3.

THE STRUCTURE AND METAMORPHISM OF the MOINIAN ROCKS IN THE GLEN CANNICH-FASNAKYLE FOREST AREA, INVERNESS-SHIRE, SCOTLAND.

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by

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ABSTRACT

The Glen Cannich-Fasnakyle Forest Area is located in the Northern Highlands of Scotland, about 40 miles WSW of Inverness. The rocks in the Area consist largely of Moine meta-sediments, with a minor amount of meta-igneous types; Lewisianoid rocks cover a very small part of the area in the northwest.

The structural geometry of the area is complex, and has resulted from five phases of deformation. The earliest major structures, which are seen to control the stratigraphy, refold an earlier set of minor folds referred to as of F-1 age. The F-2 major structures form a series of basins and domes in the eastern half of the area; in the western half, their geometry is less clear. In two localities, major folds of F-3 age refold major F-2 structures. The F-4 movement is characterized by minor folds throughout the entire area, but locally it has produced mappable folds of limited extent; folds of this phase either cut across or refold the pre-existing structures. The F-5 deformation is restricted to ubiquitous minor structures, but it is best developed in the southeastern part of the Area.

Regional metamorphism has affected all the rocks in question, and the highest grade attained during the main

progressive metamorphism is the Kyanite-Almandine-Muscovite Subfacies of the Almandine Amphibolite Facies. The main progressive metamorphism was followed by a period of retrogressive metamorphism, which in turn was followed by a second progressive metamorphism. Migmatization was active during much of the metamorphism.

A stratigraphic succession is set forth for the eastern half of the Area, but because of the presence of a slide, correlation with the rocks in the western half where exposure is poor is not possible. Sedimentary structures in one of the stratigraphic groups show evidence of pre-tectonic deformation.

A stratigraphic and structural correlation with the surrounding areas is presented.

PLATE i



Glen Cannich, Autumn 1962

Ode to Glen Cannich

O Glen Cannich, your brow is of man
But your spirit be woman;
For you hide and treasure your
Secrets with enigmatic femininity,
Fearing that should you give your all
To man, he would desert you as boring,
Would banish you as another conquered.

O.T.T.

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CHAPTER 1

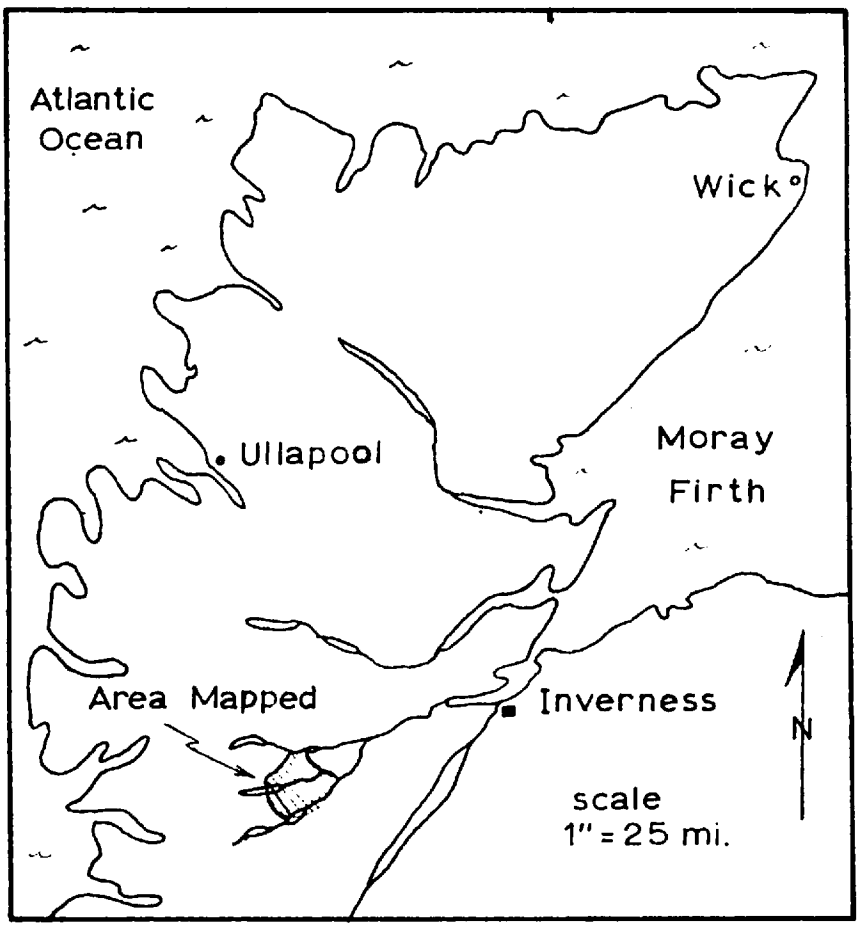
INTRODUCTION

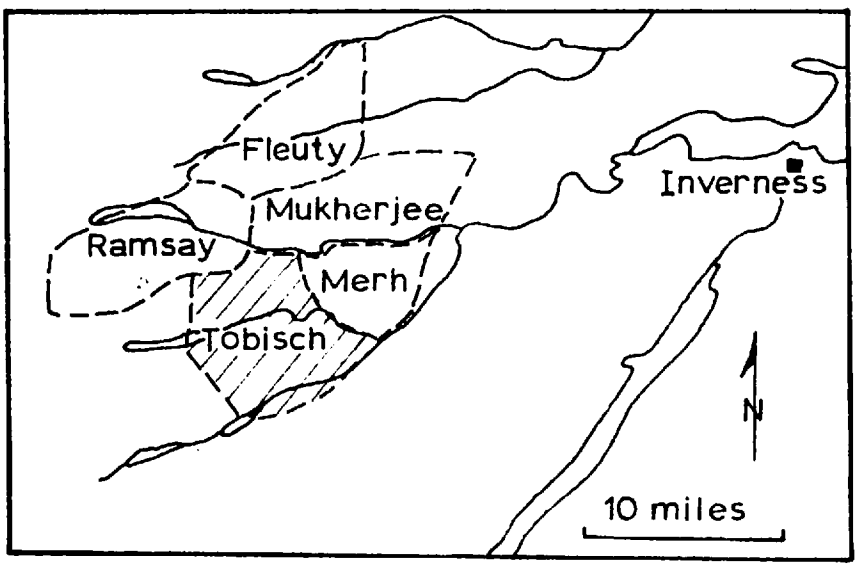
General Introduction

The area discussed in this thesis surrounds the Glen Cannich and Fasnakyle Forests of Inverness-shire, which are situated in the Northern Highlands of Scotland, about 40 miles west-southwest of Inverness, Fig. 1. Glen Cannich bisects this area, and the northern and southern boundaries roughly coincide with Glen Strathfarrar and Glen Affric respectively. The western boundary is formed by the line joining the peaks of Sgurr na Lapaich, Toll Creagach, and Beinn a' Mheadhoin, while the most eastern point is the village of Cannich. Although most of the ground mapped lies within the county of Inverness-shire, a very small portion in the west lies within Ross-shire.

The Glens of Cannich, Affric, and Strathfarrar have a minimum elevation of between 400 - 700 feet above sea level. The principal peaks in the area are Sgurr na Lapaich (3773'), Toll Creagach (3452'), Carn nan Gohbar (3251'), Creag Feusag (2824'), Meall Mor (2276'), Beinn a' Chairein (2119'), and An Soutar (2118'). The topographic relief varies from

FIG. 1 Locality Map





about 2000 to 2500 feet. The sides of the glens rise from gentle angles to about 25° from their floors, except in a few areas where their gradients are steep. On the lower slopes, Caledonian pines are found in small numbers, and the local inhabitants claim that some of these magnificent trees are over 200 years old. Birch trees are present near the foot of Glen Cannich, but are more widespread in the other two glens. Trees are rarely found over a few hundred feet above the glen floor, where the main vegetation consists of grass and heather. Peat bogs are common on the more level areas. In Glen Affric, and in the lower part of Glen Cannich, the Forestry Commission is planting softwood pines on the lower slopes. Bracken is profuse in these areas, and locally may reach over six feet in height. The greater part of the area mapped, except that enclosed by the Forestry Commission, is used as grazing land for sheep, and is stalked for deer in the later summer and early autumn. Stags and hinds are common, and are often seen in large herds of up to 200 beats. Other wild life include ptarmigan, grouse, foxes, rabbits, hares, snakes, wildcats (rare), eagles, hawks, buzzards, and other bird-life. The smaller rivers contain trout and pike, and salmon are caught in the larger rivers, such as the River Glas.

The major drainage is provided by the Rivers Affric,

Cannich, and Farrar in their respective glens, which trend roughly east-west. All these rivers eventually join the River Glas, which occupies the Strath of the same name, and flows into Beauly Firth west of Inverness. Strath Glas, which borders part of the southeastern edge of the area mapped, is considered to be eroded along one of the major NE-SW tear faults of northern Scotland (Hinxman, 1901, p.102), since it is parallel to the Strathconon and Great Glen Fault zones. Pleistocene glaciation was active in most of the area, and steep-walled corries, U-shaped valleys, and morainic deposits are common. The minor drainage pattern is locally controlled by glacial features, and also influenced by faulting, jointing, and other types of structures.

The village of Cannich is the main centre of population, and boasts about 200 people, if one includes the surrounding farms. There are several houses and a hotel in Glen Cannich as well. The principal sources of employment are the Forestry Commission, the Hydroelectric Board of Scotland, and crofting. The Hydroelectric Board has constructed dams in all three glens: Mullardoch Dam (1951), Benevean (Affric) Dam (1952), and Monar Dam (1963), of which Mullardoch Dam in Glen Cannich is the largest, having a length of over 2000 feet. Water from Loch Mullardoch is piped to the power station (3 turbines) at Fasnakyle. The

Monar Dam will have a power station of its own. There are two metalled roads from Inverness to Cannich: one going via Beauly Toll, and the other via Drumnadrochit. From Cannich, there is a narrow metalled road running to Mullardoch Dam; similar roads also run up Glen Affric and Glen Strathfarrar; these last branch off the Inverness-Beauly Toll - Cannich road at Cannich and Struy, respectively. Most of the area mapped is in rough, wild country away from the roads, and apart from the occasional ruins of a crofters cottage, is devoid of any signs of habitation.

