe east of Loch Eriboll.

Summaries of the structural histories given by various authors are shown, with the present writer's in Table VII.

The history given by the author shows close agreement with those given by Johnson (1961), Barber (op. cit.) and Wilkinson (op. cit.) but some divergence is discernible in the sequence of events leading to the formation of some of the earlier structures (Set II structures in this study).

The writer considers the mylonites, the dominant schistosity, the east-south-east plunging lineation, the often isoclinal folds and the orthorhombic quartz fabrics to have developed during a single phase of pure strain deformation which, perhaps, approximated pure shear in type.

Johnson (op. cit.), Barber (op. cit.) and Wilkinson (op. cit.) considered mylonite formation to predate isoclinal folding and lineation development and that these structures were post-dated by a period of recrystallisation during which the orthorhombic quartz fabrics developed.

The structural history given by Christie (1963) differs markedly from the other histories given in Table VII. Christie (op. cit.) considered the mylonites, the east-south-east plunging lineation and the isoclinal folds to be synchronous. The Moine Nappe was emplaced by movements within the mylonites normal to the fold axes and lineation, such that the Nappe was transported towards the/
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<tr>
<td>Slides, recumbent folds (e.g. Loch Aish fold) Precrystalline deformation Mylonites formed.</td>
<td>Mylonitisation - granulation along narrow localised bands.</td>
<td>Monoclinic movements: E.S.E. folds and mylonites formed Precrystalline deformation. Moine Nappe transported towards S.S.W.</td>
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<tr>
<td>E.S.E. folds Paracrystalline deformation</td>
<td>Isoclinal folding on E.S.E. axes</td>
<td>Orthorhombic movements (flattening). Paracrystalline deformation</td>
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<td>Orthonomal movements</td>
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<td>Paracrystalline deformation followed by static crystallisation.</td>
<td>Reorientation resulting in dominant foliation and lineation in the mylonites.</td>
<td>Orthorhombic movements.</td>
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<tr>
<td>N.N.E. - S.S.W. folds. Post-crystalline deformation</td>
<td>Asymmetric folding on N - S axes.</td>
<td>N - S asymmetric folds formed.</td>
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<td>Conjugate folds (mainly trending E - W)</td>
<td>Monoclinal folding on variable axes.</td>
<td>Thrusting</td>
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<th>Wilkinson (1965)</th>
<th>Present Thesis</th>
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<td>Blastomylonitic foliation developed.</td>
<td>Major structures (thrusts and folds?) developed.</td>
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<tr>
<td>Two double sets of conjugate folds.</td>
<td>Monoclines, conjugate folds and kink-bands developed.</td>
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<td>Thrusting</td>
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the south-south-west, not on a distinct plane of fracture but on a zone of dis-
tributed, penetrative movement which lay between two relatively stable blocks. 
According to Christie (op. cit.) the Moine Thrust is only a fault at isolated 
localities; elsewhere, the "Thrust" is merely a lithological boundary within the 
movement zone.

The monocline movements which produced the mylonites, the folds and the 
lineation were followed by a genetically related set of orthorhombic movements 
(flattening) during which the orthorhombic quartz microfabrics were established and 
the existing folds were appressed.

Christie (op. cit.) then, regarded the Moine Nappe as having been emplaced 
early in the history of the Thrust Zone. After the Nappe had been emplaced, 
it was affected by movements on the underlying Ben More Thrust and its related 
reverse faults. The movements led to the development, within the Moine Nappe, 
of north-south trending flexural-slip folds with easterly dipping axial planes, 
and of a new s-surface at an angle to the foliation of the earlier mylonites.

Some of Christie's (op. cit.) conclusions have been criticised by 
Johnson (1965). Christie (op. cit.) regarded the symmetry and vergence of the 
east-south-east plunging intrafolial folds as being of prime importance in kine-
matic analysis. Because 75% of the folds were overturned towards the south-south-
west Christie (op. cit.) concluded that movement within the mylonites and trans-
port of the Moine Nappe had been towards the south-south-west.

Johnson (op. cit.) questioned the premises on which Christie's (op. cit.) 
analysis was based and pointed out that:

1. Recent "studies of fold geometry have proved that fold axes may be 
   useless as indicators of movement" p. 673 (and see Flinn, 1962) and 
2./
Two lines of evidence presented in this thesis have a bearing on the problem -

1. The so-called east-south-east plunging folds (B-folds of Christie (op. cit) and \( f_{II} \) folds of this study) have variable axial orientations (see Fig. ). Therefore the directions of vergence are variable and cannot be used to give a coherent picture of movements within the mylonites.

and 2. The dominant lineation, \( l_{IIa} \), defines a direction of significant positive strain. The strain may have modified both the orientations and the forms of the \( f_{II} \) (B) folds so that the existing fold geometries bear little relationship to the geometries of the stress and strain patterns from which they originated.

These lead the author to conclude in agreement with Johnson (op. cit.) that Christie's (op. cit.) kinematic analysis is based on unsound principles.

Johnson (op. cit) has pointed out that one of the main difficulties in asserting "directions of movement" and "transport" is "the actual relevance of the E.S.E. (isoclinal) folds to the discussion of the thrust movements ...." (p. 675). The writer would suggest that kinematic analysis of those structures here described as Set II elements is best based on examination of the dominant foliation (\( s_{IIa} \)) and lineation (\( l_{IIa} \)) and that the folds (\( f_{II} \)) are, in this respect, of only minor importance (see pp131-138). The author would further suggest that none of the Set II structures bears any relationship to the movements responsible for the emplacement of the Moine Nappe. The Moine Thrust post-dates the formation of the mylonites and the Set II elements.

Johnson/
Johnson (op. cit.) criticised Christie's (op. cit.) statement that the Moine Thrust is not a fault but a lithological boundary within the movement zone of the primary mylonites and noted that "The mylonites were not formed at the level at which they are now seen; they have been carried forward by the moving (Moine) Thrust" (pp. 674-675).

In reply, Christie (1965) pointed out that, throughout the Moine Thrust Zone there is some "lack of consistency in identifying the structure called the Moine Thrust" (p. 678) and that differences of opinion on the position of the Moine Thrust plane are due to the differences in usage and terminology in different areas.

It should be pointed out that, in the Glen Coul area, the Moine Thrust-plane, as mapped by the officers of the Geological Survey (Their usage was adopted by Christie, 1963) is, in places, a lithological boundary. The Thrust-plane was mapped at the base of the Moines; at the Stack of Glencoul and south-east of Loch an Eircill the Moines are, however, underlain by Torridonian and Cambrian sediments which have shared the same tectonic history as the Moines. In these areas, the Moine Thrust separates "rocks of differing composition and similar fabrics". (Christie op. cit. p. 363).

The writer has redefined the position of the Moine Thrust-plane (see pp. 90-92 and Fig. 26) such that all the rocks above it, regardless of lithology, have shared a common structural history. As noted (p. 150), the author has found no evidence of either the amount or direction of displacement on the Moine Thrust-plane.

In Table VII it is proposed that the Set III structures (equivalent to the secondary/
secondary structures of Christie op. cit.) are equivalent to the north-south
trending asymmetrical folds described by Johnson (1961) and Barber (1965) in
the south of the mainland Moine Thrust Zone and by Wilkinson (1965) in the Eriboll
region. Christie's (op. cit.) kinematic analysis of the secondary structures (He
considered them to have formed in the Moine Nappe in response to movements on
the underlying Ben More Thrust) has been examined (pp144-146) and is, in the
author's opinion, untenable. If the suggested regional correlation is valid it
provides evidence that the secondary structures (Set III structures) are not
the purely local features which Christie (op. cit.) considered them to be and
that discussion of their origins cannot be framed in terms of only locally existing
conditions. Christie (1965) noted the possibility of the above correlation but
considered that "In view of the relatively large distance between the Assynt and
Loch carron areas, differences in the structures and the inferred histories may
be real" (p. 679).

It is probable that the Set IV structures (monoclines, conjugate folds, and
kink bands) are equivalent to the east-west trending folds and kink zones ascribed
by Christie (1963) to his Phase Ic (see Table VII ). Christie (1965) found no
interference of the secondary (Phase II) structures with the Phase Ic structures.

The present work has shown that the Set IV structures post-date the Set
III structures (see Fig 44 ). If the Set IV structures are equivalent to
Christie's (1963) Phase Ic structures, it follows that the Ic structures post-
date the Phase II (Set III) structures and that the east-west folds and kinks have
been misplaced in his structural history.

In conclusion, the structural history of the Moine Nappe at Glen Coul
shows/
shows striking similarities to the histories described by Johnson (1961) and Barber (1965) in the south of the Moine Thrust Zone and by Wilkinson in the area east of Loch Eriboll. Christie's (op. cit.) structural analysis differs, in many respects, from the author's analysis. In agreement with Johnson (1965) the author considers Christie's (op. cit.) hypothesis of early strike-slip transport on the Moine Thrust to be untenable; the Moine Thrust-plane is a fracture surface which developed at a late stage in the history of the Thrust Zone.

The possible correlation of the structural histories of the Eriboll, Glen Coul, and Lochcarron areas may indicate that the Moine Thrust Zone has, throughout its length, a common history differing only in detail from place to place.

(g) The Moine Nappe at Glen Coul:

General Conclusions.

In this study of part of the Moine Nappe the author has attempted to establish time relationships existing among the developed structures. On the whole, interference relationships among the structural sets are clear and it has been possible to arrange the structures in the order of their development.

Strain analysis of the deformed Pipe Rock within the Moine Nappe has been limited in scope by the lack of available data but has, nevertheless, thrown light on the problem of the origin of the mylonites, of the dominant east-south-east plunging lineation and of the dominant foliation. The lineation defines a direction of significant positive strain and the foliation and mylonitic colour banding are surfaces in which considerable strain has occurred. The mylonitic layering as suggested by Johnson (1967) is the result not of simple shear deformation but probably of pure strain (perhaps akin to pure shear) deformation such/
such that the mylonitic foliation and colour banding define the plane containing the maximum and intermediate principal strains.

The kinematic analysis of the origin of the mylonites was based on the assumption that the lineation and foliation are more reliable indicators of movement history than the associated folds. In contrast to the view that the folds ($f_{II}$) are, with respect to kinematic analysis, of relatively minor importance it should be noted that Christie (1963) based his analysis largely on interpretation of the fold geometries.

Kinematic analysis of all of the structures which post-date the dominant Set II foliation and lineation is severely hampered by the fact that analysis must be based solely on the geometries of the structures. The author considers that Christie's (op. cit.) contention that the Br.-folds and secondary mylonites (Set III structures) were formed in response to movement on the Ben More Thrust is in error. Analysis of the Set IV structures (monoclines, conjugate folds and kink bands) is greatly complicated by their extreme variability of orientation. No evidence was found of either the amount or direction of displacement on the Moine Thrust-plane.

Section V/
Section V

Area III: Durness

1. Introduction:

As noted (p 6), the Sangomore and An Fharaid Moines are two klippen of the Moine Nappe. In this section, structural analyses of these klippen are presented. Analysis has been made difficult, particularly in Sangomore, by the scarcity of inland outcrops.

Both klippen consist of Moinian metasediments and Lewisian Gneiss. In addition, Cambrian Quartzite occurs in the Sangomore klippe forming the base of the Moine Nappe. Although the Moine Thrust does not appear on An Fharaid, Peach et al. (1907) p. 487 considered the successions of the klippen to be identical.

In light of the present analyses the questions of the amount and direction of displacement on the Moine Thrust-plane are reconsidered. An attempt has been made to correlate the structural histories of the Sangomore and An Fharaid klippen with the history described by Wilkinson (1965) in the Moine Nappe east of Loch Friboll.
The position of the Moine Thrust-plane

East of Loch Eriboll, the Moine Nappe was considered by Peach et. al. (op. cit.) pp. 480 - 486 to consist of, in general upward succession from the Moine Thrust-plane: mylonised rock, frilled schists, marble, quartz-schist, Lewisian Gneiss and Moinian Psammites.

