THE STRUCTURAL AND METAMORPHIC HISTORY OF MOIDART,
SOUTHWEST INVERNESS-SHIRE.

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I. INTRODUCTION

1. LOCATION, ACCESS AND TOPOGRAPHY

The area studied is that part of Moidart, in Southwest Inverness-shire, shown on Fig. 1. To the south, the boundary is the north shore of the North Channel of Loch Moidart and part of the north shore of Loch Shiel. The eastern boundary follows the eastern edges of Inverness-shire six-inch sheets, numbers 157 and 148; north, to the saddle at the head of Gleann Dubh, between Rois Bhein (Roshven) and Sgùrr Domhuill Mòr. The northern boundary passes westwards down Gleann Dubh, to join the south shore of Loch Ailort near Roshven House, thence westwards and southwards round the coast.

Access to the area is made via Strontian on A.801. This road degenerates to B.350 at Salen and the latter just penetrates the southeast corner of the area. Small scattered communities, centred at Smearisary and Glenuig have no roads to them. They can be approached by ferry boat from Lochailort, about six miles away.

Topographically the area is one of a rugged plateau sloping gently to the west and north, and cut by the valley of the Moidart River. The highest ground lies near the northeast corner where Sgùrr Domhuill Mòr rises.
LOCATION OF AREA STUDIED

FIG. 1

SKYE  KNOYDART

SOUTH MORAR

EIGG

AREA STUDIED

MOIDART

ARDNAMURCHAN

SCALE OF MILES

0 1 2 3 4 5 6
rises to 2,337 ft. From this summit the ground falls steeply northwards, down into Gleann Dubh, then more gently westwards. West of the summit of Sgùrr Domhuill Mòr, the surface slopes fairly steeply down to near Loch nam Paitean, at an elevation of 1,300 ft. From here the plateau inclines gently westwards and northwards, and is cut by north-south trending Glenuig. A ridge rising to about 1,000 ft. separates Loch Shiel from the Moidart River.

Hill lochs occur frequently on the plateau, in bowl shaped corries and other depressions. These lochs were useful when mapping as they served as easily recognised aids to location. Drainage of the area between the Sound of Arisaig and Loch Moidart, is mostly to the north, with the watershed, a very irregular line, lying well south of the centre of the mainland. Fast southerly flowing streams, often with waterfalls, drop a thousand feet or more in about half of a mile. Northerly flowing streams tend to be longer and less rapid. They are sometimes deflected from the northerly course into a northwest trend, when they follow a system of strong joints that have broken the rocks and allowed an easily eroded gully to form.

Westwards moving ice has played an important role/
role in moulding the present surface. Superficial detritus has been scraped away, leaving the rocks fresh and well exposed, see Plate 1. Glacial striae on flat pavements indicate a west-northwest direction of movement. Roches Moutonnée are common. Glen Moidart is a U-shaped valley, and many small streams joining the Moidart River and Loch Moidart, drop from the plateau in a series of waterfalls, from hanging valleys. In places near the top of Glen Moidart, the Moidart River meanders over the wide floor of Glen Moidart. Near Loch Moidart, an artificial channel has been cut to control the river.

The surface of the plateau is strewn with erratics and perched boulders, left behind by the ice, but boulder clay and fluvio-glacial deposits are uncommon. Post glacial lacustrine deposits occur along the north shore of Loch Shiel.

Small raised beaches at about 25 ft. level are found at Forsy, Glenuig, Smearisary and Egnaig. A further feature of the old sea level is manifest by frequent caves behind these beaches. The largest area of recent sediment occurs at the head of Loch Moidart, where the meander plain of the Moidart River conceals the solid geology. Unimportant, small, recent accumulations of detritus, occur/
occur where turbulent streams discharge their load, at the base of the slope leading to the plateau, before flowing in a more sluggish manner to join the lochs and river.

Recent accumulations of peat have formed on low-lying, boggy ground. Apart from this, a thin covering of heather and rough grass on poor, shallow soil, is all that conceals the rocks. Exposure over the entire area is very good and for miles round the coast, complete exposure is available.

The flat surface of the plateau supports poor heathery moorland vegetation, but the north and south slopes leading to the plateau are covered in deciduous (oak) forest. Inaccessibility, heavy scree and rank bracken, make it difficult to map these slopes.
5.

I. INTRODUCTION (continued).

2. HISTORY OF RESEARCH

The common boundary between one-inch Sheet 61 in the north and 52 in the south, passes through the Moidart peninsula. Although these sheets have been mapped by the Geological Survey, the one inch geological maps have not been published. There is no published memoir by the Geological Survey, describing the geology of Moidart.

The Geological Survey was mapping Sheet 52, to the south of Moidart by 1921. J.E. Simpson and V.A. Eyles, under the direction of E.B. Bailey and J.E. Richey, traced the Carna Pelitic belt from Carn Mor at the mouth of Loch Moidart, to Carna in Loch Sunart. In general this belt has an outcrop width of about a mile, but due to folding, it increases in width near Loch Sunart, to about 2½ miles. It was observed to consist of three main divisions. Eastern and Western bands of garnet gneiss are separated by a mixed assemblage of pelitic, semipelitic and psammitic rocks, in which sandy calcareous seams are frequently found. At the south shore of the South Channel of Loch Moidart, V.A. Eyles found that the middle division was almost half of a mile broad, but north of the North Channel, it is reported to be much reduced in width (Summary of Progress for 1921 and 1933).

The/
The psammitic gneiss to the east of the Carna Pelitic differs from that to the west in that it shows no recognisable pebbles of quartz and feldspar, and is often very massive and bare of vegetation. In the Geological Survey Summary of Progress for 1921 (p. 90), E.B. Bailey writes, "The difference of character of the two psammitic belts flanking the Carna Pelitic makes it difficult to account for the inconstancy of the middle division of the latter as a result of folding." On tracing the pelitic rock from Carn Mor to the north coast of the North Channel, it was observed to have decreased in width from one and a half miles to three quarters of a mile.

To the south of Loch Moidart, E.B. Bailey noted an angular discordance between the Carna Pelitic and the massive psammitite to the west. Further south a flaggy psammitite is found between the Carna Pelitic and the massive psammitite to the west. Bailey thought that this plane of discordance may be due to movement at the time of folding or to a stratigraphical unconformity, (Summary of Progress for 1921 pp. 89-90).

East of the psammitic belt that is itself to the east of the Carna Pelitic belt, there is a minor band/
band of garnetiferous pelitic and semi-pelitic gneiss, the latter is succeeded to the east by another belt of psammitic gneiss. The presence of numerous garnetiferous seams in this psammitic gneiss, resembling the garnet-zoisite seams in the Carna Pelitic, serve to distinguish it from that immediately to the east of the Carna Pelitic.

The Geological Survey returned to Moidart during 1930 when A.G. MacGregor and W.Q. Kennedy worked over the area. J.E. Richey reported (Summary of Progress for 1930, p. 63), "In the west the (Moine) schists are affected solely by regional metamorphism but elsewhere they have undergone more or less intense injection metamorphism resulting in the production of various types of injection gneisses."

Work on Sheet 52 was still in progress during 1933 and that year, J.E. Richey (Summary of Progress for 1933, p. 67) states that north of the North Channel of Loch Moidart "the Carna Pelitic, accompanied on either side by psammitic schists, has been traced northwards of Eilean Shona to the northern margin of Sheet 52, where the belt is much reduced in width." Mapping of Sheet 52 was completed during the summer of 1934 and field work progressed northwards into Sheet 61 (Mallaig).

J.E. Richey
J.E. Richey began mapping in Morar during 1935 and discovered abundant sedimentary structures that enabled him and W.Q. Kennedy to establish the following succession, between Mallaig and Arisaig (J.E. Richey and W.Q. Kennedy, 1936, Rep. Brit. Assoc.).

   c) Upper Striped Schists with calc-silicate layers.

2. Striped and Pelitic Group.
   b) Pelitic Schists.
      a) Lower Striped Schists.

1. Lower Psammitic Group.

This succession was estimated to have a total thickness of 19,000 ft. and was first reported by J.E. Richey in the Summary of Progress for 1935. Here, Richey (1935, p. 79) is confident that there is no duplication of beds due to folding, in the lower part of the Lower Psammitic Group. He states that "Almost every bed shows false bedding and indicates the order of deposition. Without exception the beds are younger towards the west. Further, the average thickness of individual beds is only 9 inches."
Exposure is so good that it is possible to say without hesitation that repetition of the beds by folding does not occur. Isoclinal folding has been seen nowhere. The thickness, therefore, of this subgroup is considerable, and must amount to many thousands of feet."

V.A. Eyles returned to Moidart during 1937, to map the area that lies within Sheet 61, from Smearisary eastwards, and north to the south shore of the Sound of Arisaig. This work is very briefly reported by J.E. Richey (Summary of Progress for 1937, pp. 71 and 72) where he noted that Eyles traced the pelitic, semi-pelitic and psammitic schists mapped on Sheet 52, northwards to the Sound of Arisaig.

By this time the Morar succession was established, and with this new data available Richey, Bailey and Simpson, revisited various localities in the western part of Sheet 52, during 1937. The purpose of the revisit was to compare the Moine Schists in Sheet 52, with the stratigraphical succession established in Morar, (Summary of Progress for 1937, p. 71). Work on Sheet 61 continued during 1938 and in that year V.A. Eyles and W.Q. Kennedy revisited Moidart. J.E. Richey (Summary of Progress for 1938, pp. 71 and 72) records/
records how Eyles was able to correlate the psammitic schist to the east of Glenuig with the Upper Psammitic Group of the Morar Succession. In discussing the southern shore of Loch Ailort and westwards towards Glenuig, J.E. Richey states, "There the Upper Psammitic belt of Ardnish continues in an outcrop over 4 miles in width and is bounded to the west in the vicinity of Glenuig by a rather narrow anticline, mainly overturned towards the west. The centre of this fold is occupied by a thinly bedded psammitic series which evidently represents the upper part of the Lower Psammitic Group of Morar, with the nearest outcrop of which, on the northern shore of the Sound of Arisaig, it agrees lithologically. Along the eastern limb a group intervening between the two psammitic groups is comparable with the Striped and Pelitic Group of Morar."

In Morar the Striped and Pelitic Group is subdivided into three:

iii) laminated schists with calc-silicate layers.

ii) Garnetiferous pelitic schists.

i) laminated semi-pelitic schists without calc-silicate layers.

J.E. Richey describes how, along the western limb of the narrow anticline mentioned above (The Glenuig Anticline), the/
garnetiferous pelite is flanked by attenuated Lower and Upper Striped Sub-groups of Morar. The Upper Striped Sub-group is then succeeded westwards by inverted, calc-silicate bearing, psammite. The latter is identical with the Upper Psammitic Group on the eastern side of the anticline, east of Glenuig. Two examples of erosion surfaces, found in the inverted Upper Psammitic Group, indicated that this horizon is younger than the overlying Striped and Pelitic Group.

The great significance of these observations is clearly stated by J.E. Richey, (Summary of Progress for 1938, p. 72). "The reading of the Glenuig section is of especial importance for the elucidation of the Moine Schists in Sheet 52 to the south, as may be judged from the fact that the striped and pelitic belts of the western and eastern limbs of the Glenuig fold are the direct continuation respectively of the Carna and Dorlin pelitic and striped belts of Sheet 52. The intervening psammitic schists in the core of the Glenuig anticline correspond with the Ben Laga psammitic belt of Sheet 52, with which they are continuous. The Ben Laga group, therefore, may now be correlated almost by direct evidence with the Lower Psammitic Group of Morar, and thus forms the central member of/
of an anticline which crosses Sheet 52 from north to south
in a position corresponding with the Morar anticline."

J.E. Richey and W.Q. Kennedy published the results
of their work in Morar in 1939 (Bull. of Geol. Survey.
No. 2.). Here they give a more detailed version of the
Stratigraphical succession and the thicknesses of the
three main divisions in Morar are given:

3) Upper Psammitic Group 12,000 ft.
2) Striped and Pelitic Group 3,500 ft.
1) Lower Psammitic Group 3,500 ft.

The authors describe the sedimentary structures that enabled
them to establish the succession. This succession is
compared with that found in Central Ross-shire (Sheet 82),
and Northern Ross-shire (Sheet 93).

In Morar two series of metamorphic rocks were
recognised. The Moine Schists proper, that yielded the
succession described above, overlie a structurally complex
series of orthogneisses and paragneisses, designated the
Sub-Moine Series; a term suggested by A.G. MacGregor and
adopted by Richey and Kennedy. The structure of the
Moine Schists is stated to be simple and is described as a
north south trending anticline, plunging south in South
Morar, and north in North Morar. Separating the Moines
from/
from the Sub-Moines is a plane of unconformity. Richey and Kennedy considered that recumbent folding, metamorphism, and denudation of the Sub-Moine Series, took place before the Moine Series was deposited.

In addition to the structural and metamorphic dissimilarities between the two series, Richey and Kennedy noted the absence of calc-silicate ribs in the Sub-Moine Series. They also noted abundant pleochroic yellow epidote in the Sub-Moines; epidote was also found in the Moine Series but there it occurred as colourless scattered grains.

A. G. MacGregor visited Morar during 1947 and later, (1948) pointed out that calc-silicate rocks do occur in the Sub-Moine Series, as well as in the Moine Series. He concluded (1948, p. 268) that his new evidence suggested that "all the psammitic rocks at the head of Loch nam Uamh (including those previously referred to the Sub-Moine) should be assigned to the Moine Series."

After a re-investigation of Morar, Kennedy (1954, issued 1955), modified his original interpretations. The complex structure in the Moine-like rocks (previously referred to as Sub-Moines) is considered to be "parts of the normal Moine succession of the envelope reduplicated tectonically at a lower structural level and interfolded with/"
with slices of the basement Lewisian Gneiss." Both the Moine-like rocks and the Moine series of Morar are believed to be part of the Moine Nappe, (sensu lato), and have suffered transportation above the Moine Thrust. In this revised interpretation the normal Moine Series (the "envelope" schists) is separated from the Moine-like rocks (the "core" schists) by a plane of discordance, termed the Basal Thrust of the Morar Nappe. The formation of the Morar Nappe is thought to belong to an early phase of movement during which the complex structure seen in the core schists was imprinted. After this early movement there was a second movement that formed the Morar Anticline and this was succeeded by a period of regional injection and metamorphism. The Moine Thrust post-dates the regional injection and metamorphism.

In his re-appraisal of Morar Kennedy has made some important modifications to the original work done in conjunction with J.E. Richey. Whereas the Sub-Moine Series (now designated the "Moine-like rocks") was thought to have suffered folding, metamorphism and denudation before the Moine Series of the "envelope" was laid down, Kennedy now links the Moine Series of the "envelope" with the Moine-like rocks of the "core". The Morar Basal Thrust (the Base/
Base of the Morar Nappe, that separates the "core" from the "envelope", has been obscured by post-deformational regional metamorphism. This recent interpretation by W.Q. Kennedy aroused considerable interest and a good deal of criticism as can be seen from the discussion that follows the paper (Kennedy, 1955).

An earlier paper by W.Q. Kennedy (1949) described metamorphic zones indicated by variations in the mineral constituents of calc-silicate granulites. Kennedy demonstrated an increase in metamorphic grade from west to east, as the "injected zone" is approached. Four stable critical mineral associations, that by reaction pass one into the other, were recognised:

Group 1. garnet - zoisite - acid plagioclase - biotite
(biotite + calcite (zoisite) → hornblende) Reaction.

Group 2. garnet - zoisite - acid plagioclase - hornblende.
(2 zoisite → 3 anorthite + Ca (OH)$_2$) Reaction.

Group 3. garnet - anorthite (bytownite) - hornblende.
(hornblende → pyroxene) Reaction.

Group 4. garnet - anorthite (bytownite) - pyroxene.

W.Q. Kennedy/
W.Q. Kennedy correlates these mineral groups with Eskola's standard facies and divides part of Western Inverness-shire and N.W. Argyll into four metamorphic zones. (see Fig. 2.). These zones are named according to the leading index minerals or critical phases of each facies:

1. Zoisite - (calcite) biotite zone.
2. Zoisite zone.
3. Anorthite - hornblende zone.
4. Anorthite - pyroxene zone.

W.Q. Kennedy equates them with the Barrovian zones as follows.

<table>
<thead>
<tr>
<th>Calc-silicate zone.</th>
<th>Barrovian zone.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoisite - (calcite) biotite zone</td>
<td>Garnet zone.</td>
</tr>
<tr>
<td>Zoisite zone.</td>
<td>Kyanite zone.</td>
</tr>
<tr>
<td>Anorthite - hornblende zone.</td>
<td>Sillimanite zone.</td>
</tr>
</tbody>
</table>

In discussing his results, Kennedy considers Southwest Skye where there are three tectonic units namely, Moine Schists, Tarskavaig Moine Schists and Torridonian of the Kishorn Nappe; each is separated by a thrust plane. All three/
MAP OF METAMORPHIC ZONES IN WESTERN INVERNESS-SHIRE AND N.W. ARGYLL

FIG 2 FROM W. Q. KENNEDY 1949
three units are thought to be one great formation affected by regional metamorphism that decreases westwards. Subsequent thrusting has eliminated some of the stages of metamorphism. He therefore agrees with B.N. Peach (Peach and Horne, 1930), in correlating the Moine Series with the Torridonian.

R. St. J. Lambert (1958) has recently reinvestigated the Moine - Sub-Moine boundary, in Morar. He has concluded that it is a metamorphic boundary that transgresses the geological boundaries. A revised version of the stratigraphy is given and is compared with the sequences put forward by Richey and Kennedy (1939), MacGregor (1948) and Kennedy (1955), see fig. 3. In his conclusion Lambert states - "The Moine schists of Morar are thought to have been affected by a progressive and a subsequent retrogressive metamorphism on the basis of general petrographic evidence. Only the core schists were affected on a major scale by the retrogressive metamorphism, the outer limit of which is marked by the core-envelope boundary which, though generally mappable in the field as a line, is actually a zone of transition of variable width as now exposed." (Lambert, 1958, p. 193).
| TABLE 1 |
|-----------------|-----------------|-----------------|-----------------|
| **Richey and Kennedy 1939** | **MacGregor 1948** | **Kennedy 1955** | **Lambert 1958** |
| Upper Psammitic Group m³ | MOINE Stratigraphic succession | MOINE with associated orthogneisses | MOINE (envelope) |
| Striped and Pelitic Group m₁^{1c} m₂b m₂a | | Striped and Pelitic Group m₁^{2c} m₂b m₂a | MOINE (envelope) |
| Lower Psammitic Group m₁ | MOINE with associated orthogneisses | Lower Psammitic Group m₁ | MOINE (envelope) |
| Unconformity | | Thrust | |
| Lower Psammitic Group m₁ | | Lower Psammitic Group m₁ | MOINE (core) |
| Pelitic Group g₁' | SUB-MOINE Structural succession | Lower Psammitic Group m₁ | MOINE (core) |
| Intermediate Psammitic Group x₁' | | Central Psammitic Group m₁ | |
| Hornblende Group h | | (Base not seen) | |
| Subsidiary Pelitic Group g | | Thrusts | |
| Central Psammitic Group x | | Orthogneisses A LEWISIAN | |

**FIG. 3. (FROM LAMBERT 1958)**
In a recent publication R. St. J. Lambert (1959) studies the chemical composition of muscovite, biotite and garnet, in Morar and Knoydart. These minerals all show variation of composition with increasing metamorphic grade. The core schists do not carry garnet, instead the garnet is replaced by biotite - muscovite - epidote aggregates, locally with chlorite. Biotite and muscovite in the core have compositions similar to micas occurring on the West Coast, within the Biotite zone.

Although Lambert has studied evidence "from every source save that of microfabric analysis", he is not able to reach any firm conclusion about the detailed nature of the metamorphism responsible for the core schists. He reiterates his former conclusion that the boundary between the core and envelope is a metamorphic zone, and "is the outer limit of large-scale retrogressive activity, due to diffusion rates and possibly also to low reaction rates in the envelope in which the only widespread change is chloritization of garnet." The retrograde metamorphism is linked with localized renewed folding of the Morar Anticline, that took place after initial folding and regional metamorphism had affected the rocks. This early regional metamorphism increased in grade eastwards towards the "injection/"
"injection zone."

J. Phemister (Regional Guide, 1960, p. 31) gives a brief summary of the regional features of the "injection zone." "Recent survey in the western Highlands has proved that the injection-gneisses of the Loch Duich-Loch Hourn area are continuous with the belt of pegmatitic injection which runs north and south across Loch Shiel. The injection complex of the western Highlands thus extends for a distance of 60 miles from the Sound of Mull north to Loch Duich, its width varying from about 10 to 16 miles."

He goes on to say (1960, p. 32). "The injection-complex of Knoydart, Morar, Moidart and Sunart has not yet been described in detail. The injection is of both lit-par-lit and permeation types, yielding banded injection-gneiss, augen gneiss, and permeation gneiss indistinguishable from those of the Loch Coire Complex. The parent body of the injecting magma is not exposed, but pegmatite and granite occur locally in cross-cutting veins and concordant sheets and lenses among the injection gneisses, and are particularly concentrated along the "great pegmatite belt" about 1 1/2 miles wide, which runs north and south across the north end of Loch Shiel."

J.E. Richey/
J.E. Richey (Summary of Progress for 1930, pp. 63 and 64) reported the original work done in Moidart in the "injection zone", by A.G. MacGregor and W.Q. Kennedy (see p. 7). It is recorded, "The injection begins in force east of a line drawn from Salen on Loch Sunart to Kinlochmoidart House, and eastwards increases noticeably in intensity. It is especially obvious in a pelitic or semi-pelitic host. There is every variation between schists with pegmatitic or granitic strings and lenticles, lit - par - lit injection gneisses and permeation gneisses." Pegmatitic and granitic material occurs locally as cross-cutting veins and concordant intrusions. Either sheets or lenticles are frequently seen to invade the adjacent schists along the foliation and to form typical injection gneisses. The majority of the injected gneisses examined contain oligoclase as their feldspathic component, and the grain of these rocks is much coarser than that of the non-injected rocks to the west. In some rocks potash feldspar is abundant. The typical rocks of the injection-zone are garnetiferous, muscovite, biotite gneisses. Richey goes on to say that in rocks of the "injection zone", staurolite is sometimes present and sillimanite is locally abundant.

Tourmaline/
Tourmaline was found in pegmatites and adjacent gneiss.

W.T. Harry (1953), has recently worked on the granitic gneiss of Western Ardgour, a short distance to the east of Moidart, and has described the occurrence of oligoclase - biotite - quartz gneiss and potash-rich granitic gneiss. The former is believed to have formed by soda metasomatism of normal pelitic Moine rocks. (Harry op. cit. p. 300). The granitic gneiss is considered to be younger than the oligoclase - biotite - quartz gneiss because aplite granitic veins cut oligoclase - biotite - quartz gneiss. Also, large patches of the latter are enclosed by the granitic gneiss. Harry believes that the granitic gneiss was formed by metasomatism and replacement of oligoclase - biotite - quartz gneiss within a short time of the formation of the latter. This point hangs on inconclusive negative evidence (that there are no intrusions that pre-date one gneiss and post-date the other), also on textural evidence of crystallisation deformation structures in both gneisses (Harry, op. cit. p. 304).

In Moidart, the Geological Survey (Summary of Progress for 1930) found that sheets, and subordinate dykes of lamprophyre and coarser grained rocks, allied to the Lower/
Lower Old Red Sandstone appinites of the Glen Coe district (Bailey, 1916), are often abundant, particularly in Glenmoidart. The lamprophyres were thought to resemble some of the luciites and orbites of the Odenwald.

A few west-north-west trending dykes to the north of Loch Moidart, are cut by dykes of the Tertiary swarm. The former are pink decomposed porphyrites, resembling spessartite, and are therefore considered to be of Lower Old Red Sandstone age. Broad dykes and elongate bosses of quartz-dolerite, striking east and west, were recorded as a general feature of the area and were equated with the Permo-Carboniferous suite. The dykes and bosses are sometimes crowded with xenoliths of quartzite. They affected intense contact alteration in the adjoining schists, and spinel bearing hornfelses have been developed. Dykes of camptonite and monchiquite are frequent and are occasionally associated with lead-bearing veins. The Tertiary dykes which trend in a north-south direction, are especially abundant in Moidart. Many are reported to be feldsparphyric dolerites of tholeiitic affinities (Summary of Progress for 1930, p. 64).
Structural Analysis in the Highlands.

The axiom that minor structures parallel major structures with which they are genetically related, is well established in structural geology. These minor structures occur as folding, mullion, rodding and lineation, and are usually abundant in areas of folded rocks. Thus it is possible, by mapping the minor structures, to deduce the location and nature of major structures that may not be obvious in the field. Structural analysis is based on this premise.

In a series of papers published between 1950 and 1952, D.B. McIntyre drew attention to the widespread occurrence of minor structures that parallel the axis of folding, and demonstrated the parallelism between minor axial structures and major structures, in the Scottish Highlands. He showed how minor axial structures can be used in a structural analysis, to interpret areas of complex folding.

Recent work by Sander, Ramsay, Weiss and others has contributed considerably to our knowledge of patterns shown by the orientation of lineation and the effects of superposed folding. The results of their work are summarised below.

1)./
1). Flexure of a lineated surface.

Sander (1948) has shown that when a lineated surface is deformed by flexure folding - s-active flow (Weiss, 1956) or Concentric folding (de Sitter, 1956) - the lineation is rotated in such a way that, when it is plotted on a stereonet, it comes to lie along a small circle. This small circle is centred on the axis of flexure that has caused the lineation to be rotated.

2). Deformation of a lineated surface by shear folding.

Weiss (1959) and Ramsay (1960) have shown that the effect of shear or Similar folding (see de Sitter, p. 182, et. seq.), on a lineated surface is to deform the lineation so that when its orientation is plotted on a stereonet it lies along a great circle. Both authors also state that intermediate patterns that are neither great circles nor small circles on the stereonet, result where the movement that deforms the lineated surface is a combination of shear folding and flexure folding. Weiss (1959) regards this situation as the most likely to be found in nature. Ramsay (1960) considers that the majority of the folds seen in the Highlands, are Similar folds.

3)./
3). Superposition of a lineation on an already folded surface.

Sander (1948) shows that a lineation overprinted on a folded surface lies within a plane that is related to the stress that formed the lineation. The orientation of the superposed lineation depends upon its position on the folded surface. When the varying orientations are measured and plotted on a stereonet, they lie along a great circle. This pattern is therefore the same as that found in 2) above, but there the folding occurred after the lineation was imprinted. It is therefore of considerable importance to demonstrate the relative ages between lineations and folding in refolded rocks, before discussing the significance of lineation patterns. This point will be discussed later (see p. 148).

4). The effects of repeated folding.

In a composite paper Clifford, Fleuty, Ramsay, Sutton and Watson (1957) describe the development of lineations in areas of repeated folding. They stress the importance of correlating linear structures with the major structural elements with which they are related, before discussing the significance of linear or microfabric data.
In areas where refolding has taken place about an axis that does not parallel the original fold axis, the early linear structures and axial planes are distorted by later movement. Also the orientation of the linear structures produced during the later movement is affected by the attitudes of the s-planes on which they are imprinted. In this way, complex linear patterns evolve. Nevertheless, it is possible by detailed mapping, to demonstrate that such complexities in the linear pattern are due to refolding and that simple parallelism between related lineations, fold axes and major structures, exists.

The authors stress that observations on axial planes and axial plane foliation are of particular importance in areas of repeated folding. If it can be shown that the axial planes of one fold movement are refolded by another fold movement, the relative ages of the two movements, are established.

Weiss (1959) showed that "In general, cylindroidal folds of a later generation are on a smaller scale than those of an earlier generation because they form only in fields where s remains planar after the earlier folding." (Weiss, 1959, pp. 105-106).
5). Location of the \( a \) kinematic axis.

Ramsay (1960) and Weiss (1959) have recently shown the development of a great circle pattern on a stereonet, when an early lineation is deformed by a later Similar fold (see 2). above). They also show that the kinematic \( a \) axis (i.e. the direction of tectonic transport) of the Similar fold lies within this great circle. The kinematic \( a \) axis also lies within the shear plane surfaces of the fold. Therefore the line of intersection of a plane representing the shear surfaces and the great circle pattern of the early linear structure, defines the kinematic \( a \) axis. Ramsay shows that this axis need not necessarily be normal to the fold axis.

The structural analysis of Moidart is based on the foregoing principles. Ramsay's recent demonstration of the location of the \( a \) axis is of particular interest and attempt will be made to determine the directions of tectonic transport of the fold movements found in the area studied.

Petrofabrics.

Structural geologists have demonstrated the parallelism between minor structures and associated major structures. An analogous situation occurs in petrofabrics where/
where workers have shown how the internal grain fabric of rocks can be correlated with associated macroscopic features on the rocks. Thus the scale of related structures ranges from microscopic to regional.

The earliest analyses of grain fabric were made with the aid of a gypsum plate, and detailed grain fabric investigation using a Universal Stage was first carried out by Schmidt in 1925. Twelve years later Phillips (1937) introduced the method to Britain by applying it to a petrofabric study of rocks in the Scottish Highlands.