I have spent a total of 48 weeks in the field during the summers of 1961-62. During this period, despite the unusually cold and wet weather, I mapped a total area of about 45 square miles. This area is covered by the 6 inch to 1 mile Ordnance Survey sheets nos: 15, 16, 26, 27, 38, 39, of Inverness-shire, and nos: 120, and 121 of Ross-shire. These maps have been supplemented with aerial photographs at approximately the same scale, which facilitated precise location of exposures on the maps. The field work was done by "outcrop mapping", whereby the position and outline of each outcrop or group of outcrops was recorded on the six inch map, and the geological information obtained from that outcrop recorded within its boundary. Since this thesis is concerned primarily with the structure and metamorphism of the Moine

Rocks, alluvium and glacial deposits have not been recorded.

Acknowledgements

I wish to thank Dr. Gilbert Wilson for his help in producing this thesis, for reading the manuscript, and for his advise in many matters; Dr. John G. Ramsay for suggesting the area, and for rigorous discussions in the field and in the laboratory, which have proved invaluable in the development of ideas on the area; Dr. Michael J. Fleuty for his constructive criticisms of the manuscript; and the Geological Survey of Scotland for releasing information on the tunnel between Loch Mullardoch and Loch Benevean, as well as information on areas that are now flooded in Glen Affric. I also wish to thank Mr. and Mrs. Peter MacSwan, Mr. and Mrs. DonaldMiller, Mr. and Mrs. Dick Hamilton, and the people in the Cannich area, all of whom have contributed so much in making my stay in Cannich a richly rewarding experience. Thanks are also due to Mr. J.A. Gee for photomicrographs, and Mr. E. J. Hill for thin-sections. And finally, to my colleagues, especially Dhrubajyoti Mukherjee and Philip Simony, I wish to express my infinite thanks for their endless patience and interest in discussing the various geological problems which were encountered during the development of this thesis; and to Miss J.E. Taylor for the beauty of her helping hands.

Previous work in the Glen Cannich Area

Little previous work has been done on the area under consideration. Hinxman (1901, 1902, 1906, 1913) mapped the northern third of the area, reporting primarily on the lithologies, and commented only en passant on the structures. His survey was basically one of reconnaissance. Apart from the Lewisianoid body south of Sgurr na Lapaich which he missed (see Sheet no. 82, Geol. Surv.), I have found his lithologic mapping to be generally accurate. Because his mapping was largely reconnaissance, he grouped many pelitic and semi-pelitic horizons into one unit, and this tended to conceal the complexity of the structure. The Geological Survey marks the remaining two-thirds of the area as "unsurveyed", and to my knowledge, there is no published work from any other source.

In the summers of 1952-53, J.G. Ramsay mapped the area immediately to the northwest of my ground. In his account, Ramsay (1954, 1958) describes how the Moine and "Lewisian" rocks have undergone two phases of deformation. The tectonic history in his area largely consists of a northeast set of folds being superposed upon the east-west Loch Monar Synform. The orientation of the limbs of this Synform control the axial orientation of the later folds. Ramsay's contribution was a major step forward in elucidating the geometry of

structurally complex areas (see also Weiss and McIntyre, 1957). Since the publication of his 1958 paper, I have been in the Loch Monar area with Dr. Ramsay. In the core of the Loch Monar Synform near Toll a' Mhuic, we have both observed minor folds which are of an earlier generation than the major Synform. Furthermore, D. Mukherjee and I have observed a crumpling on axial planes which appears to be later than Ramsay's latest phase (F-2) near Monar Dam. Hence, there are at least three if not four phases of deformation in the eastern part of the Loch Monar area.

Subsequent to Ramsay's work, M.J. Fleuty mapped the Glen Orrin area, which is to the northwest of Monar; the two areas join near Loch Toll a' Mhuic. Fleuty (1957, 1961) found a structural pattern in the Glen Orrin area similar to that at Monar: a northeast folding being superposed on east-west folds. He also noted some evidence for deformation earlier than the east-west folds, and recognized a phase of folding later than the northeasterly folds. Essentially, then Fleuty outlined four phases of deformation, although it was not possible for him to demonstrate the exact nature of the first and fourth episodes because of their apparent restricted occurrence.

In an effort to clarify some of the problems that Fleuty encountered, S. Merh (1960) mapped the ground between

Glen Strathfarrar and Glen Cannich contiguous to my northeastern border. The structural pattern that Merh uncovered is considerably more complex than that defined in either Ramsay's or Fleuty's ground. This is largely because the earlier folding, that is, the pre-east-west structures of Ramsay and Fleuty, is recognizable on a major scale as defined by sedimentary structures in the psammitic units. Merh did a commendable job in trying to unravel the complex geometry of his area. However, both Mukherjee (ms) and I disagree with some of his interpretations. These disagreements are discussed later in the section under Correlation and Discussion.

Summary of the Geology

Except for a small body of Lewisianoid rock in the north-west corner, the rocks of the area are members of the Moine Series, and the lithology is characteristically Moinian. Psammites, pelites, and semi-pelites constitute the bulk of the rocks, with the remainder made up of calc-silicate lenses and amphibolites (metamorphosed sills and dykes). Certain horizons within the psammites are characterised by beautifully preserved sedimentary structures, some of which are in various stages of primary deformation. Locally, the sedimentary structures have proved invaluable in

understanding the nature of the earlier folds.

The structural geometry of the area is exceedingly complex, and has resulted from five deformations. The first phase of folding (F-1) is represented only as isoclinal minor folds and lineations. The second folds (F-2) are present as minor and major folds, the latter of which control the stratigraphy as shown by sedimentary structures. These folds are long-limbed and isoclinal. Their axial plane orientation is variable, although the major folds tend to strike in a north-south direction. In the eastern part of the area, they form a series of eyed structures; in the west, their geometry is not as clearly defined, mainly because of poor exposure. The third folding (F-3) is represented in the east by a tight fold, whose axial plane trace strikes roughly northwest-southeast; in the western part of the area, however, the axial plane traces of this phase are east-west. The fourth folds (F-4) are more open in style than those of the first three phases, but can become very tight under certain conditions. They are largely restricted to minor folding, although a number of major folds are also present. The axial plane orientation of F-4 folds shown systematic variations, which can be described as a divergence of axial plane trends, as they are followed from the north to the south of the area. The fifth folding (F-5) is generally

expressed as warpings of the foliation and crumpling of micas. In the southern part of the area, however, it becomes more intense. The orientation of axial planes is variable in any one exposure, but the trend is generallly northeast-southwest.

The maximum grade of metamorphism is reasonably constant throughout the area. Garnet of appropriate composition is found in all rock types. In the knotty semi-pelites, relic kyanite is occasionally found in the knots; and in the calc-silicate granulites, the assemblage pyroxene-anorthite is rarely present. The average anorthite content of the plagioclase of the normal Moine rocks is oligoclase/andesine. The mineralogical assemblages of the rocks indicate that the maximum grade of metamorphism attained is within the Kyanite-Almandine-Muscovite Subfacies of the Almandine Amphibolite Facies (Turner and Verhoogen, 1960).

The general sequence of metamorphic events is as follows:

1. medium-grade progressive regional metamorphism accompanied by migmatisation;
2. limited retrogressive metamorphism; and
3. sustained low-grade (?) regional metamorphism accompanied by localised migmatisation.

Event 1 was co-eval with F-1 and F-2 folding. This is shown by an axial plane cleavage of both sets of minor folds, and by the lineations, which are characterised by quartzo-

feldspathic striping and rodding. Elongated kyanite-bearing knots appear to be related only to F-2 folding. Axial plane migmatisation of F-2 folds is rarely present. The metamorphism then retrogressed to a lower grade in which the kyanite was sericitized. During F-4 folding, the metamorphism was of sufficient intensity to crystallize biotite and muscovite. This is shown by the axial plane schistosity of F-4 minor folds in the northwestern part of the area, and by some recrystallisation of sericite to muscovite in the knots. Axial plane migmatisation of F-4 folds is present in the western third of the area. Metamorphism during F-5 folding was negligible to absent.

Sometime after or possibly during the decline of F-5 folding, the rocks were subjected to jointing and faulting, which may be in part contemporaneous with the formation of the major NE-SW faults of Strathconon and Strath Glas. Most of the local faulting and major jointing in the area, however, are along north-south and east-west trends. Lamprophyric and camptonitic dykes were then intruded along these lines of weakness, preferring the east-west trend.

CHAPTER 2

PETROGRAPHY OF THE METAMORPHIC ROCKS

THE MOINE ROCKS

General

Three main rock types constitute the bulk of the Moinian rocks in the Glen Cannich and Glen Affric area: psammite, semi-pelite, and pelite. Psamitic rock is by far the most common, followed by roughly equal proportions of the other two types. Thin bands of calc-silicate granulite are sparingly present, mostly in the psammite, but locally they also occur in pelitic and semi-pelitic rocks. Amphibolites of several types are also present in all three major rock types.

Psammite

Psammitic rocks constitute more than two-thirds of the rock exposed throughout the area, and the typical exposure of the rock is found to be massive. The texture and colour of the weathered surfaces, which are a function of varying proportion of the constituent minerals, may vary rapidly over small areas. Such changes in mineral proportion in the psammitic rocks are frequently local, so that mapping semi-pelitic boundaries within the psammite is rarely

practicable. Units mapped as psammite, therefore, contain some percentage of rock which would be classed as semi-pelite from a single hand specimen.

Of the 88 specimens of psammite collected, 33 have been sectioned, and the five principal constituent minerals are quartz, plagioclase, K-feldspar, biotite, and muscovite. Close to 90% of the volume of the average specimen consists of quartz, plagioclase, and K-feldspar.

Although the typical exposure of psammite is massive in appearance, hand specimens normally have a visible planar surface which is the foliation(1). In the more micaceous psammites, a schistosity may also be visible. In the psammites of Creag Dhubh and Loch Tuill Bhearnach, which are part of the same stratigraphic unit, the schistosity commonly becomes the dominant planar surface, and the foliation is not visible except where the angle between the two surfaces becomes considerable. Such intensely developed schistosity is not characteristic of the area, however, and the foliation one seen in the typical psammite is essentially the original sedimentary surface. Even though metamorphic processes may have altered this surface to a minor degree, the presence of well-preserved sedimentary structures clearly indicates

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(1) The term "foliation" is here used to refer to the compositional banding in the rocks, and is fully defined on page 81.

that neither recrystallization nor tectonic movements have significantly changed the original sedimentary surfaces.

