THE STRUCTURE AND METAMORPHISM
OF EAST MOIDART AND WEST SUNART,
ARGYLL AND INVERNESS-SHIRE.

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(In pocket at the end of the thesis)

Figure 7 is also in the pocket at the end of the thesis.

I. INTRODUCTION

1. LOCATION, ACCESS AND PHYSIOGRAPHY

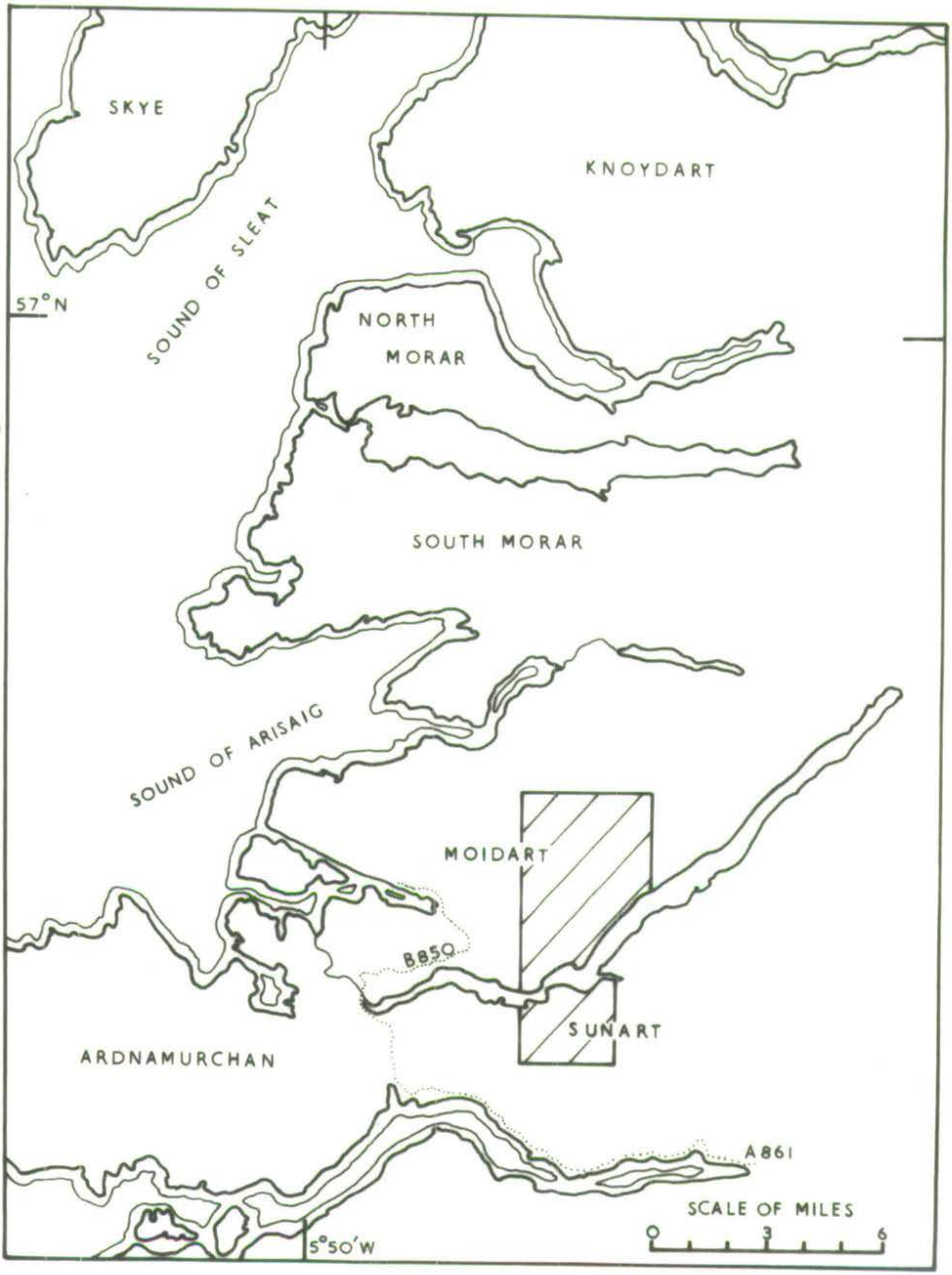
The area studied is situated to the north and south of Loch Shiel, which lies along the county boundary of Argyll and Inverness-shire (Fig. 1). The ground to the north of Loch Shiel is covered by the Ordnance Survey six-inch Sheets 149 and 158 for Inverness-shire; and to the south by Sheet 17 NE, SE and SW for Argyllshire. The area extends north from just south of the summit of Ben Resipol (National Grid Reference NM 767655) in the West Sunart district to the southern slopes of Sgùrr na ba Glaise in East Moidart (770775). The western boundary coincides with the western limit of Sheets 149 and 158 extending southwards into Sunart. The eastern limits coincide with a line running N-S through Gaskan on the north shore of Loch Shiel and a N-S line through Polloch to the south of Loch Shiel.

The western edge of the ground may be approached via Salen on the B.850 and B.8006 to Dalilea. Alternatively, the B.850 may be followed to the approaches of Kinlochmoidart, whence a road extends north-westwards along Glen Moidart to Glenmoidart House, from where a track penetrates to Glen Forslan. Apart from this track there are no roads in the area studied. The eastern boundary to the south of Loch Shiel may be approached from Strontian via a forestry road to Polloch.

A boat was used on Loch Shiel to allow ready access to the ground on both sides. The remotest part of the area, in the

FIG. 1

LOCATION OF AREA STUDIED

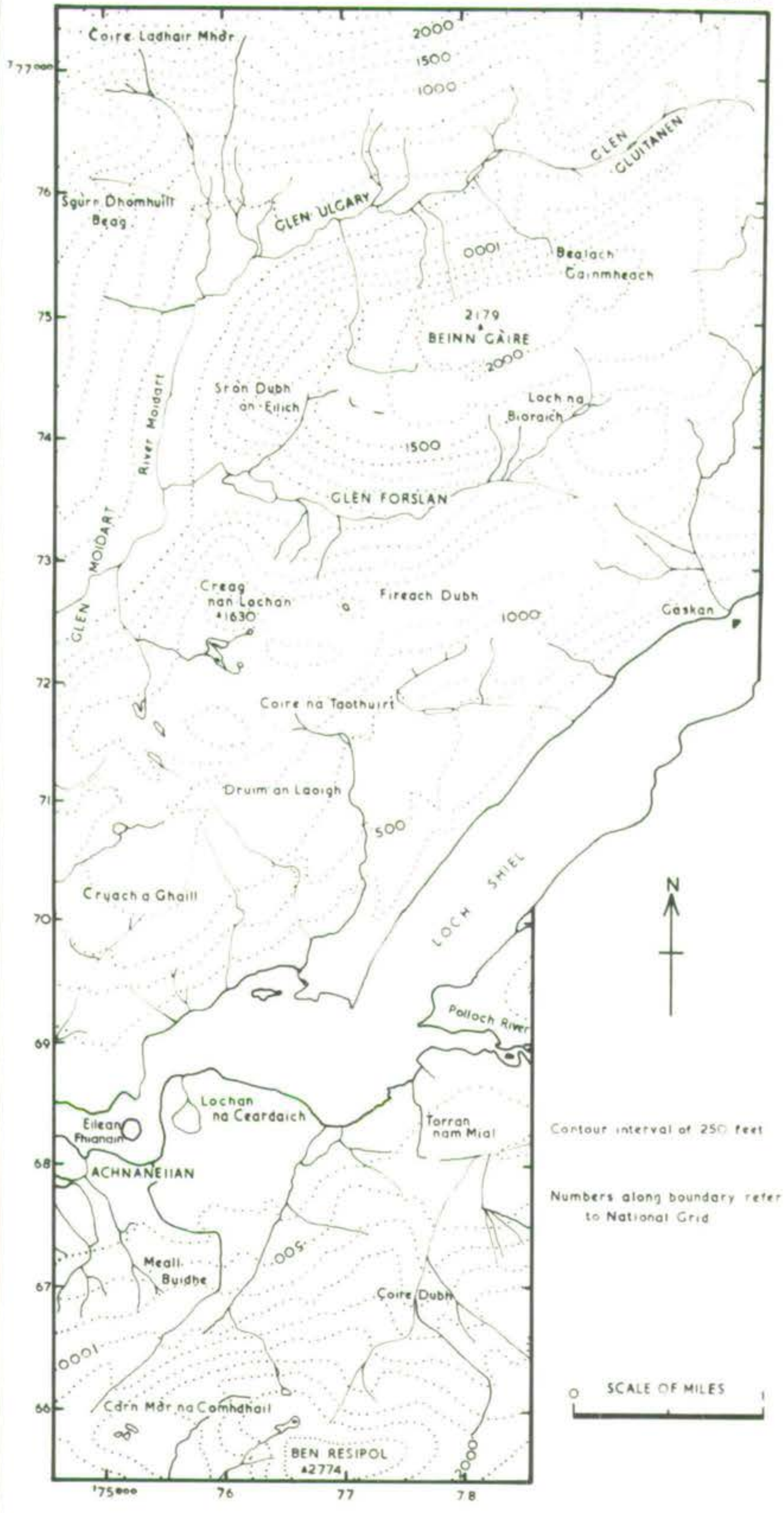


extreme northeast of Glen Gluitanen at the head waters of the Moidart River, may be reached in approximately two hours on foot from Glenmoidart House.

The terrain is that of an extensively dissected plateau. South of Loch Shiel, Ben Resipol, which dominates the scenery (Plate 1a), rises from near sea level at the shore of the Loch to a height of 2774 feet. The slopes above the north shore of Loch Shiel are steep, but not particularly rugged. However, from the top of Creag nan Lochan (1630') the ground drops steeply south-eastwards into Glen Moidart, over 1500 feet below (Fig. 2). North of Creag nan Lochan lies the SW trending Glen Forslan; an excellent example of a hanging valley, with the Glen Forslan River falling some 300 feet into the major glacial valley of Glen Moidart. The northern flanks of Glen Forslan rise extremely rapidly to the fairly flat topped hill of Beinn Gàire (2179 feet). The high ground of Beinn Gàire persists north-eastwards to northern and eastern limits of the area. The head waters of the Moidart River find their source from small burns on the slopes at the head of Glen Gluitanen, which lies to the extreme northeast (Fig. 2). From Glen Gluitanen the river meanders ESE into Glen Ulgary. Here the ground rises to the north, at first gently, but becomes increasingly steep towards the northern boundary. The culmination (2817 feet) lies just to the north on the ENE trending ridge of Sgùrr na ba Glaise. The south-eastern slopes to Glen Ulgary and Glen Gluitanen are extremely steep, with frequent near vertical cliffs. Small streams and

TOPOGRAPHY

FIG. 2



Contour interval of 250 feet

Numbers along boundary refer to National Grid waterfalls cascade down from the heights of Beinn Gàire more than 1500 feet to the valley below. Mapping on this hillside was extremely difficult, since many of the cliff faces are not reasonably accessible. From Glen Ulgary the Moidart River curves round to flow to the SSW into the broader Glen of Moidart; thence WSW to Loch Moidart some two miles from the eastern border of the area. The slopes of Sgùrr Dhomhuill Beag lie north of Glen Moidart in the NW corner and this ground is particularly rugged. Scree often masks the bedrock and exposure is only good near the highest ground. The ground of Coire Ladhair Mhòr (Map I) is only poorly exposed. Immediately to the north the terrain continues to be rugged with an elevation of 2876 feet attained on the ridge of Rois Bheinn (Map V).

Exposure for the most part is extremely good and is sometimes virtually complete on the higher ground. However, the lower slopes of the hills tend to be grassy with only small infrequent outcrops. Much of the ground in Glens Moidart, Ulgary, Gluitanen and Forslan is unexposed. Mapping is particularly difficult in the Glen Ulgary and Glen Gluitanen areas, where exposure is poor both on the valley floor and on the grassy slopes to the north.

Much of the northern shore of Loch Shiel is forested, but trees are generally not found above 400 feet. The Torran nam Mial area (Fig. 2) is also heavily forested and north of the Polloch River the ground has been forested by the Forestry Commission. Apart from these areas, vegetation is extremely sparse, with heather and rough grass growing in poor, shallow soil. Peat is common on both low and high ground and is extensive, on the flat high ground of Beinn Gàire and Fireach Dubh (Fig. 2).

I. INTRODUCTION (Continued)

2. HISTORY OF RESEARCH

The Moidart-Sunart region lies primarily in one-inch Sheet 52 and partly in Sheet 61 of the British Geological Survey. As yet the geology of these Sheets has only been briefly reported in the annual Summaries of Progress (pt. 1: 1930-31, 1933-35), and incorporated into the Ordnance Survey "Ten Mile" map. A full account of these reports is not given here, but the following observations are of particular interest.

In Sunart and East Moidart it was found that the Moine rocks had been migmatised and that "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 a semipelitic host". (Richey 1930; pg. 63). Richey further records that "a zone of complicated folding" can be traced from Ben Resipol northwards to Loch Eilt (Sheet 61). Richey also states that at the southern end of this zone, between Loch Sunart and the summit of Ben Resipol "there is a synclinal structure with a southerly pitch, traversed by north-east faults which are parallel to the adjoining margin of the Caledonian granite-complex of Strontian and Morvern ... north of Ben Resipol the zone of folding is continued in a narrow elongate synclinal fold extending in a south-north direction between Ben Resipol and Cruach à Ghaill north of Loch Shiel, and still further north in a broad synclinal fold on Beinn Gàire". (Richey 1934; pg. 65).

Phemister (1960; pg. 31) reports that the migmatites to the north and south of Loch Shiel are continuous with the "injection gneisses" in the Loch Duich - Loch Hourn area, and the migmatite belt can be traced 60 miles from the Sound of Mull northwards to Loch Duich, with a varying width of from 10 to 16 miles.

The stratigraphical succession of the Moines has long been a controversial issue which is not yet satisfactorily settled. An important area in this regard is the district of Morar, some 10 miles to the north of the Moidart-Sunart region.

Richey and Kennedy (1939) established a succession in Morar which they considered to be of regional significance. They described the Morar dome and distinguished an outer zone of Moine schists and an underlying core of sub-Moine schists, separated by an unconformity. MacGregor (1948), however, suggested that the sub-Moines are in fact part of the normal Moines. Kennedy (1954) reinvestigated the area and concluded that the "unconformity" is, in fact, a "plane of tectonic discordance". Kennedy suggested that the schists of the core have been tectonically reduplicated and interfolded with slices of Lewisian basement. Lambert (1958) found that the boundary between the core and envelope ("normal Moine") merely marks the outer limit of retrogressive metamorphism.

The successions proposed by Richey and Kennedy (1939), MacGregor (1948), Kennedy (1954), and Lambert (1958) for the Morar area are compared on Fig. 3 .

Ramsay and Spring (1962) have proposed a revised stratigraphic succession of the Moine rocks of Glenelg, Loch Hourn and Knoydart regions consisting of three dominantly pelitic members and three psammitic members. They propose a correlation of the Glenelg and Knoydart succession with the Morar succession (Ramsay and Spring; 1962: pg. 321).

Recently much of the region adjacent to the area considered in this thesis has been investigated in detail by Clark (1961), Howkins (1961), Dalziel (1963) and Powell (1963). Clark, Howkins and Powell have reported the existence of a pelitic member that is younger than the Upper Psammitic Group of Morar. The results of this new work will be further discussed in later sections.

FIGURE 3

Comparison of Moine Stratigraphical
sequences in Morar.
(From Lambert, 1958)

RICHEY AND KENNEDY 1939			MACGREGOR 1948	KENNEDY 1955			LAMBERT 1958		
Upper Psammitic Group	m^3	MOINE Stratigraphic succession	MOINE with associated orthogneisses	Upper Psammitic Group	m^3	MOINE (envelope)	Upper Psammitic Group	mE	MOINE (envelope)
Striped and Pelitic Group	m^{2c} m^{2b} m^{2a}			Striped and Pelitic Group	m^{2c} m^{2b} m^{2a}		Upper Pelitic Group	mD	
Lower Psammitic Group	m'			Lower Psammitic Group	m'		Lower Psammitic Group	mCb	
Unconformity									METAMORPHIC BOUNDARY
Outer Psammitic Group	x''	SUB-MOINE Structural succession		Thrust				mCa	MOINE (core)
Pelitic Group	g'			Pelitic Group	$m^{2a'}$	MOINE (core)	Lower Pelitic Group	mB	
Intermediate Psammitic Group	x'			Lower Psammitic Group	m''		Central Psammitic Group (Base not seen)	mA	
Hornblendic Group Subsidiary Pelitic Group	h g			Unconformity and Thrusts			Thrusts		
				Orthogneisses	A	LEWISIAN	Orthogneisses and rare Paragneisses	X	LEWISIAN
Central Psammitic Group	x						Thrusts		

FIG. 3

I. INTRODUCTION (Continued)

3. OBJECT OF STUDY AND OUTLINE OF RESULTS

The present study has been pursued in order to elucidate the structural and metamorphic history of the area and to correlate these results as far as possible with the findings of recent workers in adjacent areas.

Structural analysis demonstrates that the rocks have been deformed by four principal fold movements. Numerous major folds of the second and third episode occur, but only minor structures of the first and fourth episode have been recognised.

Quantitative studies of minor folds of the second and third fold movements have shown that the second folds are primarily of 'Similar' type but, that the third folds are modified flexural folds. However, a sharp distinction between the two fold styles has not been found. Field observations suggest that the first minor folds are not pure Similar folds and that the fourth minor folds are modified flexural folds.

Considerable variation in trend of the axial planes of major and minor third folds occurs, and is attributed primarily to the generation of conjugate and "M" shaped folds.

The plunge of second and third fold axial structures is extremely variable in direction and amount. Rotation of second fold axes occurs both through the vertical and horizontal. The orientation of the third fold axes and the amplitude of the folds is directly related to the orientation of the F2 structures, and it is not possible to consider the effects of these two movements separately.

It is suggested that the deformation ellipsoid during the third fold movement was oriented such that the longest axis was near horizontal with an approximate N-S trend and the intermediate axis was near vertical, with a resultant shortening direction trending E-W. The concept of a kinematic a axis is considered and it is concluded that no single direction of tectonic transport can account for the deformation of the second structures during the third fold movement, which is considered to be three dimensional.

The rocks throughout the area attained sillimanite grade of metamorphism prior to the second fold movement. This grade was maintained at least through the early stages of the second deformation and may have persisted until after the second fold movement had ceased. The development of extensive concordant pegmatite stringers and quartzo-felspathic foliae also occurred at this time. No sillimanite or garnet is thought to have nucleated during the third of fourth fold movements, but mica, felspar and quartz were recrystallized. Metamorphic grade was below that of sillimanite at least before the cessation of the third fold movement. No general retrogression has occurred.

Although minerals grew at different times in the metamorphic history there is no evidence to suggest that growth was momentarily interrupted at any stage. (However, the possibility that textural evidence for metamorphic discontinuities has been obliterated by later recrystallization and deformation cannot be discounted). The picture is that of a progressive increase in metamorphism up to sillimanite grade, with attendant migmatisation. The major structures seen in the area formed after this peak had been attained.

It has been possible to correlate the fold movements of the area with those of adjacent areas mapped by Clark (1961) and Howkins (1961). Also, by correlation with successions established by the above workers, together with the succession recently established by Powell in the Lochailort area (1964), it has been possible to show that the striped-pelitic rocks of Glen Moidart are stratigraphically above the Upper Psammitic group of the Morar succession.

II. STRATIGRAPHY

1. DISTRIBUTION OF ROCK TYPES

a. Psammitic Rocks.

The surface distribution of psammitic rocks is shown on the Geological Map (Map I). Calc-silicate ribs are found in all the major psammitic units and these occurrences may vary in frequency along the strike of bedding-schistosity (Map I). The psammite is commonly coarsely banded with thin pelitic bands (generally less than 3") separating larger bands of flaggy or massive psammite. With increasing size and frequency of the pelitic bands, the dominantly psammitic rock grades into a striped and banded rock. A gradational zone is well displayed in the Cruach à Ghaill area, where the Beinn Gàire psammite becomes increasingly interbanded with pelite towards the core of the F3 closure P (Maps I & II). The contact with the Achnanellan striped-pelitic rocks has been drawn along the zone where the pelitic member becomes dominant. Although the lithological boundaries throughout the area tend to be gradational over at least several yards, occasional sharp contacts do occur. The contact between the Ben Resipol pelitic rocks and psammitic rocks is particularly well defined near the summit of Ben Resipol.

The psammitic rocks are composed essentially of quartz and felspar, with subordinate amounts of mica. Accessory minerals are epidote, sphene, garnet, apatite, zircon, magnetite and other opaque minerals. The predominant felspar is plagioclase (An.28 - An.35, maximum extinction angle method), but potash felspar is invariably present and is as abundant as plagioclase in some thin sections. 1)

i) Beinn Gàire Psammite

The Beinn Gàire psammitic rocks comprise the most extensive outcrop of psammite in the area. From the NE corner of the area mapped, psammitic rocks extend SW to the summit of Beinn Gàire. In nearly every exposure minor folding can be observed. Three major F3 folds cause extensive swings in the strike of the bedding-schistosity in the Glen Forslan and Loch na Bioraich areas (see pgs. 85-89). Psammitic rocks in this area extend eastwards to the edge of the area mapped. In detail the trend of the bedding-schistosity is extremely variable, but a general NE strike exists from Gaskan northwards to Glen Gluitanen. Here the trend swings counter-clockwise to the NW, due to major F3 folding (Maps I & II).

The psammitic rocks in the Loch na Bioraich area are on the shallow NE limb of the major F2 closure B (see p. 54). South from Loch na Bioraich the psammite is folded around the closure of B, and the southern limb trends NE sub-parallel to the shore of Loch Shiel. Dominantly pelitic rocks are exposed

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1) Psammitic, semipelitic, and pelitic rocks seen in this area extend north and west into the areas mapped by Clark (1961) and Howkins (1961) respectively. The petrography of these rocks has been described in detail by both writers. For this reason a systematic petrography is omitted from the present report. However, petrographic details are given where pertinent to the discussion.

on the slopes along the northern shore of Loch Shiel for approximately 1¾ miles. They are first seen on the hillside above the Loch ½ a mile WSW of Gaskan (Map I) and extend SW. The Beinn Gàire psammite extends to the shores of Loch Shiel in the Gaskan area and is in contact with the dominantly pelitic unit. The psammite narrows to an apparent width of approximately ¾ mile where it is bounded by the pelitic rocks to the SE along Loch Shiel and by the Glen Moidart striped-pelitic rocks to the NW. Discontinuous mesoscopic pelitic bands commonly occur within the Beinn Gàire psammite in this area and one macroscopic band can be traced for over a mile (shown on Map I). Minor folding is extensively developed and two major F2 folds have been recognised (C and D; see pp.60-65).

South of Druim an Laoigh the contact between the Beinn Gàire psammite and the Glen Moidart striped-pelite is well defined, with little or no gradation occurring. However, west of the F3 closure Q (Map II) the bedding-schistosity swings to the NW and the contact becomes increasingly gradational. SW of Creag nan Lochan the narrow zone of Glen Moidart striped-pelitic rocks grades into the flaggy psammitic rocks (Map I). Apparently the Glen Moidart striped-pelitic member dies out and the Beinn Gàire psammitic rocks in the Druim an Laoigh and Coire na Taothuirt area lie within the Glen Moidart striped-pelitic rocks. This interfingering of the two rock units is thought to be due to a facies change. However, the possibility of this being due to F1 isoclinal folding cannot be discounted.(see p. 154)

The Beinn Gàire psammitic rocks shown on the Geological Map (Map I) to the south of Gaskan are readily distinguished from the semipelitic or striped-pelitic rocks. Near the summit of Beinn Gàire (781750), the rocks are coarsely banded and often have a glassy appearance. More commonly they are dull grey and tend to be flaggy. Where appinite is present, however, the psammitic rocks tend to be more micaceous and locally resemble semipelitic rocks (see pp. 25-26).

To the west and south of Gaskan the psammitic rocks are generally richer in mica and quartzo-felspathic foliae are locally developed. This is especially the case in the Druim an Laoigh area. Concordant pegmatite sheets are extremely abundant in both pelitic and psammitic rocks and this zone has suffered migmatisation to a greater degree than elsewhere in the area mapped. The prevalence of macroscopic pelite bands, especially to the north of Cruach à Ghaill, is probably due to original sedimentary intercalations.

ii) Coire Ladhair Mhòr Psammite

These psammitic rocks are exposed in the northwest corner of the area. The rock unit closes on Sgùrr Dhomhuill Beag where the F2 antiform A is refolded by the F3 antiform J (Map II and pp. 143-45). These steeply dipping to vertical rocks trend NNE except where the rock unit closes at its southwestern extremity. At the thickest point of the unit along the northern boundary of the area it is over ¾ mile wide. Exposure is generally poor where the psammite is in contact with the Glen Moidart striped-pelitic rocks, but where the contact can be seen it is well defined, with little or no gradation. The psammitic rocks have the same appearance as the grey flaggy psammites seen on Beinn Gàire (see p. 12), and are identical in thin section. Quartz stringers and sheets generally less than one-inch thick are common and frequently lie in the axial planes of F2 minor folds. They are also found folded and/or rodded by F2 and later minor folds. Quartzo-felspathic material also is found in sheets, stringers, rods and as pegmatitic 'eyes'. Many sheets are concordant and have been folded by F2 movements and cut by F2 cleavage, but some are discordant and may cross F4 minor folds (see p. 181).

Only one small calc-silicate rib has been found in the Coire Ladhair Mhòr Psammite. The unit has been mapped by Clark (1961) to the north and this writer also found the occurrences of calc-silicates to be extremely rare.

iii) Ben Resipol Psammite

A band of flaggy psammitic rock outlines the major F3 folds R and V on the ridge and slopes of Ben Resipol (Maps I & II). It varies in width from approximately 600 feet to the west of Carn Mòr na Comhdhail up to 1400 feet just east of the axial plane trace of R. This band makes a fairly well defined contact with the Achnanellan striped-pelitic rocks and the Ben Resipol pelitic rocks; however, gradation over several yards locally occurs. Along the band, the psammitic rocks are readily distinguished from the adjacent striped-pelitic rocks; however, to the extreme east the Ben Resipol pelite becomes semipelitic and the psammite becomes more micaceous. In the SE corner of the area mapped the Ben Resipol pelite becomes indistinguishable from the psammitic rocks and apparently dies out completely (Map I). In this area the psammite is locally rich in fine grained mica and is sometimes only slightly less micaceous than the semipelitic zones which occur within the Achnanellan striped-pelitic rock (see pgs.20-23

Psammitic rock occurs in the rather poorly exposed area of Torran nam Mial, and forms an arcuate contact with the Achnanellan striped-pelitic rocks. This is an area of complex folding, with the main closure being related to the F2 antiform G (see p. 68). The contact is extremely gradational except along the southern contact adjacent to the eastern limit of the area (Map I). In particular, the striped-pelite seen along the southern shore of Loch Shiel, north of the Polloch River, grades almost imperceptibly into psammitic rock.

Thin pelitic bands persist throughout the psammite in the Torran nam Mial area. However, they are usually only one or two inches thick, with complementary psammitic bands up to approximately four feet thick. East of the area mapped the pelitic bands are not as common and the rock has the same appearance as the psammitic rocks on Ben Resipol.

Concordant and discordant pegmatite sheets and stringers are fairly common throughout the Ben Resipol psammite. A few large discordant pegmatite bodies occur in the southeast corner of the area (Map I).

iv) Discontinuous psammitic units occur within the Achnanellan and Glen Moidart striped-pelitic rocks. The units within the Achnanellan group are 'clean' grey psammites in sharp contact with the striped-pelitic rocks. They are not extensive and do not exceed a thickness of 300 feet (Map I).

Psammitic units within the Glen Moidart striped-pelitic rocks are far more extensive. The large band of psammite trending NE between the Glen Moidart river and the Coire Ladhair Mhòr psammite is up to 1000 feet thick in the SW, but narrows to less than 100 feet thick in the NE. This unit dies out just south of the northern boundary of the area and where it is at its thinnest point, to the north of Ulgary, it is displaced by a small discontinuous fault (see p. 109). The contact is extremely poorly exposed, but where visible it is sharp with gradation extending for only a few yards. The psammite is similar to the Coire Ladhair Mhòr psammitic rocks, however no calc-silicate bands have been found. The continuation of this unit to the west of the area has been mapped by Howkins (1961), who traced it southwards to Loch Shiel. Howkins also found that the psammitic unit does not contain any calc-silicate bands. Two possible cross bedding features are shown on the Geological Map (Map I) within the psammitic unit and they indicate a 'younging' direction to the NW. However, they are not extremely convincing (Plate 1b).

Howkins (1961) considers this psammitic unit to be part of the Upper Psammitic Group of the Morar succession (Richey and Kennedy 1939) and suggests that its inclusion within the pelitic rocks may be due to F1 isoclinal folding. This cannot be discounted. However, in the writer's opinion the unit may simply be a thick psammite band formed originally within the striped-pelitic rocks.

Five discontinuous psammitic units lying within the Glen Moidart striped-pelitic rocks are shown on Map I. None of these are 'pure' psammites and they tend to have extremely gradational contacts. The unit to the NE of Ulgary is very poorly exposed and the boundary shown on the Geological Map (Map I) has been mainly drawn by extrapolation. The contact, where exposed, is a zone of gradation from the striped-pelite with thin psammite bands of one to two inches, to a dominantly psammitic rock, with pelitic bands of one or two inches between psammite bands up to ten feet thick. The dominantly psammitic rocks within the Glen Moidart striped-pelite on Beinn Gàire are well exposed. This unit grades gradually into the semipelitic and striped-pelitic rocks, both across the strike and along the strike of the bedding-schistosity. The gradation strongly suggests that the unit merely represents a facies change within the Glen Moidart striped-pelitic rocks. The psammitic unit extending southwards from Sròn Dubh an Eilich and the Fireach Dubh unit also have dominantly gradational contacts. The Ulgary, Beinn Gàire and Fireach Dubh psammitic units occur almost along the strike of the bedding-schistosity and it is possible that these units may be large boudins of a single horizon. However, they all tend to grade into the surrounding striped-pelitic rock along their strike and do not have sharp contacts at their northern and southern limits. This evidence suggests that the discontinuous psammitic units are original sedimentary features rather than tectonic inclusions.

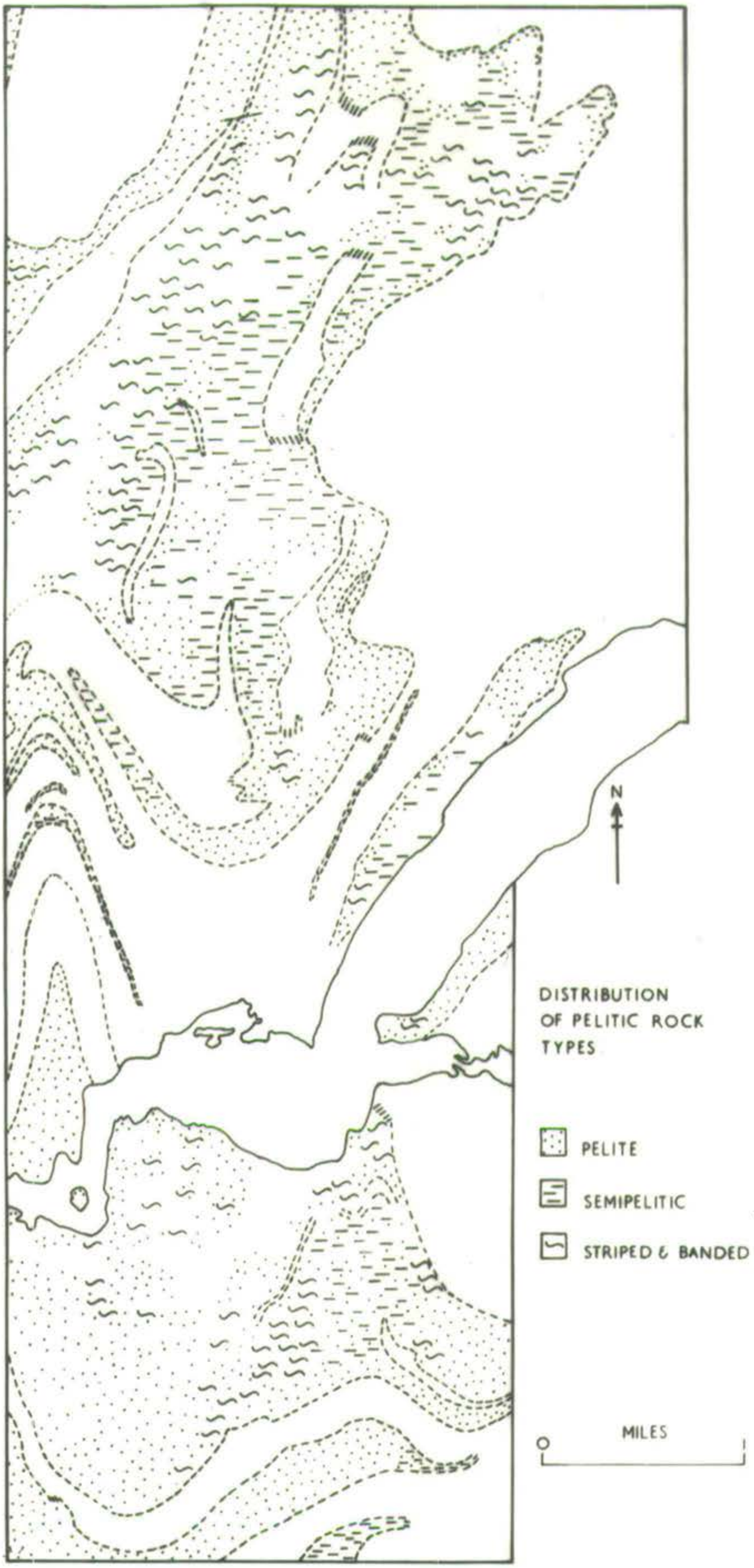
b. Striped, Pelitic and Semipelitic Rocks.

Three rock types other than the psammitic rocks can be recognised in the area. However, the three types may be found along a single horizon and gradation from one rock type to the other occurs both along and across the strike of the bedding-schistosity. Attempts to walk out the boundaries between the three types proved unsuccessful, but in the course of field mapping individual outcrops were described and ascribed to one of the three types. Fig. 4 shows the regional distribution of the Pelitic, Semipelitic and Striped and Banded rocks.

The following criteria distinguish the three types in the field:-

Pelite: The pelitic rocks are characterised by their high mica content and homogeneous appearance. They are dark brown on the weathered surface. Mica is generally present in sufficient quantities to enable the rock to be readily split parallel to available S-surfaces. The pelites are primarily gneisses rather than schists, since quartzo-felspathic foliae are generally developed.

FIG. 4


N
DISTRIBUTION OF PELITIC ROCK TYPES
PELITE
SEMIPELITIC
STRIPED & BANDED
0
MILES
1

Semipelite: The semipelitic rocks represent a mesoscopically homogeneous rock type which is intermediate between a psammite and a pelite. The rock type is identified primarily on the basis of its mica content; with an increase in mica the rock grades into a pelite, and with a decrease it grades into a psammite. Semipelite is dull grey to pale brown on its weathered surface. It is generally well foliated, but discrete quartzo-felspathic foliae are not as well developed as in the pelite. It is a garnetiferous rock, but contrary to the more pelitic rocks the garnets generally do not stand out in relief on the weathered surface.

Striped and Banded Rock: This rock type is readily distinguished in the field by the presence of thin, rhythmically interbanded psammite and pelite bands. The thickness of the bands varies but is generally less than 6 inches and usually only 1 to 3 inches. The 'bands' are composed of dull grey, massive psammite and the weathered surface frequently has a pitted appearance. The 'stripes' are composed of pelite which has a dark brown weathered surface. Garnets are not as common in the pelitic stripes as in the homogeneous pelite. The ratio of pelite to psammite is extremely variable, but pelite is generally the dominant member.

Although this rock type grades readily into pelite, semipelite or psammite, it is of a distinct type. Commonly interbanding of pelite or semipelite occurs adjacent to a major psammite contact. One such zone is shown on the Geological Map in the Cruach à Ghaill area (Map I). These gradational zones are distinguished from the regional striped and banded rocks by the coarseness of their interbanding. Bands tend to be at least a foot thick and the ratio of psammitic material increases towards the psammite contact.

The Striped, Pelitic and Semipelitic rocks are composed essentially of quartz, felspar and mica with accessory minerals of garnet, sillimanite, staurolite, sphene, apatite, epidote, zircon and opaque minerals. The felspar of the groundmass is virtually all plagioclase (An.28 - An.32, maximum extinction angle method). A few thin quartz-plagioclase-potash felspar stringers occur locally. Semipelitic rocks have minor occurrences of potash felspar in the groundmass, but it is never as abundant as in the psammitic rocks.

Concordant pegmatite sheets, foliae and 'knots' are extensively developed in the three rock types but are most abundant in the pelite. Usually the pegmatite sheets are less than 1 inch thick and tend to be discontinuous. They are commonly boudinaged, and every gradation from sheets up to ten feet long to smaller lenses, and eventually to small isolated 'knots', has been observed. In the Druim an Laoigh area (765715) the pegmatites often make up the bulk of the pelitic rock and are commonly found elsewhere interbanded with an approximately equal volume of pelite.

It is not certain that the striped, pelitic and semipelitic rocks seen in the area belong to a single stratigraphical group (see p. 32). Three main continuous units exist and these have been given regional names for the purposes of description. They are the Glen Moidart Striped, Pelitic and Semipelitic rocks, the Achnanellan Striped, Pelitic and Semipelitic rocks and the Ben Resipol pelitic rocks.

The distribution of the three dominantly pelitic rock types is illustrated on Fig. 4 . It can be seen that the three types do not everywhere occupy separate horizons, and that variations occur both parallel to, and normal to, the regional strike (see also Map I). Much of this variation is undoubtedly due to tectonic transposition of the original bedding. However, variation also occurs along the strike of the compositional layering and is apparently due to original facies changes. Striped and banded rocks commonly may change along their strike to pelite which is almost free of psammite bands; pelite may grade into semipelite and not infrequently pelite and semipelite become interbanded (e.g. Coire Dubh area - Map I).

The Ben Resipol pelite is free of striped and banded rock and only becomes semipelitic where it grades into the adjacent Ben Resipol Psammite. However, this does not imply that the Ben Resipol pelite is stratigraphically distinct from the striped, pelitic and semipelitic rocks. The pelite in the extreme NW corner of the area (Fig. 4 and Map I) is folded around the Coire Ladhair Mhòr Psammite (see also Howkins 1961 and G.S.G.B. "Ten Mile" Map). This pelite in the area mapped is partly separated from the striped, pelitic and semipelitic rocks of Glen Moidart by a psammite band that dies out to the north. But the pelite west of the discontinuous psammite band is virtually free of striped and semipelitic rock in the area mapped, save for a local development of striped rock in the Sgùrr Dhomhuill Beag area. However, in the north of the area the psammite band thins and dies out completely. Therefore, (since there is no evidence of a slide), the pelite can be directly correlated with the Glen Moidart striped, pelitic and semipelitic rocks.

Since much of the variation in the dominantly pelitic rocks is attributed to sedimentary facies changes, it is quite reasonable to expect closures to exist which are not of tectonic origin. The tongue of pelitic rock in the Druim an Laoigh area that extends NW into the Beinn Gàire psammite becomes less and less pelitic until it has graded completely into the psammite (Fig. 4 and Map I). This gradation suggests a sedimentary origin for the closure rather than a tectonic origin (see p. 155). All major folds shown on the Structural Map (Map II) have been recognised by analysis of minor structures and are not based on the presence of stratigraphical closures.

c. Calc-Silicate Rocks.

Calc-silicate bands are not common, but have been seen in all the metasedimentary rock types. They occur as disfrequently made more apparent by the presence of a quartz-felspar "halo".

The schists are composed primarily of hornblende, quartz, plagioclase (An.60 - An.68), garnet and biotite (sometimes absent), with accessory sphene, apatite and opaque minerals.

e. Intrusions.

Intrusions occurring in the area have not been studied in detail, but a few observations pertinent to the structural and metamorphic history have been made.

Large dykes and other discordant masses of pegmatite have been found which truncate minor folds of F4 and earlier fold movements. These late, unfoliated, pegmatites are extensively developed in the Carn Mòr na Comhdhail area (Map I).

Partly concordant and partly discordant sheets of appinite have intruded and pervaded the metasediments. These intrusions are ubiquitous in the Loch na Bioraich - Beinn Gàire area (Map I). The appinite in this area is extremely coarse with stumpy amphibole crystals up to the size of a sixpence (Plate 2b). The coarse grained appinite is virtually unfoliated, but some weak foliation does occur locally adjacent to contacts with the metasediments. This foliation does not appear to have any tectonic significance since it dies out laterally in only one or two feet and is probably original flow banding. The appinite has been seen to truncate F2 minor folds, but tends to follow the bedding-schistosity around the closures of F3 minor

minor folds occur in the adjacent metasediments. Also the foliation in the appinite trends N-S and is sub-parallel to the regional trend of F3 minor fold axial planes. In the same outcrop F2 axial plane cleavage trends NW and dips steeply to the SW. The dip of the foliation in the appinite is steep to the east. This evidence indicates that the foliation is probably related to F3 and that the dyke was intruded after F2 since no F2 foliation has been recorded in the appinite. If this appinite dyke is indeed of post-F2 and pre-F3 or syn-F3 origin, then it was emplaced prior to the coarse grained, unfoliated appinites.

Weakly foliated biotite granite dykes also occur (Map I). These are of restricted extent. They tend to follow the regional foliation and one such dyke in the Sròn Dubh an Eilich area follows the foliation of the metasediments around the major F3 closure P (Maps I & II). Dolerite and basaltic dykes occur, but can seldom be traced for more than a few yards. They trend WNW to NW and cut the unfoliated appinites. The only major dyke of this suite in the area can be traced for approximately 2800 feet, trending NW to within ½ mile west of Gaskan (Map I). It has an average width of approximately 15 feet. A few small dykes of unfoliated, but extensively decomposed, lamprophyre have also been noted.

The intrusive rocks in the Moidart area have been described by the British Geological Survey (Summary of Progress for 1930). The appinites are thought to be related to the Lower Old Red Sandstone appinites of the Glen Coe district (Bailey 1916).

suggests is stratigraphically below the Upper Psammitic Group. Since the pelitic rocks on either side of the Coire Ladhair Mhòr psammite can be directly correlated around the closure of the psammite, this suggestion appears to be unlikely unless considerable sliding has occurred in the succession between Moidart and the north of Loch Eilt. The pelitic rocks adjacent to the eastern contact of the Coire Ladhair Mhòr psammite can be traced northwards to the southwest shore of Loch Eilt (Clark 1961). East of the Arieniskill Pelitic Group, Powell has mapped an extensive psammitic unit (Loch Eilt Psammitic Group), which he has tentatively correlated with the Lower Psammitic Group of the Morar succession. It is not certain from the evidence presented by Powell (1963) and Clark (1961) whether the pelitic rocks east of the Coire Ladhair Mhòr psammite can be correlated, across Loch Eilt, with the Arieniskill Pelitic Group; these pelitic rocks may, in fact, extend into the Loch Eilt Psammitic Group (see Plate 1: Powell 1963). If the pelitic rocks can be correlated with the Arieniskill Pelitic Group, then the whole of the Upper Psammitic group, together with the Striped and Pelitic Group would be missing from the succession. On the other hand, if the pelitic rocks extend into the Loch Eilt Psammitic Group a similar break in the succession would be required. No evidence has been presented by Clark (1961) or Powell (1963) for the existence of a major slide in the area.

The evidence presented above indicates that the Glen Moidart striped-pelitic rocks are stratigraphically above the Upper Psammitic Group of the Morar and Moidart succession.

striped-pelitic rocks are in fact younger than the Upper Psammitic group.

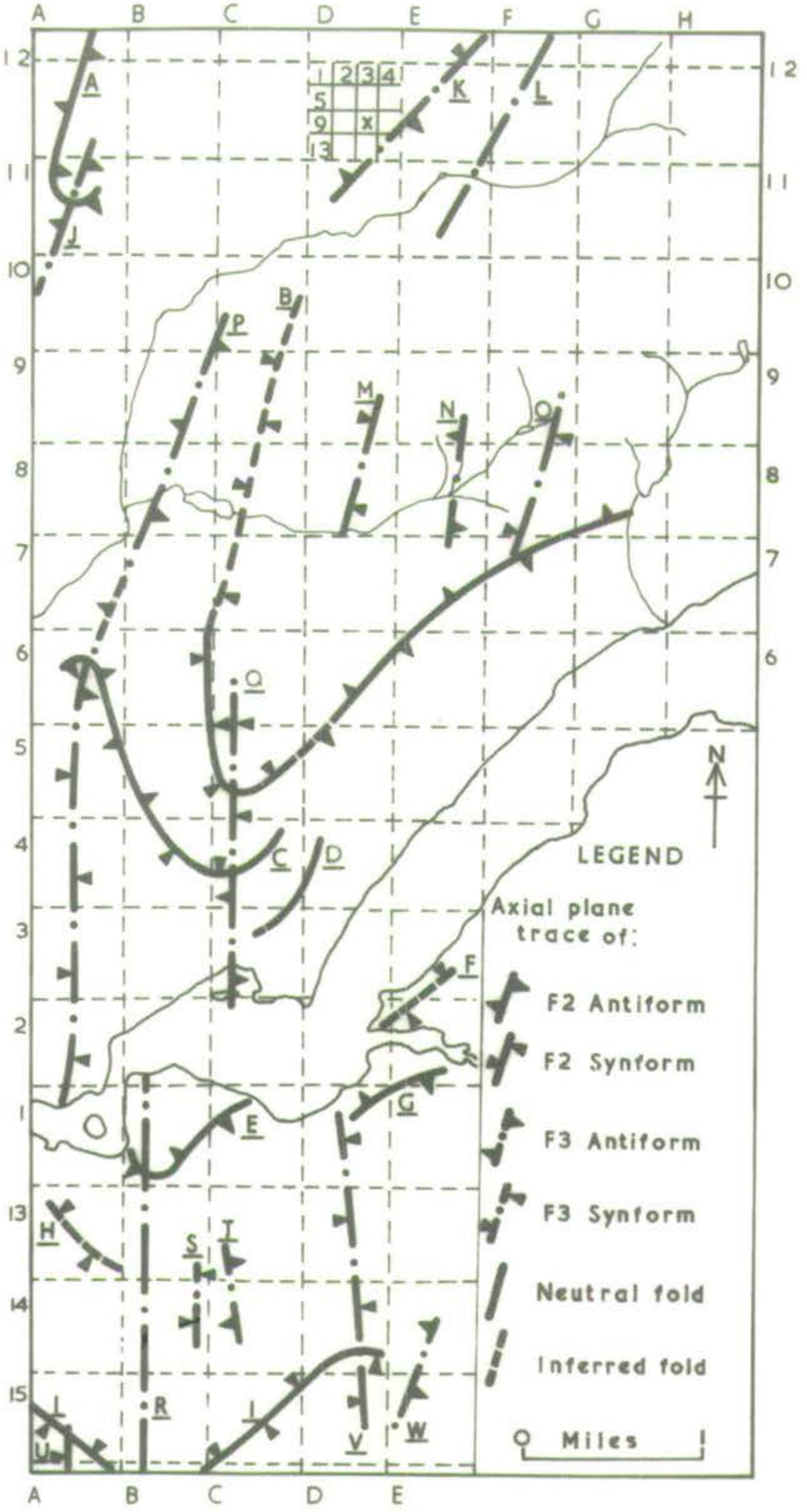
The stratigraphical successions indicated by Clark (1961), Howkins (1961), Dalziel (1963) and Powell (1963) are correlated in Fig. 5 , together with the succession suggested by the writer.

FIG. 5

	E. MOIDART	LOCHAILORT (MOIDART) Clark 1961	MOIDART Howkins 1961	N.W. ARDGOUR & S.W. LOCHABER Dalziel 1963	LOCHAILORT Powell 1964
4	GLEN MOIDART STRIPED-PELITIC GROUP	ROIS BHEINN PELITIC GROUP	ROSHVEN PELITIC GROUP		LOCHAILORT PELITIC GROUP
3	BEINN GÀIRE PSAMMITIC GROUP	UPPER PSAMMITIC GROUP	UPPER PSAMMITIC GROUP	GLEN GARVAN PSAMMITIC GROUP	ARDNISH PSAMMITIC GROUP
2		STRIPED & PELITIC GROUP	STRIPED & PELITIC GROUP	DRUIM NA SAILLE PELITIC GROUP BEINN AN TUIM STRIPED GROUP	LOCH MAMA PELITIC GROUP
1		LOWER PSAMMITIC GROUP	LOWER PSAMMITIC GROUP		LOCH NAN UAMH PSAMMITIC GROUP BEASDALE PELITIC GROUP

STRATIGRAPHICAL CORRELATION

FIG. 6



A-I =Major F2 Folds
J-W =Major F3 Folds

GRID:
x =Location D12-11

LOCATION OF MAJOR AXIAL PLANE TRACES

III. STRUCTURE

1. INTRODUCTION

a. Field Methods.

The area has been mapped on a scale of six inches to one mile. A quarter square mile grid was drawn on the six inch Ordnance Survey maps and this grid was further sub-divided into units of one sixty-fourth of a square mile, giving sixteen squares for each one quarter square mile unit. The large grid was numbered and lettered as shown in Fig. 6 and the small squares within each quarter square mile were numbered one to sixteen from the northwest corner to the southeast.

A Filo-fax loose leaf system was employed for recording the measurements made in the field, in conjunction with the above grid system, thus allowing direct plotting of the data in the field.

Aerial photographs were used to locate exposures and the grid was drawn on these photographs with corrections for distortion.

Samples were numbered according to their location on the grid. In this way the location of any sample could be ascertained at a later date simply by looking at its number.

Measurements were made in the field with the aid of a Brunton compass. The data was transferred to a base map and structural elements were recorded on stereograms.

It was found that all planar and linear structures could be measured directly by using a fibre board and the Brunton compass. Even steep linear structures could be measured accurately by placing the edge of the fibre board on the trace of the lineation and rotating the board until it was vertical, as shown by the level on the Brunton. In cases where this was not practical, the lineation was measured in terms of its pitch on the S-surface on which it lay, and the strike and dip of this surface was also recorded. The azimuth and plunge of the lineation were later calculated from the stereonet.

b. Relative Age of Minor Structures.

Despite the fact that other workers have recently established the presence of multiple folding in the Moines, a critical approach has been taken in order to determine whether or not such an interpretation can be applied to the present area.

In order to become familiar with the lithology and the minor structures, an area of about five square miles (north and south slopes of Glen Forslan) was mapped. From this it appeared that many of the minor structures had curved axial planes and that superposition of several fold movements was a possible explanation.

The same area was then mapped systematically in detail. Where possible all minor structures observed were recorded, and where one minor fold refolded another they were designated Fa and Fb respectively. Interference patterns in many cases were found within a few yards of each other. In these instances it was possible to correlate the refolded structures directly and to show that the minor folds with unfolded axial planes were related, in that they were often seen to be parasitic folds on the limbs of larger minor folds (de Sitter 1958). A study of the cleavages related to both sets of folds demonstrated that the cleavages of the refolding folds cut across and displaced the cleavages of the refolded folds. In some instances the bedding-schistosity of the refolded folds was also seen to be displaced. Such evidence allows for no other conclusion than that the refolding folds were still actively folding after the refolded folds had ceased to be active.[1] From this correlation across a few yards the same criteria can be extended to zones at greater distances apart. Where it was not possible to make a definite correlation, the minor structures were measured and described, but they were not assigned to a fold movement. As work progressed a pattern emerged and this larger scale pattern illustrated that two sets of minor folds, Fa and Fb, were of regional extent. In a few instances Fa and Fb were seen to refold an earlier set, and locally Fa and Fb were refolded. On the basis of these observations four fold movements have been established and have been designated F1, F2, F3 and F4.