Grain fabric studies are carried out using the Universal Stage, with thin sections of known orientation. The orientations of a particular mineral feature, such as the optic axes of quartz crystals, or the poles to mica cleavages, are determined and the results plotted on the lower hemisphere of an equal area net. About 300 observations from one slide are usually sufficient to portray the fabric of a specimen, when quartz c-axes are measured. In the case of mica poles to cleavage more than one slide may be required, cut from the specimen along planes of different orientation, before the complete fabric of the rock can be measured. After plotting, the points are contoured, and the resulting diagram may then be rotated so as to view the fabric in its correct field orientation.
In this way, slides from the same specimen that have been cut at differing orientations can be conveniently viewed together. Also the grain fabrics of different rocks can be compared with one another and studied with regard to the macroscopic features related to the grain fabrics. Macroscopic features are shown on the fabric diagrams and whenever possible the relationship between the macroscopic features and the fabrics is shown.

Quartz has been found to be a useful mineral for petrofabric analysis and in many cases rocks that have suffered metamorphism associated with deformation yield a girdle fabric of quartz optic axes. Maxima or maximum frequently occur within the girdle.

In his pioneer work "A fabric study of Some Moine Schists and Associated Rocks." Phillips (1937) gives a brief description of the methods employed and the uses of such a study. The value of fabric analyses is stated to be threefold. Firstly they allow a more complete petrographic description of a rock. Secondly the fabric shows how the components of a rock have responded to movement within the rock, during metamorphism. Thirdly by studying the microfabric it is possible to construct a more complete picture of the tectonics of the area from which the specimen was collected.

The/
The early work by Phillips aroused some criticism. E.M. Anderson (1948) did not agree with Phillips that the lineation seen on the schists was developed in h and that the movement that gave rise to this lineation over much of the North-west Highlands, was in the south-west by north-east sense. He pointed out that Kvale working in Norway (1945) found lineation in a. Similarly, lineations observed on Highland rocks are thought by Anderson to parallel the direction of transport. On this assumption linear structures with southeasterly plunge found near the thrust planes in the North West Highlands can be correlated with the supposed direction of thrust movements. As knowledge of structures accumulated from later work, it was generally accepted that the main lineations in the Moine are in h. The anomalous orientation of h linear structures near the thrust zone is now explained by attributing them to movement episodes that were not connected with the period of clean cut thrusting.

During 1955 the British Association, meeting in Bristol, held the first symposium on structural petrology to be held in Britain. Summaries of recent work by Christie, Wilkinson, Crampton, Johnson and Goldring, together with the discussion that followed are reported. This work is mainly concerned/
concerned with the complex fabric associated with the northwest thrust zones.

Also during 1955 Weiss, McIntyre and Kursten carried out fabric studies on specimens from the complex Ord Ban area, Mid-Strathspey. They found that the fabric could be related to two distinct structures with separate B-axes that had formed at separate times. The importance of "controls" in fabric work cannot be overstressed, especially in specimens from complex structural and metamorphic areas. Each specimen should be carefully selected from areas where the structural history is known and visible features on the specimen should be fitted into the known structural picture. Clifford et. al. (1957) have stated that it is premature to discuss the significance of fabric studies when the structure is unknown.

Many workers have carried out fabric studies on Moine schists but none of this work has been done in Moidart. However, the principles employed as outlined above, and the application of petrofabric work to structural problems are relevant to the problems in Moidart.
I. INTRODUCTION (continued).

3. OBJECT OF THESIS AND OUTLINE OF RESULTS.

The area studied lies due south of Morar and astride the western boundary of the "Injection Zone". It lies within the "steep belt" of Moine schists described by G.P. Leedal (1952). The Morar Anticline with its complex "core schists" plunges to the south in South Morar, and the Moine Series seen in Moidart is at a structurally higher level than the core of the Morar Anticline. Moidart is entirely underlain by the southern continuation of the "envelope schists" of Morar.

The object of the thesis is to study the geology of the Moine schists in Moidart, and by structural analysis, to present an interpretation of the sequence of events in the structural history of the schists. An attempt is made to correlate the results obtained with the published works on the structure of Morar. The transition between rocks with nearly horizontal fold axes in the west of the area and rocks with steeply inclined fold axes in the east, is studied. An interpretation of how this transition has taken place is given. The metamorphic history of the rocks is described and discussed. This is correlated with the structural/
structural history and the main events that occurred during metamorphism are dated with respect to the relative ages of the fold movements recognised by structural analysis.

Structural analysis indicates the relative ages of four fold movements. Two other fold movements of uncertain age are also recognised. Isoclinal minor folds formed during the first fold movement, but no major folds of this episode can be recognised. The style of these isoclines suggests that they may be correlated with the recumbent folds described by W.Q. Kennedy in the core schists in Morar. W.Q. Kennedy is of the opinion that the Morar recumbent folds formed at the same time as the Morar Nappe and so the isoclinal folds in Moidart are provisionally correlated with the movement that formed the Morar Nappe.

Tight asymmetric folds formed during the second fold movement. Many large folds of this age are recognised and one of these - The Glenuig Antiform - is correlated with the Morar Anticline. Fold axes of the second folds were nearly horizontal and after this movement the rocks in the east of the area were left steeply inclined. The third fold movement formed two major folds in the east of the area, and bent the axial planes and axes of the second folds. The second fold axes remained nearly horizontal after the third/
third fold movement. Fourth folds only occur in pelitic rocks within the "Roshven Pelitic Belt" in the east of the area studied. A calculated kinematic axis for fourth folds, plunges steeply to the southwest. It is thought that the nearly horizontal axes of the second folds, were tilted into the present steep plunge in the east of the area mapped, as a result of this movement. In the rocks to the west, the second fold axes are unaffected by the fourth fold movement.

The metamorphic grade in the area studied rises from Garnet in the west to Sillimanite in the east. Garnets in the west show two phases of growth. The first growth occurred between the first and second fold movements, and the second growth occurred during the second fold movement. The age of sillimanite in the east is not known, but it is tentatively suggested that it may have developed at the same time as the first garnet seen in the west. Migmatization occurred throughout a period that began after the first fold movement but before the second fold movement and perhaps continued until after the second folds had formed. Retrograde metamorphism took place after the most recent fold movement.
II. STRATIGRAPHY AND PETROGRAPHY.

1. STRATIGRAPHY.

The Moidart Peninsula is entirely underlain by Moine metasediments that have a prevalent north-south trend. In Morar, five miles north along the strike, across the Sound of Arisaig, J.E. Richey and W.Q. Kennedy found abundant sedimentary structures in the Moines and were able to determine the original order of deposition of the sediments. They give the following sequence (1939):

3. Upper Psammitic Group. (upwards of about 12,000 ft. near Arisaig).

b). Massive and well-bedded pink siliceous feldspathic granulitic schists, often finely pebbly with frequent semi-pelitic beds. False bedding and slump folding frequent.

a). Well-bedded greyish or white quartzose and feldspathic granulitic schists, with frequent semi-pelitic beds. False bedding abundant and slump-folding frequent.


b). Garnetiferous Pelitic Schists. Sometimes divisible into: (iii) garnetiferous pelitic schists, (ii) striped schists with calc-silicate layers, (i) garnetiferous pelitic schists.

a). Lower Striped Schists. Mainly laminated schists as in (c) but with psammitic laminae more developed, and with ribs of coarse psammitic schist. Calc-silicate bands absent.

c). Thinly bedded granulitic schists without false-bedding (absent in North Morar and Knoydart).

1. Lower Psammitic Group. (about 3,500 ft. near Mallaig).

b). Pink or grey feldspathic granulitic schists, often finely pebbly with pebbles up to an inch in diameter, and with frequent semi-pelitic beds. False-bedding frequent, and slump-folding occasionally seen.

a). Thinly bedded granulitic schists without false-bedding (absent in South Morar).

Richey and Kennedy (1939) believe that this sequence is of wide regional significance in the North West Highlands. They consider that the following features may be of value in elucidating the stratigraphy of other regions.

"1). Ribs of coarse-textured psammitic schist are characteristic of the Lower Striped Schists (2 a) along both/
both limbs of the Morar anticline.

2). Calc-silicate bands and magnetite-zoisite seams are a feature of the Upper Striped Schists (2 c). The first mentioned bands also occur near the base of the Upper Psammitic Group (3) and in the Garnetiferous Pelitic Schists (2 b), but have never been found in the Lower Striped Schists (2 a).

3). A peculiar sedimentary rhythm characterizes the Upper Striped Schists (2 c). It consists in a rapid alternation of laminated schists and psammitic bands, the latter centred by the narrow layers of calc-silicate rock."

Geological Survey officers have correlated the psammitic rocks that occupy the core of the Glenuig Antiform in west Moidart with the Ben Laga psammitic belt in Ardnamurchan and with the Lower Psammitic Group of Morar (see introduction pp. 10-12). They have also correlated the psammitic schists to the east of Glenuig with the Upper Psammitic Group of the Morar succession. The pelitic rocks found in the east of Moidart are not fitted into the Morar succession but the writer is of the opinion that they are probably structurally higher than the Upper Psammitic Group (see p. 129). This area of pelitic rock has been designated the Roshven Pelitic Group. Garnetiferous calc-silicate ribs are/
are distributed throughout the Roshven Pelitic Group. Since these ribs are not found in the Lower Striped and Pelitic Sub-group and the Lower Psammitic Group, their presence in psammitic bands within the Roshven Pelitic Group suggests that these bands do not represent the Lower Psammitic Group. This supports the structural evidence that the Roshven Pelitic Group is probably higher in the Moine Series than the Upper Psammitic Group.

Richey and Kennedy were fortunate in finding many examples of sedimentary structures that allowed them to determine facing directions in Morar. Sedimentary structures are rare in Moidart (Plate 2) and this fact, together with the complex structure, makes it impossible to estimate stratigraphic thicknesses. The following is a summary of the sequence in Moidart based on the writers observations and the correlation between Morar and Moidart given by the Geological Survey (see pp. 10-12).

A complex group made up of, 1) garnetiferous pelitic gneisses occasionally with sillimanite, staurolite and kyanite. Thin psammitic bands and calc-silicate ribs. 2) Banded semi-pelitic gneisses and quartzose feldspathic granulites with calc-silicate ribs. 3) Quartzose granulites.

b) Well bedded quartzose and feldspathic granulites. Occasional calc-silicate ribs. Pale grey or blue grey. Frequent indistinct cross bedding.

a) Well bedded or massive pale grey or white, quartzose and feldspathic granulitic schists. Garnetiferous semi-pelitic bands and occasional calc-silicate ribs. Occasional false bedding.

b) Garnetiferous Pelitic schists. Striped schists with calc-silicate ribs.

a) Striped and finely laminated schists. Frequent thin, coarse grained stripes.

Thinly bedded pink and pale grey feldspathic granulitic schists.

1). Lower Psammitic Group.

c) Pale grey and dark grey, massive and well bedded quartzose and feldspathic granulites. Occasional calc-silicate ribs.

b) Well bedded quartzose and feldspathic granulites. Occasional calc-silicate ribs. Pale grey or blue grey. Frequent indistinct cross bedding.

a) Well bedded or massive pale grey or white, quartzose and feldspathic granulitic schists. Garnetiferous semi-pelitic bands and occasional calc-silicate ribs. Occasional false bedding.

b) Garnetiferous Pelitic schists. Striped schists with calc-silicate ribs.

a) Striped and finely laminated schists. Frequent thin, coarse grained stripes.
II. STRATIGRAPHY AND PETROGRAPHY (continued)

2. DISTRIBUTION OF ROCK TYPES.

a). Lower Psammitic Group.

This Group comes to the surface in the core of the Glenuig Antiform near the west coast of the peninsula. It outcrops as a north-south trending belt about 3,000 ft. wide, passing through Loch na Bairness. Variable dip and complex structures make it impossible to estimate the thickness of the Group. A large north plunging S-shaped fold half of a mile east of Loch na Bairness (see Map 1) brings psammitic rock to surface in its antiform core and widens the breadth of Lower Psammitic Group near the North Channel of Loch Moidart to approximately 5,000 ft.

The upper limit of the Lower Psammitic Group grades into the lower limit of the Striped and Pelitic Group with increasing amount of pelitic and finely striped schists.


The Striped and Pelitic Group outcrops as two sub-parallel belts of rock that trend north-south, flanking the Lower Psammitic Group. The lines of outcrop are marked by/
by the two ridges that form Snearisary Hill (648, 755) in the west and Egnaig Hill (662, 753), Cruach na Bairness (660, 760) and Monadh Gleann Uige (660, 763) in the east.

The western outcrop is inverted and dips eastwards at about 50° under the Lower Psammitic Group. Although the dip is fairly consistent along the exposed strike-length of nearly two miles the horizontal width decreases from 3,000 ft. in the south to 1,000 ft. in the north. The western limit of the Striped and Pelitic Group is clearly defined by a sharp contact between garnetiferous pelitic schist and quartzose psammitic schist; the latter is the inverted basal member of the Upper Psammitic Group.

Folding has made the lower (west) contact of the eastern outcrop a very irregular line, (see Map 1). This contact is again transitional but the upper contact of the Striped and Pelitic Group is very sharp and often well exposed. Garnetiferous pelitic schist is overlain by well bedded granulitic schist. In the south, where the Striped and Pelitic Group meets the North Channel of Loch Moidart, it has a horizontal width of 1,500 ft.


Over half of the area mapped is underlain by granulitic/
granulitic schists of this group. Two areas of outcrop occur:

i). In the west a thin strip approximately one thousand feet wide forms the rocky western seaboard. Here the quartzose granulites are inverted and dip eastwards under the Striped and Pelitic Group, at about 50°.

ii). The main area of Upper Psammitic Group extends from the line joining Glenug Bay and the east end of Shona Beag eastwards, to a north-south line that passes through the east of Loch nam Paitean. This represents an outcrop width of nearly four miles. The outcrop width is maintained across the peninsula from north to south.

The prevalent strike trend is north-south but departures from this occur, particularly near the eastern limit of the outcrop where complex folding is found. Exposure throughout the area is very good and coast sections two miles long in the north, and one and a half miles long in the south, are available.

Complex folding is often seen in the Upper Psammitic Group and here again no estimate of the thickness can be made. Both the lower contact with the Striped and Pelitic Group in the west, and what appears to be the upper contact, with the Roshven Pelitic Group in the east, are sharp.
d). Roshven Pelitic Group.

The main area of Roshven Pelitic Group occurs in a strip approximately one mile wide, along the eastern boundary of the area mapped. This strip was mapped from Loch Shiel in the south to Gleann Dubh in the north, a distance of five miles.

Outlying to the west of the main Roshven Pelitic Group, there is a thin belt of semi-pelitic schist approximately one thousand feet wide. This can be seen passing to the west and north of Loch nam Paitean and eventually thinning out to the north near Gleann Dubh. This strip lies in the trough of a synform, formed during the second fold movement.
11. STRATIGRAPHY AND PETROGRAPHY (continued).

3. PETROGRAPHY

a). Lower Psammitic Group.

The upper part of this group is seen in Moidart. In hand specimen the rocks are pale grey or pinkish grey, thinly banded, fine or medium grained, feldspathic granulitic schists. They part along a smooth schistosity that is parallel to the thin banding, to expose a sparkling surface. When broken across the banding the surface is usually rough and the pale grey or pinkish grey bands often exhibit "pepper and salt" appearance, due to scattered small biotite crystals. Quartz, feldspar, muscovite and biotite can be recognised.

Under the microscope the rocks are seen to be recrystallised. They show granoblastic texture and are banded with fine or medium grain-size (see Plate 31a). Weak lepidoblastic texture occurs in the more micaceous dark bands. Quartz and feldspar, in about equal amounts, make up the bulk of the rock. Muscovite and biotite are abundant. Epidote and sphene are common, often occurring in bands.

Quartz/
Quartz.

Equidimensional, xenoblastic crystals of quartz with irregular boundaries form an interlocking mosaic. The average crystal size is about 0.2 mm but occasional lenticular aggregates, about 4.0 mm long and elongate parallel to the banding in the rock, are made up of crystals about 1.0 mm across. Some crystals are unstrained though others show straining with marked undulose extinction. The latter is particularly prevalent in the larger (1.00 mm) crystals. In some cases there is distinct banding seen in the rock, caused by crystals of varying size.

Feldspar.

Untwinned or weakly twinned sodic plagioclase of albite (An₆; nᵢ 1.530 ± 0.002) composition is the most abundant feldspar. It occurs as equidimensional, xenoblastic crystals about 0.2 mm in diameter. Alteration to sericite is seen round the periphery and encroaching into the crystal along the cleavage. Many crystals are fresh some are cloudy with incipient alteration. No intergrowth was observed. Occasional porphyroblasts up to 1.0 mm in diameter occur.

Microcline is sometimes present in small amounts as small xenoblastic equidimensional crystals. It is usually/
usually evenly scattered throughout the rock. The crystals have irregular boundaries and no intergrowth was observed. Some crystals are cloudy in ordinary light, indicating incipient alteration.

Micas.
Both muscovite and biotite occur. The mica content varies considerably, particularly towards the upper limit of the Lower Psammitic Group. Occasional thin semi-pelitic bands are interbedded with the granulitic schists. The texture in such bands is lepidoblastic and the rocks develop good schistosity. The ratio of muscovite to biotite varies but, on average, they are in nearly equal amounts.

In quartz feldspar granulite (psammitic schist) the micas sometimes show random orientation but more commonly they are poorly oriented parallel to the compositional banding seen in the rock. This is especially true where there is considerable mica content in the dark bands. Sometimes, even though the micas show concentration in dark bands, the crystals are oriented oblique to the bands.
It is thought that the banding represents original compositional banding while the mica orientation is the result of recrystallisation under stress.

Muscovite/
Muscovite occurs as hypidioblastic crystals. In slices cut normal to the banding the crystals are seen as lath shaped sections up to 0.4 mm in length; the majority of sections are about 0.25 mm long. The crystals are usually fresh and cleavage planes are rarely bent. Alternating crystals of muscovite and biotite occasionally occur together to form blocks of mixed micas.

Biotite also occurs as hypidioblastic crystals about the same size and shape as muscovite. Pleochroism is:

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y and Z</th>
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<tbody>
<tr>
<td>1) pale yellow</td>
<td>Dark yellowish brown</td>
<td></td>
</tr>
<tr>
<td>2) pale yellow</td>
<td>Olive green</td>
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The variety showing pleochroism to dark yellowish brown is the more common. Alteration to chlorite is occasionally seen and takes place along the cleavage planes, forming alternating layers of biotite and chlorite.

Epidote.

Epidote is a fairly common constituent and occurs as nearly equidimensional hypidioblastic crystals up to 0.3 mm in width. Crystals often show pale yellow colour and weak pleochroism but many are colourless and can be seen growing around orthite cores. Frequently the crystals are found/
found scattered throughout the rock but they also occur concentrated in the dark bands.

**Sphene.**

Hypidioblastic crystals of sphene are not nearly as common as epidote. The sphene may develop up to 0.14 mm in length but is usually less than 0.2 mm.

Garnet is rare or absent in the quartz-feldspar granulites.

Interbedded with the quartzose schists described above are occasional, usually thin, semi-pelitic bands in which muscovite and biotite make up about half of the rock. Schistosity is well developed and under the microscope the mica minerals are seen to be well oriented in the plane of schistosity, but some stubby biotites grow oblique to the schistosity and occasionally, nearly at right angles to it. Biotite is again predominantly pleochroic from pale yellow to dark yellowish brown and frequently shows alteration to chlorite. The medium grain groundmass is made up of nearly equal amounts of quartz and sodic plagioclase.

With the development of coarser grained "striping" and increasing mica, this group passes upwards into the Striped and Pelitic Group. Rapid alternation of grain size imparts/
imparts a banding on the rocks and thin semi-pelitic bands occurring with fine and coarse grained quartzose granulites are a feature of the upper members of the Lower Psammite Group. The bands are sometimes less than two inches thick.


This group has been divided into three Sub-groups in Morar and the Geological Survey have also briefly referred to three Sub-groups in Moidart (see p. 10). The writer has not been able to recognise these Sub-groups. In Moidart there is an increase in the amount of pelitic schist as the Striped and Pelitic Group is traced from its base to its top. The lower contact with the Lower Psammite Group is a very gradational one while the top of the Striped and Pelitic Group is usually well defined by a prominent band of garnetiferous pelitic schist. Some bands of medium or fine grained, finely laminated psammite schist do occur interbanded with garnetiferous pelitic schist, near the top of the group.

Calc-silicate ribs are fairly common particularly towards the top of the Striped and Pelitic Group along the north shore of the peninsula. The frequency of calc-silicate ribs in Moidart falls far short of the frequency in Morar and calc-silicate ribs are more common along the north shore/
shore of Moidart than the south shore.

1) Striped and finely laminated schists.

In hand specimen these schists are medium grey or bluish grey in colour merging into dark grey with increase in biotite. They are usually thinly bedded and often show fine stripes that are caused by very thin coarser grain-ed bands. The stripes are often numerous and though thin, they are quite persistent over several yards. At one locality on Egaig Hill (662, 753) one hundred and thirty stripes were counted in one foot. The stripes often occur in groups separated by thin medium or fine even grained bands of granulitic schist. With a hand lens the coarser grained stripes are seen to be minutely corrugated and it is this feature that imparts a strong lineation on the foliation. When broken along the schistosity the more micaceous schists have a high lustre.

Under the microscope the schists are seen to be recrystallised and are of fine or medium grain. They show granoblastic texture which merges into lepidoblastic texture with increasing mica content. Quartz and feldspar make up about 60% or less of the rock; the remainder is predomin-antly muscovite and biotite.

Quartz/
Quartz.

Quartz occurs as small xenoblastic crystals. Where it is in contact with other crystals of quartz or feldspar, the mutual boundary is very irregular. The crystals rarely exceed 0.2 mm in diameter and are usually equidimensional. Both strained and unstrained crystals occur.

Feldspar.

The feldspar, determined by maximum symmetrical extinction, is oligoclase (An₃₄) and occurs as xenoblastic equidimensional crystals about 0.2 mm wide. They form a mosaic pattern when in contact with quartz or other feldspar crystals. No intergrowth between quartz and feldspar was observed. The majority of crystals are untwinned but many show lamellar twinning. For the most part the crystals are unaltered or show cloudy appearance in ordinary light.

Micas.

Muscovite and biotite occur in varying amounts. There is usually slightly more biotite than muscovite. In the more micaceous schists the micas impart a good schistosity and are well oriented; in the less micaceous quartz feldspar mica granulitic schists the micas are less well/
well oriented. Sometimes the micas are not aligned parallel
to the bedding but have taken up orientation in the axial
plane cleavage of small folds. Occasional crystals show
slightly bent cleavage.

Muscovite occurs as hypidioblastic crystals seldom
exceeding 0.2 mm in length of lath-shaped cross-sections.
With increasing mica content the average crystal size also
increases, occasionally giving crystals 0.1+ mm in length.
This mineral is nearly always fresh and is sometimes found
with biotite in alternating very thin bands. In the more
micaceous rocks muscovite crystals form a spindle round
garnet porphyroblasts. In such cases the crystals are
rarely bent and usually they "felt" around the porphyro-
blasts.

Biotite resembles muscovite in habit. It is
pleochroic from very pale yellow to dark yellowish brown,
sometimes with a faint greenish tinge. Pleochroic haloes
are sometimes abundant and the crystals are usually fresh.

Garnet.

Garnet is more common with increasing mica content
when porphyroblasts up to 2.0 mm occur. In rocks with less
mica the garnets are seen as small xeno blastic ragged
crystals, often with many inclusions and sometimes rather
cloudy; biotite sometimes occurs with the cloudy garnets.
In rocks with larger garnets the porphyroblasts are again xenoblastic and contain many inclusions of quartz. The inclusions form trails within the garnet and are usually of smaller size than the crystals forming the matrix of the rock.

**Sphene.**

Sphene occurs as small hypidioblastic or idio-
blastic crystals and is usually rather more common than apatite and epidote, the only other accessories in any significant amounts.

In rocks where cleavage is well developed, apart from the preferred orientation of mica minerals, quartz and feldspar also show slight elongation in the cleavage planes. These minerals may also show slight elongation in semi-pelitic schists when they tend to occur in lenticular aggregates and are sometimes elongated along the schistosity.

Quartz and quartz carbonate veins are seen to be rather more coarse grained than the matrix with crystals measuring 1.0 mm across. The mutual boundaries between quartz crystals are sutured and the crystals invariably show severe straining.
2). Striped and Pelitic Group (continued).

ii). Garnetiferous mica schist.

Weathered surfaces of the schist are studded with garnets that sometimes measure half of an inch, but are usually about one quarter of an inch across. The matrix of the schist weathers away leaving the garnets projecting and in the field accumulations of garnets, weathered out of the rocks can be found in hollows and cracks. Weathered surfaces vary in colour from dark grey to pale brownish grey and quartz feldspar folia are occasionally seen. When freshly broken along the schistosity the colour is usually dark grey. Muscovite reflects the light to give a silvery lustre to the rock. Garnets are not usually seen on freshly broken surfaces but their presence is indicated by the "knotted" appearance of the schistosity, where muscovite and biotite provides a thin covering over the garnets.

With a hand lens red or pale reddish brown garnet, muscovite, biotite, quartz and feldspar, can be recognised.

Under the microscope the schists are seen to be of medium grain with variable amounts of micaceous minerals. Garnet porphyroblasts are prominent and are often altered (see Plate 31,b). The texture is predominantly lepidoblastic/
lepidoblastic and the micas are fairly well oriented. The rock is recrystallised.

**Quartz.**

Xenoblastic, equidimensional, inequigranular crystals of quartz range in size from less than 0.05 mm to more than 0.5 mm. The average grain size is between 0.15 mm and 0.3 mm. When quartz crystals are in contact with feldspar or other quartz crystals they form an interlocking mosaic and show granoblastic structure. Straining varies from weak to severe; some crystals are unstrained.

Occasional lenticular quartz-feldspar folia about 5.0 mm thick occur. In such folia the quartz is more coarsely crystalline (1.0 mm) and has sutured boundaries. Straining is severe.

Sometimes bands of granulated quartz and feldspar with very fine grained crystals can be seen cutting across the schistosity.

**Feldspar.**

Feldspar is of oligoclase composition (An 25) and occurs as xenoblastic, inequigranular, equidimensional crystals, similar in size and habit to quartz. Lamellar twinning is fairly common but some crystals are untwinned.
Slight alteration to sericite is fairly common round the periphery and this can be seen penetrating into the crystals along cleavage planes. Many crystals are quite fresh.

**Micas.**

Hypidioblastic micas impart lepidoblastic structure to the schist. Muscovite and biotite occur in nearly equal amounts and show considerable range in crystal size from very small lath shaped cross-sections to sections about 2.0 mm long. The most common size is about 0.25 mm. In general the micas are well oriented in the plane of schistosity but some stubby crystals grow oblique or at right angles to the schistosity. The micas are sometimes concentrated in folia about 0.6 mm apart and separated by a quartz-feldspar granoblastic mosaic. Within this mosaic randomly oriented small micas occur.

Where the schistosity is crinkled the mica cleavages are rarely bent and the crinkles are usually formed by crystals meeting at angles. Cleavages are also largely straight where micas form a spindle round garnet porphyroblasts; occasional bent cleavages can be found.

Muscovite often occurs in close association with biotite and occasionally alternating very thin crystals of muscovite/
muscovite and biotite occur together. In the mica spindles that develop around garnet porphyroblasts muscovite is usually more abundant than biotite.

Biotite shows pleochroism from very pale yellow to dark yellowish brown or deep amber. Pleochroic haloes are locally abundant and are nearly always present. Alteration takes place to chlorite. For the most part biotite with muscovite forms the schistosity or appears as randomly oriented very small lathes between mica folia, in predominantly quartz-feldspar mosaic, but very small biotite crystals also occur with chlorite and clinozoisite as the result of alteration of garnet porphyroblasts.

Garnet.

Hypidioblastic or xenoblastic garnet porphyroblasts up to 5.0 mm in diameter are of particular interest because of the variety of structures they exhibit; this will be dealt with later (see p. 174).

The garnets are of almandine or spessartite composition, with refractive indices that range from 1.784 to 1.802. Peripheral cracks with reticulate pattern and strong sub-parallel cracks that pass through the crystals, are common. Two phases of crystal growth can often be seen/
seen where an inner idioblastic core is surrounded by garnet showing xenoblastic or hypidioblastic shape. This feature is also exemplified by the alignment of abundant quartz, feldspar and mica inclusions within the porphyroblasts (see p. 172).

After regrowth the garnets suffered alteration that has resulted in a chlorite, biotite, muscovite and clinozoisite zone around the garnet. This zone is often seen to make embayments into the garnets and often penetrates beyond the outer garnet into the core garnet. Alteration sometimes takes place along cracks that can be seen cutting across the boundary between the idioblastic core garnet and the outer garnet. Clinozoisite occurring in the alteration assemblage is sometimes concentrated in a zone around the altered garnet.

The mica minerals and chlorite in this alteration zone are unoriented.

**Accessory minerals.**

Small idioblastic acicular crystals of apatite are fairly common and opaque iron mineral is also found. Clinozoisite occurs as occasional small hypidioblastic crystals that are slightly prismatic.
FIG. 4

BARROVIAN METAMORPHIC ZONES

SCALE 0 1 2 MILES

CALC-SILICATE METAMORPHIC ZONES

SCALE 0 1 2 MILES

iii). Calc-silicate granulitic schist.