Most of the psammites have a pale greyish to cream colour, although certain horizons contain rocks which are decidely pink. Such horizons are more common along the northwestern boundary of the area than elsewhere. The pink hue appears to be associated with the presence of abundant K-feldspar, which may or may not have been part of the original rock. Since most of the normally coloured psammites contain K-feldspar as well, the presence of the pink colour suggests a second generation of K-feldspar (see section on Migmatisation under Metamorphism).

In thin-section, the texture of the psammites is commonly granoblastic, but where the mica content exceeds about 10% , the texture becomes lepidoblastic. In some specimens, the tecto-silicates are sufficiently flattened to define the foliation, hence lepidoblastic textures are not entirely dependent on the content of mica. The average grain size in the thin-sections examined is about 0.3 mm.

The most common mineral in the psammites is quartz, which occurs in sub-rounded to sub-angular crystals, generally with smooth edges (that is, not serrated). The quartz in all slices exhibits some degree of strained extinction. Plagioclase is nearly always present in small crystals, and more frequently than not is slightly altered (to sericite?).

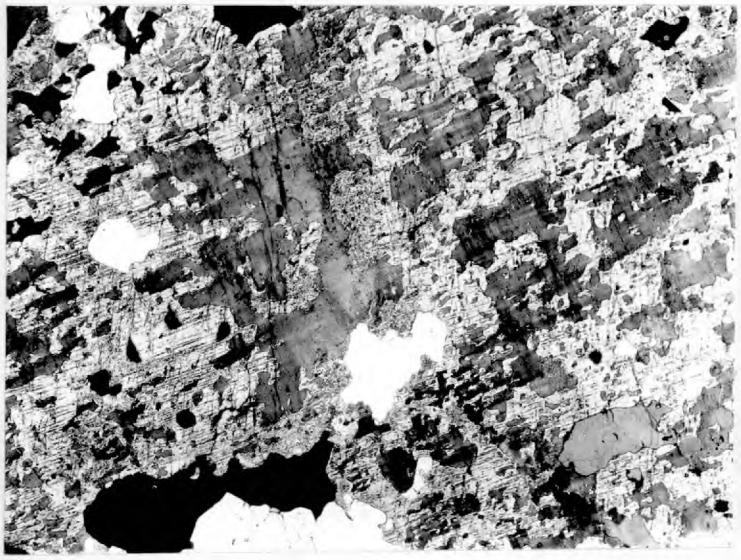
Twinning is common, and crystals in many slices show a weak zoning. The plagioclase in three-quarters of the thin-sections examined has an anorthite content of An_{25} or greater, and although it tends to be slightly altered, it may be fresh; in the remaining quarter, the anorthite content varies between An_8 - An_{16}, and the plagioclase is invariably altered, in places strongly. In some of the thin-sections from the latter group, which are typical of the pink specimens mentioned above, the plagioclase is in intimate association with the K-feldspar, suggesting that the K-feldspar was formed the later of the two (Plate I). In most thin-sections, however, the K-feldspar is present as discrete crystals, and is always unaltered. Grid twinning of the K-feldspar is common, but in some slices, untwinned crystals are predominant. Myrmekite has developed locally where crystals of plagioclase and K-feldspar are in contact. Biotite and muscovite are present in most slices in sparing amounts, with biotite usually exceeding muscovite in volume percent. Pleochroism of the biotite is commonly X= very pale tan, Y=Z= greenish brown ($Z=Y \gg X$), although in some specimens which tend toward semi-pelite, X= pale tan, Y= brown, and Z= reddish brown ($Z > Y > X$) has been observed. Garnet and members of the epidote group (pistacite, clinozoisite and zoisite) are present as minor constituents in about one half of the thin-section. The volume of these

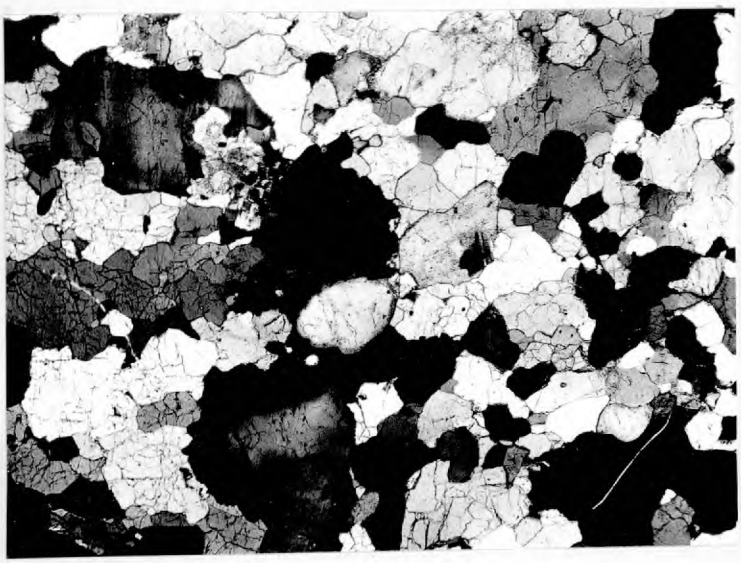
PLATE I

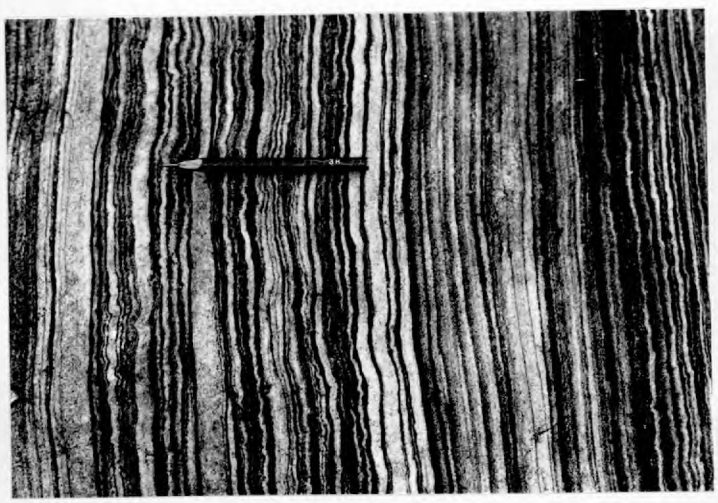
a. Photomicrograph of a psammite in which the K feldspar (cross-hatched twinning) is in intimate relation with the plagioclase; quartz is also present; one mile west of Meallan Chdar. x 25

b. Photomicrograph of a typical psammite; crystals with uneven extinction are K feldspar, the remainder being quartz; one mile NE of Mullardoch Dam. x 25

c. A typical thinly-banded semi-pelite; near Mullardoch Dam proper; pencil is 4 inches long.







two minerals is approximately one percent of the rock. The epidote commonly has cores of orthite, and inclusions of quartz and other minerals are not uncommon in the garnet. Accessory minerals include apatite, sphene, zircon, and iron ore. Chlorite in trace amounts occurs in about one-fifth of the specimens. The estimated mode as averaged from the 33 slices of psammite is: quartz 52%, plagioclase 20%, K-feldspar 19%, biotite 4%, muscovite 3%, and accessories including garnet and epidotic minerals, 2%.

Semi-Pelite

The term semi-pelite is here used to refer to rocks whose general characteristics lie between the typical psammite and pelite. Whereas the texture of a typical psammite or pelite is generally of one type, that of the semi-pelites may show considerable variation. The main types fall into the following four groups:

1. thinly-banded semi-pelite,
2. speckled semi-pelites,
3. sub-pelitic semi-pelite, and
4. knotty semi-pelite.

1. Thinly-banded semi-pelite

As the name implies, this type of semi-pelite is characterized by the alternation of mica-rich with mica-

poor bands. The bands are usually very thin, and the following 3 inch section is typical (Plate I):

m.r. = mica-rich
m.p. = mica-poor

m.p. = 0.5 inches
m.r. = 0.1
m.p. = 0.2
m.r. = 0.03
m.p. = 0.6
m.r. = 0.01
m.p. = 0.2
m.r. = 0.1
m.p. = 0.1
m.r. = 0.1
m.p. = 0.2
m.r. = 0.1
m.p. = 0.2
m.r. = 0.1

Though the texture in thin-section tends to be granoblastic in mica-poor bands, a well-developed lepidoblastic texture is characteristic of the mica-rich bands. The average grain size is near 0.5 mm in diameter; garnet and muscovite may achieve 2.0 mm. in their largest dimension. Biotite and muscovite typically occur in small plates, and may be intergrown. The pleochroism of the biotite is X= pale brown , Y= brown, and Z= red-brown ($Z \geq Y \geq X$).

Zircon with pleochroic halos is common in the biotite. Quartz crystals generally have smooth edges, and nearly always show some strained extinction. K-feldspar is always unaltered, and usually untwinned. Most of the plagioclase is fresh, and a vague zoning is present in some crystals. The anorthite content of five specimens averages to An_{26}, ranging from An_{25} - An_{28} (flat stage). Garnet is not common, but when present contains inclusions of quartz and muscovite; in some specimens it occurs as irregular, fractured crystals. Accessory minerals are zircon, sphene, apatite, epidote, and iron ore. The estimated mode as averaged from five slices, which include mica-rich and mica-poor bands, is: quartz 42%, plagioclase 20%, biotite 11%, muscovite 15%, K-feldspar 10%, garnet 1% and accessories 1%.

2. Speckled Semi-Pelite

The term "speckled" refers to the appearance of the rock in hand specimen, and is the result of the dark biotite being equally distributed throughout the lighter matrix of tectosilicates. In some specimens, the micas, though scattered are oriented and define a well-developed S-plane, whereas in others, they tend to be more randomly oriented.

The average grain size as seen in thin-section is about 0.6 mm; the maximum, found in garnet, approaches 10 mm. in

its largest dimension. The texture ranges from granoblastic to lepidoblastic, largely depending on the content of mica in the rock. Biotite and muscovite occur as robust crystals, with zircon forming pleochroic halos in the former mineral. Pleochroism of the biotite is typically X= pale brown, Y= brown, and Z= red-brown to deep red-brown ($Z > Y > X$). K-feldspar, which is not always present, is usually untwinned, whereas the plagioclase nearly always shows sharp twins. Myrmekitic textures are abundant in some slices, although generally they are uncommon. The plagioclase is normally fresh, and zoning is moderately well-developed in many crystals. The average anorthite content of five specimens is An_{32}, ranging from An_{25} to An_{41} (flat stage). Accessory minerals are apatite, sphene, zircon, iron ore, and garnet. The estimated mode as averaged from five slices is: quartz 20%, plagioclase 43%, muscovite 13%, biotite 19%, K-feldspar 4%, and accessories including garnet 1%.