The Moine Thrust does not appear on An Fharaid but in Sango Bay, "the highest members of the Calcareous series (Durine Limestone) are overlain by shatter quartzite, striped fissile schist, frilled schist and deformed gneiss, which together form part of the series above the Moine thrust-plane ... these schists can be linked with the corresponding section at Fairaird Head (An Fharaid) ... and with the sequence overlying the Moine thrust-plane east of Loch Eireboll" (Peach et al. op. cit. pp. 478 - 480).

Wilkinson (1955) considered that only the "monotonous series of quartz-feldspathic/
felopathic granulities" lay within the Moine Nappe. The Moine Thrust, as mapped by Peach and Horne, was renamed the "Eriboll Thrust". Thus, according to Wilkinson (op. cit.) the succession from the mylonites to the Lewisian Gneiss lay within the Eriboll Nappe.

If, as suggested by Peach et. al. (loc. cit.) the successions of An Fharaid and Sangomore may be correlated with the succession east of Loch Eriboll, it follows, on Wilkinson's terminology that the thrust-plane exposed in Sango Bay is not the Moine Thrust but the Eriboll Thrust and that the Moine Thrust, separating Moinian Psammites and Lewisian Gneiss, runs from Faraid Head southwards to enter Balnakeil Bay east of A' Chleit.

Wilkinson (op. cit.) analysed the orientations of the lineations within the Eriboll and Moine Nappes and concluded that, since the mean directions were only slightly different, "the lineations of the Moine and Eriboll Nappes share the same metamorphic and tectonic history except the final phase of emplacement of the nappes (p. 574)." Later work reported by Wilkinson (1965) indicates that the structural histories of the Moine and Eriboll Nappes are identical.

On the eastern shore of An Fharaid, 300 yards south of Faraid Head, the junction of the Moine Psammites and the overlying Lewisian Gneiss is clearly exposed. There is no structural discordance between the psammites and the gneiss; the foliation of the gneiss is parallel to the bedding of the psammites and the dominant east-south-east plunging lineation is developed in both psammites and gneiss. The boundary between the gneiss and psammites is a lithological boundary within a series of metamorphic rocks. The boundary could be either an unconformity or a thrust-plane so modified by metamorphism and deformation that its original characteristics have been obliterated. If the boundary is a thrust/
thrust-plane then it is clearly not the Moine Thrust-plane but a much earlier structure.

In view of the facts that the Eriboll and Moine Nappes apparently comprise a single structural unit, and that the structural plane which separates the gneiss and psammites of An Pharaid evidently pre-dates emplacement of the Moines and Lewisian to their present position, the thrust-plane and nappe terminology of Peach et al. (op. cit.) is retained. That is, the Moines of Sangomore and An Pharaid lie within the Moine Nappe and the Moine Thrust-plane is exposed in Sango Bay but does not appear on An Pharaid.
3. The Sangomore Klippe

(a) Introduction

In the work of Peach and Horne a certain degree of confusion seems to exist as to the exact nature of the succession upwards from the Moine Thrust-plane. In Peach et al. (1907), the following sequences are given:

1. Shatterly quartzite, mylonised rocks, frilled schists and deformed gneiss (op. cit. p. 478).

2. Quartz schist, mylonised rocks, green schists and phyllites, marble and Lewisian gneiss (op. cit. Fig. 20; p. 479) and

3. Quartz schist, mylonised rocks, green schists and phyllites, marble quartz schist and Lewisian Gneiss (op. cit. Fig. 23 p. 487).

In Peach's and Horne's "six inch" field map the Lewisian Gneiss is shown as apparently overlying the green schists. The marble is shown as being included within the green schists. The succession from the map is then: quartz schist (deformed Basal Quartzite) green schist (including marble) and Lewisian Gneiss.

The present author found no marble or upper quartz schist within the area and, as far as could be determined, the Lewisian Gneiss is separated from the Moinian schists by a normal fault. No evidence was found to suggest that the Lewisian overlies the Moinian.

The succession adopted in this study is, upward from the Moine Thrust; Cambrian quartzite overlain by mylonites and schistose metasediments. The Lewisian Gneiss occupies a fault block and is separate from the Moines.

In general terms, the rocks of the Sangomore Moine Nappe lie in a narrow north/
north-east - south-west trending strip which is bounded to the north-west and south-east by major faults. The Nappe rocks are faulted against, in the south-east, Sailmhor and Sangomore Limestone and, in the north-west, Durine Limestone. To the south-west the maps of the Geological Survey show the Moinian schists as being separated from Durine Limestone by the Moine Thrust-plane. In this particular area, exposures are lacking and this relationship could not be verified.

Fig. 48 is a geological and structural map of the Durness area. In Sangomore, the map differs from the Survey maps in that no marble was mapped and the Lewisian Gneiss is shown as separated by a fault from the Moinian.

(b) Petrography.

The Lewisian Gneiss:

The Lewisian Gneiss in the south-east of Sangore Bay has suffered retrogressive metamorphism; the rock is, nevertheless, distinctly gneissose in character. The gneiss is predominantly acidic and it consists of quartz, felspar, biotite, muscovite, epidote, carbonate, zoisite, amphibole and accessory ore minerals.

The gabbro is clearly intrusive into the gneiss. It is heavily altered and consists of pale amphibole, chlorite, white mica, quartz, ore minerals and plagioclase. The original igneous texture of the gabbro is obvious and some of the plagioclase has been only slightly altered. Although the shapes of the igneous ferromagnesian minerals have been preserved no definite pyroxene or olivine was identified.

The Moinian rocks:

The Moinian consist largely of mylonites and schists. The mylonites are,
for the most part, very fine grained; they consist of quartz, epidote, carbonate and ore minerals; felspar and chlorite are common accessories. The mylonites are frequently so finely grained that appear nearly opaque in thin section (plate VIlc). The Moine schists ("oyster-shell" rock) consist of quartz, white mica, chlorite, ore minerals and felspar; carbonate and epidote occur as accessories. Sedimentary clastic grains may frequently be recognised within the schistose Moine.

The Cambrian Quartzite:

The quartzite at the base of the Moine Nappe is apparently Basal Quartzite (see above p. 162). It consists very largely of quartz but is, in places, strongly felspathic. White mica and ore minerals occur as accessories. The quartzite has been strongly deformed and texturally consists of bladed and ribbon-like quartz grains in a micro-crystalline quartz matrix. Peach et al. (op. cit.) p. 478, described the quartzite as "shattery". The quartzite is, in fact, finely and irregularly fractures so that, in places, it has a "splintery" appearance.

(c) Structural sets:

The following structural sets have been recognised:

Set 0 = (b_0, s_{01,2}, f_0, t_0, g_0, z_0)

Set I = (t_1, z_1)

Set II = (s_{II}, t_{II}, f_{II}, g_{II}, z_{II})

Set III = (s_{III}, f_{III}, g_{III}, z_{III})

Set IV = (t_{IV}, s_{IV}, f_{IV}, g_{IV}, z_{IV})

Set V = (h_{V}, z_{V})

(d)
(a) Description of structural sets

Set 0:

\[ \text{b}_0 \]

Bedding within the Moines is clearly recognisable in the exposures on the beach of Sango Bay and in the area between the School Road and Loch Caladail. About half-way between Durine School and Sangomore Church an example of truncated current bedding was found which indicates that the bedding in this locality is the right way up.

\[ \text{s}_{01}, f_{01}, l_{01} \]

The Lewisian Gneiss exposed in Sango Bay has been only partly modified by Moinian deformation and metamorphism. In the unmodified gneiss, folds and lineation of Lewisian age may be recognised.

\[ \text{s}_{02} \]

\[ \text{s}_{02} \] is the colour banding of the mylonites. The mylonites occur dominantly at the north-west end of Sango Bay where they overlie the quartzite at the base of the Moine Nappe and in places between the School Road and Loch Caladail.

The mylonites are very finely laminated and are typically dark green in colour. The various colours (green, black, pink and cream) of the laminae reflect their varying mineralogies. The darkly coloured laminae are rich in epidote and ore minerals; the lightly coloured laminae are rich in quartz, carbonate mineral and felspar.

The mylonitic colour layering is tentatively considered to be Set 0 foliation or bedding so attenuated by deformation that the characteristics of the parent rock cannot be recognised.

Set I:
Set I:

\( t^I \) :

The contact between the deformed Cambrian Quartzite at the base of the Moine Nappe and the overlying mylonites and schists could be either an inverted unconformity or a thrust-plane. The absence of conglomerate in the quartzite and the tenuous evidence, from the single current-bedding truncation (p. 165) that the Moinian metasediments are not inverted, would suggest that the contact is a thrust-plane.

Examination of the deformed Basal Quartzite and the overlying mylonite shows that they have a common tectonic history. Though the deformed quartzite cannot be described as a true mylonite (see Lapworth (1885) and Christie (1960)) its finely foliated nature suggests that it shared in the deformation which resulted in mylonite formation within the Moinian. The Cambrian and Moinian may have been mylonitised when they were in juxtaposition - in which case, their contact is a pre-mylonite thrust - or they may have been mylonitised and then juxtaposed - in which case, their contact may be a thrust developed synchronously with the Moine Thrust \( (t^{IV}) \). The lack of structural discordance across the Cambro-Moinian contact (their foliations are parallel and both contain the dominant east-south-east plunging lineation, \( l^{II} \)) suggests that the contact predates mylonitisation. Since mylonitisation occurred during Set II generation (see below pp. 173-177) the contact is apparently a Set I thrust.

Set II:

\( s^{II} \):

\( s^{II} / \)
s \_II \text{ is foliation defined by the planar alignment of the a and b semi-axes (a \cdot b \cdot c) of blade and disc shaped grains (e \_II and deformed e \_o). In general, s \_II is parallel to the Set 0 bedding and foliation but in the f \_II fold hinges s \_II cuts the Set 0 layering. s \_II lies in the axial planes of the f \_II folds (Plate VIII).}

\_II:\

\_II is the dominant lineation of the Sangomere klippe. It lies in the foliation, s \_II and is defined by the preferred orientation of the a semi-axes of elongate e \_o and e \_II grains. \_II plunges at a low angle generally to the east-south-east or west-north-west (Fig.49b). The anomalous north and north-east plunging orientations of \_II (Fig.49b) were measured in the severely faulted quartzite to the north-west of Sango Bay; these orientations have probably been derived from east-west trending lineation by rotation during Set VI faulting. The lineation, \_II is parallel to the axes of the f \_II folds.

f \_II:

The f \_II folds are all minor folds; they occur in two distinct habits:

(a) In the mylonites the f \_II folds are intrafolial isoclines which approach a truly "similar" form (Fig.50). In the mylonites at the north-west end of Sango Bay f \_II folds are very rare; they are of more common occurrence in the partially mylonitised metasediments south of the School Road.

(b) In the non-mylonitic metasediments the f \_II folds are only rarely isoclinal. The folds are generally tight, asymmetrical and disharmonic and they have the forms of modified concentric folds (Fig.50 and see Ramsay 1962).

Correlation of the different forms of the f \_II folds within the differing lithologies/
Figure 49.

Sangomere Klippe, Durness. Structural data.

a. 39 poles (●) to the layering (including $b_0$, $s_{02}$, $s_{II}$ and $s_{III}$) within the Moines, and 5 poles (○) to the foliation ($s_{01}$) of the Lewisian Gneiss.

b. 83 plots of the dominant lineation, $l_{II}$.

c. 26 axes of the folds, $f_{II}$.

d. 8 poles to the axial planes of the $f_{II}$ folds.
Figure 50.

Sangomore Klippe, Durness. Profiles of $f_{II}$ folds. Solid scale lines are 1 cm. Dashed lines are 10 cm.

Folds "e" and "g" were observed in the mylonites at the north-west end of Sango Bay. The other folds are in the metasediments.
Figure 51.
Sangomore Klippe, Durness. Quantitative analysis of $f_{ii}$ folds.
A.P. - Trace of the axial plane in the fold profile.  D - Distance normal to the axial plane trace.  T - Thickness of folded layers measured parallel to the axial plane trace.