In addition to the two main rock types described above the Striped and Pelitic Group also carries calc-silicate ribs that are most common near the upper limit of the group. In the field the calc-silicate rocks are recognised as white or pale cream coloured bands up to two inches thick. They are usually fairly persistent and can be traced for several yards.

In hand specimen pale brown garnets up to one quarter of an inch in diameter can be seen in a pale grey or white matrix. Biotite in variable amounts can usually be recognised.

Under the microscope it can be seen that zoisite is the leading index mineral and sometimes there is a considerable amount of biotite, indicating that these calc-silicates ribs lie within W.Q. Kennedy's Zoisite Zone. This is as Kennedy indicates on the map of metamorphic zones (see Fig. 2), but it may be that the biotite-(calcite)-zoisite zone boundary should lie slightly further east than is indicated by Kennedy.

The calc-silicate ribs are recrystallised rocks with porphyroblastic structure. The matrix has granoblastic or/
or weakly lepidoblastic structure, depending upon the amount of biotite and muscovite present.

Zoisite.

Hypidioblastic or idioblastic crystals of zoisite are abundant and in some cases make up about 80% of the matrix of the rock. The crystals usually show prismatic habit but they vary in shape from equidimensional crystals less than 0.1 mm in diameter to long prismatic crystals up to 1.0 mm in length. Most commonly stubby prismatic crystals about 0.2 mm in length with the long axes aligned in the foliation plane occur (see Plate 28a). Cracks normal to the length of the crystals are very common.

The crystals most commonly show low birefringence with a dull grey interference colour but sometimes anomalous blue is also found. Some crystals are length slow while others are length fast.

Biotite.

Biotite varies in amount but is always less abundant than zoisite. Pleochroism is from pale yellow to deep yellowish brown and inclusions with pleochroic haloes are fairly common. The crystals are hypidioblastic and are usually aligned with the cleavage sub-parallel to the foliation/
foliation but many crystals appear to be randomly oriented. The biotite crystals are frequently aggregated in lenticular folia and often reach 1.0 mm in length of cross-section. Zoisite inclusions are fairly common and alteration to chlorite is sometimes found.

**Garnet.**

Garnet porphyroblasts up to 4.0 mm in diameter are common and vary in shape from idioblastic to xenoblastic. Some crystals are almost free of inclusions while others show poeciloblastic structure with abundant inclusions of quartz. The inclusions are sometimes arranged in bands across the garnets.

Most garnets are fresh but some show very slight alteration to chlorite and biotite around the periphery and along cracks. In some cases the weak foliation which is defined by the sub-parallel alignment of the long axes of zoisite prisms, can be seen sweeping around the garnet porphyroblasts.

**Quartz.**

Xenoblastic, equidimensional, equigranular quartz crystals with irregular smooth boundaries occur interstitially between zoisite. The average crystal size is 0.1 mm and the majority show straining.

**Feldspar.**/
Feldspar.

Feldspar crystals are of similar size and habit as the quartz crystals described above. Alteration to sericite makes it difficult to determine the composition but they appear to be acid plagioclase. There is no intergrowth between quartz and feldspar.

Muscovite.

Muscovite is less common than biotite. It usually occurs as fairly large crystals up to 1.0 mm in length and is frequently associated with biotite in lenticular folia. The majority of crystals are oriented with the cleavage planes sub-parallel to the folia but some are found with cleavage planes making any angle with the folia. Small zoisite crystals are often included within the muscovites.

Sphene.

Small idioblastic or hypidioblastic crystals of sphene rarely exceed 0.2 mm in size. They occur scattered throughout the zoisite rich matrix or are aggregated in patches of sphene-zoisite mosaic, up to 2.0 mm in diameter.

Hornblende.

Hornblende is occasionally present and occurs as xenoblastic or hypidioblastic crystals sometimes showing poeciloblastic structure. The pleochroic formula is:

\[ X/ \]
Crystals vary in size up to 1.5 mm and are found associated with biotite, zoisite and sphene. Inclusions of zoisite are common.


The writer has divided this group into three sub-groups (see p. 39). These sub-groups are not clearly defined; one merges with the other and rock types of one sub-group can appear within any of the others. For these reasons general descriptions of three rock types are given, namely: 1). Quartz feldspar granulitic schists, ii). Semipelitic schists, iii). Calc-silicate granulitic schists. This is preceded by a brief description of the field characteristics of the sub-groups.

Sub-group a).

This is largely made up of massive and well bedded, white and pale grey quartz feldspar granulites. False bedding is locally fairly common but the order of deposition could only be determined at a few localities (see Plate 2 and Map 1). Generally the cross stratification cuts across between bedding planes, without showing any curvature.

Semi-pelitic/
Semi-pelitic bands up to four feet thick, with garnet and feldspar porphyroblasts, are interbedded with the granulites.

Sub-group b).

Well bedded sometimes flaggy quartz feldspar granulitic schists make up the most of this sub-group. The colour varies from pale grey to bluish grey with increasing biotite content and small reddish-brown garnets occur in the bluish grey biotitic granulites. Interbanded semi-pelitic layers with feldspar porphyroblasts and occasional garnetiferous, biotitic, sphene rich, bands occur. The semi-pelitic bands decrease in thickness and frequency, towards the east. Calc-silicate ribs are seldom more than one inch thick.

False bedding is fairly common in some areas but the cross stratification laminae are usually straight and make acute angles with the bedding.

Sub-group c).

This sub-group consists of predominantly pale grey and bluish grey, sometimes pink, massive, well bedded, or flaggy granulitic schists. Occasional garnetiferous semi-pelitic bands and calc-silicate ribs occur. False bedding is rare or absent.

Towards the eastern boundary (i.e. the "top" of the/
the Upper Psammitic Group) there are quartz feldspar folia and these increase in frequency eastwards.


i). Quartz feldspar granulitic schists.

In hand specimen the colour of the granulitic schists varies from white through pale grey to bluish grey, with increase in biotite. The more biotitic granulites often carry small reddish brown garnets. Muscovite is widely distributed and imparts a sparkling appearance to freshly broken surfaces. Pale coloured granulitic schists often show characteristic "pepper and salt" appearance due to small scattered biotite crystals. In some cases the dark minerals are concentrated in bands. Quartz, feldspar, muscovite, biotite and occasionally garnet, can be recognised in hand specimen.

Under the microscope the granulitic schists are seen to be made up of predominantly quartz and feldspar with subsidiary amounts of muscovite and biotite.

Quartz.

Quartz occurs as xenoblastic, inequigranular crystals that are usually less than 0.3 mm in diameter. The relative proportion of quartz to feldspar varies considerably but on average they occur in nearly equal amounts and/
and make up over 80% of the granulitic schist. Crystal boundaries are usually smooth but may be irregular or rounded. This imparts granoblastic or tessellate structure to the rock. In some rocks the crystals are equidimensional but occasionally, strongly lineated rocks are seen to contain crystals that are inequidimensional. Cross-sections of such crystals may be twice as long as they are broad; the long axis lies in the plane of schistosity. The degree of straining varies from unstrained to severe straining.

**Feldspar.**

Feldspar occurs as xenoblastic inequigranular crystals and forms a mosaic pattern with quartz. The average crystal size is about 0.2 mm. Untwinned crystals are very common and this makes it difficult to distinguish sodic plagioclase from potash feldspar. To overcome this difficulty an effective method for selective staining of potash feldspar and plagioclase (Bailey, E.H. and R.E. Stevens, 1960) was used. It was found that potash feldspar and plagioclase sometimes occur together in nearly equal amounts. Usually plagioclase of oligoclase or andesine composition (maximum symmetrical extinction angle indicates a composition up to An 43) is much more abundant than potash feldspar. There is a general tendency for the feldspar to become more/
more basic towards the east.

Myrmekite intergrowth between quartz and plagioclase is rare or absent in the west and becomes common in the east (see Plate 32, b).

The amount of alteration ranges from fresh unaltered crystals to highly altered crystals. The majority of crystals are cloudy in ordinary light indicating incipient alteration and many show small sericite crystals, particularly near the periphery of the feldspars, and penetrating into the feldspars along cleavage planes. Granulitic schists, discoloured to flesh pink along joints and axial planes of late brittle folds (see p. 159), show that the feldspars have been severely altered.

Micas.

Muscovite and biotite are nearly always both present in variable proportions and amounts. They are usually seen as lath shaped cross-sections of hypidio-blastic crystals about 0.2 mm in length; some crystals may grow up to 2.0 mm in length.

The orientation of micas varies and may be:

a). Randomly oriented.

b). Oriented parallel to compositional banding.

c). Oriented oblique to compositional banding.
Random orientation occurs most frequently in granulitic schists with low mica content and small crystals. With increasing mica content there is a tendency for the micas to align parallel to the banding in the rock. At the same time the average crystal size increases and lepidoblastic structure may develop. The third orientation listed above is found in the vicinity of folds and in schists that show cleavage. The mica crystals are aligned in the cleavage planes and it is occasionally seen that although the micas occur concentrated in bands through the rock the preferred orientation of the micas is oblique to the bands.

Both muscovite and biotite may be found together and are sometimes interlaminated. Cleavage planes are rarely bent.

Muscovite occurs as small crystals that are similar in size and shape to biotite crystals, or it may occur as randomly oriented hypidioblastic porphyroblasts up to 2.0 mm in length. Biotite, quartz, feldspar and epidote inclusions occur within the porphyroblasts.

Biotite shows variable pleochroism:

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<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pale yellowish brown</td>
<td>pale brown</td>
<td>dark greenish brown</td>
</tr>
</tbody>
</table>
The variety showing pleochroism to dark brown is much more common than the variety showing dark greenish brown. Inclusions surrounded by pleochroic haloes are fairly common.

Biotite is mostly fresh but may occasionally be slightly altered to chlorite. In rocks discoloured to flesh pink colour along the axial planes of brittle folds the micas are altered to chlorite.

**Accessory minerals.**

*Epidote* occurs as hypidioblastic, inequigranular, equidimensional or slightly prismatic crystals, often with *orthite* cores. There is a tendency for epidote to occur in layers together with idioblastic or hypidioblastic crystals of *sphene* and hypidioblastic or xenoblastic *garnets*. *Apatite* occurs as small idioblastic crystals.

The accessory minerals are usually found as small crystals less than 0.2 mm in size but they may develop up to 0.4 mm.


Interbanded with the granulitic schists described above,
above, and particularly near the Striped and Pelitic Group, there are bands of semi-pelitic schist that may be up to four feet thick.

In hand specimen the semi-pelitic schists are dark grey or nearly black in colour; some carry abundant pale grey feldspar porphyroblasts one eighth of an inch across, while others have abundant reddish brown garnets that may be up to one quarter of an inch. When freshly broken the semi-pelitic schists have a high lustre owing to abundant biotite and muscovite. Biotite, muscovite, quartz and porphyroblasts of garnet or feldspar can be recognised in hand specimen.

Under the microscope the semi-pelitic schists can be seen to be of two types:

a). Garnet, biotite, sphene type, see Plate 33 a.
b). Feldspar, biotite, muscovite type, see Plate 33 b.

Type a) is predominantly made up of biotite that appears as short thick cross-sections of fresh crystals, pleochroic from pale yellowish brown to dark chocolate brown. The crystals are usually poorly aligned and muscovite is rare. Sphene is often abundant and together with biotite fills the interspaces between garnet porphyroblasts.

Type/
Type b) is made up of nearly equal amounts of muscovite and biotite that appear as long thin lath shaped cross-sections and are usually well aligned showing lepidoblastic structure. Potash feldspar porphyroblasts are abundant and sometimes show microcline cross-hatching. They are often crowded with inclusions.

**Biotite.**

Biotite is the most abundant mineral in semi-pelitic schist type a). In this rock the crystals are hypidioblastic and show considerable range in size from small to 1.0 mm in length of cross-section. The most common size is 0.3 mm. In cross-section the crystals are stubby being about half as wide as they are long. The crystals are often poorly aligned and sometimes appear to have nearly random orientation; elsewhere there is a crude alignment in the axial plane cleavage orientation of folds formed during the second generation of folding. Inclusions ringed by pleochroic haloes are fairly common.

In semi-pelitic schist type b) biotite and muscovite occur in nearly equal amounts. Biotites are pleochroic from pale yellow to dark chocolate brown and the crystals are lath shaped in cross-section: the length is about/
about five times the width. Muscovite is frequently inter-
laminated with biotite and both micas are well oriented.
Inclusions in biotite frequently have pleochroic haloes.
The biotite crystals vary in size from small, less than
0.1 mm in length, to large crystals 1.5 mm long. The average
length is about 0.3 mm. Slight alteration to chlorite may
occur.

Muscovite.

Muscovite is rare or absent in type a). When
it is found it occurs as small lath shaped crystals up to
0.3 mm in length.

In semi-pelitic schist type b) muscovite occurs
as abundant hypidioblastic crystals well aligned in the
plane of schistosity. The size and habit is similar to that
described for biotite in this rock type.

Quartz.

Quartz is sometimes uncommon in semi-pelitic schists
of type a). It occurs as xenoblastic, inequigranular, equi-
dimensional crystals filling the interspaces between
biotite crystals. When several quartz crystals occur
together the common boundaries are smooth and they form
granoblastic structure. The majority of crystals are
unstrained/
unstrained but some show weak straining.

Semi-pelitic schists of type b) contain variable and sometimes considerable amounts of small xenoblastic, inequigranular, equidimensional crystals of quartz. The crystal boundaries are irregular and where there is a considerable amount of quartz and feldspar the structure of the schist may depart from lepidoblastic to become granoblastic. The average crystal size may be less than 0.2 mm and both strained and unstrained crystals occur.

**Feldspar.**

Feldspar porphyroblasts, characteristic of type 2) will be described below.

Fresh xenoblastic plagioclase crystals of oligoclase composition (An$_{28}$), occur interstitially between biotites. The crystals rarely exceed 0.3 mm and may be quite rare in some rocks of type a).

In semi-pelitic schists of type b), plagioclase feldspar is common as fresh, xenoblastic, inequigranular, equidimensional crystals, in the matrix of the rock. The composition is near the oligoclase-andesine boundary (up to An$_{35}$). Some crystals show slight alteration to sericite around the periphery. Myrmekite intergrowth with quartz is/
is occasionally found. Many crystals are twinned but many are untwinned. The selective staining method (Bailey and Stevens: 1960) indicated that all the feldspar in the matrix is of plagioclase composition while the porphyroblasts found in this type are invariably of potash feldspar.

**Sphene.**

Idioblastic crystals of sphene that range in size from small up to 1.0 mm in length, are abundant in semi-pelitic schist of type a). The crystals show typical lozenge shaped cross-section and where schistosity has developed the crystals are aligned with the long axes in the plane of schistosity. Sometimes masses of sphene crystals can be seen sweeping round garnets.

Small idioblastic or hypidioblastic crystals of sphene occur as an accessory mineral in semi-pelitic schists of type b).

**Garnet porphyroblasts.**

Garnet porphyroblasts occur in both types of semi-pelitic schist but are most abundant in type a). In this rock they are found as xenoblastic or hypidioblastic crystals, sometimes exceeding 5.0 mm in diameter. The large porphyroblasts show poeciloblastic structure with abundant, randomly aligned, inclusions of quartz, sphene, biotite/
biotite and calcite. The small porphyroblasts are better developed crystals with few inclusions.

In semi-pelitic schist of type b) garnet porphyroblasts measuring 2.0 mm in diameter are xenoblastic, with many randomly aligned inclusions of quartz and feldspar. *Feldspar porphyroblasts.*

Feldspar porphyroblasts only occur in semi-pelitic schists of type b) in which they may reach 4.0 mm in diameter. The crystals are xenoblastic and show poecilo-blastic structure with inclusions of quartz, muscovite and biotite. The quartz inclusions are sometimes very small and elliptical in cross-section. In some porphyroblasts the long axes of the ellipses are aligned parallel to the cleavage of the porphyroblasts, but more usually the inclusions are randomly oriented.

Selective staining revealed that the porphyroblasts are potash feldspar and many crystals show microcline cross-hatching.

Muscovite and biotite crystals forming the matrix of the schist sweep around the porphyroblasts and only occasionally show bent cleavages. It would appear that the micas of the matrix have recrystallised since the porphyroblasts grew.

Accessory minerals./
Accessory minerals.

Epidote with orthite cores occurs as an accessory mineral in both types of semi-pelitic schist. Apatite as small idioblastic crystals may also occur in both types but calcite was only found in type a).


iii). Calc-silicate granulitic schists.

Calc-silicate ribs are not very common in the Upper Psammitic Group but are widely distributed. In the field they can be recognised as thin cream coloured or white bands that seldom exceed 1\(\frac{1}{2}\) inches thickness; pale brown garnets are usually fairly common within the bands. Although the ribs are thin they are frequently persistent and can be traced for several yards.

In hand specimen pale brown garnets can be recognised and in some calc-silicate rocks biotite or dark green crystals of hornblende occur.

Under the microscope the schists are seen to be recrystallised granulites predominantly made up of a quartz, feldspar mosaic, with garnet porphyroblasts. Zoisite is often abundant and in the east hornblende is abundant but is much less common in the west.

The/
The calc-silicate rocks within the Upper Psamm- 
itic Group represent two zones in Kennedy's scheme (see p. 16):

a). Zoisite zone.

Mineral assemblage, Garnet, Quartz, andesine, Zoisite, hornblende and biotite.

b). Anorthite Hornblende Zone.

Mineral assemblage, Garnet, quartz, bytownite and hornblende (see Plate 32 a).

The Zoisite zone occurs in the west and the Anorthite, hornblende zone occurs in the east.

Quartz.

Xenoblastic, inequigranular, equidimensional crystals of quartz meet along irregular or smooth curved boundaries to form a granoblastic mosaic. In some cases, particularly towards the east of the area, the boundaries may be quite smooth and the structure verges upon tessellate. The crystal size varies from very small up to 0.5 mm in diameter and the average diameter is about 0.2 mm. Both strained and unstrained crystals are common.

Feldspar.

Xenoblastic, inequigranular, equidimensional crystals of feldspar are very common and form a closely interlocking granoblastic mosaic with quartz and other feldspars.
feldspars. No intergrowth was observed and the crystal boundaries are irregular or smoothly curved.

The feldspar composition varies from andesine \((A_n^{41})\) in the west to bytownite \((A_n^{77}.A_b^{23})\) in the east. The passage from andesine to bytownite takes place suddenly and is accompanied by decrease in zoisite and increase in hornblende. Twinning on the albite law is very common.

In some thin sections the feldspars show zoning. Many crystals are quite fresh, but alteration varying in intensity from slight cloudiness in ordinary light to completely altered to sericite, is also very common. In some thin sections feldspars contiguous with zoisite or garnet show more severe alteration than other crystals, in the same slice.

**Garnet.**

Garnet is ubiquitous and occurs as small xenoblastic crystals, frequently less than 0.5 mm in diameter, also as large xenoblastic porphyroblasts that show poeciloblastic structure with many inclusions of quartz, feldspar, biotite, sphene and zoisite. The crystals are unaltered.

**Zoisite.**

Hypidioblastic \(p\)-zoisite occurs in great abundance
in some thin sections and shows considerable variation in crystal size from very small nearly equidimensional crystals to large crystals that may exceed 1.0 mm in length. Stubby prismatic crystals are very common and in some instances the crystals are acicular. The crystals are sometimes aligned with their long axes sub-parallel to the foliation but in many cases they are randomly oriented.

Birefringence is low and most crystals show a dull grey interference colour. Occasionally "Berlin Blue", yellow and higher interference colours may be found indicating other members of the zoisite-epidote group.

The crystals may occur randomly scattered throughout the rock or they may form sphene-garnet-zoisite aggregates. The crystals are always fresh.

This index mineral is widely distributed and occurs with biotite, hornblende, pyroxene and bytownite. It is therefore sometimes difficult to delimit the zoisite zone (see p. 16).

Hornblende.

Hornblende is restricted to calc-silicate rocks that occur in the east of the main outcrop of Upper Psammitic Group. Xenoblastic porphyroblasts up to 3.0 mm long show very little shape and exhibit poeciloblastic structure. Inclusions/
Inclusions of quartz, garnet, sphene and zoisite are common. Pleochroism is weak to moderate:

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<tr>
<td>Pale yellow</td>
<td>Pale yellowish green</td>
<td>Pale green or green</td>
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The crystals are randomly oriented and often occur in large aggregates up to 4.0 mm across and 10.0 mm long, associated with garnet and zoisite.

**Pyroxene.**

Pyroxene is also restricted to the eastern part of this area. It occurs as rare poeciloblastic porphyroblasts with many inclusions of quartz, garnet, zoisite and sphene. The crystals are xenoblastic and very poorly developed.

**Biotite.**

Hypidioblastic crystals of biotite are fairly common in the west but are rare in the east. They appear as lath shaped cross-sections that may be up to 1.0 mm long but are more usually about 0.3 mm. Pleochroism is from pale yellow to yellowish brown. The crystals are usually aligned in the foliation plane but many crystals can be found growing oblique to the foliation.

**Sphene.**

Idioblastic/
Idioblastic or hypidioblastic crystals of sphene are common and vary in size from very small lozenge shaped crystals up to crystals measuring 1.0 mm in length. The majority of the crystals are less than 0.2 mm long.

3. **PETROGRAPHY** (continued).

(d). The Roshven Pelitic Group.

The Roshven Pelitic Group lies within the "Injection Complex" described by the Geological Survey (see p. 19), and comprises an assemblage of psammitic, semi-pelitic and pelitic schists converted to gneisses by migmatization. Interbanded with the gneisses there are hornblende schists and calc-silicate granulitic schists. The following rock types will be described:

1. Pelitic gneisses.
2. Semi-pelitic gneisses.
3. Psammitic schists.
4. Hornblende schists.
5. Calc-silicate granulitic schists.

1. Pelitic gneisses.

The most widespread rock type in the Roshven Pelitic Group is a foliated biotite-muscovite-quartz-oligoclase gneiss.
gneiss. Where biotite and muscovite are abundant the rock splits readily along irregular foliation planes to expose reflecting plates of mica. With increasing amount of quartz and feldspar the rock grades towards semi-pelitic gneiss; it becomes massive and more difficult to split. The gneisses frequently contain augen of quartz and feldspar that have elliptical cross-section and vary in size up to one and a half inches across. Elsewhere the gneisses are banded with quartz-feldspar folia that are usually bounded by a thin biotite rich selvage.

Some varieties are richly garnetiferous and others occasionally contain knots of sillimanite and staurolite; kyanite was recognised in the field at one locality and was found in several thin sections. Tourmaline is widely distributed and may be locally quite common as black crystals up to half of an inch thick and three inches long.

Richly micaceous gneisses frequently weather to a yellowish rust colour while the other gneisses range in colour from nearly black to pale grey flecked with wisps of biotite. In hand specimen biotite, muscovite, quartz and feldspar can always be recognised; garnet, sillimanite and tourmaline can be recognised in some specimens.

Under/
83.

Under the microscope the gneisses are seen to be recrystallised rock of medium or coarse grain (see Plate 34 a). They show a wide range in composition depending upon the relative proportions of light and dark coloured constituents. The light coloured constituents are quartz and feldspar (oligoclase-andesine) and usually there is rather more feldspar than quartz.

Quartz.

Xenoblastic crystals of quartz are abundant and vary in size from less than 0.1 mm to large plates 3.0 mm across. The average grain size is between 1.0 and 2.0 mm. Many crystals are unstrained but some show slight undulose extinction.

Crystal boundaries are smooth but irregular and quartz is seen penetrating into feldspar crystals and forming large embayments into the feldspar. It is also seen enclosed by feldspar where it occurs as small, smooth, rounded blebs.

Quartz and feldspar usually make up more than half of the bulk of rock and occur together filling the interspaces between micas and as large coarse grained augen. Quartz is also found as thin fine grained bands in which the average crystal size is less than 0.2 mm. These bands/
bands are sub-parallel to the foliation of the gneiss and are seen as anastamosing tracks through the medium or coarse grained matrix.

**Feldspar.**

The feldspar constituent is plagioclase of oligoclase-andesine composition. In the majority of thin sections studied the composition falls near the oligoclase-andesine boundary ($\text{An}_{30}$) but in some slices a composition up to $\text{An}_{38}$ was found. In most instances the composition was determined using the maximum symmetrical extinction angle. The results so obtained were confirmed by occasional determination of the refractive index of $\beta$. Many crystals show fine lamellar twinning on the albite law but many are untwinned. Staining revealed that both twinned and untwinned crystals are plagioclase.

The crystals are xenoblastic and range in size up to 3.5 mm across. They frequently have irregular shape but are usually equidimensional with clean-cut smooth boundaries that are interlocked with quartz. There are large embayments of quartz into feldspar and the feldspar crystals often contain small rounded quartz inclusions. Myrmekite intergrowth is rare.

Many crystals of plagioclase are quite fresh but some/
some show slight sericitisation, particularly around the periphery and encroaching into the crystals along cleavage planes.

**Micas.**

Foliation in the gneisses may be well developed or impersistent and is defined by sub-parallel alignment of biotite and muscovite bands. The relative proportion of muscovite to biotite varies, as does the total mica content of the gneisses, but both muscovite and biotite are invariably present.

Biotite occurs as hypidioblastic or xenoblastic, ragged, crystals with lath shaped cross-section measuring up to 3.0 mm in length. The average length of the crystals is between 1.0 mm and 2.0 mm. Although the biotites are crudely aligned in the foliation many crystals can be found growing at any angle to it and in some rocks the pattern is almost decussate.

**Pleochroism is:**

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<td></td>
<td>pale yellow or pale brown</td>
<td>reddish brown</td>
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Inclusions within biotite frequently have haloes that are pleochroic from pale yellow to black. Biotite is frequently abundant along the margins of quartz feldspar bands or augen,
augen, it is crudely aligned parallel to the bands.

The majority of thin sections show biotite to be fresh but in some rocks it is altered to chlorite.

**Muscovite.**

Many hypidioblastic crystals of muscovite up to 3.0 mm in length can be seen aligned sub-parallel to the inconstant micaceous folia, but muscovite porphyroblasts up to 5.0 mm in length also occur and are randomly oriented. Thin slivers of biotite are often interlaminated with muscovite and the porphyroblasts sometimes show diablastic structure with biotite.

In gneisses containing sillimanite and staurolite muscovite is found closely associated with sillimanite-staurolite aggregates. It may occur as minute lath shaped crystals that increase in size away from the sillimanite-staurolite aggregates, eventually merging with the coarse grained matrix of the gneiss, or sillimanite needles may occur within a large muscovite crystal.

**Garnet.**

Almandine (or spessartite) garnet (R.I. 1.798 to 1.808) is nearly always present, but the amount and the crystal size varies considerably. At one locality garnets were found measuring one inch across.

In thin section the crystals may be xenoblastic or/
or idioblastic and may be inclusion free, or crowded with inclusions of quartz and occasional feldspar and biotite. The inclusions do not show any alignment but some garnets have inclusion free cores with idioblastic shape surrounded by additional garnet with many inclusions, (see Plate 36). This will be described later (see p. 187).

Sillimanite.

Sillimanite occurs in knots associated with staurolite, kyanite and muscovite, in pelitic gneiss near the western limit of the Roshven Pelitic Group, also in the strip of pelitic gneiss that lies to the west of the main area of outcrop of the Roshven Pelitic Group. It is also found associated with quartz, feldspar, staurolite and muscovite in "rods" within pelitic gneiss 2,000 ft. northeast of the summit of Sgurr Domhuill Mor.

The sillimanite crystals are small occurring in fernlike growths 4.0 mm across. They frequently surround irregular staurolite crystals (see Plate 25 a). In some cases the sillimanite crystals appear to be forming from the staurolite. They grow away from the edge of the staurolite crystals but do not penetrate the staurolite crystals. Sillimanite and kyanite were not seen together.

Staurolite.
Staurolite.

The distribution of staurolite is the same as that described above for sillimanite. The crystals may be up to 2.0 mm across and usually show hypidioblastic or idioblastic shape. In some cases the crystals have large embayments and elsewhere the crystal boundaries are ragged and surrounded by muscovite.

Kyanite.

Kyanite is rare and was recognised in hand specimens at one locality in semi-pelitic gneiss, between Loch nam Paitean and Lochan na Caillich. It appears in several thin sections as small hypidioblastic acicular crystals up to 2.0 mm long and is usually associated with staurolite and muscovite.

Tourmaline.

Idioblastic and hypidioblastic porphyroblasts of tourmaline are locally quite common and show weak pleochroism from brownish yellow to greenish yellow. Some crystals have muscovite and biotite inclusions in the core.

Apatite.

Apatite is a widely distributed accessory mineral occurring as acicular, idioblastic, small, crystals. It is not very common.
d). The Roshven Pelitic Group (continued).

ii). Semi-pelitic gneisses.

With increase in the amount of quartz and feldspar and decrease in muscovite and biotite, pelitic gneiss grades into semi-pelitic gneiss. Semi-pelitic gneiss is usually pale grey in colour and is banded with dark coloured, inconstant, lenticular folia of biotite and muscovite. Pale grey semi-pelitic rock carries a variable amount of small muscovite and biotite crystals which are frequently poorly oriented parallel to the gneissosity. Muscovite may also occur as randomly oriented porphyroblasts up to one inch across, scattered throughout the rock.

In addition to the dark lenticular folia formed by micaceous minerals there are light coloured quartz feldspar folia that are also lenticular in cross-section. These also follow the gneissosity and are frequently of irregular shape.