3. Sub-pelitic Semi-pelite

The term "sub-pelite" has been introduced to describe the type of semi-pelite which resembles certain features of the normal pelitic schist, but lacks others. Basically, the sub-pelite and pelite have a similar

mineralogy, but various differences are apparent even in the field, and may be summed up as follows:

Sub-Pelite	Pelite
a) Fine-grained,	a) Coarse-grained,
b) Less mica,	b) More mica,
c) No tourmaline	c) Tourmaline in many slices
d) Quartzo-feldspathic segregations the exception,	d) Quartzo-feldspathic segregations the rule,
e) Texture is more homogeneous	e) Texture is more heterogeneous.

The average grain size in thin-section is 0.5 mm, and the maximum in its longest dimension, found in garnet, is about 10 mm. The texture is commonly lepidoblastic, but mica-poor areas tend to be granoblastic. Quartz commonly has smooth edges, and frequently exceeds plagioclase in volume percent in the rock. Strained extinction of the quartz is common. Muscovite and biotite form robust crystals with zircon forming pleochroic halos in the biotite. The pleochroism of the biotite is typically X= pale brown, Y= brown, and Z = red-brown to deep red-brown ($Z \geq Y > X$). Plagioclase is usually fresh, although crystals show slight alteration in some thin-sections. A weak zoning is typical of the plagioclase, and twinning is well-developed. The

average anorthite content of four specimens is An_{30}, ranging from An_{25} - An_{36} (flat stage). Garnet is usually present in small amounts, and though fractured is always unaltered. Inclusions of quartz and muscovite are not uncommon in the garnet. The estimated mode as averaged from five thin-sections is: quartz 36%, plagioclase 40%, biotite 15%, muscovite 7%, garnet 2%, and accessories (apatite, sphene, zircon, K-feldspar, orthite(?), and iron ore), 2%.

4. Knotty Semi-Pelite

This type of semi-pelitic rock is usually more micaceous than the types described above. In fact, the mica content of a few specimens is close to 50%. This rock, however, is so distinct from the more typical pelite, that I have called it a "knotty semi-pelite", Plate II. Some of the distinguishing features of this type of semi-pelite in hand specimen are a) a lack of quartzo-feldspathic segregations that are so typical of the pelite; b) a maculose appearance caused by the segregation of mica + quartz (after kyanite) into knots; c) the presence of small veins of quartz which commonly lace the rock, Plate III; and d) garnets appear to be pinker than garnets in the typical pelite.

In thin-section the average grain size is about 0.5 mm,

PLATE II

a. Photomicrograph of a knotty semi-pelite; strained muscovite porphyroblast to left, "knot" to right; west of Liatrie. x 25

b. Photomicrograph of a typical quartz-kyanite-muscovite segregation from a knotty semi-pelite; Creag Feusag. x 25.

c. Photomicrograph of a bandrich in apatite running parallel to the foliation; other minerals are muscovite, biotite, garnet, and quartz; west of Liatrie. x 25



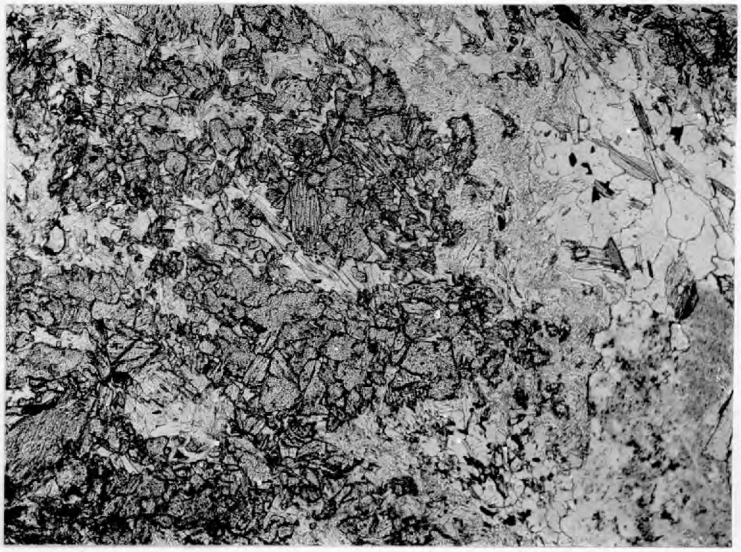




PLATE III

a. Photomicrograph of a knotty semi-pelite, showing kyanite as part of the groundmass; other minerals are muscovite, biotite, garnet, quartz, and plagioclase. One mile east of Muchrachd. x 25.

b. Photomicrograph of a typical pelite; Creag Feusag. x 25

c. A typical knotty semi-pelite, laced with quartz veins; one mile NE of Mullardoch Dam; pencil is 6 inches long.







with the maximum size attaining 6 mm in its largest dimension (muscovite). The texture generally ranges between maculose and lepidoblastic. The knots, which give the rock its maculose texture, consist of sericite and bundles of fine-grained muscovite, in which quartz and/or plagioclase make up a very small part. In some slices, relic kyanite is seen, and is invariably surrounded by sericite or muscovite, into which it is altering, Plate II.

Quartz generally has smooth edges, and most grains show some strained extinction. The feldspar is typically plagioclase. Twinning is common, though not omnipresent. A weak zoning is discernible in many crystals, and alteration of the plagioclase is slight to absent. The average anorthite content of six specimens is An_{30}, ranging from An_{23} - An_{36} (U-stage and flat stage). Muscovite occurs in three different "forms":

1. distributed throughout the groundmass with biotite,
2. in large masses (knots) of very small crystals, and
3. as very large, strained porphyroblasts in which various minerals, for example quartz, apatite, iron ore, are included.

The significance of these three generations of muscovite is discussed in the section under Metamorphism. Biotite occurs as medium-sized crystals, and is usually primary, but very

rarely it has developed as an alteration from garnet. Inclusions of zircon, which produce pleochroic haloes, and iron ore are common in the biotite. Locally the biotite is intergrown with muscovite. The pleochroism of the biotite is X= pale brown, Y = brown, and Z= brown to dark brown ($Z \geqslant Y > X$). In a few thin-sections that appear especially "messy", chlorite occurs in more than trace amounts. Its crystal habit is very similar to the biotite, and it is probably an alteration product of biotite (see section under Metamorphism). Garnet occurs as large polyhedral crystals, and is invariably fractured. Inclusions of quartz, biotite, muscovite, iron ore, and accessory minerals in the garnet is common. Kyanite occurs as small crystals, sometimes showing two well-developed directions of cleavage. It is not common since most of it has altered either to muscovite or sericite. Although the habitat of kyanite is usually restricted to the knots, in one thin-section it appears to be a primary mineral in the groundmass, Plate III. Accessory minerals are apatite, sphene, zircon, and iron ore. In thin-section, a band 3 mm wide, of which approximately 35% was composed of apatite, was observed running parallel to the foliation, Plate II. The estimated mode of the knotty semi-pelites as averaged from eight slices is: quartz 37%, plagioclase 22%, biotite 14%, muscovite 21%, garnet 3%, chlorite 1%, and accessories

including kyanite, 2%.

Pelite

Pelitic schists are widespread throughout the area. Although the total content of mica in a typical pelite may not exceed that found in some specimens of semi-pelite, the pelite is a totally different rock in appearance. The most characteristic feature of the pelite is that it nearly always contains some quartzo-feldspathic material which appears as lenses, segregations, or lits. Tourmaline, which is not found in the other rock types within the area, occurs in the pelite as an accessory. Another distinguishing characteristic of the pelite is its relative areal continuity. Whereas it is not generally possible to trace a single unit of any one type of semi-pelite for any distance, the pelite retains its characteristic texture over long distances. In the field, therefore, the pelite is a distinct rock type which differs markedly from semi-pelites. It should be noted, however, that a pelitic unit generally contains rocks other than pelite in minor amounts; but when an area on the map is marked as pelite, it means that more than 75% of the exposed area is pelite as described in this section.

In thin-section the texture of the pelites is coarser than most of the semi-pelites described, and is typically lepidoblastic. The average grain size is about 0.6 mm.,

and the maximum in its longest dimension is 6 mm., as attained by garnet, Plate III. Quartz is in moderate sized crystals with smooth edges. Its crystal habit is polyhedral, although locally it occurs in tabular form sandwiched between mica. Strained extinction of the quartz is slight except in a few thin-sections in which it is moderate to strong. Plagioclase is always present, whereas K-feldspar has never been observed in any of the thin-sections of pelite. The average anorthite content of plagioclase taken from 11 specimens is An_{29}, ranging from An_{21} - An_{39} (U-stage and flat stage). Muscovite is in robust plates, which frequently show a strained extinction when they are large (1.5 mm). The more normal sized muscovite crystals are commonly intergrown with biotite, and inclusions of quartz, apatite, and iron ore are not unusual. Biotite occurs as fresh crystals, which are generally smaller than the typical muscovite. Inclusions of zircon and orthite (?), forming pleochroic halos iron ore, and apatite are abundant in the biotite. Pleochroism is X= pale brown, Y= brown, Z= brown to red-brown ($Z \geq Y > X$). Chlorite very rarely occurs as an alteration of biotite. Garnet forms rounded blebs which are usually intensely fractured; they contain inclusions of other minerals such as quartz, muscovite, biotite, plagioclase, apatite, and iron ore. In two thin-sections from the

eastern part of the area, fractured cores of garnet, free from inclusions, are surrounded by rims of garnet with abundant inclusions, but relatively free of fractures, Plate IV. In some crystals, it is possible to detect a change in refractive index between the core and the rim (the significance of this is discussed in the section on Metamorphism). Kyanite was noted in one thin-section, where it occurs within knots which form a thin horizon in the pelite.