Some layers (e.g. a.1. and b.1.) appear to belong to modified concentric folds. Most of the other layers show complex thickness variation but b.4. approaches similar form (see Ramsay, 1962, a.)
lithologies is possible because of the ubiquity of $s_{II}$ in their axial planes.

For the most part, the $f_{II}$ axes plunge at a low angle to the east-south-east or to the west (Fig. 49c). As noted, the axes are parallel to the lineation, $l_{II}$. The anomalous north-south trending axes were measured in the faulted quartzite at the base of the Moine Nappe. As with the anomalous orientations of the $l_{II}$ these axes were probably rotated from an original east-west trend during Set VI faulting.

The axial planes of the $f_{II}$ folds are consistently nearly parallel to the Set 0 layering. Thus, the axial planes have general low dips in variable directions (Fig. 49d).

$s_{II}$:

Only partial recrystallisation of the parent rocks took place during Set II metamorphism. The degree of recrystallisation is variable from place to place; in the mylonites and in the metasediments between the School Road and Loch Caradail recrystallisation was not extensive (Plates VII b & c); in the metasediments exposed in Sango Bay and in the quartzite at the base of the Moine Nappe recrystallisation was more extensive and appears to have affected about 50% of the rock. Complete recrystallisation was never observed.

The $s_{II}$ crystals are dominantly quartz. In the quartzite, mylonites and in the metasediments in the south of the area the quartz in the foliation, $s_{II}$, is very finely grained.

In the metasediments in Sango Bay $s_{II}$ is defined by both finely and coarsely grained quartz. The reason for the dominance of quartz as the mineral defining $s_{II}$ is apparently that later Set III metamorphism has almost completely reconstituted the/
the ferromagnesian and alkali minerals which probably accompanied Set II quartz crystallisation. Since the Set III chlorite and white mica crystals generally lie in $s_{II}$, it is often most difficult to determine the generation to which the chlorite and mica belong. It is often only in the $f_{II}$ fold cores that the later nature of the Set III crystals can be established by their obliquity to $s_{II}$ (see below pp170-171).

Set III

$s_{III}$:
$s_{III}$ is, in general, the dominant foliation of the Sangomere klippe. It is defined by aligned chlorite, white mica and disc-shaped quartz crystals ($g_{III}$). $s_{III}$ tends to be wavy rather than distinctly planar and, in places, the chlorite and mica show the "herring-bone" texture of crenulation foliation. The chlorite and mica crystals often lie in pod- or lens-like clusters.

$s_{III}$ is not developed throughout the rocks of the klippe - it is, for instance, absent in the quartzite and in most of the gneiss- and where it is present, it is developed to various degrees. Where well developed $s_{III}$ obliterates all pre-existing structures and it forms the schistosity of dark green and black schists which Peach et al (1907) described as "frilled schist" (p. 478) and "oyster-shell rock" (p. 598). In the mylonites, $s_{III}$ is, in general, only weakly developed.

As a rule, and particularly where it is incipiently developed, $s_{III}$ is parallel to pre-existing compositional layering and the $g_{III}$ chlorite and white mica crystals bear a largely mimetic relationship to pre-existing structures.
Where $s_{III}$ is oblique to bedding which contains quart veins, the veins are broken into "leaves" and rotated into near parallelism with $s_{III}$ (Fig. 55). $s_{III}$ lies approximately in the axial planes of the $f_{III}$ folds.

$g_{III}$:
The dominant $g_{III}$ minerals are chlorite, white mica and quartz; iron ore and carbonate minerals are common accessories; biotite and garnet are rare.

The $g_{III}$ chlorite and white mica appear to have crystallised largely at the expense of epidote. In the mylonites epidote is common and $g_{III}$ minerals are rare; in the "frilled schists" epidote is rare.

In the mylonites, the fractures associated with the $f_{III}$ folds are infilled with "mosaics" of quartz, carbonate mineral, chlorite, and ore minerals.

$f_{III}$:
The $f_{III}$ folds are minor folds. In the mylonites, where the axial-plane foliation, $s_{III}$, is only incipiently developed, the $f_{III}$ folds are generally disharmonic and asymmetric in profile; they are frequently characterised by the presence of fractures in their axial planes (Fig. 53). These folds are modified concentric folds (Fig. 54).

In the schistose meta-sediments it is often most difficult to distinguish between the Set II and Set III folds purely by examination of the fold styles and it was sometimes necessary to determine from a thin section whether a fold had $s_{II}$ (fold then $f_{II}$) or $s_{III}$ (fold then $f_{III}$) in its axial plane. The $f_{III}$ folds in the schists are disharmonic and asymmetric in profile and they are modified concentric folds (Fig. 54). They are unlike the $f_{III}$ folds in the mylonites because they have no associated fracturing; the correlation of the differing $f_{III}$/
Figure 52.

Sangomore Nappe, Durness. Structural data.

a. 5 axes (.) and 9 poles (o) to the axial planes of the $f_{III}$ folds.

b. 3 poles (.) to $s_{III}$ and a single plot (o) of slickenside lineation on $s_{III}$.

c. Data from the "sole rock". 3 axes (.) of $f_{IV}$ folds; 2 poles (o) to the axial planes of the $f_{IV}$ folds; 2 poles (x) to the foliation, $s_{IV}$; and a plot (Φ) of the lineation, $l_{IV}$. 
Figure 53.
Sangomore Klippe, Durness. Profiles of f_{III} folds. "d" and "g" were drawn from unoriented hand specimens. Solid scale lines are 5 cm. Dashed lines are 30 cm.
Figure 54.

Sangomore Klippe, Durness. Quantitative analysis of three fIII folds.

A.P. - Trace of axial plane in the fold profile.

D  - Distance normal to the trace of the axial plane.

T  - Thickness of layers measured parallel to the axial plane trace.

These folds are apparently of modified concentric type (see Ramsay, 1962 a).
Mal.

AP, D, T

5 cm

5cm scale
Figure 55.

Sangomore Klippe, Durness.

Quartz vein (heavy black) originally parallel to bedding, \( b_0 \), broken into "leaves" by, and rotated into near parallelism with, the foliation, \( s_{III} \).
differing \( f_{III} \) folds in their different environments is possible because of the existence of \( s_{III} \) in their axial planes.

The \( f_{III} \) axes plunge at low angles to the east-south-east and west-north west (Fig. 52a). Thus they are parallel to the \( f_{II} \) axes (Fig. 49c). The \( f_{III} \) axial planes generally dip to the north-east (Fig. 52a) and the folds are, for the most part, overturned towards the south-west.

Set IV:

\( t_{IV} \)

\( t_{IV} \) is the Moine Thrust plane; according to Peach et. al. (1907) p. it is exposed on the promontory at the North-west end of Sango Bay. The dip of the Thrust-plane is variable but is generally at a low angle towards the south west. In general, deformed Basal Quartzite forms the base of the Moine Nappe but, on part of the north west side of the above promontory, quartzite is absent, and mylonite rests on the Durine Limestone. The Thrust-plane is not strictly planar; the contact of the quartzite and limestone is often sharply irregular on a relatively small scale.

In places between the quartzite and the limestone, a relatively soft, reddish, foliated rock occurs. It attains a maximum thickness of about nine feet/
feet but is generally less than two feet thick. For the sake of subsequent discussion this rock will be called the "sole rock": is quite distinct in appearance from both the quartzite and the limestone. It consists of carbonates (the existence of both calcite and dolomite was shown by staining), quartz, white mica (talc?) and iron ores. The quartz occurs in the form of very small discrete grains. The quartz and white mica are set in a "spongy" matrix of very finely grained carbonate. Carbonate and limonitic veining is common.

At one locality north-west of Sango Bay the "sole rock" is, in part, finely banded pink, cream, black and shades of green and is mylonitic in appearance.

The foliation within the "sole rock" is defined by the planar alignment of white mica and ellipsoidal quartz grains. The foliation is parallel to the Moine Thrust-plane. The orientation of $s_{IV}$ could be ascertained at only two localities on the south west side of the promontory at the north-west end of Sango Bay the foliation dips at a low angle to the west-north-west; to the north-west of the above promontory the foliation dips at a low angle to the east-south-east (Fig. 52c).

In a specimen of mylonite "sole rock", incipient crenulation foliation was microscopically/
microscopically identified at a high angle to the colour banding. The crenulation foliation is defined by mica flakes; the ellipsoidal quartz grains always lie parallel to the colour banding.

The author considers that the "sole rock" was formed during emplacement of the Moine Nappe (for detailed discussion see pp.178-180). If this is the case, then folds in the "sole rock" must either post-date or be synchronous with thrusting. For reasons explained below (pp.178-180) the author considers that such folds are synchronous with thrusting; thus the folds have been symbolised "f IV".

Three minor folds were found in the "sole rock". The profiles of two of these are shown in Fig. 56. f IV microfolds occur within the mylonitic "sole rock".

Two of the minor fold axes plunge to the east–south-east; the other plunges to the west–north-west (Fig. 52c). Two axial planes were measured; one is vertical and strikes east–south-east – west–north-west; the other strikes south–east – north-west and dips steeply to the north–east. (Fig. 52c)

It is difficult to ascertain the orientations of the f IV microfolds; the axes appear to plunge at low angles to the south–east.

The f IV folds are concentric folds (Fig. 56; and see Ramsay, 1962a). In the minor folds illustrated (Fig. 56) the foliation, s IV, is defined by the planar alignment of ellipsoidal quartz grains. s IV is folded by the f IV/
Figure 56.

Sangomore

a. and b. Concentric folds from the "sole rock" beneath the Moine Thrust-plane.

"c" is a field sketch of the relationship of fold "a" to unfolded Durine Limestone.
$f_{IV}$ folds. In the mylonitic "sole rock" the incipient crenulation foliation appears to lie in the axial planes of the $f_{IV}$ microfolds.

The synclinal $f_{IV}$ minor fold (Fig. 56 c ) appears to lie in a groove in the Durine Limestone.

$1_{IV}$:

A very faint lineation is discernible in the mylonitic "sole rock"; it plunges at a low angle to the south-east (Fig. 52 c ).

$2_{IV}$:

In the "sole rock" the most significant metamorphic changes have been the crystallisation of white mica (talc?) and the recrystallisation of the carbonate minerals. No quartz recrystallisation was detected.

If the white micaeous mineral is talc, metamorphism took place at a very low temperature (see Tilley, 1951).

Set V

$3_{IV}$:

The faults which have affected the rocks of the Sangomare klippe strike in general, north-south or north-east - south-west. Stratum contouring has shown that the major faults are vertical; the faults are apparently normal faults. The directions of downthrow are indicated on the structural map (Fig. 48 ).

(e) **Set Generation:**

In this section, the mechanisms of formation of some of the structures developed/
developed in the Sangomere area are considered. The mechanics of thrusting and faulting are not discussed below; thus the Set I and Set V structures have not been considered.

Genetic analysis has been seriously handicapped by the lack of quantitative strain data. Since conclusions are based largely on examination of the structures they must be considered to be tenuous.

Set II generation.

(i) Examination of the Set II elements.

\[ s_{II} \parallel l_{II} \]

The foliation, \( s_{II} \), and the lineation, \( l_{II} \), form, in combination, an L–S tectonite (Flinn 1965). As noted (p. 128 ) Flinn (op. cit.) correlated L–S tectonites with orthorhombic strain ellipsoids such that the longest axes of the ellipsoids are parallel to the lineation and the longest and intermediate axes lie in the foliation. Flinn's (op. cit.) analysis suggests the following relationships between the axes of the strain ellipsoid \( (x > y > z) \) and \( s_{II} \) and \( l_{II} \):

\[ X \cdot Y \cdot s_{II} = 0^\circ; x \cdot l_{II} = 0^\circ; \text{ and } Z \cdot s_{II} = 90^\circ. \]

\[ f_{II} \]

The author is unable to suggest what mechanisms caused the \( f_{II} \) folds. Flinn (op. cit.) has suggested that tectonites of the L–S fabric system have developed/
developed by homogeneous straining. If this is the case, the $f_{\text{II}}$ folds may have may have developed from local strain inhomogeneities within an overall pattern of homogeneous strain.