Rocks of this type are usually massive and do not split readily along the foliation. Fresh surfaces frequently have a silvery lustre due to muscovite. Garnets occur in variable and sometimes considerable amounts. Since this rock is very similar to the pelitic gneiss described above/
above it will not be re-described in detail.

In addition to the massive semi-pelitic gneiss described above there is a coarsely banded semi-pelitic gneiss. This rock is made up of alternating bands of psammitic granulitic schist and pelitic gneiss. The bands are persistent and can be traced for considerable distances along the strike. This is again a variable rock type and with decreasing thickness of psammitic granulitic schist bands, it grades into pelitic gneiss. With decrease in the thickness of the pelitic gneiss bands the rock becomes a flaggy granulitic schist with thin pelitic partings. This, in turn, grades into massive psammitic granulitic schist.

Coarsely banded semi-pelitic gneisses and schists are normally made up of alternating bands about three inches thick.

d). The Roshven Pelitic Group (continued).

iii). Psammitic schists.

The distribution of the main areas of psammitic schist is shown on the geological map at the back of the thesis (Map 1). In the field the rock ranges from a massive pale grey or white quartzitic psammitic schist, to a flaggy quartz-feldspar-muscovite-biotite psammitic that weathers/
weathers to a yellowish brown colour. In addition to the areas shown, thin psammitic bands that are frequently isoclinal fold cores, are widely distributed in the pelitic gneiss.

Under the microscope the psammitic schist is seen to be recrystallised rock and is predominantly made up of quartz and feldspar with subsidiary amounts of muscovite and biotite.

Quartz.

Xenoblastic inequigranular crystals of quartz with smooth rounded boundaries show tessellate structure. The crystals may be equidimensional or elliptical in cross-section and both strained and unstrained varieties are common. The average crystal size varies from 0.2 mm to about 0.4 mm in diameter but crystals measuring 1.0 mm across are not uncommon.

Feldspar.

The feldspar is plagioclase with a composition that falls near the oligoclase-andesine boundary (An\textsubscript{30}). It occurs as xenoblastic, smoothly rounded, inequigranular crystals, and forms tessellate texture with quartz. Lamellar twinning on the albite law is common.
Crystal size varies from very small to about 1.0 mm but the average dimension is between 0.2 and 0.5 mm. Some crystals are fresh but the majority show alteration to sericite around the periphery and along cleavage. Complete sericitisation occurs in some cases. The larger feldspar crystals frequently have smoothly rounded quartz inclusions.

**Micas.**

Biotite occurs as hypidioblastic, ragged, lath shaped crystals that may be up to 0.5 mm long and show pleochroism from very pale brown to reddish brown or red. The crystals are randomly oriented and occasionally have inclusions surrounded by pleochroic haloes.

Muscovite is not common but may occur in the less quartzitic psammitic granulites as porphyroblasts up to 5.0 mm across.

**Epidote.**

The yellow variety of epidote showing weak pleochroism and bright interference colours, occurs as an accessory mineral.

d). The Roshven Pelitic Group (continued).

iv). Hornblende schists.

This/
This rock type was only found in pelitic gneiss of the Roshven Pelitic Group. It is most common to the north and northeast from the summit of Sgùrr Domhuill Mòr, but is also found at many scattered localities throughout the main outcrop of this group.

In the field hornblende schist occurs as bands and lenticular pods that may vary in thickness from three or four inches up to four feet. They frequently occur as fold cores that formed during the first period of folding. Schistosity in the hornblende schist is parallel to the foliation in surrounding gneiss. It is an axial plane cleavage schistosity formed during the first period of folding.

In hand specimen the schists are nearly black. In some rocks the hornblende needles are aligned sub-parallel to one another imparting a good lineation on the rock. The schists are frequently studded with quartz-feldspar encrusted garnets that appear as pale grey knots up to one quarter of an inch across.

Under the microscope the schist is seen to be predominantly hornblende showing nematoblastic structure. Garnet porphyroblasts are often abundant and interstitial quartz/
quartz and feldspar varies in amount.

**Hornblende.**

Massive hypidioblastic or idioblastic crystals of hornblende measuring 4.0 mm in length and 0.7 mm in width appear as large bladed crystals. Pleochroism is:

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<tbody>
<tr>
<td>pale brown</td>
<td>greenish</td>
<td>dark green</td>
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</table>

The crystals are usually fresh and many have rounded inclusions of quartz. Small idioblastic crystals of sphene and fragments of black iron mineral are also included in hornblende.

**Garnet.**

Xenoblastic garnet porphyroblasts have very irregular shape and may be up to 5.0 mm in diameter. They show poeciloblastic structure with many inclusions of quartz, feldspar, sphene, biotite and iron mineral. In most garnets the inclusions have random distribution, but occasionally a parallel banding can be recognised.

**Quartz.**

The amount of quartz varies but it is generally small, occurring in the interspaces between hornblende and as occasional aggregates of quartz-feldspar mosaic.
The average size of the crystals is 0.3 mm but some measure up to 1.0 mm. Both strained and unstrained crystals are common.

**Feldspar.**

The feldspar is plagioclase of labradorite composition (An$_{54}$) and occurs as small xenoblastic crystals filling the interspaces between hornblende, or around garnet porphyroblasts. It is never very common and is usually sericitised.

**Biotite.**

Biotite occurs in small amounts and is usually aligned parallel to the schistosity. Pleochroism is from pale brown to deep yellowish brown.

Lozenge shaped cross-sections of sphene and irregular blebs of opaque black iron mineral are common accessories in the hornblende schists.

d). The Roshven Pelitic Group (continued).

v). Calc-silicate granulitic schists.

Calc-silicate granulitic schists are widespread in the Roshven Pelitic Group but are most abundant in coarsely banded semi-pelitic gneiss where they occur as pale grey ribs about two inches thick. In hand specimen quartz,
quartz, feldspar and pale brown garnet can nearly always be recognised; in some rocks hornblende can also be identified.

**Quartz.**

The bulk of the granulitic schist is made up of quartz and feldspar. Quartz occurs as xenoblastic crystals that are usually equidimensional and inequigranular, ranging in size from small to plates 0.6 mm in diameter. The average grain size is about 0.3 mm. It forms a closely interlocking mosaic with feldspar and imparts granoblastic structure to the rock. In some thin sections the crystal boundaries are smooth and rounded and the texture is tesselate. Both strained and unstrained crystals are common.

**Feldspar.**

The feldspar is plagioclase of bytownite composition \((\text{An}_{85} \text{Ab}_{15})\). It is always present and usually occurs in about the same abundance as quartz. The crystals are xenoblastic, equidimensional and inequigranular and may reach 1.0 mm in diameter; the average crystal size is about 0.4 mm. Rounded inclusions of quartz are found in the large crystals. The amount of alteration varies from unaltered crystals through every gradation to completely sericitised crystals.

**Amphibole.**/
Amphibole.

Hornblende is the most common amphibole present and usually occurs as massive porphyroblasts up to 4.0 mm long. The porphyroblasts are randomly oriented and are often seen in aggregates associated with zoisite and garnet. Massive crystals are idioblastic or hypidioblastic, but in some rocks poorly formed ragged porphyroblasts show poeciloblastic structure. Pleochroism is moderate or strong:

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<tr>
<td></td>
<td>pale brown</td>
<td>greenish</td>
<td>dark green</td>
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In addition to the massive hornblende crystals described above, there are small fibrous crystals of green actinolitic amphibole that rarely exceed 0.3 mm in length. This fibrous amphibole is of restricted distribution and frequently occurs near pyroxene crystals.

Clinopyroxene.

Clinopyroxene is not very well developed and occurs as colourless poorly formed poeciloblastic crystals. The crystals are randomly oriented and sometimes occur in aggregates.

Garnet.

Xenoblastic garnet porphyroblasts measuring up to 5.0 mm in diameter are very common. The crystals show poeciloblastic structure and have spongy appearance with many inclusions/
inclusions of quartz, feldspar, amphibole and clinopyroxene. The refractive index was found to be 1.751 indicating grossularite composition.

Zoisite.

Hypidioblastic crystals of zoisite showing anomalous "Berlin blue" interference colour are common. The crystals are usually poorly formed and are equidimensional or slightly prismatic.

Sphene is a fairly common accessory mineral and biotite is occasionally present. Opaque black mineral occurring as irregular shaped masses and small lath shaped bodies is also common in some rocks.
II. STRATIGRAPHY AND PETROGRAPHY (continued).

4. INTRUSIVE ROCKS

Foliated biotite granite dykes are restricted to the eastern part of Moidart. The largest of these dykes is about 120 ft. thick and is well exposed on the north slope of Sgùrr Domhuill Mòr. There is a tendency for dykes of this type to follow the foliation in the pelitic gneiss, but some are seen to be transgressive. Also confined to the eastern part of the area mapped, and extending as far west as Loch Ard a'Phuill there are pegmatite intrusions that may measure up to 100 ft. in thickness. Quartz, feldspar and muscovite are very common and many of the pegmatites also contain garnet. Biotite and apatite were found near the eastern margin of the area mapped.

Lamprophyric dykes of "apinite" type, which are thought to be of Lower Old Red Sandstone age, (see p. 22) may be common locally and kersantite-spessartite lamprophyres trending east-west occur to the north of the North Channel of Loch Moidart. One such dyke was traced for over two miles (see Map 1) from near Loch na Draiipe to the south-west corner of the peninsula.

Quartz-dolerite/
Quartz-dolerite bosses are usually elongated in an east-west direction and are most common in the southern part of Moidart. J.E. Richey (Summary of Progress 1930, p. 64) has referred to the xenoliths of quartzite frequently found in this type of intrusion. This feature is illustrated in Plate 3 a.

North-south trending Tertiary dolerite and basalt dykes are a feature of the area mapped. The dykes are well exposed along the coast (see Plate 3 b) and can frequently be traced inland as persistent ridges. They were seen cutting through east-west trending lamprophyre at two localities.
III. STRUCTURE

1. INTRODUCTION

a). Summary of Results.

Four significant fold movements are recognised in the area mapped. These are designated $F_1$, $F_2$, $F_3$ and $F_4$. The style, distribution and effect of each of these fold movements is described in turn. A summary of the data recorded during field work is shown on the Structural Map at the back of the thesis (Map 2). The area mapped is divided into sixteen sub-areas and the field observations within these sub-areas are shown on stereograms, (see Fig. 24).

The earliest fold movement formed isoclinal "Similar type" minor folds the axial planes of which parallel the foliation and bedding-schistosity. No major folds of this generation were found. Detached psammitic isoclinal cores occur as tectonic inclusions within pelitic rock. In psammitic schist minor isoclinal folds vary in size from small folds to large isoclines where one hinge can be traced continuously for thirty feet. Lineated quartz rods and lineation parallel to $F_1$ folds occur in the west of the area mapped.
mapped. The present regional foliation and bedding-schistosity were formed at this time. The writer is of the opinion that this fold movement may have formed major nappe type folds, such as W.Q. Kennedy (1954, issued 1955) postulates in Morar, but none were found in the area studied.

Following the period of isoclinal folding, there was an episode of tight asymmetric "Similar type" folding, that produced major folds such as the Glenuig Antiform; Lochan a'Mhuilinn Synform; Lochan na Caillich Antiform and Sgùrr Domhuill Mòr Antiform. Over much of the area studied the present foliation and bedding-schistosity orientation is related to these folds. The axial planes of $F_2$ folds are nearly vertical in the east of the area mapped and dip gently to the east in the west. Over most of the area, $F_2$ fold axes are nearly horizontal but near the eastern boundary the axes plunge steeply to the south. Minor folds, axial plane cleavage and lineation, related to this fold movement are widespread. The minor folds are of variable shape but are usually tight and show good "movement sense". They are often disharmonic and in some areas fold shape has been greatly influenced by lithology.

Axial plane cleavage in $F_2$ folds has imprinted a new foliation on pelitic rocks at some localities. In the east/
east of the area mapped quartz-feldspar veins frequently occur in this axial plane cleavage orientation.

Major and minor $F_2$ folds refold $F_1$ isoclines. Lineation related to $F_2$ folding, overprints $F_1$ lineation and $F_1$ quartz rods. Quartz rodding related to $F_2$ folds cuts earlier rodding. Axial structures formed during the first fold movement are reoriented during the second movement to come to lie along a great circle when plotted on a stereonet. The direction of tectonic transport of the Glenuig Antiform plunges at about $40^\circ$ to the east.

Evidence of the third fold movement is restricted to the eastern part of the area mapped. Major folds formed at this time are the Lochan Meall a'Mhadaidh Synform and the Loch nam Paitean Antiform. Both trend north-south in the north, and swing round to northwest-southeast trend in the south. The axial planes dip at $80^\circ$ to the west in the north, and $45^\circ$ to the southwest in the south.

Minor folds related to the major $F_3$ folds are abundant and are of "Similar type" (see p. 24). The style of the minor folds varies from very tight to open and "movement sense" is generally apparent. The tight minor $F_3$ folds occur in the vicinity of the tight major Synform while/
while open minor folds are related to the open Loch nam Paitean Antiform. This supports findings of previous workers that minor folds resemble related major folds in style and orientation. Mica crinkling with the axial planes of the "crinkle" folds parallel to axial planes of $F_3$ minor folds, occurs in pelitic gneiss to the southeast from Loch nam Paitean.

After the second generation of folding the foliation and bedding-schistosity were left contorted. It was on these contorted surfaces that $F_3$ folds were formed. As a result of this, although the orientation of $F_3$ axial planes may remain constant, the $F_3$ minor fold axes show considerable variation in plunge.

Axial plane cleavage develops in semi-pelitic rock near the hinge of Lochan Meall a Mhadaidh Synform, and imparts a new foliation ($S_3$) in this area. There is no visible $F_3$ cleavage in psammitic rocks.

$F_3$ major and minor folds refold $F_1$ minor folds and $F_2$ major and minor folds. $F_2$ axial structures are rotated by $F_3$ folding to come to lie along a great circle. The direction of transportation for $F_3$, plunges at $25^\circ$ to $343^\circ$ (see p.140). The $F_3$ major folds were probably formed by/
by a movement in which the west of the area moved north, relative to the east of the area.

The only major folds formed during the fourth fold movement occur on the ridge between Loch Shiel and the Moidart River, near the southeast corner of the area mapped. The axial planes of these folds have very regular orientation and dip at $75^\circ$ to $295^\circ$. Related minor folds with open style are common in pelitic rocks in the east of the area, but rarely penetrate into the Upper Psammitic Group. Mica crinkle folds, with axial planes parallel to the axial planes of $F_4$ minor folds, are widespread throughout the Roshven Pelitic Group.

$F_1$, $F_2$ and $F_3$ folds are refolded by the fourth fold movement. Near the summit of Sgùrr Domhuill Mòr, $F_2$ minor fold axes are rotated by $F_4$ minor folds, to lie along a great circle. $F_4$ was a "Similar type" movement in this area and the direction of tectonic transport for $F_4$ plunges at $70^\circ$ to the southwest. Where $F_2$ minor folds are refolded round the major $F_4$ folds, on Ceann Loch Uachdrach, a stereographic projection showed that the $F_2$ axes do not lie on a great circle or on a small circle. $F_4$ folding in this area may have been part "Concentric type"/
type" and part "Similar type". The author is of the opinion that originally flat plunging $F_2$ fold axes were tilted into the steep plunge that they have in the east of the area studied, during the fourth fold movement.

Two fold movements of uncertain age are described and their significance in the structural history of Moidart is discussed. The first of these movements to be described, has formed a number of monoclines which warp $F_2$ fold axial planes. The second movement to be described formed folds with more brittle style than any of the previous movements. Jointing, faulting and discoloration in the Upper Psammitic Group, occurs along the axial planes of the brittle folds. Mica crinkle folds in the west of the area mapped, have axial planes which are parallel to the axial planes of the brittle folds.

A summary of the results is given in the table Fig. 5, and Fig. 6 shows the axial plane trends of the major folds mapped.

b). Procedure.

Structural analysis necessitates recording a large number of observations on the orientation of minor structures. To facilitate handling the data recorded during mapping, the area was initially divided into a grid/
<table>
<thead>
<tr>
<th>FOLD SYSTEM</th>
<th>DISTRIBUTION</th>
<th>MAJOR FOLDS</th>
<th>STYLE</th>
<th>TYPE OF FOLDING</th>
<th>DIRECTION OF TECTONIC TRANSPORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>Regional</td>
<td>None</td>
<td>Isoclinal</td>
<td>Similar</td>
<td>Plunges at 40° to the east, calculated on the Glenuig Antiform</td>
</tr>
<tr>
<td>$F_2$</td>
<td>Regional</td>
<td>Glenuig Antiform</td>
<td>Tight</td>
<td>Similar</td>
<td>Plunges at 25° to the north</td>
</tr>
<tr>
<td>$F_3$</td>
<td>Restricted to the east of Maidart</td>
<td>Lochan Meall a'Mhadaidh Synform, Loch nam Poitean Antiform</td>
<td>Tight</td>
<td>Similar</td>
<td>Plunges at 70° to the southwest</td>
</tr>
<tr>
<td>$F_4$</td>
<td>Roshven Pelitic Group</td>
<td>Ceann Loch Uachdrach Fold</td>
<td>Open</td>
<td>Similar &amp; Concentric</td>
<td></td>
</tr>
<tr>
<td>Monoclines</td>
<td>Regional</td>
<td>None</td>
<td>Monoclinal</td>
<td>Concentric²</td>
<td></td>
</tr>
<tr>
<td>Brittle folds</td>
<td>Regional</td>
<td>None</td>
<td>Open</td>
<td>Brittle</td>
<td></td>
</tr>
</tbody>
</table>

**FIG. 5.** TABLE SUMMARISING THE RESULTS OF THE STRUCTURAL ANALYSIS
AXIAL PLANES OF MAJOR FOLDS

- Antiform

- Synform

SECOND FOLD MOVEMENT

THIRD FOLD MOVEMENT

FOURTH FOLD MOVEMENT

SCALE 0 1 2 MILES
grid of one quarter of a square mile units. Each topographic feature within each unit was located from aerial photographs, transferred to the map, and numbered. The features were copied into a field notebook. Geological boundaries were drawn on field maps in the field, but structural data was recorded in the field notebook and then transferred to the maps later.

During field work, structures of the same fold movement were mapped and recorded together, and were distinguished from those of a different fold movement. Style and trend enabled this to be done. Related structures were plotted on the field maps in the same colour of ink, and each set of structures was assigned a different colour. When the relationships between the sets of structures were discovered, a sequence of episodes of folding was established. This was then correlated with the colours assigned to the structures on the field maps.

c). Structures observed.

The structures observed are described below. A brief statement of how they were measured and the significance of the structures in the area mapped is given. Structures have been divided into:

1). Planar structures and 2). Axial structures.

i).
108.

1). Planar structures.

a). Foliation and bedding-schistosity (s-planes). Measurement of the orientation of s-planes was carried out using a liquid prismatic compass and a clino-rule.

The earliest s-plane seen in the rocks is the original bedding; this has been called s. This has largely been modified during the first fold movement to form bedding-schistosity and foliation, in the axial planes of the first folds (s.). Since the first fold movement is isoclinal, s is usually coincident with s, but departures from this occur at the hinges of isoclinal folds.

Pelitic gneiss found in the Roshven Pelitic Group is sometimes massive and shows little tendency to split along the foliation, but over most of the area the rocks weather to expose the foliation and bedding-schistosity. This has been widely mapped and the data are recorded on stereograms in Fig. 24. Poles to foliation, when plotted on a stereonet, normally lie along a great circle in folded areas. The normal to this great circle coincides with the axis of folding (McIntyre, 1951, p.68).

Foliation develops in the axial planes of F₂ and F₃ folds; these surfaces have been designated s₂ and s₃.

b)./
b). Axial planes. Wherever possible a large number of fold axial planes were recorded. In areas of repeated folding axial plane measurements assume a special significance (see Clifford et al., 1957). Where the first folds are not isoclinal the attitudes of the axial planes of the folds are more-or-less constant but the bedding or foliation is left in differing orientations, depending upon their positions on the folds. The effect of refolding on this situation has been discussed by L.E. Weiss (Weiss, 1959). The axis of folding of the early fold axial planes will be constant, but the fold axes formed by refolding the already folded foliation, vary. The variable foliation fold axes and the constant axial plane fold axis, all lie within the axial plane of the later folding.

Where refolding has taken place more than once, foliation may be so contorted as to be of little value as an aid to working out the geometry of folding. By tracing axial planes in areas of repeated folding, it is possible to work out the sequence of events in the structural history. The relative ages between fold movements can be determined when one set of minor folds is seen to refold the axial planes of an earlier set. Where refolding on the minor scale is not seen, relative age can be ascertained by tracing/
tracing the axial planes of early folds round later major fold hinges. In such cases, the axial plane trend of the later structures will remain constant, while the trend of the early fold axial planes varies in such a way that when the poles to the axial planes of the latter are plotted on a stereonet, they lie along a great circle.

c). Axial plane cleavage.

This planar structure was not as useful as fold axial planes, in Moidart. Cleavage is not always developed and is sometimes restricted to certain rock types. In areas of repeated folding cleavage may be overprinted; it may also be destroyed by recrystallization during metamorphism. It was found that, provided a sufficient number of fold axial planes could be measured, axial plane cleavage orientation need not be recorded. Presence of axial plane cleavage is an important feature of fold style and its occurrence should always be noted. Folds that show cleavage are of "Similar type".

ii). Axial structures.

a). Fold axes.

Axes of minor folds are often well exposed in Moidart and minor folds can be correlated with genetically related/
related major folds. Parallelism in style and orientation between major and minor folds occurs through the complete range of scale, from minute crinkling of the foliation, to large minor folds and ultimately to major folds.

Two procedures were followed in measuring the orientation of fold axes. Where an axis had shallow plunge an accurate bearing measurement could be obtained by sighting along the fold hinge with a compass. The inclination of the axis was measured in the vertical plane. Where the plunge of the fold axis was steep it was difficult to obtain an accurate measurement of the bearing of the axis by sighting down the hinge. It was found that more accurate results were obtained by first measuring the orientation of the fold axial plane. Then, with the mapping case aligned in the axial plane orientation, the pitch of the fold axis in the axial plane was measured. The inclination and orientation of the axis was calculated from a stereonet, using the observations recorded.

b). Lineation.

Lineation parallel to the fold axes (l lineation) is ubiquitous throughout the area. As was the case with fold axes, two procedures were adopted in measuring the orientation of lineation. Where lineation occurred on a flat/
flat lying surface, or had shallow plunge on a steeply inclined surface, the bearing and plunge were measured. Where steeply plunging lineation occurred on a steeply inclined surface the orientation of the surface and the pitch of the lineation in the surface plane, was measured. The plunge and bearing of the lineation was then calculated from a stereonet.

Three types of lineation occur: 1) mineral alignment, 2) cleavage and foliation intersection and 3) crinkling or corrugation of the foliation and bedding-schistosity. Before lineation can be used in the structural analysis it must be related to the fold movement during which it formed. This can usually be done satisfactorily by finding folds with which the lineation is seen to be related (see Plate 4 b). Since there is rarely more than one lineation preserved in any small area, it is possible to infer to which fold movement a lineation should be assigned, by studying the lineation and comparing it with nearby fold/lineation associations. Variations in style of the lineations are useful aids in assigning lineations to their related fold episodes.

c). Rodding.

Quartz/
Quartz and quartz-feldspar rods are common. More than one generation of rods occurs and occasionally one rod can be seen cutting across another, forming a quartz cross, (see Plate 5 a). In such cases it may be possible to obtain a relative age relationship between the two rods. It can be seen in Plate 5 a that the rod plunging south cuts through and is therefore younger than that plunging north. The two rods are alike and where two systems of quartz rodding are nearly parallel it is usually impossible to distinguish one from the other. With the exception of the west and southwest of the area mapped, little use is made of rodding.

Quartz-feldspar rods occur in the east of the area mapped. In addition to the quartz-feldspar rods, a feature that resembles rodding occurs where pelitic gneiss, which is made up of alternating biotitic and quartz-feldspar bands, is crinkled. Where the foliation is exposed, ridges of crinkled micas weather off, exposing the underlying quartz-feldspar band. This gives the appearance of quartz-feldspar rodding parallel to the mica crinkle fold axis.

d). Boudinage.

Current ideas on the origin and nomenclature of boudinage have been discussed by N. Rast (1956). This structure/
structure is found in Moidart near the eastern boundary of the area mapped (see Plate 5 b). "Barrel-shaped" boudinage is formed in psammitic bands in the Roshven Pelitic Group, on Ceann Loch Uachdrach. A similar type of structure but with more elongate cross-section, in which the psammitic band is enclosed as a "tectonic inclusion" in pelitic gneiss, is found on Sgùrr Domhull Mòr. The term "tectonic inclusion" is suggested by N. Rast (1956) to include "any isolated body which has been held to be formed by the tectonic disruption of any originally more or less extensive layer".

Quartz veining occurs in the neck between adjacent boudins and can be seen penetrating short distances into the psammitic rock. Boudinage formed during the second fold movement. It is not a widespread structure and is not used in the structural analysis.

e). Mullion structure.

Bedding or fold mullions (Wilson, 1953), occur in the area mapped, where isoclinally folded psammitic bands break off, to form tectonic inclusions in pelitic rocks. This is a common structure in the Roshven Pelitic Group and is usually associated with the first fold movement. It is not mapped separately as mullion structure but is grouped with the observation of isocline fold hinges.
III. STRUCTURE

2. THE FIRST FOLD MOVEMENT ($F_1$)

The earliest folding recognised formed long limbed isoclinal axes, the axial planes of which parallel the foliation and bedding-schistosity. The present regional foliation ($s_1$) was formed during this fold movement and represents the axial plane cleavage of isoclinal folding. In psammitic rock, where original bedding is still preserved, the foliation is usually coincident with the bedding, sometimes producing a flaggy appearance (see Plate 6 a). Wherever refolding occurs the isoclines are seen to be the earliest folds and axial planes of isoclinal folds can be traced round major second fold hinges.

No major folds of this movement can be recognised within the area mapped. It may be that what appear to be stratigraphic irregularities are structural effects caused by isoclinal duplication or limb attenuation. An example of this occurs in the west of Moidart where the western outcrop of the Striped and Pelitic Group shows considerable variation in thickness over a strike distance of two miles (see p. 7 and p. 41). Many minor $F_1$ structures occur in this/
this area and it may be that they indicate the presence of a large $F_1$ fold that has been obscured by subsequent movement.

Absence of marker horizons and the scarcity of sedimentary structures in the Upper Psammitic Group, make it difficult to detect long limbed isoclinal folds. Towards the eastern limit of the Upper Psammitic Group, south of Loch nam Paitoan, long isoclines of pelitic gneiss can be seen interdigitated with psammitic schist. These isoclines are of $F_1$ age and it is possible that the alternating psammitic and pelitic assemblage seen in the Roshven Pelitic Group is the result of isoclinal folding, but this has not been proved. In the east of the area mapped, minor structures formed during the first fold movement are largely obliterated by post-$F_1$ refolding, recrystallization and migmatization. Thus minor structures are rarely seen and so do not assist with the problem of locating major isoclines.

$F_1$ minor structures.

$F_1$ minor structures are most abundant in the Lower Psammitic, the Striped and Pelitic, and the basal members of the Upper Psammitic groups, in the western part of the area mapped. A mineral elongation lineation is still well/
preserved in this area. In thin section quartz grains are seen to be about twice as long as they are broad and this feature is responsible for the lineation on the bedding-schistosity. Parallel with this lineation there are lineated, isoclinaly folded, quartz rods, (see Plate 6 b). The foliation in the rock is parallel to the axial planes of the isoclinal rods, and the lineation is parallel to the fold hinges.

Two types of rods occur, they show variable cross-section, (see Fig. 7). One type consists of a solid core of quartz, with thin stringers tapering off, along the foliation (see Fig. 7 a). Another type commonly developed consists of detached small fold hinges (see Fig. 7 b). The latter tend to be more common in semi-pelitic rocks while the former occur frequently in both psammitic and pelitic rocks. Rods often occur in great abundance within two feet thick layers of psammitic schist, and occasionally the remains of a reticulate pattern, now distorted to give isoclinal quartz rods, can be recognised. The quartz may have been injected into the rock, or formed as a result of segregation, but F1 movement has reshaped it into the tectonic feature now preserved.
In the west of Moidart isoclinal folding of the compositional banding is less common than quartz rods and lineation. Axes of the occasional isoclines are seen to be parallel to the quartz rods and lineation. The folds always show marked limb attenuation and hinge thickening indicating that they are of "Similar type," (see Fig. 7 c).

Folded compositional banding is best seen in the pelitic rocks of the Striped and Pelitic Group where psammitic bands and occasional calc-silicate ribs are isoclinallly folded. Folds can also be found in the psammitic rocks of the Lower and Upper Psammitic Groups and are often sharp pointed, with extreme limb attenuation. Recrystallization has "welded" these folds into the rock and they can only be detected as "shadow" structures that are usually only visible in two dimensions. It is very rarely possible to measure the orientation of the fold hinge. Where semi-pelitic bands are folded with psammitic rock, the contact between the two rock types in the hinge area, frequently becomes diffuse, (see Plate 7 a).