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[1] The term "active folding" is here used in reference to folds whose limbs are rotating towards each other about the fold axis. "Passive folds" are those folds whose limbs are opening or closing about a new fold axis, which may or may not be parallel to the original fold axis.

It has been suggested by some writers that refolded folds may form in extremely mobile rock by turbulent flow, and a field example has been described from the Canadian Grenville by Wynne-Edwards (1963). In such circumstances, it is possible for a later fold to flow around the crest of an earlier fold. However, if this were the case two distinct sets of cleavage would not develop. One fold movement may overlap another in the present area, but active folding of an earlier fold movement definitely precedes active folding of the later movement.

Where only two sets of folds are developed it is often easy to separate the minor folds with fairly constant axial plane trend from those of variable trend, but if the two sets are nearly coplanar, other criteria must be used. When more than two sets of minor folds occur the use of axial plane trend to distinguish one set of folds from another was found to be most unreliable. Also variation of axial plane trend need not imply more than one generation of folding. The F3 folds often show a regional variation of axial plane trend from NNE to NNW, and this variation has been found to be primarily due to the development of conjugate sets. Some variation also occurs where a later axial plane is superimposed on an earlier fold (see p. 113).

The style of the minor folds has been carefully recorded, and it has been found that characteristics of style can only be used as aids to distinguishing the relative age of minor structures in special cases, and that in general, fold style is not a reliable criterion. Isoclinal folds with limbs of up to fifteen feet long can change in a single outcrop to fairly open folds with limbs only two or three feet long. Folds of the same generation vary also from nearly pure "Similar" to nearly pure "concentric" in shape. Also, in folds known to be of the same generation, a penetration cleavage may give way to a mica crenulation with no cleavage. Lithology is often a major factor controlling the style of minor folds. Thin laminated rocks with wide viscosity differences tend to be more folded than rocks of a more uniform viscosity, and the folds in the former are often tighter and more persistent than those in the latter. Position of the minor fold with respect to the major closure also plays an important role. Minor folds tend to become tighter and longer limbed away from the closures of the major folds. Also minor folds with a well developed foliation parallel to their axial planes are best developed on the limbs of the major closure, and these may give way to folds with a crenulation and little or no axial plane cleavage towards the closure.

Fold style and trend are not, therefore, reliable guides to the differentiation of fold movements in this area. However, local characteristics are often an aid to correlation, which has been based in the first instance on the observation of the later folds superimposed on the earlier folds.

c. Structures Observed.

A brief description of the planar and linear structures observed, together with discussion on their relative importance to structural analysis follows.

i) Planar Structures

(a) Bedding-Schistosity, foliation and cleavage.

Throughout the area varying amounts of movement have taken place both parallel to and at angles to the bedding planes, hence little true bedding is preserved. This is especially true in the pelitic rocks, where often in zones of tight folding, the original bedding has been completely destroyed. The following nomenclature will be used to designate the various S-surfaces:

S_s = bedding-schistosity

S_1 = foliation parallel to axial planes of F1 minor folds

S_2 = foliation parallel to axial planes of F2 minor folds

S_3 = foliation parallel to axial planes of F3 minor folds.

The dominant foliation where transposition of bedding has occurred is usually S_2, parallel to the axial planes of the F2 minor folds. The F1 folds are isoclinal and, therefore, the bedding-schistosity (S_s) is parallel, on the limbs, to the F1 axial plane cleavage (S_1). Foliation parallel to F3 axial planes is locally developed (S_3), but no foliation has been seen parallel to the F4 axial planes.

Any foliation that is sub-parallel to an axial plane is here termed 'axial plane cleavage' when referred to specifically. The F2 folds exhibit axial plane cleavage more commonly than do the other fold generations. Also in the case of the second fold movement visible displacements of compositional layering sometimes have occurred along these cleavage planes. Such a cleavage is here termed 'a penetration cleavage'. The F3 folds may also display a penetration cleavage, but only very slight displacements occur. More often the cleavage seen in the third folds is related to movement along planes parallel to the axial planes of mica crenulations, coaxial and coplanar to the mesoscopic folds. This cleavage is commonly called 'strain-slip cleavage', but the writer prefers to use the term 'crenulation cleavage' (Rickard 1961). The F4 folds sometimes display a weak crenulation cleavage, but no penetration cleavage has been seen. The F1 isoclines show a penetration cleavage, but in the few examples seen in this area it is not well developed.

(b) Axial Planes.

Minor folds are well developed throughout the area, and as many measurements of their axial plane orientations were made as possible. In this area minor axial planes were found to be the most reliable guide to interpretation of the structure.

ii) Linear Structures

(a) Fold Axes.

Fold axes are the most important linear structures in the area, since they can be directly correlated with the various major fold generations. Lineations developed in the absence of minor folds are often ambiguous and positive correlation is difficult. In most instances differential weathering allows the orientation of the minor fold axes to be readily measured. Where the rock is fairly homogeneous it is sometimes not possible to ascertain the plunge of the axes, and only the trend of the axial plane trace of such minor folds can be measured.

(b) Mineral Alignment.

Quartz and felspar grains are often elongated in the fold axes of minor folds and become a prominent feature when seen in the pelitic rocks.

Sillimanite and muscovite-felspar pods are often found elongated in the axial plane of the F2 minor folds and usually the longest axis of each pod is parallel to the adjacent F2 fold axis (see p. 177).

(c) Axial Plane Cleavage: Foliation Intersection.

This feature is common in the F2 and F1 minor folds and is locally well developed in the F3 minor folds, but is not seen in association with the F4 folds. Since minor folds are ubiquitous the measurement of this lineation is not important, but wherever seen its presence has been recorded as an aid to distinguishing the various fold generations.

(d) Mica Crenulation.

Mica (predominantly biotite) crenulation is developed to varying degrees in the F2, F3, and F4 minor folds. The F2 folds more often have mica aligned parallel to the axial plane, but many instances of a tight crenulation have been seen. In some cases this crenulation is found in conjunction with mica that is aligned parallel to the axial plane (axial plane cleavage), and the resulting cleavages are often a combination of crenulation and penetration types (see p. 41). Mica crenulations are sometimes found where larger minor folds are not developed but, when the two are found together and are coplanar, they are also coaxial.

(e) Tectonic Inclusions.

The term "tectonic inclusion" is applied to any discontinuous body of rock which is thought to have formed by the tectonic disruption of an originally more or less extensive layer (Rast 1956).

Rods, Mullions and Boudinage are the main tectonic inclusions seen in the area.

Rods and Mullions: Quartz and quartz-felspar rods are developed parallel to the fold axes of the F1 and F2 folds, but only quartz-felspar rods are found associated with the F3 folds.

These rods can be seen in various stages of development. Concordant sheets of quartz or quartz-felspar are folded and the limbs become attenuated. Where folding is intense, disruption takes place, and the final stage is a set of rods as remnant fold cores.

Mullions are developed in the same manner where thin psammite bands in pelite become isolated. Many such isolated folds have been found in the area, and all have been readily correlated with the second fold movement. An example is given on Plate 9b . Such disruption appears to be due to tension developed in the folded psammite band, due to its higher viscosity relative to the surrounding pelitic rocks.

Boudinage: Boudinage structures are not common in the area and where they occur it is often difficult to relate them with any certainty to a specific fold movement. However, both F2 and F3 boudins have been recognised and their axes are sub-parallel to the axes of adjacent minor folds of the same deformation. "Barrel-shaped" boudinage similar to the structures produced experimentally by Ramberg (1955) are the most common. One such boudinage is shown in Plate 3b . Complete necking has occurred with attendant influx of the less competent surrounding rock. Plate 4a is an example of pinch and swell structures in a banded zone of the Ben Resipol Psammite, close to the Coire Dubh synform V of the third fold movement (Map II). Note the staggered positions of the attenuated zones. The boudin axis here is parallel to the F3 axis of the Coire Dubh synform. Jointing displaced the bands after they had been attenuated.

Since the occurrences of boudinage are rare in this area, and only a very few can be definitely related to a specific fold movement, it has not been possible to use their orientation as aids to the structural analysis of the area.

III. STRUCTURE (Continued)

2. STRUCTURAL ANALYSIS

In this section the geometry of the major structures and their associated minor structures is discussed in detail. Each fold movement is discussed separately and then the interrelationships of the movements are considered. Where possible the observed geometry is interpreted in terms of a possible "movement picture", and the third fold movement has been particularly studied from this point of view.

For the purposes of analysis the area has been divided into 18 sub-areas. The structural data from each sub-area has been recorded on stereograms and is illustrated in Fig. 7 .

a. First Fold Movement (F1)

No major F1 folds have been recognised in the area. Minor folds that have been refolded by probable F2 folds have only been seen in five localities. The F1 minor folds are long limbed isoclines, and they occur as isolated closures with no visible complementary fold (Plate 4b). There is no way of being absolutely certain that the isoclines are not F2 folds refolded by F3, but in all cases the refolding folds have a well developed axial plane cleavage, and their vergence agrees with adjacent minor folds that are seen to be refolded by F3 folds.

Foliation is usually parallel to the axial planes of the F1 isoclines and is, therefore, sub-parallel to the bedding-schistosity (S_s), except around the F1 closures. However, F2 minor folds are also commonly isoclinal or sub-isoclinal, with foliation usually parallel to the axial planes. When foliation is parallel to bedding-schistosity and minor F1 folds are absent there is no reason for considering the foliation to be necessarily S_1. Where F2 minor folds exhibit a foliation parallel to the axial planes together with a mica crenulation (Plate 28a) the crenulated foliation may be S_1. However, the mica may have nucleated during or shortly after F2. The existence of a pre-F2 foliation can only be demonstrated with certainty where penetrative movement has occurred along S_2, displacing the bedding-schistosity (S_s) and its parallel foliation.

Throughout this area the second and third fold movements have caused intense deformation and it is quite reasonable to suppose that the first folds have been obliterated. In fact, it seems most likely, in the areas where bedding (S_s) has been completely transposed that complete destruction of F1 structures would occur. However, in parts of the Beinn Gàire Psammitic group, where only weak F2 folding is present (North of Gaskan on Map II), no regional development of F1 has been seen.

Although lithological relationships in the area are complex, it has not been necessary to invoke a major fold movement prior to F2 to explain their disposition.

There is, therefore, no evidence to suggest that the first fold movement has played an important role in the structural history of this area and the development of pre-F2 isoclines may be of only local significance.

It is of course possible that the pre-F2 folds seen could be sedimentary slump structures. This hypothesis cannot be tested in an area of such intense deformation, since truncation of the limbs of some of the F1 folds could well be of tectonic origin. However, the fact that a foliation developed prior to the second fold movement suggests that tectonic activity occurred prior to F2.

b. Second Fold Movement (F2)

i) Minor Folds.

The minor folds of the second fold movement are of regional extent and vary in style from isoclinal to broad open folds. Examples of the various styles are given in Plates 5a & b - 12a & b.

Although it is true to say that the majority of F2 minor folds seen in the area are moderately tight and generally display an axial plane cleavage, it can be seen from the photographs that generalizations as to style can be misleading.

The following observations of F2 style can be made:-

(a) Extreme variations in style may occur over distances of only a few yards.

(b) Tight near-Similar folds and more open near-Concentric folds can be developed about the same closure.

(c) Pelitic bands deformed during F2 are usually less competent than the psammitic bands, but in some localities no great difference in competence is seen (Plate 10a).

(d) Brittle and plastic deformation can occur in the same locality during a single deformation.

Plate 10b illustrates a variation from brittle shear to plastic deformation (or vice versa). The near-Similar folds seen at the bottom left of this plate can be correlated with adjacent F2 minor folds. Since the rock is all banded psammite and the composition of the rock in the case of plastic deformation is the same as in the zone of "brittle" deformation, it seems most likely that the variation in style is not due to a variation in rock competence. In a fold where the thickness, measured perpendicular to the bedding surfaces, increases towards the crest or is otherwise extremely variable, plastic or viscous flow must have occurred (see p. 114). Carey (1953 p. 71) has called a substance that deforms by viscous flow below its melting point a Rheid, and has pointed out that such deformation is time dependent. From this it follows that deformation rate is an important factor in the determination of fold style (Biot 1961). It seems likely, therefore, that the variation in the mode of deformation seen in Plate 10b is a reflection of a variation in the deformation rate.

(e) Folds can develop in nearly homogeneous rock. Plate 8b is an example of F2 folds generated in almost massive Psammite. The folds are outlined where extremely thin micaceous bands have been differentially weathered. A weak foliation parallel to the axial plane of the folds can just be discerned.

The folds are of "Similar" type and the deformation is probably due to plastic flow parallel to the axial plane. Since the rock is so nearly homogeneous the folds have probably formed as a result of active folding in adjacent less homogeneous rock (see p. 125).

(f) Axial plane cleavage may develop in both psammitic and pelitic rocks, but is best developed in pelitic rocks. Plate 11b is a typical example of F2 penetration cleavage in pelitic and semipelitic rock, where the original compositional layering has been transposed.

(g) Micas are usually aligned parallel to the axial plane of the minor folds as in Plate 11b , but in many instances the micas follow the limbs and form a cremulation across the closure, and in some instances both orientations are present.

(h) Extreme variations in fold axis orientation occur, and minor folds are usually cylindroidal for distances of only a few yards.

(i) Vergence (S or Z shape of asymmetrical folds) of the F2 minor folds is not necessarily directly related to the major closures. If the major closures in the area are considered to be the macroscopic folds and the smallest folds developed are the microscopic folds, all scales in between are mesoscopic. Mica crenulations seen in thin section may change in vergence several times and in the hand sample this change can be seen to be related to larger scale folding. The vergence of these larger folds in turn is determined by their relationship to folds of perhaps several yards in wave length, and so on up to the scale of the largest structures developed. It is, therefore, not surprising to find that the vergence of the minor F2 folds varies on the limbs of the major folds. Where the major fold is moderately open, it is usually a simple matter to determine the dominant cleavage : bedding-schistosity relationship on the outcrop scale and, hence the vergence that emerges is related to the major closure. Where the F2 folds are sub-isoclinal the vergence of the minor folds is often extremely variable and, in the absence of converging bedding-schistosity, it may be extremely difficult to locate the axial plane trace of the fold, or for that matter, to prove that the closure actually exists.

The variation of vergence of the F2 folds is one of the most difficult problems to overcome in this area, where few lithological boundaries are available and where, in the pelitic rocks, the bedding-schistosity has often been almost obliterated.

Where the major closures cannot be located with certainty their axial plane traces have been drawn on the Structural Map with a dashed line. Map III shows the vergence of the F2 minor folds in the area, together with the major F2 axial plane traces. From this map it can be seen that many small closures not shown on the Structural Map are suggested by the variation in vergence of the F2 minor folds. None of these, however, continue for any considerable distance. An example of one such fold is shown in Plate 5b from locality C7-10 (Fig. 6) in the Glen Moidart striped-pelitic and semipelitic rocks.

ii) Major Second Folds.

The axial plane traces of the major folds which have been recognised in the area are shown in Fig. 6 and on Map II. The folds have been named according to the locality in which they are best developed, but since the long Gaelic names are sometimes cumbersome, and also to avoid confusion, they have been lettered A to I as follows:

A	Coire Ladhair Mhòr Antiform
B,C,D	Druim an Laoigh folds
E	Lochan na Ceardaich fold
F,G	Torran nam Mial synform and antiform
H	Achnanellan synform
I	Ben Resipol synform

The folds change their orientation along their axial plane traces and where this results in a change in the closing direction upwards or downwards, the closure is simply termed "fold".

The following is a description of the geometry of the nine major second folds and their associated minor structures.

Coire Ladhair Mhòr Antiform - A

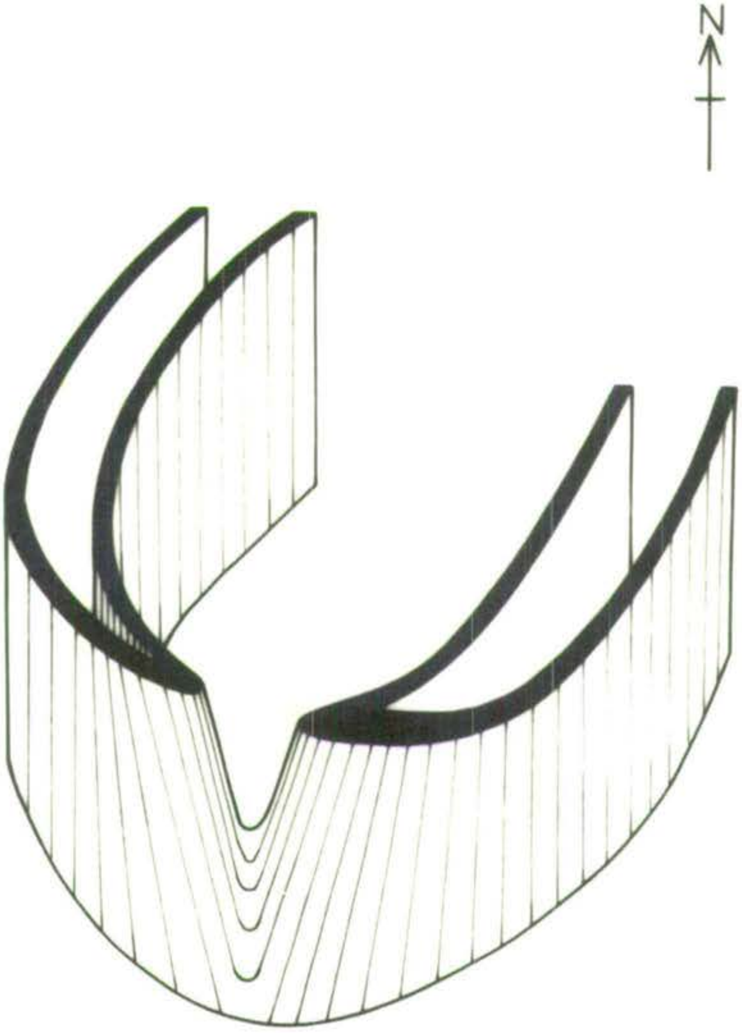
The fold is a near isoclinal antiform, the nose of which has been refolded by a tight antiform of the third fold movement (see p. 80). The axial plane trace of the second closure is entirely contained within the Coire Ladhair Mhòr psammitic rocks in the area mapped.

The structural elements of the antiform are illustrated on the stereograms of sub-area 1 (Fig. 7) and also on Map II. The π diagram A shows that foliation and bedding-schistosity planes in the sub-area are predominantly vertical, with a maximum trend NE. This maximum represents the trend to the east of the refolding F3 antiform J, and since far fewer measurements were taken to the west of the axial plane trace of J, no complementary maximum appears on the stereogram. The more open convergence of the foliation and bedding-schistosity due to refolding of the F2 closure is shown by the incomplete girdle outlined by the 1 per cent. contour.

Poles to F2 minor axial planes are dispersed in a great circle close to the primitive due to refolding during the third fold movement. Where the minor folds have not been refolded the axial planes trend NNE with near vertical dip and the minor fold axes plunge steeply to 190 degrees. Where the axes have been reorientated by later folding, the resulting pattern on the stereogram (Fig.7 - 1c) is neither a great nor small circle. The relationships between the second and third structures in the sub-area are discussed in detail on page 143 .

Since the F2 antiform is nearly isoclinal, convergence of bedding-schistosity towards the fold axis is not obvious in the field. However, the vergence of the F2 minor folds shows a consistent change across the axial plane trace, especially

FIG. 8



REFOLDED DURING F3

NOT TO SCALE

COIRE LADHAIR MHÒR F2 ANTIFORM : A

where the effects of later folding are weak (Map III). Where this change occurs a narrow zone of extremely intense F2 minor folding is seen. Within this zone (often not more than about 10 yards across) the minor folds are virtually isoclinal, with moderately short limbs, and the vergence is not consistent. Vergence on either side of this zone indicates that the zone is apparently the core of the fold. On this basis the existence of the closure is established. Also, the change in vergence coupled with the steep plunge towards 190 degrees demonstrates that the fold is an antiform. Refolding during F3 moves the F2 axes through the horizontal, while the vergence of the F2 minor folds is reversed and, therefore, the closure remains antiformal (see p. 80).

Clark (1961; p.113) has mapped the continuation of this antiform to the north (Rois Bheinn Antiform) where its axial plane trace maintains a trend NNE. The fold axis continues to vary but has a general trend of 80 degrees to the SSW.

The block diagram of Fig. 8 illustrates the geometry of the Coire Ladhair Mhòr Antiform in this area. Refolding of the F2 closure during the third fold movement is discussed on page 143.

Druim an Laoigh fold - B

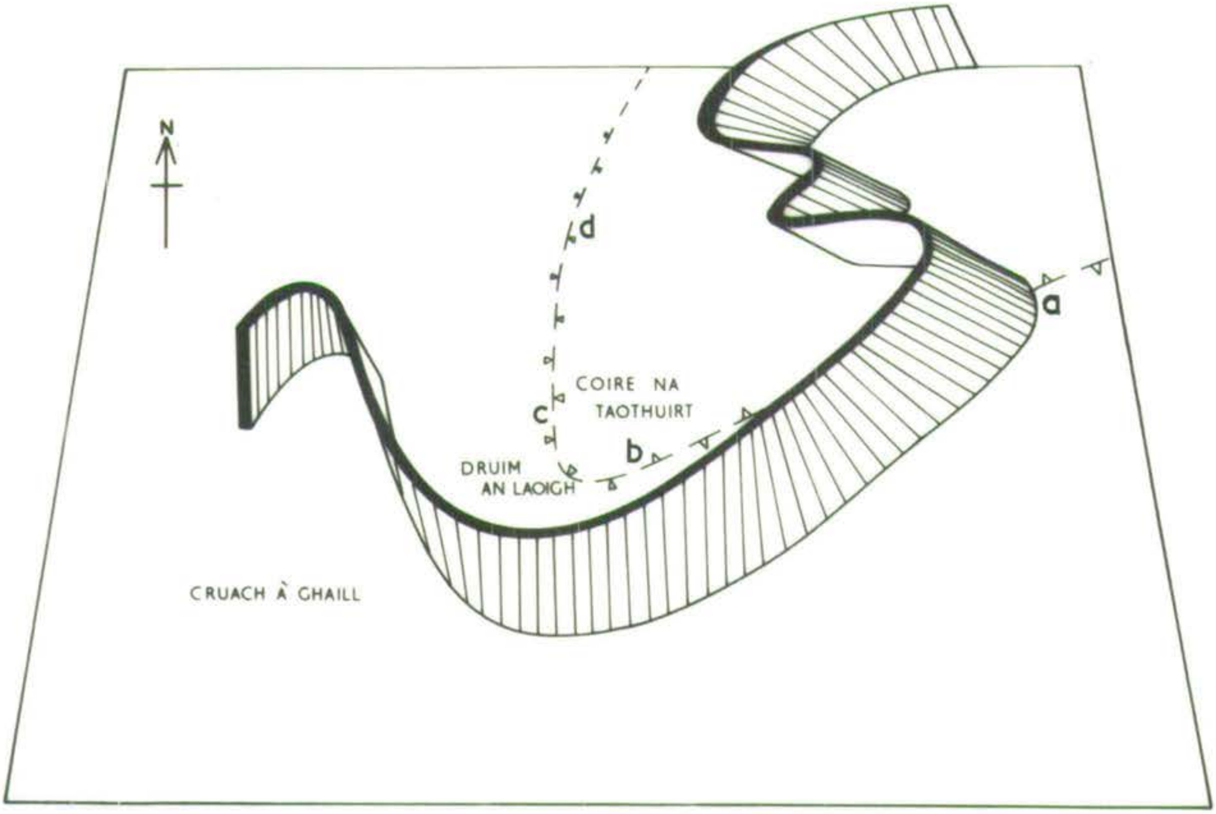
This large fold is of a complex nature. Both limbs have been affected by strong F3 folding and local F4 folding, with attendant variations in the orientation of the associated minor structures.

The axial plane trace is shown on the Structural Map (Map II) and the lithological boundaries drawn on Map I outline the shape of the structure as exposed on the surface. The general trend of bedding-schistosity on the limbs is shown on Map I and Figs. 9A and 9B are simplified block diagrams, showing the geometry of the fold.

The southern limb is very steep and is vertical where it folds around the Coire na Taothuirt F3 closure Q. To the west of Q, the southern limb dips steeply northeast and to the east of Q it dips steeply southeast. The northern limb is shallow with dips in the region of 35 to 45 degrees north through east. F3 major folds developed on the northern limb, in the Glen Forslan area, are open and plunge gently north, whereas the F3 folds on the southern limb are generally tighter and have near vertical plunge.

In sub-area 7 (Fig. 7), the closure dies out to the east. Both F2 and F3 minor folds become broad, open structures, with shallow plunge and their interference patterns give a characteristic "egg-basket" effect (Plate 12a). Poles to bedding-schistosity and foliation (Fig. 7 - 7a) give an incomplete girdle with a beta axis of 40 degrees towards 35 degrees. The F2 minor fold axes for the whole sub-area are widely dispersed and fall neither on a great nor small circle, but the axes measured adjacent to the axial plane traces of B are concentrated close to the above beta axis and, therefore, define the F2 B axis of the closure in this sub-area. Poles to F2 minor axial

FIG. 9A

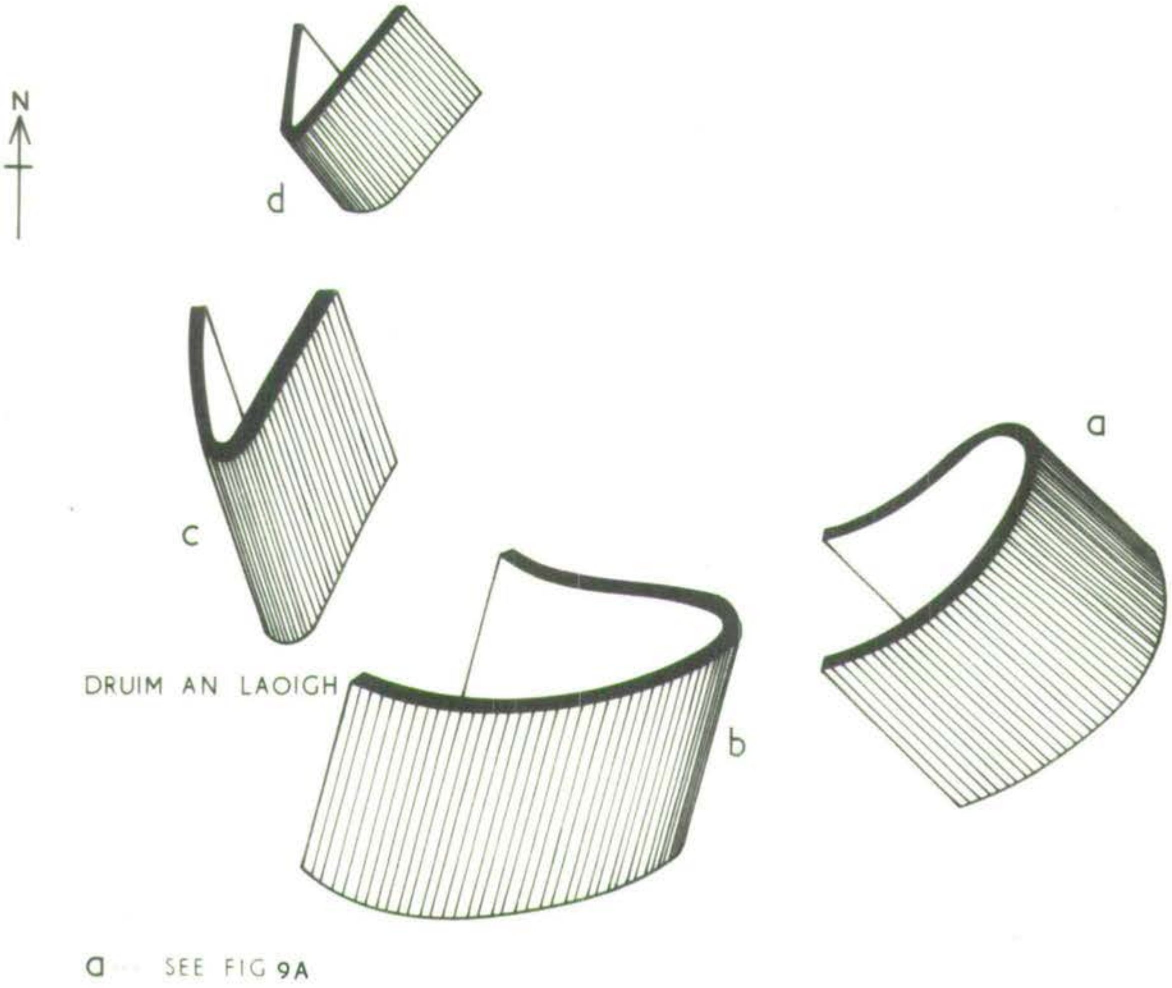


NOT TO SCALE

LIMBS REFOLDED DURING F3

DRUIM AN LAOIGH F2 FOLD: B

FIG. 9B



SCHEMATIC DIAGRAM
NOT TO SCALE

REFOLDING OF F2 FOLD-B ABOUT F3 FOLD-Q

planes in sub-area 7 are somewhat dispersed due to later refolding, but a fairly good concentration occurs for an axial plane trend of 50 degrees with a dip of approximately 60 degrees SE (Fig. 7 - 7b). The presence of a major F2 closure in this sub-area is readily demonstrated by the convergence of bedding-schistosity and by the change in vergence of the F2 minor folds (Maps I & III).

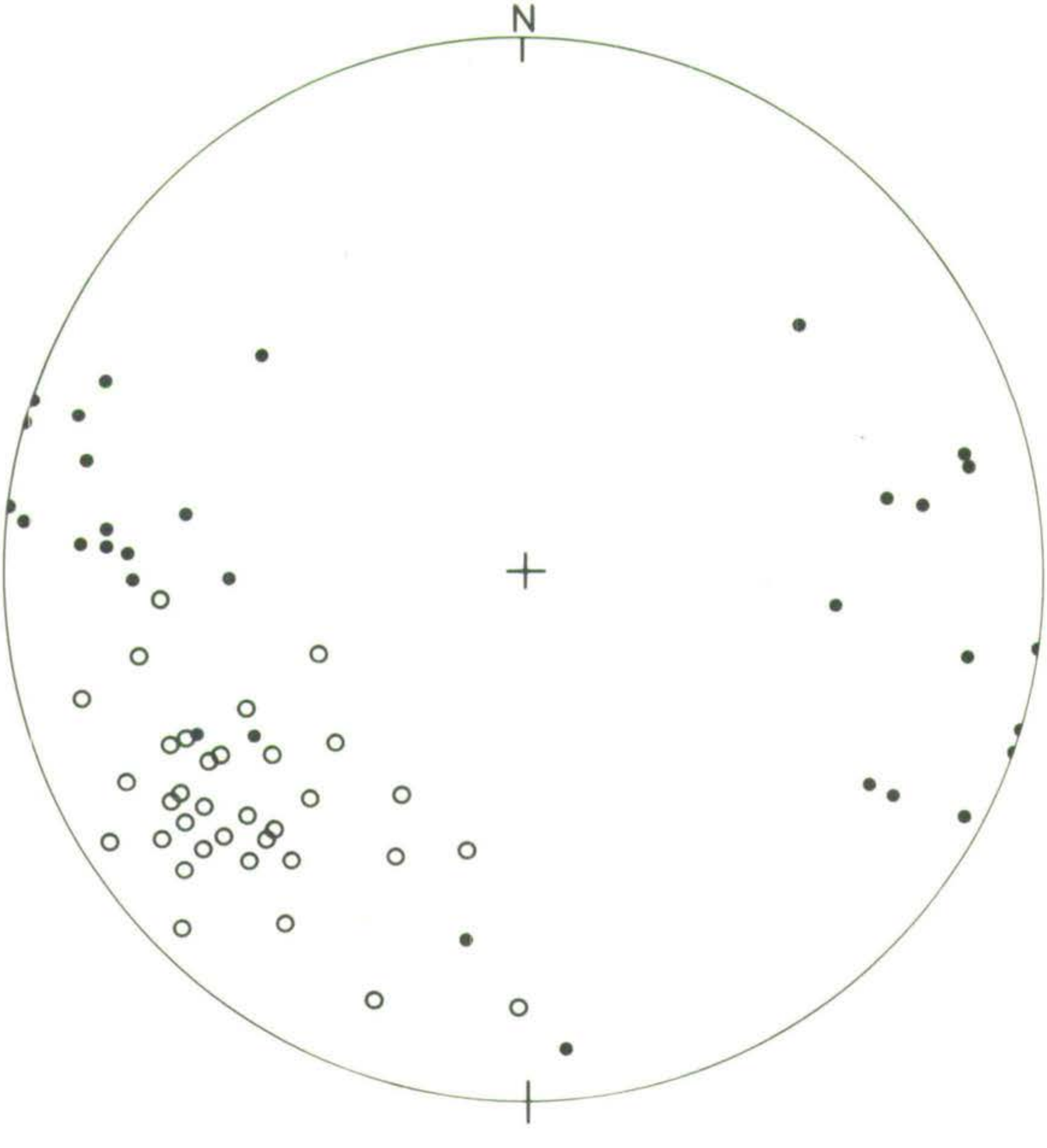
From sub-area 7 the axial plane trace of B continues SW into sub-area 10, where the trace of the limbs is outlined by the Glen Moidart striped-pelite : Beinn Gàire psammite boundary. Here the southern limb has a fairly constant strike of approximately 30 degrees, with dips of 60 to 80 degrees SE. The northern limb on the other hand changes in trend from SW, clockwise through north to NNE. The dip remains shallow to the north and east with dips of around 30 degrees predominating. The change in strike of S_s is accompanied by a complementary change in trend of the F2 minor axial planes, whereas the F3 and F4 axial planes remain fairly constant.

Poles to S_s from the northern limb in sub-area 10 form a nearly complete great circle girdle, with a beta axis of 35 degrees towards 40 degrees (Fig. 7 - 10a). This axis is nearly coaxial with the calculated F2 axis for sub-area 7, but no complementary closure of F2 age exists here, since the F2 minor folds all follow the change in strike of S_s (Map II); the change in orientation of the northern limb of B at this point is thought to be due to later refolding (see pp. 135-139).

F2 minor fold axes in sub-area 10 are dispersed due to intense refolding by F3 and locally by F4, but a moderate plunge of 40 to 60 degrees to the NE is generally maintained. Even in the core zone of B, the minor folds show considerable variation and are seldom cylindroidal for more than a few yards. From sub-area 10 the axial plane trace of B continues SW into sub-area 9 and here it swings sharply round to just west of north. The minor F2 fold axes steepen up and move through the vertical to assume a variable plunge to the north (see p. 133). Once through the vertical the closure becomes a synform, as shown by the vergence of the minor folds in relation to the plunge of the fold axis (Maps II & III). The southern limb becomes vertical as the trend swings to EW and then tilts over to dip steeply NE.

It is not possible to demonstrate the exact orientation of the two limbs in the pelitic rocks as most of the bedding-schistosity has been obliterated and the S-surface measured is primarily F2 axial plane cleavage. In the flaggy psammitic rocks of sub-area 9 cleavage is not as strongly developed and here an estimation of the attitude of the limbs can be gained. S_s of the western psammitic limb has a mean dip of approximately 65 degrees NE whilst on the eastern limb S_s dips approximately 75 degrees E. The western limb is, therefore, slightly shallower in dip than the eastern limb for this sub-area. Also the bedding-schistosity dips northwards in the core of the closure (Fig. 10). These observations support the evidence of the F2 minor folds which indicate that the major F2 fold B, in sub-area 9, closes downwards. This

FIG.10



○ POLES TO BEDDING SCHISTOSITY ON WESTERN LIMB

● POLES TO BEDDING SCHISTOSITY ON EASTERN LIMB

SUB AREA 9 : F2 MAJOR FOLD-B

complex zone of sub-area 9 and its relation to the third fold movement is discussed later on pages 133-135 .

The axial plane trace of B can be followed north from sub-area 9 into sub-area 4. Throughout this area mesoscopic folding is extremely intense. The foliation here is parallel to F2 axial plane cleavage and the original bedding has been transposed. Minor folds are outlined, often only by thin discontinuous psammitic and pegmatitic bands. In Fig. 7 , diagrams A and B for sub-area 4 illustrate the concordance of the poles to F2 axial planes and poles to foliation and bedding-schistosity. The poles to F2 axial planes are weakly dispersed due to refolding by F3, but a general trend NNE predominates with dips from 40 to 60 degrees east. The F2 minor fold axes are also variable, but have a dominant plunge of from 20 to 40 degrees towards NNE. On the low southern slope of Glen Forslan exposure is poor and only seven minor F2 folds have been measured. Four of these give shallow plunges to the south, but north of the Forslan River all the F2 minor fold axes seen in sub-area 4 plunge to the NNE.

Since the bedding-schistosity in sub-area 4 has been transposed it is difficult to prove that the axial plane trace of B continues north of Glen Forslan. Many discontinuous F2 closures of outcrop scale can be seen in this sub-area, similar to that shown in Plate 5b and, therefore, the vergence of the asymmetrical F2 minor folds changes throughout the sub-area (see pp. 50-51). The S and Z shapes recorded for the F2 minor folds are shown on Map III. The inferred axial plane trace of B, shown as a dashed line on Map II, is the line of best fit for the vergence of the minor F2 folds. The closure in sub-area 9 is a synform and the plunge to the N and NNE is maintained. Also the gross distribution of asymmetry of the F2 minor folds in sub-area 4 suggests that B continues to close to the south. On this evidence the inferred closure in sub-area 4 is apparently still synformal.

North of sub-area 4, in sub-area 2, bedding is again transposed and in the Glen Moidart striped-pelitic rocks the F2 minor folds are commonly seen as tectonic inclusions (Plate 9b). Map III shows the extreme variation in vergence of the F2 minor folds. Every change in vergence of minor folds of the same age must be related to a mesoscopic closure unless the plunge of the minor folds moves through the horizontal. Many such closures can be seen in this sub-area similar to that shown in Plate 5b . Some die out rapidly, but others can be traced several hundred feet. Attempts to locate the axial plane traces of all these small F2 closures in sub-area 2 and to relate them to the macroscopic geometry proved unsuccessful due to the relatively poor exposure over much of this sub-area. The data available suggests that the second synform B degenerates to a series of extremely tight mesoscopic closures that have been intensely refolded during the third fold movement; it is thought that the axial plane trace B probably dies out just north of sub-area 4.

In sub-area 4, the F2 minor fold axes plunge from 20 to 40 degrees NNE. Directly north of this sub-area, the F2 axes become variable with shallow plunges to the south. The change in plunge occurs through the horizontal and, therefore, vergence of the associated folds is reversed. Where this overturning occurs the minor folds have broad open limbs and the vergence is variable (loc. C10; Fig. 6). Diagrams 2B and 2C of Fig. 7 illustrate the orientation of the poles to F2 minor axial planes and F2 minor fold axes respectively. Poles to F2 axial planes are dispersed in a great circle close to the primitive, but the majority lie in the NW quadrant and indicate a mean axial plane trend of NE, with moderate dip to the SE. F2 minor fold axes lie almost entirely in the SE and SW quadrants and where they lie in the mean axial plane the plunge is approximately 40 degrees towards south. This data indicates that if the major fold axial plane trace B extends north from sub-area 4 into sub-area 2, its axis would move through the horizontal and the fold would remain downwards closing. This change in plunge of the F2 axes is considered to be due to later refolding and is discussed on pages 139-43.

Druim an Laoigh fold - C

The axial plane trace of this F2 fold is shown on the Structural Map (Map II) and is, for the most part, contained within the Beinn Gàire psammitic rocks (see pp. 12-14). In the NE corner of sub-area 11 the closure is distinct, but becomes complex to the W.

Poles to foliation and bedding-schistosity in the NE of sub-area 11 lie along a partial great circle whose beta axis is 70 degrees towards 125 degrees. F2 minor fold axes cluster around this axis which, therefore, defines the attitude of the fold axis of C. Poles to F2 minor axial planes are slightly dispersed due to refolding, but remain sub-parallel to the major axial plane as defined by near vertical bedding-schistosity intersections and change in vergence of the F2 minor folds. The strike of the major axial plane is 38 degrees. The fold axis is contained within the axial plane and the calculated dip of the axial plane is 70 degrees SE. The plunge of the fold axis is, therefore, approximately down dip and the fold at this point is a neutral closure.

Both limbs of C have been intensely refolded by F3 and local F4 movements. In the NE corner of sub-area 11 the southern limb has a fairly constant strike of 10 to 20 degrees with dips from 60 to 85 degrees SE. This trend is maintained towards Loch Shiel, where a sharp swing to the west occurs as bedding-schistosity and pre-F3 foliation swing to the NW and attain a fairly constant trend of 150 degrees, with dips from 85 to 75 degrees NE. F2 minor axial planes now are sub-parallel to the bedding-schistosity and hence the minor folds are dominantly sub-isoclinal. The NW trend continues into sub-area 8, where bedding-schistosity and F2 axial planes fold around the Cruach à Ghaill F3 closure P. S-surfaces steepen up to vertical and then dip steeply south and SE as the F3 axial plane trace is crossed (loc. A6; Fig. 6).

Where the axial plane trace of C folds around the F3 closure Q (here an antiform - loc. C4; Fig. 6), the F2 minor folds are almost completely destroyed by minor F3 and F4 folds. This zone of refolding is further discussed on pages 133-135 . Immediately west of this zone F2 minor folds have variable plunge and the vergence on either side of the F2 axial plane trace is reversed (Map III). Close to the western flank of the axial plane trace of Q, the F2 minor fold axes adjacent to the axial plane trace of C plunge steeply SSE, and at this point C is a complex synform, closing to the NNW. Continuing NNW, the bedding-schistosity becomes sub-parallel to the F2 axial planes and the F2 minor fold axes steepen up and swing through the vertical to plunge mainly north.

The northern limb of C, in sub-areas 8 and 9, is sub-parallel to the axial plane trace and dips from 70 to 85 degrees NE. Due to refolding the plots of minor F2 axes do not give good concentrations on a stereogram, but the poles to axial planes are not widely dispersed. The F2 minor axial plane trend is approximately 160 degrees, with an average dip of 75 degrees NE. Intersection of fold axes with this axial plane gives an approximate fold axis of 55 degrees N. C in this area is, therefore, an antiform closing to the NNW according to the plunge and minor fold vergence relationship. Where the vergence is variable, the existence of a fold cannot be proven, and where this is the case the axial plane trace has been drawn with a dashed line on the Structural Map (Map II).

The extension of the axial plane trace of C around the F3 Cruach à Ghaill fold P (loc. A6; Fig. 6) has been made primarily on the basis of lithology and convergence of the bedding-schistosity, since only a few F2 minor folds can be detected in this area. However, the vergence and trend of the minor F2 folds seen agree with this extension. In A5 (Fig. 6) many F2 minor folds have been mapped. Their vergence does not change around the F3 closure P and F2 minor axes swing round to plunge steeply SE and are generally down the dip of their axial planes. Only one F2 minor fold axis was measured adjacent to the closure in A6 and this plunges 70 degrees towards 140 degrees, suggesting that the closure is still slightly antiformal. Also, F2 minor folds mapped by Howkins (1961) directly west of A6 agree with the above orientation. It, therefore, appears that C remains antiformal around the Cruach à Ghaill F3 closure.

If the above interpretation of the evidence is correct, it would appear that the closure is extremely complex. The F2 axes vary considerably and swings, both through the horizontal and vertical, have been observed on the minor scale and apparently occur on the major scale. The bedding-schistosity on the surface forms a closed pattern in sub-area 11. The axis of the neutral fold closing to the northeast, to the east of the F3 fold Q, must swing through the horizontal since the vergence of the F2 minor folds and convergence of bedding-schistosity have reversed around the F3 Coire na Taothuirt closure Q. Also, since this swing has rotated the neutral fold into a downward closing orientation, it appears that the fold axis rotated in a clockwise direction from east to west. NW of the synform, the fold becomes antiformal without a change in the vergence of the minor folds and, therefore, this change was brought about merely by a continuation clockwise through the vertical. The structure considered as a whole is, therefore, downwards closing and is similar to the structure described by Ramsay (1962b) as a "Dunce's Cap".

Druim an Laoigh fold - D

D is an isoclinal neutral fold whose axial plane trace lies within the Beinn Gàire psammitic rocks, exposed in sub-area 12 to the SE of C. The evidence of the minor structures indicates that it closes to the SW and is complementary to the NE closing direction of C.

In sub-area 12 the poles to bedding-schistosity and foliation are closely grouped and form a 10 per cent. maximum for an S-surface trend of 20 degrees, with a mean dip of 75 degrees ESE (Fig. 7 - 12A). Also S_2 in sub-area 12 is sub-parallel to the bedding-schistosity and the minor F2 folds are sub-isoclinal to isoclinal. A distinct change in vergence of F2 minor folds occurs in the SW of sub-area 12 and on this evidence an axial plane trace has been drawn (Maps II & III). Since the fold is sub-isoclinal, no distinct convergence of bedding-schistosity can be detected, but the vergence of the F2 minor folds indicates that D closes to the SW. As in the case of the Coire Ladhair Mhòr antiform A, a zone of intense F2 minor folding coincides with the change in vergence and further substantiates the existence of a fold. In the NE of sub-area 12, the vergence becomes uniform and is related to the southern limb of B and, therefore, D apparently dies out. The axial plane trace of D cannot be extended into sub-area 11 due to lack of exposure, but where the exposure improves to the west no evidence for the continuation of D has been found. It is, therefore, assumed that D dies out in sub-area 11.

The axial plane of D as shown by the orientation of the F2 minor fold axial planes has a mean strike of 20 degrees and dips 75 degrees ESE. The F2 minor fold axes are slightly dispersed but trend predominantly down the dip of the mean axial plane and, therefore, the closure is a neutral fold.

Lochan na Ceardaich Antiform - E

Sub-area 14, south of Loch Shiel, is completely within the Achnanellan striped-pelitic group. The F2 axial plane trace of E is only detected in this sub-area, but it almost certainly continues both east and west into Loch Shiel. Refolding of the early structures by F3 minor folds with varying trends, and locally by F4 minor folds, rendered the sub-area inhomogeneous, and the scale of folding is too small to allow further subdivision into homogeneous zones. Nevertheless, the structure of this area can be understood by close consideration of the structural elements.

The majority of F2 minor folds here are isoclinal to sub-isoclinal. They are only well preserved in the presence of psammitic bands. In the pelitic rocks the foliation is F2 axial plane cleavage, which is nearly everywhere crenulated by superimposed F3 minor folds. Lithologic layering is sometimes seen faintly outlining the F2 minor folds.

The vergence of the F2 minor folds show a consistent change, and the axial plane trace of E has been drawn primarily on this basis, (Map III). Poles to S_s (Fig.7 - 14A) form an incomplete girdle whose beta axis represents the dominant F3 fold axis since S_s is primarily F2 axial plane cleavage.

In the NE corner of sub-area 14, the axial plane of E trends EW (on the shore of Loch Shiel) and dips steeply south as shown by the orientation of F2 minor folds and F2 cleavage. The plunge is variable due to refolding but the dominant trend is 60-70 degrees towards 110 degrees. The vergence show that the fold closes to the east and hence is an antiform. Also the style of the F2 minor folds suggests that the closure is sub-isoclinal. West from Loch Shiel S_2 swings SW, and the axial plane trace of E can be followed SW towards the Meall Buidhe F3 closure R. At this point the area is poorly exposed, but the closure can be detected west of R and apparently swings around the F3 closure. Minor F2 axial planes and S_2 west of R trend NW and dip steeply to the NE. The change in vergence is maintained and the axial plane trace can be drawn to the west shore of Loch Shiel. F2 minor fold axes and lineations are not abundant west of R in sub-area 14 and those measured are variable. However, the dominant plunge is steep to the south and the closure is apparently still antiformal.

Torran nam Mial Synform - F

The inferred axial plane trace of this F2 synform is shown on the Structural Map (Map II). The existence of this closure cannot be definitely proven since exposure in the area is poor and the structural data available rather sparse. The area under consideration is on the southern shore of Loch Shiel in the north of sub-area 17 (Fig. 7). In the Achnanellan striped-pelitic rocks exposed here the F2 minor folds are only well preserved by discontinuous psammitic bands. These minor folds are predominantly sub-isoclinal and the dominant foliation is S_2. The Achnanellan group grades SE into the Resipol psammitic rocks and here both bedding-schistosity (S_s) and S_2 are present. The F2 minor folds in the psammite are also sub-isoclinal, with bedding-schistosity sub-parallel to S_2. Map III shows that only one measurement of an F2 minor fold with a clear "Z" asymmetry is recorded north of the inferred axial plane trace F. This minor fold alone would of course not be sufficient evidence for postulating the existence of a macroscopic closure, but it is supported by the vergence of F2 minor folds on the NW shore of Loch Shiel. Also bedding-schistosity outlined by thin psammitic bands, suggests a closure at the northern juncture of Polloch River and Loch Shiel (Map I). Since this evidence cannot be considered conclusive in an area where later deformation is known to be intense, the closure can only be inferred and its axial plane trace is, therefore, shown as a dashed line on the Structural Map (Map II).

Poles to S_2 in this area give an axial plane trend of 35 degrees with near vertical dip. F2 minor fold axes vary due to refolding and plunge from 40 to 85 degrees SW.

The evidence suggests that a closure exists and that it is a sub-isoclinal non-cylindroidal synform, with near vertical axial plane and moderately steep plunge to the SW. It is most probable that this fold extends SW under Loch Shiel and can be correlated with the Lochan na Ceardaich antiform E since it also closes to the NW.

Torran nam Mial antiform - G

The arcuate boundary between the Achnanellan striped-pelitic rocks and the Ben Resipol psammite, as seen in sub-areas 16 and 17, apparently does not represent a large single closure. In both the psammitic and striped-pelitic rocks the geometry is one of tight F2 and F3 mesoscopic folding. Exposure is poor and only one F2 axial plane trace can be located with any degree of certainty.

At the boundary zone of the above striped-pelite : psammite contact, along the axial plane trace G (Map II), large minor folds of variable style and orientation can be seen. These structures extend into the Achnanellan striped-pelitic rocks, where they are refolded by F3 minor folds. They also extend NE across Polloch River, and in one instance refold an earlier (F1) minor isocline. The minor folds at the boundary, therefore, are undoubtedly of F2 age. The boundary is shown at this point as discontinuous NE trending lines (Map I), and represents a zone of interbanded psammite and striped-pelite, which has been intensely folded by the often extremely tight F2 minor folds. Across this zone, the F2 minor folds have opposing vergence and, therefore, the zone is considered to be the core of an F2 closure (ie. G). The minor folds are non-cylindroidal and vary in plunge from 45 to 85 degrees towards SSW and S. The minor axial plane trend is also variable and although this variation may be partly due to refolding, it is also apparently due to the variation in rock type. The interbanding of striped-pelite and psammite is not regular and the irregular variation in competency appears to have caused some of the folds to be disharmonic. Distortion of F2 axial plane cleavage in the striped-pelitic bands is related to the psammitic closures of adjacent F2 minor folds. Such distortion of cleavage could arise either during or after the second fold movement by the action of flattening. Flattening of one minor fold by the other with attendant distortion of fold axes and axial planes has been observed elsewhere in the area; an example is illustrated in Plate 12b. (The concept of flattening is discussed by Ramsay 1962a). The dominant axial plane trend, however, is NE with near vertical dip and the relationship between the vergence and plunge of the minor folds indicates that the closure is an antiform.

The axial plane trace of the antiform can be extended from the lithological boundary NE into the Resipol psammite and SW into the Achnanellan striped-pelitic rocks. To the SW, F3 folding becomes extremely intense and the axial plane trace of

G can only be extended as far as the Coire Dubh (V) F3 closure. Extension NE is limited by the lack of exposure and G cannot be traced further than the hills just south of Polloch River (Map II).