The estimated mode as averaged from 15 slices of pelite is: quartz 32%, plagioclase 30%, biotite 16%, muscovite 18%, garnet 2%, and accessories 2%. It should be noted that the low total volume of mica (34%) is probably not real. In many thin sections, coarse-grained quartzo-feldspathic segregations take up a large part of the thin-section. Hence the total volume of mica as judged from these thin-sections is probably less than that of the whole rock from which the section was taken.

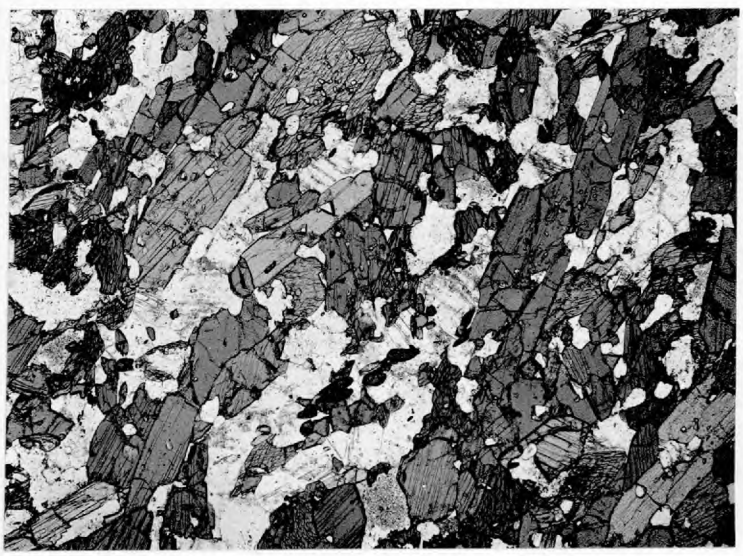
Amphibolites

The amphibolites found in the Moine Series of Glen Cannich represent pre-metamorphic intrusives, probably sills and dykes, which have since undergone the same sequence of folding and metamorphism as the sediments. The contacts

PLATE IV



a. Photomicrograph of garnets in pelite, some of which have inclusion loaded rims: near Loch na Gobhlaig; x 25



b. Photomicrograph of a typical amphibolite, type 2b: in Glen Affric; x 25

between the amphibolite and enclosing sediments are usually concordant, although a number of cross-cutting relationships have been noted in the field (Fig. 2). Merh (1960, plate 2) and Mukherjee (personal communication) have noted similar relationships in the surrounding areas. That these intrusives were injected before or during the early folding is apparent from the fact that minor folds of early age are seen to fold the amphibolite sheets.

The amphibolites can be divided into two main groups:

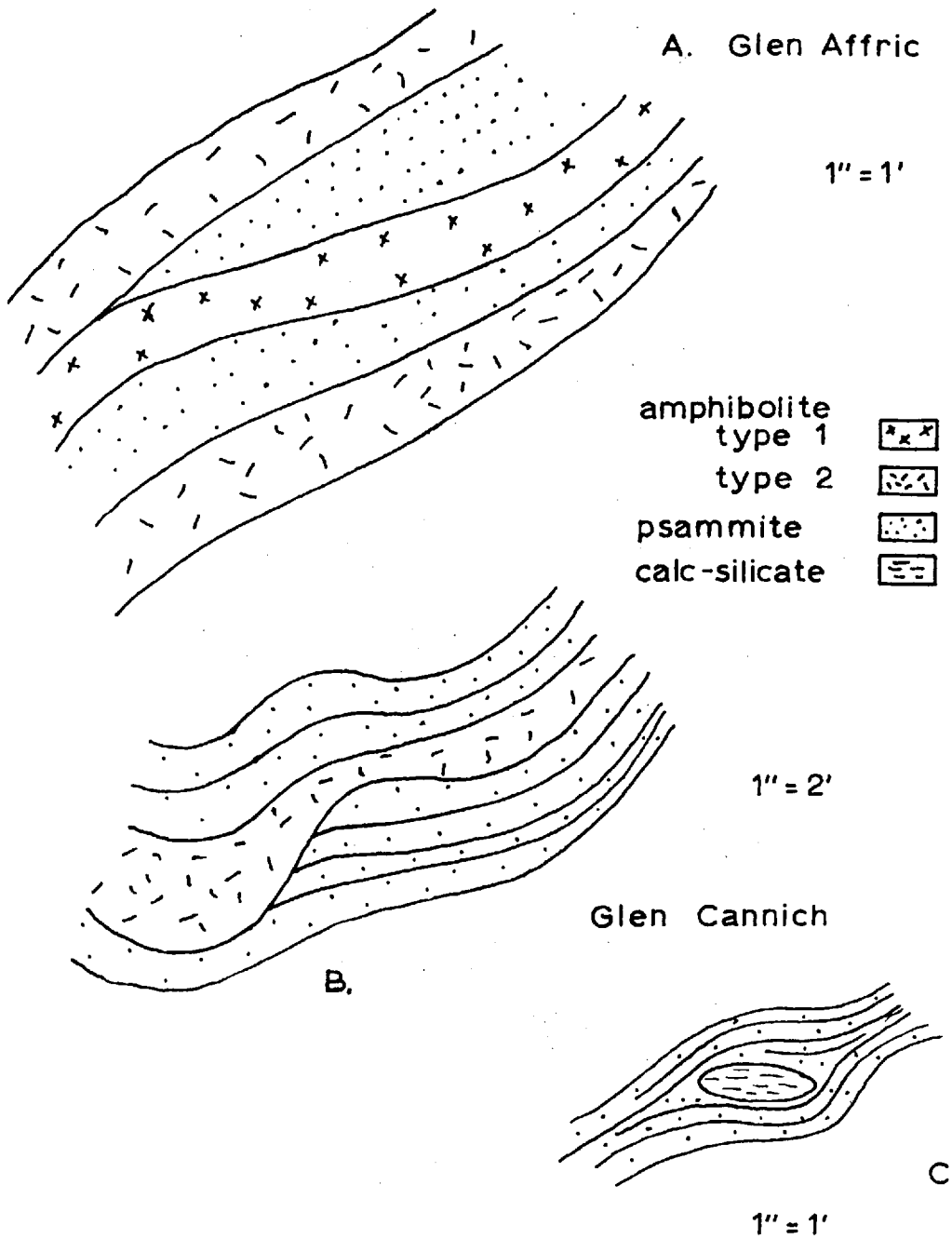
1. Garnet-quartz amphibolites
2. Garnet-free amphibolites
    a. quartz-bearing
    b. quartz-free.

Generally speaking, type (1) is found sporadically throughout most of the area. Type (2) is rarely found in the western two-thirds of the area, but is very common in the east, especially in one psammitic unit which borders the eastern edge of the area. Although different types of amphibolite tend to occur in different host rocks, the mineralogy of the amphibolites is largely a function of its original bulk composition.

1. Garnet-Quartz Amphibolite

The typical environment of this rock is as small pods or lenses in the pelitic units. Since the amphibolite

FIG. 2 Field Relationship Between Amphibolites And Country Rock



commonly contains a good deal of biotite, and has much the same colour index as the pelite, it is easy to miss small pods in the field when they are enclosed in the latter rock. Hence, this type of amphibolite may be more common than I suspect it to be in certain parts of the area. In Glen Affric and areas to the northeast, type (1) amphibolites are more common than usual, and occur in psammitic as well as pelitic rocks.

In hand specimen, the rock is usually foliated, but in exposures where the rock is very coarse-grained, the foliation is not apparent. Garnet is always obvious, and in some areas, for example Glen Affric, the garnets are commonly two inches in diameter, and have well-developed crystal faces.

In thin-section, the texture is lepidoblastic except in coarse-grained rocks. The average grain size is about 0.8 mm., and the maximum dimension, attained by garnet, exceeds the area of a thin-section. Quartz occurs as rounded blebs with smooth to sub-angular edges. When the foliation is well-developed, tabular shaped crystals are not uncommon. Strained extinction of the quartz is moderately well-developed. Plagioclase, though not an abundant constituent of the rock, is nearly always present in small amounts. Zoning is common in the plagioclase, and alteration is essentially absent. Measurable twins are rare, and many crystals exhibit a

chequerboard type of extinction. Because of poorly-developed twinning, only one determination of anorthite content was possible out of the five specimens investigated; the results showed An_{61} (U-stage). Approximations of refractive indices of feldspar above balsam in the other thin-sections suggest that their anorthite content is of a similar value. Hornblende[1] occurs as robust crystals which are usually fresh; rarely, they are intergrown with, or altering to biotite. Inclusions (e.g. quartz iron ore, sphene) are common in the hornblende in some thin-sections, but rare in others. Pleochrosim is variable, but the two most common schemes are: X= light tan, Y= tan, and Z= pale green (Z>Y>X), and X= straw, Y=Z= yellowish-brownish green (Z = Y>X). Some optical data on the hornblendes are included in Table I, page . Garnet is always present in the rock, and is

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(1) The amphibole in type (1) amphibolite (as well as type (2)) show characteristics (see Table I) that might classify the mineral as actinolitic or hornblendic. Deer (et al 1963) states that "there is a continuous range of composition between tremolite and ferroactionolite and the pargasitic, hastingsitic, and tschermakitic hornblendes". Turner and Verhoogen (1951, 1960) report that actinolites from Greenschist Facies rocks contain up to 4% Al_2O_3 (replacing SiO_2), from which one may conclude that there is some miscibility between the tremolite-actinolite and hornblende series. Rather than "sit on the fence" and call this mineral in the amphibolites actinolitic-hornblende, I will use the term hornblende; it should be appreciated, however, that the composition of the hornblende in some specimens tends to be actinolitic.

usually in large, rounded porphyroblasts. An intensely sieved texture is typical of the garnet, and the inclusions may be a combination of the following minerals: quartz, zoisite, iron ore, amphibole, sphene, and calcite (rare). The garnet is always fractured, and inclusions locally appear in "trains" parallel to the fractures, as well as cutline successive "shells" of growth. Alteration of the garnet is absent. Biotite is usually but not always present. The crystals are robust and appear to be primary rather than an alteration product (of garnet). Inclusions of various minerals (zircon, quartz) in the biotite are not uncommon. Pleochroism is X= colourless to pale tan, Y= brown, Z= deep grown to deep red-brown ($Z \geq Y > X$). Sphene is a common minor constituent, and normally occurs in euhedral crystals of variable size. Accessory minerals include zircon, apatite, iron ore, epidote (including zoisite), and calcite (rare). An estimated mode as averaged from five slices is: hornblende 48%, quartz 19%, garnet 19%, biotite 6%, plagioclase 5%, sphene 2%, and accessories 1%.