F₁ isoclines are not very common in the Upper Psammitic Group just east of Glenuig but are more frequent near the eastern limit of this group. The isoclines again show the features described above, limb attenuation, hinge thickening,
FIG. 7 STRUCTURES FORMED DURING THE FIRST FOLD MOVEMENT.
thickening, and with axial planes parallel to the bedding-schistosity, (see Plate 7). Hinge areas show considerable variation in shape and it is frequently found that a tightly folded blunt hinge, when traced along the axial plane, becomes drawn out to a long tapered point (see Fig. 7 c). In some cases movement may be sufficient to shear out a bed. In such cases, considerable movement may have taken place along the bedding-schistosity (see Fig. 7 c).

Near the eastern limit of the Upper Psammitic Group, in the vicinity of Loch nam Paitean, there is a tendency for $F_1$ minor folds to occur in batches. One batch occurs due north of Lochan Meall a'Mhadaidh. In this area, $F_2$ folds have contorted the $F_1$ axial planes; the $F_1$ axes plunge to the south at $70^\circ$ to $80^\circ$. In another batch to the northeast of Lochan Meall a'Mhadaidh, one axial plane can be traced (not in continuous outcrop) for over 100 ft. Here the axes plunge south at $45^\circ$.

West of Loch nam Paitean isoclines of considerable size are found (see Plate 8 a). In one such fold the axial plane was traced for thirty feet. One horizon was only three feet apart after being traced thirty feet to the axis, then thirty feet back along the other limb of the fold. In this large minor fold there is no indication of a complimentary/
complimentary hinge, so the intermediate limb is at least thirty feet long.

$F_1$ minor folds are not preserved in pelitic rocks in the Roshven Pelitic Group, but they can be seen in psammitic bands and calc-silicate ribs occurring within the predominantly pelitic rocks, (see Plate 8 b). They frequently occur as detached psammitic fold cores.

Post-$F_1$ folding has modified the trend of $F_1$ axial structures. In the west they make a large angle with $F_2$ folds and can be seen refolded by the Glenuig Antiform. To the east of Glenuig, around Lochan na Caillich $F_1$ and $F_2$ folds are co-axial but the axial planes of $F_1$ folds are seen refolded by $F_2$ folds, thus the orientation of axial planes together with the fold style, provide the criteria for distinguishing one set from the other. In the Roshven Pelitic Group $F_1$ and $F_2$ folds may be coplanar and co-axial and difficulty may arise in distinguishing one from the other. Evidence that both $F_1$ and $F_2$ folds occur in the Roshven Pelitic Group is found where $F_1$ axial planes can be traced round the hinge of the Sgùrr Domhuill Mòr ($F_2$) Antiform. Also, occasional examples of an $F_2$ isocline refolding an $F_1$ isocline, are found. This will be discussed later. Where the rocks are least disturbed by folding and occasionally/
occasionally preserve sedimentary structure, for example about one mile southeast of Glenuig Bay, $F_1$ axial structures trend northwest-southeast. This may represent the original orientation of $F_1$ fold axes.

Conclusion.

Minor folds formed during the first period of folding occur throughout the area mapped. Although no major folds were found, $F_1$ was never-the-less a period of regional movement and caused local repetition of the stratigraphy. Its wider influence cannot be ascertained. This renders it impossible to estimate stratigraphic thickness in Moidart.

The axial trend of the $F_1$ minor folds is variable due to superposed folding. Where rocks are least disturbed by later movement, and still preserve sedimentary structures, the axial trend is northwest-southeast. The regional foliation and bedding-schistosity was formed during $F_1$, in the axial plane cleavage of $F_1$ folds.
III. STRUCTURE

3. THE SECOND FOLD MOVEMENT ($F_2$)

This fold movement formed the majority of the major folds found in Moidart, namely, Glenuig Antiform, Lochan a'Mhuilinn Synform, Lochan na Caillich Antiform and Sgùrr Domhùill Mòr Antiform. Minor structures related to these major folds are, folds, lineation, rodding, boudinage and cleavage. S- and Z- shaped minor folds assisted in determining the location of major folds. The folds are of "Similar type" and axial plane cleavage is frequently well preserved; they vary in style from open to tight.

a). Major $F_2$ folds and associated minor structures.

i). The Glenuig Antiform.

This large fold trends north south and is overturned towards the west. It has an axial plane that dips at $45^\circ$ to the east. The axial plunge is gentle throughout its length, and is inclined to the south in the north, reversing to plunge north in the south, (see Fig. 24 and Map 2). The fold can be traced across Moidart from the North Channel of Loch Moidart to the south shore of the Sound of Arisaig. J.E. Richey (Summary of Progress, 1938, )
first reported the presence of this fold and has commented on its significance (see p. 11). Richey correctly referred to the fold as the Glenuig Anticline but the writer has adopted E.B. Bailey's more general nomenclature-antiform (Bailey, E.B and W.J. McCallien, 1937), to avoid confusion in areas where $F_1$ isoclinal folding may have resulted in inverted sequence of rocks.

Current bedding in the Upper Psammitic Group about one mile southeast of Glenuig Bay (683, 767) indicates that the rocks here are right way up (see Plate 2). This occurs on the gently inclined eastern limb of the antiform, which is delineated by the Striped and Pelitic Group east of Loch na Bairness. An associated large s-shaped fold can be seen outlined by the lower contact of the Striped and Pelitic Group (see Map 1). This Group passes westwards over the eroded hinge of the antiform and re-appears as the inverted western limb, trending north-south through Smearisary Hill. Inverted Upper Psammitic Group exposed along the western seaboard, dips at between 28° and 60° under inverted Striped and Pelitic Group. The Lower Psammitic Group occupies the core of the antiform. The foliation trends north-south over most of the area underlain by this fold, (see Fig. 24, sub-areas 1 and 11).
Minor folds genetically related to the Glenuig Antiform are best developed along the eastern limb, in the Striped and Pelitic Group. They also occur quite frequently in the Striped and Pelitic Group along the western limb, but are rare in the inverted Upper Psammitic Group along the western limb.

Some illustrations of $F_2$ fold style in this area are given in Fig. 8 and in Plate 9. These illustrations show that the minor folds are of "Similar type" with distinct limb attenuation, cleavage and hinge thickening. The scale of minor folding varies from minute "herringbone" crinkling (see Fig. 8) to large folds. Folds frequently occur together in great abundance and are usually asymmetrical. Their S- or Z- shape indicates the movement sense.

Cleavage is widespread with folds of this generation and occurs in both psammitic and pelitic rock types. Plate 10 a shows axial plane cleavage in semi-pelitic rock between two psammitic bands. The early foliation and bedding-schistosity ($s_1$) is preserved within the psammitic rock and in semi-pelitic rock contiguous with the psammite. As the semi-pelitic rock is traced away from the psammite, $F_2$ axial plane cleavage imparts a new foliation $s_2$, that gradually/
FIG. 8  FOLDS FORMED DURING THE SECOND FOLD MOVEMENT.
gradually supercedes \( s_1 \). Disharmony usually occurs at the expense of limb attenuation and hinge thickening in semi-pelitic bands, (see Plate 10a). Convergence of the axial plane cleavage round the hinge of this fold can be seen where incompetent cleaved, semi-pelitic rock, thickened over the fold hinge, is pinched by the overlying psammitic band. Somewhat analogous structures are illustrated by de Sitter (1959, Figs. 169 and 237).

On the limbs of minor \( F_2 \) folds cleavage which is parallel to the axial planes of the minor folds, may also occur, (see Plate 10b). Development is again most conspicuous in semi-pelitic rock and occasionally the cleavage generates a new \( s \)-plane \( (s_2) \), oblique to the regional bedding-schistosity \( (s_1) \), (see Plate 10b).

East of the eastern outcrop of the Striped and Pelitic Group, \( F_2 \) minor folds can be seen in banded psammitic schist of the Upper Psammitic Group. In this rock type the folds are usually more open, but may be tight with marked limb attenuation (see Plate 11). Cleavage is well developed and lineation parallel to the fold axis is prominent (see Plates 11a and 14b). East of Glenug Bay, a southerly plunging antiform, overturned towards the west, brings/
brings garnetiferous pelitic schist to the surface, near Carn Mor (680, 775). This rock is very similar to that immediately underlying the Upper Psammitic Group. It outcrops as a belt approximately 150 ft. wide and closes to the south, west of Lochan Bealach na Gaoithe (682, 768). The antiform is part of an asymmetric fold with movement sense in harmony with the Glenuig Antiform. This asymmetric fold can be traced from near Loch a'Chairn Mhoir (680, 777) to the south coast of Moidart passing through sub-areas 2 and 12 (Fig. 24).

In sub-area 2 the axial plane dips due east at 40° and the fold axis plunges at 16° to 160° (see Fig. 24). Minor fold axes and axial structures vary in orientation within the axial plane. To the south, in sub-area 12, the mean plunge reverses to become 10° to 10° and the axial plane steepens to dip at 50° to 94° (see Fig. 24). Both sub-areas 2 and 12 show good foliation girdles and this is largely due to the effect of $F_2$, but is also in part due to a series of north-south trending monoclines which warp $F_2$ axial planes (see p. 158).

As the Upper Psammitic Group is traced eastwards into sub-areas 3, 8 and 13 the bedding-schistosity planes steepen to dip at an average of 60°, eastwards. The general strike/
strike swings from west of north in the north, to east of north in the south. Because of the regular orientation of the bedding—schistosity, the poles group giving a maximum (see Fig. 24). Although tight folding can be seen in the psammitic schists, no major folds are recognised. Instead, a series of small disharmonic folds of "Similar type" and variable style, develop. Alternating antiforms and synforms cause one horizon to remain near the surface for considerable distances across the strike, even though the dominant dip is about 60° to the east.

In sub-area 3, F2 axial planes dip at 50° to the east and axial structures plunge at 30° to 156°. To the south, in sub-area 13, the axial planes of minor folds dip at 75° to 100° and the axial structures plunge at 8° to 8° (see Fig. 24, also Maps 1 and 2).

ii). Lochan a Mhuilinn Synform and Lochan na Caillich Antiform.

These folds traverse sub-areas 4 and 9, also the western part of sub-area 5 and the eastern part of sub-area 13. Over most of their length the folds trend north south and have nearly vertical axial planes. In the north they plunge at about 25° to the south and reverse to plunge at/
at 30° to 345° in the south (see Fig. 24, sub-areas 4 and 9).

Open minor folds, with cleavage and showing limb attenuation, indicate that folding is of "Similar type". Thin quartz-feldspar veins in the axial plane cleavage of the minor folds, occur in great abundance at some localities. In some cases the veins fan around the hinge, (see Plate 12b). Fanning such as is illustrated is the normal pattern that develops when cleavage has formed perpendicular to stress (de Sitter, 1959, p. 214). This can be contrasted with the cleavage pattern over the hinge of the fold shown on Plate 10a. In the latter, heterogeneity in lithology has played an important part in controlling the axial plane cleavage orientation.

Minor folds associated with the major folds are frequently disharmonic, (see Plate 13). An open bench shaped fold in psammitic schist encloses semi-pelitic schist with thin, highly contorted, psammitic bands. Considerable slip has probably taken place along the contact between the psammitic and semi-pelitic schists. This style of folding is common where rocks of varying composition are folded together. In more homogeneous rock such as the quartz-feldspar granulitic schist, seen southeast of Lochan na Caillich/
Caillich, folding is of much more regular style.

S-shaped asymmetric minor folds occur to the east of the Lochan na Caillich Antiform. Beyond the thin strip of semi-pelitic gneiss that passes west and north of Loch nam Paitean, the minor folds are Z-shaped. This indicates that the semi-pelitic gneiss occupies the trough of an $F_2$ synform. This synform has been refolded during $F_3$ (see pp. 139-141). East of this synform, there is an antiform, also refolded during $F_3$. South of Loch nam Paitean the Roshven Pelitic Group can be seen passing over the hinge of this antiform and the topography, together with this fold, have formed the small outlier of Roshven Pelitic Group that caps the hill to the southwest of Loch nam Paitean (see Map 1).

North of Loch nam Paitean the synform mentioned above, with semi-pelitic gneiss in its trough, plunges to the south, and the semi-pelitic gneiss is seen to thin out towards Gleann Dubh.

The structure of this area indicates that, with respect to the second fold movement, the Roshven Pelitic Group is structurally higher than the Upper Psammitic Group. The effect of $F_1$ on the inter-relationship between the Upper Psammitic Group and the Roshven Pelitic Group is unknown,
unknown, and the absence of sedimentary structures makes it impossible to give a definite order of deposition between these two groups.

iii). Sgùrr Domhùill Mòr Antiform.

There is a clearly defined antiform of F₂ age, in the Roshven Pelitic Group, on Sgùrr Domhùill Mòr. This antiform trends north-south and has a nearly vertical axial plane; it plunges to the south at about 70°. A tightly folded psammitic band about 250 ft. thick on the limbs of this antiform is thickened to about 800 ft. over the hinge. The fold can be traced south, to Ceann Loch Uachdrach, where a pelitic band in the Roshven Pelitic Group thins from 2,000 ft. to 300 ft. as a result of this major fold. The axial plane trend is shown on Fig. 6, (see also Map 2).

Minor folds related to this major fold are of "Similar type" and are common throughout the area of the Roshven Pelitic Group. Coarsely banded rock made up of alternating psammitic and semi-pelitic ribs show the structures most clearly. Axial plane cleavage is usually well developed in both psammitic and semi-pelitic rocks, and micas in the semi-pelitic bands are frequently aligned in the axial plane cleavage orientation. Elsewhere, the micas form very/
very tight small "crinkle" folds, the axial planes of which parallel the axial planes of $F_2$ minor folds. The minor folds are frequently disharmonic with one fold developing from an open roll to an asymmetric fold, and occasionally to an isocline, along an axial plane distance of six feet. The axes of minor antiforms can be seen converging and eventually merging, to continue as a single antiform eliminating the intervening synform.

Limb attenuation and hinge thickening occurs in both psammitic and pelitic rocks. Minor $F_2$ folds are not well preserved in pelitic gneiss. Where they do occur, they are usually very tight and have disharmonic shape. In banded pelitic and psammitic rocks, a new foliation ($s_3$), induced in pelitic rock by $F_2$, can be seen meeting the compositional layering, at varying angles.

Between Sgùrr Domhuill Mòr and Sgùrr Domhuill Beag, there are many $F_2$ fold cores, plunging south at 70°. These occur in a coarsely banded psammitic and semi-pelitic rock. There is a tendency for weathering to strip off the more friable semi-pelitic rock exposing the underlying psammitic fold core, thus giving the appearance of "fold core" type mullions. The psammitic cores however, are not detached/
detached from the limbs of the folds. A cleavage and foliation intersection lineation develops parallel to $F_2$ minor fold axes, but it is largely overprinted by later structures.

b) Refolding of $F_1$ by $F_2$.

Axial planes of $F_1$ minor folds are refolded by $F_2$ major and minor folds. Since the axial planes of $F_1$ folds parallel the foliation and bedding-schistosity, the effect of $F_2$ on $F_1$ axial planes gives the same pattern as that shown on the foliation diagrams, (see Fig. 24).

The Glenuig Antiform affords the best opportunity for studying the effect of $F_2$ folding on linear structures formed during the first fold movement. This is so because many $F_1$ axial structures are well preserved in this area, also the Glenuig Antiform is not severely affected by later movement.

On the inverted western limb of the antiform, $F_1$ axial structures occur as quartz rodding, mineral lineation and occasional $F_1$ minor fold axes. These axial structures plunge to the northeast (see Map 2). East of the axial plane of the antiform, similar $F_1$ axial structures plunge to the southeast, (see Fig. 24, and Map 2).

Post $F_2$ folding has caused slight warping of $F_2$ axial planes and axes, (see Figs. 9 and 24). The same effect/
FIG. 9

DIAGRAM A
- $F_1$ AXIAL STRUCTURES
+ $F_2$ POLES TO AXIAL PLANES

DIAGRAM B
--- GREAT CIRCLE TRACE OF $F_1$ AXIAL STRUCTURES
----- MEAN $F_2$ AXIAL PLANE

"$a_2$" AXIS PLUNGES AT 40° TO 110°
effect must have been overprinted on $F_1$ axial structures deformed by $F_2$. $F_1$ axial structures plotted on a stereonet come to be along a path through which two great circles are drawn (Fig. 9). The divergence between these great circles is about the same as the spread of $F_2$ poles to axial planes (see Fig. 9). It is concluded that $F_2$ refolded $F_1$ axial structures in a "Similar" manner, causing them to lie along a great circle. This great circle has subsequently been distorted by later movement which also affected the orientation of $F_2$ axes and axial planes. Since the shear planes formed during $F_2$ lie in the axial planes of $F_2$ folds (axial plane cleavage), by plotting the mean $F_2$ axial plane, and noting where this plane intersects the great circle patterns of $F_1$ axial structures, an $a_2$ axis (direction of tectonic transport) for the Glenuig Antiform can be calculated (Ramsay, 1960) (see Fig. 9). This $a_2$ axis plunges at 40° to 110°. The movement direction that produced this major $F_2$ fold was therefore oriented nearly east-west.

On the minor structure scale, $F_2$ lineation can be seen superposed on, and locally obliterating $F_1$ lineation. $F_2$ lineation is also found superposed on lineated $F_1$ rods and $F_1$ rods occur folded round $F_2$ folds. Occasional examples of /
of $F$, isoclines refolded by $F_2$ folds occur throughout the area mapped, (see Plate 14).
III. STRUCTURE (continued)

4. THE THIRD FOLD MOVEMENT ($F_3$).

The third fold movement is of restricted extent. It occurs in an area approximately one and a half miles wide, that trends north-south and passes through Loch nam Paitean. $F_1$ and $F_2$ folds are refolded by $F_3$ folds. This is a "Similar type" fold movement.

a). Major $F_3$ folds and related minor folds.

The major $F_3$ folds are, a tight southerly plunging synform - the Lochan Meall a’Mhadaidh Synform - and a complementary large open antiform - the Loch nam Paitean Antiform. Both have nearly vertical north-south trending axial planes in the north, but as the axial planes are traced southwards they hinge over to dip to the southwest at about 45°.

In the area affected by $F_3$ folding, $F_3$ minor folds are abundant and are the most conspicuous folds. The majority of folds occur in banded psammitic schist of the Upper Psammitic Group and frequently show marked asymmetric shape (see Fig. 10). Near the tight Lochan Meall a’Mhadaidh Synform hinge, minor folds are tight while the minor folds associated/
FIG. 10 FOLDS FORMED DURING THE THIRD FOLD MOVEMENT.
associated with the Loch nam Paitean Antiform are open, (see Plates 15a and 15b), confirming that minor folds simulate genetically related major folds.

$F_2$ minor folds frequently exhibit unusual shape, (see Plate 16). This illustrates "box-folds" in banded psammitic schist. In Plate 16a the axial plane of a small antiform splits and a box-fold develops. The axial plane of the left-hand corner of the boxfold splits again to give a second box-fold that is slightly oblique to the first fold. This type of structure is fairly common in $F_3$ minor folds and is occasionally found in $F_2$ minor folds.

$F_3$ fold style is influenced by variations in lithology (see Plate 16b). A large open fold in quartz-feldspar granulite near the top of this picture is represented by many much smaller folds in semi-pelitic schist. Minor folds intermediate in size occur in quartzitic bands within the semi-pelitic schists. As a rule, minor folds in psammitic schists are much larger than those developed in pelitic and semi-pelitic schists. Mica crinkling and small minor folds are common in pelitic rock, while minor folds in psammitic rock may exceed 20 ft. in amplitude. An amplitude of up to one foot is the most common size. The style of $F_3$ minor folds indicates that they are of "Similar type". Many show limb attenuation and hinge thickening and minor folds can frequently/
frequently be traced along the axial plane, for consider-
able distances, without showing significant change of shape.
Cleavage is not seen in psammitic rocks, but near the hinge
of the Lochan Meall a'Mhadaidh Synform $F_3$ axial plane
cleavage imparts a new foliation, $s_3$, to semi-pelitic gneiss.

Since the foliation and bedding-schistosity was
already folded by $F_1$ and $F_2$ fold movements before $F_3$ folding
was superposed, $F_3$ folding has resulted in a complex orient-
ation pattern of the foliation, (see Fig. 24, sub-areas 10
and 14). Also as a result of this, although the orientation
of $F_3$ axial planes may remain constant, $F_3$ minor fold axes
show considerable spread in the axial plane, (see Fig. 11a).
$F_3$ was therefore non-cylindroidal when it was formed and
illustrates the features already described by other workers
(see Clifford, et. al., 1957 and Weiss 1959). In the area
north and west of Loch nam Paitean, post $F_3$ movement has
caused the axial planes of $F_3$ minor folds to dip south of
west at from 50° to 60° and $F_3$ minor fold axes plotted on
a stereonet show considerable spread in the southwest
quadrant (see Fig. 11b).

4b. **REFOLDING OF $F_1$ BY $F_3$**

Isoclinal/
FIG. 11. LOCH NAM PAITEAN AREA

- POLES TO AXIAL PLANES OF FOLDS FORMED DURING THE THIRD FOLD MOVEMENT

+ AXES OF FOLDS FORMED DURING THE THIRD FOLD MOVEMENT
Isoclinal folds formed during the first fold movement are common within the area affected by $F_3$. Where they are found together excellent examples of refolding result, (see Plate 17).

The $F_1$ fold style is very well represented in these photographs and it is of interest to note that even in small adjacent isoclines (Plate 17b), the intermediate limb of the isoclinal folds is not fully exposed. These photographs also emphasise the difficulty of estimating the stratigraphic thickness of metasediments in Moidart.

The axial planes of $F_1$ folds parallel the bedding-schistosity, thus the poles to $F_1$ axial planes lie along a great circle that is normal to the $F_3$ fold axis. The area north of Lochan Meall a'Mhadaidh, near the synform hinge illustrates this (see Fig. 12). $F_3$ axial planes and axes have constant, steep orientation while the $F_1$ poles to axial planes scatter along a great circle. $F_1$ axes maintain a steep plunge to the south and it is not possible to define the deformation pattern superposed on $F_1$ by $F_3$.

Refolded Upper Psammitic Group is exposed near the east bank of the Irine Burn (see Map 2). $F_1$ fold axes from this area when plotted on a stereonet, lie along a great/
FIG. 12. $F_1$ FOLDS REFOLDED BY $F_3$ FOLDS

DIAGRAM a
- POLE TO $F_1$ AXIAL PLANE
+ $F_3$ FOLD AXIS
○ AXIS OF REFOLDING OF $F_1$ AXIAL PLANES

DIAGRAM b
- $F_1$ FOLD AXIS
+ POLE TO $F_3$ AXIAL PLANE
great circle, (see Fig. 13a) and the mean axial plane of $F_3$ intersects this great circle to give a direction of tectonic transport ($\alpha_3$) for $F_3$ (see Ramsay, 1960), that plunges gently to the south (see Fig. 13b). The mean great circle trace of $F_3$ axial planes and the great circle distribution of $F_1$ axial structures are nearly of the same orientation. Thus slight variations in drawing these great circles on the stereonet, result in considerable alteration of the orientation of $\alpha_3$. Also the effect of $F_2$ folding on $F_1$ is not known. For these reasons little reliance is placed on this calculation of $\alpha_3$. In making the above calculation it is assumed that transportation during $F_3$ took place in the axial planes of $F_3$ folds. This assumption is supported by evidence from elsewhere (see p. 137), where $F_3$ axial plane cleavage was observed.

4c. REFOLDING OF $F_2$ BY $F_3$

Axial planes of $F_2$ minor folds can be traced round the $F_3$ major folds, (see Map 2). Poles to $F_2$ axial planes lie along a great circle and indicate an axis of folding of the axial planes that plunges at $70^\circ$ to $193^\circ$ (see Fig. 14). Since $F_2$ axial planes had more or less constant/
FIG. 13. $F_1$ AXIAL STRUCTURES AND $F_3$ AXIAL PLANES
EAST OF IRINE BURN

DIAGRAM a
- $F_1$ AXIAL STRUCTURES
- GREAT CIRCLE TRACE OF $F_1$ AXIAL STRUCTURES
+ POLES TO $F_3$ AXIAL PLANES

DIAGRAM b
- GREAT CIRCLE TRACE OF $F_1$ AXIAL STRUCTURES
- MEAN $F_3$ AXIAL PLANE
FIG. 14. AXIAL PLANES OF $F_2$ FOLDS REFOLDED DURING THE THIRD FOLD MOVEMENT

- POLES TO $F_2$ FOLD AXIAL PLANES
- GREAT CIRCLE DEFINED BY $F_2$ FOLD AXIAL PLANE POLES
- AXIS OF FOLDING OF $F_2$ AXIAL PLANES
- MEAN AXIAL PLANE OF $F_3$ FOLDS
constant orientation at the time of F₃ folding the great circle distribution is well defined (c.e.f. the foliation diag. Fig. 24, sub-area 10). Post F₃ warping is seen to have caused slight variation in the axial plane trend of F₃ folds, and it is this warping that causes the imperfect great circle distribution of F₂ poles to axial planes. In areas where F₃ axial planes are not affected by later movement, the axis about which the F₂ axial planes are refolded lies within the mean axial plane of the F₃ folds, (see Fig. 14).

F₂ fold axes are rotated by F₃ folding to lie along a great circle, (see Fig. 15). The style of F₃ folding indicates that this movement is of "Similar type". Shearing seen in semi-pelitic gneiss shows that movement has taken place in the axial plane of F₃ folds and the mean axial plane of F₃ intersects the great circle defined by refolded F₂ axes, to give a direction of tectonic transport (a₃) for F₃, that plunges at 25° to 343°, (Ramsay, 1960).

From the evidence stated above it is deduced that movement during F₃ took place in a nearly horizontal north-south direction, and from the shape of the F₃ major folds,
CALCULATION OF "a_3" AXIS
LOCH NAM PAITEAN

DIAGRAM A
F_2 AXIAL STRUCTURES & MEAN GREAT CIRCLE

DIAGRAM B
+ F_3 POLES TO AXIAL PLANES
----- F_3 AXIAL PLANES
----- GREAT CIRCLE OF F_2 AXIAL STRUCTURES
MEAN "a_3" AXIS PLUNGE AT 25° TO 343°

FIG. 15
141.

folds, it can be seen that the west of the area has moved north, relative to the east of the area. Where $F_3$ folds are undisturbed by later movement, they have nearly horizontal north-south trend. $F_3$ folding has bent the axial planes and axes of $F_2$ folds but, apart from minor local effects, the horizontal plunge of $F_2$ axes is maintained after $F_3$ folding. The effect of $F_3$ folding on $F_2$ folds is shown in the block diagram, (see Fig. 16), drawn from a plasticine model of the area around Loch nam Paitean.

Refolding of $F_3$ minor folds by $F_4$ minor folds is occasionally seen (see Plate 18a). In this plate an open $F_3$ fold with axial plane parallel to the pocket knife bends the axial plane of an open asymmetric $F_2$ fold. A discontinuous quartz-feldspar vein in the axial plane cleavage orientation of $F_2$ is also bent by $F_3$.

Occasionally $F_1$, $F_2$ and $F_3$ folds can be found together (see Plate 18b). Towards the left side of this picture an $F_1$ isoclinal is bent by a tight $F_2$ fold to form a hook shaped structure. Open $F_3$ folds in semi-pelitic gneiss on the right hand side of this photograph do not penetrate the psammitic rock on the left. The axial plane orientation of $F_3$ folds is different from that of $F_1$ and $F_2$ folds.
BLOCK DIAGRAM OF THE AREA AROUND LOCH NAM PAITEAN

FIG. 16

F3 Synform
F3 Antiform
F2 Antiform
F2 Synform
III. STRUCTURE (continued).

5. THE FOURTH FOLD MOVEMENT ($F_4$)

Structures related to this fold movement are common in the Roshven Pelitic Group. Folds diminish in size rapidly as they are traced into the Upper Psammitic Group, but thin psammitic bands and calc-silicate ribs within pelitic rock are folded. Open style mica crinkle folds, with axial planes that parallel the axial planes of $F_4$ minor folds, are widespread throughout the Roshven Pelitic Group. The only major fold of $F_4$ age occurs in the southeast of the area mapped, (see Map 2).

a) Major $F_4$ fold and related minor structures.

In the southeast corner of the area mapped, the general north-south trend of the foliation in the Roshven Pelitic Group, is disturbed to form a large S-shaped fold. The intermediate limb of this fold is approximately one mile long, at the boundary between the Upper Psammitic Group and the Roshven Pelitic Group. The axial plane of this open fold has regular orientation and dips at $76^\circ$ to $295^\circ$, (see Maps 1 and 2).

As this fold is traced to the southwest, into the/
the Upper Psammitic Group, it dies out rapidly. To the northeast, the fold is again diminished in size but it is of more tight style where it can be seen folding a psammitic band within the Roshven Pelitic Group, on Ceann Loch Uachdrach (see Map 1). Rapid variation of shape is a feature of "Concentric type" folding and it will be shown later (see p. 154) that F₄ may be in part "Concentric type" and in part "Similar type" folding, in this area.

The following important observations establish the relative ages of F₃ and F₄ major folds.

1. The orientation of F₄ folds is constant but the orientation of F₃ folds varies.

2. The "movement sense" required to produce the major F₃ folds necessitates that the west of the area moves north relative to the east, but the reverse is required to form the major F₄ fold.