Diagram 17A of Fig. 7 shows the distribution of poles to bedding-schistosity and foliation for sub-area 17. The girdle described has an approximate beta axis of 70 degrees towards 200 degrees. In diagram 17C (Fig. 7), minor F2 and F3 fold axes are dispersed, but have a maximum centred on the above beta axis. Also the great circle pattern described by poles to F2 minor axial planes (Diagram 17B: Fig. 7) gives a beta axis of 70 degrees towards 235 degrees. Only seven minor F3 folds were seen in this sub-area and these trend from N to NNW with steep dips to the west. It is concluded from this data that the large structure to the east of the area mapped, implied by the arcuate boundary of the striped-pelite : psammite contact in sub-areas 16 and 17, has a fold axis close to that of F2 and F3, and an axial plane trend NE - SW. The extreme variation in the orientation of F2 minor folds and their variation in vergence (Maps II & III), suggests that this large closure is complex. The great circle pattern of poles to F2 axial planes is in part due to later refolding and major F3 folds may refold the closure to the east of the area mapped. However, the evidence of the F2 minor folds discussed above suggests that much of the variation may be due to flattening. If the less competent Achnanellan striped-pelitic rock has been flattened about the more competent Resipol psammite, the minor axial planes would tend to toe in towards the core of the closure. Where flattening may be extreme in the pelitic rocks, the axial planes and foliation (S_2) may come to lie sub-parallel to the bedding-schistosity of the psammite.

Achnanellan Synform - H

The existence of this closure in the Achnanellan striped-pelitic rocks of sub-area 13 (Fig. 7) is inferred from the change in vergence of the F2 minor folds (Map III) and, since no convergence of bedding-schistosity can be seen, the trace is drawn as a dashed line on Map II. The axial plane trace can only be followed for just over half a mile and the fold apparently dies out to the NW and SE.

F2 minor folds adjacent to H are sub-isoclinal and fairly long limbed (five to six feet). A strong axial plane cleavage (S_2) is developed and bedding-schistosity is faint and discontinuous. S_2 is crenulated by NS trending F3 minor folds, but refolding of F2 in this area is generally weak. F2 minor axial planes and F2 cleavages have a fairly constant trend. The mean axial plane calculated from the plots of poles of F2 minor axial planes is approximately 150 degrees, with a dip of 80 degrees SE. F2 minor fold axes are weakly dispersed about a point on the mean axial plane, giving an approximate plunge of 65 degrees towards 175 degrees. This plunge, together with the vergence of the F2 minor folds, indicates that the fold is a synform. In the absence of bedding-schistosity trends, the extent and geometry of this structure can only be judged by the geometry of the minor structures. All F2 minor folds adjacent to H are extremely tight and many are isoclinal. It is therefore most probable that the major closure H is sub-isoclinal.

Ben Resipol Synform - I

The core of this synform lies within the Resipol Pelite, which is therefore at a structurally higher level than the Resipol Psammitic rocks. F3 folding has been intense along the length of the closure, causing variation in the trend of F2 minor axial planes and axes. Also discontinuous mesoscopic F2 folds occur on both limbs, causing considerable variation in vergence of the F2 minor folds. The style of the F2 minor folds is variable, but they are predominantly sub-isoclinal to isoclinal. The regional foliation in the Resipol Pelite is S_2, which is sub-parallel to the bedding-schistosity. East of the F3 Coire Dubh synform V, the vergence of the F2 minor folds becomes variable and it is not possible to extend the axial plane trace of I around V on this basis. The closure probably continues as a series of complex mesoscopic folds, and eventually dies out to the east. Between the F3 closures V and R the synform is not refolded on a macroscopic scale. F2 minor axial planes adjacent to I do vary, but their poles define a mean axial plane of approximately 62 degrees with a dip of 80 degrees SE. Minor F2 axes are dispersed but intersect the mean axial plane at a plunge of 60 degrees towards 226 degrees. Vergence of the minor folds is fairly consistent here and the change across I indicates that the fold closes to the NE and is, therefore, a synform.

Unfortunately time did not permit the closure to be mapped around R, but the Resipol Pelite continues around R to the north of the area mapped and reappears in the SW corner of the area. Here the F3 folds U and R (Map II) have refolded the F2 minor structures. West of R, minor F2 axial planes strike approximately 130 degrees and have a mean dip of 80 degrees SW. S_2 is folded around U, but north towards the Resipol pelite, U dies out and S_2 maintains the above trend. Where refolding by U occurs the minor F2 fold axes are variable, but a general plunge of approximately 65 degrees towards 155 degrees is maintained.

The vergence of F2 minor folds does not show a consistent change, but the approximate location of a major axial plane trace can be drawn in (Map III). This closure is a synform plunging SE, and on the basis of the style of the minor folds it is probably sub-isoclinal. However, the effect of U will be to open the fold since only the southern limb is refolded and, therefore, the closure may die out rapidly to the west of the area mapped. F2 minor folds are refolded about R and U to the south of the area mapped and this F2 closure in the southeast corner of the area is undoubtedly the extension of I.

c. Third Fold Movement (F3)

Deformation during the third fold movement in this area has been extensive. Fourteen major folds have been recognised and F3 minor structures occur throughout the area mapped. The variations in plunge and axial plane trend of the major and minor F2 folds described in the previous section are primarily attributed to this movement. Where the major third folds are open structures, the regional strike approximates an east-west trend around their hinges and this is particularly apparent on Ben Resipol - to the south of Loch Shiel - and around the F3 closure Q in sub-area 11. The axial planes of the F3 major and minor folds do not have a constant trend. Variations from NNE to NNW occur and are attributed to the development of conjugate and "M" shaped folds, both on a minor and major scale. The F3 fold axes vary in plunge from vertical to extremely shallow and this variation is apparently due primarily to the superposition of the third folds on the previously folded surface. Local variation is also attributed to the fourth fold movement.

i) Minor Folds.

The following is a summary of the style of the minor structures formed during the third fold movement:-

(a) Some are extremely tight and often cannot be distinguished from the shape of the F2 minor folds. The only generalisation that can safely be made in this regard is that the F3 folds are never isoclinal and the open F3 folds tend to be more open than the open F2 folds.

(b) Conjugate minor folds are fairly common. A few examples are shown in Plates 13b, 14 a & b, 15a & b and their significance is discussed on pages 76-78 .

(c) Mica crenulation is usually well developed in the pelitic rocks and is sometimes present in the dominantly psammitic rocks. The crenulation may be open or tight, depending upon the style of the associated minor folds (Plate 16a).

(d) A penetration cleavage is sometimes developed (see p. 41), but is not nearly as common as it is in the F2 folds. More often the cleavage, if present, is a crenulation cleavage (Plate 16b).

(e) Nearly pure "Similar" to near pure "Concentric" folds have been seen, but the majority are a mixture of Similar and Concentric style. The mechanism of deformation during the third fold movement has been quantitatively investigated and is discussed on pages 120-24 .

(f) Even in areas of intense F3 folding, the minor folds often tend to die out rapidly (Plate 13a).

(g) The vergence of the F3 minor folds is primarily related to the major folds, rather than to intermediate mesoscopic folds. However, the fact that the third folds are superimposed on the F2 folds makes the rigorous use of vergence for locating the axial plane traces of major F3 folds an impossibility in some areas. This is particularly true in sub-area 2, where the F2 and F3 minor folds are nearly coplanar and the vergence of the F3 minor folds changes across the F2 mesoscopic folds (see p. 83).

Conjugate folds with orthorhombic symmetry have been described by Johnson (1956) in the Moine Thrust zone in the Loch Carron and Coulin Forest areas of Wester Ross. He ascribed these folds to lateral extension and attendant compression of the laminated rocks involved in the thrusting. Ramsay (1962) has pointed out that for conjugate folds with monoclinic or triclinic symmetry, the orientation of the fold axes is not directly related either to the rock movements, or to the stress conditions which produced them. The stress axes, however, can be readily calculated by measuring the orientation of the two conjugate axial planes. The intersection of the two surfaces will be the intermediate stress direction and the bisectors of these will give the maximum and minimum stress directions. The possibility of calculating stress axes in the area under present discussion by the above method is considered on pages 106 & 132.

Paterson and Weiss (1962) have produced conjugate folds, at room temperature, in a phyllite and mica schist by compressing cylinders of rock jacketed in brass and copper. The following is a summary of their findings, which may be pertinent to a study of the conjugate folds seen in this area:-

(i) Slip along foliation planes plays a dominant role in the mechanism of deformation.

(ii) At small strains, narrow bands of kink folding appear at approximately 50 degrees to the direction of shortening and when both sets are developed the kink bands form conjugate folds.

(iii) Where kink bands intersect, symmetrical folds are developed with axial planes perpendicular to the specimen axis and they are of a Similar style.

(iv) Where the compression was inclined at 25 degrees and 45 degrees to the foliation, only one set of kink bands generally appears.

The style of the natural conjugate folds seen in Moidart and Sunart is often similar to the style of the folds produced by Paterson and Weiss. The conjugate minor folds seen in the field are often orthorhombic when developed at the closures of the major F3 folds, but are monoclinic or triclinic when developed on the limbs of the major folds.

Plate 13b is an example from sub-area 18 (loc. D14-11; Fig. 6) and is typical of the conjugate minor folds developed in this area. The conjugate sets trend NNE and NNW and where the two axial planes intersect a single fold is formed with a N-S trend. The conjugate folds are best developed in the thinly laminated rocks. The axial planes of the folds are very seldom planes of dislocation, and the folds are not of a brittle nature. However, where the rock is of interbanded psammite and pelite, with psammitic bands of two or three inches or more, the axial planes of the folds do, in some instances, tend to be planes of dislocation, (Plate 15b). Conjugate folds may also develop in fairly homogeneous psammite, but are only generated in the presence of thin quartzite bands (Plate 14b).

Thin quartzite bands often form folds in relatively unfolded psammite. These folds must have formed by compression, since the feature which generates a given set of pure "Similar" folds ("bending folds") cannot be more than one wavelength from the folded layer, (Ramberg 1963b). An example of such F3 folding is shown in Plate 17a from the Coire Ladhair Mhòr psammitic rocks in sub-area 1 (loc. A12-16; Fig. 6). The quartzo-felspathic rock close to the quartzite bands has folded incompetently with considerable thickening in the hinges. Very little thickening has occurred in the competent quartzite bands. Plate 17b is a further example of ptygmatic folding of competent quartzite bands in banded psammite from the same locality. Here a relatively thick quartzite band that has been isoclinally folded is refolded by open F3 folds with converging axial planes. The thin quartzite bands on the other hand form much tighter folds and the axial planes of these tight folds sometimes show extreme variations (Plate 17b). Ramberg (1963a) has demonstrated that initially a layer will deform by uniform compression prior to buckling and that thin bands of competent material will buckle under compression prior to the thick, less viscous, surrounding material. If compression continues, then the thick outer beds may themselves buckle. The thicker bands would form folds of greater wavelength than the thin bands and these folds would rotate the folds formed in the thin competent bands. Ramberg (1963) has pointed out that drag folds may be generated in this way. It is also apparent that if the initial orientation of the bands is oblique to the stress field, then local refolding of the earlier formed folds could occur (Loudon 1963; p.14).

Another effect of varying viscosity is illustrated in Plate 16b. These F3 minor folds have formed in alternating pelitic and semipelitic rock. The following is a possible explanation of the tension effects seen in the competent bands:-

(i) Flexure of the highly viscous psammitic bands with attendant crenulation of the less viscous pelite.

(ii) Further folding achieved by plastic flow in the pelitic rocks.

(iii) The more viscous semipelitic rock could not thicken in the hinges as readily as the pelite and, therefore, the increasing deformation in the pelite bands created tension in the semipelitic bands. Boudinage occurred in the more viscous bands and where complete breaks occurred, continued folding of the less viscous bands could occur.

ii) Major Folds.

The following is an account of the geometry of the major folds developed during the third fold movement. Passing reference is made to the influence of the second folds on the geometry of the third folds, but a detailed account of their inter-relationship is given in a later section (pp. 129-149). The nomenclature for the major third folds is as follows:

J	Coire Ladhair Mhòr Antiform
K,L	Glen Gluitanen Folds
M	Glen Forslan Synform
N	Loch na Bioraich Antiform
O	Loch na Bioraich Synform
P	Cruach à Ghaill Fold
Q	Coire na Taothuirt Fold
R	Meall Buidhe Antiform
S,T	Meall Buidhe Folds
U	Meall Buidhe Synform
V,W	Coire Dubh Folds

Coire Ladhair Mhòr Antiform - J

This antiform of sub-area 1 refolds the nose of the F2 closure A described on page 52, and causes extensive folding of the Coire Ladhair Mhòr psammitic rocks, together with the adjacent Glen Moidart striped-pelitic rocks. Its axial plane trace is shown on Map II and the trend of 10 degrees has been drawn on the basis of convergence of bedding-schistosity and S_2, together with the vergence of the F3 minor folds.

From diagram 1B of Fig. 7 it can be seen that the F3 minor axial planes trend from NNE to NNW. This variation is due primarily to the development of minor conjugate and "M" shaped folds. Although both sets can be measured in this area, the NNE trending folds are better developed than those whose axial planes trend NNW and the structural data indicates that the major fold in this area has developed only along the NNE trend.

Minor F3 fold axes vary in attitude due to superposition of F3 on the previously folded surface. However, they are clustered around a point on the calculated axial plane - striking 10 degrees with vertical dip - to give a mean plunge of approximately 75 degrees towards 190 degrees. Since the fold closes to the south it is therefore antiformal.

Considerable variation in the style of the F3 folds occurs, but they are typically short limbed and in the pelitic rocks form a moderately tight to open mica crenulation, similar to that shown in Plate 16a. F3 minor folds in the Coire Ladhair Mhòr psammitic rocks are not well developed and are only common where thin quartzite bands have been ptygmatically folded, (see p. 78). Since F3 minor folds are not common in the north of sub-area 1, it has not been possible to extend the axial plane trace further than is shown on Map II. Also F2 minor folds are not strongly refolded in the north of sub-area 1 and, therefore, J probably dies out to the north of the refolded closure A. Extension of J to the southwest would carry the closure into the ground west of the area mapped. This area has been mapped in detail by Howkins (1961), who did not recognise this closure. From inspection of Howkins' maps it is apparent from the disposition of the lithological units that J probably extends just into his area and dies out rapidly. Correlation between the area mapped by Howkins and that mapped by the writer is discussed in detail on pages 157-164. Also the geometry of sub-area 1 is further elucidated in discussion on the relationships between the second and third fold movements (see pp. 143-145 also Fig. 8).

Glen Gluitanen Folds - K and L

The contact between the Glen Moidart striped-pelitic rocks and the Beinn Gàire psammite trends NE along the ridge of Bealach Gainmheach to the extreme NE of Glen Gluitanen (Map I). Exposure at this point is poor and the actual contact for the most part is unexposed. However, the approximate position of the contact can be ascertained and, at the head of Glen Gluitanen, the Beinn Gàire psammite swings round to the north and forms a closure as the swing continues round to assume a SW trend. The contact is not seen in the low ground of the Glen, but is exposed on the slopes just north of the Moidart River. Here the trend is NNW and, therefore, the contact must swing round in Glen Gluitanen as shown on Map I. The contact continues NNW on to the high ground at the northern edge of the area mapped. Here it swings sharply counter-clockwise and strikes to the SW. Along this strike the exposure again becomes poor, but the contact can be approximately located as it swings round to trend EW and then continues to swing clockwise until it strikes NNE at the northern edge of the area. Bedding-schistosity trends in the Beinn Gàire psammite in sub-area 2 reflect this variation in the trend of the lithological contact; however, it is only weakly reflected in much of the Glen Moidart striped-pelitic rocks, since here the bedding-schistosity is transposed and the foliation measured is primarily S_2 and S_3. Surprisingly few minor structures have developed in the psammite and it is difficult to be certain of structural relationships in this area. F2 and F3 minor folds are common in the striped-pelitic rocks, but their axial planes are predominantly sub-parallel. It has not been possible, on the basis of these minor structures, to prove conclusively whether the closures outlined by the lithological boundary are of F2 or F3 age. However, F2 minor folds have been mapped in the psammitic rocks of the western closure, (K on Map II) where they are sub-isoclinal, with their axial planes remaining sub-parallel to the bedding-schistosity around the closure. Therefore, this fold is post-F2. Also in the striped-pelitic rocks immediately southwest of the contact, F3 minor folds trend NE and refold F2 minor folds. The closure K is, therefore, considered to have formed during the third fold movement. Such evidence is not available for the closure to the east (L on Map II), where no F2 minor folds have been seen moving round the closure. However, to the north of the area mapped, F2 and F3 minor folds have been recognised by Clark (1961). The axial planes of the F2 folds follow the bedding-schistosity which is trending ESE. These F2 minor folds are refolded by F3 minor folds trending NNE. The closure L apparently dies out in the ground mapped by Clark, but the evidence of the minor structures leaves little room to doubt that the closure L can be other than an F3 fold.

The closure K at the lithological boundary is slightly synformal since the bedding-schistosity at the closure dips steeply (85 degrees) to the NE. However, north of the area mapped and to the southeast in the striped-pelitic rocks, the foliation and bedding-schistosity around the closure dip to the SW, and therefore the fold is predominantly antiformal. Also F3 minor fold axes in this area plunge fairly steeply (50 to 80 degrees) to the SE. F3 minor axial planes adjacent to K vary from vertical to 70 degrees SE and the mean axial plane dips steeply to the east. Exposure to the SW of the closure K is extremely poor and the available data does not allow confident extension of the axial plane trace further than is shown on Map II.

The plunges of the F3 minor fold axes adjacent to the axial plane trace L are variable since many F2 minor folds are developed in this area. However, the majority dip down the axial planes suggesting that the major closure is a neutral fold with an axial plane dipping approximately 70 degrees ESE. No minor F3 folds have been recognised on the ground immediately south of the Moidart River and the foliation at this point has an uniform trend NE. The closure, therefore, is thought to die out at this point.

The two closures outlined by the lithological boundary to the east of L in Glen Gluitanen cannot be identified since the ground is practically unexposed. However, the vergence of the F2 minor folds seen in this area does not change across the

Glen and these closures are, therefore, probably associated with the third fold movement. Further elucidation of the geometry of this poorly exposed ground will have to await a detailed mapping of the ground to the northeast of Glen Gluitanen.

Glen Forslan Synform - M

The Glen Forslan synform is a complex structure since it has been superimposed on a surface which has been previously intensely folded by F2 mesoscopic folds and their attendant minor folds. Later folding by F4 minor folds has also been detected and these have caused local distortion of the F2 and F3 structures. Also F3 minor conjugate folds are developed, thus giving rise to variations in the trend of the minor fold axes and axial planes.

Diagram 5B of Fig. 7 illustrates the variation in trend of the poles to minor F3 axial planes for this area, from NNE to NNW. In the few instances where the dip is not near vertical, this is apparently due to refolding during the fourth fold movement. Although minor conjugate and "M" folds are common, on the basis of the vergence of the minor folds and convergence of S_s and S_2 only the NNE trend can be detected here on a major scale. Diagram 5C of Fig. 7 illustrates the varying attitudes of the F3 minor fold axes, none of which are steep and the change from a shallow plunge north to a shallow plunge south occurs through the horizontal. F3 minor fold axes adjacent to the axial plane trace of M show variations from 40 degrees towards NNE through to 50 degrees towards SSW. However, the majority plunge to the NNE at approximately 30 degrees. The associated minor folds are sometimes broad open structures and, where they cross the tighter recumbent F2 minor folds, an "egg-basket" effect often occurs. Tight F3 folds are also seen especially in the north of sub-area 5 and these have a similar style to many of the minor F2 folds. Open mica crenulation is commonly associated with the F3 minor folds seen in the pelitic rocks. In the psammitic rocks, thin laminations are often folded into corrugations, the crests of which show some degree of thickening.

The synform occurs on the refolded northern limb of the major second closure B, described on pages 54-60 . At the southern extremity of the axial plane trace of M, the boundary between the Beinn Gàire psammite and the Glen Moidart striped-pelitic rocks indicates that the fold here is an open monocline. North of the boundary, adjacent to the axial plane trace, the monocline tightens up to an open synform which becomes steadily tighter to the north. In the extreme north of sub-area 5 the F3 minor folds again become broad open structures and in sub-area 6 very few minor F3 folds are seen. The synform apparently dies out in the north of sub-area 5 and does not extend into sub-area 6.

Loch na Bioraich Antiform - N

This structure in its southern extent is a broad monocline as seen in the southeast corner of sub-area 5. The fold tightens up to the north to form an open antiform, the axial plane trace of which can be followed to the northeast corner of sub-area 5. The axial plane trace N, drawn on the Structural Map (Map II), has not been extended into sub-area 6 because there are too few measurements of minor F3 structures available in this area. However, several minor F2 structures are refolded by minor F3 folds in sub-area 6 and the broad open warping of the contact between the Beinn Gàire psammite and the Glen Moidart striped-pelitic rocks is probably due to weak F3 folding. The regional orientation of the F3 minor folds for sub-area 5 has previously been discussed (see pp. 85-86). Measurements of the orientation of F3 minor folds adjacent to N give axial plane orientations from 190 to 170 degrees, with dips from 60 degrees east to vertical. The NNE trending minor folds are best developed and convergence of bedding-schistosity indicates that the axial plane trace of the major fold trends between 5 and 10 degrees. Fold axes are dispersed but tend to cluster about a trend of 30 degrees towards 10 degrees, which lies on a mean axial plane striking at 5 degrees with a dip of 80 degrees east.

Loch na Bioraich Synform - O

Bedding-schistosity and foliation in sub-area 7 have a dominant NE trend related to the Druim an Laoigh F2 closure B. However, the northern limb of B has been refolded by a broad open synform, which can be correlated with the F3 minor structures.

Where this synform refolds B, the NE trend is deflected through E-W to WNW and NW (Map II). Poles to F3 minor axial planes vary from NNE to NNW (Fig.7 - 7A) and, as in sub-area 5 (see p. 85), this variation is apparently due primarily to the development of F3 minor conjugate and "M" shaped folds. Foliation and bedding-schistosity trends seen on Map I demonstrate that only the trend just east of north is developed on a major scale. F3 minor axial planes are all steep and give a mean vertical axial plane. The F3 minor fold axes are variable but form a maximum, whose centre lies on the mean axial plane and gives an approximate plunge of 40 degrees towards 5 degrees. Beta diagrams prepared from measurements of foliation and bedding-schistosity adjacent to the axial plane trace of N give a concentration of beta axes centred approximately at 40 degrees towards 5 degrees.

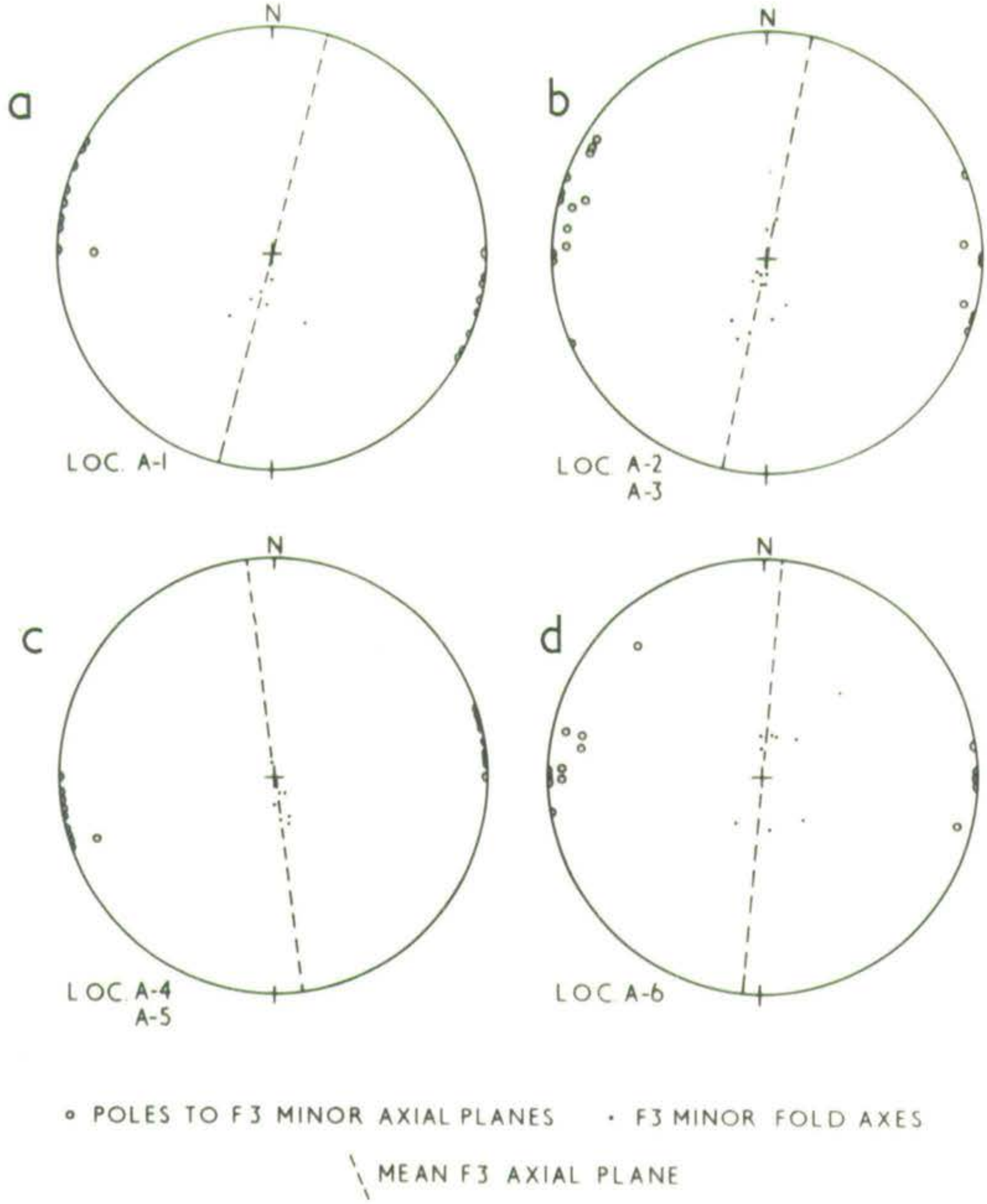
The closure dies out to the north and south. Only the northern limb of B has been refolded and so N would appear to die out in the core of B. North of Loch na Bioraich few minor F3 folds have been recognised and the closure cannot be extended on the basis of convergence of bedding-schistosity. However, in the extreme north of sub-area 6 the bedding-schistosity forms an irregular pattern that closes to the north with shallow dips to the south. F2 minor folds are folded around this closure, which is therefore thought to be related to the third fold movement. The few F3 minor folds that have been recognised in sub-area 6 are open folds with moderate to shallow plunge. In order to completely understand the geometry of this sub-area, the better exposed ground to the east will have to be mapped. However, the available data suggests that the third folds N and O recognised in the Loch na Bioraich area degenerate to broad basin and dome structures in sub-area 6 and their shallow plunge to the north - observed in sub-area 5 - swings through the horizontal to plunge gently south in sub-area 6.

Cruach à Ghaill Fold - P

Map I illustrates the tight nature of this closure. The relative thicknesses of the pelitic and psammitic units across the axial plane trace are close to the true thicknesses, since the fold axis has a near vertical plunge, except at its northern extremity across Glen Forslan. The fold is best developed in sub-area 8 and it is here that the location of the closure is well outlined by the disposition of the psammitic and pelitic units, thus allowing an accurate comparison of the attitude of the major structure with that of the associated minor structures.

Diagrams 8A, 8B and 8C of Fig.7 illustrate the general geometrical relationships for sub-area 8. Poles to foliation and bedding-schistosity lie on a great circle, whose beta axis plunges very steeply SSE and this is in agreement with the general distribution of F3 minor fold axes. Poles to F3 minor axial planes are near horizontal and vary in trend from NE to NW, giving a mean vertical axial plane striking N-S. By further

FIG. 11



CRUACH À GHAILL F3 FOLD - P

breaking down this data, it can be shown that the variation in the orientation of the F3 minor fold axial planes is mainly due to changes in the orientation of the major axial plane, and also due in part to the generation of F3 minor conjugate folds. Fig. 11 shows the orientations of F3 minor fold axes and poles to axial planes for the various localities along the major axial plane trace. Where the major axial plane crosses the south shore of Loch Shiel (loc. A1; Fig.11a, also see p. 35), the mean axial plane calculated from the trend of the F3 minor folds strikes at approximately 15 degrees and is vertical. Fold axes in this axial plane plunge at near 75 degrees towards 195 degrees. Small minor conjugate and "M" shaped folds are developed in this area, giving rise to variations in axial plane trend from 0 degrees to 30 degrees. However, the larger minor folds trend just east of north and are tight single closures. In the variable open folds an open mica crenulation is developed, but in the tighter folds the crenulation is also tight and is often accompanied by a crenulation cleavage. The open folds can be seen to tighten up into the more regular tight folds with attendant thickening at the hinge. No refolding occurs between the tight and open structures and there is no reason for considering them to be of separate generation.

North from Loch Shiel along the axial plane trace (loc. A2, A3; Fig.11b), the NNE minor axial plane trend is at first maintained but this gives way to a N-S trend in A3 and, in the north of A3, a NNW trend develops. Very few minor conjugate folds are seen in this area. Where the swing to N-S occurs, the minor folds are only developed in the core of the major closure and these are tight with short limbs. Considerable thickening of pelitic bands occurs at the hinges of the minor folds, but only slight thickening occurs in the psammitic rocks. The plunge of minor fold axes varies, but a steep plunge (85 to 60 degrees) to the south is generally maintained (Fig.11b).

From Loch Shiel to the north of A3 the axial plane trace of P is completely within the Achnanellan pelitic rocks. The plunge is predominantly steep to the south and hence the closure is a synform.

In the north of A3 the pelitic rocks become interbanded with thick bands of psammite (1 to 3 feet across). This zone of interbanding continues north for 2200 feet to just south of Lochan ã Mhuilinn (loc. A4-3; Fig.6), where it is in contact with the Beinn Gàire psammitic rocks. This gradational zone is shown on Map I and it demonstrates the considerable thickening of the hinge which has occurred here (further discussed on pp. 20-21). The transition from pelite to psammite is accompanied by a marked change in style of both the major fold and its associated minor structures. The tight near-Similar folds seen in the Achnanellan pelitic rocks become more open in style as the rock becomes steadily more psammitic. The major fold in the pelitic rocks has a hinge zone of often only a few yards and this is a zone of intense tight folding. In the psammitic rocks the hinge becomes a zone of large open folding, with symmetrical folds extending across an average distance of approximately 300 yards.

The trend of the major axial plane trace in the north of A3 is maintained in A4 and A5 (Fig. 11c). Poles to F3 minor axial planes are well clustered and give a mean vertical axial plane striking 172 degrees. Minor fold axes are near vertical, with an average plunge of approximately 80 degrees towards 172 degrees and, therefore, the closure is still a synform.

Stereogram d of Fig. 11 demonstrates the fairly constant trend of minor F3 axial planes in locality A6. The trend of just west of north in A4 and A5 has swung around to trend just east of north at approximately 5 degrees. There is also some variation in dip, but a mean near vertical dip is maintained. The minor fold axes show a variation in plunge and this is due to superposition of the F3 closure on the F2 Druim an Laoigh closure C. F3 minor fold axes swing through the vertical to plunge steeply to the south, where they cross F2 minor folds. However, where the major F2 and F3 axial plane traces intersect, the F3 minor fold axes maintain a steep plunge to the south. Bedding-schistosity and S_2 also dip southwards at this point and hence the F3 closure is synformal. In the north of A6 the F3 minor fold axes are all plunging to the north and, therefore, the closure at this point is antiformal.

North of A6 the ground drops steeply down into Glen Moidart, where exposure is extremely poor. North of the Moidart River there is no evidence for the continuation of the Cruach à Ghaill closure P and, therefore, P must die out, be cut out by a slide, or change its axial plane trend. The first suggestion is most unlikely since the closure is very strong south of the Moidart River and there is no evidence to demonstrate the existence of a slide. The structural data of sub-area 3 suggests that there has been a swing in the axial plane trace P to the NNE and that the closure seen on Sròn Dubh an Eilich (Maps I & II) can be correlated with the F3 Cruach à Ghaill closure.

In sub-area 3 only two sets of minor structures have been recognised. The early structures can be correlated with the F2 structures of adjacent sub-areas. These early structures have been refolded by minor folds of varying style and trend, but the variation in trend cannot be correlated with the variation in style. Diagram 3B of Fig.7 illustrates the variation in strike of F3 minor axial planes from NE to NNW and the moderate variation in dip. The mean axial plane strikes approximately 10 degrees and dips 80 degrees E. The variation of the late minor folds can often be seen in a single outcrop and in such cases there is no evidence of refolding. Where the varying trends occur together minor conjugate and "M" shaped folds are developed. Mica crenulation accompanies all these minor folds and, when varying trends occur together, one trend of crenulation grades into the other; they have never been seen to cross or refold one another. These minor folds are, therefore, considered to be of the same generation and are correlated with the regional third fold movement. The predominant style of the F3 minor folds is that of small, moderately open structures. The shape of the hinge varies considerably with rock type, being broad where the rock banding is relatively thick (more than 3 or 4 inches), and narrow (chevron) where the banding is thin.

On Sròn Dubh an Eilich (loc. B9; Fig.6) convergence of bedding-schistosity is well developed. F3 minor axial planes cross this convergence, but the F2 minor axial planes follow the convergence. Therefore, the closure is F3, (Map IV). Although the F3 minor axial planes vary, their mean trend is sub-parallel to the trend traced out by the convergence of the bedding-schistosity. In the north of sub-area 3, the convergence of bedding-schistosity and S_2 give way to a strong NNE trend, which is predominantly sub-parallel to S_2. The axial plane trace of P can only be drawn with certainty as far as the south of sub-area 2. Minor folding continues in sub-area 2 and extreme variations in the minor F2 axes occur as a result of refolding. However, no major F3 folds have been detected in the Glen Ulgary area and the closure apparently dies out in this area. F3 folding in sub-area 2 has been discussed in detail on pages 82-85 .

In sub-area 3 the F3 minor fold axes and lineations are variable as shown on stereogram 3C of Fig. 7 . The variation in attitude of the axes is controlled by the variation in attitude of S_s. South of Glen Ulgary the F3 minor fold axes predominantly have a moderate plunge SSW and the closure is synformal. On Sròn Dubh an Eilich (Maps I & II) they momentarily swing through the vertical and the closure becomes antiformal, with moderate to shallow plunge NNE. SSW of Sròn Dubh an Eilich the fold again moves through the vertical to become synformal with moderate plunge to the SSW, across Glen Forslan. North of Glen Forslan the ground is unexposed where the extrapolated axial plane trace would be expected to lie. Only a few F3 minor folds have been recognised on either side of this area, but they have axes plunging northwards and, therefore, the continuation of the closure is probably antiformal.

Maps I and IV show that S_s and S_2 in the Glen Moidart area are converging towards an axial plane trace trending approximately NNE across the unexposed ground and that this convergence to the south swings round to indicate an axial plane trace trending approximately N-S. On this evidence the axial plane trace of the Cruach à Ghaill closure P has been extrapolated NNE across the unexposed ground to the closure on Sròn Dubh an Eilich.

Coire na Taothuirt Fold - Q

This large fold has played a major role in the evolution of the geometry of the area in that it has strongly refolded the Druim an Laoigh F2 closures B and C. It is complementary to the Cruach à Ghaill F3 closure P whose eastern, southeast trending limb, is folded about Q.

The axial plane trace of Q extends from the shores of Loch Shiel in sub-area 11, north to the northern boundary of sub-area 9. Stereograms 9B, 9C, 11B and 11C of Fig. 7 illustrate the orientations of the F3 minor structures in these sub-areas.

In both sub-areas the typical variation in F3 minor axial planes is present. This variation is in part due to the development of minor conjugate folds, but is also due to weak refolding by F4.

The south of sub-area 11 is poorly exposed and only a few measurements of F3 minor folds have been observed. However, the poles to bedding-schistosity and foliation give a statistical beta axis of 82 degrees towards 120 degrees and, therefore, the closure in this area is an antiform. Also convergence of bedding-schistosity and S_2 indicates that the axial plane trace trends N-S.

The northern part of sub-area 11 is well exposed and a complex geometry is apparent. Minor F2, F3 and F4 folds are ubiquitous and complex interference patterns arise where the three sets of minor structures occur together. However, the F4 minor folds only gently warp the F2 and F3 minor structures. The mean F3 axial plane strike is 170 degrees with a dip of approximately 80 degrees E. The F3 minor fold axes adjacent to Q and south of the F2 closure C are variable, but the majority plunge steeply to the south (60 degrees - 80 degrees). Immediately north of C the axes swing through the vertical and then plunge steeply north. This change in plunge of the minor F3 axes across an F2 closure well illustrates the effect of superposition of folds on a previously folded surface. The steep plunge to the north is maintained in sub-area 11 and the closure is synformal. Where the axial plane trace of Q crosses the F2 axial plane trace B, variation in the F3 minor fold axes again occurs, but since B is sub-isoclinal in this area and its axial plane dips steeply to the N and NE, the F3 minor fold axes do not generally show a reversal in plunge across B. From stereogram 9B of Fig. 7 it can be seen that the mean F3 axial plane for sub-area 9 strikes N-S and dips approximately 80 degrees east. F3 minor fold axes, shown in stereogram 9C, are dispersed along the mean axial plane, but display a definite maximum of approximately 70 degrees towards 36 degrees. This steep NNE plunge is also in good agreement with the π diagram for poles to S_s (Fig.7- 9A). It is, therefore, concluded that the Coire na Taothuirt closure is a synform in sub-area 9.

In the north of sub-area 9, the open style of Q seen in the south tightens up and the closure becomes sub-isoclinal. Here the axial plane trace of Q is sub-parallel to the axial plane trace of the F2 closure B. Minor F3 folds are developed on the limbs of the fold and the vergence changes across the core. However, the F3 minor folds do not tighten up as the major closure becomes sub-isoclinal and they remain moderately open structures, which refold the sub-isoclinal F2 minor folds. It is concluded from this that the main closure here was generated during the second fold episode and that the effect of the third fold episode has been to refold the pre-existing structure (further discussion on pp.133-135). F3 minor structures die out in the extreme north of sub-area 9 and in the south of sub-area 4 the vergence becomes variable and the axial plane trace Q cannot be extended north of sub-area 9.

From the bedding-schistosity trends (Map I) it would appear that this closure extends southwards across Loch Shiel and that the Meall Buidhe antiform R is the southern extension of the closure Q. However, in order to correlate these two closures across Loch Shiel it is necessary to infer a change in trend from generally N-S, observed both to the north and south of the Loch, to north-east across the unexposed ground beneath the Loch. This does seem unlikely, although not impossible, in an area where the observed F3 folds are known to vary in trend. The other possibility, of course, is that a post-F3 fault has displaced the rocks in the Loch Shiel area. This possibility is discussed in detail on pages 111-114.

The relationships between the second and third fold movements in sub-areas 9 and 11 are discussed on pages 133-135. Also, the geometry of the F3 deformation south of sub-area 9 and the significance of Q are discussed later on pages 137 - 138.

Meall Buidhe Antiform - R

West of the summit of Ben Resipol the Meall Buidhe antiform is outlined on the surface by the Ben Resipol Psammite (Maps I & II). The axial plane trace of the antiform can be followed from the southern edge of the area mapped due north through sub-area 13 into sub-area 14.

In sub-area 13, F2 and F3 minor folds are ubiquitous and F4 minor folds are locally developed. F2 minor folds are refolded about the antiform and the F4 minor folds maintain a constant trend across the axial plane trace of the antiform. F3 minor axial planes are sub-parallel to the major axial plane trace, as outlined by the convergence of bedding-schistosity and S_2 (Maps I & IV) and, therefore, the antiform must be related to the third fold movement. Stereograms 13B and 13C of Fig. 7 illustrate the orientations of the poles to F3 minor axial planes and that of the F3 minor fold axes for sub-area 13. F3 minor axial planes vary from NNE to NNW and the calculated mean axial plane is vertical and strikes N-S. Some of the variation is due to refolding by minor F4 folds, but primarily it is due to the development of F3 minor conjugate folds. F3 minor fold axes are only weakly dispersed and give a mean axis orientation of approximately 60 degrees towards 180 degrees, thus confirming that the closure is an antiform.

F3 minor folds are well developed in the south of sub-area 13. In the Resipol psammite the folds are broad open structures, but in the pelitic rocks the folds show extreme variations in style. However, the dominating feature of all the F3 minor folds is that very little thickening of the crests occurs and many die out rapidly. An open mica crenulation accompanies the minor folds developed in the pelitic rocks and in the tighter structures a strong crenulation cleavage is often developed. These features indicate that the closure is predominantly concentric in this area. No marked thickening of the Resipol psammite is seen at the hinge of the antiform and this fact supports the contention that folding has taken place primarily by a flexural mechanism. The closure steadily opens northwards and in the north of sub-area 13, adjacent to the F2 synform I, the fold apparently dies out completely. However, the foliation trends shown on Map I indicate that the closure in fact has not died out, but that it has been displaced approximately 1300 feet to the east. This displacement could be due to post-F3 sliding, but since disharmonic F3 folding is common on the mesoscopic scale, it is thought that original disharmony is the most likely explanation. Also no other evidence has been found in this area to support a slide hypothesis.

This small antiform to the east of the Meall Buidhe Antiform R cannot be extended north into sub-area 14 due to lack of exposure. However, it apparently dies out, since it cannot be detected in the north of sub-area 14 where exposure is fairly good.

Sub-area 14 is a zone of extremely complex geometry. The Lochan na Ceardaich F2 antiform E recognised in this sub-area has previously been described (see pp. 65-66). Bedding-schistosity is transposed here and is primarily sub-parallel to S_2. F3 minor folds vary in trend from NNE to NW and the varying axial planes often intersect to form conjugate folds. In the northeast of sub-area 14, F4 minor folds refold the F3 and F2 minor folds. Unfortunately, the southern part of this sub-area is virtually unexposed and extrapolation across the unexposed area is exceedingly difficult. However, the trend of the F2 minor axial planes from the east to the west of the ground swings from a NE trend through E-W to trend NNW and the folding of these minor axial planes is visibly due to the superposition of the variable F3 folds. The vergence of the F3 minor folds is variable and two F3 closures can be inferred (Map I). One trends approximately north-south in the west of sub-area 14 and, from the foliation trends, is a tight fold closing to the south. The other trends NW and foliation trends suggest that this fold is an open fold closing to the north. The exact orientation of this open fold cannot be ascertained and, since it causes only local variation in the F2 minor axial planes and cannot be detected SE of sub-area 14, no axial plane trace has been drawn on the Structural Map (Map II). The N-S trending axial plane trace has caused a major swing in the F2 minor axial planes and it is this trace that is apparently related to the Meall Buidhe antiform R. Although the F3 minor fold axes vary the majority plunge steeply to the SSE and S and the closure is still antiformal.

Meall Buidhe Synform - S and Antiform - T

These folds are small discontinuous structures developed in the Achnanellan striped-pelitic rocks of Meall Buidhe. The axial plane trace of S trends at 5 degrees and extends for approximately 3080 feet, while that of T trends SSE for approximately 2600 feet (Map II). The folds are little more than undulations developed on the eastern limb of the Meall Buidhe antiform R. The dominant trend of this limb in sub-area 15 is NE with s steep dip to the SE (Fig. 7-15A). Poles to F3 minor axial planes vary within the sub-area from NNE to NNW, indicating a mean axial plane striking 170 degrees and dipping approximately 80 degrees W. F3 fold axes are only weakly dispersed and have a mean plunge of 65 degrees towards 190 degrees (Fig. 7-15B, 15C).

Adjacent to the axial plane trace of S only a few F3 minor folds have been mapped and these are variable due to local refolding by F4. However, the general trend of F3 minor axial planes is in agreement with the trend of 5 degrees indicated by the convergence of bedding-schistosity and foliation (primarily S_2). The dip of F3 minor axial planes adjacent to S vary from steep west to steep east and the mean axial plane is approximately vertical. A possibly more exact orientation is given by the relative orientations of S_2 foliation and bedding-schistosity adjacent to the estimated axial plane trace of S. These S-surfaces when plotted on a stereogram are symmetrically disposed about an axial plane, with a strike of 5 degrees and a dip of 85 degrees west, and they define a beta axis of approximately 60 degrees towards 190 degrees. F3 minor folds adjacent to T are also variable, but define a mean axial plane with a strike of approximately 170 degrees and a dip of 80 degrees west. Minor F3 fold axes have a fairly consistent trend and define a mean axis of 70 degrees towards 200 degrees.

The differing axial plane trends and attitude of the fold axes of these two closures are reflected in the varying attitude of the minor folds. Where these minor folds appear together, no refolding of one trend by the other occurs. One trend grades into the other and a conjugate fold is formed. Mica crenulation is well developed in the F3 minor folds and the attitude of this crenulation varies with the attitude of the minor folds.

The Achnanellan striped-pelitic rocks in sub-area 15 are rhythmically interbanded with thin semipelitic and psammitic bands (average 1 to 2 inches thick). F3 minor folds formed in this rock type show some thickening at the hinge in pelitic bands, often accompanied by weak crenulation cleavage, whereas little or no thickening at the hinge occurs in the semipelitic and psammitic bands. The F3 folds S and T are, therefore, considered to be modified flexural folds.

Meall Buidhe Synform - U

This F3 synform is restricted to the Resipol pelitic rocks in the southwest corner of the area mapped and does not extend north into the Resipol psammite. The closure is complementary to the Meall Buidhe antiform R and probably becomes important to the south of the area mapped. F3 minor folds are well developed in the Resipol pelite adjacent to the axial plane trace of U. The folds are moderately tight with short limbs and pelitic bands thicken in the hinges.

F3 minor fold axial planes adjacent to U vary from NNE to NNW giving a mean axial plane trend of approximately 175 degrees, with vertical dip. The major axial plane trace has been drawn on the Structural Map (Map II) on the basis of vergence of the minor folds and convergence of S_2 and S_s and is in agreement with the mean trend of the F3 minor axial planes. F3 minor fold axes show slight variation, but indicate a mean fold axis of 65 degrees towards 170 degrees and, therefore, since U closes to the north, the major fold is a synform.

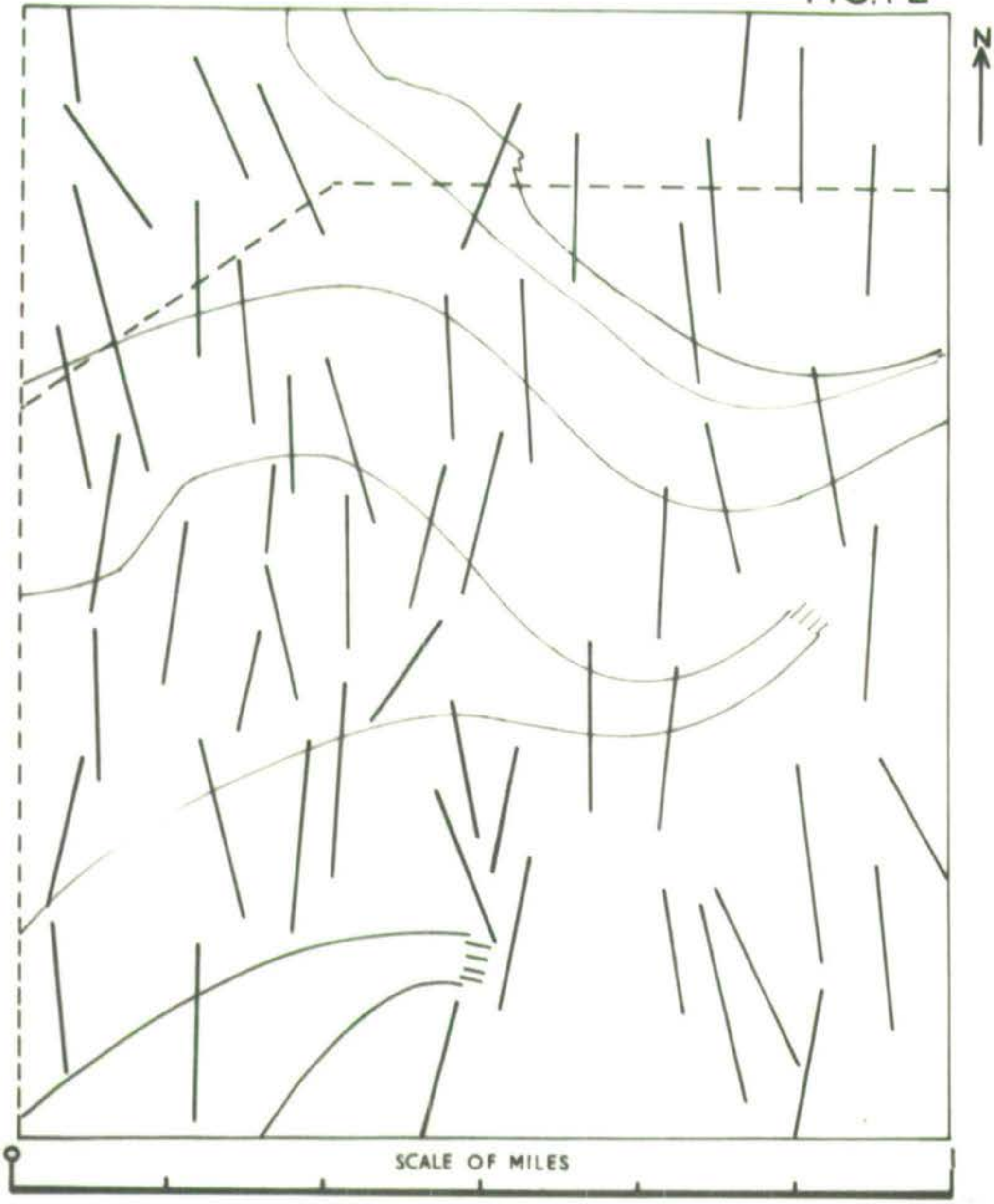
The F3 synform has been superimposed on the southern limb of the Ben Resipol F2 synform I, but since U dies out in the core zone of I, the F2 synform has not been appreciably refolded. However, wherever the F3 minor folds are superimposed on the F2 minor folds, considerable refolding of the F2 structures occurs.

Coire Dubh Synform - V and Antiform - W

The Coire Dubh synform is a complex structure, the axial plane trace of which extends from the south of sub-area 18, trending just west of north, through sub-area 16 to the shores of Loch Shiel. It is complementary to the Meall Buidhe F3 antiform R and folds its eastern limb. F2 minor folds and the Ben Resipol F2 synform are refolded by this closure, which is of undoubted F3 origin.