2. Garnet-free Amphibolite

This type of amphibolite is most commonly found in the psammitic rocks that border the eastern edge of the area, and but for a few exceptions, is absent from the western

two-thirds. In hand specimen, the amphibolite typically shows a well-developed foliation, and the grain size is considerably finer than the usual garnet-bearing amphibolite. The quartz-free and quartz-bearing amphibolite are not separable in the field, as they appear identical in hand specimen.

In thin-section, the texture is lepidoblastic, Plate IV. The average grain size is 0.5 mm., while the maximum size is about 5.0 mm., in its largest dimension, which is attained by plagioclase. The mineralogy of these rocks will be discussed in two sections:

a). quartz-bearing amphibolite, and

b). quartz-free amphibolite.

a). Quartz-bearing amphibolite

Quartz occurs in small rounded crystals and shows a slight strained extinction. Plagioclase is apparently rare, and is present in one out of the two specimens sliced. It forms large crystals, and is loaded with inclusions such as hornblende, quartz, biotite, and zoisite. Most of the crystals of plagioclase are zoned, and twinning is usually "fuzzy", which prevented determination of the anorthite content. Hornblende is in small discrete crystals, which are usually unaltered. Its pleochroism is weak, and is:

X= pale straw, Y= light green to yellowish green, and Z= pale green to green ($Z \geq Y > X$). Some optical data on the hornblende is included in Table I, page [illegible]. Zoisite and some clinozoisite occurs in large to small tablets, which are commonly fractured in two directions. Some are intimately mixed with the plagioclase and/or hornblende. Rare biotite is present in small crystals, and appears to be primary rather than an alteration product of hornblende. Pleochroism is X= very pale tan, Y= brown, and Z= reddish brown ($Z > Y > X$). Accessories comprise sphene, iron ore, and zircon. An estimated mode as averaged from the two slices is: hornblende 54%, quartz 13%, zoisite 14%, plagioclase 15%, biotite 3%, and accessories 1%.

b. Quartz-free amphibolites

This type of amphibolite is dominantly made up of plagioclase and hornblende. The plagioclase is in small polyhedral crystals, and is usually fresh. Zoning in the plagioclase is strongly developed, and twinning is common. The anorthite content appears to vary from specimen to specimen, and the following results were obtained from four specimens, respectively: An_{69}, An_{52}, An_{42} and An_{32} (An_{69} = U-stage, the rest = flat stage). Hornblende occurs in small tabular crystals, and is usually unaltered. Pleochroism is

TABLE I

Some Optical Properties of the Hornblende

Specimen Number	No.140 (type 1)	No.141 (type 2a)	No.48 (type 2b)
$Z \wedge c$	15°	16°	17°
Range of $Z \wedge c$	13-16°	14-17°	16-18°
Out of	4	4	3
2V	$2V_z$=88°	$2V_x$=88°	$2V_x$=87°
Range of 2V	87-88°	84-88°	84-87°
Out of	4	4	4
[H]Refractive Indices	$N_{z'}$= 1.679±003 $N_{x'}$= 1.662±004	$N_{z'}$ = 1.655±001 $N_{x'}$ = 1.641±003	$N_{z'}$= 1.679±004 $N_{x'}$= 1.665±002

[H]Measured in white light. All measurements except R.I. have been carried out on the 4-axis U-stage.

generally weak, and is: X= colourless to pale greenish-tan, Y= yellowish-green to green, and Z= pale yellowish-tan to green ($Z \geq Y > X$); further optical data is included in Table I. Accessory minerals included zoisite, clinozoisite,

sphene, apatite, biotite (rare), and iron ore. An estimated mode as averaged from four slices is: plagioclase 42%, amphibole 55%, and accessories 3%.

In one thin-section, a veinlet or sheet of calcium-rich minerals, including zoisite, sphene, and tremolite-actinolite, separates a bleb of pyroxene-bearing rock from the host. The pyroxene is colourless, and is probably diopsidic; it forms robust crystals which are filled with inclusions of sphene. It is not possible to determine if the pyroxene is a relic of the original amphibolite, or if solutions rich in CaO have provided a special environment for the formation of the pyroxene. The latter may be more probable, since no traces of pyroxene are found outside the envelope of CaO-rich minerals.

Calc-Silicate Granulites

The calc-silicates are found in all parts of the area but usually in very small amounts. In two areas, however, one at Loch Choire a' Bhig and the other in Glen Affric, there are zones where the calc-silicate granulites occur in relative abundance. The host rock is psammite, but some occurrences of the calc-silicates in semi-pelitic and pelitic rocks have also been noted.

The typical mode of occurrence of the calc-silicate

granulites is as pods and sheets of up to 5 inches in thickness, and they cannot be traced along their strike for more than a few feet. In hand specimen, the matrix of the rock is light grey or buff, and is peppered with groups of individual minerals of a much darker colour. In many specimens, the dark minerals define a well-developed foliation; in others, a more homogeneous texture is prevelant. Still other specimens have a glomeroporphyritic texture, in that groups or aggregates of small dark minerals are irregularly scattered throughout the lighter matrix.

The texture seen in thin-section is normally granoblastic, although in some slices, it is lepidoblastic. The average grain size is about 0.4 mm., the largest grain approaches 3 mm. in its largest dimension. All the rocks of this type possess a basic mineralogy: quartz, plagioclase, epidotic minerals (including zoisite and clinozoisite), sphene, and in all but one thin-section, hornblende. With this basic mineralogy are found five other minerals, which may or may not be present: biotite, garnet, K-feldspar, pyroxene (rare), and calcite (rare). It is interesting to note that garnet and K-feldspar do not occur in the same rock.

Quartz is in crystals with smooth edges, and some strained extinction is usually evident. Plagioclase crystals occur in various sizes in which the alteration is

slight to absent. A weak zoning is usually present, and twinning is common. The average anorthite content in 8 out of 9 specimens is about An_{40} ranging from An_{25} - An_{61}, (U-stage and flat stage). The plagioclase in the remaining specimen is anorthite, An_{92} (U-stage). Zoisite, clinozoisite, and rare opidote are present as shapeless blebs and slender prisms of varying dimensions. Orthite is not uncommon as inclusions in the epidote. Biotite is usually present in small amounts, and occurs as small crystals. Pleochroism is X= light straw, Y= yellowish brown, and Z= brown to red-brown to black ($Z > Y > X$). Inclusions of zircon are common in the biotite, and have pleochroic halos. Hornblende ($Z \wedge C = 21^{\circ}$) occurs in slight crystals that are normally free from alteration. The pleochroism varies, but a typical scheme is X= colourless to pale tan, Y= bluish-green, and Z= deep bluish green ($Z > Y > X$). Sphene occurs as small crystals, which are usually subhedral, but not uncommonly euhedral. K-feldspar is present in half of the specimens as small crystals. Twinning is absent, and the crystals are unaltered. Garnet, which is present in the remainder of the specimens, appears as blebs that are filled with inclusions of quartz, epidotic minerals, amphibole, biotite, and iron ore. Because some specimens contain certain minerals which others do not, an average mode of the

specimens examined would be misleading, and hence is not presented.

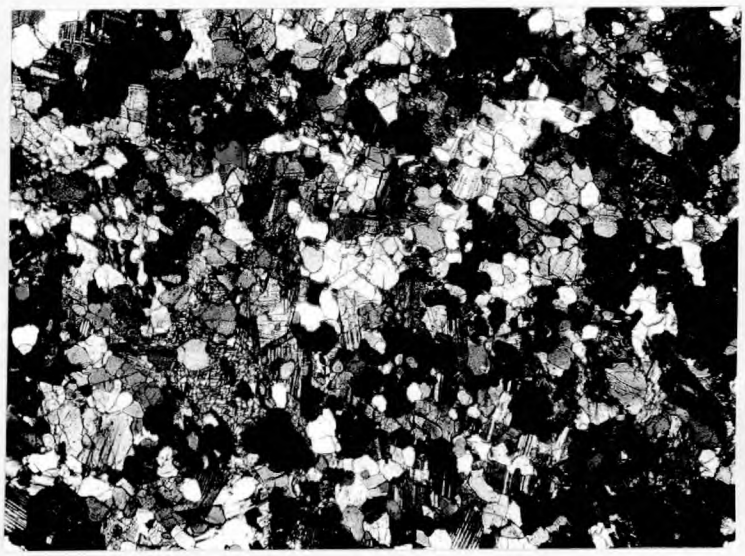
One thin-section (no. 192) of calc-silicate granulite from the western part of the area contains pyroxene and anorthite (An_{92}), Plate V. The pyroxene is colourless with a $2V_z = 58^\circ$ (U-stage). Considering the accompanying assemblage of zoisite, sphene, calcite, and amphibole, the pyroxene is probably diopsidic. Some crystals of the pyroxene appear to be essentially fresh, although others are altering to amphibole. Garnet occurs as large crystals, and usually contains abundant inclusions of quartz, calcite, zircon, and amphibole. Quartz is present in the groundmass as small, rounded crystals. Accessory minerals include apatite, zircon, and iron ore.