3. The variation of trend seen in the axial planes of F₃ major folds, is consistent with the "movement sense" required to form the major F₄ fold.

Minor structures that can be related to the major F₄ fold are: a) Minor folds and, b) Mica crinkle folds.

a). Minor folds are abundant in pelitic gneiss,
and in banded psammitic and pelitic gneiss, in the vicinity of the major $F_4$ fold. The minor folds are usually small and seldom exceed two feet in amplitude. The folds may be asymmetric or symmetric; the latter are particularly abundant near the major fold hinges. The style may vary from very open to fairly tight, (see Plate 19), and in some areas of marked asymmetric folds one fold limb may show slight shearing. Where asymmetric folds occur on Ceann Loch Uachdrach, the "movement sense", as indicated by the fold shape, is invariably in harmony with the major folds in this area. Tectonic thickening is not pronounced near the major fold, but it may be conspicuous further north, near Sgùrr Domhuill Mòr. There is no visible cleavage associated with $F_4$ minor folds. The orientation of $F_4$ axial planes on Ceann Loch Uachdrach is very regular, and the axial plunge, though generally steep, shows a considerable spread within the axial plane (see Fig. 17). This is attributed to the superposition of $F_4$ folds on variable foliation.

b). Mica crinkle folds.

Mica crinkling is a widespread minor structure associated with this fold movement. The axial planes of the/
FIG. 17. F$_4$ MINOR FOLDS ON CEANN LOCH UACHDRACH

- POLES TO AXIAL PLANES
+ FOLD AXES
the mica crinkle folds parallel the axial planes of associated minor folds, but mica crinkle folds also occur without attendant minor folds. The size of the crinkle folds varies as does the style. In some localities the folds may occur with only half of an inch between adjacent axial planes.

In banded psammitic and semi-pelitic gneiss, the crinkle folds are confined to the semi-pelitic bands and can be seen stopping abruptly against the psammitic band contact, (see Plate 20a). The contacts between the pelitic and psammitic bands were probably planes of movement at the time when the crinkle folds were formed. Mica crinkle fold hinges impart a strong regular lineation to the foliation, in pelitic and semi-pelitic rocks, (see Plate 20b). This lineation is parallel to the axes of $F_4$ minor folds.

5B. REFOLDING OF $F_1$ BY $F_4$

This was only seen in the Roshven Pelitic Group. Minor $F_1$ isoclinal folds occur as tectonic inclusions within pelitic gneiss. The axial planes of these isoclines parallel the foliation and are bent round $F_4$ minor folds. Since/
Since \(F_1\) isocline axes are rarely measurable, it is not possible to study the deformation of \(F_1\) by \(F_4\).

\(F_4\) mica crinkle folds with axial planes oblique to \(F_1\) fold axial planes are more common than refolding of \(F_1\) by \(F_4\) minor folds. In isoclinal folds with pelitic rock in the core of the isocline, the axial planes of the crinkles can be traced from the limbs of the isocline through the pelitic core. The axial plane foliation of the isocline is crinkled on the same orientation as the pelitic rock flanking the isocline (see Plate 8b).

5c. **REFOLDING OF \(F_2\) BY \(F_4\)**

Refolding of \(F_2\) by \(F_4\) is well developed in two areas:

i) Sgùrr Domhuill Mòr.

ii) Ceann Loch Uachdrach.

5ci). Sgùrr Domhuill Mòr. This area affords excellent opportunity for studying refolding of \(F_2\) minor folds by \(F_4\) minor folds. Though both \(F_2\) and \(F_4\) minor folds are superficially alike in this area, close inspection shows that whereas the mica crystals in the hinge area of \(F_2\) folds may be aligned in the axial plane of the folds, the micas in \(F_4\) hinges show open style crinkling. Psammitic bands/
bands folded by $F_2$ may show cleavage, but cleavage is not seen in psammitic bands folded by $F_4$. The axial planes of $F_4$ minor folds have nearly constant orientation while $F_2$ fold axial planes are refolded by $F_4$ folds. $F_2$ axial plane cleavage can be seen crinkled by $F_4$ mica crinkle.

$F_2$ minor folds, related to the Sgùrr Domhuill Mòr Antiform, were traced from the relatively undistorted limbs of this major fold, into a zone of complex folding that lies 2,000 ft. due south of the summit of Sgùrr Domhuill Mòr. Two types of superposed folding occur in this area: a) $F_4$ mica crinkle superposed on an $F_2$ fold, without causing significant distortion of the $F_2$ fold axis.

b) $F_2$ minor folds refolded by $F_4$ minor folds, resulting in considerable displacement of $F_2$ by $F_4$ and forming non-cylindroidal $F_4$ minor folds.

a) Minor folds of the second fold movement occur on the eastern limb of the Sgùrr Domhuill Mòr Antiform, in coarsely banded psammitic and semi-pelitic gneiss. Many fold hinges can be seen plunging steeply to the south. The micas of the semi-pelitic rocks are crinkled by $F_4$ movement, this crinkling affects micas aligned in the axial planes of $F_2$ folds. The crinkle axes do not coincide with the/
the $F_2$ fold axes and one crinkle axis can be traced round an $F_2$ fold hinge. This is a situation analogous to that described by Sander, (see p. 25).

An $F_2$ fold was selected and the orientations of the foliation planes round the fold hinge were measured, the $F_2$ fold axis was also measured (see Fig. 18). The orientation of $F_4$ mica crinkle axes on the measured foliation planes is also shown. The mica crinkle axes plotted on a stereonet lie along a great circle that coincides with the measured axial plane of mica crinkling in this area.

It is shown that the late linear structure ($F_4$ mica crinkle axis) when superposed on an existing fold, lies along a great circle which defines the axial plane of the late structure. This emphasizes the importance of determining the relative ages between two structures in an area of complex folding, before using a lineation pattern to calculate the direction of tectonic transport. Sander has described this great circle pattern (1948) and has shown that it is related to the stress that formed the lineation.

b). An outcrop about 150 ft. long occurring 2,000 ft. south of the summit of Sgùrr Domhuill Mòr shows $F_2$/
FIG. 18. F$_4$ MICA CRINKLE SUPERPOSED ON F$_2$ MINOR FOLD

- POLES TO FOLIATION
- AXIS OF F$_2$ MINOR FOLD
+ F$_4$ MICA CRINKLE AXES
- AXIAL PLANE OF F$_4$ MICA CRINKLE
F₂ minor folds refolded by F₄ minor folds, and non-cylindrical F₄ folds. In this area, there is no evidence of F₃ folding, and since the outcrop studied is very small, it is assumed that F₂ folds were cylindrical before F₄ folding. This is supported by evidence nearby, where cylindrical F₂ folds, unaffected by F₄, plunge steeply to the south, on the south face of Sgùrr Domhuill Beag.

Where F₂ minor folds are affected by F₄ movement, the axial planes of the former are deflected from the regional north-south trend and in the outcrop studied, the F₂ axial planes swing round to nearly east-west trend. One F₂ minor fold showed an axial plane that varied from a dip of 70° to 136°, to a dip of 75° to 153°, within a distance of three feet (see Plate 21). When F₂ poles to axial planes are plotted on a stereonet they show considerable scatter, (see Fig. 19). F₄ poles to axial planes in the same area form a close group, (see Fig. 19).

F₂ fold axes show considerable variation in orientation within short distances, as they pass round the F₄ fold hinges, (see Fig. 19 and Plate 21). This gives rise to unusual structures, where a single steeply plunging F₂ axis may come to surface, reverse in plunge, and occasionally/
FIG. 19. POLES TO AXIAL PLANES ON SGÙRR DOMHUILL MÒR

- POLES TO $F_2$ AXIAL PLANES
+ POLES TO $F_4$ AXIAL PLANES
occasionally double back on itself to plunge steeply in its original direction (see Fig. 20). Axial culminations on $F_2$ antiforms occur over $F_4$ antiforms and axial depressions on $F_2$ antiforms occur where they are bent round $F_4$ synforms. Where a number of parallel $F_2$ folds occur together and they are affected by $F_4$ movement, the axial culminations and depressions on $F_2$ axes, occur in rows that lie along the axial planes of the $F_4$ folds. This occasionally results in a row of small steep sided domes.

$F_4$ synforms cut across $F_2$ synforms, causing axial depressions in the $F_2$ synform axes. This results in the formation of "canoe shaped" folds, or sometimes almost symmetric bowl shaped hollows.

Exposure in this small outcrop is excellent and the coarsely banded semi-pelitic and psammitic rock has weathered out along the foliation to display the structures. The writer was able to trace the same $F_2$ folds and measure their orientation over considerable distances and study their change of orientation, (see Fig. 21). On this Figure, broken lines indicate the tracks along which the $F_2$ axes lie as they vary in orientation. The $F_2$ axes describe a complete great circle (see Fig. 21).

$F_4$ minor folds nearby show slight tectonic thickening/
FIG. 20. BLOCK DIAGRAM TO SHOW THE VARIABLE PLUNGE OF $F_2$ FOLDS WHERE THEY ARE AFFECTED BY $F_4$ FOLDS.

SGÜRR DOMHUILL MÒR
thickening in the hinge areas. Cleavage is not seen in $F_4$ minor folds but semi-pelitic gneiss shows "mica crinkling", the axial planes of the crinkle folds parallel axial planes of the minor folds. It is thought that the mechanism of mica crinkling, with recrystallization in psammitic rock has taken the place of shearing and cleavage in the axial planes of the $F_4$ minor folds. It is apparent that the great circle pattern of $F_2$ fold axes could not be formed by north-south trending concentric folds. It is therefore concluded that $F_2$ axes were rotated by $F_4$ movement, in a "Similar" manner. By plotting the mean axial plane of $F_4$ folds, a direction of tectonic transport for $F_4$ ($A_4$), that plunges at 70° to the southwest is found, (see Fig. 21), (after Ramsay, 1960, see also p. 27 of this thesis).

Since the foliation was already folded by $F_2$ at the time when the $F_4$ folds were superposed, the $F_4$ folds are non-cylindroidal. This can be clearly demonstrated in this area where $F_4$ fold axes can be traced down the limbs, and over the hinges, of $F_2$ folds. Although the plunge of the $F_4$ folds varies, the axial planes remain at constant orientation. In contrast with this, both the plunge and axial planes of $F_2$ folds vary where they are refolded by $F_4$. The/
FIG. 21. CALCULATION OF $d_4$ AXIS
SGURRE DOMHULL MòR

- $F_2$ FOLD AXES
- OBSERVED CHANGE IN ORIENTATION OF $F_2$ FOLD AXES
+ POLES TO AXIAL PLANES OF $F_4$
MINOR FOLDS
— MEAN $F_4$ AXIAL PLANE
○ $d_4$ AXIS
The area described above illustrates the important part played by $F_4$ minor folds in controlling the present orientation of $F_2$ minor folds, also the control on $F_4$ folding exerted by $F_2$ folds. The $a_2$ direction has been calculated. By applying the axiom that minor structures simulate genetically related major structures, it is inferred that the effect of $F_4$ major folds on $F_2$ major folds, is to cause considerable rotation of the major $F_2$ fold axes. It is also possible that $a_4$ for the major $F_4$ folds has steep plunge.

In the area described above, and over the entire area of the Roshven Pelitic Group, there is no evidence of severe post $F_4$ movement. It is therefore concluded that this was the last significant fold movement to affect this area.

It has been shown earlier (see p. 139), that where $F_2$ folds are apparently unaffected by later movement, the axes of both major and minor $F_2$ folds have nearly horizontal plunge. Also, the calculated $a_3$ axis (i.e. direction of tectonic transport for $F_3$ movement) plunges at 25° to 343° and the effect of $F_3$ on $F_2$ has been to rotate the bearing of $F_2$ folds but to cause very little variation in the/
the plunge of $F_2$ axes. It is only in the Roshven Pelitic Group that major and minor $F_2$ folds show steep plunge, and it is only in the area underlain by this group that $F_4$ major folds occur. $F_4$ folds rarely penetrate the Upper Psammitic Group and it is thought that lithology has played an important role in localising the distribution and effect of this fold movement. From the facts stated above it is deduced that nearly horizontal $F_2$ axes were tilted into the steep orientation that they now have in the Roshven Pelitic Group, during the fourth fold movement. It is thought that considerable "adjustment" may have taken place near the western boundary of the Roshven Pelitic Group, in order to accommodate the transition between steeply inclined $F_2$ axes in the east and nearly horizontal $F_2$ axes in the west. The likelihood of major $F_4$ folds developing would depend on the orientation of $a_4$, with respect to the foliation at the time of $F_4$. Where $a_4$ lies within the foliation folds are not developed (see Ramsay, 1960).

5cii). Ceann Loch Uachdrach.

The only major $F_4$ fold occurs on the ridge between the Moidart River and Loch Shiel (see p. 142). In this area very/
very tight $F_2$ folds with steep axial planes and steep plunge can be traced round the $F_4$ fold. The poles to $F_2$ axial planes lie along a great circle (see Fig. 22a). The axis of folding of the $F_2$ axial planes lies very near the great circle plot of the mean $F_4$ axial plane, (see Fig. 22b). Also, since the $F_2$ folds are very tight, the axis of folding of the axial planes falls near the cluster of $F_4$ fold axes, (see Fig. 22c).

$F_2$ minor fold axes plotted on a stereonet give a diffuse group near the centre (Fig. 23). It is not possible to draw a great circle or a small circle to indicate the pattern of $F_2$ axes. The following possible explanations for this irregularity in the $F_2$ axial structures distribution can be given:

1). Post $F_4$ movement has distorted an original clearly defined pattern.

2). $F_2$ axes were not rectilinear at the time when $F_4$ movement took place.

3). The $F_4$ fold movement was part "Concentric type" and part "Similar type", resulting in a distribution pattern of $F_2$ axes that is intermediate between the two "ideal" cases of small or great circle patterns.

Considering/
FIG. 22 CEANN LOCH UACHDRACH

DIAGRAM A
- POLES TO $F_2$ AXIAL PLANES
- AXIS OF FOLDING OF $F_2$ AXIAL PLANES

DIAGRAM B
- POLES TO $F_4$ AXIAL PLANES
- MEAN $F_4$ AXIAL PLANE
- AXIS OF FOLDING OF $F_2$ AXIAL PLANES

DIAGRAM C
+ $F_4$ FOLD AXES
- AXIS OF FOLDING OF $F_2$ AXIAL PLANES
- MEAN $F_4$ AXIAL PLANE
FIG. 23. CEANN LOCH UACHDRACH

+ F₂ FOLD AXES
• POLES TO F₄ AXIAL PLANES
—MEAN F₄ AXIAL PLANE
Considering 1) above. There is no indication of post $F_4$ folding in this area. This field observation is supported by the close grouping of $F_4$ minor fold poles to axial planes. It is therefore concluded that this possibility is unlikely. With respect to 2) above it should be pointed out that the Ceann Loch Uachdrach fold lies near the area affected by $F_3$ folding already described. It is therefore possible that $F_2$ fold axes were rotated during $F_3$ and so were not rectilinear at the time of $F_4$. However, there is no evidence in support of this, in the field. Where $F_2$ axes are unaffected by $F_4$ folds they are apparently rectilinear. It would appear that 3) above is the most probable of the possibilities listed.

J.G. Ramsay (1960) and L.E. Weiss (1959) have pointed out that combinations of "Concentric type" and "Similar type" folding are likely; Weiss considers that folding intermediate between the two ideal types is the general rule in nature, (see p. 24). Weiss (1959) has also shown that an initial "Concentric type" fold may develop into a "Similar type" fold.

It was pointed out earlier (see p. 143), that the major Ceann Loch Uachdrach fold shows characteristics found/
found in "Concentric type" folding. Evidence from Sgùrr Domhuill Mòr shows that, at least locally, $F_4$ movement was of "Similar type". The writer is therefore of the opinion that $F_4$ was a combination of "Concentric type" and "Similar type" folding, with the latter predominating at some localities.

Minor folds related to the major Ceann Loch Uachdrach Fold are occasionally seen refolding $F_2$ minor folds, causing warping of the $F_2$ fold axial planes, (see Plate 22a). Elsewhere, $F_2$ folds in banded psammitic and pelitic rock show no axial plane distortion but mica crinkle folds that can be related to minor $F_4$ folds, are seen to crinkle the axial plane foliation of the $F_2$ minor folds, (see Plate 22b).

$F_4$ minor folds are rarely seen in the Upper Psammitic Group, but occasionally, near the eastern boundary of the Upper Psammitic Group, $F_2$ minor folds show variation in plunge that give rise to "eye folds", (see Plate 23a). Where several $F_2$ folds occur together they can be seen to change plunge along a line that has the same bearing as $F_4$ minor fold axial planes in the Roshven Pelitic Group, nearby. It is thought that the change of plunge is due to $F_4$ movement.
5d). **REFOLDING OF $F_3$ BY $F_4$**

The major $F_3$ folds show variation in axial plane trend and orientation (see p. 135); this is attributed to the effect of $F_4$ major folds on $F_3$. Since neither $F_3$ nor $F_4$ major folds are well developed in the area where this change of axial plane trend occurs, the effect of $F_4$ on $F_3$ cannot be studied.

$F_3$ minor folds are not seen refolded by $F_4$ minor folds so it is not possible to obtain a direct age relationship between these two fold movements. However, it can be shown that the $F_3$ minor folds change in axial plane trend and orientation as they are traced from north to south, (see Map 2). Also $F_4$ minor folds, oriented nearly at right angles to $F_3$ minor folds occur, to the southeast of Loch nam Paitean. The $F_4$ minor folds have constant axial plane orientation. The relative ages of $F_3$ and $F_4$ are established on these observations.
III. STRUCTURE (continued).

6. FOLDING OF UNCERTAIN AGE.

Two periods of movement, the relative ages of which have not been established, occur. Both are considered to be later than the fourth fold movement described above.

The first of these fold movements to be described occurs as broad monoclines that trend north-south, with vertical axial planes and nearly horizontal plunge. Monoclines are not seen in the Roshven Pelitic Group. Occasional folds occur in the Upper Psammitic Group, on the south side of Gleann Dubh, and thin, interbedded pelitic bands occurring with the psammitic schists, show open mica crinkle folds, with axial planes that parallel the axial planes of the monoclines.

Monoclines occur most frequently west of Loch Ard a' Phuill where they warp the axial planes of $F_2$ folds, causing the $F_2$ poles to axial planes to spread along a great circle, (see Fig. 24, sub-areas 2 and 12). This great circle is normal to the monocline fold axis. Since the monocline fold axis is nearly coincident with that of $F_2$, the $F_2$ axial structures are only slightly rotated out of their original orientation by the monoclines.

The regional significance of this movement is uncertain/
uncertain. It is possible that before the monoclines formed, $F_2$ axial planes were nearly vertical throughout the area, and that these folds have caused the disparity between nearly vertical $F_2$ axial planes in the east and gently inclined $F_2$ axial planes in the west.

Monoclines are frequently seen to warp $F_2$ fold axial planes and it is thought that they may also be partly responsible for the variable orientation of $F_3$ axial planes near Loch nam Paitean. Since $F_4$ folds and monoclines were not seen together, it is not possible to say definitely whether the latter preceded or followed the fourth fold movement.

The second fold movement of uncertain age is probably the most recent of the events described in this structural history of Moidart. Folds of this episode are most common in the Upper Psammitic Group and show characteristic "brittle" style (see Plate 23b). Numerous strong joints develop along the axial planes of these folds, and the psammitic schist is nearly always discoloured from pale grey to flesh pink, along the axial planes. The close association between folding, jointing and discoloration suggests that/
that all three are related. Folds of this movement period are always asymmetric and invariably indicate that the southwest of the area has moved northwest, relative to the northeast.

In the west of the area mapped, minor $F_2$ folds related to the Glenuig Antiform show variation in orientation. This can be seen along the west coast of Glenuig Bay, also on the hill between Glenuig Bay and Loch na Bairness, (see Map 2). There are no minor folds that are apparently related to this change of $F_2$ orientation, but mica crinkle folds occasionally develop. The axial planes of these small crinkle folds trend northwest-southeast and are approximately parallel to the orientation of the "brittle" folds seen in the Upper Psammitic Group. Also, the change in orientation seen in the $F_2$ minor folds indicates the same "movement sense" as that indicated by the brittle folds. $F_2$ axial plane cleavage in minor folds to the west of Loch na Bairness is "crinkled" by minute asymmetric folds and asymmetric minor folds also occur in the western outcrop of the Striped and Pelitic Group. The orientation and "movement sense" indicated by these minor structures is the same as that seen in the brittle folds.

Minor/
Minor folds in the Roshven Pelitic Group west of the summit of Sgurr Domhull Mor are also sub-parallel with, and show the same "movement sense" as, the brittle folds seen in the Upper Psammitic Group.

Shattering along the axial planes of the brittle folds, has made the Upper Psammitic Group easy to erode, and stream courses frequently follow along these axial planes, cutting a deep gully. Tertiary dykes normally trend north-south, following the regional bedding-schistosity. They also tend to follow the jointed zones, and some dykes show a step-like path, following the strike of the bedding-schistosity then deviating along a jointed zone for a short distance, before resuming the regional north-south trend, (see Map 1). A camptonite dyke with associated lead-bearing vein, has been noted by the Geological Survey (see p. 22); this intrusion which may be of Permian age, follows a zone of brittle deformation.

\( F_4 \) folds have been seen displaced by this movement but no relationship between \( F_4 \) was observed. The brittle style of the folds in psammitic rock, suggests that this represents a late phase movement.
III. STRUCTURE (continued).

7. CONCLUSION.

G.P. Leedal (1952) has given the distribution of the "steep" and "flat-lying" belts of rock in the Moines. Moidart lies within the "steep belt" as described by Leedal, and the area studied may be divided into a western area in which \( F_3 \) fold axes are nearly horizontal, and an eastern area where \( F_2 \) fold axes are frequently steeply inclined. The area mapped also lies due south of Morar, where W.Q. Kennedy (1954 issued 1955) has made a reinterpretation of earlier work done by Richey and Kennedy (1939). The area studied is therefore a key area, linking the areas of steeply inclined and nearly horizontal \( F_2 \) fold axes. It also provides the most direct correlation between Morar and the Moines to the south.

The area is shown to be structurally complex and four significant movements are recognised. The relative ages of these movements is demonstrated by a detailed structural analysis. A table, (see Fig. 5), summarising the work is given. It has been shown that each successive generation of folding refolded preceding generations to build up the complex geometry that is now preserved in Moidart.

a)/
a). The transition from the steeply inclined fold axes to nearly horizontal fold axes.

The earliest fold movement formed long limbed isoclines that are only recognised on the minor fold scale. This was followed by a movement that formed tight folds with nearly vertical axial planes. After this fold movement the bedding-schistosity and foliation were left steeply inclined. Most of the major folds seen in the area mapped were formed at this time. The axes of these major folds are thought to have been nearly horizontal at the time when the folds were formed.

The third fold movement has restricted extent and a calculated direction of tectonic transport for this movement indicates that movement took place along a nearly horizontal, north-south axis. The third folds bent the second fold axes but did not cause significant change in the inclination of the \( F_2 \) axes.

The fourth fold movement is restricted to the eastern part of the area mapped where steeply inclined \( F_2 \) fold axes occur. It has a direction of tectonic transport that plunges at 70° to the southwest. On the minor fold scale, the fourth fold movement causes considerable variation in the inclination of \( F_2 \) axes. The writer is of the opinion that/
that the steep orientation of $F_2$ fold axes in the steeply
dipping rocks in the east of the area mapped, was super-
posed at this time.

Monoclinal flexuring has probably caused the
nearly vertical $F_2$ axial planes to hinge over and dip at $45^\circ$
to the east, in the west of the area mapped. No monoclines
were seen in the Roshven Pelitic Group.

It is suggested that the foliation in this area
of the steep belt of Moines, attained that attitude during
the first or the second fold movement. The rocks were
left steeply inclined after the second fold movement. The
steep plunge of the $F_2$ fold axes in the east of the area
studied was superposed during the fourth fold movement.
Fourth folds rarely penetrate the Upper Psammitic Group,
thus the $F_2$ axes within this Group retain nearly horizon-
tal plunge.

b). Correlation between Morar and Moidart.

Morar is five miles to the north of Moidart
and any correlation across this distance in an area as
complex as this is shown to be is speculative. This attempt
to link Morar with Moidart is made because the Sound of
Arisaig separates the two areas and prevents more direct
correlation.

W.Q. Kennedy/
W.Q. Kennedy's most recent interpretation of the structure of Morar has been outlined in the introduction (see pp. 13-15). He states "the outcrop of an upper Moine nappe, here designated the Morar nappe, frames exposures of a much broken lower Moine or basement nappe." Kennedy records that recumbent folding seen in the core schists does not extend outwards into the envelope schists and the boundary between the core and the envelope is named the basal slide of the Morar nappe. He is of the opinion that the recumbent folding seen in the core, formed at the same time as the Morar nappe and that these folds, together with the basal slide of the Morar nappe are refolded by the Morar anticline. R. St. J. Lambert disagrees with Kennedy. He states that recumbent folds occur in both the envelope and the core and that the boundary between the core and the envelope is a metamorphic boundary.

The metasediments of Moidart represent the southern continuation of the envelope schists of Morar, and recumbent isoclinal folds in Moidart are formed during the first fold movement. Although no major folds of this movement were found, the writer is of the opinion that the style of the minor folds suggests that related major folds, will be/
be similar to the Morar nappe, postulated by W.Q. Kennedy. Furthermore, the Morar nappe and related recumbent folding represents the earliest movement episode recognised in this area. The isoclinal minor folds seen in Moidart also represent the earliest movement recognised in Moidart. It is therefore suggested that the first fold movement of Moidart can be tentatively correlated with the movement phase that formed the Morar nappe and the recumbent folds formed at the same time as this nappe, in Morar.

In Morar, following the formation of the Morar nappe, there was a more open style of folding that formed the Morar Anticline. This movement preceded regional injection and metamorphism (Kennedy, 1954 and 1955). J.E. Richey (1946) in describing the Morar Anticline writes "In contrast to the prevalently unfolded rocks of the western limb of the Morar Anticline, the schists forming the eastern limb are almost everywhere affected by dragfolding on a relatively small scale; the amplitudes of the folds being usually a matter of yards. A further detail of interest is that the apices and troughs of the drag-folds are thickened and the limbs thinned. Owing to the distortion of the rocks, cross-bedding is rarely identifiable, but the various groups/
groups and sub-groups of the Morar succession are distinguished by their lithological characters as well as by their relations to each other and to the centrally-situated belt of so-called Sub-Moine rocks."

Geological Survey officers (see p. 11) have correlated the Glenug Antiform with the Morar Anticline, and from the above description of the latter given by Richey, the writer accepts this correlation. The similarity between the Glenug Antiform and the Morar Anticline is striking. Minor folds associated with the Glenug Antiform are very common on the eastern limb and are much less common on the western limb. Also the "detail of interest" given by J.E. Richey (see above), clearly indicates that minor folds associated with the Morar Anticline are of "Similar type", as are the $F_2$ minor folds associated with the Glenug Antiform.
LOCATION OF SUB-AREAS

DIAGRAM A
AXIAL STRUCTURES OF FIRST FOLD MOVEMENT
AXIAL STRUCTURES OF SECOND FOLD MOVEMENT
AXIAL STRUCTURES OF THIRD FOLD MOVEMENT
AXIAL STRUCTURES OF FOURTH FOLD MOVEMENT
POLES TO FOLIATION AND BEDDING-SCHISTOSITY CONTOURED AT 1, 2, 5 & 10% PER 1% AREA
576 NUMBER OF POLES PLOTTED

DIAGRAM B
POLES TO AXIAL PLANES OF SECOND FOLD MOVEMENT
POLES TO AXIAL PLANES OF THIRD FOLD MOVEMENT
POLES TO AXIAL PLANES OF FOURTH FOLD MOVEMENT

MAP 24: STRUCTURAL ANALYSIS
IV. **METAMORPHISM**

1. **INTRODUCTION**

The complex structural history demonstrated in the previous section is matched by an equally complex metamorphic history. The metamorphic grade in Moidart increases from garnet in the west, to sillimanite in the east. Evidence from garnets found in the west of Moidart (from the Striped and Pelitic Group), indicates that garnet grade of metamorphism was reached twice during the metamorphic history. It would appear that the rocks were metamorphosed to garnet grade after the first period of folding. The second metamorphism of garnet grade was a syntectonic phase and was probably attained during the second generation of folding.

Regrowth of garnet is common in the west but is absent in the east and it is thought that, while the rocks in the west were being metamorphosed to garnet grade for the first time, the rocks in the east reached sillimanite grade of metamorphism. Garnets in the east do not preserve relic structures. The present calc-silicate metamorphic zones were probably imprinted during the period of regional metamorphism.
metamorphism that took place before the second fold movement. In Moidart the zones range from "zoisite" in the west to "anorthite-pyroxene" in the east. There is a parallelism between Barrovian Zones and Calc-silicate Zones. Extending over a period that began before the second folding took place and probably continued after the second folds had formed; the eastern part of the area was migmatized. Lenticular quartz-feldspar folia formed during migmatization, were disrupted by cleavage formed during the second fold movement. Also, quartz-feldspar sheets occupy the axial plane cleavage of second folds. Migmatization is most apparent in pelitic and semi-pelitic rocks and is confined to the eastern part of Moidart.