Sub-area 18 is of particular interest in that the varying attitudes of the F3 minor folds and their relation to the F3 major folds can here be readily demonstrated. From stereogram 18B of Fig.7 it can be seen that the poles to F3 minor axial planes vary from NNE to NNW. Fig. 12 shows the

FIG. 12



AXIAL PLANE TRENDS OF F-3 MINOR FOLDS IN SUB-AREA 18

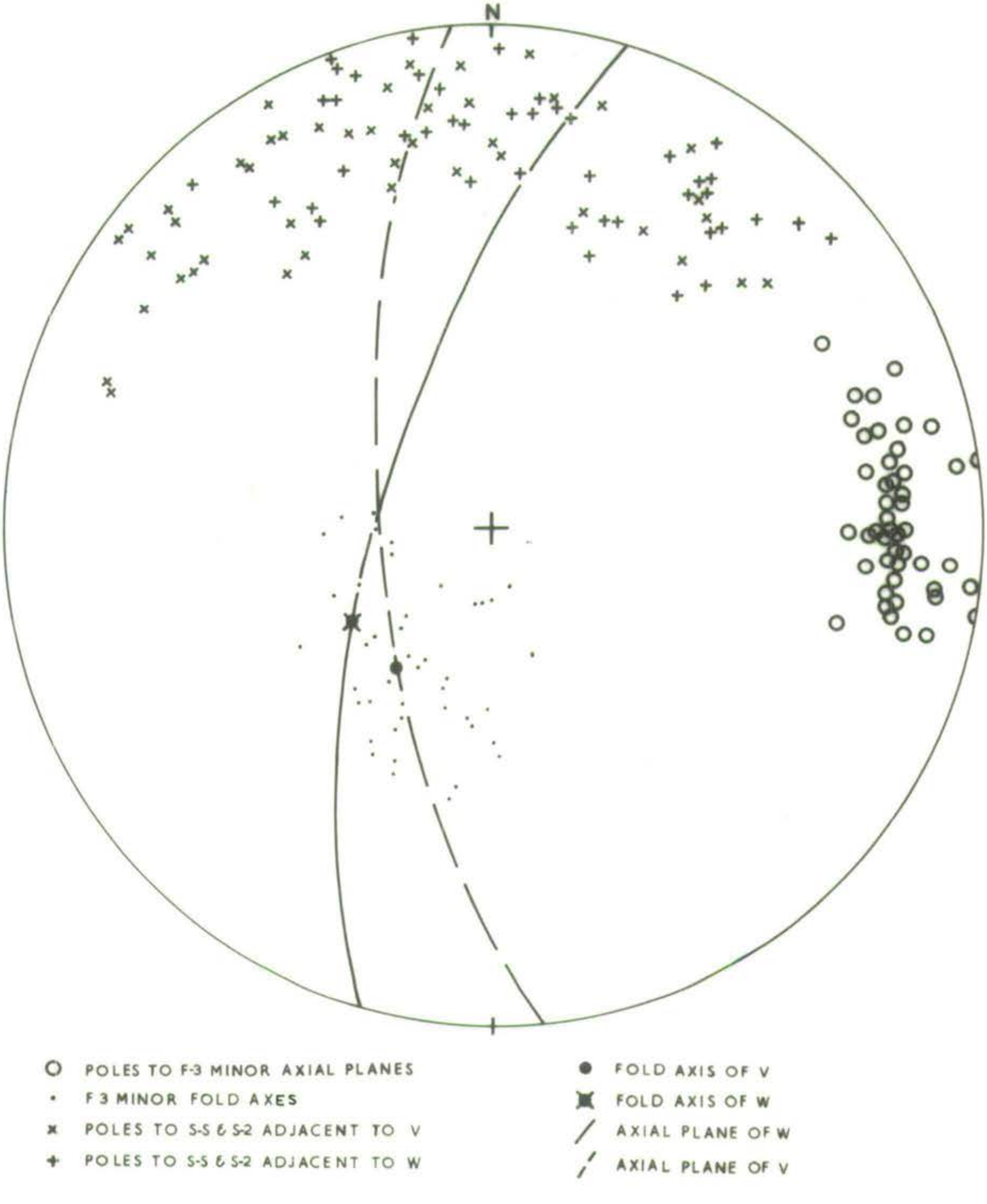
Strike of F3 minor fold axial planes
Trend of lithological boundaries

distribution of the F3 minor axial planes for sub-area 18 and it can be seen that the various orientations are distributed at random throughout the sub-area. Two axial plane traces can be drawn that are related to the change in vergence of the F3 minor folds. One trends at 170 degrees - the Coire Dubh synform V; the other trends at approximately 10 degrees - the Coire Dubh antiform W.

The minor folds trending NNE to NNW refold F2 minor folds, but are themselves never refolded (no F4 in this sub-area), and as is the case throughout the area mapped, these minor folds form conjugate folds whenever the varying trends occur together. Also, quite commonly the N-S trending axial planes split to form the NNE and NNW trending axial planes (eg. Plate 13b). It is, therefore, quite clear that these minor folds of varying trend are of the same generation and can be correlated with the F3 fold episode.

Since the orientation of the F3 minor folds varies, it is not possible to derive the exact axial plane and fold axis orientations for V and W directly. However, despite the variation in strike of the minor axial planes, a constant dip of near 70 degrees is maintained with only a few exceptions (Fig. 7 - 18B) and, therefore, the dips of V and W must both be approximately 70 degrees west. On this basis the axial plane trace of V and W can be projected to a horizontal plane and hence the true strike is known. The strike for the axial planes is 175 degrees and 18 degrees for V and W respectively. The

FIG.13



COIRE DUBH FOLDS-V&W

plunge of the fold axes has been calculated from π diagrams, compiled from measurements of the trend of bedding-schistosity and foliation (S_2) adjacent to the axial plane traces V and W. B^W= 62 degrees towards 238 degrees and B^V= 62 degrees towards 218 degrees. B^W lies on the great circle for the calculated axial plane of W and B^V lies on the great circle for the calculated axial plane of V. Also B^W and B^V both lie within the zone of concentration of F3 minor fold axes. Fig. 13 illustrates these geometric relationships.

The axial plane traces of V and W do not intersect in the field, but the intersection of the two great circles on a stereonet representing the attitude of the axial planes, gives a line of intersection with an attitude of 70 degrees towards 284 degrees. The possible significance of this intersection is discussed on pages 129-133.

The Coire Dubh antiform W dies out within sub-area 18, but the synform V extends into sub-area 16, where its axial plane trace is completely contained within Achnanellan striped-pelitic rocks. From the foliation trends (Map I), it can be seen that the fold appears to tighten up to the north of sub-area 18 into sub-area 16. Minor F3 folds are well developed in sub-area 16 and are generally tighter than those seen in sub-area 18. Where the closure becomes extremely tight an axial plane cleavage is developed, giving rise to S_3 (loc. D13; Fig. 6). F2 minor folds are also well developed and when F3 minor folds are superimposed on them they are strongly refolded.

Stereogram 16C of Fig. 7 shows the variation of poles to F3 minor fold axes and it is of interest to compare this stereogram to stereogram 18C of sub-area 18. The spread of the poles to F3 minor axial planes is approximately the same in both diagrams, but in 16C instead of being centred about a N-S axial plane trend, they are now centred about a NNE axial plane trend. There has also been a change in the mean dip from 70 degrees west in sub-area 18 to 80 degrees west in sub-area 16. There are no extensively developed lithological boundaries here and bedding-schistosity has been partly obliterated by the development of F2 and F3 axial plane cleavage. The thin discontinuous psammitic band in the north of sub-area 16, however, does give some guide to the style of this closure (Map I). The suggestion is that in the north the axial plane trace has split and trends of N and NW have developed. Poor exposure in this area does not permit the locating of these axial plane traces with any degree of accuracy and so they have been omitted on the Structural Map (Map II), but it is quite probable, in the light of the evidence of sub-area 18, that the spread of F3 minor axial planes here is due to the development of two major diverging axial planes. This suggestion is further supported by the fact that the variation in vergence of the F3 minor folds in the north of sub-area 16 (SW shore of Loch Shiel) is not compatible with the drawing of a single axial plane trace.

d. Fourth Fold Movement (F4)

Minor folds with axial planes trending ESE have been found to refold F2 minor folds and to gently warp F3 minor folds. Where F3 and F4 mica crenulations occur together, the F3 crenulation is distorted while the F4 crenulation maintains a constant axial plane trend. Only forty-five such minor folds have been clearly identified. They occur in all but six of the sub-areas and are most common in areas where F2 and F3 interference structures are well developed, eg. sub-area 9.

Vergence is determined by the pre-existing orientation of the foliation and bedding-schistosity with respect to the F4 axial planes and, therefore, may vary across pre-F4 closures. This occurs in sub-area 9, but the F4 minor folds here are small kink bands which have probably only caused gentle warping of the foliation and no major F4 fold is thought to exist at this point.

The following features characterise the F4 minor folds:-

(a) Many of the minor folds are kink bands with an associated open mica crenulation.

(b) Some have a style identical to many of the F3 minor folds, but whereas the F3 folds may have a tight crenulation or an axial plane cleavage, the F4 folds are always characterised by an open mica crenulation.

(c) The F4 mica crenulation is often developed in the absence of larger minor folds.

(d) In areas of refolding the F4 minor folds and associated crenulations maintain a near constant axial plane trend.

When all the poles to F4 axial planes are plotted on a stereogram, twenty form a group with vertical axial planes and trend from 120 to 90 degrees. Twenty-one poles show a similar strike but vary in dip from near vertical to 30 degrees. Four poles are dispersed. There are too few measurements to draw any positive conclusions about this variation. However, analysis of the F3 folds has illustrated the presence of conjugate folds and Paterson and Weiss (1962) have shown that kink bands may develop along conjugate shear planes prior to the formation of complete conjugate folds. Many of the F4 minor folds are apparently kink bands similar to those produced by Paterson and Weiss and the variation of the F4 minor axial planes may also be due to the development of conjugate sets. The F4 fold axes are widely dispersed and this is readily explained by the fact that F4 folds have been superimposed on the previously folded surface.

Examples of F4 structures are given in Plates 18a & b, 19a .

e. Faults and Joints.

No major faults have been observed in the area, but small displacements along approximately E-W trending joints have been noted. One such displacement is shown on the Geological Map (Map I) to the north of Glen Ulgary. The actual fault zone is not exposed, since a gully has formed due to differential erosion. However, the thinning psammite band (Map 1) can be traced northeast from sub-area 1 to the gully - which is approximately ten yards wide - reappearing to the north roughly 100 feet to the east.

East-west trending joints (mainly vertical) occur throughout the area and small discontinuous displacements along these joints are fairly common. They have been seen cutting across minor folds of each generation and are, therefore, apparently post-F4 in origin.

NNE-NNW and N-S trending joints are found in the psammitic rocks throughout the area. They are nearly vertical in most instances and are, therefore, sub-parallel to the F3 axial plane trends. Displacements of one or two feet commonly have been observed and the sense of movement along these joints is invariably in agreement with the movement sense of adjacent F3 minor folds. A pink discolouration of the psammite along the joints is a common feature and occasionally thin pegmatite sheets follow the joint trends. Plate 19b is an interesting example from sub-area 18, close to the core of the F3 Coire Dubh synform V. A concordant quartz vein has been folded, probably during the second fold movement and has been displaced along a N-S trending joint. Pegmatite has formed along the joint which has been displaced by movement along the bedding-schistosity. Adjacent to the pegmatite sheet, an open fold has developed that is apparently related to the third fold movement. An incipient shear plane has formed along the axial plane of this fold which in turn is parallel to the larger N-S jointing. This evidence suggests that the jointing is related to the third folds and that the joints formed prior to the cessation of tectonic activity in this area.

f. Correlation of Structures across Loch Shiel.

The Cruach à Ghaill F3 fold P cannot be recognised on the south shore of Loch Shiel in the Achnanellan striped-pelitic rocks. The closure is not distinct on the north shore of Loch Shiel and may be dying out at this point. Exposure on the south shore of Loch Shiel, at the western boundary of the area is poor but there is some evidence to suggest that the closure P can just be extended south across Loch Shiel and that it dies out at Achnanellan. F2 and F3 minor folds are exposed on the south shore of Loch Shiel at the western boundary of the area mapped. F3 minor folds are moving out of a fold closing northwards to the east; F2 minor folds are refolded by the F3 minor folds and trend approximately NE (Map II). Foliation at this point trends at 5 degrees and dips steeply to the west. However, directly to the south the foliation swings to the SSE and is related to the Meall Buidhe antiform R. West of the area mapped, the south shore of Loch Shiel is marshland and the few small exposures available indicate that the foliation trend has swung round to the SSE. No evidence of faulting has been found, either along the shores of Loch Shiel or on St. Finnan's Island (Fig. 2) and foliation trends suggest that the structure is continuous across the Loch at this point.

The Coire na Taothuirt F3 closure Q has been accurately traced to the north shore of Loch Shiel and the trend of F3 minor axial planes, together with the convergence of bedding-schistosity, indicates that the axial plane of the major fold trends N-S. There is no evidence to suggest that this trend changes on the north shore of the Loch. This large closure is obviously related to the Meall Buidhe F3 antiform R. However, the two closures cannot be joined unless a change in trend from N-S to NE is assumed to occur under Loch Shiel. The Meall Buidhe antiform R is a complex closure in the Lochan na Ceardaich area, on the south shore of Loch Shiel (see pp.98-101). F3 minor folds in this area have varying trends, but the mean trend is NNW rather than the NE trend that would be expected if the main closure were to swing to the NE across the Loch. Two possible explanations of this discontinuity may be suggested:

(a) Faulting has occurred under Loch Shiel.

(b) The folds are disharmonic in the Loch Shiel area. The first suggestion cannot be ruled out, but does seem rather unlikely since there is no direct evidence for extensive brittle movement in the rocks to the east and west of the narrows of Loch Shiel (Map I). The second suggestion does have some evidence to support it, viz. it has been demonstrated that disharmony occurs in the Meall Buidhe antiform and this is thought to be due to original disharmonic folding rather than post-F3 sliding or faulting (see pp. 100-101). Disharmony of F3 minor folds is extremely common throughout the area and this is especially true in areas where F3 minor folds are superimposed on larger F2 minor folds. Deflection of later structures where they cross earlier folds has been recorded elsewhere in the Moines (Ramsay 1958; Fleuty 1961; Dalziel 1963). Ramsay considered the deflections observed in Loch Monar in terms of the tightening up of the earlier fold at a late stage in the formation of the superimposed structures. Fleuty, on the other hand, concluded that the later structures formed with originally curved axial plane surfaces. The variations noted by Dalziel are related to mesoscopic structures and this writer concluded that the curvature of the later minor axial planes may be due to deflection of the less competent pelitic rocks around the more competent psammite bands in the core of the earlier minor folds.

In the Moidart-Sunart region there is ample evidence to demonstrate the fact that F3 minor and major axial planes have varying trends. For the most part the axial plane variations are thought to be due to original variation in trend, and these variations are thought to be related to the development of conjugate folds. However, variation on the mesoscopic scale, similar to that described by Dalziel, has also been recorded and the writer also considers these variations to be lithologically controlled. Variation in the F2 minor axial planes has been previously described in the Torran nam Mial area and here the mechanism would appear to be flattening of the pelitic rocks around the more competent psammitic rocks (see pp. 68-70).

The Beinn Gàire psammitic rocks will be in contact with the Achnanellan striped-pelitic rocks under Loch Shiel. It is suggested that movement may have occurred along this contact, due to a similar flattening effect as described in the Torran nam Mial area. Such movement may have continued late in the third fold movement and may perhaps have brought about the apparent discontinuity between the Meall Buidhe antiform R and the Coire na Taothuirt closure Q.

From the above discussion it is apparent that discontinuity of structure does occur across Loch Shiel, but that this discontinuity does not necessarily imply large scale faulting and may be due to disharmonic movement during the third fold movement.

g. Quantitative Study of Fold Style.

The geometry of Similar folds is such that the thickness of individual beds measured along a line parallel to the axial plane is constant, whereas the thickness measured at right angles to the bedding surfaces (or compositional banding) is variable. In the case of concentric folding, the thickness measured at right angles to the bedding surfaces will be constant. Ramsay (1962a) has recently examined examples of natural folds and found that many flexural folds show a degree of thickening at the hinge. De Sitter (1958) found that crustal shortening by flexure folding, other than flexural concertina folding, can never exceed 36 per cent. of the original length of the beds and suggested that further tightening of the folds could be achieved by a process of flattening. However, Ramsay found that thickening of beds in the hinge of folds often occurred early in deformation and well before the limbs became parallel to the axial plane. "Flattening" is defined by Ramsay as "the process of deformation whereby an original rock shape is plastically changed by compression. This compression results in contraction in a direction parallel to that of the principal compressive stress and in expansion at right angles to this in the direction of minimum stress". (Ramsay 1962a; pg. 313). Ramsay further found that perfect Similar folds are uncommon, but that folds of "general Similar type" are common, especially in zones of intense deformation and suggests that these folds are formed by a mechanism of differential flattening. Folds of "Similar type" are differentiated from modified flexure folds primarily on the basis of measurements parallel to the axial planes. In modified flexure folds Ramsay found that the hinge always is a zone of minimum thickness, whereas the thickness at the hinge of folds of "Similar type" can be either a maximum or minimum.

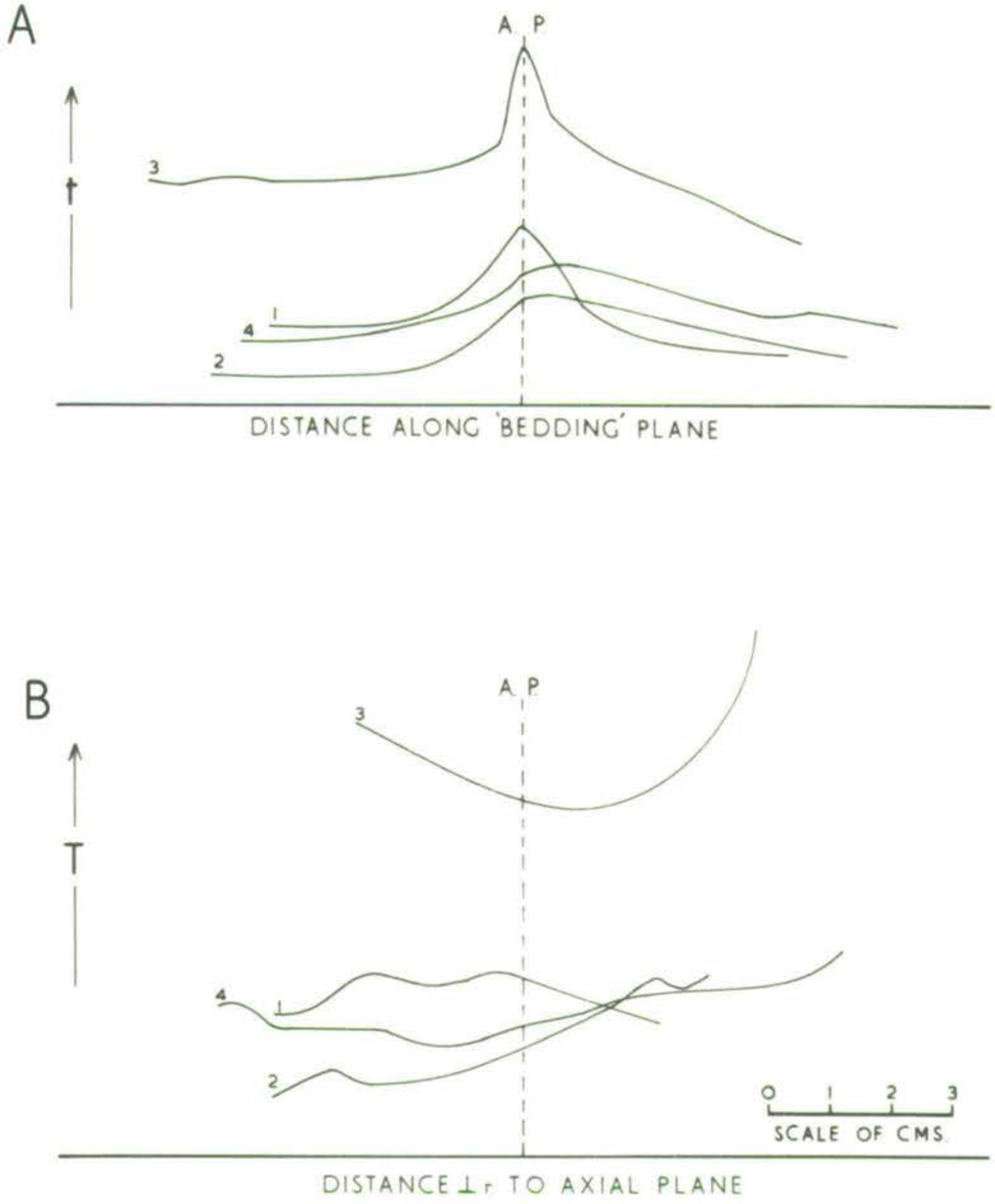
Measurements of several folds from the present area have been made. A few examples are given here in order to further elucidate the mechanism of deformation during the successive fold movements and to compare these results with Ramsay's classification.

First Folds: It has not been possible to obtain any suitable samples of F1 minor folds, but some pertinent observations from photographs and field sketches have been made. Since all the F1 folds seen are isoclinal, it would be of no avail to measure thickness parallel to the axial plane of these folds. Considerable increases in thickness of compositional banding towards the hinge usually occur and, therefore, the isoclinal folds cannot be pure flexure folds. At the same time, the F1 folds that are truly isoclinal cannot have originated solely by a mechanism of axial plane shear, since in the limiting case of "shear" folding, the limbs could only become sub-isoclinal. Isoclinal folds would, however, be the end point of a flattening mechanism.

<u>Second Folds</u>: Major and minor F2 folds seen in the area mapped vary in style from isoclinal to moderately open structures. Lithological marker horizons are not adequate to allow a quantitative study of style of the major folds, but several minor folds have been measured in detail. No true Similar or true Concentric folds have been found. All are a combination of Similar and Concentric styles.

The results of measurements of two typical F2 minor folds are graphically illustrated in Figs. 14 & 15 The first (Fig. 14) is drawn from measurements of various bands in the fold shown in Plate 24a and is typical of the moderately tight F2 folds seen in the Beinn Gàire psammite. (Band numbers marked on Plate 24a).

FIG.14



t THICKNESS OF BAND MEASURED NORMAL TO COMPOSITIONAL LAYERING

T THICKNESS OF BAND MEASURED PARALLEL TO AXIAL PLANE

F2 MINOR FOLD (PLATE 24a)

Band 1: Dominantly quartz and felspar with extremely small amounts of fine grained biotite. Some of this near microscopic biotite is oriented parallel to the axial plane and some sub-parallel to the compositional banding.

Band 2: Heterogeneous zone of pegmatite, with fine grained quartz-felspar and medium to fine grained biotite. Small asymmetrical folds have developed in the pegmatite, with axial planes and biotite parallel to the main axial plane. In places, the pegmatite has been slightly displaced along these mica cleavage planes (see p. 179).

Band 3: Somewhat thicker than bands 1 and 2, but of similar composition to band 1. The band has a well developed foliation parallel to the bedding-schistosity. However, numerous small mica flakes are oriented sub-parallel to the axial plane.

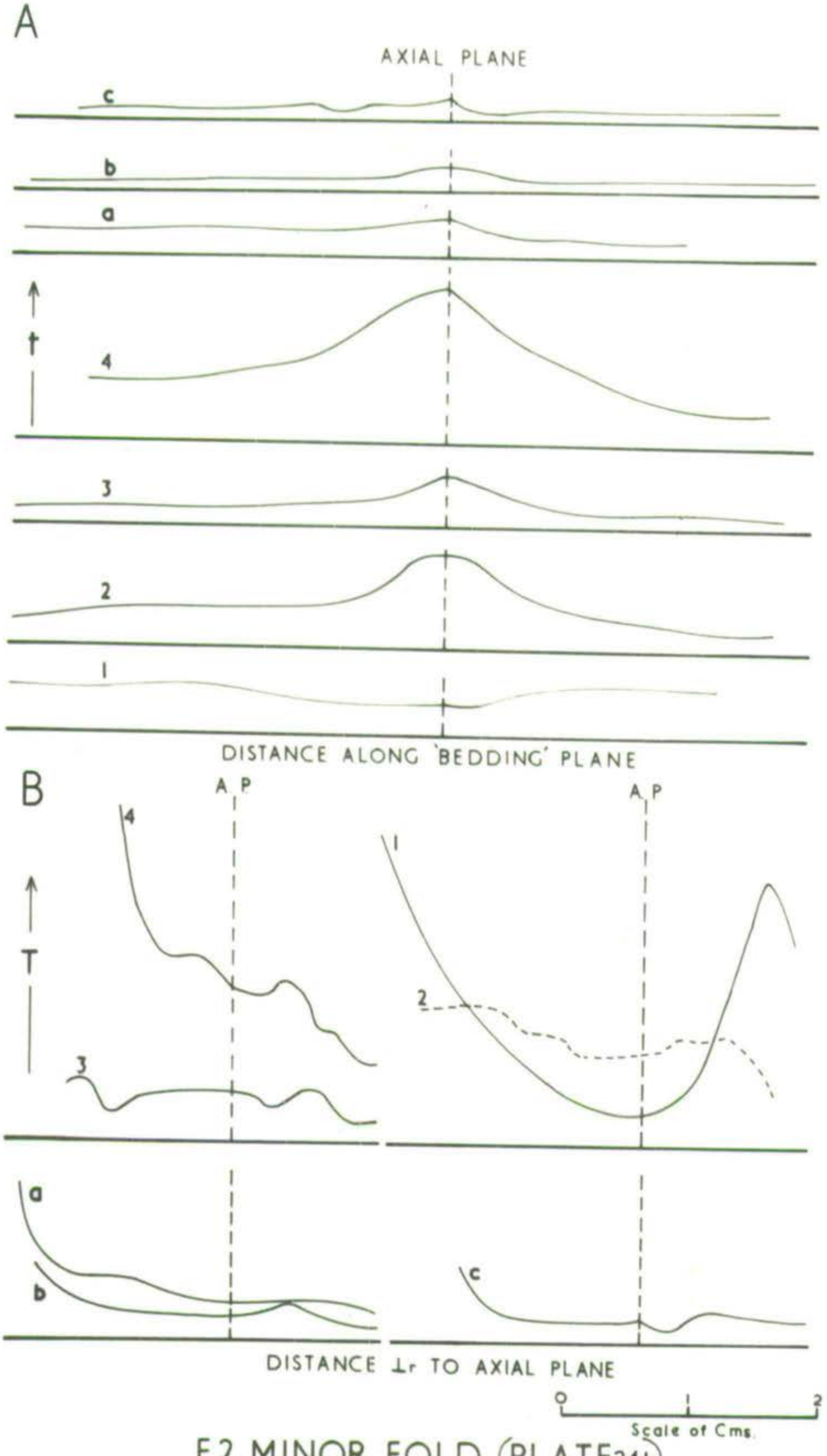
Band 4: Thinly interbanded micaceous and quartzo-felspathic material, together with a thin band of pegmatite.

Graphs 1 to 4 for measurements at right angles to the band surfaces (Fig. 14A) show that all four bands have thickened considerably at the hinge and, therefore, the fold has not deformed purely by flexure. Bands 1, 2 and 4 give relatively straight line graphs for measurements parallel to the axial plane (Fig. 14B), which suggests that these bands have probably deformed by shear or flow sub-parallel to the axial plane. However, band 3 - the thickest and most uniform band in the fold - shows a marked depression close to the hinge and, therefore, has not deformed in a pure Similar manner. The fact that the thickness in the hinge of band 3 is less than the thickness parallel to the axial plane on the limbs, suggests that this band has been more competent than bands 1, 2 and 4 during the deformation. A possible interpretation of these measurements is that the rock deformed in the first instance by flexure. Unit 3 was the band most resistant to flow and this resistance created areas of differential stress, which were taken up by passive flow or shear of units 1, 2 and 4.

It is difficult to classify the fold since bands 1, 2 and 4 indicate that the fold is nearly a "pure Similar" structure and band 3 indicates that the fold is a modified flexural structure. This evidence suggests that modified flexural folds may be flattened to such a degree that they resemble folds of Similar type. Since flattening appears to have played a dominant role in the formation of the fold, it is best classified as a fold of "Similar type". There can be little doubt, however, that some degree of flexure has controlled its formation.

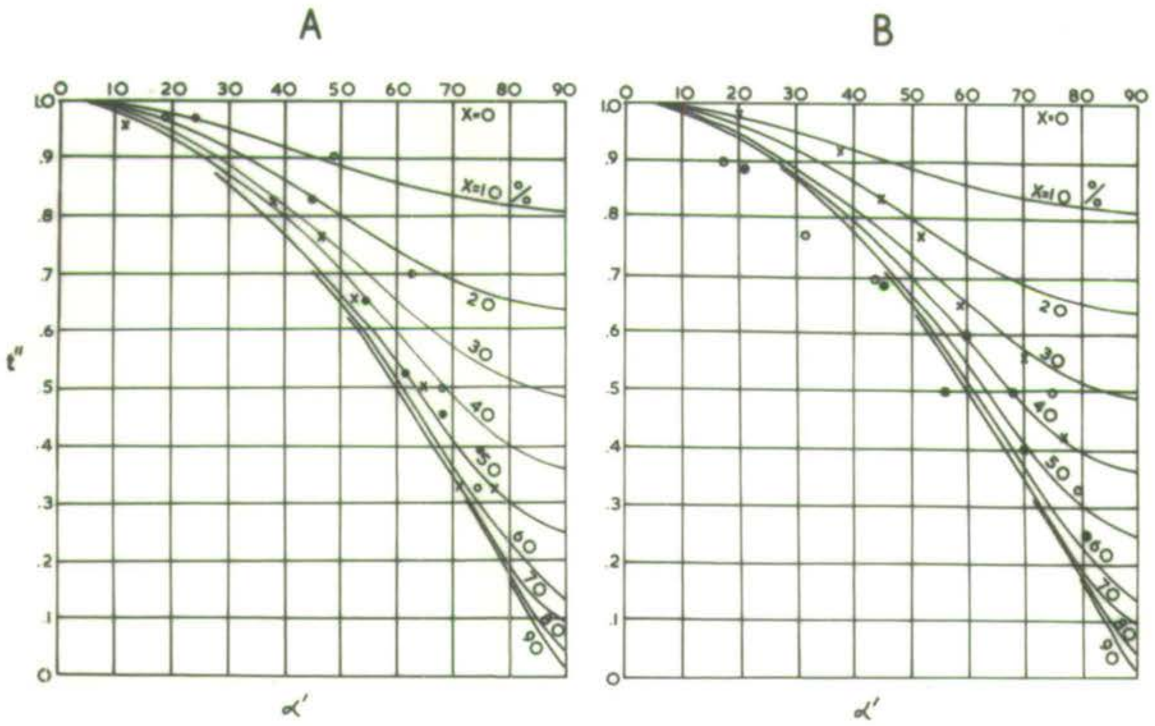
The second example is of a small F2 fold in a thin banded quartz-felspar-biotite gneiss. Measurements were made on an enlarged photograph of the sample, shown in Plate 24b and both psammitic and pelitic bands have been studied. No strong axial plane cleavage has been developed, but biotite in the thin micaceous bands has a weak preferred orientation sub-parallel to the axial plane. Also some quartz grains are elongated in the axial plane. Four psammitic bands and three thin micaceous

FIG. 15



F2 MINOR FOLD (PLATE 24b)

FIG.16



t'' = t' WHERE BEDDING DIPS AT α' / MEASUREMENT OF t' AT FOLD HINGE (RAMSAY 1962d)

x = PERCENT FLATTENING

A

- • BAND - 2
- x BAND - 3
- o BAND - 4

B

- x BAND-a
- • BAND-b
- o BAND-c

FLATTENING OF F2 MINOR FOLD (PLATE 24b)

bands have been measured and the results are shown in Fig. 15 (see Plate 24b for location of bands in fold). Measurements perpendicular to the compositional layering (Fig. 15a) give varying results. Bands 1 to 4 are primarily quartz and felspar with only minor amounts of fine grained mica. Bands 2, 3 and 4 show marked increase in thickness in the hinge, but band 1 is fairly uniform with slight decrease in the hinge. The thin micaceous bands a, b and c show slight increases in the hinge, but none are as great as the increase in thickness of the psammitic band number 4. Since all bands show variation in the hinge area this fold could not have deformed entirely by flexure.

Measurements parallel to the axial plane are shown in Fig. 15b. Variations occur in all bands, but the variation is only related to the hinge in the case of band 1. Such variations suggest that the fold is not pure Similar, but is probably of "Similar type". Since no strong axial plane cleavage has developed, the deformation probably was achieved by plastic flow of the bands rather than by shear.

A method for calculating the amount of flattening undergone by a modified flexural fold has been derived by Ramsay (1962a). The above F2 minor fold is apparently of "Similar type" and the amount of flattening may be expected to vary. The results of measurement of flattening in six bands of the F2 fold (example 2) are shown in Fig. 16 and it is apparent that considerable variation in the degree of flattening has indeed occurred. Variation in the amount of flattening also occurs in the first example.

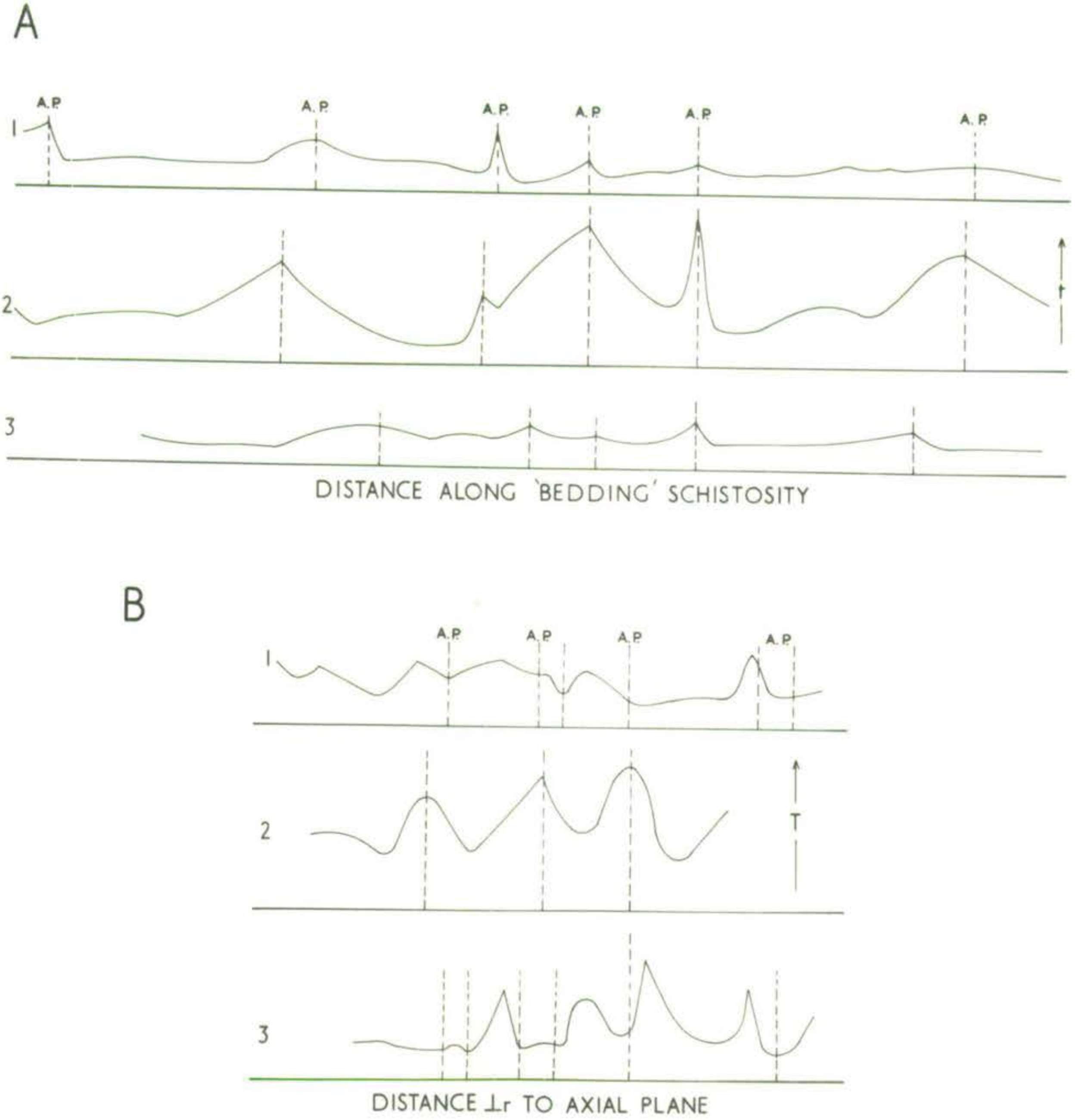
Two other F2 minor folds have been measured and they gave similar results to the two examples described above. Measurements have been limited to folds in dominantly psammitic rocks. In the pelitic rocks a strong axial plane cleavage usually accompanies the F2 minor folds and S_s is often only poorly defined. Where the dominant foliation is parallel to S_2 the faint outline of S_s may only have been a passive marker of the deformation. The shape of these folds may well be "pure Similar" but their generation would be dependant upon active folding in adjacent, less homogeneous, rock.

Third Folds: Several minor F3 folds and one major fold have been measured and the results suggest that the mechanism of folding is complex. The effects of flexural folding are apparently more pronounced in the third folds which have been measured than in the second folds.

The results from measurements of a typical F3 minor fold are given in Fig. 17. The sample is from the finely banded pelitic schists within the Beinn Gàire psammitic rocks and the minor folds are associated with the major Cruach à Ghaill F3 closure P (loc. A6-4; Fig. 6). Plate 25a is a photograph of this sample normal to the fold axis. The photograph was enlarged to enable accurate measurements to be made.

Two thin quartzo-felspathic bands have been measured, together with the somewhat thicker micaceous band sandwiched between them (Plate 25a for locations in fold). Figs. 17a & 17b

FIG. 17



t = Thickness of band measured normal to compositional banding

T = Thickness of band measured parallel to axial plane

F3 MINOR FOLD (PLATE 25a)

show the graphs resulting from measurements normal to the compositional banding and parallel to the axial plane respectively. Graphs 1 and 3 have been drawn from measurements of the two quartz-felspar bands. Measurements along the compositional banding of these two bands give fairly uniform lines with small peaks at the hinge zones; whereas measurements parallel to the axial planes show marked variations with both thinning and thickening occurring at the hinges. The fact that some thickening occurs in the hinges (Fig. 17a, 1 and 3) indicates that the bands did not deform completely by flexure. Also the extreme variation in measurements parallel to the axial planes (Fig. 17b, 1 and 3) suggests that a modified flexural mechanism predominated over folding by flow or shear parallel to the axial plane.

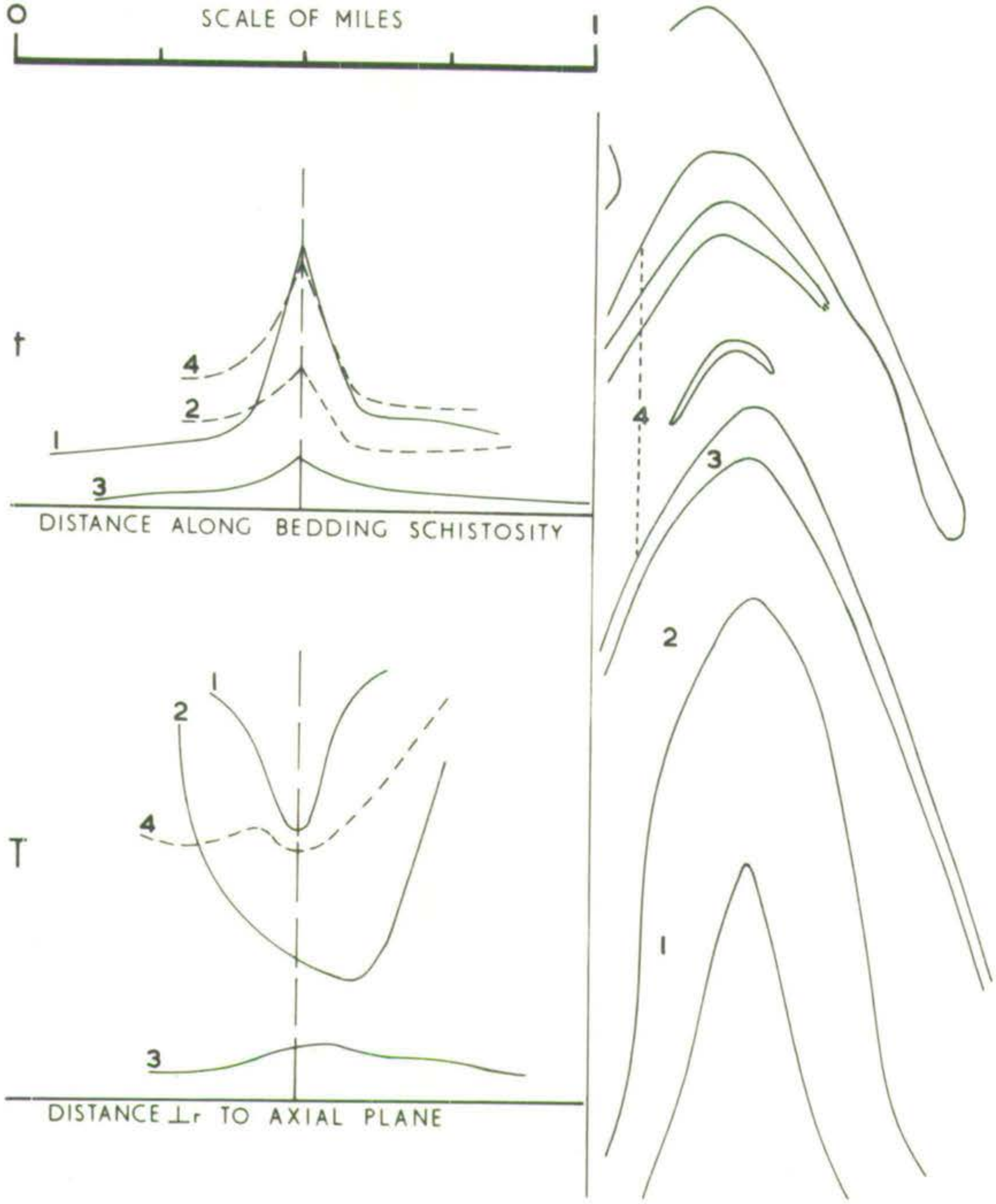
Graph 2 (Fig. 17) is drawn from measurements of the pelitic band sandwiched between the two quartz-felspar (psammitic) bands. Fig. 17a well illustrates the extreme variation in measurements along the compositional banding for the pelitic unit as compared to graphs 1 and 3 for the psammitic units. Extreme increases in thickness occur at the hinges of the pelitic unit indicating that the band has deformed by flow rather than by flexure. Fig. 17b shows that graph 2 is not a straight line for measurements parallel to the axial planes. In fact, extreme variation occurs with maximum values at the hinges and minimum values on the limbs. The implication from this is that although flow must have occurred, in the pelitic unit, it was not uniform.

It would appear that the less competent pelitic band has thickened at the hinges in order to accommodate the modified flexural folding of the more competent psammitic bands. This flow in the pelitic bands, with restricted flow in the psammitic bands, allows the folds which would otherwise die out rapidly to persist. With increasing flow in the competent bands the folds would closely resemble Similar folds. It is evident, therefore, that folds of near Similar style could be generated by the combination of flexure and flow.

Ramsay (1962a) found that folds formed by a modified flexural mechanism had suffered uniform flattening. None of the three bands measured from the above F3 minor fold gave consistent values of flattening. The structural analysis indicates that movement was complex during the third fold movement and that deformation was three dimensional. This implies that flow has occurred in both the plane normal to the axial plane and in the axial plane. If the F3 minor folds measured are in fact modified flexural folds, then the varying values of flattening may well be attributed to differential flattening in both the ab and ac planes of the folds.

The major third fold that has been measured is the Cruach à Ghaill fold P, shown on Maps I and II. The profile is very nearly a true section normal to the fold axis since the axis is nearly vertical in the area being measured (sub-area 8). Four rock units from sub-area 8 have been studied (Fig. 18).

FIG. 18



t THICKNESS OF BAND MEASURED NORMAL TO COMPOSITIONAL LAYERING
T THICKNESS OF BAND MEASURED PARALLEL TO AXIAL PLANE

F3 MAJOR FOLD - P

Number 1 is the gradational zone of rhythmically interbanded psammite and pelite (stratigraphic details on p. 21); number 2 is a flaggy psammite zone of the Beinn Gàire psammitic group; number 3 is a thin pelite unit within the Beinn Gàire psammite and number 4 is a thick zone of flaggy psammite with two macroscopic pelite units and numerous discontinuous mesoscopic pelitic bands. Fig. 18 illustrates the graphs drawn from measurements perpendicular to the bedding-schistosity and parallel to the axial plane. Units 1, 2 and 4 show marked increases in thickness perpendicular to bedding-schistosity and marked decreases in thickness measured parallel to the axial plane, towards the fold hinge. The asymmetry of units 4 and 2 reflects the variation in the axial plane trend and the fact that the limbs have not reacted uniformly to compression. Minimum values at the hinge for measurements parallel to the axial plane, together with maximum values for measurements perpendicular to bedding-schistosity, indicate that the bands have deformed by a modified flexure mechanism. Unit 3, however, gives a weak maximum at the hinge for measurements parallel to bedding-schistosity and, therefore, has a near Similar style. Mica crenulation with crenulation cleavage and some penetration cleavage has developed in this pelitic unit and it seems most likely that the unit has been folded passively by the more competent bands enclosing it.

The measurements of the Cruach à Ghaill fold P indicate that the lithological layering has played an active role during the deformation and that the fold probably formed by buckling of the layers together with flow or shear of particles within the individual layers. Measurements of the amount of flattening gave results varying from 30 to 70 per cent. and no single band gave uniform results. This fold appears to be a modified flexural fold and differential flattening is attributed to three dimensional deformation, together with varying reaction to compression due to the varying viscosities of the rock units.

Fourth Folds: It has not been possible to obtain samples of F4 minor folds suitable for quantitative study. The style of the minor structures has been previously discussed on pages 108-9 and field observations suggest that the F4 folds are primarily flexure folds. Kink bands are a common feature of the fourth fold movement and these undoubtedly formed by flexure. Some of the F4 folds, however, show thickening in the hinges and these are probably modified flexure folds, since they usually die out rapidly.

Discussion: The quantitative study has shown that none of the folds measured are "pure Similar" or "pure Concentric" folds. The F2 folds measured are primarily of "Similar type" and the F3 folds are "modified flexural folds". Ramsay finds the division between the two types of folding to be quite distinct in that flattening of flexure folds tends to be uniform, whilst flattening of folds of "Similar type" is usually not uniform, the hinges of the folds usually being zones of maximum or minimum flattening. The distinction in this area is apparently not as well defined, in that the modified flexure folds have not been modified by uniform flattening, but by differential flattening. It is not contrary to the evidence to suggest that the F2 folds may be extreme cases of modified flexure folds (see p. 118).

Ramsay agrees with the opinion of Gonzalez-Bonarino (1960) that shear folds cannot be generated by uniform plastic flattening as described by de Sitter (1954). Ramsay suggests that shear folds may be formed by differential flattening and that transmission of differential shear could give rise to pure Similar folds. This mechanism implies that pure Similar folds are generated by the formation of impure Similar folds. Ramsay also considers the generation of nearly true Similar folds to occur in regions where the rock reacts as a near homogeneous body and the individual rock bands exert little or no control on the wavelength or amplitude of the folds, (Ramsay 1962a; p.322). In the final analysis it is apparent that pure Similar folds can only form in rock which reacts as a homogeneous unit to stress. However, it is well known that active folding cannot occur in a homogeneous body as a result of homogeneous strain. Folds formed prior to the homogenization may, however, be passively folded or unfolded (Flinn 1962).

This evidence perhaps suggests that modified flexural folds may approach a Similar style and that pure Similar folds are only generated where the lithological layering is only a passive marker of the deformation. Ramberg (1959) has demonstrated experimentally that sheets of material enclosed in a less viscous body will deform by buckling when in the zone of compression. Ramberg has also pointed out that folds may form in a homogeneous body as a result of heterogeneous strain (Ramberg 1963b). By deforming multi-layered rectangular blocks consisting of two sets of alternating rubber sheets with unlike rigidity, Ramberg has been able to produce folds varying from quasi-concentric to Similar style and has concluded that variation in the style of folding of the rubber block was solely due to a change in stress distribution across the composite body (Ramberg 1962 and 1963b). Although the above experiments were carried out on elastic models, there is great similarity in buckling behaviour between elastic and viscous materials (Biot 1957). The results of Ramberg's experiments appear to indicate that variations from concentric to Similar styles of folding are to be expected in areas where rocks composed of layers of varying viscosities have been deformed. It also follows that Similar folds observed in natural rocks may not have formed by shear movements parallel to their axial planes.

The F2 minor folds of Similar type observed in the Moidart-Sunart region have suffered some movement parallel to their axial planes. This is demonstrated by the observation of the displacement of S_s and S_1 by movement parallel to the axial plane cleavage S_2. However, it cannot be demonstrated that shear parallel to the axial planes was the initial cause of folding. On the contrary, the evidence presented above suggests that some degree of flexure occurred (see p. 118). Once the lithological layering has been disrupted by a penetration cleavage, it is difficult to understand how reactivation of these surfaces could take place. It is, therefore, suggested that the folds probably deformed initially by a combination of flexure and plastic flow controlled by the varying viscosities of the layers and, that the axial plane cleavage was imposed after the initial folding had occurred. Where the rock was of nearly uniform viscosity the folds would be of nearly Similar type and folding would progress passively. Where a sufficient viscosity difference existed to allow active folding the folds formed could be of near Similar type or quasi-concentric. As deformation progresses, active folds may become passive as the fold axes rotate away from a principal direction (Flinn 1962). Any folds which may have actively formed as flexural or modified flexural folds may later be passively opened or closed and it is probable that such folds would assume a near Similar style.

The F3 folds measured can be classified as modified flexural folds in that the varying viscosities of the layers apparently controlled the formation of the folds throughout the deformation. But it is apparent that the division between folds of Similar type and modified flexural folds in the Moidart-Sunart region is only a matter of degree.

h. Deformation of F1 by Later Structures.

The origin and significance of the F1 minor folds in the area mapped is problematical, since so few of these structures have been seen (see p. 46). The main evidence for tectonic activity prior to F2, apart from the few minor folds, is the fact that a pre-F2 foliation parallel to the lithological layering has been regionally developed (see pp. 47-48).

No lineations have been positively correlated with the first folds and the only real indication of the manner of deformation of the F1 isoclines comes from the shape of the later folds. Only F2 minor folds have been found refolding F1 folds and these are probably of "Similar type" (see pp. 116-120). In plate 4b a long limbed isoclinal fold is refolded by an open second fold with a fairly well developed axial plane cleavage. The F1 isocline has a rather weak foliation parallel to its axial plane (i.e. parallel to the bedding-schistosity). A mica crenulation is also developed in the F2 folds and this crenulation folds the F1 axial plane cleavage (S_1). Wherever the F3 structures have folded the bedding-schistosity no F1 minor folds have been recognised, but foliation parallel to the bedding-schistosity has been crenulated by the F3 fold movements.

The first fold movement is further discussed on pages 154-155 , where the results from this area are considered with reference to the results of recent work in adjacent areas.

i. Superposition of F3 on F2.

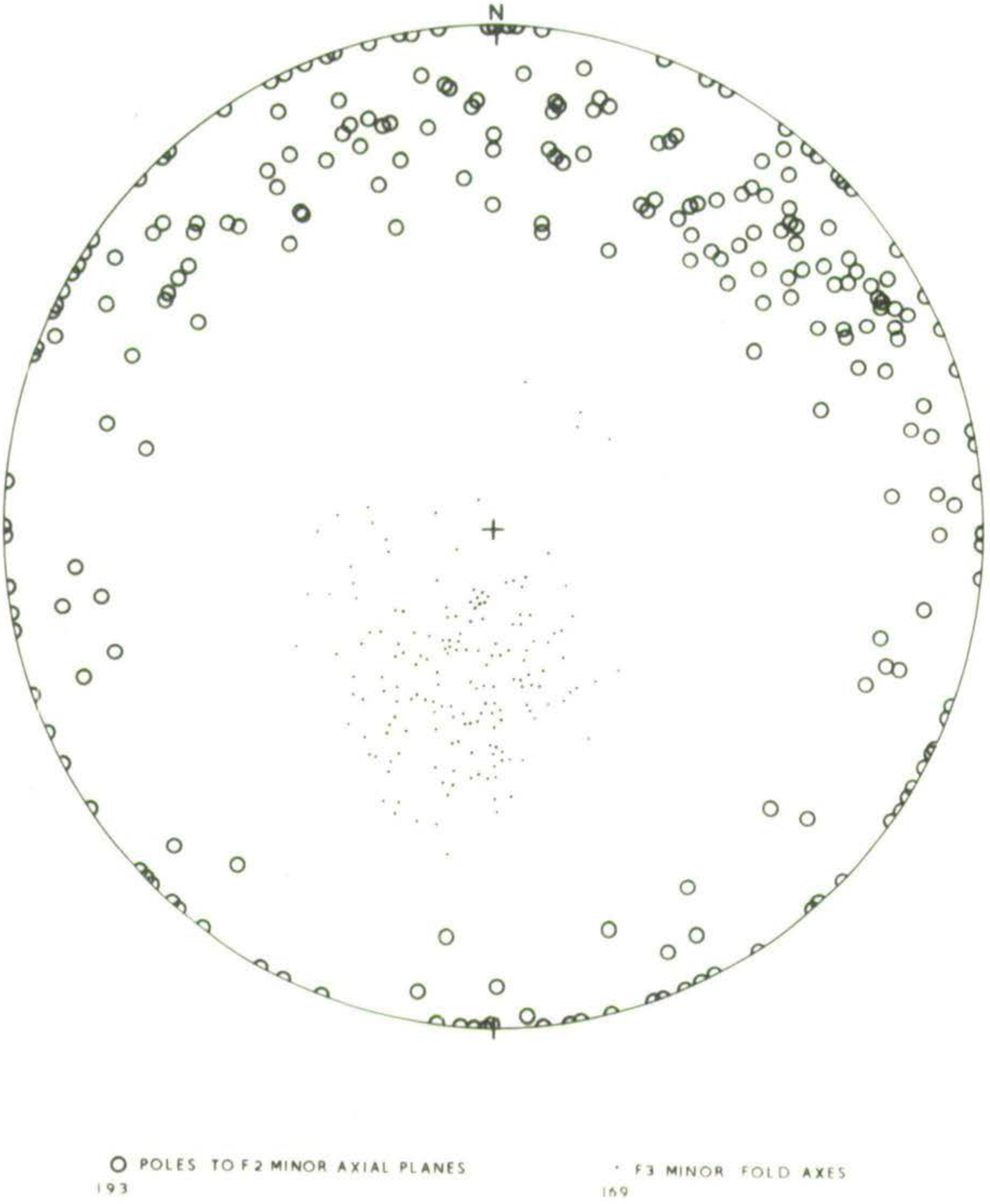
The geometry of the F2 and F3 structures has previously been described and some mention has already been made of the complex inter-relationships of these fold movements. In this section the effects of the superposition of F3 on F2 are studied in detail. Bearing in mind the geometry as a whole, for the purposes of this discussion it is convenient to divide the area into five units.

i) Sub-Areas 13 - 18.