$\varepsilon_{\text{II}}$:

The fact that only partial recrystallisation of the Sangomore rocks occurred during Set II generation suggests that deformation took place under conditions of low grade metamorphism. It is probable that metamorphism occurred under conditions of the quartz-albite-muscovite-chlorite subfacies of the greenschist facies (see Turner and Verhoogen (1960) pp 533-537.

(ii) The deformation of the Set 0 elements by Set II generators

As noted (p. 165) the author considers that the mylonitic colour banding ($s_{02}$) is Set 0 foliation or bedding so modified by mylonitisation that the character of the original layering is unrecognisable. The mylonites are tentatively considered to have resulted, during Set II generation, by the extreme compression, at relatively low temperatures, of Set 0 layering.

The Sangomore mylonites occur in two localities; firstly at the north-west end of Sango Bay where they overlie the deformed Passal Quartzite and secondly between the School Road and Loch Caladail. The parent rock of the mylonites in Sango Bay is unknown but the inland mylonites appear to be with undoubted sediments. It is, therefore, probable that the mylonites south-west of the School Road have been derived from parent sedimentary rocks.

It has not been possible to make quantitative estimates of strain from a study.
study of the shapes of the deformed \( g_0 \) clastic grains but their blade-like forms in the Basal Quartzite indicate that strain was, at least locally, extreme.

Set III generation:

\[ f_{III}, \quad s_{III}. \]

Study of the \( f_{III} \) folds yields little evidence pertinent to the problem of the natures of the Set II\(^1\) generators. The existence of the folds shows that strain was, at least locally, inhomogeneous.

The "frilled schists" show no distinct lineation (though a faint slickenside like streaking is not uncommon within them). Thus in the terminology of Flinn (1965) the Set III tectonite is an S-tectonite. As noted, (p 128) Flinn (op. cit.) correlated S-tectonites with oblate strain ellipsoids such that \( X \) and \( Y \) lie in the schistosity and \( X > Y \).

The difficulty inherent in assigning the Sangomere Set III tectonite to the S tectonite category of Flinn (op. cit.) is that \( s_{III} \) is not distinctly planar. Thus, deduced XY planes would be variably oriented over short distances. In addition, it would appear that pre-existing planar and compositional anisotropies have controlled, to some extent, the orientations of the \( g_{III} \) micaceous minerals. Thus, \( s_{III} \) may often be oblique to the XY plane of the strain ellipsoid. The author would consider therefore that identification of \( s_{III} \) with the XY plane is highly tenuous.

\[ \varepsilon_{III} \]

The Set III mineral assemblage (dominantly quartz, chorite and white mica) apparently
apparently belongs to the quartz-chlorite-albite-muscovite subfacies of the green-schist facies of regional metamorphism, though the presence of biotite indicates that locally, metamorphism took place under quartz-albite-epidote-biotite subfacies conditions.

Turner and Verhoogen (1960) p. 524 noted that "Estimates of temperatures and pressures of low grade regional metamorphism are little better than a guess. A possible range is 300° - 500° C. and $P_{H_2O} = 3,000$ to 8,000 bars".

Set IV

The "sole rock!"

The "sole rock" exists in a thin band between the Basal Quartzite at the base and of the Moine Nappe and the Durine Limestone of the foreland. It is quite distinct in appearance from both the quartzite and the limestone (see Plate VIII). The author can only conclude that the "sole rock" originated during thrusting perhaps by the intermingling of granulated quartzite and limestone. It should be noted, however, that the mylonitic "sole rock" (see page 172) could be a lens of Moinian mylonite beneath the Basal Quartzite. Where the "sole rock" is not mylonitic in character it is clearly not of Moinian origin.

$s_{IV}$:

The foliation, $s_{IV}$, in the "sole rock" may have formed either during or after thrusting, perhaps in response to the pressure exerted by the weight of the static Moine Nappe on the unfoliated "sole rock".

$f_{IV}$:
The \( f_{IV} \) folds are distinctive in that:

1. They occur only within the "sole rock"
2. They resemble none of the folds in the Moinian, and
3. They occur in juxtaposition to unfolded Durine Limestone (see Fig. 56c).

The author considers that the \( f_{IV} \) folds developed during thrusting and he would tentatively suggest the following mechanism of formation:

As the Moine Nappe moved, the "sole rock" formed on the base of the Nappe by the intimate co-mingling of granulated quartzite and limestone. The foliation \( s_{IV} \), developed, during thrusting, sub-parallel to the Moine Thrust-plane; \( s_{IV} \) formed in response to the pressure exerted by the weight of the Nappe. It was noted (p171 and see Fig. 56c) that the Moine Thrust-plane is often sharply irregular. The author would suggest that protuberances in the base of the Nappe cut grooves, running parallel to the direction of movement, in the underlying limestone. The grooves cut by the moving nappe would be infilled by "sole rock" in such a way that the "sole rock" would accommodate itself to the irregularities in the limestone. Thus synclinal \( f_{IV} \) folds would form in grooves in the limestone, anticlinal \( f_{IV} \) folds would form on the intervening ridges and the fold axes would be parallel to the direction of movement of the Nappe. The \( f_{IV} \) fold axes (Fig. 52c) trend east-south-east - west-north-west; thus, the indicated direction of movement of the Moine Nappe is either towards the east-south-east or towards the west-north-west. It should be noted, however, that the axial directions of the \( f_{IV} \) folds indicate/
indicate the direction of only the final phase of movement since only the latest grooves cut by the nappe may have survived.

\[ l_{IV} \]

The significance of the lineation, \( l_{IV} \), in the "sole rock" is unknown; \( l_{IV} \) may be parallel to the direction of movement of the Moine Nappe.
4. The An Fharaid Klippe

(a) Introduction:

The Moinian metasediments and the Lewisian Gneiss of An Fharaid are separated from the Durness Limestone of the foreland by a major fault which strikes east-south-east - west-north-west from Creag Thairbe to the southern margin of Balnakeil Bay.

The Moine Thrust-plane does not appear on An Fharaid; Peach et al. (1967) p. 487, show the Thrust-plane dipping eastwards at ten degrees and entering the sea just off the westerly tip of An Fharaid.

The An Fharaid succession, upwards from the Moine Thrust, is given by Peach et al (loc. cit.) as follows:--

Mylonised Rocks, Green Schists and Phyllites; marble; and Quartz-schist: c.a. 500 feet thick.

Lewisian Gneiss: 500 feet.

Moine-schists: c.a. 1,500 feet.

The "one-inch" geological map (Sheet 114-1889) shows the Lewisian Gneiss to be separated by thrust-planes from the schists above and below.

The present author found no mylonites on An Fharaid. The Quartz-schist beneath the Lewisian Gneiss is a pale-coloured psammite and is not shown in the author's geological map (Fig. 48). The author considers that the rock thicknesses shown by Peach et al (loc. cit.) are in error since the bedding and foliation dip more steeply (see Fig. 48) than Peach et al (loc. cit.) indicate. The author would modify the succession given by Peach et al. (loc. cit.) as follows:

Schistose metasediments: Pelites and psammites with thin bands of marble.
600 feet minimum

Lewisian Gneiss: 1,000 feet
Metasediments: Psammites with thin inconstant pelitic bands
2,500 feet minimum.

(b) Petrography

Lewisian Gneiss:

The least deformed gneiss occurs on A'Chleit. It is here that the original Lewisian structures are most obvious. The thin basic sills and dykes on A'Chleit consist of hornblende, quartz, epidote, biotite, carbonate and accessory ore. No pyroxene was observed but "ghost" pyroxene crystal shapes are common.

The gneiss of A'Chleit is, for the most part, basic. It consists of quartz felspar, hornblende, biotite, muscovite, epidote, chlorite and ore minerals.

Generally, the Lewisian Gneiss of An Fharaid has been deformed and the gneissose foliation attenuated and rotated into parallelism with the bedding into the Moinian above and below. The gneiss is mostly acidic; it consists of quartz, felspar, muscovite, biotite, epidote, chlorite, carbonate and ore. Felspar plenocrysts are common (Plate 1 X g). At the base of the Lewisian there is a thick band of hornblendic gneiss.

The Moinian:

The Moinian rocks are metasediments; they are predominantly psammites and pelites but thin limestone bands occur in the Moinian beneath the Lewisian Gneiss.

The psammites consist of quartz, muscovite, biotite, epidote, felspar, garnet and ore.

The pelites consist of quartz, chlorite, muscovite, ores, felspar and carbonate.

Sedimentary/
Sedimentary clastic grains may sometimes be recognised in the pelites.

(c) Structural sets

Fig. is a geological and structural map of the Durness area.

The structures developed in the rocks of An Fharaid have been grouped into the following structural sets:

Set 0 = \( (b_0, s_0, f_0, l_0, e_0, z_0) \)
Set I = \( (x_1, z_1) \)
Set II = \( (s_{II}, l_{II}, f_{II}, e_{II}, z_{II}) \)
Set III = \( (s_{III}, l_{III}, f_{III}, e_{III}, z_{III}) \)
Set IV = \( (f_{IV}, l_{IV}, z_{IV}) \)
Set V = \( (f_V, z_V) \)
Set VI = \( (h_{VI}, z_{VI}) \)

(a) Descriptions of structural sets

Set 0:

\( b_0 \):

The dominant layering of the Moinian metasediments above and below the Lewisian Gneiss is bedding. The bedding has a general north-south strike and it dips eastwards generally at 20 - 30° (Figs. 48 & 57c).

Truncated current-bedding in the psammites above the Gneiss indicates that the psammites are the right-way-up. (For details of the cross-stratification in these psammites, see Williams (1967)).

\( s_0, f_0, l_0 \):

The structures of the Lewisian of A'Chleit have not been significantly modified/
modified by post-Lewisian deformation (but see above p. 182) and Lewisian foliation; folds and lineation may be recognised. Throughout most of the Lewisian however $f_0$ and $l_0$ may not be positively identified and $s_0$ has been modified by deformation and rotated so that it is concordant with the Moinian bedding.

The foliation has a general north-north-east — south-south-east strike; it dips to the east-south-east generally at about $30^\circ$ (Fig. 48).

Set I:

1. Both contacts are unconformities
2. The upper contact is an unconformity; the lower contact is a thrust
3. Both contacts are thrusts.

As noted (p. 160) the upper gneiss-psammite contact is exposed south of Gob nan Leac. There is no discordance between the Lewisian and the Moinian; the Lewisian foliation is parallel to the Moinian bedding. The evidence from current bedding truncations indicates that the psammites young away from the gneiss. Thus, the upper Lewisian-Moine contact could be an unconformity. It should be noted, however, that the Moinian adjacent to the Lewisian is not conglomeratic.

If both contacts are unconformities then the Lewisian would lie in the core of a major isoclinal fold. The author considers the existence of such a fold to be unlikely since, throughout the considerable thickness of psammites above the Lewisian/
Lewisian there is no evidence of a major "turnover". In addition, some similarity of lithology would be expected to exist between the Moinian in each fold limb. For the most part, the Moinian above and below the Lewisian are lithologically different - pelites are abundant below the Lewisian but rare above.

In conclusion, it would appear that the lower Moine-Lewisian contact is a thrust. The upper contact would be either an unconformity or a thrust; the author would tentatively suggest, in accordance with the views of Peach and Horne that it is a thrust.

Set II

$s_{II}$:

$s_{II}$ is the dominant foliation of An Pharaid. It is defined by the planar alignment of blade-shaped quartz grains and grain clusters and muscovite and biotite crystals. The abundant felspar porphyroblasts in the Lewisian Gneiss are only weakly aligned in $s_{II}$ (Plate IXg).