The most recent recrystallization took place during or after the last period of folding. This is indicated by the absence of bent cleavage planes in mica crystals that form "mica crinkling", correlated with the fourth generation of folding. The micas meet at varying, sometimes acute angles, to form the small crinkle folds that are widespread over the area.

After this recrystallization there was a period of regional retrograde metamorphism during which garnets
in the west of Moidart were altered to a chlorite-biotite-clinozoisite assemblage. Biotite is altered to chlorite at some localities. In the east of the area, sillimanite-staurolite aggregates were altered to muscovite and garnets were retrograded to chlorite and biotite. Since the minerals formed during the retrograde metamorphism show no alignment, it is concluded that the retrograde metamorphism took place after regional movement and recrystallization had ceased.

This phase of retrograde metamorphism may be associated with the intrusion of quartz-feldspar-muscovite pegmatites and the formation of randomly oriented muscovite porphyroblasts. However, the two latter features are restricted to the eastern half of Moidart, whereas the retrograde metamorphism is regional.
IV. METAMORPHISM (continued).

2. BARROVIAN METAMORPHIC ZONES

The map shown in Figure 4 illustrates the distribution of Barrovian Zones. The metamorphic isograds trend north-south and are approximately parallel to the prevalent strike. The western boundary of the Kyanite Zone is conjectural. This boundary lies somewhere within the four miles wide outcrop of the Upper Psammitic Group - an unfavourable formation for the development of zonal minerals.

a). Sillimanite Zone.

Sillimanite was only found in the Roshven Pelitic Group, near the eastern boundary of the area mapped. It is not abundant but can be found persistently near the western boundary of the main outcrop of the Roshven Pelitic Group, in richly garnetiferous pelitic schist. Northeast of Sgùrr Domhuill Mòr (see p. 87) sillimanite was found as rare rod-like aggregates of crystals. The "rods" were apparently oriented with the long axes parallel to the axes of folds formed during the second generation of folding. If this correlation is correct it suggests that the sillimanite metamorphism and the second generation of folding may be related. It should be pointed out however that:

a)/
a). The "rods" are rare.

b). The rod-like habit may merely be a phenomenon of the growth habit of sillimanite.

c). Both \( F \) and \( F_2 \) fold axes have the same plunge in this area.

For these reasons, little reliance can be placed on this apparent parallelism.

b). Kyanite Zone.

Kyanite is a rare mineral in Moidart and was only found in hand specimen at one locality (see p. 88). It occurs in several thin sections and is usually associated with staurolite and muscovite.

c). Garnet Zone.

Garnets are ubiquitous throughout the pelitic rocks of Moidart, and are often abundant. The parallel outcrops of the Striped and Pelitic Group seen in the west of the area lie within the Garnet Zone, and it is in these rocks that crystals showing a variety of relic structures occur. The relic structures can be seen as alignments of inclusions within the garnets and many crystals showing two phases of garnet growth were found. In crystals showing two/
two phases of growth an inner "core" garnet showing idio-
blastic or hypidioblastic form is surrounded by an outer
hypidioblastic or xenoblastic crystal. The boundary between
the inner and outer garnet is often sharply defined and
frequently the inclusion alignment in the core is markedly
different from that in the outer garnet. Refractive index
determinations revealed that the inner and outer garnets are
of almandine or spessartite composition, and that the core
garnets have slightly higher refractive indices than the
outer garnets.

In order to determine the refractive indices of
both core and outer garnets, thin sections that were about
three times normal thickness were prepared. Fragments of
core and outer garnet were carefully removed under a micro-
scope and the refractive indices determined. The following
results were obtained:

<table>
<thead>
<tr>
<th>Slide No.</th>
<th>a) Interior (core) garnet</th>
<th>b) Exterior (outer) garnet</th>
<th>a-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4/15</td>
<td>1.790</td>
<td>1.783</td>
<td>+0.007</td>
</tr>
<tr>
<td>L4/15</td>
<td>1.790</td>
<td>1.784</td>
<td>+0.006</td>
</tr>
<tr>
<td>N7/7</td>
<td>1.785</td>
<td>1.777</td>
<td>+0.008</td>
</tr>
<tr>
<td>N7/7</td>
<td>1.792</td>
<td>1.785</td>
<td>+0.007</td>
</tr>
<tr>
<td>N5/14</td>
<td>1.802</td>
<td>1.796</td>
<td>+0.006</td>
</tr>
<tr>
<td>N5/14</td>
<td>1.804</td>
<td>1.796</td>
<td>+0.008</td>
</tr>
</tbody>
</table>
It can be seen from the above table that there is a slight but consistent difference between core and outer garnet.

The arrangement of inclusions in rolled garnets from Morar has recently been described by J.S. Peacey (1961). The writer has found similar rolled garnets in Moidart and other arrangements of inclusions that have not been reported before from this area, were found. The arrangement of inclusions in garnets is described and discussed below, under the following headings:

1). Garnets with straight inclusion trails.

ii). Garnets with curved inclusion trails (rolled garnets).

iii). Garnets with straight inclusion trails in the core and rolled outer garnet.

iv). Garnets with straight inclusion trails preserved, followed by movement then regrowth of garnet.

The nomenclature used below has been discussed by H.H. Read (1949), pp. 110 et seq.) and F.J. Turner (1948).

1). Garnets with straight inclusion trails.

Plate 26a illustrates a garnet porphyroblast
4.0 mm in diameter with inclusions of quartz and opaque ore. The porphyroblast has smooth outline and is enclosed in a spindle of recrystallized mica. Muscovite is much more abundant than biotite in the mica spindle, and opaque ore is common round the outside of the garnet.

Quartz is the most common mineral included within these garnets and is frequently found as crystals showing elliptical cross-section and forming straight, parallel trails, across the porphyroblasts. The long axes of the ellipses may measure up to 0.15 mm and parallel the inclusion trails. Quartz frequently occurs as long slivers that are again parallel to the inclusion trails and are seen to be made up of chains of small quartz crystals, that often have barrel shaped cross-sections. Although the slivers may be 1.0 mm long, the individual crystals rarely exceed 0.15 mm in length. The crystal size of quartz in the matrix of the rock is approximately twice that seen in the inclusions. Some quartz inclusions are strained, others are unstrained. In addition to the quartz and opaque ore inclusions, there are straight parallel trails of minute inclusions that can be recognised at +450 magnification, as specs of light under crossed nicols.

The/
The following important observations are made on one slide.

1). The straight trails of inclusions in the porphyroblasts ($s_1$) do not parallel the present schistosity in the rock ($s_e$).

2). The orientation of $s_1$ seen in garnet porphyroblasts in the same slide varies from one garnet to another.

3). The inclusion trails within the garnets are consistently straight but the schistosity shows many small asymmetric folds.

From the observed difference in grain size between $s_1$ and $s_e$ and with regard to observations 1) and 3) above, it is concluded that the inclusions illustrate helicitic texture and preserve a planar structure that is earlier than the present schistosity seen in the rock. Furthermore, considering observations 1) and 2) it is deduced that since the porphyroblasts grew, they have been rotated without destroying the helicitic texture. The porphyroblasts were not rotated by the same amount, so inclusion trails in neighbouring porphyroblasts are not parallel to one another. The author prefers to interpret the non-parallelism between $s_1$ planes in neighbouring crystals as rotation of the porphyroblasts.
porphyroblasts, rather than to adopt the other alternative, that the helicitic texture represents a folded pre-existing s plane, because:

1). There is evidence elsewhere (see below) that movement has taken place since the straight inclusion trails were preserved, and

2). In the large porphyroblasts seen in the slide considered above, there was no indication of folding in the sj planes preserved.

ii). Garnets with curved inclusion trails (rolled garnets).

Garnets that show one phase of growth and illustrate para-crystalline deformation are not very common in Moidart. They occur as small porphyroblasts up to 0.5 mm in diameter. This is also the size of the rolled garnets described by J.S. Peacey (1961), from Morar.

Plate 26b illustrates a rolled garnet 0.5 mm in diameter with inclusions of quartz, opaque ore and biotite. The xenoblastic shape of the porphyroblast is typical of this type of garnet and many crystals have spongy appearance. Inclusions of quartz are most abundant and frequently measure/
measure about 0.10 mm by 0.02 mm. The S- or Z- shaped alignment of inclusions is a feature of para-crystalline deformation and it is frequently observed that the inclusion trails do not come into parallelism with the present schistosity. In one thin section the inclusion trails can be seen making different angles with the schistosity. It is thought that garnet growth took place during movement (paratectonic crystallization), and that movement continued after growth had stopped, thereby rotating the porphyroblasts into positions where the trails do not pass into alignment with the schistosity.

Tight minor folding of the schistosity is apparently related to the garnet rolling. These minor folds have the same style as the abundant F₂ minor folds seen in this area, so it is thought that the paracrystalline structures were formed during the second period of folding.

iii). Garnets with straight inclusion trails in the core and rolled outer garnets.

Garnets showing this pattern are abundant in garnetiferous pelitic schists of the Striped and Pelitic Group, west of Glenuig. Plate 27a illustrates this structure in/
in a garnet porphyroblast 2.5 mm in diameter. It can be seen that the porphyroblast is equidimensional and is made up of an idioblastic core about 1.8 mm in diameter surrounded by an outer garnet fringe that is about 0.35 mm thick. The crystal boundaries of the idioblastic core are clearly defined except where chlorite, formed as a result of retrograde metamorphism, has encroached into the core garnet. In other examples, the porphyroblasts may reach 5.0 mm in diameter, and it is seen that they are made up of a large core garnet, surrounded by a thin xenoblastic or hypidioblastic envelope garnet. It has been shown that the refractive index of the core garnet is consistently slightly higher than that of the outer garnet. Inclusions in both inner and outer garnet are about the same size, and are predominently quartz and opaque ore. The quartz inclusions are mostly unstrained and rarely exceed 0.15 mm by 0.08 mm.

Many garnet crystals showing this structure were studied and the inclusion trails of the inner garnet are invariably straight, with the long axes of the quartz inclusions parallel to the trails. This is identical with the structure described in i) and the core garnets are thought to represent the same phase of crystallization as that described in i). Two garnets were found showing poorly developed/
developed straight inclusion trails, indicated by quartz inclusions that are concentrated in the form of a cross, (see Plate 36b). The latter is thought to reflect variations in the growth pressure within the garnet crystal (Harker, 1932, reprinted 1952, pp. 41 and 42).

The inclusion trails in the outer garnet (see Plate 27a) show curved arrangement similar to that seen in rolled garnets and described in ii). The outer garnet is therefore correlated with the paratectonic garnets described in ii) and is considered to have formed during the second fold movement. Paratectonic garnet enclosing garnet crystals identical with the porphyroblasts described in i), corroborates the interpretation put forward for the varying orientations of $s_1$ planes in the porphyroblasts described in i). The inclusion trails in the outer garnets do not always come into parallelism with the present schistosity, and this is interpreted as continued rolling of the garnets after regrowth had ceased.

iv). Garnets with straight inclusion trails preserved, followed by movement then regrowth of garnet.

Garnets that show this structure are not equidi-
equidimensional (c.f. iii)), but show elliptical cross-section with the long axis of the ellipse lying in the schistosity (see Plate 27b). This porphyroblast is 3.0 mm long and 1.0 mm across, and has apparently grown out along the schistosity. Inclusions are predominantly of quartz and opaque ore. The core garnet with straight inclusion trails is again clearly defined. The inclusions in the outer garnet appear to be larger than those in the core; but the large slivers of quartz in the outer garnet are made up of chains of small quartz crystals. These small quartz crystals are about the same size as the quartz inclusions in the core, 0.15 mm by 0.3 mm.

It can be seen (Plate 27b) that the straight inclusion trails of the of the core garnet are not parallel to the schistosity ($s_e$). The inclusion trails of the outer garnet, and in particular those seen at the right side of the core, are of special interest. The curved arrangement of the inclusion trails is not consistently in the same direction, as is the case in a rolled garnet (Plate 27a). There is a tendency for the inclusion alignment to sweep away from the core garnet to come into alignment with the schistosity. Furthermore, the elongate elliptical cross-section/
cross-section of the porphyroblast is incompatible with the shape of a rolling crystal. The core garnet is not disrupted, therefore the elongation of the porphyroblast is not due to shearing.

The writer interprets this type of structure as having formed as follows:

1). Crystallization of the core garnet preserving a helicitic texture ($s_1$).

2). Rotation during the second generation of folding, turning $s_1$ out of alignment with $s_e$ (as in 1)), and forming an "eye" pattern of small matrix quartz crystals around the garnet porphyroblast.

3). Towards the end of the second fold movement and continuing after movement had ceased, regrowth of garnet took place. Outer garnet was formed and added to the hypidioblastic core garnet, preserving the "eye" pattern of the matrix crystals. This garnet growth extended out along the schistosity giving the crystal elliptical cross-section.

It is thought that the second garnet growth described above, is closely related in time to the second period of folding, and to the paratectonic garnets described in ii) and iii).
IV. METAMORPHISM (continued).

3. CALC-SILICATE METAMORPHIC ZONES.

W.Q. Kennedy (1949) has described the metamorphic zones displayed by calc-silicate granulites in Western Inverness-Shire. He has pointed out that the sillimanite isograd lies a short distance to the west of the pyroxene isograd (op. cit. p. 52). The writer has also observed this, and this is illustrated on the maps shown on Figure 4. The calc-silicate mineral isograds mapped in Moidart (see Fig. 4), differ slightly from those shown by W.Q. Kennedy in this area (see Fig. 2), but the regional pattern is unchanged.

a). Anorthite-Pyroxene Zone.

The petrography of calc-silicate rocks falling within this zone has been described (pp. 48 et. seq.). Since this general petrographic description embraces calc-silicate rocks that fall within both the anorthite-hornblende and the anorthite-pyroxene zones, some additional points concerning the anorthite pyroxene zone only, are made below.

The average grain size of the quartz-feldspar groundmass mosaic, though noticeably coarser than that of the calc-silicate rocks in the zoisite zone, is rarely more than/
than 0.5 mm diameter. Pyroxene is poorly developed as irregular, spongy, porphyroblasts, and is usually colourless showing a large extinction angle. It is frequently associated with bright green acicular crystals of actinolitic amphibole. W.Q. Kennedy interprets this as an effect of retrograde metamorphism.

In Moidart pyroxene is sometimes found with massive hornblende and it is sometimes difficult to decide which is the leading index mineral. This zone is not well developed in Moidart and only occurs near the eastern boundary.

The analysis of an anorthite-pyroxene calc-silicate rock given by W.Q. Kennedy (op. cit. Table II - 3), is done on a specimen collected from a point "1,630 yards E. 10° S. of General Ross’s Cairn". This point falls near the eastern boundary of the area mapped, on the ridge between the Moidart River and Loch Shiel.

b). **Anorthite-hornblende Zone.**

The petrography of anorthite-hornblende calc-silicate rocks has been described (pp.95 – 98; 76 – 81). Throughout this zone there is a gradual increase in grain size of the quartz-feldspar mosaic from west to east. W.Q. Kennedy/
W. Q. Kennedy (1949, p. 48) has pointed out the sudden rise in anorthite content seen in the plagioclase feldspars near the zoisite-anorthite boundary, and this was also found in Moidart (see p. 78). Pale green hornblende occurring as poeciloblastic porphyroblasts up to 3.0 mm long, is the leading index mineral of this zone.

c). Zoisite Zone.

Calc-silicate rocks from this zone have been described (see pp. 59-63). Prismatic crystals of zoisite are often abundant and biotite is fairly common near the west coast of Moidart. Although zoisite occurs in all the calc-silicate zones, the prismatic crystals abundant in west Moidart, do not occur in the high grade zones to the east. In the zoisite zone, garnet porphyroblasts are frequently massive with few inclusions and crystal faces are common. In the anorthite-pyroxene zone the garnets are xenoblastic, spongy crystals, crowded with inclusions. The average grain size of the matrix in the zoisite zone is between 0.1 mm and 0.2 mm.
IV. **METAMORPHISM** (continued).

4. **MIGMATIZATION**

The area mapped lies astride the western boundary of the "Injection Complex" described by J. Phemister (Regional Guide, 1960). Migmatization is restricted to a strip about two miles wide, along the eastern boundary of the area mapped. In this area the rocks are a mixed assemblage of psammitic and pelitic types, comprising the Roshven Pelitic Group, and the eastern members of the Upper Psammitic Group.

Petrographic descriptions of the migmatized rocks are given on pages 63 – 95.

Migmatization has converted pelitic rock types to partly permeated pelitic gneisses with quartz feldspar folia, and permeation gneisses in which quartz and feldspar are abundant. The permeation gneisses are pale grey in colour, they do not split readily and preserve a poorly defined foliation. This foliation is formed by inconstant lenticular folia of biotite and frequently imparts a streaky appearance to the gneisses.

Migmatized pelitic rocks are more coarsely crystalline than the pelitic rocks in the west of Moidart, where there is no evidence of migmatization. Large plates of quartz/
quartz and acid plagioclase measure up to 2.0 mm across. They have irregular shape and meet along sharp boundaries. No intergrowth was observed between quartz and feldspar, but the quartz forms large embayments into plagioclase, and is often seen as rounded inclusions within plagioclase. The plagioclase usually shows some alteration to sericite.

Biotite is frequently more abundant along the edges of quartz-oligoclase folia, forming a biotite-rich selvage. The biotites show pleochroism to reddish brown and occur as large crystals, poorly aligned in the foliation. Post-migmatization movement and recrystallization has modified the biotite arrangement.

Garnet crystals are not well developed in coarsely crystalline gneiss, and occur as xenoblastic spongy crystals. Hypidioblastic garnets are common in medium grained pelitic gneisses. Inclusion trails common in the west of Moidart (see pp. 174-180) are absent in garnets seen in pelitic gneiss. One thin section of a rock from Gleann Dubh (see Map 1), showed well formed round garnet porphyroblasts up to 2.0 mm across, in banded pelitic gneiss. These garnets have an idioblastic core that is almost free from inclusions, surrounded by additional garnet with many inclusions, (see Plate/
(see Plate 36a). The inclusions in the outer garnet are quartz, biotite and opaque ore, and are abundant near the crystal faces of the core garnet. Biotite flakes are usually tangential to the core garnet. The size and frequency of the inclusions decreases away from the core garnet towards the periphery.

Lenticular quartz-feldspar folia parallel the foliation in pelitic gneiss. This foliation is the axial plane cleavage of structures formed during the first fold movement. Quartz-feldspar folia were not seen folded by structures of the first generation of folding, but are frequently "drawn out" along the limbs of second folds. The quartz-feldspar folia can be seen cut by cleavage formed during the second generation of folding, (see Plate 24a). From the evidence stated above it is deduced that migmatization post-dates the first period of folding and, at least in part, ante-dates the second period of folding.

In addition to the development of quartz-feldspar folia in psammitic rocks, the following differences between psammitic schists in the west and east of the area mapped can be seen:

1)
1). Psammitic schists in the west have an average grain-size that may be up to 0.2 mm, but within the zone of migmatization the average grain-size may be up to 0.4 mm.

2). Myrmekite is absent in psammitic schists from the west and may be fairly common in psammitic schists from the east (Plate 32b). The significance of myrmekite has been interpreted in various ways by different authors, (c.f. Y.C. Cheng, 1944, p. 140, and W.T. Harry, 1953, p. 296).

3). Biotite showing pleochroism from pale yellow to reddish brown is only found in psammitic rocks from the east of the area.

4). Thin quartz-feldspar and quartz veins in the axial plane cleavage of second folds occur in the east of the area but are absent in the west of the area (c.f. Plates 9 and 12). This indicates that migmatization, which commenced before the second folds had formed (see p. 188), continued until after the second generation of folding. Veining ceased before the third generation of folding because it is not found with third and later folds.

W.Q. Kennedy (1949, p. 52) and H.H. Read (1931) have pointed out that the isograd which marks the zoisite-anorthite zone boundary, in calc-silicate ribs, coincides almost/
almost exactly with the western limit of regional injection, (Kennedy, 1949, p. 52). This statement holds good in Moidart.

W.T. Harry (1953) has worked on the granitic gneiss of Western Ardgour; this work has been referred to in the introduction (see p. 21). Harry recognises an early phase of soda metasomatism followed by potash metasomatism. The soda metasomatism produced oligoclase-biotite-quartz-gneiss and this rock type is very similar to the pelitic gneiss seen in Moidart. It is likely that the oligoclase-biotite-quartz-gneiss seen in Ardgour, and the pelitic gneiss seen in Moidart, belong to the same phase of metasomatism. There is no granitic gneiss in the area mapped, and the potash metasomatism recorded in Ardgour is not represented.

Late pegmatite dykes that were injected into the rocks after the fourth generation of folding, can be found in an area that extends from the eastern boundary, west to a line that runs north south through Loch Ard a Phuill. The dykes are largely composed of quartz and acid plagioclase, with muscovite, biotite, garnet, tourmaline and rare apatite in variable amounts. In the east of the area mapped the dykes are usually concordant and one apatite-bearing pegmatite,
pegmatite, with muscovite that occasionally measured six inches across, was traced along the strike of the foliation for 800 ft. Pegmatite dykes in psammitic rock may be up to 60 ft. thick and are frequently discordant (see Plate 24b). The minerals in the pegmatites are randomly oriented. Randomly oriented muscovite porphyroblasts are widely disseminated in both psammitic and pelitic rock-types in the eastern part of the area mapped. It is thought that the muscovite porphyroblast and the pegmatite dykes were formed at the same time.
IV. METAMORPHISM (continued).

5. RECRYSTALLIZATION

The evidence seen in Moidart suggests that recrystallization probably occurred during the first second and third fold movements. The most recent recrystallization occurred during or after the most recent fold movement.

a). F₁ recrystallization.

It has been stated earlier (see p. 115) that the regional foliation and bedding-schistosity represents the axial plane cleavage of F₁ isoclines. In the west of Moidart F₁ lineation is still preserved and is defined by the parallel alignment of quartz crystals that have elliptical cross-section (see p. 117). Although the quartz crystals may have recrystallized since they were aligned in the lineation, the shape and alignment can be attributed to the F₁ fold movement.

b). F₂ recrystallization.

Mica alignment in the axial plane cleavage of F₂ folds provides evidence of recrystallization associated with the second fold movement. This can frequently be seen in the field (see Plates 10, 12), and is equally common in thin/
thin sections (see pp. 44–75). It is important to note that this cleavage cuts quartz-feldspar folia, formed during migmatization, in the east of the area mapped (see Plate 24).

Garnet crystals occurring in the west of Moidart show paratectonic growth during the second fold movement (see pp. 177–180). It is therefore apparent that the metamorphic grade reached during the second fold movement was sufficient to cause significant recrystallization of the rocks in this area.

c). $F_3$ recrystallization.

The third fold movement is of restricted extent (see pp. 135). Axial plane cleavage in semi-pelitic gneiss in the core of the Lochan Meall a’Mhadaidh Synform, indicates recrystallization associated with this movement. Elsewhere, in the psammitic schists, minor folds show hinge thickening and limb attenuation. The absence of cleavage suggests that this took place by recrystallization.

d). Most recent recrystallization.

The relative ages of four fold movements have been established and the presence of two sets of folds of unknown age has been recorded (see Section III). Mica crinkling in the east of the area mapped is related to the fourth/
fourth fold movement. The age of a similar structure from the west of the area mapped, is unknown.

The crinkle folds are formed by interlocking crystals of mica that meet at varying angles. Cleavage planes in the mica crystals are rarely bent. From this it is deduced that the micas recrystallized during or after the movement that aligned them. Quartz crystals are frequently unstrained or show slight straining, and albite twin lamellae seen in plagioclase crystals are straight. These features indicate recrystallization late in the structural history of the rocks.
IV. METAMORPHISM (continued).

6. RETROGRADE METAMORPHISM.

Retrograde metamorphism is seen throughout the area mapped. Garnets from the Striped and Pelitic Group are frequently enclosed in a zone of chlorite, biotite, muscovite, clinozoisite and opaque ore (see Plate 30a). The clinozoisite crystals may be up to 0.5 mm long and are usually well formed prismatic or acicular crystals.

The boundaries of altered garnets are very irregular and the alteration assemblage frequently penetrates deep into the garnets. In some cases the garnet porphyroblasts are completely destroyed. The minerals formed during retrograde metamorphism are not aligned even though late mica crinkle folds occur in the mica crystals forming the matrix of the schist. From this it can be deduced that the retrograde metamorphism occurred after the mica crinkle folds were formed.

Biotite crystals in the matrix of both psammitic and pelitic rock types are sometimes altered to pale green, weakly pleochroic chlorite. Chlorite may completely replace the biotite flakes or may be interlaminated with them.

Garnets/
Garnets from the eastern part of the area mapped occasionally show peripheral alteration to chlorite and biotite, and biotite is sometimes altered to chlorite.

Aggregates of sillimanite, staurolite and rare kyanite in pelitic gneiss, are frequently sheathed in small muscovite crystals (Plate 30b). The muscovites become progressively larger as they are traced away from the sillimanite, staurolite aggregates. Elsewhere, sillimanite needles and staurolite are enveloped in muscovite porphyroblasts. This suggests that the retrograde metamorphism of the high grade minerals producing muscovite is associated with the formation of muscovite porphyroblasts. The small muscovite crystals and the muscovite porphyroblasts are randomly oriented even though mica crinkle folds occur in the micas of the pelitic gneiss. The mica crinkle folds are related to the fourth fold movement. Therefore the retrograde metamorphism occurred after this movement had ceased.

Calc-silicate granulites within the anorthite-hornblende and anorthite-pyroxene zones frequently contain irregular shaped crystals of zoisite that show anomalous "Berlin Blue" interference colour. Pyroxene bearing calc-silicate/
calc-silicate rocks often contain fibrous green actinolitic amphibole. W.Q. Kennedy (1949) interprets both of these features as indications of retrograde metamorphism.
IV. **METAMORPHISM** (continued).

7. **RELATIONSHIPS OF MIGMATIZATION, METAMORPHISM AND MOVEMENT.**

This subject has been discussed throughout the text but, since it is of considerable interest, the salient points in arguments put forward to establish the relationships are grouped here.

The episodes comprising the metamorphic history and migmatization are correlated with four significant fold movements. The relative ages of these movements are established by structural analysis and this has been dealt with in Section III. (see Table, Fig. 5, for a summary of the results). Structural analysis has provided the dimension of time, and the sequence of metamorphic events is built up on the basis of structural work.

1). Migmatization took place after the first fold movement and before the second fold movement. The evidence supporting this statement is:

a). Lenticular quartz feldspar folia are not seen folded by F₁ folds.

b). The quartz feldspar folia occur in the axial plane foliation formed during F₁ movement.

c). /
c). Axial plane cleavage of $F_2$ folds cuts through the quartz-feldspar folia.

It has been stated that thin veins of quartz and feldspar occur in the axial plane cleavage of $F_2$ folds. This indicates emplacement during or after $F_2$. These veins are more glassy in appearance and more quartz rich than the lenticular quartz-feldspar folia and their connection with migmatization is obscure. They were not seen cutting the lenticular quartz-feldspar folia. If these veins are related to migmatization, they provide evidence of continuation of migmatization during or after the second fold movement. There is no indication of migmatization during the third and fourth fold movements. Pegmatite veins were injected after the fourth period of folding.

2). Metamorphism. The earliest recognisable metamorphism took place after the first fold movement and before the second fold movement. The evidence in support of this statement comes from the western part of Moidart and is summarised below:

a). Garnets show two phases of growth. The outer garnet is paratectonic and was formed during the second fold movement.

b)./
b). Inclusion trails within the inner garnet are invariably straight. This garnet must therefore have or formed either before the first fold movement or after the first fold movement.

c). Where "early" garnets are protected in an outer garnet envelope formed during the second fold movement, the inner garnets are idioblastic.

d). Where the "early" garnets are not protected by outer garnet, the idioblastic shape has been modified to give a rounded garnet without crystal edges. This is attributed to rolling of early garnet during the second fold movement, (c.f. Plates 26a and 27a).

e). The first fold movement formed very tight folds and imprinted the regional bedding-schistosity. It is considered unlikely that a garnet formed before such a movement could survive, preserving idioblastic shape, such as is seen in the core of compound garnets. The contrast between "protected" and "unprotected" early garnets as a result of the less intense second fold movement supports the argument that early garnets would have been modified during the first fold movement, if they had been in existence before the movement took place.
The writer is of the opinion that the early garnets formed during the period that intervened between the first and second fold movements, and that the helicitic structure preserved by the early garnets \((s_1)\), represents the bedding-schistosity formed during the first fold movement. It is therefore apparent that the early garnet phase must be nearly contemporaneous with the main migmatization, seen in the east of Moidart.

The age of kyanite and sillimanite in the east of Moidart is not known. It is likely that these minerals were formed at the same time as either the early or late garnets seen in the west. The early garnets were formed at about the same time as migmatization. Migmatization increases in intensity eastwards, so it is reasonable to suppose that the metamorphic grade at this time also increased eastwards, perhaps reaching sillimanite. The contrast between garnets with a variety of structures shown by inclusion trails in the west, and those with no inclusion trails in the east, is striking. If the sillimanite metamorphism in the east was imprinted during migmatization, then either the second growth of garnet seen in the west did not take place in the east, or evidence of second garnet growth in the east has been obliterated by subsequent recrystallization.
recrystallization. Recrystallization is known to have occurred after the second fold movement throughout the area, but inclusion trails are never-the-less well preserved in the west.