The major folds of the second and third fold movements recognised in the ground to the south of Loch Shiel have previously been described. It was found that the F2 folds are sub-isoclinal and the F3 folds tend to be moderately open structures, with zones of local tightening.

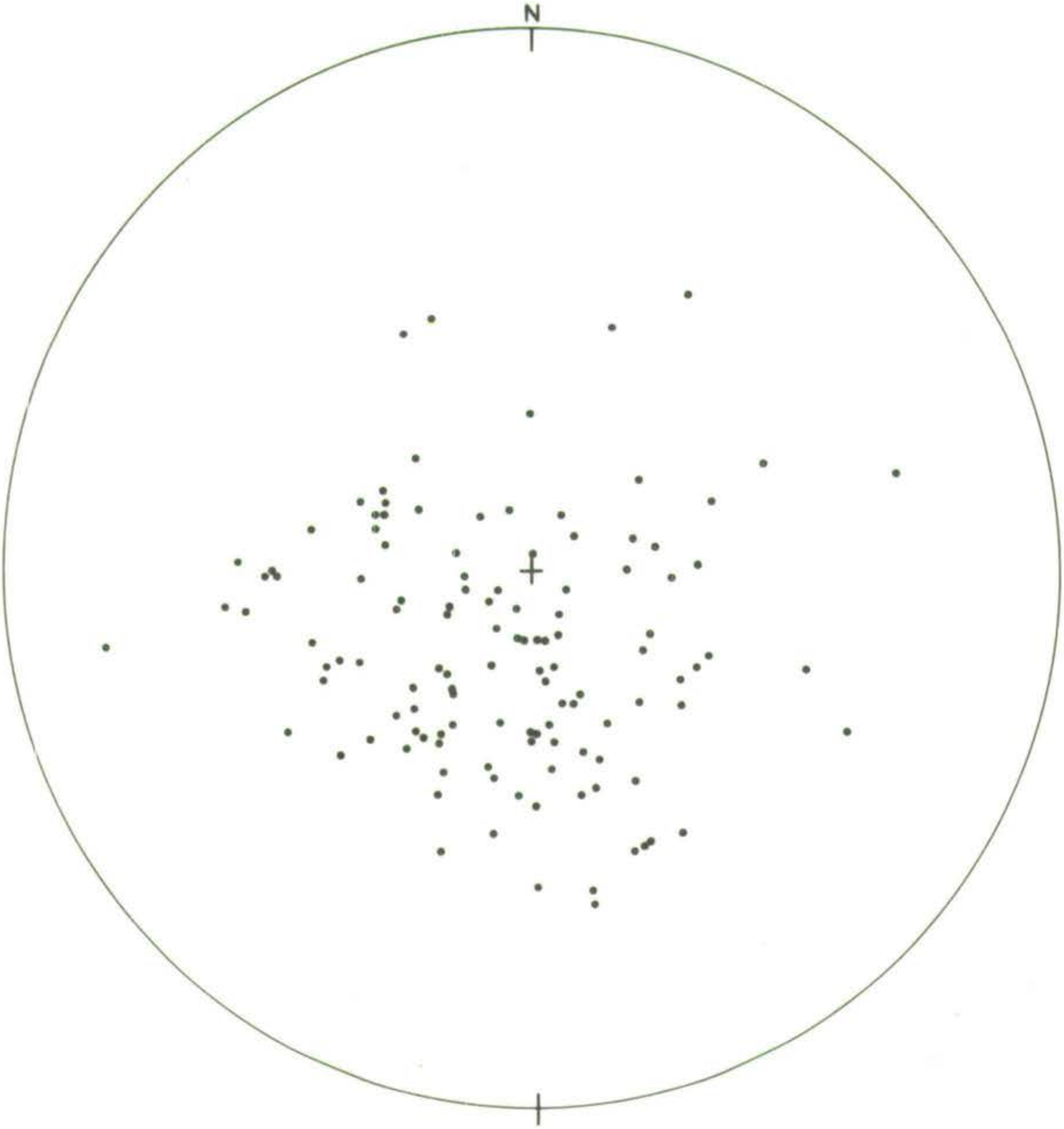
The poles to all F2 minor axial planes measured in this area have been plotted on a stereogram and are shown in Fig. 19 . They fall on a well defined great circle girdle. Also shown on the stereogram is the distribution of F3 minor fold axes and it can be seen that the beta axis of the great circle girdle lies within the cluster of F3 minor fold axes. The F2 minor folds have been refolded during F3 and, since the F3 minor fold axes are closely clustered around the axis of refolding of the F2 minor axial planes, the F2 folds are sub-isoclinal. Fig. 20 is a plot of all the F2 minor fold axes.

FIG.19



SUB-AREAS 13-18

FIG. 20



• F2 MINOR FOLD AXES
119

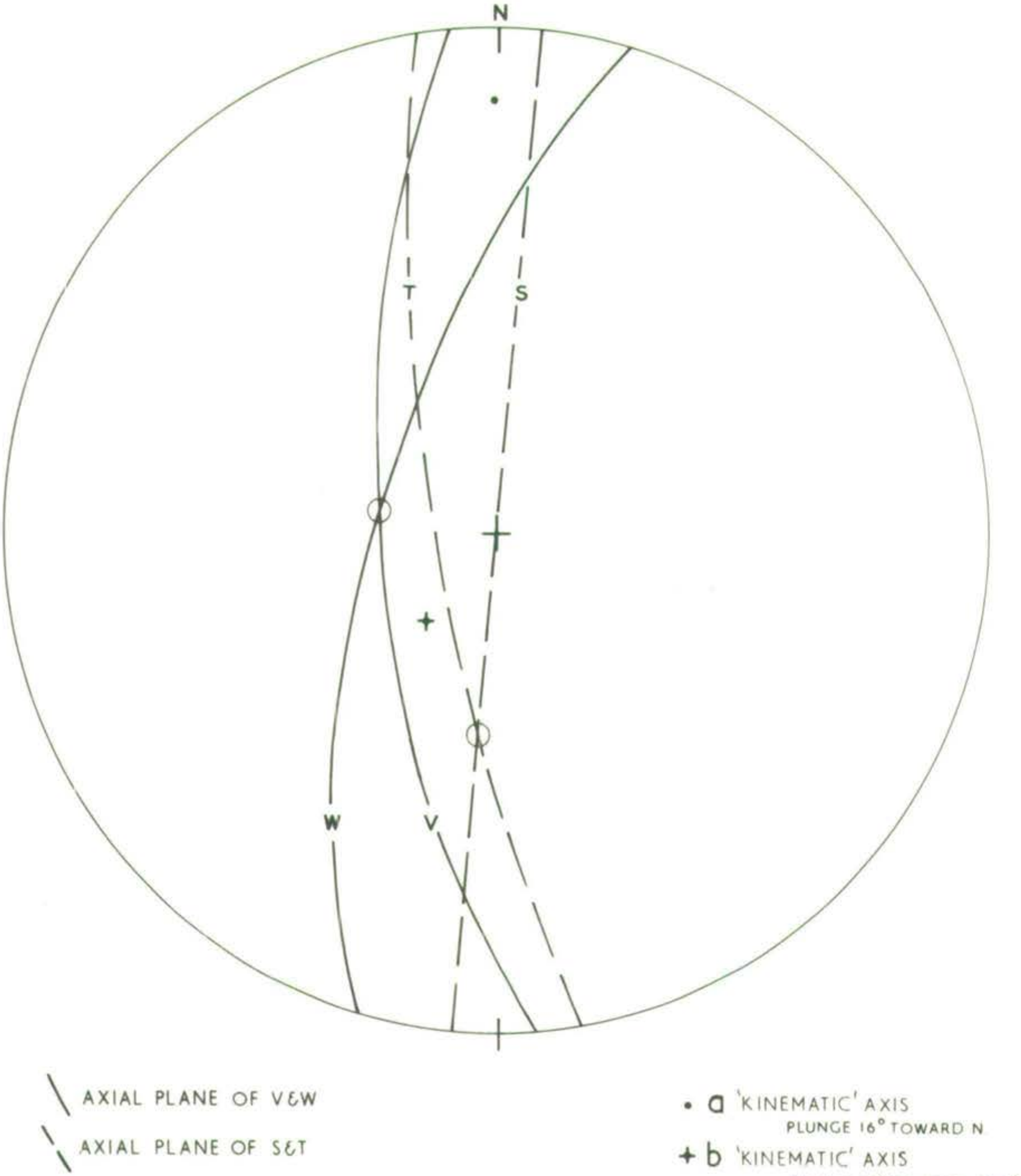
SUB-AREAS 13-18

They have been dispersed, but do not define either a great or small circle pattern. Regardless of the mechanism of folding during F3, the fact that the centre of dispersal of the F2 axes lies within the cluster of F3 axes and that the area of dispersal with respect to the F3 cluster is not great, indicates that the F2 and F3 folds in this area are nearly coaxial. Very few F4 minor folds have developed here and so refolding of F2 is primarily due to the superposition of F3. The pattern of the F2 axes, therefore, suggests that folding during the third fold movement to the south of Loch Shiel was neither of a pure "Similar" nor a pure "concentric" style. This conclusion is supported by the observation that the style of the F3 minor folds is indicative of modified flexural deformation (see pp. 120-124).

It has already been shown that the F3 axial planes tend to converge both on a minor and major scale and that where the varying trends occur together "M" shaped and conjugate folds are formed. Most structural geologists consider the axis defined by the intersection of conjugate axial planes to be parallel to the intermediate axis of the deformation ellipsoid (eg. Ramsay 1962). However, Flinn has pointed out that in areas where deformation has been primarily due to finite homogeneous strain, axial planes bear no special relation to the axes of the deformation ellipsoid. The attitude of the axial plane in a newly generated fold cannot be predicted, but once formed it will rotate towards the longest axis of the deformation ellipsoid (Flinn 1962; pg. 424). Flinn has not discussed the geometry of three dimensional deformation where rock heterogeneity may play an active role throughout the deformation. In the present area the evidence indicates that lithological control has been considerable, especially during the third fold movement (see pp. 120-124). Such heterogeneity may well have inhibited or completely prevented rotation of the axes of the folds formed during the third fold movement. This may be true to the south of Loch Shiel, where the F3 minor fold axes form a strong maximum since it is unlikely that this maximum could be preserved during a rotation towards the longest axis of the deformation ellipsoid under heterogeneous conditions. It could, of course, be suggested that the cluster represents complete rotation in that the fold axes are now sub-parallel to the longest axis of the ellipsoid. However, since the F3 folds are modified flexural folds (implying that deformation was extremely inhomogeneous) and not Similar type folds (see p. 124), it seems reasonable to suggest that large passive rotations of the F3 fold axes have not occurred; and that the axis defined by the intersection of the converging axial planes is probably sub-parallel to the intermediate axis of the deformation ellipsoid. If rotation of the ellipsoid has occurred, then the intermediate and largest axes of the ellipsoid could have rotated with respect to the F3 structures. However, there is no evidence to support this suggestion.

F3 folds with converging axial planes are common on a minor scale and the intersection of their axial planes generally

FIG. 21



ORIENTATION OF AXIAL PLANES OF
MAJOR FOLDS S-T & V-W

defines a near vertical axis. "M" shaped folds are the most common style of folds formed and true paired monoclines are rather rare. However, the "M" shaped folds and the paired monoclines have been seen together and they certainly formed at the same time. Naturally, the angle of convergence of the axial planes in the "M" shaped folds is smaller than that for the paired monoclines. In several instances a variation from paired monoclines to tight "M" folds has been observed and the two sets of axial planes may become sub-parallel (Plate 14a).

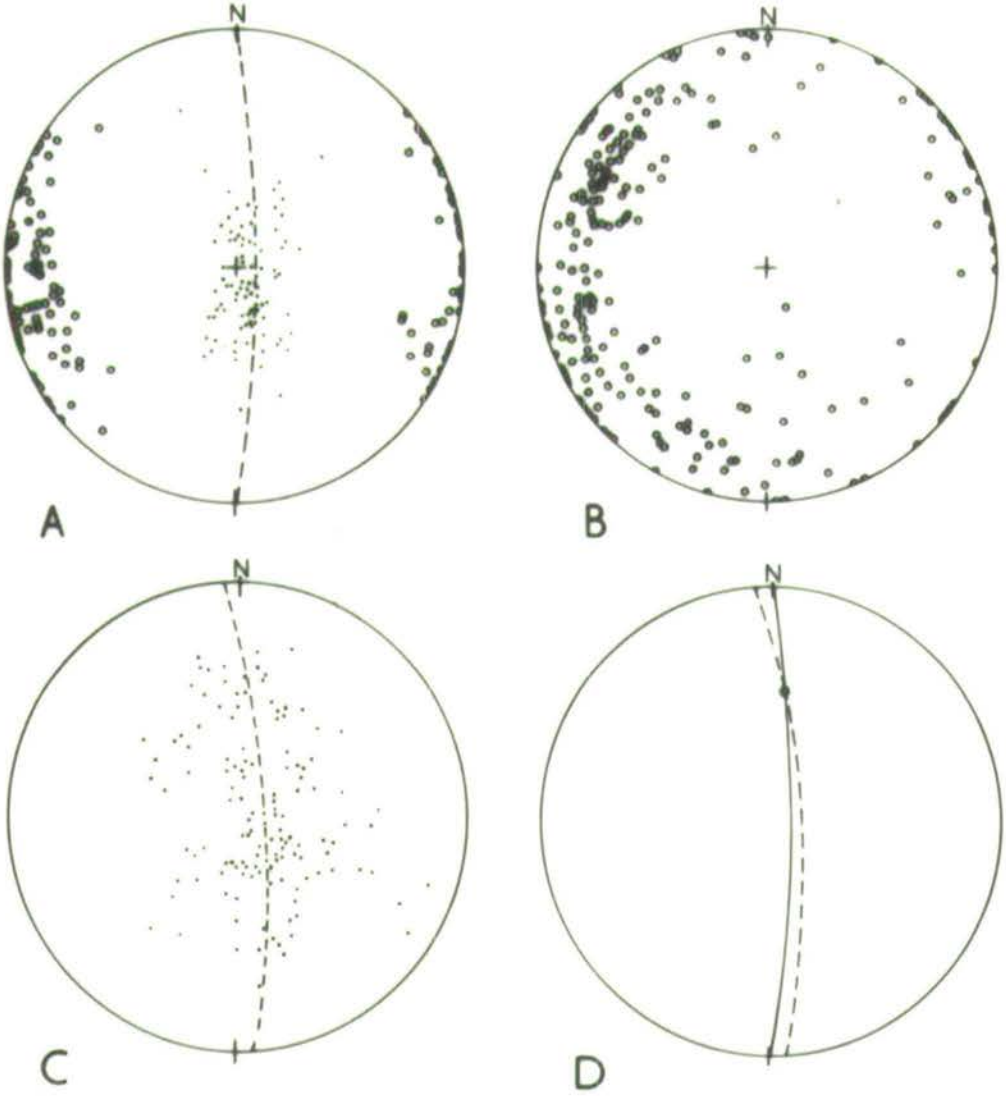
In the area south of Loch Shiel two sets of converging F3 axial planes are developed on a major scale. Although the resulting folds are not true conjugate folds and are better termed "M" folds, their formation is considered to be related to the same stresses which gave rise to the minor conjugate and "M" folds in this area. The paired axial planes are plotted as great circles on a stereogram shown in Fig. 21 . Where intersections occur between non-paired great circles, the intersection is not considered to be of kinematic significance, since such intersections do not occur in the field. The two intersections of the paired axial planes lie fairly close together on the stereogram and both indicate a steep axis. Also the two intersections lie within the cluster of the F3 minor fold axes (Fig.19). If this intersection is in fact sub-parallel to the intermediate axis of the deformation ellipsoid, then the b-kinematic axis in this area is sub-parallel to the mean F3 fold axis. Also the longest axis of the ellipsoid (a-kinematic axis) should lie in the plane bisecting the obtuse angle between the axial planes and, therefore, must trend approximately N-S with near horizontal plunge (Fig. 21).

The regional significance of these "kinematic" axes is discussed on pages 146-149.

ii) Sub-Areas 8, 9, 11 & 12.

The major F2 and F3 folds seen in these sub-areas have already been described and it has been concluded that the F3 folds have been superimposed on the F2 folds (see p. 94 , also p. 96). All the measurements of F2 and F3 minor structures from the sub-areas are shown on Fig. 22 . Stereogram A of this figure is of poles to F3 minor axial planes and F3 minor fold axes. The great circle represents the attitude of the mean F3 axial plane. F3 axes lie close to this great circle. Some dispersion has occurred along the great circle, but the majority of F3 axes are moderately steep. It has been shown that this dispersion is due to the superposition of the F3 structures on the previously folded surface. Stereogram B (Fig. 22) shows the poles to F2 minor axial planes. Dispersal is considerable, but not random. The pattern is close to that of a great circle and the axis of the great circle lies approximately on the great circle of the mean F3 axial plane. Also the axis lies within the cluster of the F3 axes, indicating that the F2 folds in this area are extremely tight. The fact that a mean axial plane can be drawn for the F3 minor folds and, that the F2 minor axial planes have rotated about this mean axial plane, on an axis

FIG. 22



A ° 90 POLES TO F3 MINOR AXIAL PLANES

· 89 F3 MINOR FOLD AXES

B ° 194 POLES TO F2 MINOR AXIAL PLANES

C 131 F2 MINOR FOLD AXES

D \ MEAN F3 AXIAL PLANE

\ GREAT CIRCLE OF F2 MINOR FOLD AXES

• a'_3 AXIS

SUB-AREAS 8,9,11 & 12

within the cluster of F3 axes, demonstrates the relationship between F2 and F3 in this area; and indicates that the F2 folds were formed prior to the superposition of the F3 folds.

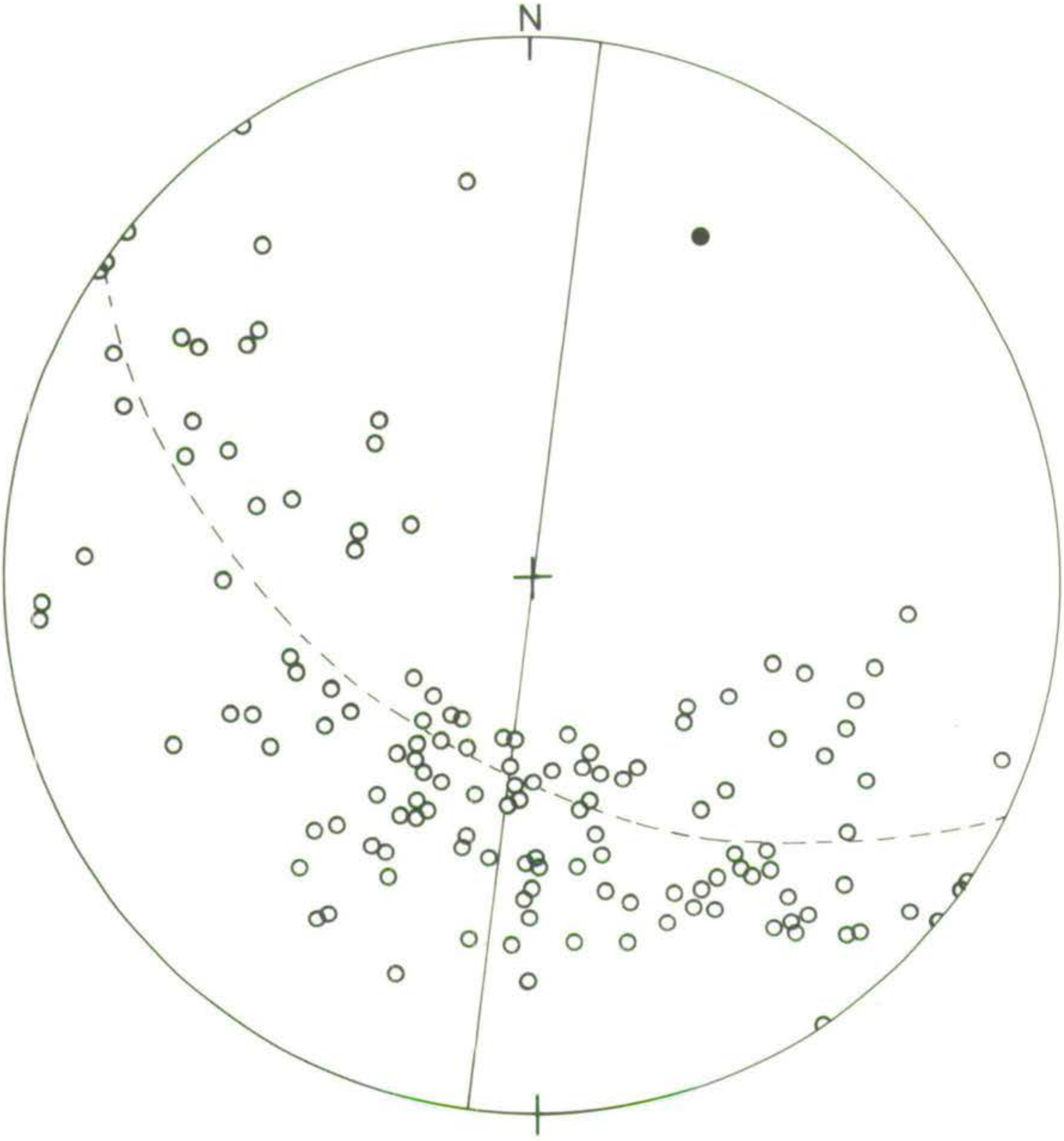
Stereogram C (Fig. 22) shows the distribution of F2 minor fold axes for this area. The pattern suggests a diffuse great circle distribution. Refolding of F2 axes during the fourth fold movement accounts for some of the variation from a great circle pattern. However, measurements of major and minor F3 folds from this area indicate that the mechanism of folding during the third fold episode has been complex and, therefore, a complex pattern of refolded lineations is to be expected (see pp. 120-24). The fact that the pattern resembles a great circle distribution rather than that of a small circle, suggests that here the F3 folds are approximately of "Similar type" and that they were formed at least in part by movement parallel to their axial planes. For pure Similar folds, the intersection of the mean F3 axial plane with the plane defined by the great circle distribution of the F2 axes, would define the direction of tectonic transport (a-kinematic axis) (Weiss 1959; Ramsay 1960). Stereogram D (Fig. 22) shows the mean great circle for the distribution of F2 minor fold axes and its intersection with the great circle for the mean F3 axial plane. This in itself is a doubtful operation since the great circles lie so close together, but the approximate orientation of the axis of intersection is calculated to be 38 degrees towards 5 degrees. Since the F3 folds are not pure Similar folds, this calculated axis possibly does not represent the true kinematic a axis, but it should represent the direction of movement of particles within the F3 axial plane and, as such, is a component of tectonic transport. This component is designated an á-axis and its kinematic significance is further discussed on pages 146-49.

iii) Sub-Areas 5, 7 & 10.

Each major fold seen in this area has already been discussed in detail and the purpose of this further discussion is to attempt to explain the geometrical relationships between these major structures.

Major folds M, N and O (Map II) are related to the F3 minor structures and the major fold B is related to the F2 minor structures (see pp. 85-9 & 54). From the structural data shown in Fig. 7, for the three sub-areas above, it can readily be seen that no simple relationship exists between the F2 and F3 minor structures. In the other sub-areas studied it has been found that the axis of rotation of the F2 minor axial planes lies on the great circle for the calculated mean F3 axial plane. Fig. 23 shows the relationship between the mean F3 axial plane and the poles to F2 minor axial planes for the three sub-areas under discussion. The axis of rotation for the F2 minor axial planes plunges approximately 30 degrees towards NNE and the calculated mean F3 axial plane is vertical and strikes at 8 degrees. The F3 minor fold axes, however, are

FIG. 23



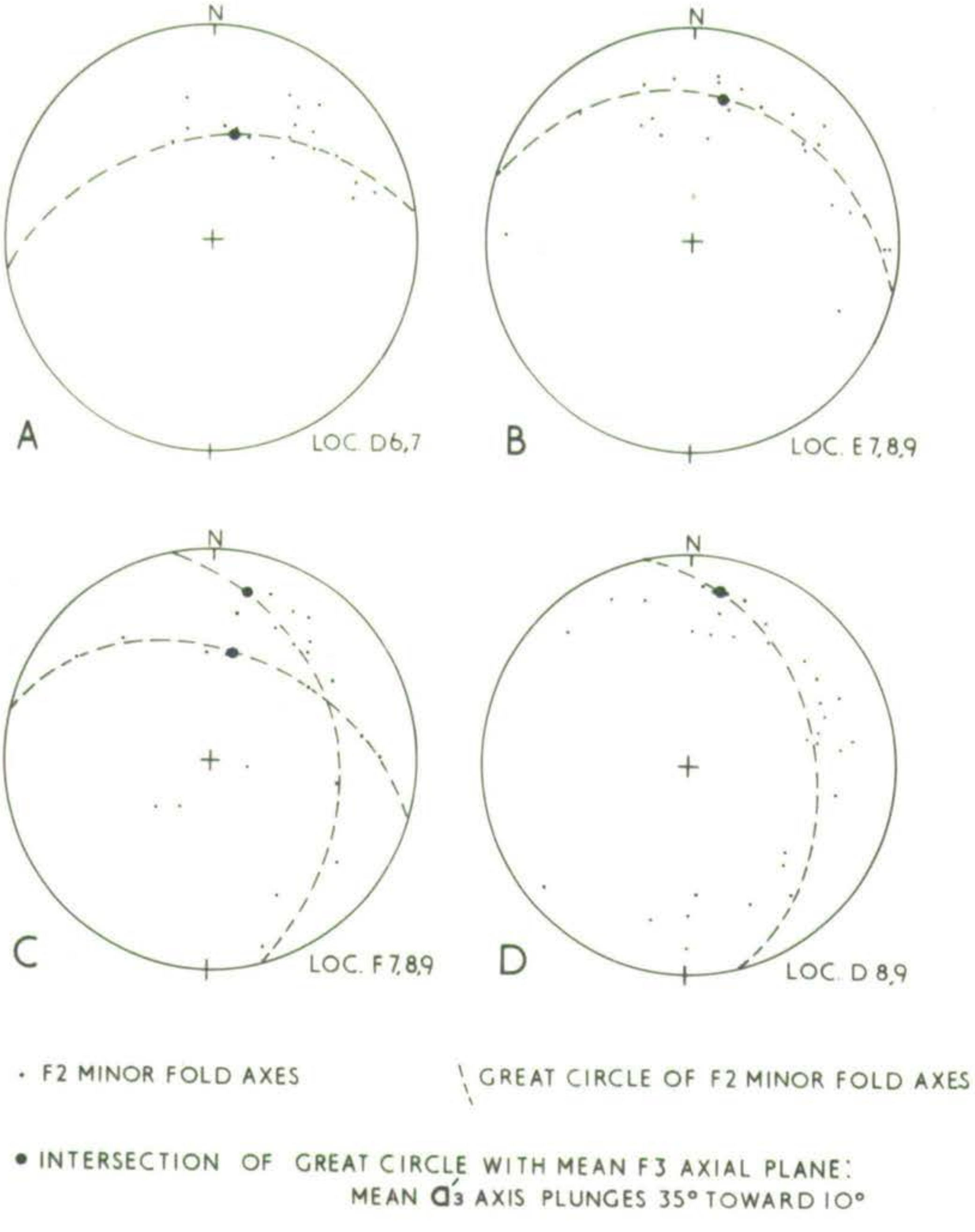
O POLES TO F2 MINOR AXIAL PLANES
131

\ MEAN F3 AXIAL PLANE

● MEAN ROTATION AXIS OF F2 MINOR AXIAL PLANES

SUB-AREAS 5,7&10

FIG. 24



SUB-AREAS 5,7 & 10

variable throughout the three sub-areas, but the majority have a shallow plunge to the north and the calculated beta axis for rotation of F2 minor axial planes lies close to the mean F3 fold axis. A plot of all the F2 minor fold axes from the three sub-areas gives a pattern on a stereogram which is closer to a small than a great circle and the axis of this small circle is near vertical. Since the area is not cylindroidal with respect to either F2 or F3, an attempt has been made to study it in terms of smaller units. Stereograms were prepared for each quarter square mile of the grid (Fig. 6) within the three sub-areas and all the structural data was recorded. The variation of the F3 axes was found to be spread throughout the three sub-areas and is apparently due primarily to superposition of the minor F3 folds on the mesoscopic F2 folds. However, the variation in the F2 minor axes appears to be systematic. In each of the quarter square mile units the F2 axes lie along a great circle and the small areas can be grouped according to the orientations of these great circles. Fig. 24 shows the great circles for the various groups together with the attitudes of the individual axes.

Since the F3 minor axial planes have not been rotated, the deformation of the F2 structures must be either syn-F3 or pre-F3. The evidence from the rest of the area mapped indicates that the distortion of the F2 structures is intimately related to the superposition of the F3 structures and, therefore, it is most probable that the distortion of the F2 structures in these three sub-areas is also related to the third fold movement. It has been demonstrated that the mechanism of folding during F3 varies from one part of the area to another and that there is a complex interplay of Concentric and Similar styles. Attention has also been paid to the fact that the style of deformation in the psammitic rocks varies considerably from that of the pelitic rocks and that, in general, the psammitic units have reacted to folding in a more viscous manner than the pelitic units. Also, the disparity in the relative competency of these two rock types becomes more pronounced as the thickness of units increases. In the area under consideration the Glen Moidart striped-pelitic rocks are in contact with the comparatively massive Beinn Gàire psammite. It is most probable that this contact has been a strong controlling influence on the deformation, which probability must be taken into account when considering an interpretation of the data given above.

The major F3 folds M, N and O in this area are moderately open structures on the north-eastern limb of the relatively large F2 closure B and could not in themselves account for the major swing in the orientation of the F2 structures. In the writer's opinion the explanation that best fits the data is that the southwest limb of B - the Druim an Laoigh closure - has been refolded about the Cruach a Ghaill closure P and the Coire na Taothuirt closure Q, thus causing the F2 closure B to rotate in a counter-clockwise direction (geometry illustrated in Fig.9A-B). The result of such rotation would cause B to 'unfold'. Also, compression in the region between the rotating closure and the relatively static northeast limb of B (see p.141) would generate the folds M, N and O. The mechanism of deformation would be a combination of concentric and Similar folding (see pp.120-124). If this is a correct picture of the deformation of the Druim an Laoigh closure B, then the folds M, N and O were generated late in the third fold movement and were superimposed on the refolded north-eastern limb of B.

Further analysis of the data appears to support this deformation picture. In order that folds of high amplitude and near vertical axial plane may develop on the steep south-western limb of the Druim an Laoigh fold B, the main direction of tectonic transport would have to have a fairly shallow plunge. It has already been shown (see p.134) that deformation of this limb during the third fold movement was to a large degree of "Similar type" and that the movement direction of particles due to the component of Similar folding was apparently 38 degrees towards 5 degrees. If this axis is of regional significance, then only folds of small amplitude should develop on the fairly shallow dipping south-eastern limb of B and this is precisely what has happened (i.e. folds M, N and O). Also, if the great circle distribution of the F2 axes for each of the sub-divisions within sub-areas 5, 7 and 10 are plotted together with the calculated mean F3 axial plane, the axes of intersection all lie close together with plunges from 20 - 50 degrees towards 10 degrees (Fig. 24 A, B, C & D).

The fact that these á directions (see pp.134-135), calculated from both the steep and shallow limbs of the F2 closure B, are in close agreement and further, that their mean direction is the direction of transport to be expected from the geometry of the structures, strongly suggests that the calculated á-axes are significant and may represent the dominant movement direction of particles in the area.

The conclusion that M, N and O formed late in the third fold movement would account for the disparity between the axial planes of these folds and the beta axis for the poles to F2 minor axial planes, in that the bulk of the rotation of the F2 minor structures took place prior to their superposition.

From the geometry alone it is not possible to tell whether Similar folding is followed by concentric folding; the reverse of this, or; whether both mechanisms were active at the same time (Ramsay 1960). However, the analysis of minor folds treated on pages 120-24 suggests that one mechanism is dependent on the other and that Similar and concentric mechanisms acted together throughout the deformation.

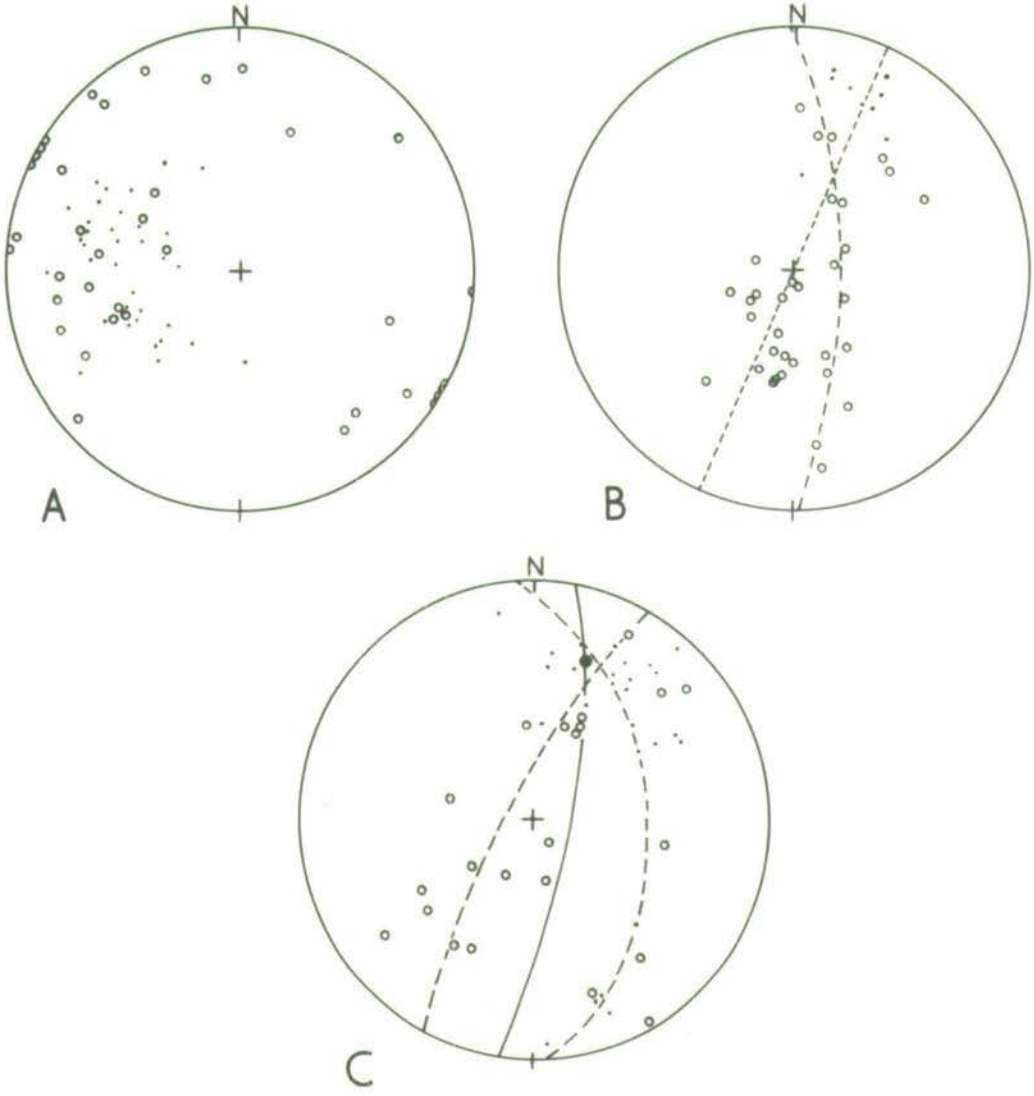
iv) Sub-Areas 3 - 4.

The extension of the axial plane trace of the F3 major closure P from sub-area 8 into sub-area 3 has been discussed on page 92. Also, the inferred extension of the F2 major closure B from sub-area 9 into sub-area 4 is discussed on page 58. These two sub-areas are here considered together in order to further investigate the relationships between the structures of the second fold episode and the third fold episode. The structure is complex and interpretation is somewhat hampered by the lack of exposure in Glen Moidart, but some important generalisations can be made.

The most obvious difficulty in sub-area 3 is that neither the F2 nor F3 folds are cylindroidal even on the mesoscopic scale. In sub-area 4, the F2 minor folds predominate and relatively few F3 minor folds are developed. Therefore, the F2 axes form a maximum on a stereonet and only five axes are strongly dispersed, (Fig. 7- 4C: also, Fig. 25c). However, in sub-area 3 where F2 and F3 minor folds are equally well developed and tend to be the same relative size, extreme variations occur in the orientations of both the F2 and F3 minor fold axes.

F3 minor axial planes display the usual variations from NNE to NNW. The mean axial plane for the two sub-areas strikes 10 degrees and dips approximately 80 degrees E. Only slight dispersal of F2 minor axial planes occurs in sub-area 4 and a trend of NNE with dips from 40 degrees to 60 degrees E predominates. Foliation and bedding-schistosity trends coincide approximately with the F2 minor axial plane trends for both sub-areas and this is especially true in sub-area 4. Stereograms 3A and 4A of Fig. 7 illustrate the relationship between the S_2 trends of the two sub-areas. The maximum seen in stereogram 4A coincides with the maximum for poles to F2 minor axial planes in sub-area 4 and, the girdle of stereogram 3A reflects the dispersal of F2 minor axial planes in sub-area 3. Fig. 25A is a plot of

FIG. 25



A POLES TO F2 MINOR AXIAL PLANES **B** F3 MINOR FOLD AXES

C F2 MINOR FOLD AXES ● MEAN a_3' AXIS: PLUNGE 35° TOWARD 18°

╲ MEAN F3 AXIAL PLANE

╲ GREAT CIRCLES TO F2 & F3 MINOR FOLD AXES

○ SUB AREA 3 · SUB AREA 4

SUB-AREAS 3&4

all the poles to F2 minor axial planes for both sub-areas. The NNE trend of the F2 minor axial planes swings to the north around the major F3 closure P to trend SW on the eastern limb of P. The important point here is that a marked steepening of the dip of the F2 minor axial planes (and bedding-schistosity) occurs where the swing around P takes place. It may, therefore, be concluded that the F2 minor folds in sub-area 4, with constant trend and moderate dip, probably represent a pre-F3 trend and, that the effect of the third fold movement has been to steepen up the F2 minor axial planes as they are rotated about the F3 folds. Also, the axis of rotation of the F2 minor axial planes is close to the vertical.

If the F2 minor folds were isoclinal in sub-area 3 during the superposition of the F3 folds, then one would expect the F3 minor fold axes to form a maximum close to vertical, but such is not the case. No post-F3 minor folds have been seen in sub-area 3 and, therefore, the variation in F3 axes is probably due primarily to superposition of the F3 folds on the previously folded surface. The style of the F2 minor folds varies considerably especially in sub-area 3. In sub-area 4 the F2 minor folds are predominantly sub-isoclinal. Also S_2 is the dominant foliation and bedding-schistosity is often very faint and discontinuous. But in sub-area 3 many of the F2 minor folds are open structures. Thin psammite bands within the Glen Moidart striped-pelitic rocks are much more common in sub-area 3 than in sub-area 4 and, where they occur, S_2 is only well developed in the pelitic bands;

the orientation of the F3 minor fold axes being controlled by the orientation of the bedding-schistosity of the psammite bands rather than by S_2. Fig. 25B is a plot of the F3 minor fold axes for both sub-areas. The great circle pattern is not distinct because the F3 minor axial planes are variable, and the two diffuse great circles are apparently related to the development of minor F3 conjugate folds. Fig. 25C shows the distribution of F2 minor fold axes for both sub-areas. The concentration of axes in the NE quadrant of the stereogram is made up primarily of axes from sub-area 4 and may represent the trend of F2 prior to deformation by the third fold movement. The dispersal from this concentration falls roughly along two great circles (shown as dotted lines). If this dispersal can be attributed entirely to F3 then the double girdle is a reflection of the tendency for conjugate and "M" shaped folds to develop during the third fold movement. Also, the fact that these girdles are near great circle patterns suggests that the third folds here are primarily of "Similar type". However, by observation it can be seen that the F3 minor folds are not true Similar folds. Where an axial plane cleavage is developed, it is primarily a crenulation cleavage. Pelitic bands tend to show considerable thickening in the hinge of F3 minor folds, but only slight thickening occurs in the thin psammitic bands within the Glen Moidart striped-pelitic rocks. The F3 minor structures suggest, therefore, that the rocks in this area deformed during the third fold movement, by a combination of Concentric and Similar folding (see pp. 120-124).

It cannot be said with certainty whether or not the pattern shown in Fig. 25C is significant, but it is of interest to note that the great circle drawn on Fig. 25C for the calculated mean F3 axial plane lies close to the intersection of the great circles drawn through the distribution of F2 axes. If it is assumed that the F3 folds are primarily Similar in style, then a mean a′-axis can be located with a trend of 35 degrees towards 18 degrees. The fact that this calculation is in close agreement with the calculated a′-axes elsewhere in the area mapped further suggests that a shallow 'transport direction' played an important role during the third fold movement (see pp. 134-135).

v) Sub-Area 1 (Coire Ladhair Mhòr Antiform).

To the north of sub-area 1 a major fold - the Rois Bheinn antiform - has been described by Clark (1961), whose mapping extended into sub-area 1. The actual closure of the Coire Ladhair Mhòr (Rois Bheinn) psammitic rocks was not mapped however. Clark found that the axial plane trace of the Rois Bheinn antiform is not symmetrically disposed within the psammitic rocks and the writer's continuation of this axial plane trace (A) into sub-area 1 is in agreement. The bedding-schistosity, adjacent to A in the north of sub-area 1 and further north, is near vertical and the dip of the axial plane is approximately vertical. The axial plane trace of A should, therefore, lie close to the centre of the psammitic closure if the closure is in fact related to A (see Map II; Clark 1961). Clark found that the F2 minor fold axes vary considerably and that they trace out a vertical great circle when plotted on a stereogram. Also, this variation often occurs in areas where no later minor folds are present. The closure, as outlined by the Coire Ladhair Mhòr psammite (sub-area 1), has been mapped in detail by the writer and a possible explanation for these anomalies has been found.

As shown on the Structural Map (Map II), the F2 minor axial planes and axial plane cleavages do not continue SSW, but instead remain sub-parallel to the bedding-schistosity around the closure. Where this occurs minor folds with a SSW trend refold the earlier structures. The major closure outlined by the Coire Ladhair Mhòr psammitic rocks is post-F2 and can be correlated with the F3 fold movement. The proposed shape of this structure is shown in Fig. 8 (see pp. 52-54).

Stereograms 1B and 1C of Fig. 7 show the orientations of the minor fold axes and poles to minor axial planes for F2 and F3 in sub-area 1. The F2 axial planes are dispersed in a great circle whose axis plunges steeply to the SSW and this coincides with the cluster of F3 fold axes. The F2 axes are dispersed, but lie neither on a great nor small circle pattern; in fact, their centre of dispersal lies close to the cluster of the F3 fold axes. If the F2 structures have been rotated primarily by refolding during F3, then the mechanism of folding is apparently not one solely of either shear parallel to the F3 axial plane or slip along bedding-schistosity planes.

The fact that the F3 minor folds are best developed in the pelitic rocks and die out rapidly in the psammite suggests a strong lithological control on deformation. In the more competent psammitic rocks adjustment towards equilibrium may have come about by large scale rotation with attendant slip along bedding-schistosity planes, whereas in the less competent pelitic rocks, adjustment may have been achieved by folding of the bedding-schistosity. No strong axial plane cleavage is developed in the F3 minor folds in either the pelitic or psammitic rocks and the structures are never pure Similar folds. Also, F3 minor conjugate folds and "M" folds are developed and so the major rotation of F2 structures during F3 was probably controlled by movement relative to more than one plane. Under such conditions no single direction of tectonic transport could account for the deformation.

The variation of F2 minor fold axes noted by Clark may well be due to movement along bedding-schistosity planes, caused by the refolding recognised in sub-area 1.

The variation in the F2 minor fold axes and axial planes is similar to the deformation picture recognised throughout the area. The F2 axes have rotated through the horizontal and the rotation has not been confined to a single plane of movement. This pattern of deformation again suggests that deformation during the third fold movement has been three dimensional and may best be explained in terms of near horizontal and near vertical principal directions.

Discussion:

The investigation of the effect of the superposition of the third folds on the second folds has revealed a complex movement picture for the third fold movement. The F3 folds have formed in a part concentric and part Similar manner. The re-orientation of the F2 fold axes and axial planes can be partly explained in terms of a transport direction, with gentle plunge to the north. The F2 folds have been passively opened and closed throughout the area and, there is some evidence to suggest that steepening of the F2 axial planes has occurred around the hinges of the F3 folds. Further investigation, however, indicates that a shallow transport direction cannot entirely account for the extreme variations in plunge of the F2 axes observed in many parts of the area. Before pursuing this further, the geometry of interference patterns shall be considered.

Ramsay (1962b) has classified the three dimensional surface forms which result from the superposition of two phases of folding and has described the types of interference patterns seen in two dimensions. Ramsay has found that, for folds of Similar type which have formed by a process of differential flattening (Ramsay 1962a), three basic types of interference patterns arise. Type 1 consists of interlocking basins and domes, produced where the a direction of the second folds lies close to the axial plane of the first folds. Type 2 tends to produce complex patterns, varying from simple domes to a mushroom-like pattern, produced where the a direction of the second folds makes a high angle with the axial plane of the first folds, and the axis of the first folds lies at a moderate to high angle with the axial planes of the second folds. In type 3 the closed surface patterns characterising the first two types give way to a continuously converging or diverging surface form, produced where the a direction of the second folds makes a high angle with the axial plane of the first folds; the axis of the first folds lying at a low angle to the axial plane of the second folds.

The fact that the majority of the interference patterns, produced by the superposition of the third folds on the second folds, in the area are of type 3 would appear to support the contention that a shallow movement direction has prevailed. Examples of type 3 patterns are shown in plates 20a & b, 21a & b . However, many instances of F2 'eye' folds have been seen and most of these cannot be explained in terms of a near horizontal a direction. Plates 22a and b, 23a & b show some examples of the closed outcrop patterns seen in the area. Plate 23a is a particularly good example from the Resipol psammite, in the core of the Coire Dubh F3 synform V (in north of sub-area 18). F2 and F3 axial planes both have steep dips; F3 axial planes strike N-S and F2 axial planes strike approximately E-W. At this point both F2 and F3 minor fold axes are steep and the resulting structure is a typical "Dunce's Cap" (Ramsay 1962b). Unless the second fold axes were extremely variable prior to the superposition of the third folds, it seems most unlikely that this structure could have formed solely by a near horizontal movement. Again

Plate 22a illustrates a typical 'eye' fold pattern seen in the north of sub-area 8, where the F2 closure C is refolded by the F3 closure P and the suggestion here, from the geometrical relationships, is also that movement could not be entirely near horizontal; on the contrary, a near vertical direction of movement is implied.

In sub-area 11 the foliation and bedding-schistosity outline a macroscopic pattern about the F2 closure C, which is intermediate between Type 1 and Type 2 patterns (Map II). The F2 axis has rotated through the horizontal and the structure closes downwards (see pp. 60-64). It has previously been suggested that the F3 fold in this sub-area is approximately of Similar type, since the F2 lineations describe a pattern on a stereogram that is closer to a great than a small circle. The intersection of this great circle with the F3 axial plane, indicates an a′-axis with shallow plunge to the north. This shallow movement direction could explain the disposition of the F2 axial planes but does not account for the extreme variation in the F2 axes. The shape of the closed structure seen in sub-area 11 can be explained only in terms of movement resolved into components with near horizontal and near vertical axes.

The closed outcrop patterns usually are found juxtaposition to open patterns throughout the area and the evidence of these relationships indicates movement of particles in a near horizontal and near vertical direction. Since it has been previously demonstrated that the third folds are not pure Similar folds or pure Concentric folds, a complex movement pattern is to be expected. If the F3 folds formed primarily as modified flexure folds and the modification is due to flattening or differential flattening (see p. 115), then one would expect movement to occur in more than one direction within the axial plane.

If the movement of particles has occurred along two principal directions, it is suggested that these directions may be the principal extension directions of the deformation ellipsoid during the third fold movement. From the discussion of the structures to the south of Loch Shiel (see pp. 129-133), it was concluded that the longest axis of the deformation ellipsoid may have a near horizontal N-S attitude, the intermediate axis being near vertical. The difficulties involved in trying to relate visible deformation to a deformation ellipsoid have previously been enumerated (see p. 130). However, the evidence from the area as a whole appears to suggest that during the third fold movement the deformation ellipsoid had the orientation indicated above, with a resultant near horizontal shortening direction trending approximately E-W.

j. Deformation of Pre-existing Structures during the Fourth Fold Movement.

Since relatively few F4 minor structures have been developed and no major F4 folds occur, it is thought that the fourth fold movement has not influenced the geometry of the area to any great degree.

Plate 18b illustrates the effect of refolding by F4 of a minor F2 fold. The limbs of the F2 fold are bent around the crest of the F4 fold and an open mica crenulation folds the axial plane cleavage of F2. Considerable variation in plunge of the F2 axis occurs. The sense of closure of F2 often changes over the crest of the F4 minor folds.

An extremely complex pattern is seen where F4 is superimposed on F2 folds which have been refolded by F3. Plate 19a is a typical example. Thin psammitic bands in the Achnanellan striped-pelitic rocks outline small isoclinal folds trending generally E-W across the photograph. Refolding by F3 has caused considerable variation in the trend of F2 - note that here both the NNE and NNW trends of F3 are developed. The F4 mica crenulation can be seen in the centre of the photograph. This crenulation has a constant axial plane trend just south of east. The F4 crenulation has been superimposed on the F2 axial plane cleavage, which had previously been crenulated during F3. F4 in this case has refolded both the F2 and F3 minor folds. Quite often only the mica crenulation is developed and refolding of the bedding-schistosity does hot occur on a larger scale.

It is interesting to note that the F4 minor structures are most abundant in areas where refolding of the second structures by the third fold episode is most intense and, that in areas where F2 folds are only refolded on a minor scale, the F4 minor folds are virtually absent. When folds which are not isoclinal are refolded the generation of considerable shearing stress is to be expected (Ramsay in Johnson and Stewart 1963). It is possible that such stresses caused the generation of the fourth folds. However, there is no direct evidence to support this view.