$s_{II}$ is, for the most part, parallel to the bedding in the Moinian and to the foliation of the Lewisian. $s_{II}$, therefore, strikes generally north-south and dips consistently east at about $20 - 30^\circ$ (see Fig. 57a).

$l_{II}$:

$l_{II}$ is the dominant lineation of the area. It lies in $s_{II}$ and is defined by the preferred orientation of mica flakes and quartz grains and clusters.

$l_{II}$ plunges consistently, at a low angle, to the east-south-east (Fig. 57b).

$f_{II}$:

The $f_{II}$ folds are minor folds. The fold profiles are very variable in form; $f_{II}$ includes intrafolial isoclines, asymmetric, disharmonic anticlines and fairly/
Figure 57.
An Pharaid Klippe, Durness. Structural data.

a. 186 poles to dominant layering (including $b_0$, $s_0$ and $s_{II}$) of the An Pharaid Moine and Lewisian. Contours 20%, 10%, 5%, 1%, 0.5% per 1% area.

b. Composite plot of the lineations ($l_{II}$, $l_{III}$ and $l_{IV}$). 294 readings. Contours 25%, 10%, 5%, 2.5%, 1% and 0.34% per 1% area.

c. 54 axes of the $f_{II}$ folds.

d. 49 poles to the axial planes of the $f_{II}$ folds.
Figure 58

An Pharaid Klippe, Durness.

Profiles of $f_{II}$ folds. Dashed scale lines are 25 cm. Solid lines are 2.5 cm.

See also Plates, IX a-f.
An Fharsaid Klippe, Durness. Quantitative analyses of $f_{II}$ folds.

A.P. - Trace of the axial plane in the fold profile.

D - Distance normal to the axial plane trace.

T - Thickness parallel to the axial plane trace.

These folds are apparently modified concentric folds. In fold "a", however, layer "2" tends towards similarity of form (see Ramsay 1962a).
fairly open anticlines and synclines (Fig. 58). Geometrically, the folds vary from being similar to concentric in type (Fig. 59; and see Ramsay 1962a).

The $f_{II}$ fold axes plunge at low angles to the east-south-east (Fig. 57c); the axes are parallel to the lineation, $l_{II}$. The axial planes are variable in orientation but have a general easterly dip. $s_{II}$ lies generally in the $f_{II}$ axial planes.

$E_{II}$:

The dominant Set II minerals are quartz, felspar (sodic plagioclase and orthoclase) muscovite, biotite and epidote. Chlorite, garnet and ore and carbonate minerals are common accessories. Hornblende is common in the metamorphosed Lewisian igneous rock of A'Chleit.

The Set II mineral assemblages indicate that metamorphism took place under amphibolite facies conditions.

Set III

$s_{III}$:

The foliation $s_{III}$ is defined by the alignment of chlorite and white mica crystals and ellipsoidal quartz grains. The micaceous minerals tend to occur in pod-like clusters so that $s_{III}$ is wavy rather than distinctly planar. It is the development of $s_{III}$ within the pelites, such as those below the Lewisian Gneiss, that led Peach et al. (1907) to describe the resultant schist as "frilled schist", "oyster-shell rock" and "corrugated schist"; (op. cit. pp 478 and 598; and Peach's and Horne's "six-inch" field map).

$s_{III}$ is, in general, parallel to pre-existing layering; where oblique to earlier layering, $s_{III}$ strikes generally north-east - south-west and dips to the south/
south-east (Fig. 60b).

\( l_{III} \):

Where \( s_{III} \) is oblique to pre-existing layering (for example, in the hinges of the \( f_{III} \) folds) \( l_{III} \) is defined by the intersection of the planar structures. In the psammites where \( s_{III} \) tends to have the form of an incipient crenulation foliation the intersections of \( s_{III} \) and \( b \) are in the form of minute crenulations which resemble mica crinkle lineation.

\( l_{III} \) plunges generally at a low angle to the east (Fig. 57b).

\( f_{III} \):

The \( f_{III} \) folds are minor folds; they are variable in form but tend to be asymmetric and disharmonic and to have the geometric forms of modified concentric folds (see figs. 51-52; and Ramsay op. cit.)

The \( f_{III} \) axes are variable in orientation; they plunge either to the north-east or to the south-east generally at low angles (Fig. 60a). The axial planes dip generally to the south-east.

\( s_{III} \) and \( l_{III} \) are not always developed in association with the \( f_{III} \) folds but where these structures are in association, \( l_{III} \) is parallel to the fold axes and \( s_{III} \) lies generally in the fold axial planes.

\( e_{III} \):

The commonest minerals to crystallise during Set III generation were quartz, white mica and chlorite. Ore minerals are very common accessories; carbonates and biotite are less common.

The Set III mineral assemblage is characteristic of the greenschist facies of metamorphism. The scarcity of biotite suggests that the assemblage belongs to/
An Paran Klippe, Durness. Structural data.

a. 21 axes of $f_{III}$ folds.

b. 17 poles (●) to the axial planes of the $f_{III}$ folds and 10 poles (○) to the foliation, $s_{III}$.

c. 19 axes (●) of the monoclinal ($f_v$?) folds and 17 poles to their axial planes.

d. 3 axes of the open folds ($f_{IV}$?) in the Lewisian of Gob nan Leaq.

(See Plate XIe).
Figure 61

An Phasaid Klippe, Durness.

Profiles of $f_{III}$ folds. Dashed scale lines are 25 cm. Solid lines are 2.5 cm.

See also Plates XI a-d.
Figure 62.

An Fharaid Klippe, Durness. Quantitative analyses of three folds.

A.P. - Trace of axial plane in the fold profile.

D. - Distance normal to the trace of the axial plane.

T. - Thickness measured parallel to the trace of the axial plane.

Thickness variations are complex but, on the whole, indicate that these folds are of modified concentric type (see Ramsay, 1962a).
to the low temperature, quartz-albite-muscovite-chlorite subfacies (see Turner and Verhoogen (1960) pp 533-537).

The Set III structures are sporadically developed throughout the area. They are best developed in the pelitic Moines beneath the Lewisian. Only one f_{III} fold was found in the psammites above the Lewisian.

Set IV:

f_{IV}:
The f_{IV} folds are minor, very gentle anticlines and synclines (Plate Xie ). The f_{IV} fold axes plunge at low angles to the north and south (Fig. 60d).

l_{IV}:
The lineation l_{IV} is generally developed as minor corrugations. It plunges at low angles to the north and south (Fig. 57b).

The Set IV structures are very rare. The f_{IV} folds were found only in the Lewisian of Gob nan Lecc; in consequence, correlation of l_{IV} with these folds is tentative since l_{IV} occurs in the Moinian above and below the Lewisian.

Set V:

f_{V}:
The f_{V} folds are monoclines (Fig. 63 ). They are not commonly developed; they were found only in the psammites in the cliffs below Cnoc nan Sgliat.

The monoclinal fold axes are near horizontal and they trend consistently north-south; the axial planes all dip steeply to the west. (Fig 60c)

Set VI:

h_{VI}:

h_{VI} is the major fault which separates the metamorphic rocks of An Fharaid from/
Figure 63

An Pharaid Klippe, Durness.

Profiles of the monoclinal $f_y$ folds. Dashed line is 10 m. Dot-dash line is 1 m. Solid line is 2.5 cm.

See also Plates, XI fig.
from the Burness Limestone of the foreland. The fault strikes from Creag Thairbe west-north-west to the southern margin of Balnakeil Bay. Stratum contouring indicates that the fault plane is vertical. The north-eastern edge of Creag Thairbe is a fault scarp; the cliff is nearly vertical. Fault breccia is common in the cliff but the author could find no structures indicating the direction of movement on the fault.

The Geological Survey "One-inch" map (Sheet 114; 1889) shows this fault running mostly in the sea, a distance of about nine miles from An Garbh-eilan to Eilan Roan. Peach et al. (op. cit.) pp 477 and 487, considered the fault to be a normal fault. The possibility exists, however, of the fault being a sinistral tear fault which carried Moinian and Lewisian rocks at least seven miles from east of Loch Eriboll.

(g) Set Generation

It is not possible to discuss at any length the mechanisms of formation of the An Pharaid structures because of the lack of strain data and because the natures of the structures are such that any conclusions regarding their modes of origin would necessarily be tenuous. It is merely intended to note that:

(a) The Set II tectonite is an L-S tectonite (Flinn, 1965). Thus, it may have resulted by homogeneous strain such that, where X, Y and Z are the semi-axes of the strain ellipsoid \( X > Y > Z \):

\[
\begin{align*}
S_{II} \cdot XY &= 0^\circ; \\
L_{II} \cdot X &= 0^\circ; \\
S_{II} \cdot Z &= 90^\circ
\end{align*}
\]

The lineation, \( L_{II} \), may define a direction of significant positive strain.

(b) The Set III tectonite is possibly an S-tectonite (Flinn op. cit.) which may/
may have resulted by compression such that $s_{III} \cdot XY = 0^\circ$ and $X = Y$. Correlation of $s_{III}$ with an S-tectonite is, however, highly tenuous since $s_{III}$ is not sharply planar and since it is occasionally of crenulate form.
5. The Durness Area: Conclusions.

(a) Structural synthesis:

The structural histories of the Sangomore and An Fharaid klippen are markedly similar. Their early histories are apparently identical; both klippen have suffered early thrusting followed by the development of strong foliation containing the dominant east-south-east plunging lineation, in turn, followed by metamorphism and deformation giving rise to the characteristic "oyster-shell" foliation. Thus, in both klippen the structures described as belonging to Sets I - III are present.

In the Sangomore klippen no structures were found to have developed between Set III generation and the emplacement of the Moine Nappe. On An Fharaid the Moine Thrust is not exposed but the author would suggest that nappe emplacement post-dated the formation of the Set V monoclines. Thus, with reference to the An Fharaid structures, the Moine Thrust-plane would be a Set VI structure while the major fault separating the An Fharaid metamorphic rocks from the foreland limestones would be a Set VII structure. The relationships between the Sangomore and An Fharaid structural histories, up to the emplacement of the Moine Nappe, are illustrated in Table.VIII.

The major faults which affect the rocks of the Moine Nappe form, as noted by Peach et. al. (op. cit.) p. 477, "a double system ..... one set trending N.N.E. and S.S.W., while the other, which appears to be newer, runs more or less at right angles to the first series". Thus, Peach et al. considered the fault dividing the An Fharaid and the foreland rocks to post-date the faults affecting the/
the Sangomore Moines. They also considered all of the faults to be normal faults.

(b) The amount of displacement on the Moine Thrust-plane

In their discussion of the extent of displacement of the nappes of the Moine Thrust Zone, Peach et al. (op. cit.) p. 469, noted that: "In the extreme north of Sutherland the various rock-groups included under the Eastern schists, and overlying the Moine thrust-plane, can be shown to have been driven westwards for a distance of ten miles from the hill-slopes on the east side of Loch Eriboll to the centre of the Durness basin and the promontory of Far-a'ird Head"

The minimum distance from the Moines of the Sangomore klippe to the Moines east of Loch Eriboll is six miles. It would therefore appear that the minimal displacement on the Moine Thrust-plane is six miles.

The major fault which strikes east-west from Creag Thairbe to the south of Balnakeil Bay, and which separates the An Fharaid Moines and Lewisian from the foreland limestones could be either a normal fault downthrowing to the north or a sinistral tear fault.

If the fault is a tear fault then the An Fharaid Moines and Lewisian do not lie in a klippe but have been transported on the fault, at least seven miles, from east of Loch Eriboll. If the fault is simply a normal fault then the An Fharaid rocks constitute a klippe of the Moine Nappe and, since the minimum distance from the most westerly point on An Fharaid to the Moinean east of Loch Eriboll is nearly nine miles, a minimal displacement of nine miles on the Moine Thrust-plane is indicated.
In conclusion, the existence of the Sangomore klippe affords good evidence that the amount of displacement on the Moine Thrust-plane was at least six miles. The An Fharaid Moines and Lewisian provide less conclusive evidence but indicate a displacement of at least nine miles.