Pyroxene-Albite Rocks

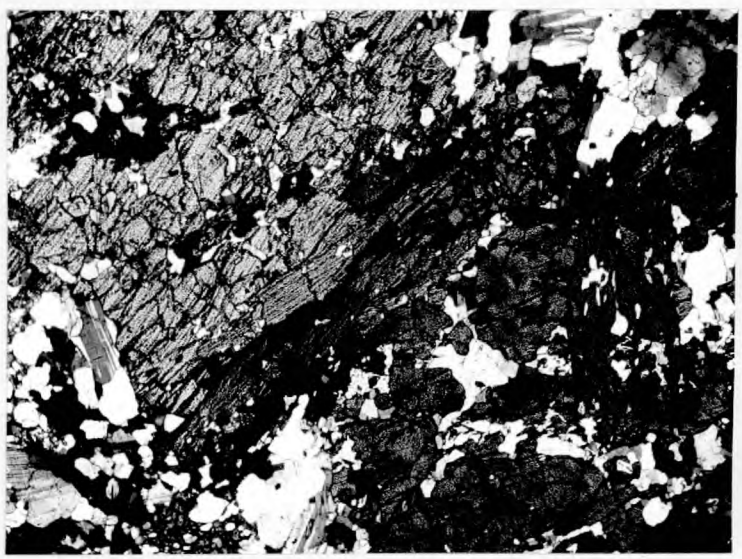
Description

Only two occurrences of this rock type have been observed, and they are just east of Mullardoch Dam; they outcrop about one mile apart along the same strike line, and are probably the same general horizon, Fig. 3. The rock occurs in sheets between one to two feet in thickness, and only rarely can be traced for more than 10 - 20 feet along

PLATE V



a. Photomicrograph of an anorthite-diopside bearing calc-silicate granulite; near Loch a' Choire Bhig; x 25.



b. Photomicrograph of a pyroxene-albite rock; note the mottled extinction of the pyroxene in the lower right quarter of the photograph; also the amphibole in the upper left corner and far right of photograph; ½ mile NE of Mullardoch Dam. x 25.

the strike. Two-thirds of a mile southwest of Mullardoch Dam, however, one band has been observed where the thickness is about 50 feet, and it can be followed for about 300 feet. It is not possible to be sure if the thickness is entirely original or has resulted from tectonic thickening.

Dark porphyroblasts of ferromagnesian minerals are the only indicator by which the rocks can be identified in the field. These porphyroblasts, abundant in one locality, may decrease gradually as one walks normal to the foliation strike, until they appear to be absent. Yet another few feet away, further blotches of porphyroblasts may suddenly appear. Hence, the boundaries between these rocks and the typical Moine psammite appear to be very diffuse. Quartz veins or blebs as well as some quartzo-feldspathic segregations locally occur in these rocks.

Minor folds are evident within some exposures of the pyroxene-albite rock. North of the River Cannich, one band has been folded by an F-2 minor fold, and the ferromagnesian minerals are seen to lie in the plane of the schistosity. Their longest dimensions are parallel to the local F-2 fold axes, and they form a very well-developed lineation.

The texture in some hand-specimens is glomeroporphyritic, in which the porphyroblasts are individual or groups of ferromagnesian minerals. In other specimens, the

ferromagnesian minerals are more evenly distributed throughout the rock, and locally give it a banded appearance. The colour of the groundmass is cream, which contrasts markedly with the dark green to black porphyroblasts. In some examples, the ferromagnesian minerals constitute a large portion of a specimen, giving the impression that the rock is an ultrabasic.

In thin-section, the texture ranges from granoblastic to porphyritic. The groundmass is made up of albite and quartz, in which are set the porphyroblasts of pyroxene and amphibole. In areas of the thin-section where the ferromagnesian minerals are present, the texture is porphyroblastic; where they are absent, the texture is granblastic. The average grain size in the groundmass is about 0.5 mm. The maximum size of the porphyroblasts, as attained by pyroxene, is about 4 - 5 mm. in its largest dimension. In most slices, the groundmass appears "messy"; i.e. quartz and albite appear to be reacting with each other, and texturally, these minerals are intimately related to each other. Both are present in sizes which range from less than 0.1 mm. to a few millimeters across, and commonly occur as aggregates of tiny crystals.

Although quartz occurs in some slices, in others it is absent. In the latter instances, albite, is seen to form

the bulk of the groundmass. The albite is essentially unaltered, and twinning is usually well-developed. A weak zoning is discernible in some grains; in others, inclusions of small crystals of the same mineral are present. The extinction of the albite in many crystals is uneven. The anorthite content, as measured on the U-stage is An_4.

Pyroxene is present in most but not all of the thin-sections made. It occurs in large porphyroblasts as well as smaller crystals, and its appearance differs somewhat from slice to slice, Plate V. Inclusions of albite (+ quartz ?) and amphibole in the pyroxene are common in all the thin-sections examined. In most slices the mineral is relatively unaltered and despite a strong body colour, is recognizably pleochroic. A typical scheme, though variable, is: X= plae green to grassy green, Y= pale green, and Z= pale yellowish tan to yellowish apple green ($Z \gtrsim Y \gtrsim X$). Some optical properties of the pyroxene are:

$Z \wedge c = 55^\circ$ (average of 6 U-stage determinations ranging from $53^\circ - 55^\circ$);

$2V_z = 65^\circ \pm 2^\circ$ (average of 5 U-stage determinations (one axis), ranging from $63^\circ - 66^\circ$);

$N_y = 1.713 \pm 0.0007$ (measured in white light).

Judging from the optical properties given above, the pyroxene appears to be a sodic diopside. By using the

information in Winchell (1951, p. 414), Trŏger (1956, p. 64), and Deer et. al. (1963, p.87), it is possible to make a very rough estimation of the relative percentages of the Diopside ($CaMgFeSi_2O_6$) and Aegerine ($NaFeSi_2O_6$) molecules in the pyroxene: $Di_{80}Aeg_{20}$. In a few slices, however, the pleochroism and body colour of the pyroxene is slight, and many of these crystals are altered to a greater or lesser extent to a deep blue-green amphibole. The pyroxene in these slices may be richer in the Diopside molecule than that indicated above.

Amphibole occurs in fair-sized crystals, which are normally smaller than the pyroxenes, and contains inclusions of plagioclase (+ quartz ?) and epidote + orthite). Much of the amphibole, even when in contact with the pyroxene, appears to be primary, although as mentioned above, some of it is an alteration product. Pleochroism of the amphibole is intense: X= strawish yellow, Y= green to dark green, and Z= deep blue-green ($Z > Y > X$).

Epidote occurs in more than accessory amounts, and is usually in skeletal or shapeless forms. Orthite cores are common in the epidote. Sphene occurs in one thin-section as large sub-euhedral crystals; and intersertal calcite is present in another slice. Accessory minerals are iron ore, zircon, and biotite. An estimated mode as

averaged from two of the slices is: albite 53%, sodic diopside 23%, amphibole 16%, quartz 4%, epidote 2%, sphene 1%, and accessories, 1%. It should be appreciated, however, that the modes vary rapidly over distances of an inch or so.

Discussion

Metamorphic rocks largely similar to those described above have been reported from the Moine Granulites in Glen Lui, Aberdeenshire (McLachlan, 1950), and Ben Loyal, Sutherland (King, 1942). Both these authors attribute the formation of the soda-pyroxene in the granulies to metasomatian processes associatied with contiguous igneous intrusions.

Along the eastern shores of Loch Hourn, P.W.G. Tanner has shown me small outcroppings of rock within the Moine granulites which are strikingly similar, and in many exposures identical in appearance to the soda-rich rocks from Glen Cannich. These outcroppings are restricted to a zone about ½ mile wide, and about 2 miles long. In slices of this rock, Tanner (personal communication) has found that these rocks contain soda-pyroxene (aegerine-augite) and abundant albite. The nearest igneous body to these rocks is the Ratagain Syenite, which is at least five miles away. The pyroxene-albite rocks from Glen Cannich and Loch Hourn

therefore, appear to be similar in essential mineralogy, macro- and microscopic textures, field relations within the immediate area of a given outcrop, and apparent lack of an igneous body within reasonable distance to relate the source of excess soda in the rocks as indicated by the albite and the sodic pyroxene.

The genesis of these rocks is discussed in the section on Metamorphism.

Inclusions

Ellipsoidally-shaped inclusions have been observed in pelitic as well as psammitic rocks in a number of localities west of Mullardoch Dam. The inclusions are commonly about 1 foot long and half as wide. Their longest dimension is normally oblique to the foliation of the country rock, and a crude internal foliation is present parallel to the longest axis of the ellipsoidal form, Fig. 2c. In hand specimen, the rock appears massive, and the mineralogy is not easily identifiable. Judging from the field occurence (i.e. pod-like) and the mineralogical assemblages (see below), these inclusions are most probably akin to the calc-silicate granulites.

I have recognized two types of these inclusions. In both types, the texture in thin-section is essentially

granoblastic.

Type 1): Garnet makes up about two-thirds of the rock and appears as one mass which includes quartz, pyroxene, and iron ore. The pyroxene is colourless, and is probably diopsidic. Iron ore is scattered throughout the rock. A rough estimation of volume percentages is: garnet 59% quartz 23%, pyroxene 12%, and iron ore 6%.

Type 2): Quartz and plagioclase make up the bulk of this type of inclusion. The plagioclase is usually fresh, although a slight alteration is locally present. Twinning is very well-developed, but zoning is absent. Extinction of the plagioclase is sometimes "blotchy". The anorthite content is An_{77} (flat stage). Amphibole (tremolite-actinolite) occurs in shapeless and well-formed crystals that include other minerals such as garnet, sphene, iron ore, plagioclase, and quartz. Pleochroism of the amphibole is very faint, and varies from colourless to very pale green. Garnet is scattered throughout the rock as rounded blebs. Zoisite occurs in small to large crystals. Accessory minerals are sphene, apatite, biotite, iron ore, muscovite, chlorite, and calcite. A rough estimation of the mode from the two slices is: quartz 30%, plagioclase 49%, amphibole 13%, garnet 3%, zoisite 2%, and accessories 3%.

Pegmatites

Limited amounts of pegmatites occur throughout the area. They usually form sheets which cross-cut the foliation, but non-descript blotches are also common, and rarely of considerable size (i.e. a few tens of feet in largest dimension). The genesis of the pegmatites is discussed in the section on Metamorphism; but the mineralogy of the rock type under consideration is briefly outlined below.

In hand specimen, the pegmatites are usually very coarse-grained, but not invariably so. The rock is a pale colour, and consists predominantly of plagioclase, K-feldspar, and quartz, with muscovite and locally garnet as minor constituents. In the one thin-section of pegmatite examined, K-feldspar occurs in very large (15 mm. and larger) crystals, and typically shows the grid twinning characteristics of microcline. The plagioclase is strongly altered. Judging from its refractive index against balsam, the plagioclase is probably in the oligoclase-andesine range. Myrmekitic texture is common. A rough estimate of the mode is: K-feldspar 57%, plagioclase 17%, quartz 23%, muscovite 2%, and garnet 1%.