III. STRUCTURE (Continued)

3. CONCLUSIONS

Four fold movements have been established in the Moidart-Sunart region. F2 and F3 major structures have been recognised, but F1 and F4 movements only generated minor structures. E-W trending joints are post-F4, but jointing subparallel to F3 axial planes may have preceded F4. The geometry of the area is interpreted primarily in terms of deformation during F2 and F3. There is no structural evidence for suggesting that large scale isoclinal folding occurred prior to F2 and "interfingered" pelitic and psammitic units that have been folded by F2 (i.e. in the Coire na Taothuirt area) are thought to be due to sedimentary facies changes. Only gentle warping is attributed to F4.

Variation in trend of the F3 axial planes is attributed primarily to the generation of conjugate and "M" shaped folds.

The tectonic style of the F1 minor folds cannot be quantitatively ascertained, but the true isoclines are not pure "Similar folds". The F2 folds are primarily of "Similar type" and the F3 and F4 folds are modified flexural folds; however, the distinction between the two types is not well defined.

It has not been possible to determine the movement picture during F2 but an attempt has been made to relate the variation of the F2 structures to the deformation ellipsoid during F3. It is suggested that the longest axis was near horizontal with an approximate N-S trend and that the intermediate axis was near vertical, with a resultant horizontal shortening direction trending E-W. No single direction of tectonic transport can account for the deformation of the F2 structures during F3, since the deformation is considered to have been three dimensional.

The orientation of F3 axes and the amplitude of the folds is directly related to the orientation of the F2 structures and it is not possible to consider the effects of these two movements separately. Where the foliation or bedding-schistosity prior to F3 was at a high angle to the F3 axial planes, folds of large amplitude have been produced, with attendant rotation of the F2 structures. Variation of F2 minor fold axes has been recorded in the absence of F3 minor folds and, in such instances, the foliation and bedding-schistosity are sub-parallel to the regional trend of the F3 axial planes.

Since the major and minor folds are thought to have formed by a complex combination of flexure and flow and the resultant geometry is exceedingly complex, no attempt at 'unrolling' has been made.

a. Structural Succession.

In the light of the structural analysis the establishment of the structural succession can be attempted.

The first consideration is the possible presence of major folds in the area associated with the first fold movement. Since very few F1 minor folds have been recognised it has not been possible to establish the existence of any major F1 folds in the area. In adjacent areas where F1 minor structures have also been reported (Howkins 1961; Clark 1961; Dalziel 1963; Powell 1963), no F1 major folds have been found. Also, Dalziel has found that where current-bedding evidence is available, the younging directions are consistent with the geometry established on the basis of a second and third fold movement. The F1 structures are further discussed below.

The dominant structural feature in the area north of Loch Shiel is the refolded second closure - Druim an Laoigh fold B. In the Beinn Gàire psammitic rocks of sub-area 10, the axis of this fold plunges moderately to the NE. Here the closure is an antiform (see p. 54), and the Beinn Gàire psammitic rocks overlie the Glen Moidart striped-pelitic rocks. However, to the SW along the axial plane trace of the antiform, the fold axis steepens up and swings through the vertical, around the F3 fold of Coire na Taothuirt Q. The swing in plunge of F2 brings the Glen Moidart striped-pelitic rocks above the Beinn Gàire psammite. The flaggy psammitic rocks that outline the closure within the Glen Moidart striped-pelite unit cannot be explained in terms of the variation in plunge of the second folds and must be due either to isoclinal folding during the first fold movement or to original sedimentary variation. Since no F1 structures have been recognised within either the pelitic or psammitic rocks in this part of the area, the latter is probably the case. However, the possibility that the F1 minor structures have been destroyed by the later deformation cannot be discounted. The division between the flaggy psammite rocks and the semipelitic and pelitic units is very seldom well defined and, under such conditions, interfingering of sedimentary units is not unlikely (see pp. 22-23). From the steep plunge of the second fold axes around the third closure (Coire na Taothuirt Q), the F2 minor fold axes assume a moderate to shallow plunge to the NNE in sub-area 4 and, therefore, it is assumed that the Beinn Gàire psammite still underlies the Glen Moidart semipelite. Further north in sub-area 2, third minor folds become more abundant and the second axes become variable, assuming a moderately steep plunge to the south. This change in plunge brings the Beinn Gàire psammite back to the surface where it is folded by the Glen Gluitanen F3 folds in the northeast corner of the area (see pp. 82-85).

Before attempting to establish the structural relationship between the Glen Moidart striped-pelitic group and the striped-pelitic rocks to the south, the relationship between the areas to the north and south of Loch Shiel will be considered. The pelite within the Cruach à Ghaill F3 closure P exposed in the south of sub-area 8 can certainly be extrapolated south across Loch Shiel (see p. 111). This large body of interbanded pelitic and semipelitic rock - Achnanellan group - is structurally above the closure of psammitic rock in sub-areas 16 and 17. The closure in this area is the F2 antiform of Torran nam Mial, which plunges steeply southwest. According to the "Ten Mile" Geological Survey Map, Sheet 1, the psammitic rocks of Ben Resipol in the south of the area mapped can be correlated with the psammite exposed on Torran nam Mial (sub-area 17). Also, the Ben Resipol pelite lies within the Resipol psammite in the core of the F2 synform I and is, therefore, structurally above the Ben Resipol psammitic group. Since there is no evidence of an antiform within the Ben Resipol psammite to the north of the F2 synform I, then the psammitic rock separating the Ben Resipol pelite from the Achnanellan striped-pelitic group probably represents an original sedimentary intercalation.

The question arises as to whether or not the Achnanellan striped-pelitic rocks can be correlated with the Glen Moidart striped-pelitic rocks and, unfortunately, the available evidence in the area mapped does not afford a clear answer. There are minor lithological differences between the two groups, but the rocks within both groups also tend to show variations which are attributed to facies changes (see pp. 22-23). The structural evidence is ambiguous. In sub-area 11 the dominant structural feature is the downward closing F2 structure C within the Beinn Gàire psammitic rocks. The fact that the Druim an Laoigh fold B, directly north of C, is also downwards closing suggests that an intermediate antiform has been cut out and that movement has occurred at the boundary between the Glen Moidart striped-pelitic rocks and the Beinn Gàire psammitic rocks in this area. Movement also probably occurred along the boundary between the Achnanellan striped-pelitic rocks and the Beinn Gàire psammitic rocks. Even if the rocks under Loch Shiel were exposed, it still might be difficult to be certain of the three dimensional structural relationships. However, the structural and stratigraphical relations along the western border of the area mapped suggest that the Beinn Gàire psammitic group is continuous with the Ben Resipol psammitic group and corroboration is found in the lithological boundaries drawn on the Geological Survey "Ten Mile" Map. On this evidence the Ben Resipol pelite can be directly correlated with the Glen Moidart striped-pelitic rocks (see also Map I; Howkins 1961). From the above it may be inferred that the Achnanellan striped-pelitic rocks can be correlated with the Glen Moidart striped-pelitic rocks.

b. Structural Correlation with Adjacent Areas.

i) Correlation of Minor Folds.

Howkins (1961) recognised four significant fold movements in the Moidart area. The eastern border of the area mapped by Howkins coincides with the western border of the area under discussion (Map V). Along this boundary Howkins has mapped minor structures of all but the third fold movement. Along the western boundary of sub-area 1 it is possible to correlate the F3 minor folds with those mapped by Howkins as F4.

However, the writer is in agreement regarding the correlation of F1 and F2. Howkins states that F3 minor folds have not been seen refolded by F4 minor folds and establishes the relative ages of F3 and F4 on the following criteria:

(a) F3 minor folds change in axial plane trend and orientation as they are traced from north to south.

(b) F4 minor folds occur, oriented nearly at right angles to F3 minor folds.

(c) The F4 minor folds have constant axial plane orientation (Howkins 1961; pg. 157).

(d) F3 and F4 major folds have opposing "movement sense" (Howkins 1961; pg. 143).

Howkins found the third fold movement to be of restricted extent; also, that although F2 axes have been bent during F3, no significant change in the inclination of the F2 axes occurred at this time. The calculated F3 a-axis was found to plunge at 25 degrees to the north. On the other hand, the calculated a-axis for F4 plunges at 70 degrees to the southwest. This calculation was made from observations in the Sgùrr Dhomhuill Mor area (just west of the northwest corner of the area under discussion). Howkins concluded that the steep orientation of the F2 fold axes in the east of his area was caused by the superposition of the fourth fold movement. Further south it was found that F2 lineations deformed during F4 fell neither on a great nor small circle pattern and Howkins, therefore, concluded that F4 was a combination of concentric and Similar type folding.

From this discussion it is apparent that the tectonic style of the fourth fold movement mapped by Howkins is similar to the third fold movement seen in the Moidart-Sunart region. It has been demonstrated that no single "tectonic transport direction" can account for the deformation attributed to the third fold movement in this region. This observation is in agreement with the results of the quantitative study of F3 fold style, in that the F3 minor folds measured were found to be modified flexural folds.

The area mapped by Clark (1961) is shown on Map V. This writer has recognised four significant fold movements and where the boundary overlaps that of the area under discussion to the north of Glen Ulgary, it has been possible to correlate the minor structures. Thus, the four fold movements recognised by Clark appear to be the same four movements recognised by the writer in the Moidart-Sunart region. Also, Clark has not found any minor folds intermediate between F3 and F4 movements to coincide with the fourth folds mapped by Howkins. The writer has traced the F3 minor folds mapped by Clark into the Sgùrr Dhomhuill Mor area and they are apparently the same minor folds that have been mapped by Howkins as F4. The fourth folds mapped by Clark have been directly correlated with the fourth folds recognised by the writer in sub-area 1. These minor folds trend south of east and have been seen to refold the F2 and F3 minor folds of the Moidart-Sunart region. These fourth folds, therefore, are certainly not related to the fourth fold movement recognised by Howkins.

Clark found that the axial planes of the second folds were nearly vertical prior to the superposition of the third fold movement. The F2 axes are variable throughout the area, but tend to fall on a partial great circle trending NE-SW, with a strong maximum plunging at 76 degrees to the SSW. Clark was not able to determine the trend of the F2 axes prior to F3, but he considered the variation in plunge to be primarily due to the superposition of the third fold movement. The F2 axes deformed by the third folds in the Diollaid Bheag area (Map V), describe a great circle pattern on a stereonet and its intersection with the plot of the major F3 axial plane (Diollaid Bheag Antiform) suggests a near vertical movement direction, which is approximately coincident with the calculated F3 fold axis. This appeared to be a contradictory situation, since with a nearly vertical movement direction in nearly vertical rock, no third folds should form. Elsewhere (An Stac - see Map II; Clark 1961), Clark found that deformation of F2 linear structures during the third fold movement did not result in a great circle pattern. The above facts led Clark to conclude that deformation during the third fold movement was of both "Similar" and "Concentric" type. He also considered the possibility of the F2 axes being non-rectilinear prior to the third fold movement, but did not consider this to be a likely explanation (Clark 1961; pp. 151-159).

As has been previously stated, the numbering of fold movements should only be used to imply relative ages of structures within the area mapped and no regional significance is necessarily implied. In attempting to correlate the structures of the areas mapped by Howkins, Clark and the writer the significance of this statement is verified. If the third fold movement recognised by Clark and the writer can, in fact, be correlated with the fourth fold movement recognised by Howkins, then this movement is the third event to have affected all three areas. Since the third fold movement recognised by Howkins is considered by him to be of "restricted extent" (Howkins 1961; pg. 135) and has apparently not extended into the areas mapped by Clark and the writer, it may be best to designate this movement F3'. Therefore, the sequence of fold movements for the Moidart-Sunart region is F1, F2, F3', F3 and F4.

The suggestion has previously been made by the writer that F2 minor folds in Moidart and Sunart may be of the same generation as the second folds mapped by Dalziel (1963) between Loch Shiel and Loch Eil (see p. 33). There is no direct evidence in support of this suggestion, but since the earliest major folds developed in both regions have been independently designated F2, it seems most likely that these major folds are related to the same fold movement. Dalziel concluded that his area has been affected by four fold movements and that major folds were developed during the second and third fold movements. Refolding of one set of minor structures by the other was seen in all cases except F3 by F4. Fourth folds were mapped by Dalziel with certainty where they folded F2 structures and formed a distinct set of structures with different axial plane trend from the F3 folds in the vicinity (Dalziel 1963; pg. 110). Dalziel found the trend of F4 to be just north of east and that of F3 to be just east of north. These trends are in close agreement with the trends of F3 and F4 in the Moidart-Sunart region. However, since in the writer's opinion a reliable correlation of structures cannot be made solely on the basis of axial plane trend, a positive correlation between the post-F2 folds in Moidart and Sunart with those between Loch Shiel and Loch Eil cannot be made until the ground between these areas has been mapped in detail. A few observations of interest may, however, be made. Howkins found F3 (F3') folds to be of local significance and the F4 (regional F3) folds were only developed in the east of his area. Dalziel found that F3 folds occur throughout his area and that the F4 folds occur as isolated pockets in two localities, but are relatively rare elsewhere. Both the above writers considered the F3 folds to be primarily of Similar type. Howkins calculated that the direction of transport during F3 plunged at 26 degrees N; Dalziel calculated that the transport axis during F3 had a moderate to shallow plunge to the NNE. Both considered the F2 axes to have been originally sub-rectilinear with shallow plunge. However, Dalziel explains the present extreme variation in terms of shallow transport during the third fold movement, whereas Howkins considers the steepening of F2 axes in Moidart to be primarily due to near vertical transport during his fourth fold movement. The writer's results indicate a complex movement picture during F3, involving transport that may be expressed in terms of near horizontal N-S and near vertical axes (see pp. 146-49). The F2 axes are variable throughout the Moidart-Sunart region and this variation appears to be the result of complex deformation during the third fold movement, with both steep and shallow trends resulting from the interplay of steep and shallow movement directions. This three dimensional deformation of the F2 structures is considered to have occurred during a single phase of deformation with only small movements after the third fold movement. Since Dalziel and Howkins did not find F3 folds refolded by F4 folds, it is possible that F3 and F4 movements in the areas mapped by the above writers are intimately related. Therefore, it may be that these movements are equivalent to the single complex F3 movement of the Moidart-Sunart region.

ii) Correlation of Major Folds.

The axial plane traces of the major folds mapped by Howkins, Clark, Dalziel and the writer are shown on Map V. A major F4 fold, the Ceann Loch Uachdrach fold, has been mapped by Howkins in the southeast of his area. The minor structures associated with this major structure extend into the area under discussion and have been correlated with the third fold movement recognised by Clark (1961) and the writer. The major fold extends northeast into sub-area 3, but can only be recognised by the vergence of the F3 minor folds. This change in vergence dies out rapidly and the asymmetry of the minor F3 folds becomes related to the Cruach à Ghaill closure P (see p. 89). There is, therefore, no evidence for extending the Ceann Loch Uachdrach fold northeast and it is thought to die out on the slopes to the west of the Moidart River.

The only major fold mapped by Clark which extends into the area mapped by the writer is the Rois Bheinn antiform (Map V), which is considered by both writers to have formed during the second fold movement. The axial plane trace of the fold extends into sub-area 1, where it has been named the Coire Ladhair Mhòr antiform A. Refolding of the closure by the F3 antiform J in sub-area 1 has not been recognised by Clark and this is in agreement with the writer's conclusion that the F3 fold dies out in the north of sub-area 1, (see p. 80). The Glen Gluitanen F3 folds recognised in the northeast of the area have not been recorded by Clark. However, the F3 minor folds shown by this writer on a Structural Map (see Map II; Clark 1961) can apparently be correlated with the F3 minor folds related to the Glen Gluitanen folds. The northwards closing Glen Gluitanen fold K certainly dies out to the north of the area mapped, but the southwards closing fold L, in the opinion of the writer, may extend some way north in the ground mapped by Clark.

IV. METAMORPHISM

1. INTRODUCTION

By studying the textures of the rocks in thin sections it has been possible to distinguish periods of mineral growth and to relate these to the various fold movements.

Although minerals grew at different times in the metamorphic history there is no indication, from the textural relations, of a break in the metamorphic evolution of the metamorphic rocks. Metamorphism to sillimanite grade, together with extensive migmatisation took place prior to and during F2. The growth of minerals is thought to have continued after F2, but to have ceased prior to or early in F3. However, recrystallization continued at least up to the end of F4. A summary of the structural and metamorphic history is given in Fig. 26.

The area under discussion lies entirely within the regional migmatite belt and is considered by past workers to be a zone of injection and permeation gneisses (Richey 1930; Phemister 1960). A study of the mechanics of migmatisation is beyond the scope of this report and the term "migmatite" is used by the writer only as a descriptive field term. Sederholm first used the term "migmatite" in reference to rocks composed of two elements of different genetic value, one a schistose sediment (or foliated eruptive), the other formed by "resolution" of material like the first, or by injection from without (Sederholm 1907). The metasediments in the area mapped exhibit discrete quartz-felspar foliae (mainly in the pelitic and semi-pelitic rocks) and concordant pegmatite sheets are ubiquitous. Therefore, the rocks are true migmatites irrespective of whether the quartz-oligoclase sheets and foliae formed from the metasedimentary host by a process such as metamorphic segregation, or by the introduction of new material. In fact, both processes may have taken place. The relationships between the concordant pegmatitic material and the metasediments as seen in the field and in thin sections do not, in the writer's opinion, supply sufficient evidence for speculation regarding the mode of origin of the migmatites.

IV. METAMORPHISM (Continued)

2. METAMORPHIC FACIES

Both pelitic and psammitic rocks have suffered migmatisation throughout the area mapped. Sillimanite is ubiquitous and the sillimanite grade of regional metamorphism has everywhere been attained. Metamorphic grade decreases rapidly to the west and the sillimanite zone only extends approximately two miles west of the area. Isograds trend approximately from N-S to NNE-SSW, parallel to the regional strike (Kennedy 1949; Howkins 1961).

The following metamorphic assemblages occur:

Pelitic and quartzo-felspathic assemblages: (Metasediments)
    Quartz-oligoclase - sillimanite - garnet -
    muscovite - biotite (Staurolite-potash felspar)

Calcareous assemblage: (Calc-silicate metasediments)
    Labradorite:bytownite - hornblende:clinopyroxene -
    garnet-quartz (biotite-zoisite)

Basic assemblage: (Amphibolite schists)
    Hornblende - Labradorite - garnet-quartz (biotite)

(Recrystallized appinites discussed on p. 26)

The pelitic and quartzo-felspathic assemblage together with the basic assemblage, indicate that the sillimanite-almandine sub-facies of the almandine amphibolite facies has been attained. However, the plagioclase in the majority of the calc-silicates studied is basic labradorite (An.60 - An.71, maximum extinction angle method), with only occasional departures toward bytownite. According to Kennedy (1949, p. 49) bytownite-anorthite should be the stable plagioclase. Also small crystals of beta zoisite occur, whereas it is thought to be stable only up to the staurolite-quartz sub-facies of the almandine amphibolite facies (Kennedy 1949, p. 49; Fyfe, Turner and Verhoogen 1958, p. 231). These anomalies have also been recorded by Clark (1961) to the north of the area under discussion and by Dalziel (1963), between Loch Shiel and Loch Eil. Dalziel suggests that the beta zoisite may be a relic of an earlier, lower grade, metamorphism while admitting that it could also be a product of retrogression. Actinolitic amphibole sometimes occurs in association with clinopyroxene and is indicative of retrograde metamorphism (Kennedy 1949). This association has also been recorded by workers in adjacent areas (Clark 1961; Howkins 1961; Dalziel 1963). Dalziel suggests that the anomalous plagioclase composition may also be due to retrogression, with attendant development of clinozoisite.

IV. METAMORPHISM (Continued)

3. RELATIONS OF STRUCTURE AND METAMORPHISM

The relationships between the metamorphic minerals are here studied from a textural point of view. Where possible mineral growth is dated with respect to S-surfaces developed during the various fold movements. Only limited success has been possible since recrystallization has accompanied each fold movement and a coarse fabric has been regionally developed.

a. Mineral growth in the Pelitic and Quartzo-felspathic assemblages

i) Growth of Mica.

Muscovite and biotite have crystallized with (001) sub-parallel to all S-surfaces. F1 and F2 minor folds usually have an associated axial plane cleavage and locally F3 axial plane cleavage is developed (see p. 75). Mica has grown with (001) parallel to these cleavages but has also grown parallel to the bedding-schistosity.

Plate 28a is an example of an F2 microscopic crenulation. Biotite outlines the crenulation, but the individual laths are not bent and, therefore, syn - or post- F2 mimetic recrystallization occurred. Biotite is also aligned sub-parallel to the axial plane of the F2 crenulation and it is this mica that gives rise to the F2 cleavage. Where the mica is absent no cleavage can be detected. The F2 cleavage is thought to have formed during the second fold movement (see p. 127) and it is concluded that mica crystallized at this time sub-parallel to F2 minor fold axial planes.

Mica is found locally sub-parallel to F3 axial plane cleavage, but usually only an F3 mica crenulation is developed (see Plate 28b). No bent or strained mica has been found associated with the F3 crenulations and, therefore, mica must have recrystallized during or shortly after the third fold movement. Similarly, F4 mica crenulation is locally developed and mica recrystallization has taken place.

Large porphyroblasts of mica occur and these are usually unoriented. The porphyroblasts are commonly of muscovite and often form as a replacement of dimensionally oriented sillimanite pods (see p. 175). However, the (001) cleavage of muscovite does not show any preferred orientation with respect to the sillimanite pods. The majority of porphyroblasts show no sign of strain. Since these micas are not oriented with respect to any of the main fold movements recrystallization probably continued until after F4. However, a few weakly strained muscovite porphyroblasts have been noted, but these probably record weak post-F4 movements (Plate 29a).

No regional retrogression of mica has been recorded in the pelitic and quartzo-felspathic assemblages, but some local chloritisation of biotite has taken place.

The above evidence indicates that mica was stable throughout the area during the four main fold movements.

Mica formed early in the deformation history and mimetic recrystallization occurred during the later fold movements. Recrystallization of mica continued after the fourth fold movement but some post recrystallization movement has occurred (probably related to local movement along E-W trending joints - see p. 109).

ii) Growth of Garnet.

Garnet is a common mineral in the metasediments. However, inclusions for the most part are irregular and only in a few instances can an attempt be made to interpret the garnet growth history.

Howkins (1961a) has established in the West of Moidart that post-F1 and pre-F2 garnet growth occurred and that this was followed by syn- and post- F2 growth. This growth history was only recognised to the West of the migmatite belt. In the migmatites the inclusions within garnets are irregular and Howkins was not able to recognise the above growth patterns. Dalziel (1963), working within the migmatite belt, between Loch Shiel and Loch Eil, found poorly developed inclusion trails which he considered to indicate the same growth history as that demonstrated by Howkins.

The following evidence suggests that no garnets grew during or after the third fold movement in the area mapped:-

(a) Whenever garnets are found in the presence of an F3 or F4 mica crenulation the folded schistosity is not overgrown by the garnets and no S_3 or S_4 inclusion trails have been seen.

(b) Very few idioblastic garnets have been seen and none have been found in the presence of an F3 or F4 mica crenulation.

An example of garnets with curved inclusion trails has been found in the Glen Moidart striped-pelitic group (Plate 30a). A crude 'S' trail can be distinguished in the central portion of the garnet and in the outer area the inclusions define a fairly straight trail, which runs into the schistosity of the ground mass. Although this is far from being a text book example, it is certainly suggestive of syntectonic growth in the core with post-tectonic growth in the outer zone of the garnet. The present shape of the garnet suggests that it grew outwards in the foliation after the kinematic phase. If no garnet growth occurred during or after F3, then this garnet may reflect either syn-F1 : post-F1 : pre-F2 growth or syn-F2 : post-F2 : pre-F3 growth. Since the area has suffered intense migmatisation after F1 and prior to F2, the latter is more likely to be the case.

Garnets with inclusions much finer than the fabric of the ground mass have been observed. Usually these inclusions are randomly oriented, but a few garnets have been found with straight trails of fine quartz and biotite. The trail may be parallel to the schistosity in the thin section or inclined (Plate 29b). These garnets are thought to have formed early in the structural history since they are xenoblastic, often have mica spindles and have been rotated relative to the present schistosity. The inclusions are considerably smaller than the grains of the ground mass and this may indicate that the garnets have overgrown a fabric much finer than that presently seen in the ground mass. However, the difference in size may be due entirely to partial absorption of the inclusions by the garnets. The fact that many garnets have been found with quartz inclusions only slightly smaller than the quartz of the ground mass lends support to the first suggestion.

It will be shown later that migmatisation and sillimanite growth occurred prior to F2 and, therefore, some garnet growth probably took place prior to F2. Some xenoblastic garnets have sillimanite spindles (Plate 30b) and, therefore, apparently grew before the last growth of sillimanite. Also garnets have been seen to include fibrolite and, therefore, some garnets grew after the first growth of sillimanite (Plates 31a, 31b).

The above evidence indicates the following growth history of garnet:

(i) Pre-F2 and pre-early sillimanite

(ii) Syn-F2 and post-F2

(iii) No new growth during or after F3.

A few garnets have been found with a distinct zoned arrangement of inclusions (Plate 32a). Commonly these 'zoned' garnets have an inclusion free core which is outlined by a zone of fine quartz inclusions which may be accompanied by biotite and opaque minerals. The outer garnet also tends to be free of inclusions and may be xenoblastic to idioblastic. Similar inclusion patterns have been recorded by Howkins (1961) and Dalziel (1963). Dalziel suggests that this type of internal structure may be due to expulsion of inclusions during recrystallization of the porphyroblasts. It is also possible that the inclusion free areas of the garnet represent zones of slow garnet growth, thus allowing for complete absorption of the inclusions and, that the zone of inclusions represents increased rate of garnet growth with attendant preservation of the partially absorbed inclusions (cf. Rast & Sturt 1957). Another interesting type of porphyroblast found has a mica free halo of quartz and oligoclase. The most likely explanation of this phenomenon is that the garnet has grown at the expense of the mica adjacent to it. Chloritisation of garnet occurs locally, which probably took place after F4, since its occurrence is not related to the development of F4 structures.

iii) Growth of Staurolite.

Staurolite has only been found in one sample from the Glen Moidart striped-pelitic rocks, in the Glen Gluitanen area (loc. F11-4; Fig. 6). The staurolite is hypidioblastic and appears to be partly replaced by quartz and felspar, since fragments of the main crystal are isolated in the ground mass (Plate 32b). Sillimanite lying in the schistosity of the ground mass is overgrown by staurolite and elliptical inclusions of quartz form a trail sub-parallel to the schistosity of the ground mass. Staurolite, therefore, grew after the first growth of sillimanite.

iv) Growth of Sillimanite.

Sillimanite occurs usually with biotite, quartz and muscovite in pods oriented with their longest axes sub-parallel to $S_s - S_1$ or S_2 (Plate 25b). The sillimanite within the pods is predominantly fibrolite, but small discrete crystals of sillimanite are sometimes seen surrounded by fibrolite felts. Sillimanite porphyroblasts also occur in one locality (loc. E9-16; Fig. 6). These are xenoblastic and where broken, fibrolite is sometimes found in the cracks.

The fibrolite is commonly intimately intergrown with biotite and frequently is seen to have grown on the biotite. However, fibrolite felts also occur in the absence of biotite. The impression gained from inspection of sillimanite with biotite in thin sections (Plate 33a) is that the biotite has actually been partly replaced by the sillimanite, rather than the biotite merely acting as a nucleating agent. (Chinner 1961). Some potash felspar, haematite and magnetite occur where the sillimanite pods are found and, therefore, the complementary reaction products exist to support this hypothesis. However, the possibility that sillimanite crystallized at the expense of unstable kyanite cannot be excluded. No kyanite has been recognised in the area mapped.

The sillimanite pods elongated in $S_s - S_1$ have been folded during F2 and subsequent movements and, therefore, the pods must have formed prior to F2. Plate 33b illustrates a sillimanite pod that is oriented in $S_s - S_1$. The fibrolite within the pod is parallel to S_2, the F2 axial plane cleavage. The shape of the pod and its ragged boundary suggest that the pod has been displaced along the cleavage planes outlined by the fibrolite. The pod undoubtedly formed before or early in F2. The fact that the fibrolite is oriented parallel to S_2 suggests that it recrystallized during F2. Where pods are found in $S_s - S_1$, in the absence of S_2, the fibrolite is invariably sub-parallel to the elongation of the pod. Therefore, sillimanite probably crystallized before F2 in $S_s - S_1$ and where F2 movements caused shearing of the pods, the fibrolite recrystallized sub-parallel to S_2. In some instances the pods aligned in $S_s - S_1$ have been folded during F2 rather than sheared and here the fibrolite has folded and recrystallized. Plate 34a is an example of a pod aligned in $S_s - S_1$ which has been partly folded during F2 and partly sheared. Where folding has occurred, the fibrolite has recrystallized mimetically and where the pod has been sheared along S_2 new sillimanite has grown. However, the sigmoidal shape of some of the fibrolite felts suggests that the cleavage is primarily a crenulation cleavage and that probably some of the fibrolite rotated towards S_2, rather than crystallized in S_2. Some pods are elongated sub-parallel to S_2. The shape of these pods is variable. Some are disc shaped and show no lineation within S_2. Others are elongated within S_2 sub-parallel to adjacent F2 minor fold axes and some are elongated in S_2 at a high angle to adjacent F2 minor fold axes. Dalziel (1963; p. 140) has reported sillimanite pods from the Loch Shiel - Loch Eil area, which are elongated in S_2 at 60 degrees to the F2 fold axes. He considers that this orientation may be parallel to the a direction of the F2 folds. The fact that some pods seen in the area presently under discussion are oriented sub-parallel to local minor F2 fold axes may be a reflection of extension in this direction. It has not been possible to relate the various orientations of the sillimanite pods to structural movement directions.

The fibrolite within the pods oriented sub-parallel to S_2 is either sub-parallel to S_2 or crenulated with axial planes parallel to S_2. These pods may have formed in S_s - S_1, prior to F2 and then have been rotated into S_2 during F2. There is no reason, however, for rejecting the possibility that new sillimanite pods formed in S_2 during the second fold movement. Since new fibrolite crystallized in the pre-F2 pods during F2, new pods may well have formed at this time.

No pods of sillimanite have been found elongated in the axial planes (S_3) of the F3 folds. Pods lying in S_s - S_1 or S_2 have been folded during F3. The fibrolite within the pods forms small crenulations. Under high magnification there is often evidence of mimetic recrystallization of the fibrolite. However, in some pods the fibrolite appears to be bent, with little or no recrystallization (Plate 34b). Plate 35a illustrates a pod lying in $S_s - S_1$ which has been folded during F3. The edge of the pod is outlined by a thin zone of muscovite. The small muscovite crystals include and mimetically replace fibrolite. No bent fibrolite is seen in this pod under high magnification and a few needles of the fibrolite are oriented sub-parallel to S_3.

From the above evidence it is concluded that sillimanite first crystallized prior to the second fold movement. Recrystallization took place during and probably after F2. New sillimanite was generated during F2. No new sillimanite formed during or after F3, but sillimanite partly recrystallized during F3. By the end of F3 the metamorphic grade was probably below that of sillimanite. Some alteration to muscovite occurred mimetically and, therefore, probably occurred towards the close or immediately after F3. Widespread retrogression to muscovite was, however, post F3 and probably post F4, since large muscovite porphyroblasts with randomly oriented cleavages have partially replaced some of the sillimanite pods (Plate 35b).

v) Growth of Felspar - Migmatisation

Both pelitic and psammitic rocks have been regionally migmatised throughout the area mapped. Migmatisation has profoundly effected the pelitic rocks and quartz-felspar foliae are extensively developed. In places the quartzo-felspathic material predominates over the pelitic material (Plate 27b). In the psammitic rocks, quartz-felspar foliae and pegmatite 'knots' and stringers are ubiquitous, but are not as uniformly pervasive as in the pelitic rocks. The felspar in the foliae is predominantly oligoclase, but minor amounts of potash-felspar locally occur. Where sillimanite-muscovite pods have developed in the pelitic rocks, potash-felspar is invariably present (see p. 175). Potash-felspar in the ground mass of psammitic rocks is usually as abundant as oligoclase and it is considered to be primary in origin.

The quartz-oligoclase foliae lie primarily in $S_s - S_1$ and where folded by F2 minor structures they are cut by axial plane cleavage (S_2). Where penetrative movement has occurred along S_2 the foliae are also displaced. Concordant sheets of quartz-oligoclase pegmatite commonly occur and these also have been folded and cleaved by F2 movements (Plates 27a & 24a). This evidence indicates that migmatisation first occurred prior to the formation of F2 axial plane cleavage.

Quartz-oligoclase sheets are also found oriented parallel to the axial planes of F2 minor folds and these must have formed during or after F2. No such sheets are generally found parallel to the axial planes of F3 minor folds. However, thin pegmatite stringers are occasionally found within joint planes sub-parallel to F3 minor fold axial planes (Plate 19b). Porphyroblasts of plagioclase occur in the pelitic rocks and they frequently contain inclusions of ground mass size. Also some porphyroblasts have been found to have overgrown sillimanite (Plate 36). No porphyroblasts of oligoclase have been found overgrowing an F3 crenulation. Plagioclase porphyroblasts grew after the first formation of sillimanite and after the coarsening of the fabric of the ground mass.

Porphyroblasts have been found containing inclusions of quartz and mica of ground mass size which are aligned parallel to the schistosity of the ground mass. No trails of inclusions have been found to suggest that the plagioclase porphyroblasts grew synkinematically. It is suggested that they grew after F2 and were formed later than the main migmatisation. The relationship between the porphyroblasts and F3 is not clear since few large plagioclase crystals have been seen together with an F3 crenulation. However, no porphyroblasts have been found which have overgrown an F3 fabric and mica forming F3 crenulations either is truncated by the porphyroblasts or is deflected around them. There is, therefore, no evidence of growth of new plagioclase during F3.

A few small stringers of potash-felspar, oligoclase and quartz have been observed in thin sections. They are rare occurrences and the exact time of their formation is not known. A few potash-felspar crystals have been noted in both pelitic and psammitic rocks, which are larger than the grains of the ground mass. In a few instances these porphyroblasts have overgrown mica, quartz and plagioclase of near ground mass size. Where potash-felspar porphyroblasts occur, myrmekite is invariably developed in adjacent plagioclase. Only one occurrence of a potash-felspar porphyroblast in contact with a plagioclase porphyroblast has been recorded. In this instance, the plagioclase has developed extensive myrmekite and embayments into the potash-felspar porphyroblasts occur. The significance of the myrmekite is not clear and it is not certain whether the myrmekite formed as a result of replacement of the potash-felspar or by exsolution (Sen 1959; Carman and Tuttle 1963).

Partly concordant and partly discordant pegmatites are found which cut F2 minor structures and are folded around F3 minor structures. Dykes of pegmatite also occur which cut the minor structures of the four fold movements. Some of these late stage dykes are up to six feet thick. The macroscopic pegmatite bodies are shown on Map I.

It is concluded that migmatisation was initiated prior to the second fold movement and pegmatites only formed locally after F2. Felspar porphyroblasts probably grew after F2. No new felspar is thought to have formed in the metasediments during or after F3, but since no unhealed strain effects have been recorded prior to the end of F4, recrystallization must have continued up to this time.

b. Growth of Minerals in the Calc-silicate rocks.

Recrystallization of the calc-silicates probably first took place during the initial regional metamorphism - ie. prior to F2. However, the present fabric of the calc-silicates only adequately demonstrates the existence of a syn- or post- F2 metamorphism. Growth of minerals has occurred along $S_s - S_1$

and S_2. Hornblende with intergrown clinopyroxene has grown along S_2 and is also found oriented with the long axes of the prisms roughly sub-parallel to F2 axial structures (Plates 26a, 26b). Garnets are usually 'spongy' and are often elongated in the bedding-schistosity, but do not have a distinct linear alignment.

The orientation of hornblende prisms indicates that metamorphism of the calc-silicates took place during or after the second fold movement. Since the alignment of hornblende prisms in S_2 is often very weak, with some crystals aligned with their long axes across S_2, it is thought that growth of hornblende probably occurred mimetically after F2. According to Fyfe, Turner and Verhoogen (1958, p. 231), epidote minerals should be absent from the calcareous assemblages of the sillimanite - almandine sub-facies. However, beta zoisite occasionally occurs as small hypidioblastic crystals in the labradorite-bytownite, pyroxene bearing calc-silicate rocks. This beta zoisite may, therefore, be a relic of an earlier metamorphism. However, the beta zoisite could also be a product of retrogression or may, in fact, have crystallized at sillimanite grade (Miyashiro and Seki 1958). The presence of basic labradorite rather than bytownite or anorthite may also be due to retrogression. Pyroxene is sometimes seen to be altered to actinolitic amphibole which is randomly oriented. This may be due to late stage retrogression.

c. Growth of Minerals in Garnetiferous Amphibolite Schists.

The amphibolite bodies are generally not well foliated since micaceous minerals are not present in abundance. Hornblende prismatic sections tend to lie in $S_s - S_1$ and/or S_2. Biotite when present is oriented with (001) lying in the same S-surface as the hornblende, and is often seen to be a replacement of the hornblende.

F3 crenulations in the amphibolites have not given rise to bent or strained crystals and, therefore, complete recrystallization occurred during or after the third fold movement.

Garnets sometimes have inclusions of fine quartz grains. These inclusions are usually randomly oriented but a few trails have been noted. Some straight trails of fine inclusions are not oriented parallel to the schistosity in the ground mass and may be a relic of an early fine grained schistosity (see p. 172). A few garnets have been found with curved inclusion trails similar to the example described on page 172 and these are also considered to be demonstrative of syn-F2 growth. Some garnets have been partly or completely replaced by plagioclase and the resulting 'eye' is filled with plagioclase, quartz, biotite and sphene. Hornblende is also sometimes partly replaced by plagioclase.

It is concluded that garnets probably grew prior to F2, during F2 and after F2. There is no evidence of garnet growth during or after F3. Hornblende recrystallized during F2 and F3. There is no evidence of garnet retrogression during F3.

IV. METAMORPHISM (Continued)

4. CONCLUSIONS

Observations in the field and microscopic textural studies have thrown little light on metamorphic conditions prior to F1. The metasediments were foliated prior to F2 and micas have grown sub-parallel to the axial plane cleavage of F1 minor folds. Therefore, crystallization of the rocks started during or shortly after F1. Quartz sheets lying in S_s and folded by F1 minor folds may have been formed prior to or during F1, but no positive example of displacement of quartz sheets by F1 axial plane cleavage has been found in the area mapped.

Sillimanite first grew prior to F2 and migmatisation occurred prior to F2 and early in F2. It is probable that garnets grew before F2 and before the first growth of sillimanite. This conclusion may be supported by the observation of garnets with fine grained quartz inclusions. If the fine inclusions do represent a pre-F2 fabric, then the fact that some of the garnets have straight inclusion trails of fine quartz and biotite would imply post-F1 : pre-F2 garnet growth. The presence of beta zoisite in the calc-silicate rocks may also imply an early metamorphism below sillimanite grade. Staurolite, garnets and oligoclase porphyroblasts grew after the first growth of sillimanite. Some garnet and sillimanite is thought to have grown during F2 and there is evidence of garnet growth after F2.

Minerals in the calc-silicate rocks recrystallized mimetically after the cessation of F2 movements.

There is no conclusive evidence for the growth of new minerals during F3 but complete recrystallization of mica, quartz and felspar occurred. Some fibrolite needles are oriented with their long axes sub-parallel to the axial planes of F3 microscopic crenulations, but this may have been brought about by rotation from S_s - S_1 and/or S_2. Some fibrolite appears to have been bent during F3 and this indicates that the metamorphic grade had dropped below that of sillimanite by the end of F3. Muscovite has been found in one thin section to have mimetically replaced F3 crenulated fibrolite. All minerals affected by F4 movements have recrystallized. Muscovite porphyroblasts grew post mimetically after F4. Some weakly strained porphyroblasts are thought to be indicative of local post-F4 movements. Local retrogression of biotite and garnet to chlorite probably occurred after F4.

The relationships between the metamorphic events and the four fold movements are given in Fig. 26.

Although minerals grew at different times in the metamorphic history there is no evidence to suggest that growth was momentarily interrupted at any stage. The available evidence suggests that there has been a progressive increase in metamorphism up to sillimanite grade, with attendant migmatisation. However, the possibility that textural evidence of metamorphic discontinuities has been obliterated by later recrystallization and deformation cannot be discounted.

Comparison of these results with the structural and metamorphic relations proposed by Clark (1961), Howkins (1961) and Dalziel (1963) in adjacent areas indicates that although some differences are implied, the major relationships deduced in this area are of regional significance. Clark, Howkins, Dalziel and the present writer consider the main metamorphism and migmatisation to be post-F1 and pre-F2. Although Clark and Howkins could not date the first growth of sillimanite with certainty, they suggested that it grew prior to F2 and was nearly contemporaneous with migmatisation. This suggestion has been confirmed by Dalziel and the present writer. Also it is agreed that no new garnet growth occurred during F3 but that recrystallization of strained minerals generally continued until after the cessation of the last significant fold movement.

STRUCTURAL AND METAMORPHIC HISTORY OF EAST MOIDART AND WEST SUNART

FIG. 26

STRUCTURAL TIME SCALE		PRE-F1	F1	POST-F1, PRE-F2	F2	POST-F2, PRE-F3	F3	F4	POST-F4
STRUCTURE		BEDDING (S-S)	MINOR FOLDING BEDDING SCHISTOSITY (S-S) FOLIATION (S-1) ? LINEATION Deformation & disruption of quartz veins		FOLDING, FOLIATION (S2), LINEATION & BOUDINAGE Crenulation of S-S, S-1 Deformation & disruption of: Concordant pegmatites & quartz oligoclase foliae Sillimanite pods in S-S, S-1		FOLDING CRENULATION OF S-S, S-1 & S-2 LOCAL FOLIATION (S3) Deformation of preexisting pegmatites	MINOR FOLDING CRENULATION OF S-S, S-1, S-2 & S3	LOCAL FAULTS
SEGREGATION AND/OR INJECTION		QUARTZ VEINS BASIC INTRUSIONS		?— — — FORMATION OF REGIONAL MIGMATITES: — — Quartz oligoclase foliae in S-S, S-1 PEGMATITES: mainly concordant with S-S, S-1	Quartz-oligoclase foliae in S-2 — — — — → Pegmatite mainly concordant with S-2	←?— — ? Early appinite dykes	Minor pegmatite	←? — — — —	DISCORDANT PEGMATITES UNFOLIATED APPINITE MINOR INTRUSIONS
MINERAL GROWTH	PELITIC AND QUARTZO-FELSPATHIC ASSEMBLAGES	QUARTZ & FELSPAR	DEVELOPMENT OF SCHISTOSE FABRIC	— — — — Growth: — — — — regional migmatites	— — COARSENING OF FABRIC — — Continued growth, recrystallization	— — — — →	RECRYSTALLIZATION	AT LEAST LOCAL RECRYSTALLIZATION	HYDROTHERMAL ALTERATION
		MICA		— — — — — — — —	— — — — — — and transposition Growth on S-S, S-1 & S-2 — — —	— — — — → — — — — →			
		GARNET		Static growth — — — — — —	— Syntectonic growth — — — —	— Static growth →		←?— —	Local retrogression to biotite & chlorite
		STAUROLITE		— — — — — Overgrows sillimanite	— — — — — — — —	— — — — →			
		SILLIMANITE		— — — Growth on S-S & S-1 — — —	Growth on S-S, S-1 & S-2 — — — — — — — Transposition & recrystallization	— — — — →	Local recrystallization	←? — —	Retrogression to muscovite
	BASIC ASSEMBLAGE		DEVELOPMENT OF FINE FABRIC	Growth of garnet — — Hornblende affected by migmatization	Growth of garnet & hornblende — — — — — — Coarsening of fabric	— — — — →	Recrystallization	←?— —	Minor retrogression
	CALCAREOUS ASSEMBLAGE			?Growth of garnet & zoisite — — — — — —	Growth of garnet hornblende & pyroxene — — — — — — Coarsening of fabric on S-S, S-1 & S2	— — — — →	Recrystallization	←?— —	Minor retrogression

V. SUMMARY OF CONCLUSIONS

Four principal fold movements have been recognised. Nine major folds of the second movement and fourteen major folds of the third movement have been mapped, but the first and fourth movements generated only minor structures in the area studied.

Minor folds of the first fold movement are extremely rare. They occur as long limbed isoclines, with axial plane cleavage parallel to the bedding on the limbs.

Major and minor folds of the second fold movement vary from broad open structures to true isoclines. Measurement of second minor folds indicates that they are of "Similar type". However, it is suggested that the folds formed initially by a combination of flexure and viscous flow. A few "brittle" structures, thought to be associated with the second fold movement, have been found and it is suggested that these formed as a result of local increase in the rate of deformation. The majority of the second folds have a well developed axial plane cleavage and this frequently is accompanied by a mica crenulation.

The third folds vary from open to extremely tight, but are never isoclinal. They are usually accompanied by a well developed mica crenulation and, locally by an axial plane cleavage. Measurement of third minor folds and part of the Cruach à Ghaill major fold has demonstrated that these are modified flexural folds; ie. the folds were initiated by flexure which induced viscous flow with movement of material towards the crests, primarily in the less competent pelitic bands. Axial plane shear is not thought to be a dominant mechanism in the formation of these folds.

Considerable variation occurs in trend of the axial planes of major and minor third folds and is attributed primarily to the generation of conjugate and "M" shaped folds.

The regional strike of bedding-schistosity and foliation is from N-S to NNE-SSW. This trend swings to E-W around the more open third closures, giving rise to a regional E-W trend to the south of Loch Shiel.

The fourth minor folds are of limited extent and it is thought that this movement has had little or no effect on the macroscopic geometry. The minor folds are open structures which are usually accompanied by a mica crenulation. They are mainly of modified concentric style.

No major faults have been observed, but small displacements along approximately E-W trending joints have been noted. These joints are thought to have formed after the fourth fold movement. However, some N-S trending joints appear to be closely related to the third fold movement.

Since the structural geometry has been primarily determined by deformation during the second and third fold movements, the inter-relationships of these movements have been studied in detail. Extreme variation in the trend of second fold axes and axial planes has occurred and is attributed primarily to the superposition of the third folds. A major second antiform may change, along its axial plane trace to a neutral fold, then to a synform with reversal of closing direction, and finally to an antiform. Such variation requires the fold axis to swing both through the horizontal and vertical. The third fold axes vary in trend due to superposition of the folds on the previously folded surface. This variation, however, occurs through the vertical without a reversal in closing direction.

The third fold movement is considered to be three dimensional and it is concluded that no single direction of tectonic transport can account for the deformation of the second structures during this movement. It is suggested that the deformation ellipsoid during the third fold movement was oriented such that the longest axis was near horizontal, with an approximate N-S trend, and the intermediate axis was near vertical, with a shortening direction trending E-W.

By using the fold movements as "time markers", it is possible to relate the metamorphic history to the structural history of the area. The rocks were probably below garnet grade of metamorphism during the first fold movement, with the first garnet growth occurring prior to the second fold movement.

Sillimanite grade was attained prior to the second fold movement. This grade was maintained at least through the early stages of the second deformation and may have persisted until after the second fold movement had ceased. Migmatisation, involving the development of extensive concordant pegmatite stringers and quartzo-felspathic foliae, occurred prior to and continued during the second movement. No sillimanite or garnet is thought to have nucleated during the third or fourth fold movements, but mica, felspar and quartz were recrystallized. The metamorphic grade was probably below that of sillimanite at least prior to the cessation of the third fold movement. However, no general retrogression has occurred. No evidence has been found to suggest that mineral growth was momentarily interrupted at any stage. It is suggested that a progressive increase in metamorphism occurred up to sillimanite grade, with attendant migmatisation. The major structures formed after this peak had been attained.

The fold movements recognised in the Moidart-Sunart region have been correlated with those recognised in adjacent areas by Clark (1961) and Howkins (1961). It is concluded that the four fold movements recognised by the writer are equivalent to those recorded by Clark. Also, that the first, second and fourth movements recorded by Howkins in Western Moidart are equivalent to the first, second and third movements recognised by the writer in the Moidart-Sunart region. It is also inferred that at least the first and second fold movements mapped by Dalziel (1963), between Loch Shiel and Loch Eil, are equivalent to the first and second movements recognised by the writer.

By correlation with successions indicated by Howkins (1961) and Clark (1961), together with the succession recently established by Powell (1964) in the Lochailort area, it has been possible to show that the Glen Moidart Striped-Pelitic Group is stratigraphically above the Upper Psammitic Group of the Morar-Moidart succession. Further, it is suggested that the Beinn Gàire Psammitic Group can be correlated with the Upper Psammitic Group. Structural evidence also suggests that the Ben Resipol Pelitic Group can be correlated with the Glen Moidart Striped-Pelitic Group and it is inferred that the Achnanellan Striped-Pelitic Group may also be correlated with the Glen Moidart Striped-Pelitic Group.

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PLATE 1.

a. View looking south across Loch Shiel to Ben Resipol.

b. Cross-bedding (poorly defined).

Loc. B10-3

(From Psammite band within Glen Moidart Striped-Pelitic Group.)

(See Figure 6 for locations)

a

b

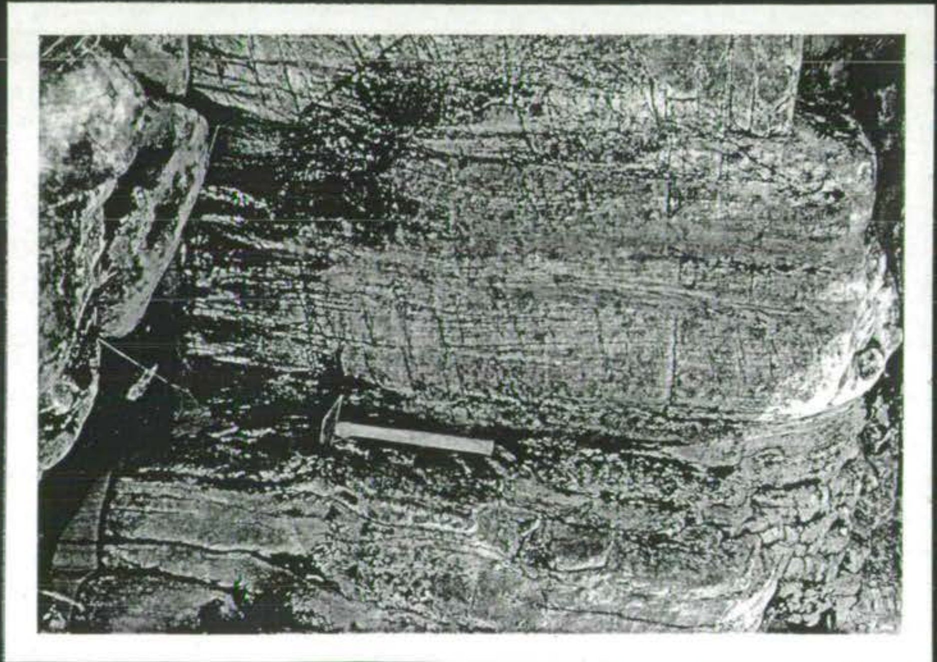


PLATE 2.

a. Garnet amphibolite lens in Achnanellan Striped-Pelitic Group.

Loc. A3-14

b. Coarse grained, unfoliated Appinite.