The alternative possibility is that sillimanite grade of metamorphism was reached during the second fold movement, when paratectonic garnet was forming in the west. While sillimanite was forming in the east garnets were completely recrystallized and any inclusion trails that may have been in existence, were destroyed.

The writer favours the development of sillimanite with migmatization and this is supported by evidence from calc-silicate granulites. In the west zoisite prisms are sometimes aligned with the long axes sub-parallel to the bedding-schistosity. This is considered to represent mimetic control over crystallization. Garnet crystals in calc-silicate ribs occasionally preserve a parallel alignment of inclusions and have been rotated during $F_2$ without additional garnet being added. These garnets are probably of the same age as the early garnets seen in pelitic rocks so the metamorphism which formed them is correlated with migmatization. In the east of the area, there is no apparent alignment of large hornblende and pyroxene crystals. This/
This is taken to indicate that crystallization of hornblende and pyroxene was not controlled by movement. It is therefore suggested that the calc-silicate metamorphism was imprinted before the second fold movement, at the same time as migmatization. If this is so, then the calc-silicate rocks indicate that the rocks were metamorphosed up to sillimanite grade in the east of Moidart, during migmatization.

Recrystallization occurred during or after the fourth fold movement. This is indicated by the absence of bent or ruptured micas that form mica crinkling correlated with the fourth period of folding.

Retrograde metamorphism occurred throughout the area after the fourth fold movement because minerals formed as a result of retrograde metamorphism are not crinkled during the $F_4$ movement. Muscovite porphyroblasts seen in the east of the area are also randomly oriented. The foregoing data is summarized in a table (Fig. 25).
FIG. 25.
V. PETROFABRICS

F.C. Phillips (op. cit. 1937) has given a brief description of the method employed in grain fabric studies and this has been summarised in the introduction to this thesis (see pp. 27-31). The preparation of petrofabric diagrams is described by J.C. Haff (1938).

Other workers, notably Clifford et. al. (1957), have stressed the importance of correlating minor structures with related major structures, before discussing the significance of microfabric data. It has been shown that Moidart has suffered four significant fold movements and that there is evidence of several periods of recrystallization throughout the metamorphic history of the rocks. For these reasons it is essential that the macroscopic structures seen in specimens selected for microfabric analysis, be correlated with the known structural pattern. Attempt is made to relate the microfabric to the macroscopic structures and thus to the regional structural interpretation.

Specimens of structures formed during the four significant fold movements have been studied and the results obtained are described below. Two specimens showing superposed/
superposed folding have also been studied and the microfabric of quartz inclusions within garnet porphyroblasts, is reported.

1. Microfabric of specimens showing $F_1$ structures.

Minor structures related to the first fold movement are most abundant in the west of the area studied. From here, two specimens showing $F_1$ structures were selected for fabric analysis. Apart from $F_2$ folding, the west of Moidart is not severely affected by later movement, (see p.132).

1) An $F_1$ isocline in a quartz-feldspar granulitic schist band within the Striped and Pelitic Group, was collected from Smearisary Hill, west of Loch na Bairness. 300 $c$ - axes of quartz crystals were measured and are represented on a stereonet, (Fig. 26a). The axial plane and the fold axis are also shown.

The $c$ - axes of quartz crystals group to form a maximum concentration that lies near the axial plane, and the fold axis plots about $30^\circ$ away from this maximum. There is a tendency for an incomplete girdle to develop. This girdle is apparently unrelated to the $F_1$ fold axis.

2) A similar pattern to that described above was obtained/
c-axes of 300 quartz crystals
Contours at 1, 2, 3, and 4% per 1% area
Maximum concentration:
5% per 1% area

FIG. 26 F₁ MICROFABRIC
obtained from a specimen of quartz-feldspar granulitic schist showing $F_1$ lineation, (see Fig. 26b). This specimen was collected from inverted Upper Psammitic Group near the west coast of Moidart and in thin section the quartz crystals are seen to be slightly flattened in the bedding-schistosity. The maximum concentration of $c$-axes of quartz crystals falls near the bedding-schistosity, and there is an incomplete girdle that is almost normal to the $F_1$ lineation, (see Fig. 26b).

The specimens described above show only $F_1$ macroscopic structure and they have yielded similar fabrics. It is of interest to note that although the girdles develop approximately normal to the axial plane and bedding-schistosity, the angle between the $F_1$ axial structures and the girdles, varies considerably.

2. Microfabric of $F_2$ fold.

300 $c$-axes of quartz crystals were measured from an asymmetric fold occurring in the Striped and Pelitic Group, between Glenuig Bay and Loch na Bairness (see Fig. 27). This $F_2$ fold occurs on the upper limb of the Glenuig Antiform and axial plane cleavage is visible in hand/
FIG. 27. $F_2$ MICROFABRIC

c-axes of 300 quartz crystals.
Contours at 1, 2, 3% per 1% area.
hand specimen. Under the microscope, small mica crystals are seen to be aligned parallel to the axial plane of the fold. Quartz crystals are equidimensional and show strain.

The microfabric analysis shows a very diffuse maximum approximately normal to the axial plane of the fold, (Fig. 27). Within this diffuse maximum, there are weak concentrations of c-axes. These concentrations make angles of about 50° with the axial plane. Very few c-axes lie within the axial plane of the fold, (c.e.f. the microfabric obtained from specimens showing F₁ structures). It is possible that the microfabric shown on Fig. 27 is not entirely due to the F₂ fold and that it represents breakdown of a pre-existing F₁ fabric.

3. Microfabric of F₃ fold.

Two fabric diagrams were prepared from an F₃ fold from the Upper Psammitic Group northwest of Loch nam Paitean, near the hinge of Lochan Meall a’Mhadaidh Synform. The fabrics were measured in thin sections from different positions on the fold, (see Fig. 28a).

Both/
FIG. 28. $F_3$ MICROFABRIC

c-axes of 300 quartz crystals.

Contours at 1 2 3 5% per 1% area

Maximum concentration: diagram b 53%
    diagram c 57%
Both fabric diagrams (Fig. 28b and 28c) are alike in that they consist of incomplete broad girdles, approximately normal to the \( F_3 \) fold axis. However, the gaps in the girdles and the maxima within the girdles, do not have constant orientation. In both diagrams the maxima are normal to the gaps in the girdles.

Two alternatives are presented to explain this situation:

a). The fabrics preserved are not related to \( F_3 \) movement and represent an earlier fabric which has been folded by \( F_3 \) without an \( F_3 \) fabric developing.

b). The fabrics were formed during the \( F_3 \) movement and continued movement about the \( F_3 \) fold axis after the fabric had developed, caused rotation of the already oriented quartz crystals, without reorienting them.

The writer has no preference for either of the two alternatives stated above.

4. Microfabric of an \( F_4 \) fold specimen.

An \( F_4 \) fold occurring in a psammitic band within the Roshven Pelitic Group 2,000 ft. south of the summit of Sgùrr Domhuill Mòr, gave the quartz fabric shown in Fig. 29a.
FIG. 29. F_4 & F_2 MICROFABRIC

C-AXES OF 300 QUARTZ CRYSTALS ON EACH DIAGRAM

CONTOURS AT 1, 2, 3 & 5% PER 1% AREA

MAXIMUM CONCENTRATION DIAGRAM

a 8%
b 5.5%
c 6.7%
d 6%
The well developed maximum (8% per 1% area) lies 45° off from the $F_4$ axial plane and 73° away from the $F_4$ fold axis. There is no apparent relationship between $F_4$ structure and the quartz microfabric.

5. Microfabrics of a specimen showing mica crinkle folds superposed on a quartz isocl ine.

The microfabrics of three oriented thin sections from a specimen of pelitic schist from the Striped and Pelitic Group, east of Loch na Bairness, were studied (Fig. 30).

In hand specimen the schist has a well developed schistosity ($s_1$ plane) on which there is a strong mica crinkle lineation that is correlated with the second fold system of uncertain age, (see p. 159). An $F_1$ isoclinal quartz fold can also be seen.

Under the microscope the quartz isocl ine is seen to consist almost entirely of quartz, with rare feldspar crystals. The quartz crystals are mostly elongate with elliptical cross-section; the long axis is usually parallel to the schistosity. On average, the ratio of the long dimension to the short is 1:3. Grain size varies from less/
550 QUARTZ C AXES FROM MATRIX OF SECTION B
MAXIMUM 2.7%

230 QUARTZ C AXES FROM QUARTZ ISOCLINE IN SECTION C
MAXIMUM 8.3%

MICA CRINKLE -QUARTZ ISOCLINE
ONE INCH

400 MUSCOVITE POLES TO CLEAVAGE SECTIONS A & B
MAXIMUM 15.6%

450 BIOTITE POLES TO CLEAVAGE SECTIONS A & B
MAXIMUM 15%

CONTOUR INTERVAL
QUARTZ
MICA

OM MICA CRINKLE AXIS
O1 QUARTZ ISOCLINE AXIS

FIG. 30.
less than 0.05 mm to about 2.0 mm. Small crystals are usually unstrained but severe straining is invariably present in larger crystals. Frequently the lines of straining in the large crystals of quartz are parallel to the schistosity, but sometimes they curve away from the schistosity, dividing the crystals into long arcuate splinters.

The main constituent of the quartz isocline (Section c, Fig. 30) is the mosaic of small elongate grains and it was these grains that were measured in the petrofabric study of the isocline, described below.

Quartz crystals that form, with micas, the pelitic matrix are in marked contrast to these in the isocline. In the matrix, (Section B, Fig. 30), quartz occurs as inequigranular, equidimensional unstrained, crystals, that range in size from very small to 0.2 mm in diameter.

Pleochroic dark yellowish brown to pale brown biotite flakes, together with muscovite, define the s-plane. The micas are often intimately interlaminated. Pleochroic haloes around inclusions are common in biotite. The mica crystals range in size from very small up to 2.0 mm in length of section. An obvious feature of the rock, both/
both in hand specimen and under the microscope, is the strong mica crinkle fold lineation. Under the microscope this is seen to be due to small, often asymmetric, folds in the $s_i$-planes. Mica cleavages are not bent in forming these folds; many crystals meet at varying sometimes acute angles. The axial planes of the "crinkle" folds are nearly at right angles to the $s_i$-planes and the axial plane of the quartz isocline.


In order that the complete mica fabric be measured two sections (A and B, Fig. 30), were studied. Poles to mica cleavage planes were recorded and the resulting diagrams for both muscovite and biotite showed girdles normal to the mica crinkle fold axis (see Fig. 30). A strong maximum present in each girdle coincides with the pole to the $s_i$-plane. The mica fabric can therefore be correlated with the fold movement that formed the "crinkle" folds.

b). Fabric of the quartz isocline.

There is a well defined girdle of quartz c-axes normal to the isocline fold axis (see Fig. 30), with a maximum/
maximum in the axial plane of the isocline. It is thought that this represents an $F_1$ fabric imprinted during the formation of the isocline.

c). Quartz Matrix.

There is a marked contrast between the fabrics described above and that obtained from quartz grains in the matrix of the schists. At first 275 c-axes of quartz crystals were measured and when these were plotted they indicated an apparent random scatter. A further 275 crystals were measured from another part of the thin section and the same result was obtained, indicating that the fabric in this thin section is homotactic. The quartz diagram illustrated (Fig. 30), represents the combined results from the two studies and shows the orientation of 550 c-axes of quartz.

Conclusion.

It is thought that a fabric akin to that seen in the quartz isocline may also have been imprinted on the matrix of the schist, during the $F_1$ fold movement. This has since been destroyed. As a tentative explanation it is suggested that the quartz crystals in the matrix were rendered/
rendered more easily reoriented during later movement, by
the abundant contiguous micas. It could be argued that if
this is so then the matrix quartz crystals should readily
take up a new fabric during movement and so should now be
aligned with respect to the last movement, as are the micas.
But it may be that although the later stress was sufficient
to re-align the micas, it was unable to do the same for the
quartz crystals in the matrix. It may have partially broken
down the early fabric, without imprinting its own. At the
same time, the massive quartz isocline was able to resist
reorientation during later movement and so preserves the
early (F₁) fabric.

6. Microfabrics of specimens from Sgùrr Domhuill
Mòr.

The quartz microfabrics of specimens collected
from the area 2,000 ft. south of the summit of Sgùrr
Domhuill Mòr, where F₂ and F₄ folds occur together (see
pp. 146-153), are shown, (Fig. 29b, c and d). In this area,
the orientations of F₄ fold axial planes remains constant
while the F₂ axial planes vary, (see Fig. 19). Fig. 29b,
c and d) all show a similarity, with the maximum number
of c-axes trending approximately north-south. Since F₂
fold/
fold axial planes vary in orientation it is probable that the similarity amongst the fabric diagrams indicates that the fabrics are related to $F_4$ movement.

The maximum in Fig. 29, is more diffuse than those in Figs. 29b and 29c and this may represent the remains of an earlier quartz fabric which has not been completely re-oriented during $F_4$. It may also be that the pattern shown on Fig. 29a, which is apparently unrelated to $F_4$ (see above p. 208), is also a relic fabric. The weak north-south, nearly horizontal, maximum in Fig. 29a, may represent an incipient $F_4$ fabric. Fig. 29d may represent the intermediate stage between the fabrics shown on Fig. 29a, and b or c.

7. Microfabrics of a folded calc-silicate rib with garnets showing straight inclusion trails.

A calc-silicate rib, folded by the second fold movement showed two garnet porphyroblasts 3.5 mm in diameter, with abundant inclusions of quartz. The quartz crystals showed straight inclusion trails that are oblique to the present foliation seen in the calc-silicate rock and are also oblique to each other.
The orientations of c-axes of 300 quartz crystals occurring within the matrix of the rock, were measured, as were the c-axes of the quartz crystals included within the garnets (see Fig. 31). The quartz crystals in the matrix show a maximum concentration in the axial plane of the F₃ fold, about 60° away from the fold axis. This maximum may be due to the intersection of two incomplete girdles inclined at 30° to the primitive circle of the projection.

100 c-axes of quartz crystals were measured from one garnet porphyroblast and 80 c-axes from the other (see Fig. 31b and 31c). In diagram b a line of three maximum concentrations of c-axes can be seen trending north-south near the eastern margin of the primitive circle. A similar fabric is shown by Fig. 31c, but in this case the orientation of the maxima has swung round to trend northwest by southeast, and is located in the northeast quadrant of the projection.

The trends of the inclusion alignments in the two garnets are also shown on the diagrams, and it can be seen that the rotation required to alter the trend from that/
FIG. 31. Diagram a  c-axes of 300 quartz crystals
Contours at 1,2,3,5% per 1% area
Maximum concentration 5.3%

Diagram b  c-axes of 100 quartz crystals in garnet porphyroblast
Contours at 1,2,3,5% per 1% area
Maximum concentration 7%

Diagram c  c-axes of 80 quartz crystals in garnet porphyroblast
Contours at 12,3,5% per 1% area
Maximum concentration 6.25%
that shown in Fig. 31b, to that in Fig. 31c, is the same as the rotation required to change the positions of the three maxima from the orientation in b to that in c.

It is concluded that the fabrics of the quartz crystals within the garnets have been preserved and rotated with the garnets. The fabric shown by the quartz crystals in the matrix is dissimilar to that preserved by the quartz inclusions within the garnet crystals. The former was probably imprinted later than the fabric preserved with the garnets, at the time when the garnets were being rotated.

8. Microfabrics of a pelitic schist and garnets showing two phases of growth.

Garnets with straight inclusion trails preserved, the growth of which was followed by movement then regrowth of garnet, have been described (see p. 180 and Plate 27b). The microfabrics of two such garnets have been studied, together with the microfabric of the pelitic schist in which the garnets occur. The method followed was similar to that described as Achsenverteilunganalysen (A.V.A.), (see Weiss 1954, p. 63, also Sander 1950, Pt. II, pp. 161-217). Photomicrographs of the garnets were used as maps of the quartz/
quartz inclusions and as the orientation of the optic axis of each crystal was measured, the crystal was numbered on a tracing overlay on the photomicrograph. In this way, it was possible to relocate any of the crystals measured. After measuring the orientations of the c-axes, they were plotted on a stereonet and were also represented as arrows on a tracing from the photomicrograph, (see Figs. 32 and 33).

The fabric from the matrix shows an incomplete girdle normal to a poorly defined $F_2$ lineation, with the maximum concentration of c-axes normal to the schistosity. The fabrics from the quartz crystals included within the garnets are also shown, (see Fig. 32). The fabrics obtained from the inclusions within the outer garnets are shown in Fig. 32 cl and c2, and that obtained from the matrix in Fig. 32a. Insufficient quartz inclusions occur in the core garnets, to enable any definite conclusions to be drawn (Figs. 32, b1 and b2), but it would appear that there is a dissimilarity between the orientation of quartz crystals in the core garnets and the outer garnets. There is a faint resemblance between the fabric shown in diagram cl and diagram a, in Fig. 32, suggesting a correlation between the/
FIG. 32.  

DIAGRAM A: 300 C-AXES OF QUARTZ CRYSTALS FROM THE MATRIX OF GARNET MICA SCHIST.  
CONTOURS AT 1.2 & 5% PER 1% AREA.  MAXIMUM CONCENTRATION 53%.  

DIAGRAMS b1 & b2: 45 & 25 C-AXES OF QUARTZ CRYSTALS THAT FORM STRAIGHT INCLUSION TRAILS IN THE CORES OF GARNETS SHOWING REGROWTH.  
CONTOURS AT 1.2 & 5 POINTS PER 1% AREA.  

DIAGRAMS c1 & c2: 62 & 69 C-AXES OF QUARTZ INCLUSIONS IN THE OUTER ZONE OF GARNETS THAT SHOW REGROWTH.  
CONTOURS AT 1.2 & 5% PER 1% AREA.
the matrix quartz fabric in the rock and the quartz fabric of the inclusions in the outer garnet.

The orientations of the quartz c-axes are also represented by arrows (Fig. 33). It can be seen that there is no constant relationship between the elongation direction of the quartz inclusions forming the inclusion trails and the orientation of the optic axes of the quartz crystals.
FIG. 33. ORIENTATION OF C-AXES OF QUARTZ INCLUSIONS IN GARNET PORPHYROBLASTS
VI. SUMMARY OF CONCLUSIONS

Detailed geological mapping and structural analysis of Moidart revealed that the area has been folded more than once. The relative ages of four fold movements have been established and two additional movements of uncertain age have been recognised.

The earliest movement preserved is represented by minor isoclinal folds and axial structures, but no major folds were found. Extreme tectonic thickening is seen in the isoclines and the regional foliation and bedding-schistosity was imprinted during this fold movement. The isoclinal folds seen in Moidart are tentatively correlated with the movement that formed the Morar Nappe.

Following the isoclinal folding, there was a period of movement during which tight asymmetric folds with well developed axial plane cleavage formed. The majority of the major folds seen in Moidart formed at this time and J.E. Richey reporting work done by V.A. Eyles and W.Q. Kennedy (see p. ii ), has correlated one of these major folds, (the Glenuig Antiform), with the Morar Anticline.
Anticline. This was a period of "Similar type" folding and abundant minor structure, that can be related to the major folds, were formed in Moidart, at this time. Axial structures formed during the first fold movement were reoriented during the second fold movement in such a way that when the former are plotted on a stereonet, they come to lie along a great circle.

Evidence of the third fold movement is restricted to the eastern part of the area mapped. Major and minor folds of the second fold movement are seen refolded by third folds. Where second folds are undisturbed by later folding, they have nearly horizontal plunge. This nearly horizontal plunge is largely maintained where the second folds are refolded by the third fold movement.

Fourth folds occur near the eastern boundary of the area mapped and it is in this area that second folds have steep plunge. On the minor fold scale, one of the effects of the superposition of fourth folds on second folds, is to cause the second fold axes to change inclination and frequently become steeply inclined. This is also thought to have occurred on the major fold scale and the reorientation/
reorientation of second fold axes from their original nearly horizontal inclination, to the steep inclination seen in the east of Moidart, is attributed to the fourth fold movement.

The sequence of events in the metamorphic history of the rocks, is correlated with the structural history. Migmatization is considered to have taken place during a period that began after the first fold movement and before the second fold movement, and may have continued until after the second fold movement. Evidence of the ages of metamorphisms comes from the west of the area studied and is largely based on inclusion trails preserved within garnet porphyroblasts. During the period that intervened between the first and second fold movements, the rocks in the west, were metamorphosed to garnet grade. A second garnet grade metamorphism occurred in the west during the second fold movement.

The ages of kyanite and sillimanite, seen in the east of Moidart, are not known, but the writer is of the opinion that they may have formed during the period between the first and second fold movements. They are probably contemporaneous/
contemporaneous with migmatization and the first garnet grade metamorphism seen in the west.

Retrograde metamorphism took place after the last fold movement had ceased. This metamorphism has caused chloritisation of garnet and has altered sillimanite to muscovite.

From the foregoing summary, it is apparent that the complex structural history in Moidart is matched by an equally complex metamorphic history. The metamorphic events are related to a time-scale provided by the results of structural analysis.
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VIII. BIBLIOGRAPHY


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PLATES
PLATE I.

a). A view looking west from above Lochan a Mhuilinn. The islands of Eigg and Rhum can be seen in the distance.

b). Looking north across Lochan na Caillich. The ice has scraped away superficial detritus leaving the rocks well exposed.
a and b. False bedding in psammitic schists occurring near the base of the Upper Psammitic Group, about one mile southeast of Glenuig Bay. In this area the rocks are right way up.
a). Xenoliths of quartzite in a quartz dolerite dyke about half of a mile east of Loch na Bairness.

b). Tertiary feldsparphyric dolerite dyke cutting folded quartz feldspar granulite east of Glenuig Bay.
a). Lineation formed during the second fold movement on a bedding-schistosity surface. East shore of Glenuig Bay.

b). Lineation formed during the second fold movement parallel to an $F_2$ minor fold. Striped and Pelitic Group, Egnaig Hill.
a). Intersecting quartz rods. The rod plunging to the left cuts through that plunging to the right.

a). Flaggy psammitic schist in the Upper Psammitic Group north of Lochan Meall a'Mhadaidh.

b). Lineated F, quartz rods in the Striped and Pelitic Group on Egnaig Hill.
a and b. Isoclinal folds formed during the first fold movement.
a). Large $F_i$ isocline in the Upper Psammitic Group west of Loch nam Paitean. The limbs of this isocline can be traced for thirty feet and there is no indication of a complementary fold.

b). Small $F_i$ isocline seen as a folded psammitic band in predominantly pelitic rock. The limbs are severely attenuated. (Roshven Pelitic Group).
a). Asymmetric south plunging fold formed during the second fold movement, on the hill between Glenuig Bay and Loch na Bairness.

b). Asymmetric minor folds in the Striped and Pelitic Group, on Egnaig Hill. The axial planes are nearly horizontal and the fold axes trend north south.
a). Axial plane cleavage in the core of an $F_2$ fold occurring in Striped and Pelitic Group west of Loch na Darafe. Variations in the lithology have controlled the shape of the fold.

b). Near the same locality as a). The bedding-schistosity represents $s_1$, a new schistosity, $s_2$, parallel to the axial plane cleavage of $F_2$ folds, develops in the semi-pelitic rocks.
a). An open $F_2$ minor fold in the Upper Psammitec Group with lineation parallel to the fold axis. Located on the north coast of Moidart about half of a mile east of Glenug Bay, viewed looking north.

b). Near the same locality the folds show a variety of styles, some are fairly tight. Viewed looking south, the axial planes dip to the east and the folds plunge gently to the south.
a). Quartz feldspar veins in the axial plane cleavage of folds formed during the second fold movement. Located in the Upper Psammitic Group between Loch Ard a Phuill and Lochan a Mhuilinn.

b). Near the same locality. In this photograph, the quartz feldspar veins fan around the hinge of a minor F₂ antiform.
a and b. Disharmonic folding in rocks of varying lithology.
Occurring in the Upper Psammitic Group west of Lochan a'Mhuilinn.
a). Refolding of $F_1$ by $F_2$ in the Striped and Pelitic Group west of Loch na Draipe.

b). Refolding of $F_1$ by $F_2$ in the Upper Psammitic Group south of Lochan na Caillich.
a). Minor folds formed during the third fold movement. Occurring in the Upper Psammitic Group west of Loch nam Paitean, near the hinge of the Loch nam Paitean Antiform. Viewed looking south, the axial planes dip steeply to the west.

b). Minor folds formed during the third fold movement. Occurring in the Upper Psammitic Group near the hinge of the tight Lochan Meall a'Mhadaidh Synform.
a). Boxfold formed during the third fold movement in Upper Psammitic Group west of Loch nam Paitean. The axial plane of a small antiform splits to give an M-shaped fold. The left hand axial plane splits again to form a second M-shaped fold oblique to the first.

b). Variations in the style of \( F_3 \) minor folds controlled by variations in the lithology.
a). Refolding of $F_1$ by $F_3$. This outcrop occurs one thousand feet west from the southwest corner of Loch nam Paitean and is located in the Upper Psammitic Group. Viewed looking south. The axial planes of $F_3$ minor folds dip southwest and the contorted axial plane of an $F_1$ minor fold can be traced from the bottom left-hand corner to the top right-hand corner.

b). Refolding of $F_1$ by $F_3$ west of Loch nam Paitean. The axial planes of two isoclines pass diagonally across the photograph from top left to bottom right. Folding such as this renders it impossible to estimate stratigraphic thicknesses in Moidart.
a). Refolding of $F_2$ by $F_3$. The folded quartz-feldspar vein follows the axial plane of the $F_2$ fold while the axial plane of the $F_3$ fold trends north-south and is parallel with the pocket knife.

b). $F_1$, $F_2$, and $F_3$ folds occurring in the Roshven Pelitic Group southeast of Loch nam Paitean. An $F_1$ isoclinal at the left side of the photograph is bent into a hook shaped structure. Another $F_1$ isoclinal occurs near the bottom right. Open $F_3$ folds trend nearly at right angles to the foliation.
a). Open $F_4$ minor fold in the Roshven Pelitic Group on the south side of the Moidart River.

a). $F_4$ mica crinkle folds confined to semi-pelitic rocks in banded psammitic and semi-pelitic rock in the Roshven Pelitic Group, on Ceann Loch Uachdrach.

a). Variable plunge of $F_2$ antiform as a result of $F_4$ folding. Occurring in the Roshven Pelitic Group 2,000 ft. south of the summit of Sgùrr Domhuill Mòr.

b). Near the same locality. Shows the variable plunge of an $F_2$ synform, also the non-cylindroidal style of $F_4$ minor folds as they pass round the hinge of $F_2$ folds.
a). $F_2$ minor fold southeast of Loch nam Paitean in the Roshven Pelitic Group, refolded by $F_4$ minor folds.

b). $F_4$ mica crinkle folds have axial planes that parallel the pocket knife. These crinkle folds bend the axial plane cleavage of $F_2$ minor folds. Roshven Pelitic Group on Ceann Loch Uachdrach.
a). Eyefold formed as a result of reversal in plunge of $F_2$ minor fold. Upper Psammitic Group east of Lochan na Caillich.

b). Brittle style of folds. Axial planes trend northwest by southeast. In the Upper Psammitic Group the rocks are discoloured from pale grey to flesh pink in the vicinity of the axial plane.

b). Discordant pegmatite dyke in Upper Psammitic Group south of Loch Ard a’Phuill.
a). Staurolite, kyanite and muscovite aggregate in pelitic rock near Lochan Meall a Mhadaidh. Magnification X 35.


PLATE 27.

a). Garnet porphyroblast showing two phases of growth. The inner idioblastic garnet has straight inclusion trails while the outer garnet shows syntectonic growth. Striped and Pelitic Group northwest of Loch na Bairness. Magnification X 10.

b). Garnet porphyroblast showing two phases of growth. The inner garnet has straight inclusion trails while the inclusion trails in the outer garnet are bent. Striped and Pelitic Group between Loch na Bairness and Glenuig Bay. Magnification X 15.

b). Calc-silicate rock from the Zoisite Zone, with hornblende garnet and biotite. Magnification X 20.
a). Calc-silicate rock from the Anorthite-Hornblende Zone. Hornblende, poeciloblastic garnet, feldspar and quartz can be seen. From the Upper Psammitic Group near the Irine Burn. Magnification X 20.

b). Calc-silicate rock from the Anorthite-Pyroxene Zone showing fibrous actinolitic amphibole. Magnification X 20.

b). Retrograde metamorphism showing sillimanite surrounded by small muscovite crystals that increase in size away from the sillimanite. Magnification X 20.

PLATE 32.


b). Myrmekite in psammitic schist from the Upper Psammitic Group near Loch nam Paitean. Magnification X 50.
PLATE 33.

a). Photomicrograph of semi-pelitic schist showing garnet, biotite and sphene. Magnification X 15.

Magnification X 10.

b). Psammitic schist from a band of psammitic rock in the Roshven Pelitic Group on Sgùrr Domhuill Mòr.
Magnification X 10.

a). Garnets showing inclusion free cores occurring in pelitic rock within the Roshven Pelitic Group near Gleann Dubh. Magnification X 15.

b). Inclusions in a garnet crystal from the Striped and Pelitic Group northwest of Loch na Bairness. Two garnet growths are represented and the inclusions within the inner garnet are distributed in the form of a cross. The inclusions in the outer garnet indicate syntectonic crystallization. Magnification X 15.