(c) The direction of displacement of the Moine Nappe

As noted (p.192), Peach et. al. (loc. cit.) considered that, in north Sutherland, the Moine Nappe had been "driven westwards". The evidence for this opinion seems to be twofold:

1. The An Fharaid and Sangomore successions are comparable to the succession above the Moine Thrust-plane east of Loch Eriboll. Thus, the An Fharaid and Sangomore klippen have been "derived" from the Moinian to the east of Loch Eriboll, and

2. In the Cambrian of the northern Moine Thrust Zone, Peach et. al. (op. cit.) p. 471, noted the elongation of quartz and felspar grains, the bending over and drawing out of pipes in the direction of movement and "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".

In the author's opinion neither line of evidence is conclusive:

1. Inspection of the "one-inch" geological map (Sheet 114; 1889) shows that there is no marked lateral variation in the sequence above the Moine Thrust east of Loch Eriboll and that the northern extent of the sequence is unknown.

There are no lateral lithological or tectonic breaks in either the Eriboll or the Durness/
Durness Moinian. Thus, the Durness Moines cannot be "matched" with the Moinian succession at any particular locality east of Loch Eriboll. It follows, then, that the Durness Moines, assuming that they are derived from the main body of the Moinian, could have been emplaced by movement from south to north or, perhaps, from north-east to south-west.

and (2) Peach et al. (op. cit.) give no proof that the structures developed within the Cambrian are the direct result of the emplacement of the Moine Nappe. It may be, as at Kempie, that the structures in the Cambrian beneath the Moine Thrust originated by pre-thrusting deformation.

The author considers that the "sole rock" (plate VII b) beneath the Moine Thrust-plane developed during thrusting. He has suggested that the folds in the "sole rock" are oriented with their axes parallel to the last phase of thrust movement (see pp 179-180), and that during this phase movement was towards either the east-south-east or the west-north-west. The author's evidence is, however in common with that of Peach et al. (op. cit.), inconclusive.

In conclusion, it would appear that the suggested direction of movement from east to west, though perhaps probable, has no certain evidence in its favour.

(d) The relationship of the present work with other work in the Moine Thrust Zone

The structural history of the area east of Loch Eriboll described by Wilkinson (1965) is set out, with the author's histories of the Sangomore and An Pharaid klippen, in Table VIII. The first and second phases described by Wilkinson (op. cit.) that is, mylonitisation and the development of the east-
<table>
<thead>
<tr>
<th>Wilkinson 1965</th>
<th>Sangomere Klippe</th>
<th>Present Thesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eriboll and Moine Nappes east of Loch Eriboll</td>
<td>Thrusting?</td>
<td>Major thrusting</td>
</tr>
<tr>
<td>Blastomylonitic foliation developed</td>
<td>Mylonitisation: Foliation and E.S.E. lineation formed. Folds developed with E.S.E. plunging axes.</td>
<td>Dominant foliation and E.S.E. plunging lineation developed. Folding on E.S.E. axes.</td>
</tr>
<tr>
<td>Greenschist facies metamorphism. E.S.E. lineation formed with isoclinal folds.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two double sets of conjugate kink folds developed.</td>
<td>Thrusting</td>
<td>Thrusting</td>
</tr>
</tbody>
</table>

Monoclinal folds formed.
south-east lineation, are equivalent to the Set II generation described in this thesis since the author considers that mylonitisation was the result of the same deformation which produced the dominant Set II foliation and lineation.

Wilkinson's (op. cit.) third phase (north-south folds with easterly dipping axial planes and associated crumple lineation and crenulation foliation) is apparently equivalent to Set III of Sangomore and An Fharaid. It would appear, however, that the structures in both areas are differently oriented and that a higher metamorphic grade was attained in the Durness Moinian.

The author found no conjugate folds in the Durness area. Thus, it would appear that the fourth phase conjugate kink-folds of Wilkinson (op. cit.) are not represented at Durness. It may, however, be suggested that the An Fharaid monoclines (Set V folds) are synchronous with the phase four conjugate kink-folds east of Loch Eriboll since, in other parts of the Moine Nappe (see Table VII) monoclines and kink-folds are synchronous.

It is difficult for the author to comment on the relationship proposed by Wilkinson (op. cit.) p. 241 that "late thrusting occurs both prior to and synchronous with, the phase four folding". At Sangomore the emplacement of the Moine Nappe apparently post-dated the Set III structures (equivalent to third phase structures east of Loch Eriboll); on An Fharaid no relationship could be established between the monoclines and the thrusting.

As noted (p151) Table VII shows the structural histories given by Johnson (1961) Barber (1965) Christie (1963) Wilkinson (op. cit.) and the author for various areas within the Moine Thrust Zone. The Sangomore and An Fharaid histories/
histories are similar to those described by Johnson (op. cit.), Barber (op. cit.)
the author at Glen Coul (above pp105-150), and as noted, Wilkinson (op. cit.)
Christie's (op. cit.) analysis of the Glen Coul area has been discussed above
pp150-156). It would appear however that the north-south asymmetric folds of
other regions are equivalent to the east-west asymmetric folds and other Set III
structures of Durness.

(e) General Conclusions

The similarities existing between the histories described by the author
and by Wilkinson (op. cit.) in the north of the Thrust Zone, and the histories
described by the author in Glen Coul, and by Johnson (op. cit.) and Barber (op.
cit.) south of Kinlochave, suggest that Barber's (op. cit.) p. 241 conclusion
"that the Tochcarron - Lochalsh sequence could be extended to the whole of the
thrust-zone" is generally correct.

The existence of the Sangomore Klippe shows that there has been a dis-
placement (assuming "orthodox" transport) of at least six miles on the Moine
Thrust-plane. If the An Fharaid Moines and Lewisian lie in a klippe, that is,
if the fault which separates them from the foreland is not a tear fault, then
displacement has exceeded nine miles. The direction of displacement on the
Thrust-plane is unknown but studies of the geometry of the folds in the "sole
rock" of Sango Bay suggest that the last phase of displacement was either towards
the east-south-east or towards the west-north-west.
SECTION VI

GENERAL CONCLUSIONS

This study has been primarily concerned with strain analysis of deformed Pipe Rock (at Kempie and Glen Coul) and with detailed structural analysis (at Kempie, Glen Coul and Durness).

At Kempie, strain analysis was used, in conjunction with fold geometry, as a possible key to understanding the mechanisms by which the described planar, linear and fold structures had developed. It was found that, although the mechanisms of formation of the various structures could not be uniquely determined, it was possible to exclude certain mechanisms from discussion.

In the Moine Nappe at Glen Coul strain analysis has shown that the dominant east-south-east plunging lineation (\( l_{II} \)) very probably defines a direction of significant positive strain. Study of the quartz-microfabrics (\( d_{II} \)), pipe strain, and the dominant foliation (\( s_{II} \)) and lineation (\( l_{II} \)) suggests that deformation approached homogeneity and that it may have been of pure shear type. Folds (\( f_{II} \)) apparently synchronous with major deformation do, however, provide evidence of strain inhomogeneity. The author (in contrast to Christie, 1963) has interpreted the folds as being "red herrings" in analysing deformation mechanics. The \( f_{II} \) folds are considered to represent local inhomogeneities in an overall near homogeneous strain pattern.

The presence of the Sangomore and An Pharaid Klippen at Durness indicates that displacement on the Moine Thrust-plane was at least six miles and may have approached ten miles. There is no positive evidence of the direction of displacement but the geometries of minor folds found beneath
the Moine Thrust-plane in Sango Bay suggest that displacement was generally either from east to west or from west to east.

Finally, in the author's opinion, it would appear that the extreme variability of strain over short distances in deformed Pipe Rock precludes the possibility of strain analysis of Pipe Rock being used to show regional variation of strain throughout the Moine Thrust-zone.
ACKNOWLEDGEMENTS

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Finally, I should like to thank my wife and parents for their unfailing support.

Andrew McLeish.
Appendix I

The sampling of pipe sectional ratios

Sample size

If it be assumed that the population distribution of \( \log \frac{a}{b} \) is normal, then the sampling theory of normal distributions may be applied where \( n > 30 \). (Samples of size \( n > 30 \) are large samples, those of size \( n < 30 \) are small samples) Where \( n < 30 \) the small sampling theory of "Student's" t distribution is applicable. Since collected \( \frac{a}{b} \) samples are almost invariably smaller than 30 only small sampling theory will be considered.

Parameters calculated from sample data are only estimates of population parameters. The sample size required such that the sample parameters are close in value to the population parameters may be found from:

\[
N = \left( \frac{s \cdot t_p}{d} \right)^2 \quad (1) - \text{see Krumbein and Graybill (1965) pp. 164-165.}
\]

where \( N \) is the required sample size; \( s \) is the standard deviation; and \( t_p \) the percentile value for "Student's" t distribution (with \( v \) degrees of freedom) of a test sample; and \( d = \mu - \bar{x} \), where \( \mu \) is the population mean and \( \bar{x} \) the sample mean. \( d \) is chosen such that any required degree of accuracy is obtained.

The number of degrees of freedom, \( v \), of a statistic is the number, \( n \), of independent observations in the sample minus the number, \( k \), of population parameters which must be estimated from sample observations \( (v = n - k) \).
With small samples, the sample mean may not be a good estimate of the population mean. The limits within which the population mean lies may, however, be estimated; the confidence limits are:

\[ \bar{X} \pm t \frac{s}{\sqrt{n-1}} \]  

(2) - see Spiegel (1961) p. 189

\( t \) depend on the sample size and the level of confidence desired.

The use of formulae (1) and (2) is illustrated with respect to the data from Kempie, Position II.

The data are as follows:

\[ n = 10.0 \quad \bar{X} = \frac{\log \frac{a}{b}}{n} = 0.4364 \]

\[ s = 0.11 \]

Since only the population mean is under consideration, \( k = 1.0 \) and \( v = 9.0 \)

Let \( d = 0.05 \) and let \( p = 0.975 \)

From (1)

\[ N = \frac{(0.11 \times 2.26)^2}{0.05} = 25 \]

Thus in a sample of \( N = 25 \), there is a probability of 0.95 that \( \mu \) lies within 0.05 of \( \bar{X} \) and, in collecting samples of \( \frac{a}{b} \) pipe sectional ratios, at least 25 readings are desirable.

The 95\% confidence limits of the population mean are from (2):

\[ 0.4364 \pm 2.26 \frac{0.11}{3} \]

Taking/
Taking antilogs \( e = 2.73 \div 1.21 \). In this sample of \( n = 10 \) there is a probability of 0.95 that the population mean lies within the range 1.51 to 3.94.
Appendix II

Specimen calculation of pipe and bedding strain

Data for Kempie, Position II; is as follows:

<table>
<thead>
<tr>
<th>$\frac{2a}{2b}$ mm</th>
<th>16, 7, 10, 9, 8, 8, 16, 9, 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{a}{b}$</td>
<td>2.66, 2.0, 2.26, 2.57, 2.25, 2.0, 4.0, 4.0, 3.6, 2.29</td>
</tr>
<tr>
<td>$B_2$, $p_2$, $n$, $G$</td>
<td>$90^\circ$, 320$^\circ$</td>
</tr>
<tr>
<td>$17.65^E$</td>
<td>125, 325$^E$</td>
</tr>
</tbody>
</table>

$$\lambda_P = G^2 = 7.45 \quad \text{see eq. (1) p. 19}$$

$$\lambda_B = \left(\frac{1}{6 \sin \omega}\right)^2 = 0.48 \quad \text{eq. (2) p. 19}$$

$$\frac{t_2}{t_1} = \frac{1}{\sqrt{\lambda_B}} = 1.44 \quad \text{see p. 24}$$

From:

$$
\tan 2\phi_B' = \frac{\lambda_B}{\lambda_P} \sin 2\omega \\
\tan 2\phi_B' = \frac{0.48}{1.44} \frac{0.6988}{0.4384} = 1.7876
$$

and $\phi_B' = 30.40^\circ$

Since:
Since \( \phi'_P = \omega - \phi'_B \) (see Fig 3a)
\( \phi'_P = 1.60^\circ \)

From:
\[ \tan \phi'_B \tan \phi'_P = \lambda^2 \]
\[ \text{eq. (8) p. 22} \]
\[ \lambda_3 = 0.1282 \]

Since
\[ \lambda_1 \lambda_3 = 1 \]
\[ \lambda_1 = 7.8025 \]
\[ \varepsilon_1 = \sqrt{\lambda_1} - 1 = 1.793 \]
\[ \varepsilon_3 = \sqrt{\lambda_3} - 1 = 0.642 \]

Since \( \phi'_P = 1.60^\circ \), the direction and plunge of \( X \) are 125\(^\circ\), 34\(^\circ\) SE and of \( Z \) are 305\(^\circ\), 56\(^\circ\) NW.
\[ \gamma_{\text{max}} = \frac{\lambda_1 - \lambda_3}{2} \]
\[ = 3.837 \]
\[ \gamma_{BP} = \cot \omega \]
\[ = 1.60 \]

From \( \tan \phi_B = \lambda_1 \tan \phi'_B \)
\[ \phi_B = 77.68^\circ \]

Since \( \phi_B + \phi'_P = 90^\circ \)
\[ \phi'_P = 12.32^\circ \]
Redding rotation in the plane of pure shear equals:

\[ \phi_B - \phi'_B = 47.46^\circ \]

Pipe rotation:

\[ \phi_P - \phi'_P = 10.72^\circ \]

Rotating \( P_2 \) gives the plunge of \( P_1 \). The direction and plunge of \( P_1 \) are 125°, 22°E.