Loc. F10-7

2

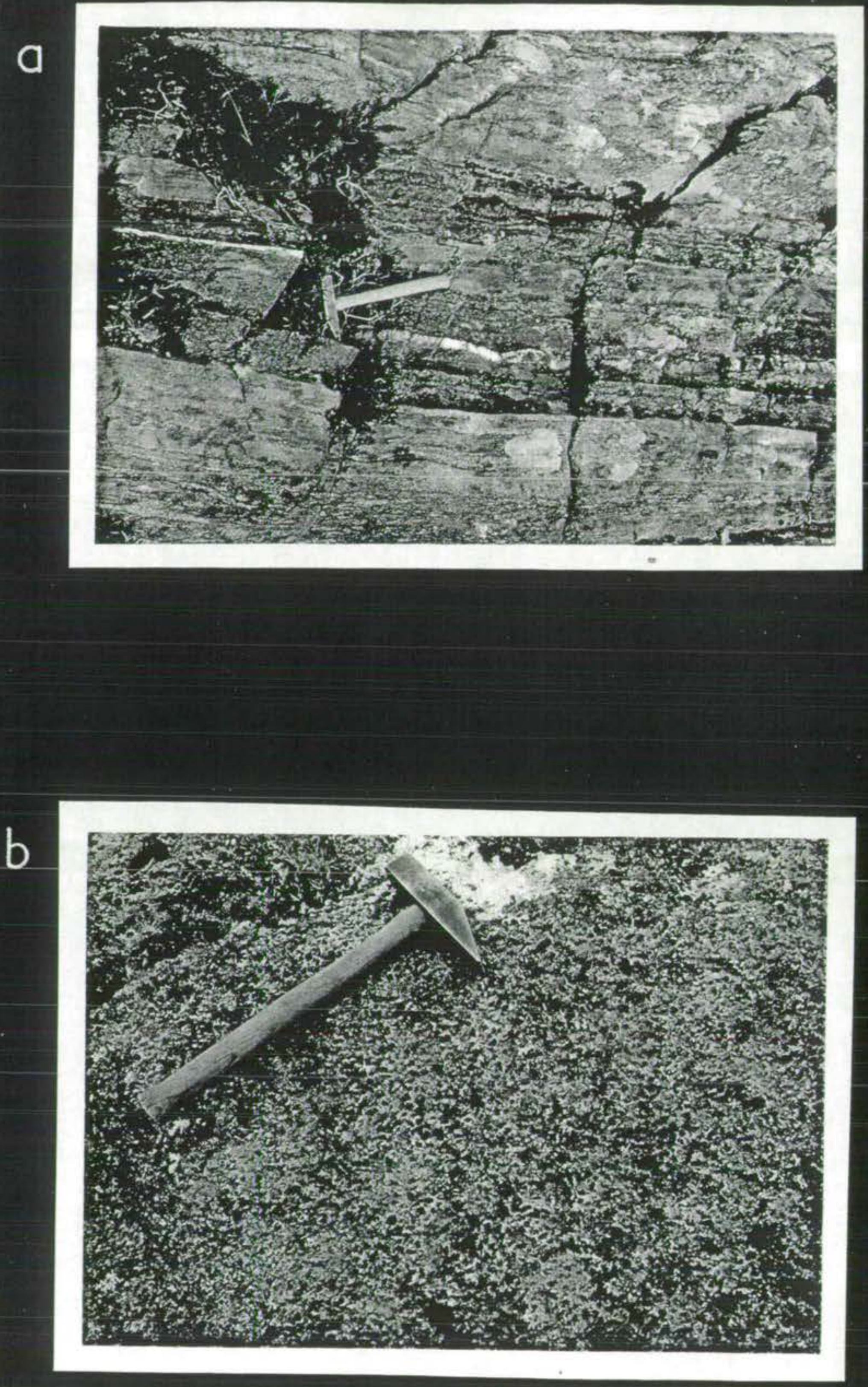


PLATE 3.

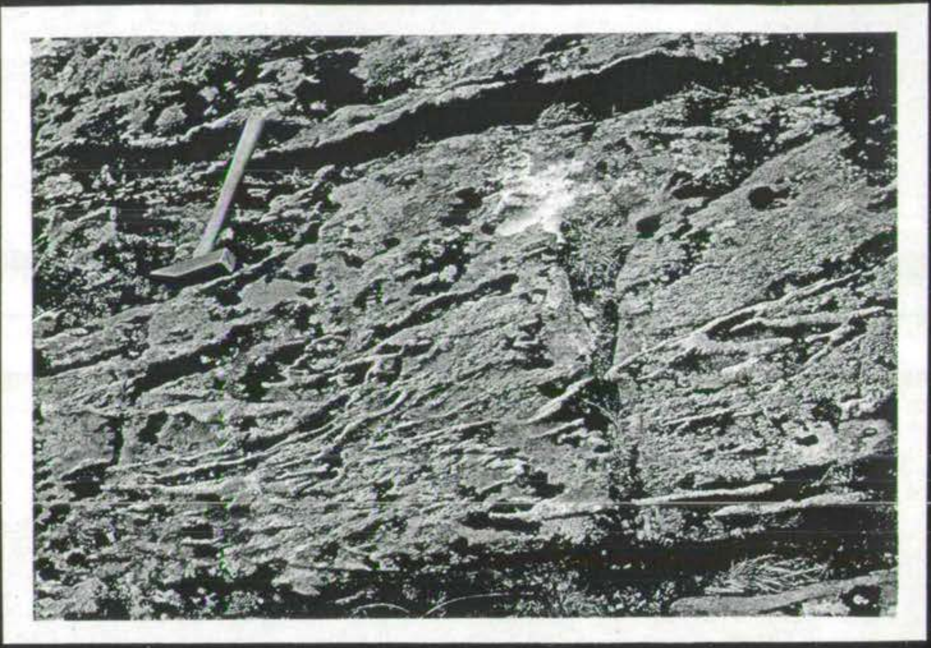
a. Appinite pervades Beinn Gàire Psammitic Group. Thin psammite bands outline relic F2. minor folds.

Loc. F8-6

b. Boudinage in Glen Moidart Striped-Pelitic Group, formed during the third fold movement.

Loc. C8-7

a



b

PLATE 4.

a. Boudinage in Ben Resipol Psammitic Group, formed during the third fold movement.

Loc. D15-8

b. F1 minor isocline refolded by F2 minor fold in Ben Resipol Psammitic Group.

Loc. D15-8

a

b

PLATE 5.

a. F2 minor folds of variable style in Glen Moidart Striped-Pelitic Group.

Loc. C10-1

b. F2 mesoscopic closure in Glen Moidart Striped-Pelitic Group. Note variation in style of F2 minor folds.

Loc. C7-10

a

b

PLATE 6.

a. F2 minor fold in Beinn Gàire Psammitic Group. Note incipient thrusting of gently dipping limb over the steeper limb.

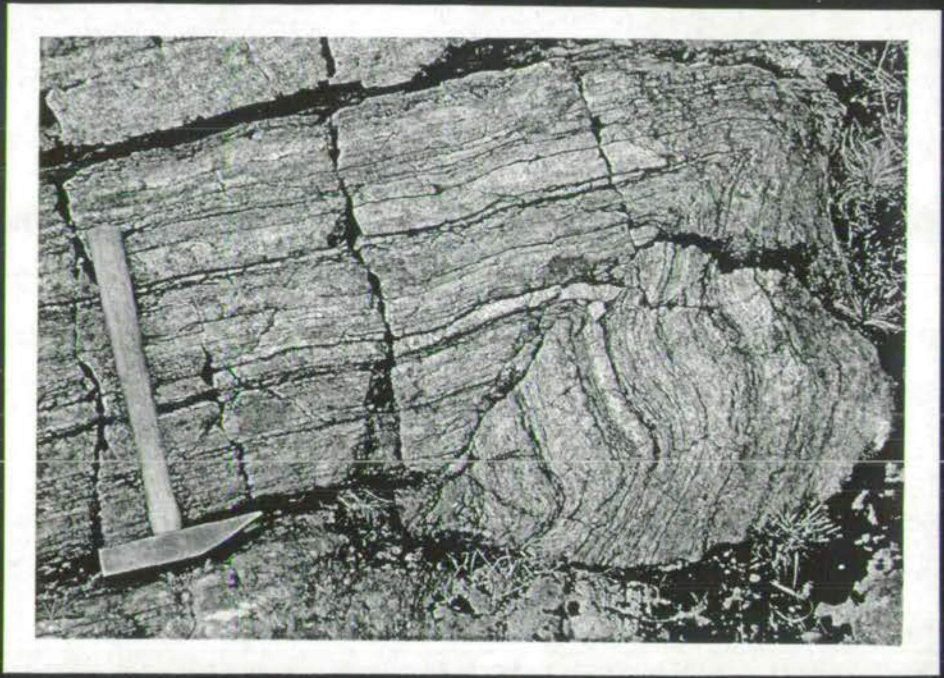
Loc. F8-1

b. F2 minor fold in Beinn Gàire Psammitic Group. Note displacement parallel to the axial plane and quartz stringer in the plane of displacement.

Loc. F8-5

6

a



b

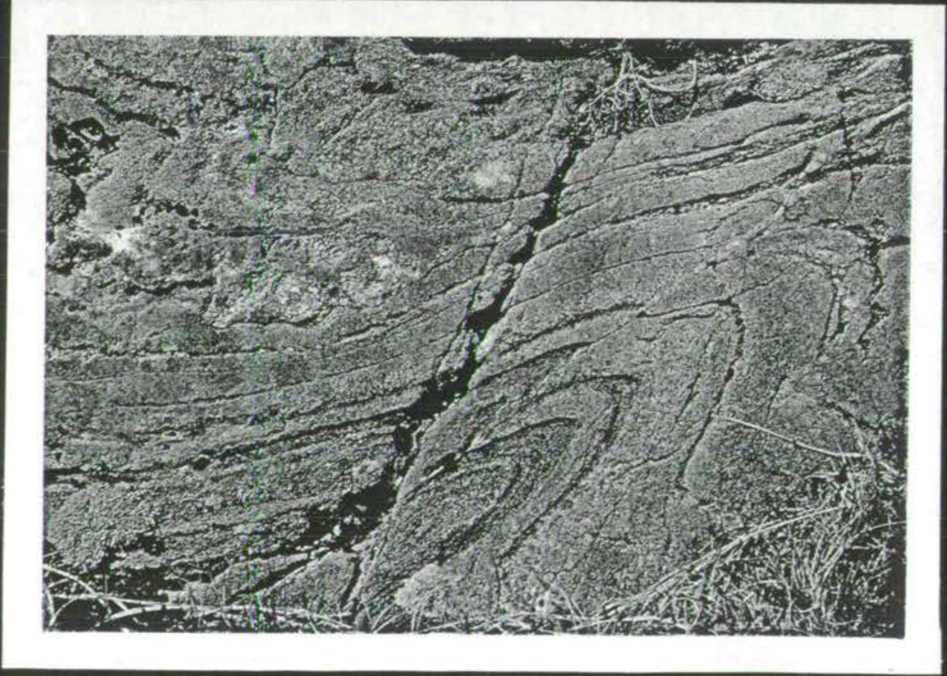


PLATE 7.

a. F2 minor folds in Ben Resipol Psammitic Group. Note the near Similar style of the folds and the increasing development of axial plane cleavage from left to right across the picture.

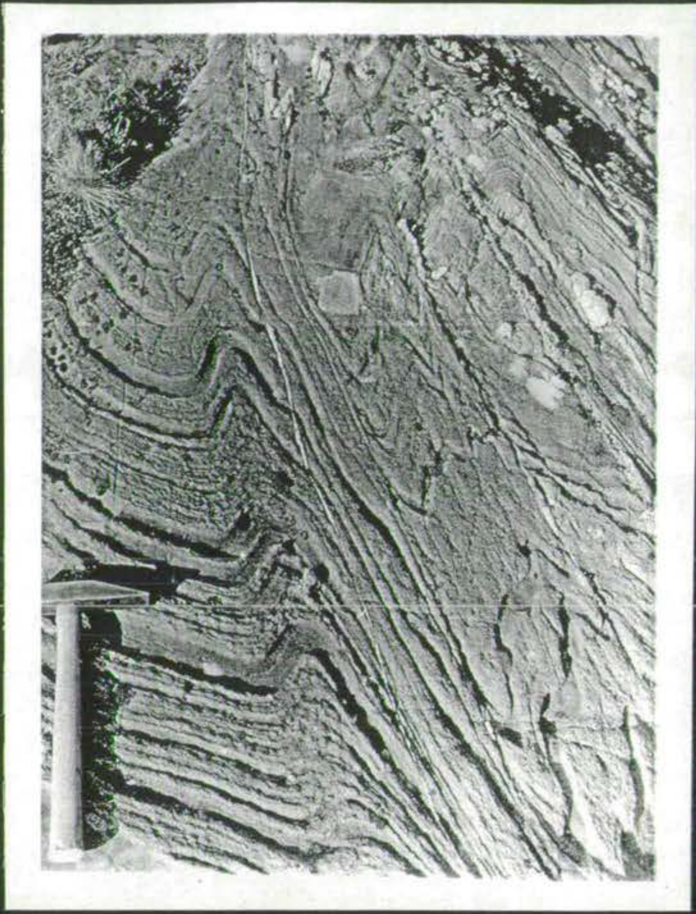
Loc. E13-8

b. F2 mesoscopic fold in Beinn Gàire Psammitic Group. The fold is nearly concentric; a strong axial plane cleavage is developed in the micaceous bands.

Loc. D8-2

7

a



b

PLATE 8.

a. Recumbent F2 minor folds in Beinn Gàire Psammitic Group.

Loc. D10-15

b. F2 minor folds developed in nearly massive psammite of the Coire Ladhair Mhòr Psammitic Group.

Loc. B11-5

a

b

PLATE 9.

a. F2 minor isoclinal fold in Beinn Gàire Psammitic Group.

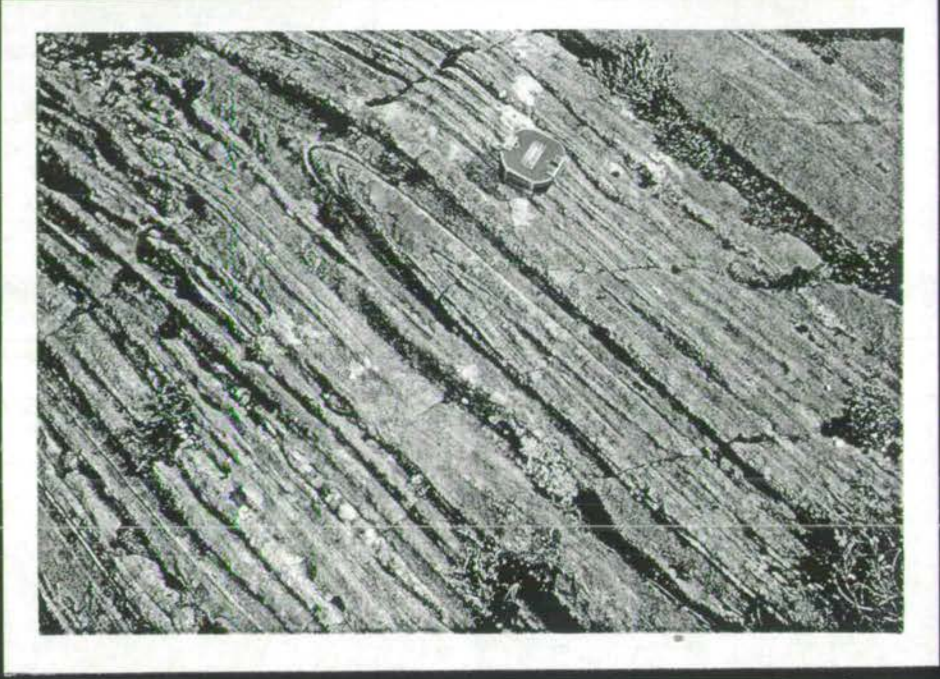
Loc. A5-10

b. F2 minor isoclinal folds preserved by psammite bands as tectonic inclusions in the Glen Moidart Striped-Pelitic Group.

Loc. D11-12

(Drawn from photograph)

a



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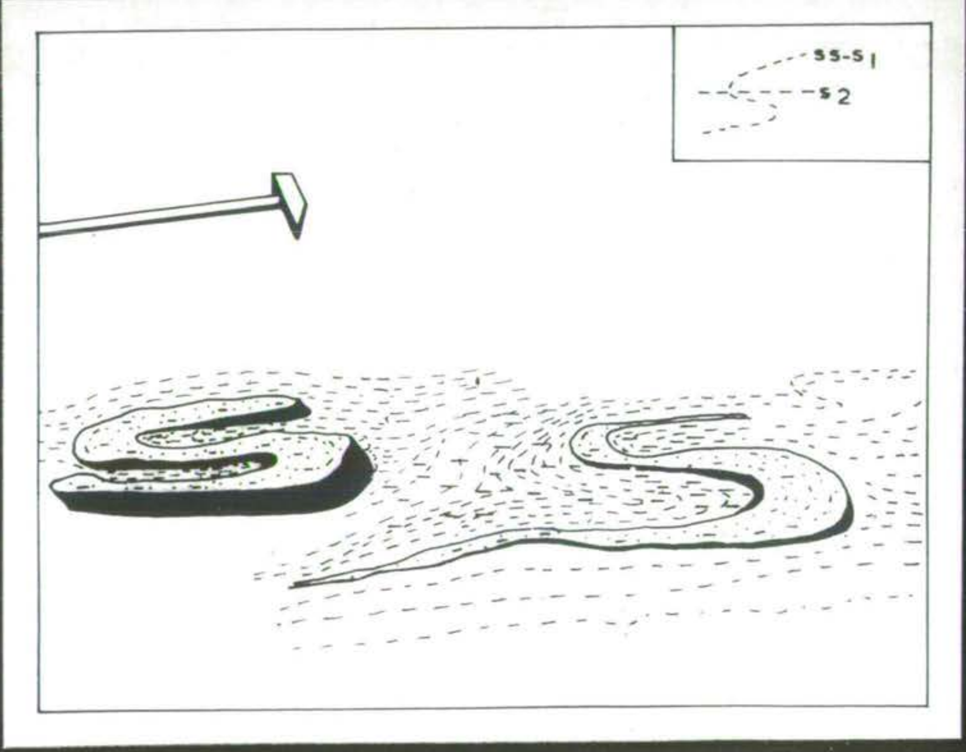


PLATE 10.

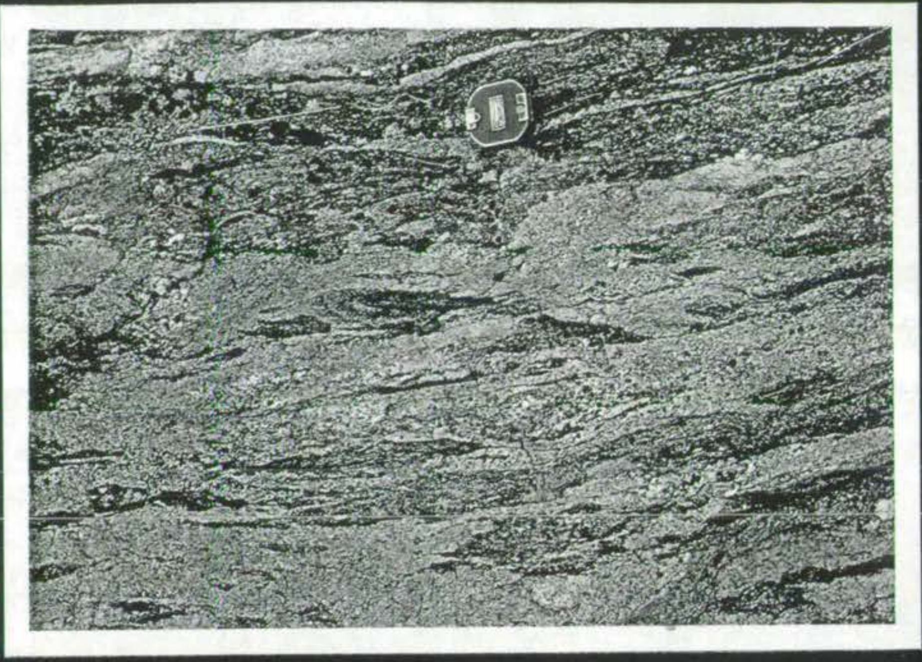
a. F2 minor folds in Glen Moidart Striped-Pelitic Group. Note the transposition of both psammitic and pelitic bands.

Loc. C11-5

b. Psammitic bands in Beinn Gàire Psammitic Group sheared and folded by F2 movements.

Loc. D10-15

a



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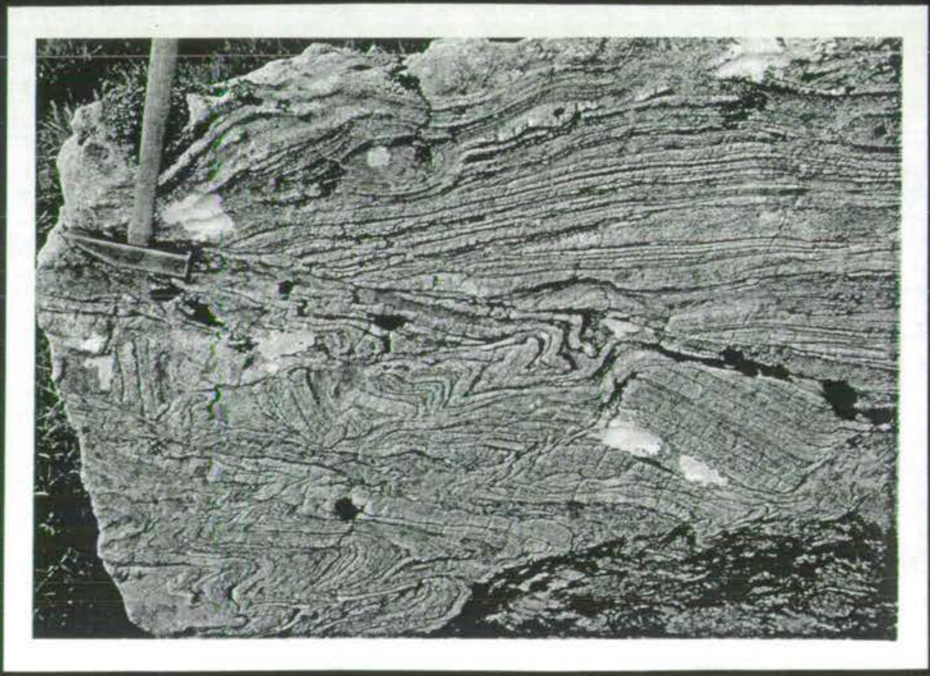


PLATE 11.

a. Quartz stringers in Glen Moidart Striped-Pelitic Group folded by F2.

Loc. C10-7

b. F2 minor folds in striped-pelitic zone within Beinn Gàire Psammitic Group. Strong foliation (S_2) is parallel to axial plane of minor folds.

Loc. E6-1

a

b

PLATE 12.

a. F2 and F3 open minor folds in Beinn Gàire Psammitic Group create "egg basket" effect. Hammer handle along F2 trend.

Loc. F7-2

b. F2 minor folds with curved axial planes due to flattening of one fold against the other. The penetration cleavage (S_2) has also been weakly crenulated by F3 movements. The folds are within a striped and banded zone of the Beinn Gàire Psammitic Group.

Loc. D4-10

a

b

PLATE 13.

a. F3 minor fold in Beinn Gàire Psammitic Group. Note the extensive thickening in the hinge, where the fold is well developed, and the fact that the fold dies out very rapidly.

Loc. A5-8

b. F3 minor conjugate fold in Ben Resipol Pelitic Group. Folds and mica crenulation are developed on NNE, NNW and NS trends.

Loc. D14-11

13

a

b

PLATE 14.

a. "Paired" F3 minor conjugate fold in Ben Resipol Pelitic Group.

Loc. D14-11

b. F3 minor conjugate folds generated by folding of concordant quartz bands in Coire Ladhair Mhòr Psammitic Group.

Loc. A12-16

14

a

b

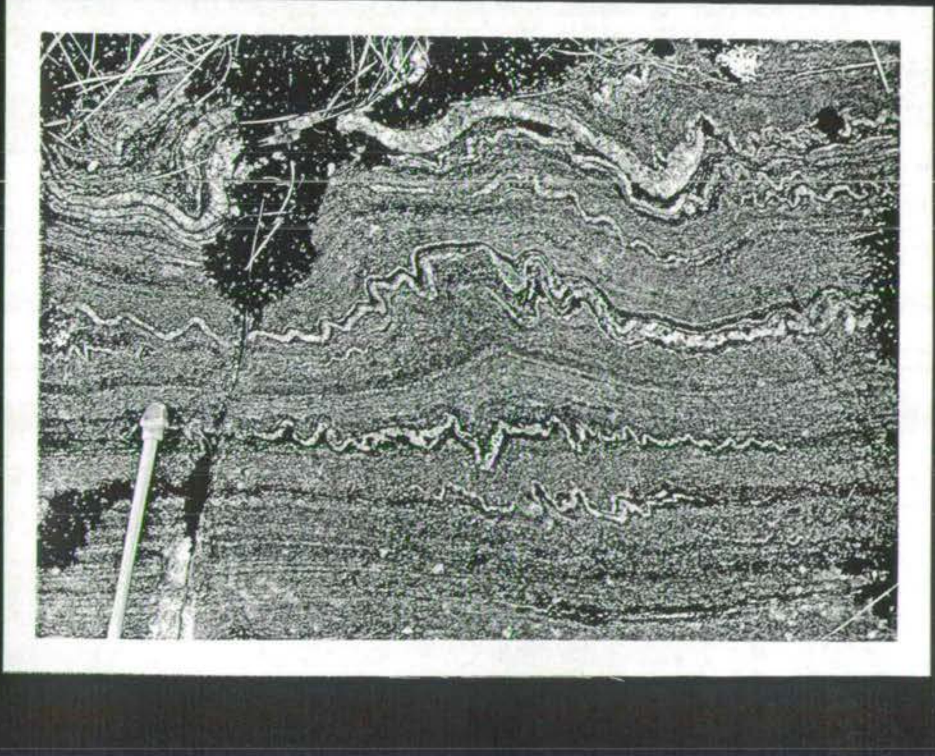


PLATE 15.

a. F3 minor conjugate fold in Glen Moidart Striped-Pelitic Group.

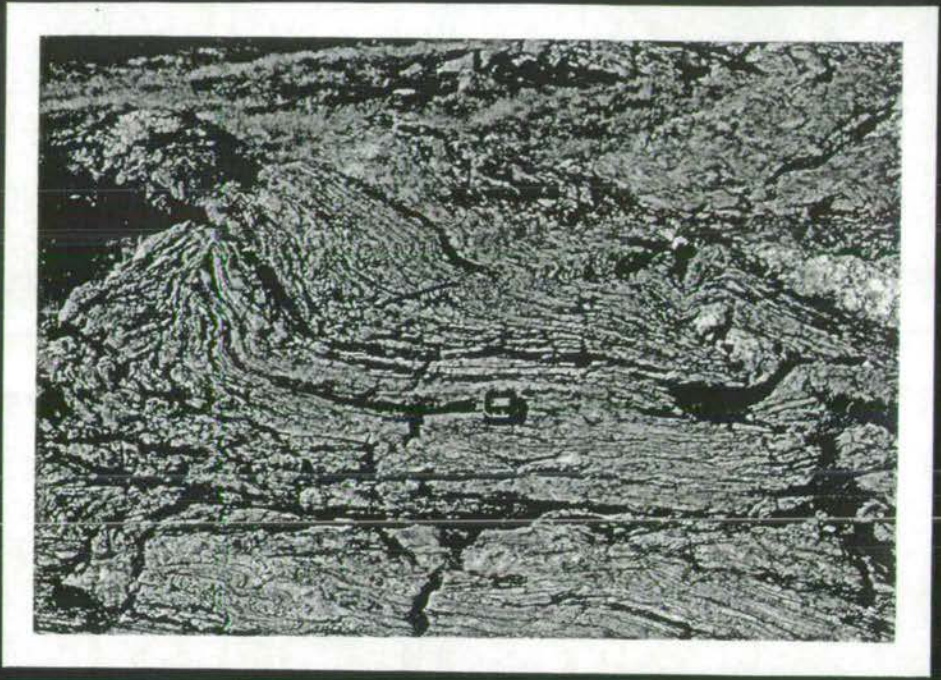
Loc. D8-15

b. F3 minor folds in striped and banded zone of the Ben Resipol Psammitic Group. Note the displacement parallel to the axial plane trends and tendency for the development of conjugate folds.

Loc. E14-9

15

a



b

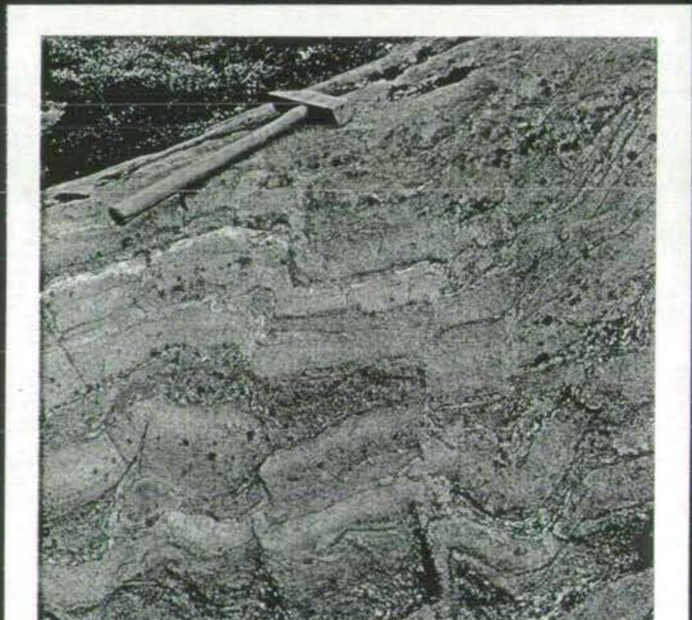


PLATE 16.

a. Open F3 minor folds with mica crenulation, developed in Achnanellan Striped-Pelitic Group.

Loc. A2-4

b. F3 minor folds in Ben Resipol Pelitic Group. Note the boudinage developed in "competent" psammitic bands.

Loc. D14-11

a

b

PLATE 17.

a. F3 minor folds developed in thin quartzite bands within relatively unfolded psammite of the Coire Ladhair Mhòr Psammitic Group.

Loc. A12-16

b. Open F3 minor folds have formed in thick quartzite band, whereas small tight minor folds have formed in thin quartzite bands. The adjacent psammitic rocks (Coire Ladhair Mhòr Psammitic Group) are relatively unfolded. The thick quartzite band is probably folded into a minor F1 isocline.

Loc. A12-16

a

b

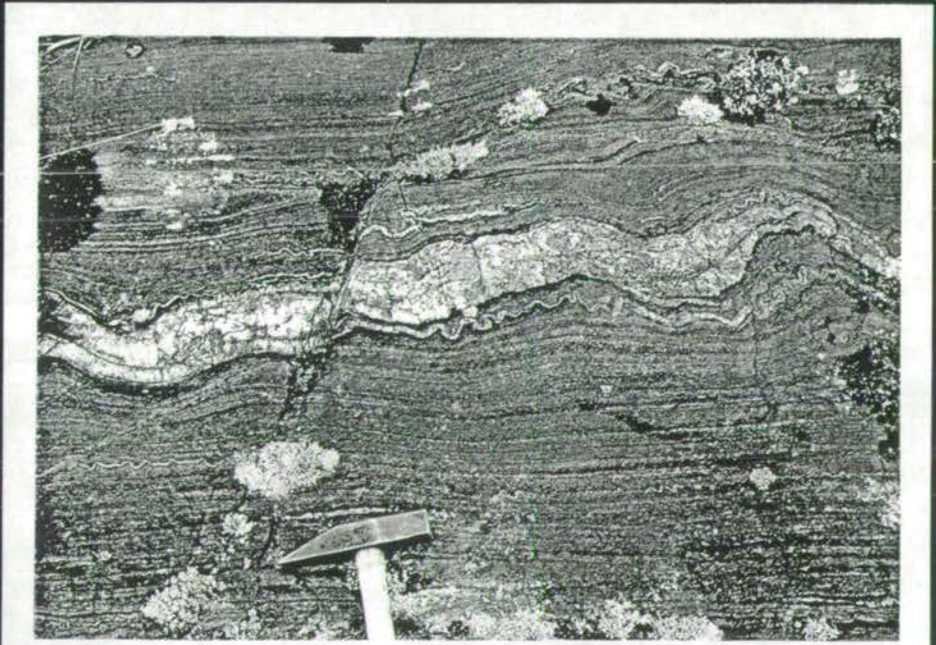


PLATE 18.

a. F4 minor folds and "kink bands" in Glen Moidart Striped-Pelitic Group.

Loc. B5-2

b. F2 minor fold refolded by F4 minor fold in the Achnanellan Striped-Pelitic Group. The F2 axial plane cleavage has also been crenulated by F4.

Loc. C1-1

a

b

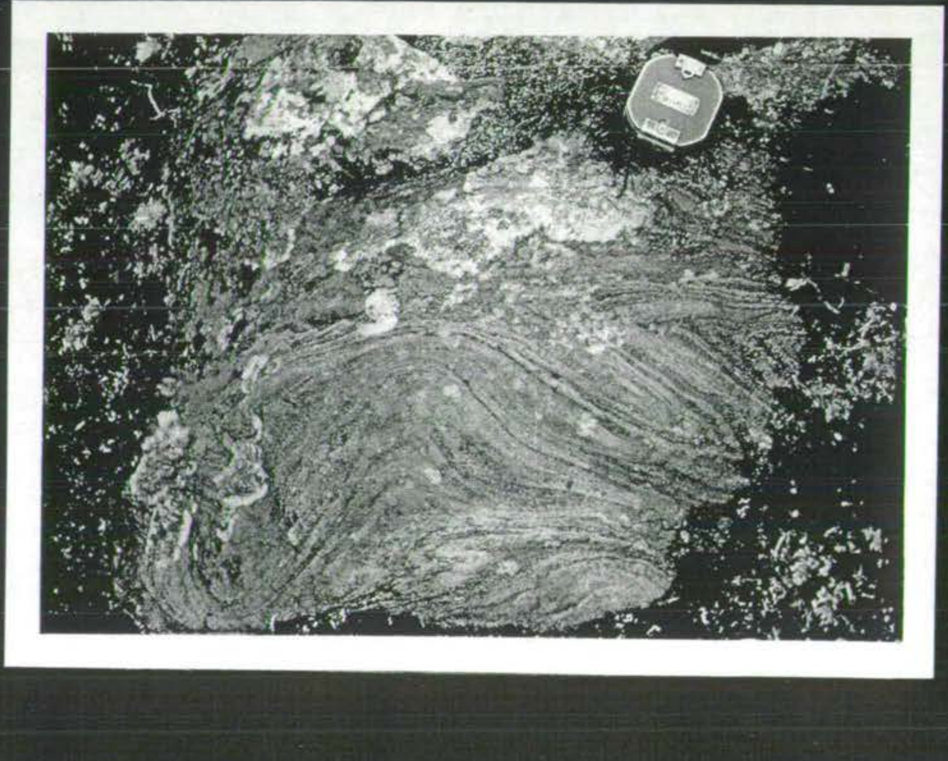


PLATE 19.

a. F2, F3 and F4 minor folds in Achnanellan Striped-Pelitic Group. F3 crenulation trends N-S up the photograph and F4 crenulation trends just S of E. The longer F2 minor folds are sub-isoclinal and are outlined by the thin psammitic bands.

Loc. C1-1

b. F2 minor fold, in quartzite band within Ben Resipol Psammitic Group, has been displaced along a N-S trending joint which is sub-parallel to adjacent F3 axial plane trends. Pegmatite has formed in the joint which has then been displaced by movement along bedding-schistosity.

Loc. D14-8

a

b

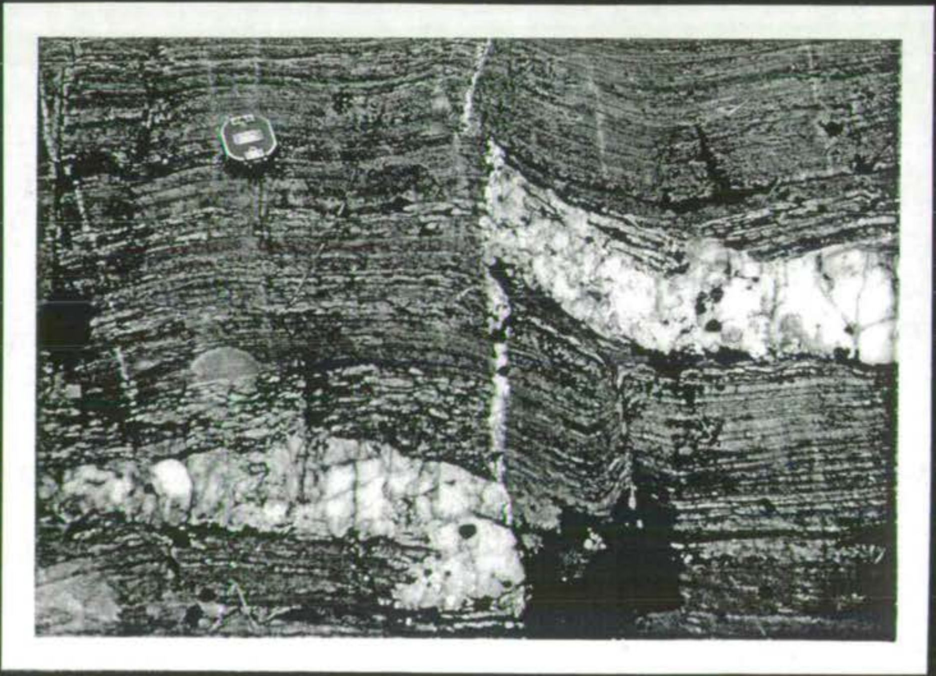


PLATE 20.

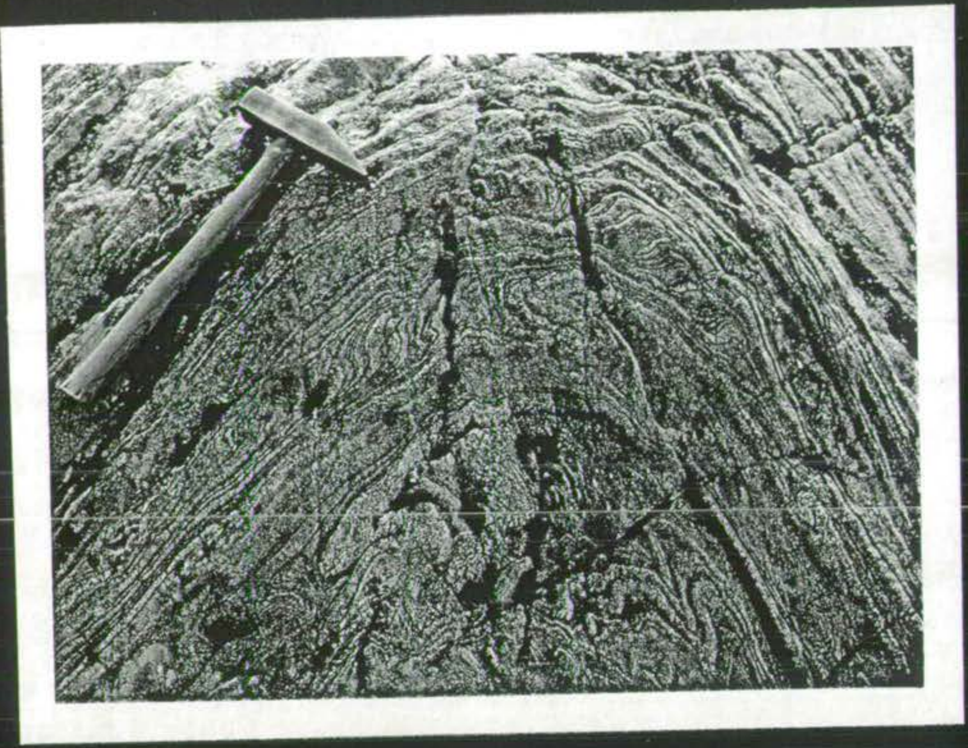
a. F2 minor folds refolded by F3 minor folds in Beinn Gàire Psammitic Group. The F2 minor folds vary considerably in style around the F3 minor fold. Note that the "S" and "Z" sense of F2 folds does not change around the F3 fold.

Loc. A5-8

b. F2 sub-isoclinal minor folds refolded by open F3 minor folds. Note that a thin pegmatite sheet cuts across both F2 and F3 minor folds. (Glen Moidart Striped-Pelitic Group).

Loc. C6-14

a



b

PLATE 21.

a. F2 minor fold refolded by F3 minor fold. The compass lies along the F3 minor fold axis. (Beinn Gàire Psammitic Group)

Loc. F9-16

b. F2 minor fold and F2 axial plane cleavage folded by F3 crenulations. (Ben Resipol Pelitic Group)

Loc. A15-10

a

b

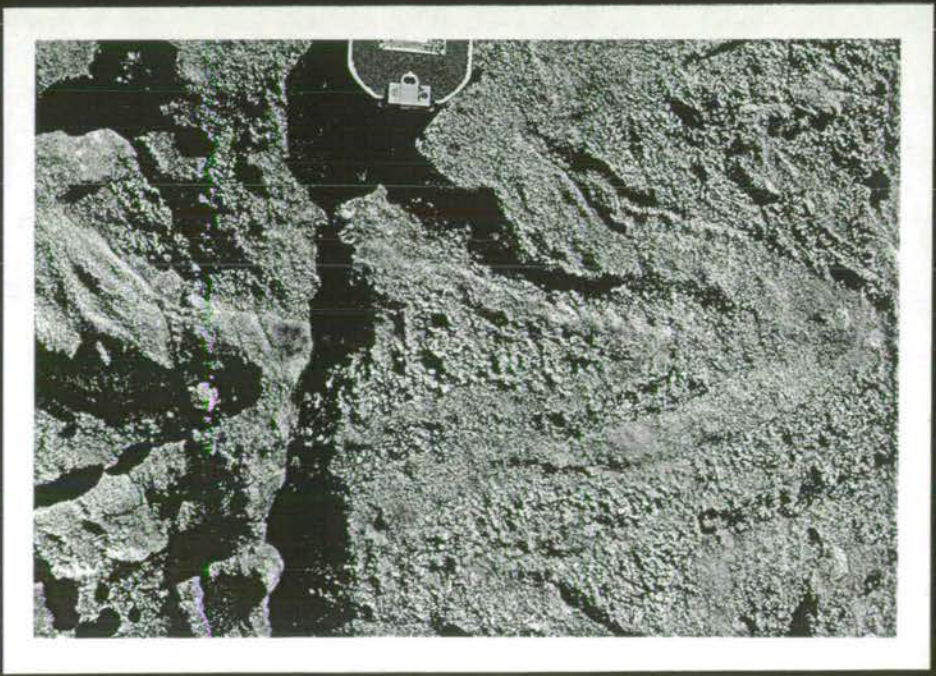


PLATE 22.

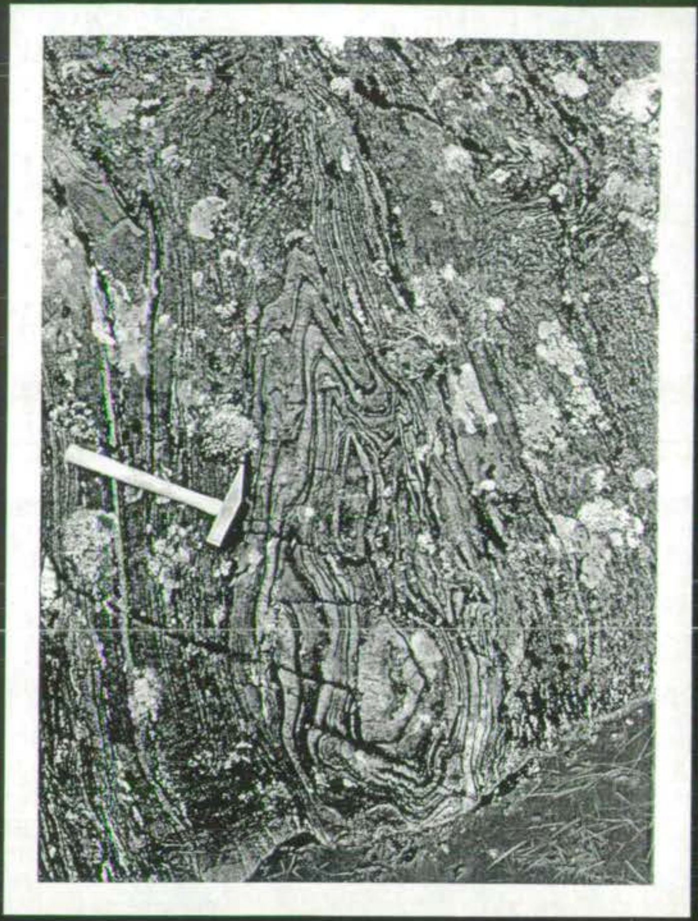
a. Refolding of F2 minor folds by F3, forms "eye" folds. (Striped-Pelitic band within Beinn Gàire Psammitic Group).

Loc. A6-13

b. F3 minor folds with axial plane traces trending approximately N-S from the top right hand corner of the photograph, to the bottom left hand corner, have refolded F2 minor folds, with axial plane traces trending approximately ENE-WSW. (Ben Resipol Pelitic Group)

Loc. E15-2

a



b

PLATE 23.

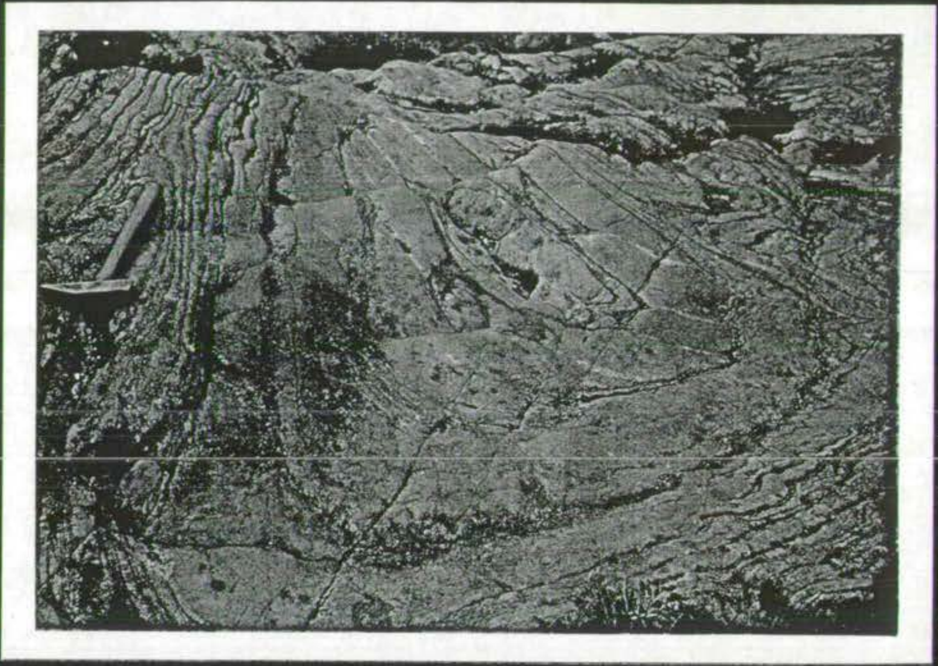
a. "Dunces Cap" formed by refolding of F2 minor fold by F3 minor fold. F3 axial plane trace trends from bottom left to top right of the photograph. F2 axial plane trace trends from bottom right to top left of the photograph. (Ben Resipol Psammitic Group)

Loc. D14-7

b. Mesoscopic F2 "eye" fold formed by refolding during F3. (Glen Moidart Striped-Pelitic Group)

Loc. C11-6

a



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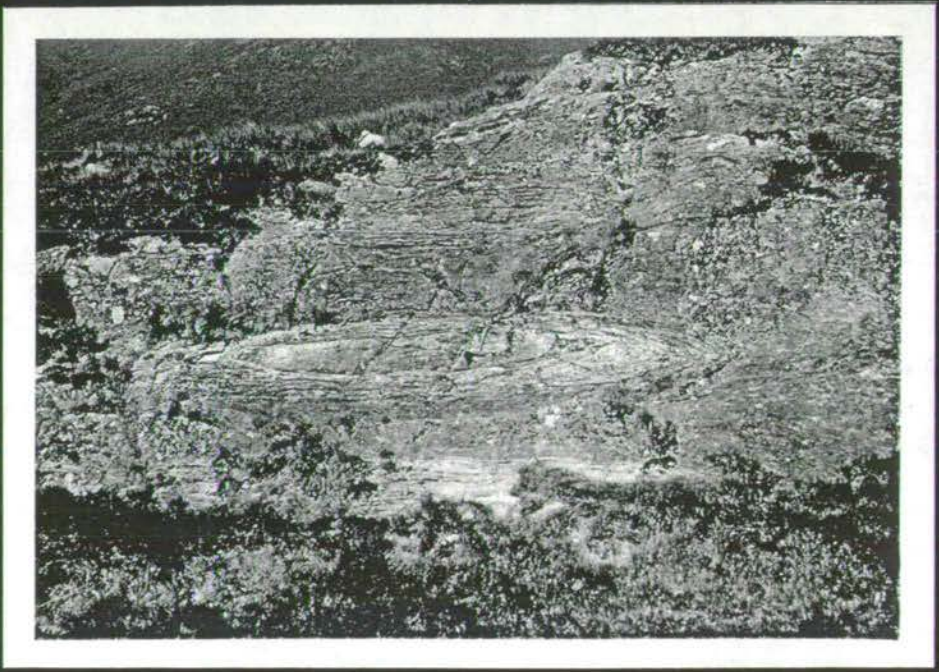


PLATE 24.

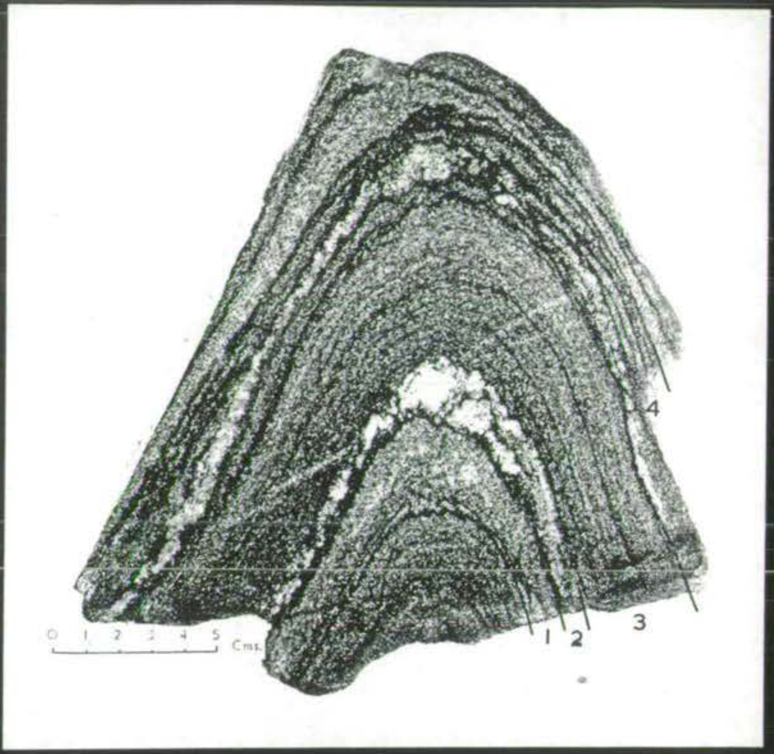
a. F2 minor fold in Beinn Gàire Psammite. Note the disruption of the concordant pegmatite bands by the weak axial plane cleavage. (See pp. 116-118 for analysis of fold style).

Loc. F9-16

b. F2 minor fold in psammitic band within Glen Moidart Striped-Pelitic Group. (See pp. 118-120 for analysis of fold style).

Loc. C6-12

a



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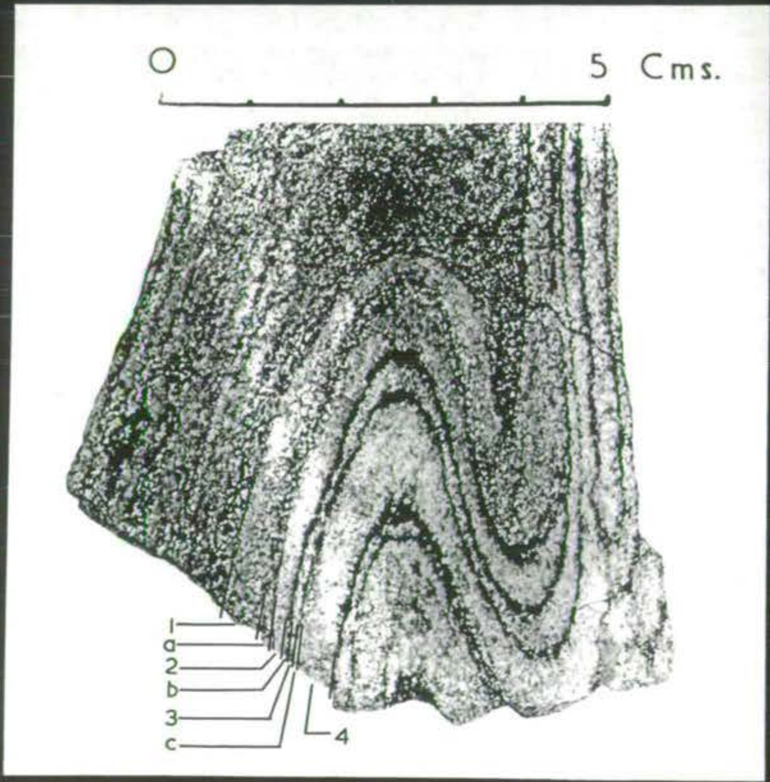


PLATE 25.

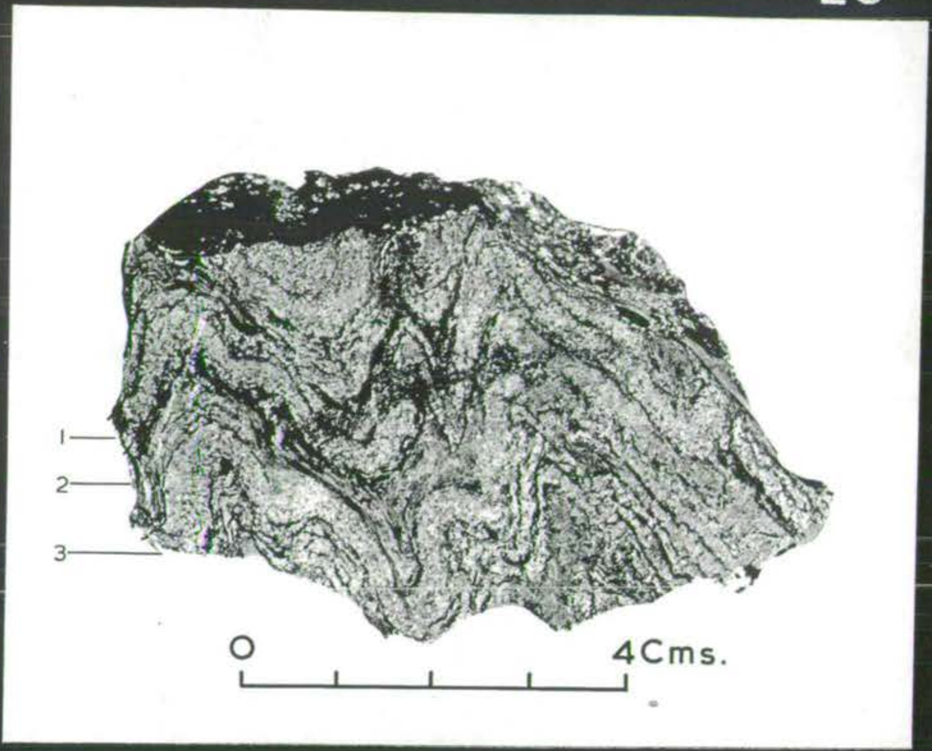
a. F3 minor folds in pelitic schist band within the Beinn Gàire Psammitic rocks. (See pp. 120-122 for analysis of fold style).

Loc. A6-4

b. Sillimanite pods in semipelitic rock within the Glen Moidart Striped-Pelitic Group. The pods in this example lie with their long dimensions in S_2 (sample is cut normal to S_2).

Loc. C7-11

a



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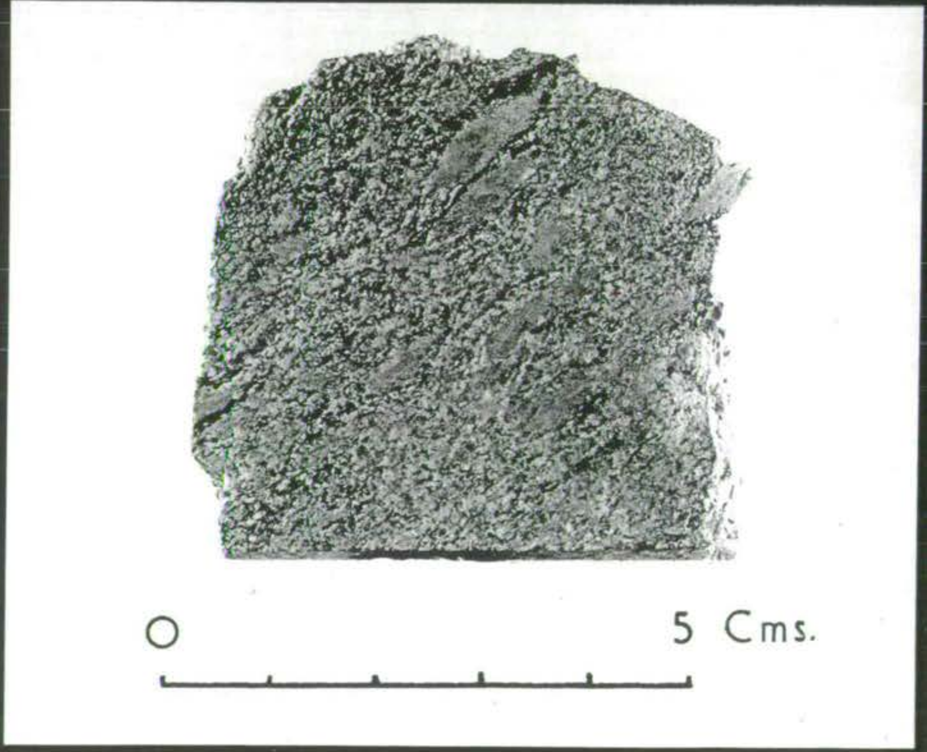


PLATE 26.

Samples of calc-silicate rock from Glen Moidart Striped-Pelitic Group.

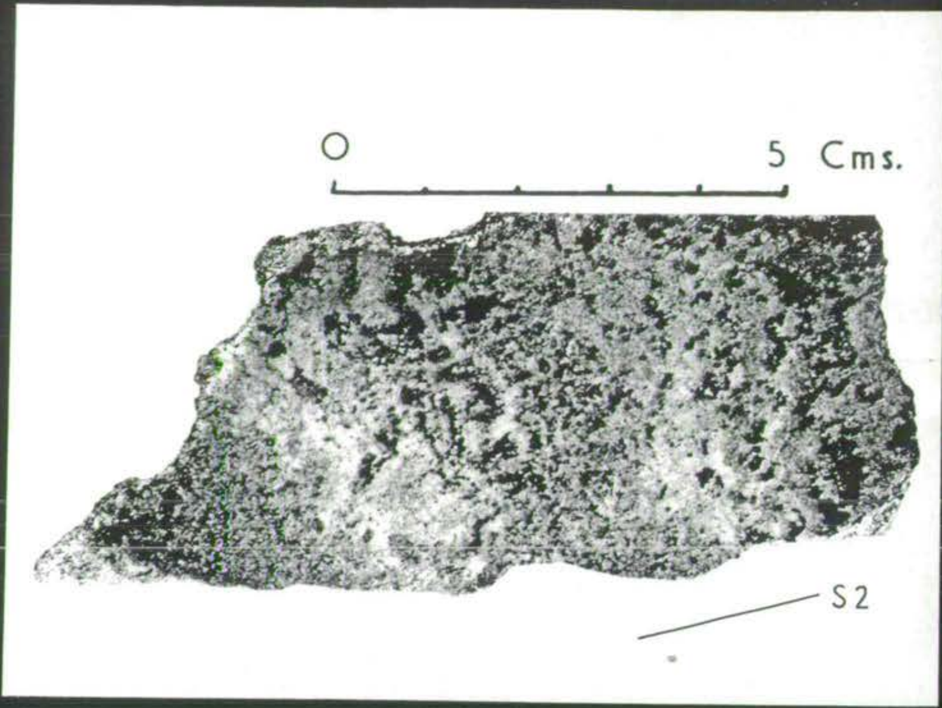
a. Surface shows hornblende prisms lying sub-parallel to S_2.

Loc. D11-11

b. Surface shows alignment of hornblende prisms sub-parallel to F2 axial structures.

Loc. D12-14

a



b

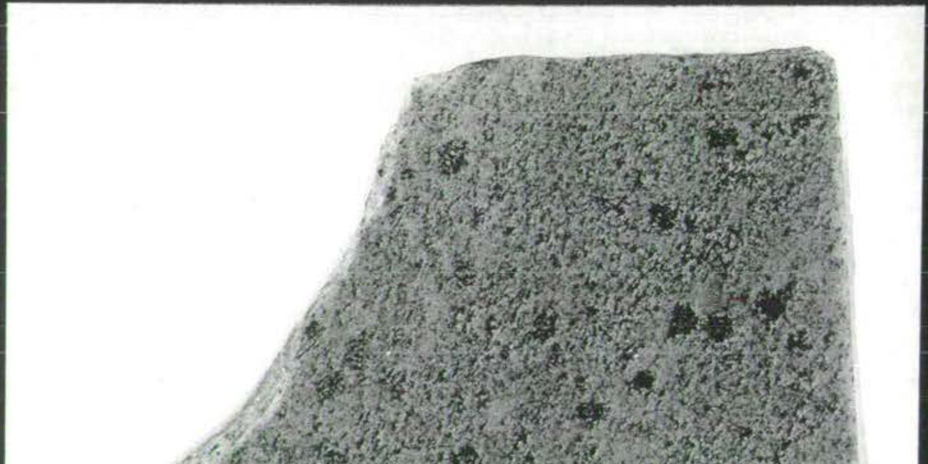


PLATE 27.

a. Pegmatite bands concordant with bedding-schistosity (S_s) are folded by F2 and displaced by F2 axial plane cleavage (S_2). (Glen Moidart Striped-Pelitic Group)

Loc. B6-11

b. Extensive development of pegmatite concordant with bedding-schistosity (S_s) in Glen Moidart Striped-Pelitic Group.

Loc. C4-2

a

b

PLATE 28.

a. F2 crenulation in Glen Moidart Striped-Pelitic Group. Note mica is oriented in S_s and S_2.

Ordinary light; magnification x 28;

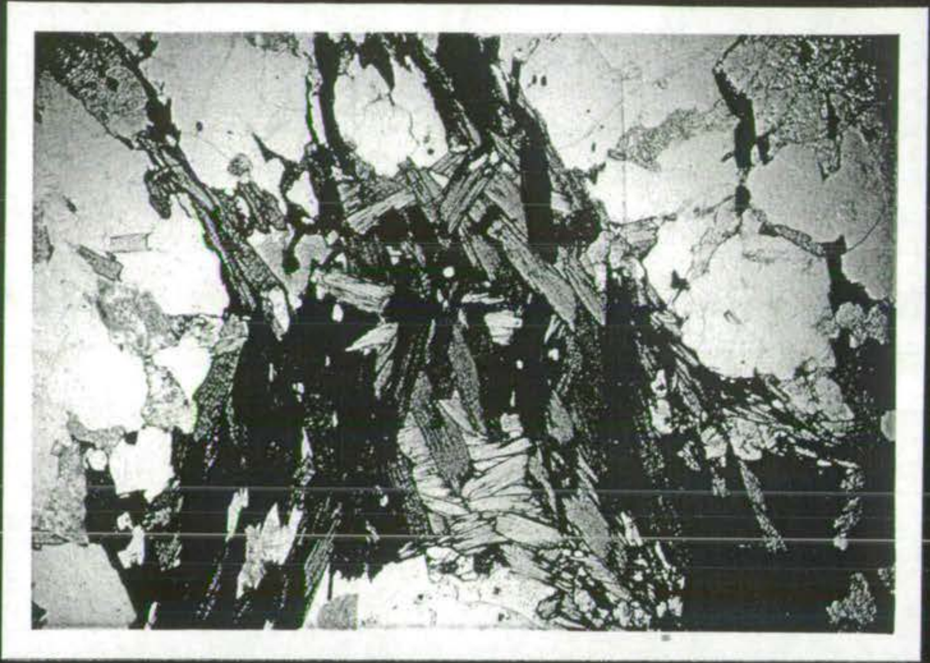
Loc. C6-12

b. F3 crenulation in Achnanellan Striped-Pelitic Group.

Crossed nicols; magnification x 28;

Loc. C1-2

a



b

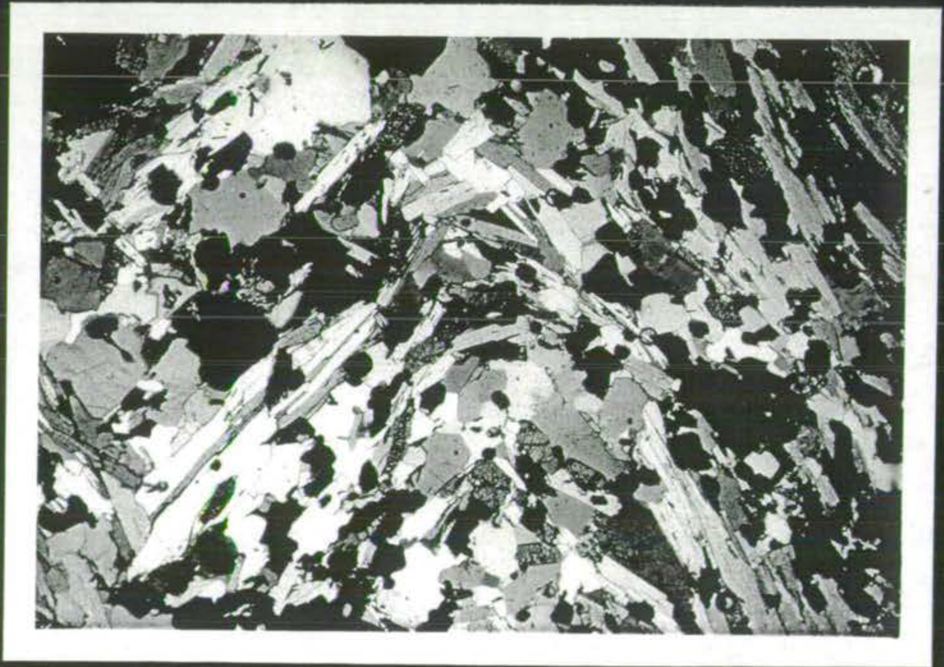
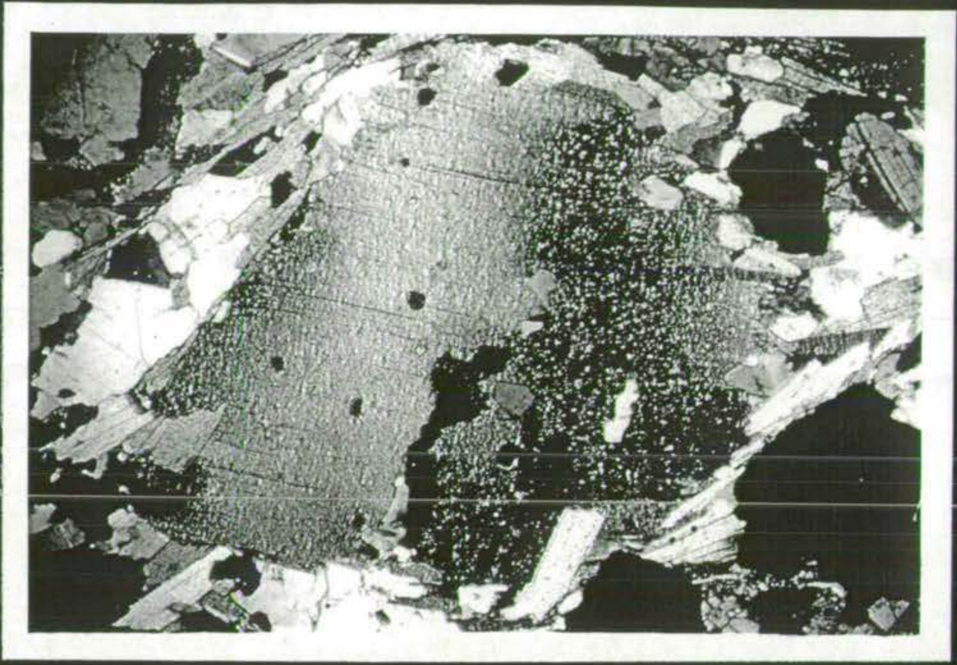


PLATE 29.

a. Bent muscovite porphyroblast in Glen Moidart Striped-Pelitic Group.
Crossed nicols; magnification x 28;
Loc. A6-12

b. Quartz and biotite included in the garnets are much smaller than the minerals in the ground mass. Note the straight inclusion trail which is not parallel to the schistosity of the ground mass (Garnet at top of plate).
(Pelitic band within Beinn Gàire Psammitic Group)
Crossed nicols; magnification x 28;
Loc. A5-9

a



b

PLATE 30.

a. Quartz inclusions display a curved trail near the centre of the garnet and a fairly straight trail towards the outer margins. The straight trail is parallel to and extends into the schistosity of the ground mass. (Glen Moidart Striped-Pelitic Group)

Ordinary light; magnification x 28;

Loc. C4-1

b. Garnet surrounded by fibrous sillimanite. From a thin pelitic band within the Beinn Gàire Psammitic Group.

Ordinary light; magnification x 48;

Loc. E9-16

a

b

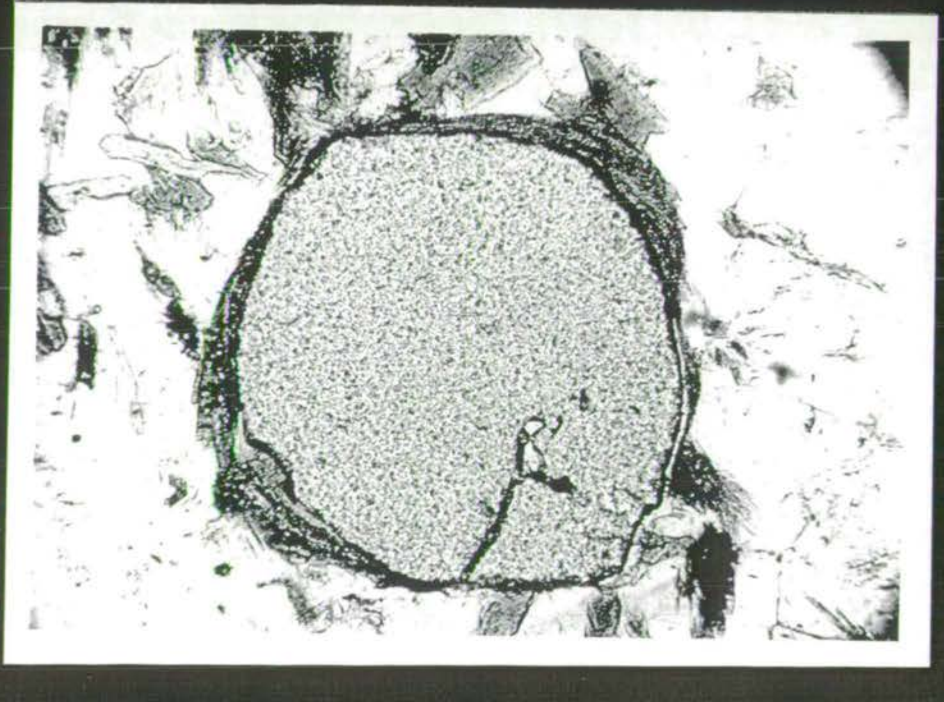


PLATE 31.

a. Sillimanite pod lying in the bedding-schistosity has been overgrown by garnet. Note the fine quartz inclusions form a trail parallel to the schistosity of the ground mass. (Glen Moidart Striped-Pelitic Group)

Ordinary light; magnification x 28;

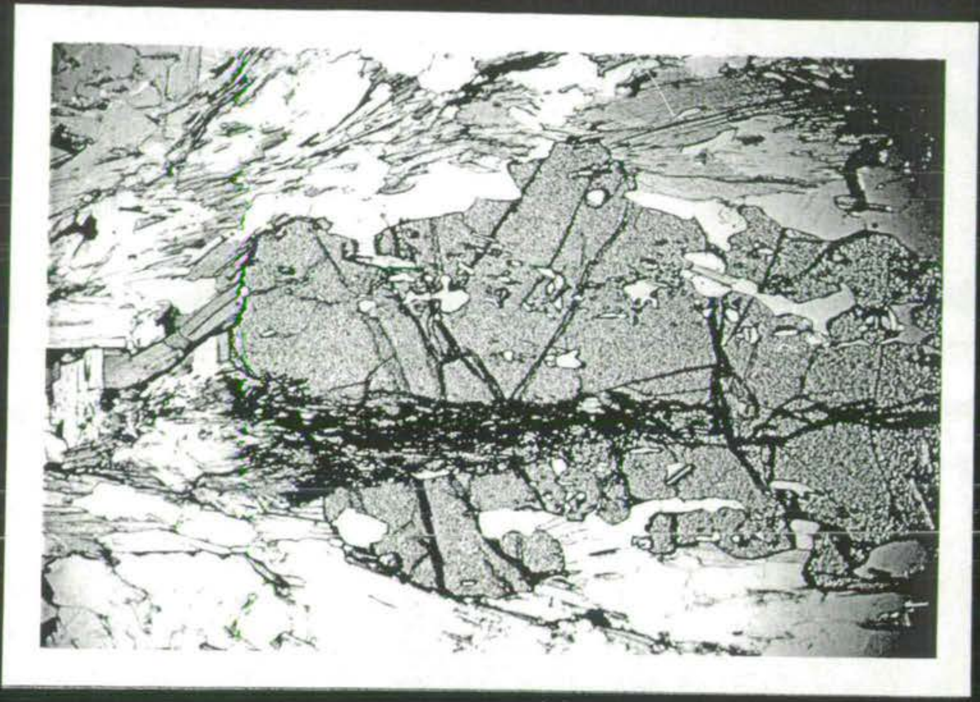
Loc. B4-4

b. Garnet has overgrown fibrous sillimanite. Note that the fibres are not aligned in the schistosity of the ground mass. From a thin pelitic band within the Beinn Gàire Psammitic Group.

Crossed nicols; magnification x 48;

Loc. E9-16

a



b

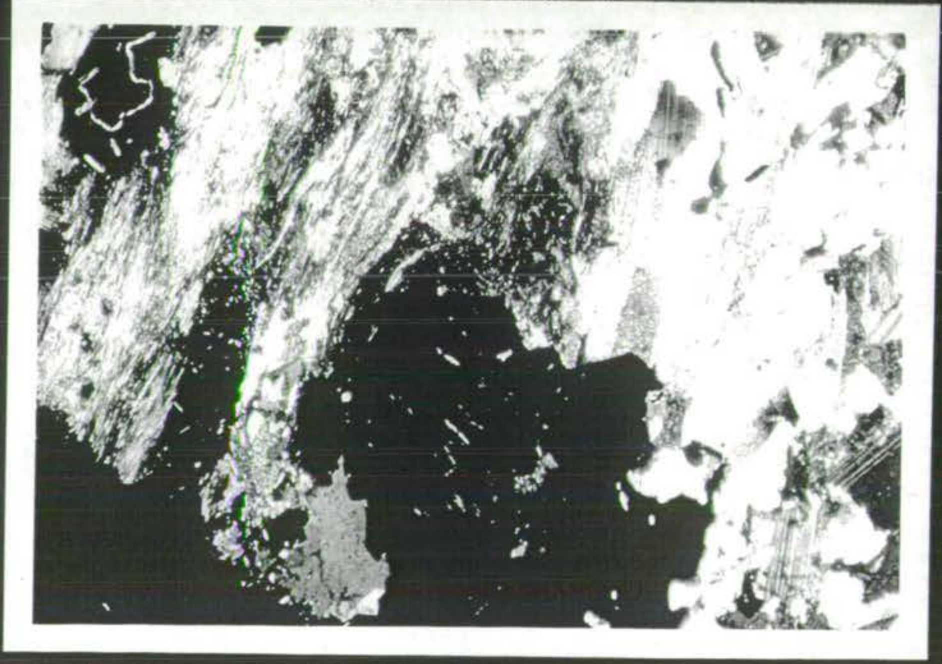


PLATE 32.

a. Garnet with inclusion free core and outer zone. (Achnanellan Striped-Pelitic Group). Ordinary light; magnification x 28;

Loc. A2-4

b. Crystal of staurolite has overgrown sillimanite oriented in the schistosity of the ground mass. Staurolite is partly replaced by felspar and quartz. (Glen Moidart Striped-Pelitic Group). Ordinary light; magnification x 28;

Loc. F11-4

a

b

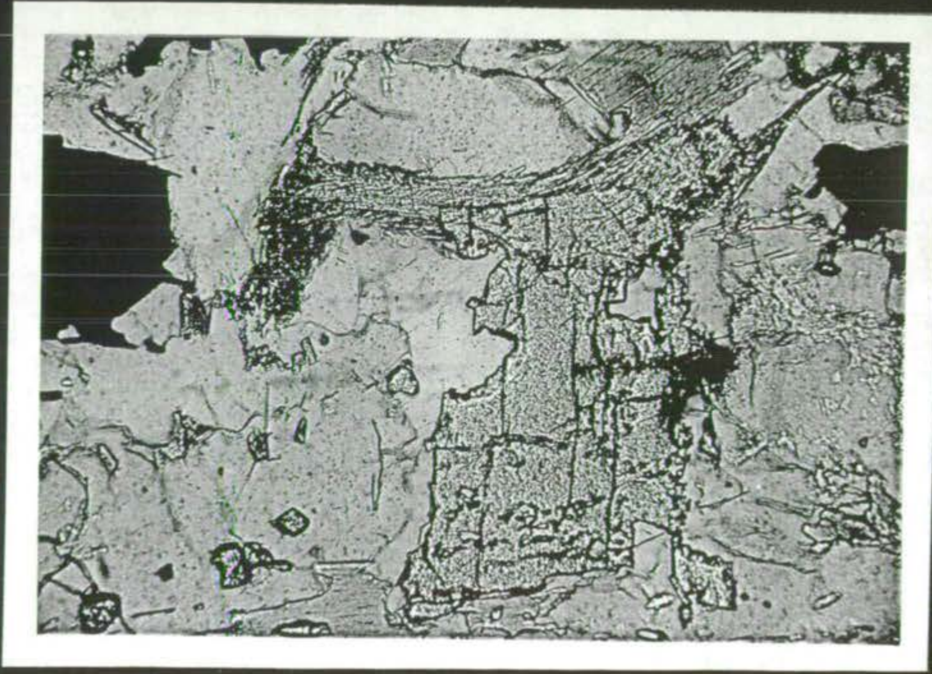


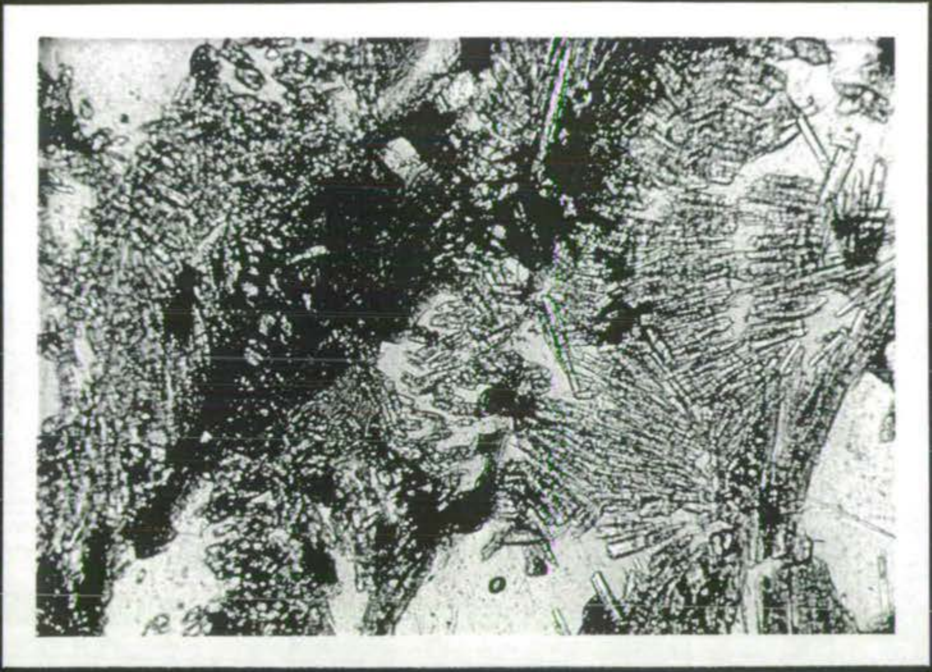
PLATE 33.

a. Sillimanite overgrowing biotite.
(Glen Moidart Striped-Pelitic Group)
Loc. D6-2
Ordinary light; magnification x 85.

b. Sillimanite pod elongated in the bedding-schistosity (S_s). Fibrous sillimanite within the pod is oriented sub-parallel to F2 axial plane cleavage (S_2). Semipelitic rock within the Glen Moidart Striped-Pelitic Group.
Ordinary light; magnification x 28;
Loc. D7-13

33

a



b

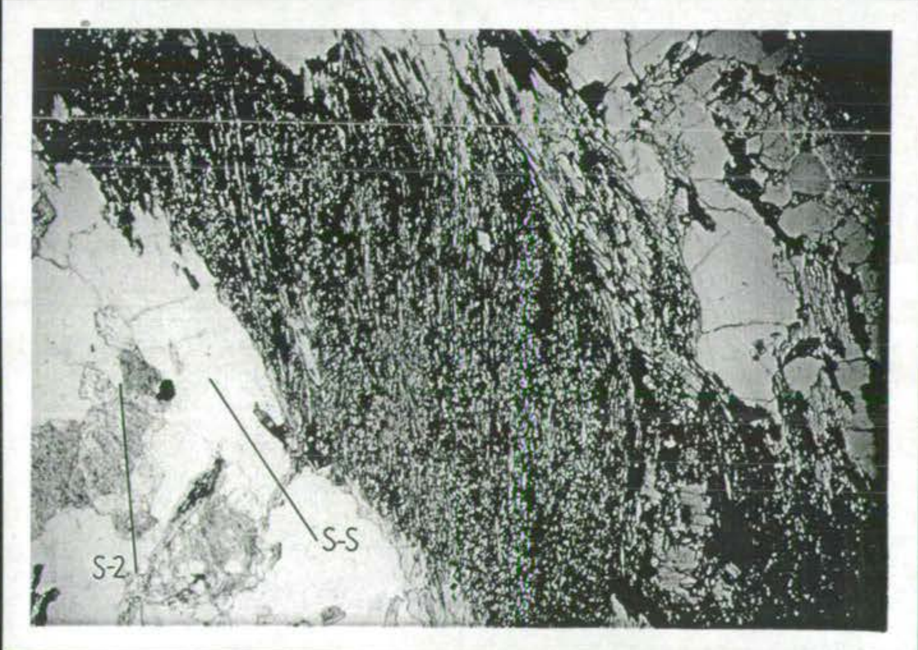


PLATE 34.

a. Sillimanite pod lies in the bedding-schistosity (S_s). Some of the fibrous sillimanite within the pod is folded into F2 crenulations and recrystallized. Somewhat coarser fibres are sub-parallel to S_2. Note the sigmoidal shape of a few of the coarse fibres.

Semipelitic rock within the Glen Moidart Striped-Pelitic Group.

Ordinary light; magnification x 28;

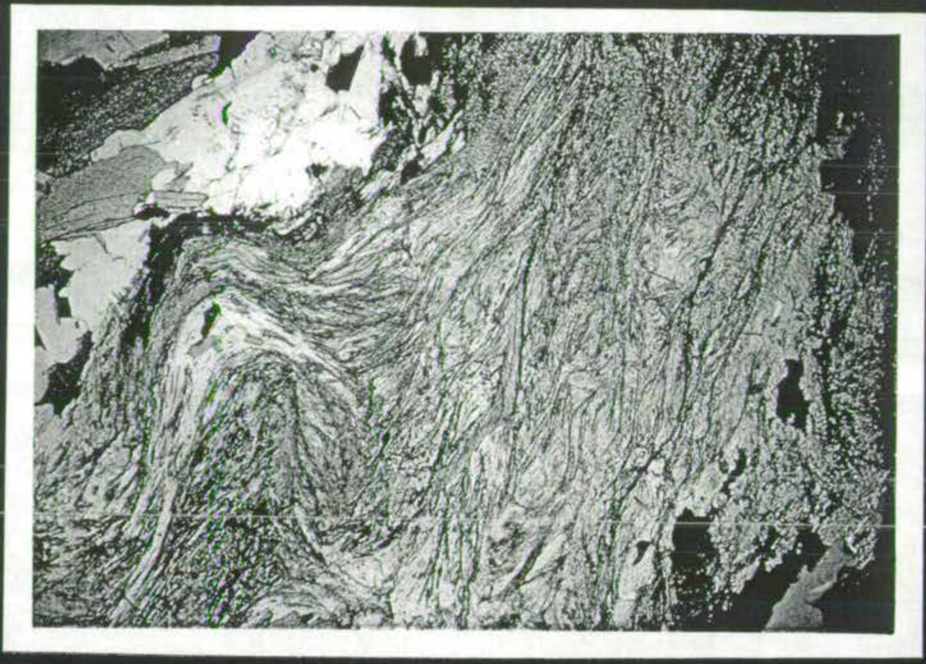
Loc. D6-1

b. F3 crenulation of fibrous sillimanite. Many of the fibres have been bent and broken by F3 movements. (Glen Moidart Striped-Pelitic Group)

Ordinary light; magnification x 48;

Loc. D7-1

a



b

PLATE 35.

a. F3 crenulation of sillimanite pod. Note the mimetic alteration of fibrolite to muscovite particularly around the edge of the pod. Semipelitic rock within the Glen Moidart Striped-Pelitic Group.

Ordinary light; magnification x 28;

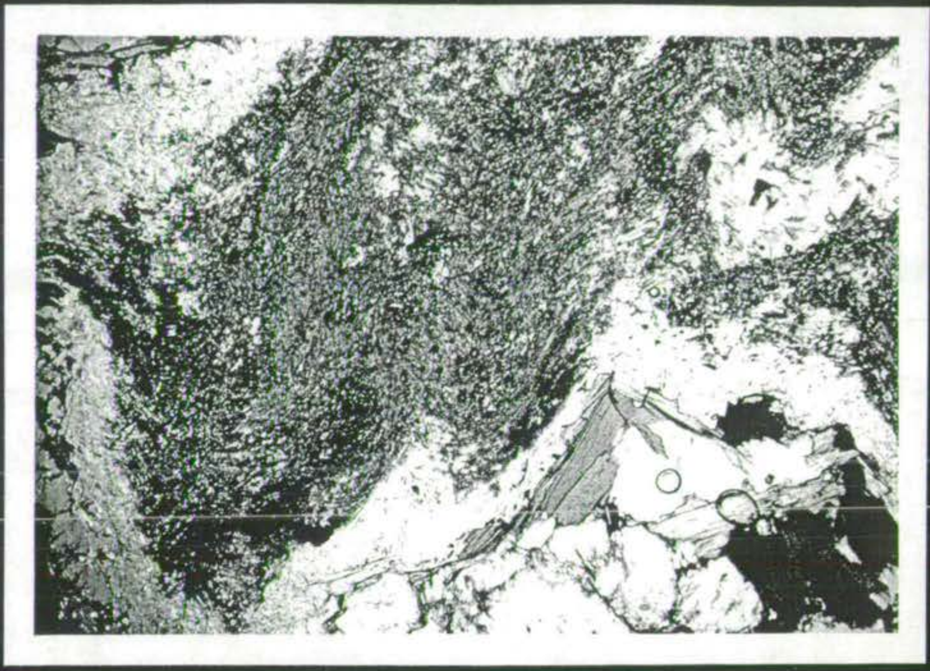
Loc. C6-9

b. Sillimanite and biotite lying in the schistosity of the ground mass have been overgrown by unoriented muscovite porphyroblast. (Glen Moidart Striped-Pelitic Group)

Ordinary light; magnification x 85;

Loc. C6-3

a



b

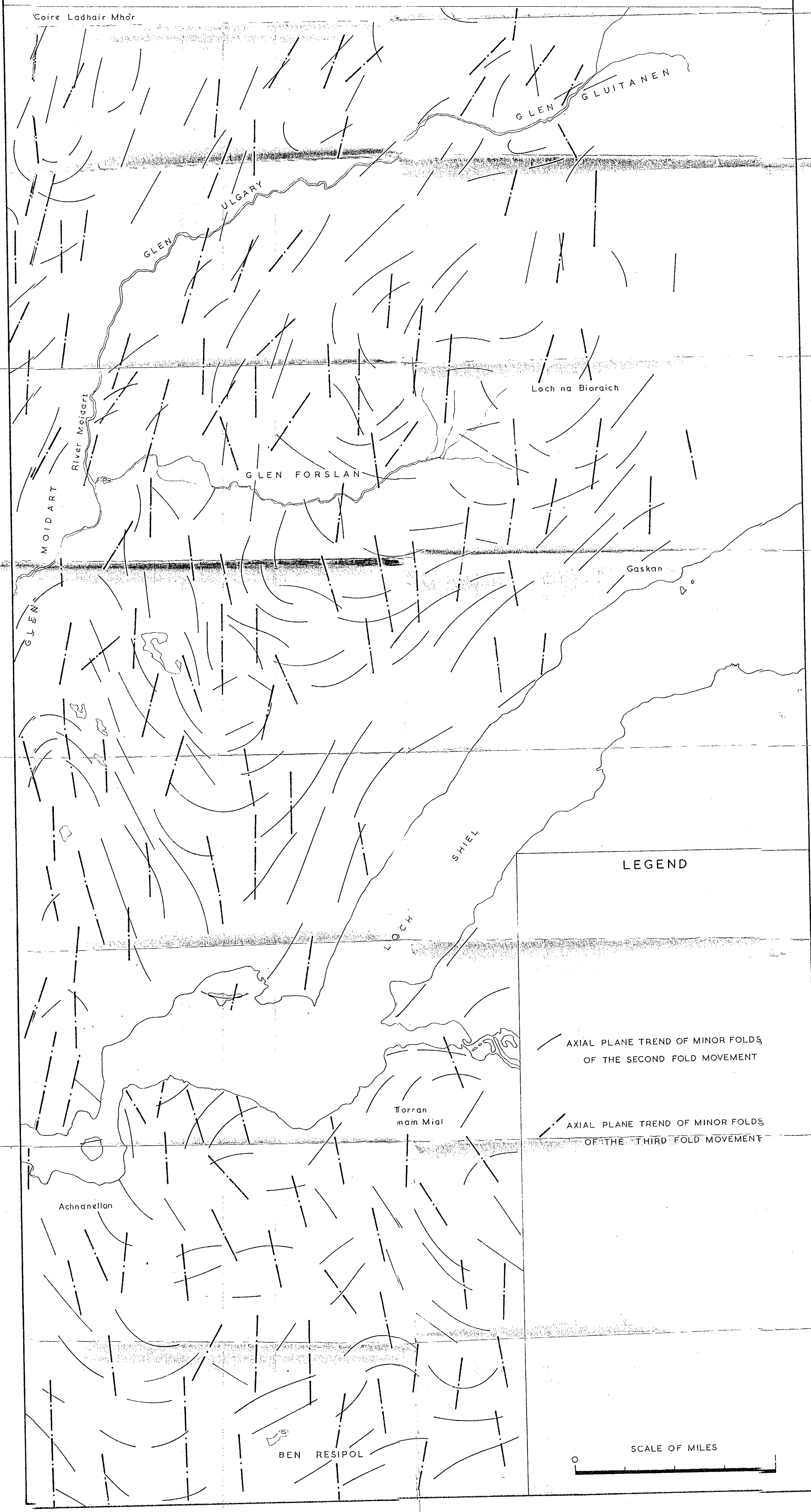
PLATE 36.

Sillimanite and biotite overgrown by plagioclase porphyroblast. From a thin pelitic band within the Beinn Gàire Psammitic Group.

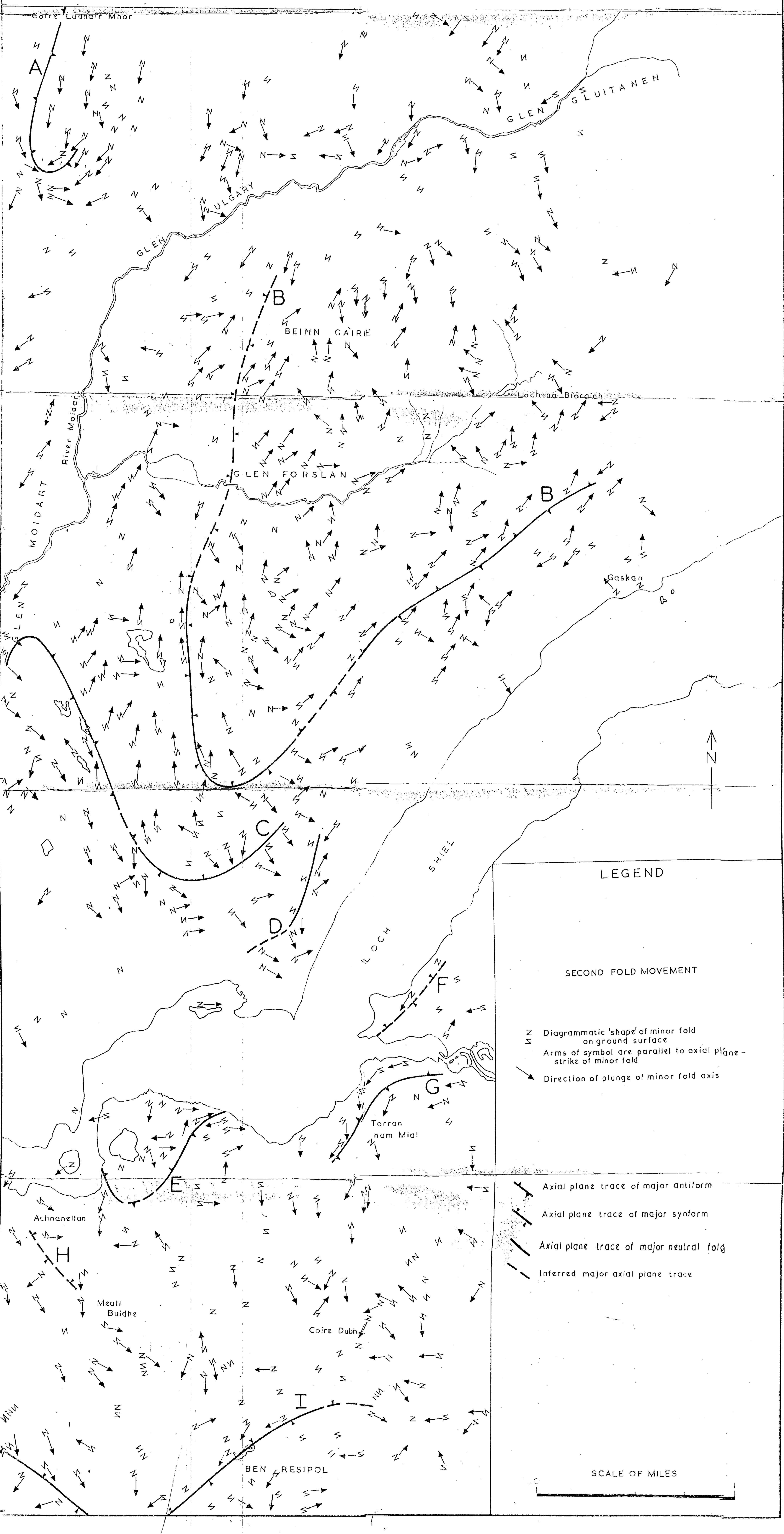
Crossed nicols; magnification x 48;

Loc. E9-16

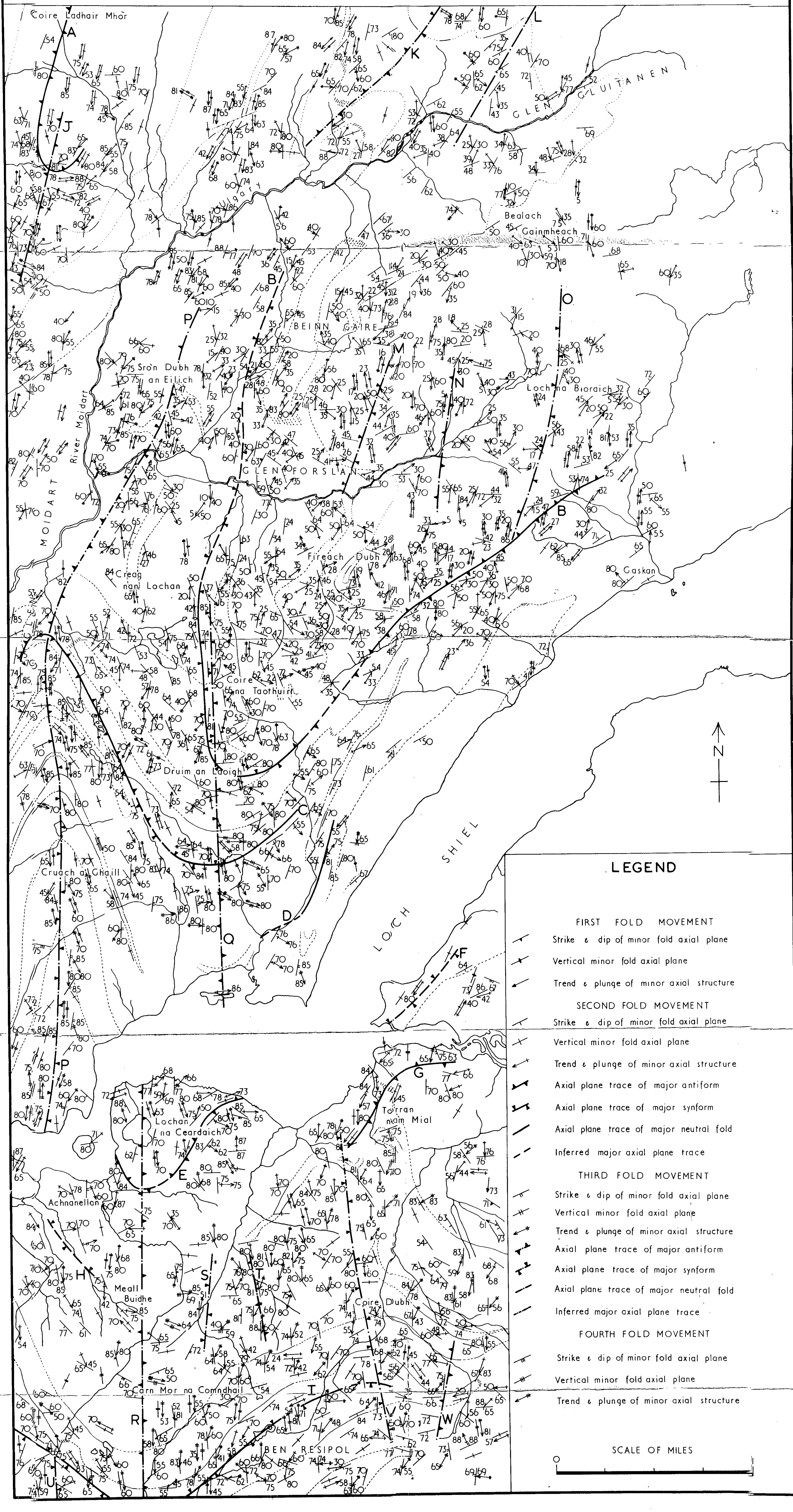
AXIAL PLANE TREND OF MINOR FOLDS OF THE SECOND & THIRD FOLD MOVEMENTS



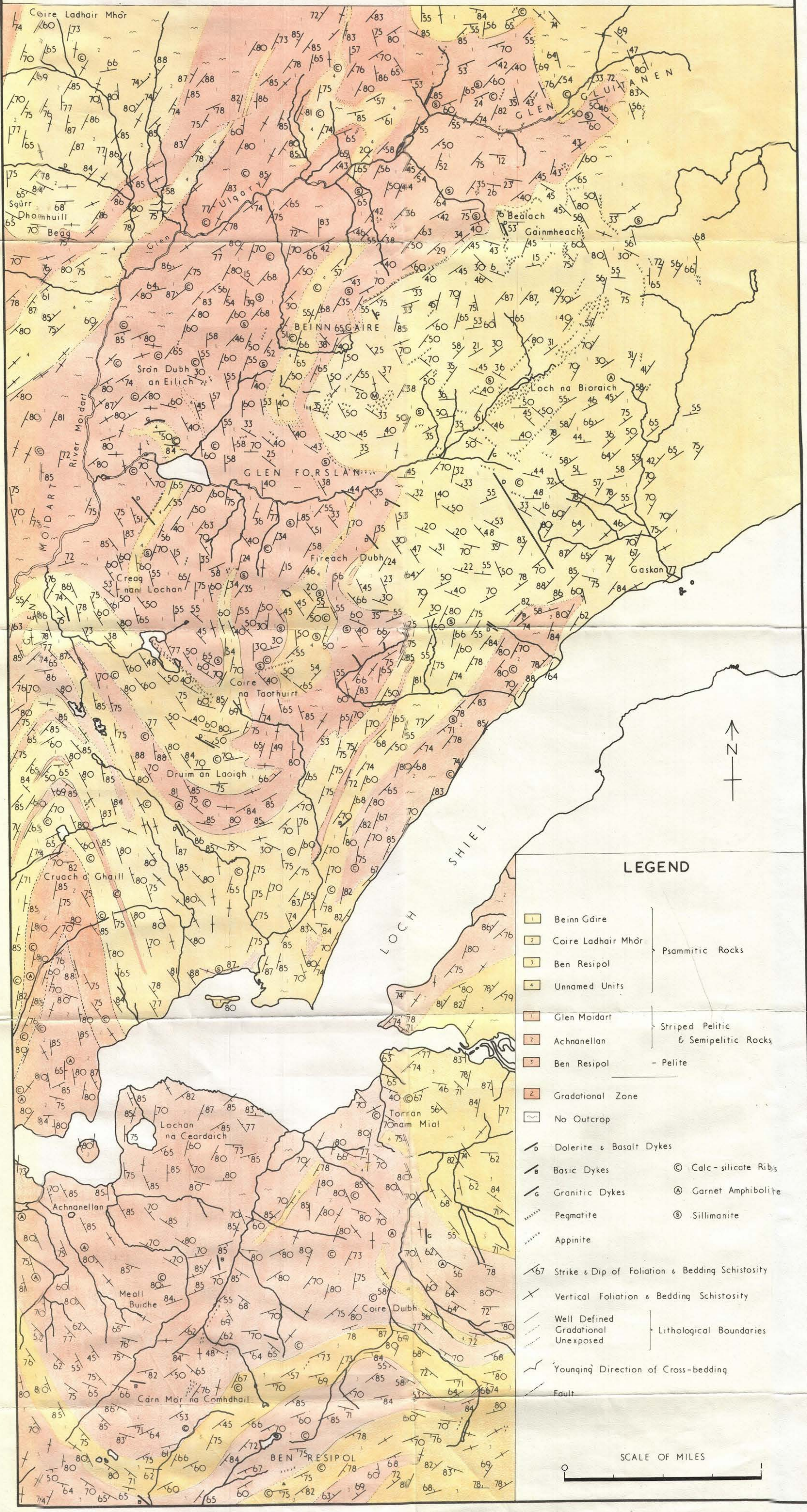
VERGENCE OF MINOR FOLDS OF THE SECOND FOLD MOVEMENT



STRUCTURAL MAP OF EAST MOIDART AND WEST SUNART, ARGYLL AND INVERNESS-SHIRE.



GEOLOGICAL MAP OF EAST MOIDART AND WEST SUNART, ARGYLL AND INVERNESS-SHIRE.



STRUCTURAL ANALYSIS

FIG.7