Since \( P_1 \) is the pole to \( B \), the strike and dip of \( B \) are 35°, 68° NW.

(See Fig A1)

In simple shear:

\[ \gamma_s = \varepsilon_1 - \varepsilon_3 \]

\[ = 2.44 \]

\[ \tan \alpha = \gamma_s \]

\[ \therefore \alpha = 68^\circ \]

\[ \tan \beta'_1 = -\frac{\varepsilon_3}{\varepsilon_1} \]

\[ = 0.358 \]

\[ \therefore \beta'_1 = 20^\circ \]

The orientations of the two possible sets of simple shear planes are:

\( S_1: \ 35^\circ, 14 \) SE

\( S_2: \ 35, 54 \) SE

Considering \( S_1 \):

\[ \Theta_{P_2} = S_1 \cdot P_2 = 18^\circ \]

From:

\[ \cot \Theta_{P_1} = \cot \Theta_{P_2} - \gamma_s \]

\[ = 0.358 \]
Figure A1.

Kempie, Loch Eriboll. Plot of data from Pipe Rock, Position II.

See Table V and Appendix.

Directions of shear on \( S_1 \) and \( S_2 \) (poles shown as \( \theta \)) are indicated by arrows.

\( P \) is the orientation of \( P_1 \) calculated where deformation is assumed to have been by pure shear.

\( P' \) and \( P'' \) are the orientations of \( P_1 \) found by rotation on \( S_1 \) and \( S_2 \) respectively.
Pipe Rotation in the $\varepsilon_1 \varepsilon_3$ plane of simple shear equals

$$\theta_{P_1} - \theta_{P_2} = 39^\circ$$

The direction and plunge of $P_1$ are $125^\circ, 71$ SE. Since $P_1 \cdot B_1 = 90^\circ$, the strike and dip of $P_1$ are $35^\circ, 19^\circ$ NW.

Similarly for $S_2$:

$$\theta_{P_2} = 22^\circ, \theta_{P_1} = 88^\circ$$

and the pipe rotation is $66^\circ$. The orientations of $P_1$ and $P_1$ are:

- $P_1 = 205, 34$ NW; $P_1 = 35, 56$ SE

See Fig. A1

These data are shown in Table V. For the most part, the data given in Tables V and VI were calculated by computer. All data concerning geographical orientations were calculated manually.
Appendix III

Pipe Rock at Skia Bridge, Loch Assynt

Foreland pipe rock is very well exposed in a road cut, about 100 yards long, on the Kylesku road at Skia Bridge, Loch Assynt.

The pipes in the main body of the rock are perpendicular to the bedding but numerous shaly partings exist in which the pipes are not normal to the bedding. The partings generally lie between the massive bedding units but they also occur thinly within the units. In the partings the pipes exhibit a variety of orientations (Fig.A2 a); the pipe sections are generally elliptical (Fig.A2,b-fh).

In the partings, the pipes are much more coarsely grained and much less chloritic than the matrix (Plate XI h). It may be inferred that they are much stronger than the matrix.

During weak deformation (which may have been the result of diagenetic compression) the pipes have apparently been able to rotate as relatively rigid rods, suffering less strain than their matrix.

Thus, in studying pipe and bedding strain it should be noted that, in incompetent partings:

1. The pipes before the considered tectonic straining may not have been normal to the bedding.

2. The pipes may rotate as semi-rigid rods and the relationship:

$$\frac{\lambda}{B} = \left(\frac{b}{a \sin \omega}\right)^{\frac{1}{2}}$$

may not hold.
Figure A2.

Foredland Pipe Rock, Skiag Bridge, Loch Assynt.

a. Pole to bedding and plunge of undeformed pipes - 0.

Plunges of deformed pipes - e.

b - f. Details of deformation in thin, relatively incompetent inter-bedding layers. B = bedding, P = pipe.

The scale lines are all 5 cm.
Appendix IV

Fold deformation by pure shear; numerical example (see pp.133-136)

Throughout, the orientations of lines are given as direction and plunge; the orientations of planes are given as strike and dip.

Let:
\[ \lambda_1 = 4.0 \quad \lambda_3 = 0.25 \quad (\lambda_1 \lambda_3 = 1) \]
\[ X = 110, 20E; \quad Y = 20, 0; \quad Z = 290, 70W \]

\[(X', Y', Z')\]

\[ F_2 = 102, 37E \quad AP_2 = 345, 40E \]

\[(AP_2 \text{ is the axial plane of the fold whose axis is } F_2)\]

From Fig. A 3a:
\[ \alpha' = 18^\circ; \quad \beta' = 84^\circ; \quad \text{and} \quad \gamma' = 73^\circ \]

From eq. (4) p134:
\[ \lambda_{F_2} = 1.73 \]

From eqs. (1), (2) and (3) p.133:
\[ \alpha = 51^\circ; \quad \beta = 82^\circ; \quad \text{and} \quad \gamma = 39^\circ \]

Thus the orientation of \( F_1 \) is \( 88, 70E \) and of \( b \ c \) is \( 358, 20W \) \( (F_1 \cdot bc = 90^\circ) \)

ac and \( a \ b \ c \) are given orientations such that \( a \cdot b \cdot c = 90^\circ \):
\[ ac = 45, 76 SE; \quad ab = 312, 76 NE \]

\[ \psi = \frac{x}{y} D \quad (\text{Fig. A3b}) \]

\[ \psi_{1bc} = 78^\circ \]

From eq. (5) p134:
\[ \psi_{2b'c'} = X' D' = 67^\circ \]

\[ \phi_{1bc} = Z' E' = 80^\circ \quad (\text{Fig. A3b}) \]
From eq (6) p. 134:

\[ \phi_{2bc'} = Z \cdot E' = 85^\circ \]

b' c' passes through D' and E'; thus its orientation is 49°, 103E (see Fig. A3b)

\[ \psi_{1ab} = X \cdot G = 17^\circ \]

From eq (5) p. 134:

\[ \psi_{2ab'} = X \cdot G' = 9^\circ \]

\[ \phi_{1ab} = Z \cdot H = 22^\circ \]

From eq. (6) p. 134:

\[ \phi_{2a'b'} = Z \cdot H' = 39^\circ \]

The orientation of a' b' is 312, 57 NE (see Fig. A3b)

\[ \psi_{1ac} = X \cdot J = 61^\circ \]

from eq. (5) p. 134: \[ \psi_{2a'c'} = X \cdot J' = 42^\circ \]

\[ \phi_{1ac} = Z \cdot K = 52^\circ \]

from eq. (6) p. 134:

\[ \phi_{2a'c'} = Z \cdot K' = 69^\circ \]

The/
The orientation of a'c' is 230 43 SE
(see Fig. A3b)

Since a'c' and a'b' intersect in F2 (ξ a') J' and F2 and G' and F2
could have been used to define the orientations of the a'c' and a'b' planes respectively.

In Fig A3c: \( \text{L} \parallel \text{ac} \) and \( \text{M} \parallel \text{a'c'} \)

\[ \omega_{ac} = L \cdot Z = 58^\circ \]

\[ \theta_{ac} = M \cdot Z = 27^\circ \]

From eq (7) p.135:

\[ Q_{a'c'} = 0.85 \]

In Fig A3c: \( \text{R} \parallel \text{ab} \) and \( \text{S} \parallel \text{a'b'} \)

\[ \omega_{ab} = R \cdot Z = 69^\circ \]

\[ \theta_{ab} = S \cdot Z = 52^\circ \]

From eq (7) p.135:

\[ Q_{a'b'} = 0.86 \]

In Fig A3c: \( T \perp b'c' \), \( F_2 \cdot T = 63^\circ \) and \( F_2 \cdot b'c' = 27^\circ \).

and/
and:

\[ b'c' = 77^\circ; \quad a'(F_2) \cdot b' = 35^\circ; \quad \text{and} \quad a'(F_2) \cdot c' = 61^\circ. \]

U and K' are the orthographic projections of b' and c' on the profile plane (pp_2) of F_2. V is the trace of AP_2 on pp_2:

\[ U \cdot K' = 71^\circ \]
\[ U \cdot V = 29^\circ \]

From Fig A4d:

\[ \delta = b' \cdot U \]
\[ U = b' \cos \delta = \cos \delta \quad (\text{where } b' = 1) \]

Similarly:

where \[ \Delta = c' \cdot K' \]
\[ K = \cos \Delta \quad (\text{where } c' = 1) \]

From Fig A3c:

\[ \delta = 55^\circ, \quad \Delta = 30^\circ \]

and \[ U = 0.57 \quad \text{and} \quad K = 0.87^\circ \]

Fig A4 shows grids constructed from the above data and, from the methods given on p.135, the profile of the undeformed fold, F_1, is constructed from the deformed fold F_2.

The trace of AP_1 on bc is A. b \cdot A = 35^\circ. In Fig A3d, AP_1 is drawn through F_1 and A (AP_1 is the axial plane of the fold whose axis is F_1).
Figure A3.

For explanation see text.
Figure A4.

a. Profile of fold whose axis is $P_2$.

b. Projection of UKE on b’c’.

c. Projection from b’c’ to bc, that is, the profile of the fold whose axis is $P_1$.

d. For explanation see text.
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NOTE

Since metric units are those most commonly used in scientific description and calculation it was intended to use them in this thesis. Thus, scales in the diagrams are in metric measure. It was found, however, in preparing the text, that because the used Ordnance Survey maps were on a scale of six inches to one mile, it was better, in describing distances, to use British measure (that is, feet, yards, etc.)
PLATE I

a. $f_{\text{L}}$ fold in Fucoid Beds, Kempie. Looking south. Part of this fold is shown in Figure 18.

b. $f_{\text{L}}$ fold core in limestone west of Kempie. Rucksack middle right. Looking south-east.

c. $f_{\text{L}}$ folds in limestone. Roadside west of Kempie. Looking south.

d. Conjugate $f_{\text{L}}$ fold in Fucoid Beds. Shore west of Kempie. Hammer middle right. Looking south. (See p58).

e. Folded pipes in core of anticline west of Kempie. In these pipes the $P_2$ and a dimensions are coplanar. See also Figure 10. Looking west.

f. $a_1$ (Crenulation foliation?) in limestone. Roadside west of Kempie. Looking south.

g, h. Photomicrographs of part of III sp. (See Table V and Figure 20). Pipe on left in "g", in centre in "h". The bedding is folded. g = plane polarised light. h = nicols crossed. x 4.5.
PLATE II

Photomicrographs of Kempie rocks.

a. Apparently unstrained Pipe Rock, shore 100 yards east of Kempie. Crossed nicols. x 18.

b, c. Pipe Rock, roadside east of Kempie. Sections from adjacent specimens. "e" is nearer a bedding margin and is more strained than "b". Crossed nicols. x 18.

d. Pipe Rock

Foliation, s_i, is incipiently developed. Limonite filled fracture cleavage, s_i_b, is parallel to s_i_a. Plane polarised light x 18.

e. Basal Quartzite near contact with Lewisian. Crossed nicols. x 18.
The quartzite has partially recrystallised. s_i_a is well developed.

f - h. Crenulation foliation and folded chert bands in limestone, Fucoid Beds, Kempie.

f. Folded chert band parallel to bedding. Ore filled fracture cleavage, s_i_b, is parallel to s_i_c. Plane polarised light. x 18.

g. Partly different field from same section as "f". Crossed nicols. x 18.

h. s_i_c in the axial plane of a microscopic f_i_a fold. Crossed nicols. x 18.
PLATE III

a - e  Glencoul Nappe, Glen Coul.

f - h  Lewisian Gneiss, Moine Nappe.

a.  Fold core in Basal Quartzite near the Stack of Glencoul.  Looking south.

b.  Deformed Pipe Rock near the Stack.  Looking south.


d.  Sections of deformed pipes, Lochain Feith an Leothaid.


g.h.  Lewisian Gneiss of the upper "μ-rock", Glen Coul.  Crossed nicols.  g. x 18.  L. x 4.5.
Moine Nappe, Glen Coul.

a. Large scale fold (f_1 or f_II?) in Pipe Rock south-east of Loch an Eircill. Axis 130°, 14° S.E. Axial plane - 335°, 30° N.E. Rucksack right centre. Looking south-east.

b. Locality and rock as "a". f_II fold. Axis - 0°, 9° N. Axial plane - 335°, 20° N.E. Looking north.

c. f_II fold in Basal Quartzite south-east of Loch an Eircill. Axis - 299°, 0°. Axial plane - 299°, 15° S.W. Looking south-east. The lineation, l_IIa, is folded by this fold.

d. Locality and rock as "a". f_II fold. Axis 262°, 16° E. Axial plane - 230°, 30° N.E.

e. f_II folds, north of An Sniomh. Looking east.

f. f_II folds in mylonite, Stack of Glencoul. Looking south-east.

g. f_II fold core in Moinian schist, Glen Coul. Plane polarised light. x 4.5.

h. As "g". Crossed nicols.
PLATE V

Moine Nappe, Glen Coul.

f_III folds.

b. Locality as "a". Looking north.
d. South-east of the Stack. Looking north.
e. Locality as "a". Looking south-east.
f. Locality as "a". Looking south.
g. Glen Coul. Looking east.
h. f_III folds on right, f_II folds on left. North of An Sniomh. Looking south-east.
PLATE VI
Moine Nappe, Glen Coul.

a. Set III foliation, $s_{III}$, defined by platy quartz crystals in the axial plane of an $f_{III}$ fold, Glen Coul. In the bottom left of the microphotograph $s_{III}$ is defined by white mica which is oblique to $s_{III}$ above and which is parallel to pre-existing compositional layering. Crossed nicols. x 18.

b. Mica laths defining $s_{III}$:
Note the incipient crenulate nature of the foliation in the mica cluster on the right. Crossed nicols. x 18.

c. $f_{III}$ folds in mylonite, Stack of Glencoul. Plane polarised light. x 4.5.

d. Part of "c" showing that the foliation $s_{II}$ is folded by $f_{III}$. Crossed nicols. x 18.

e. $f_{IV}$ monoclinal folds. Glen Coul. Looking west.

f. $f_{IV}$ folds in Moine south-east of Loch an Eircill.
Looking south-east.

g. $k_{IV}$ kink-band, south-east of the Stack of Glencoul.
Looking east. Note the $f_{II}$ folds to the left of the hammer head.

h. Photomicrograph of $k_{IV}$, Glen Coul. Plane polarised light x 4.5. Note the $f_{II}$ fold right centre.
PLATE VII

Sangomore Klippe, Durness.

Photomicrographs of Klippe rocks.


b. Moinian metasediment, near Sangomore Church. \( s_{II} \) foliation incipiently developed. Crossed nicols. x 18.

c. Mylonite, near Sangomore Church. Opaque layers are mostly epidote and ores. Light layers are mostly quartz. Plane polarised light. x 4.5.

d. Deformed Basal Quartzite from above the Moine Thrust-plane, Sango Bay. Foliation is \( s_{II} \). Crossed nicols. x 18.

e.f. \( f_{II} \) folds in mylonite, near Sangomore Church. e - Plane polarised light x. f - Crossed nicols. x 4.5.

g. \( f_{III} \) folds in mylonite, Sango Bay. Axial plane fractures are characteristic of these folds in mylonite. Plane polarised light x 4.5.

h. Part of the core of an \( f_{III} \) fold in mylonite, Sango Bay. The foliation, \( s_{II} \), is folded by \( f_{III} \). Crossed nicols, x 18.
a. $f_{III}$ folds in mylonite in bay north-west of Sango Bay. Looking east.

b. Grey Durine Limestone (bottom right) overlain by reddish "sole rock" (Beside hammer) which is, in turn, overlain by Basal Quartzite and mylonite. The Moine Thrust-plane is at the base of the Quartzite.

c - e Photomicrographs of fold ($f_{IV}$) in "sole rock".

c. Plane polarised light. x 4.5.

d. Crossed nicols. x 4.5.

e. Part of "d". Foliation $s_{IV}$ is folded by $f_{IV}$.
   Crossed nicols. x 18.
PLATE IX
An Pharaid Klippe, Durness.

a. \( f^\text{II} \) fold in Lewisian Gneiss, Gob nan Leac. Looking south-east.

b. \( f^\text{II} \) folds in Moinian psammites beneath Lewisian. Looking east.

c. \( f^\text{II} \) fold on left with \( f^\text{III} \) folds on its lower limb. In psammite below Lewisian. Looking east.

d. \( f^\text{II} \) folds in marble of Moines below Lewisian. Looking east.

e. \( f^\text{II} \) folds in Lewisian south of Gob nan Leac. Looking North-east.

f. \( f^\text{II} \) folds in Lewisian Gneiss, Gob nan Leac. Looking south-east.

g. Photomicrograph of Lewisian Gneiss near lower contact with Moines. Clouded felspar phorphyroblasts are common. Crossed nicols. x 18.

h. Lewisian Gneiss, Gob nan Leac. The gneiss has apparently suffered complete recrystallisation as a result of Set II metamorphism. Crossed nicols. x 18.
Photomicrographs of Moinian Rocks. Crossed nicols. x 18.

a - c. Moine psammite from above the Lewisian Gneiss.
   a. Section normal to foliation, $s_{II}$, and parallel to lineation, $l_{II}$.
   b. Section normal to both foliation and lineation.
   c. Section parallel to foliation.

d. Moine pelite from beneath the Lewisian Gneiss.

$s_{III}$ foliation is defined by mica laths and clusters. Note the incipient crenulate nature of $s_{III}$ in the left mica cluster.
a - g. An Fharaid Klippe, Durness.

a. $f_{III}$ fold in Lewisian Gneiss. Looking north-west.

b,c. $f_{III}$ folds in pelites beneath the Lewisian.
   b - Looking north-west. c - Looking east.

d. $f_{III}$ folds in psammites beneath the Lewisian.
   Looking east.

e. Open $f_{IV}$ folds in Lewisian of Gob nan Leac.
   Looking north-west.

f,g. Monoclines ($f_{V}$) in Moine psammites on the shore beneath Cnoc nan Sgliat.
   f - Looking north. g - Looking south.

h. Section of Pipe Rock from Skiag Bridge, Loch Assynt (see Appendix III). Pipe is parallel to bedding. Plane polarised light. x 4.5.
ABSTRACT OF THESIS

Name of Candidate  ANDREW J. McLEISH

Address  NELSON COTTAGE, NEW ROAD, BATHGATE, WEST LOTHIAN.

Degree  Ph.D.  Date  15th NOVEMBER, 1967.

Title of Thesis  A STRUCTURAL STUDY OF THE MOINE THRUST ZONE IN SUTHERLAND.

Three areas - at Kempie (Loch Eckiboll), Glen Coul and Durness, - have been studied. This thesis is primarily concerned with detailed structural analysis but, in addition, at Kempie and Glen Coul, strain analyses of deformed Pipe Rock are presented. The methods used in calculating strain and shear parameters are fully described.

The systems of symbolic nomenclature of Rast (1958) and Turner and Weiss (1963) have been examined and, in the author's opinion, found inadequate for describing structural histories. In this study a symbolism based on the Boolean concept of sets has been developed and used.

At Kempie, the folded and faulted Cambro-Ordovician of part of the Arnaboll Nappe are described. Pipe strain has been related to fold geometry in an attempt to analyse the possible mechanisms by which the various planar, linear and fold structures developed. The major folds are of modified concentric type. Inter-bedding slip during folding has apparently contributed, in large measure, to pipe deformation.

At Glen Coul, parts of the Glencoul and Moine Nappes have been studied. Strain analysis of deformed Pipe Rock lying within the Moine Nappe has shown that the dominant east-south-east plunging lineation defines a direction of significant positive strain. The dominant fabric and the mylonites are thought to have resulted from approximate pure strain deformation. Christie's (1963) structural analysis is critically reviewed; his conclusions that the Moine Thrust is a strike-slip fault developed synchronously with mylonitisation, and that the north-south folds formed in response to movement on the Ben More Thrust are considered to be in error.

The existence of the Sangomore and An Fharaid klippen indicates a minimal displacement of six miles on the Moine Thrust-plane. There is no positive evidence of the direction of displacement but the geometries of minor folds under the Moine Thrust in Sango Bay suggest that movement took place either from east to west or from west to east.

These analyses are comparable with structural histories described by various workers in other parts of the Moine Thrust Zone and it appears that the Thrust Zone has, throughout its length, a common history differing only in detail from place to place. The extreme local variability of strain within the Pipe Rock requires that strain analyses of deformed Pipe Rock cannot be used to measure variations of regional strain throughout the Moine Thrust Zone.
Durness: Geological and structural map.

Legend:

- Strike and dip of bedding ($b_0$) and foliation ($s_0$ and $s_1$)
- Strike and dip of foliation ($s_1$)
- Direction and plunge of lineation ($l_{10} \rightarrow l_{31}$ and $l_{12} \rightarrow l_{31}$)
- Direction and plunge of minor fold axis ($f_{10} \rightarrow f_{31}$ and $f_{12} \rightarrow f_{31}$)
- Direction of horizontal axis

Legend:

- $a_2$: Limestone
- $a_1$: Quartzite
- $M$: Moinian
- $A$: Lewisian Gneiss
- $G$: Gabbro

Geological boundaries

MTP: Moine Thrust-plane

Normal fault with direction of downthrow
Kempie, Loch Eriboll: Geological and structural maps.

Legend

- $a_5$: Durness Limestone
- $a_4$: Serpulite Oolit
- $a_3$: Fucoid Beds
- $a_2$: Pipe Rock
- $a_1$: Basal Quartzite
- $a$: Undifferentiated
- $M$: Rocks of the Moine Nappe
- $A$: Lewisian Gneiss

- $T$: Strike and dip of bedding ($a_2$)
- $T'$: Strike and dip of cleavage and foliation ($s_1$)
- $t_{a}$: Direction and plunge of grain elongation lineation ($l_{a}$)
- $t_{b}$: Direction and plunge of $b_{b}, f_{b}$ intersection lineation ($l_{b}$)
- $t_{l}$: Direction of $l_{b}$ where horizontal
- $t_{f}$: Direction and plunge of axes of minor folds ($f_{a}$)
- $t_{p}$: Direction and plunge of deformed pipes ($p_{a}$)