Pelitic Gneiss

The term pelitic gneiss is used to describe a type of

gneissic rock which occurs in thin bands (about 1 foot thick) in the psammites. They are not uncommon in certain groups, such as the Loch Carrie Psammitic Group (see section on Stratigraphy), and are good indicators of schistosity/ foliation relationships. The pelitic gneisses differ from the typical pelite, which may locally have a gneissic texture, in the following ways:

Pelitic Gneiss	Pelite
1) Alway contains K-feldspar	1) Never contains K-feldspar
2) Less mica	2) More mica
3) Augen texture well-developed.	3) Augen texture not common

In hand specimen, a well-developed gneissic foliation is visible, and augen of feldspar are usually common. Thin-section examination shows the augen to be K-feldspar, which are typically unaltered. Grid twinning of the K-feldspar is present, although many crystals are untwinned. The plagioclase is always altered to some extent, and may form myrmyketic textures when in contact with the K-feldspar. A weak to moderate zoning occurs in the plagioclase, and twinned crystals are common. The average anorthite content of the plagioclase in two slices is An_{21}, ranging from An_{17} - An_{26} (flat stage). Quartz is present in small crystals that rarely show a strained extinction. Biotite occurs in

slender lathes and stubby plates. Zircon is commonly included in the biotite, and forms pleochroic halos. Pleochroism of the biotite is X= pale tan, Y= brown, and Z= greenish-brown to brown to deep red-brown (Z > Y > X). Accessory minerals are apatite, zircon, muscovite, sphene, garnet, and iron ore. An estimated mode as averaged from three specimens is: quartz 22%, plagioclase 36%, K-feldspar 26%, biotite 13%, and accessories 3%.

THE LEWISIANOID ROCKS

The rocks to which I refer as "Lewisianoid" are restricted to a small area south of Sgurr na Lapaich, which is in the northwest corner of the map. The nature and field occurrence of these rocks is discussed in the section on Stratigraphy.

I have not differentiated in the field between the various types of Lewisianoid, and have shown them on the map as a single composite body. Within this composite body are three main types of rock:

1. banded and massive calc-silicates;
2. epidote-biotite-quartz rocks; and
3. striped hornblende gneiss.

The calc-silicates constitute the bulk of the Lewisianoid

body, and correspond to the calc-silicate rocks that Ramsay (1954, pp.89-90) has described. The remaining two types make up only a small volume of the body. I will outline the mineralogy of the various types below.

1. Banded and Massive Calc-Silicate Rocks

In some hand specimens, these rocks are strongly banded, the alternating bands ranging in colour from pale green to yellowish-green to dark green. Equally as common are rocks with massive textures and generally lighter shades of cream and green. Whereas in the former rock the concentration of similarly coloured minerals defines the bands, in the latter the massive texture is a result of the equal distribution of these minerals throughout the rock. In thin-section, the texture ranges from granoblastic to lepidoblastic. The grain size tends to be larger in the granoblastic types. The following mineralogy is typical of the calc-silicate rocks: amphibole, pyroxene, epidote, K-feldspar, quartz and plagioclase.

The amphibole is in tabular crystals, and is usually free of inclusions. Pleochroism is barely discernible as a very pale green, but more commonly the amphibole is colourless. This lack of pleochroism combined with the fact that the $Z \wedge C$ is low suggests that the amphibole is

probably tremolite. The pyroxene is also colourless and is probably diopside. It occurs in stubby crystals usually fresh, but some are in the first stages of alteration to amphibole. Epidote is invariably present, in places as large blotches, and it exhibits a yellow pleochroism. K-feldspar occurs as squarish crystals, with grid twinning commonly well-developed. Plagioclase is not common, but when present is usually slightly altered. It shows zoning, but twinned crystals are uncommon. The anorthite content is in the oligoclase/andesine range. Quartz is invariably present, and rarely shows a strained extinction. Accessory minerals are biotite, phlogopite, sphene (not common), muscovite, and iron ore.

2. Epidote-Biotite-Quartz Rock

This type of rock has been found in only two localities within the Lewisianoid body. In hand specimen it is pale to dark grey, and is crudely foliated. The minerals appear to be more equigranular, rather than platy as in the calc-silicates described above. In thin-section, the foliation is more obvious. The mineralogy differs from the calc-silicates in that amphibole and pyroxene are absent, whereas mica is present in considerable quantities. The typical mineralogy is quartz, epidote, biotite, and muscovite; K-feldspar and plagioclase may or may not be present.

Quartz is in various sized crystals, which invariably show some strained extinction. Pale yellow epidote and locally clinozoisite are common, and occur as small to large crystals. Biotite (phlogopite ?) is in small plates which are frequently intergrown with slivers of muscovite. Pleochroism of the biotite is X= colourless to pale green, Y=Z= very pale tanish-green to olive green (Z = Y>X). Muscovite occurs in small crystals and slivers, and commonly appears to grow across the foliation. K-feldspar and/or plagioclase may be present in small amounts. The K-feldspar is normally twinned, while the plagioclaselacks twins but is zoned. Accessory minerals are apatite.

3. Striped Hornblende Gneiss

The striped hornblende gneiss has been found only in one locality. The hand specimen is dark with black bands of hornblende alternating with the pale tanish tectosilicates. In thin-section, the average grain size is about 0.5 mm. The maximum grain size, attained by hornblende, is 6 mm. in its largest dimension. Quartz locally shows an intense strained extinction, and the edges of the crystals are commonly serrated. Plagioclase occurs in squarish form, and crystals are slightly to moderately altered. Twinning and zoning are well-developed. The anorthite content of

the plagioclase is in the andesine range. Hornblende occurs in large, slender crystals, which typically lie with their longest axis in the foliation. Quartz and accessories minerals are locally included by the hornblende. Pleochroism is X= tan, Y= green, and Z= blue-green ($Z > Y > X$). Epidote is acattered throughout the rock in small amounts. Accessory minerals are sphene, zircon, and iron ore.

A few hundred feet from where the above rock occurs, is a lens which consists predominantly of quartz, epidote, and iron ore. The hand specimen is pale grey with streaks of darker grey (iron ore) and bright chartreuse (epidote). In thin-section, blotches of iron ore make up about 15% of the rock; weakly pleochroic epidote occurs in small rounded crystals, and makes up about 20%; the remainder of the rock consists of quartz, which shows intense strained extinction and serrated edges. Sphene, orthite, and rare amphibole are present as accessory minerals.

PETROGRAPHY OF THE IGENEOUS ROCKS

DYKES

General

A swarm of camptonitic dykes from the Loch Monar area, which lies just to the north of Glen Cannich, has been described by Ramsay (1955). Dykes of similar types are

also found in the Glen Cannich-Glen Affric area, but they are of a very restricted occurrence. The intrusions cropout as narrow sheets along lines that are controlled by jointing or foliation. The thickness of these sheets averages between one and two feet, and attains a maximum of about 10 feet. The dykes always cross-cut the foliation at some place along their outcrop. Generally, the dykes trend east-west, although in a number of occurrences it was not possible to determine the strike of individuals because of the small area of outcrop.

The exact age of these dykes in the Glen Cannich area is not known. If they are the same age as those found at Loch Monar, then they may be either of Tertiary age as proposed by Flett (in Peach and others, 1913), or of Permian age, as proposed by Richey (1939).

The dykes can be divided petrographically into 3 types: minette-vogesite lamprophyres, plagioclase-amphibole-biotite rock and camptonitic lamprophyres; these are discussed briefly below.

Minette-Vogesite Lamprophyres

I have observed only one occurrence of this rock type. In hand specimen, the rock has a brick red colour, and is speckled with dark porphyroblasts of ferromagnesian minerals. In thin-section, the texture is similar to that in the hand

specimen. The groundmass appears as a reddish, murky mass of feldspar (+ zeolite ?). The feldspar has a R.I. lower than balsam, and does not exhibit twinning; it probably is K-feldspar. Porphyroblasts of ferromagnesian minerals in all sizes are scattered throughout the groundmass. Biotite occurs in stubby crystals with " 'battlement' ends" (Williams et al, 1955), and sometimes includes other minerals. Pleochroism of the biotite is X= pale tan, Y= brown, and Z= red-brown (Z > Y > X). Pyroxene is in idiomorphic crystals, sometimes up to 3 mm. in its largest dimension. It is colourless to very pale green, and zoning and/or twinning is rarely developed. Epidote is present as small crystals, which generally show a yellowish-green pleochroism, and apatite occurs in slender prisms and polyhedral plates. Accessory minerals are iron ore, calcite, chlorite, and serpentine (?).

Plagioclase-Amphibole-Biotite Rock.

Two specimens of this type of dyke rock have been collected. Its basic mineralogy of plagioclase, amphibole, and biotite suggests that it is chemically akin to a gabbro. In hand specimen, the rock is dark green to black, and one of the samples has a chilled margin (no. 199). The texture in thin-section, however, is not truely igneous. The

matrix consists of plagioclase crystals intimately intergrown to form a continuous matt. This matt includes all the other minerals. The extinction of the plagioclase is irregular and spotty, partly because of a zoning. Twinning is rare and poorly developed, and a certain amount of alteration has taken place. Optical properties suggest that the plagioclase is a calcic-oligoclase. Amphibole occurs in large and small sub- to euhedral crystals. Pleochroism is X= very pale tan, Y=Z= pale green ($Z = Y > X$). Biotite is in small crystals, which sometimes are in clusters. Pleochroism of the biotite is X= colourless to tan, Y= greenish-brown to brown ($Z \geqslant Y > X$). Epidote may occur in more than accessory amounts in some slices (No. 199), and calcite is not uncommon as large porphyroblasts including amphibole in another thin-section (No. 221). Accessory minerals are chlorite, and iron ore.

The genesis of the texture of this type of dyke rock is puzzling, since the texture is neither igneous nor metamorphic, but rather half way between. It is highly unlikely that the change in texture (assuming that the rocks had an igneous texture at one time) is a result of Caledonian metamorphism. The dykes commonly cut the foliation at large angles (90°), and there is no evidence to suggest that they have been affected by even the latest folding (F-5), by the end of

which phase all metamorphism of any import has ceased (see section on Metamorphism). Furthermore, one specimen (No. 199) shows a chilled margin, indicating that the country rocks must have been relatively cool when the dykes were intruded. Possibly some type of autometamorphism is responsible for the non-igneous texture.

Camptonitic Lamprophyres

The camptonitic lamprophyres are the most common type of dyke in the Glen Cannich area. In hand specimen, the rock is basaltic grey, and, in fact, superficially resembles a basalt in general appearance. Ocelli of light coloured minerals locally are scattered throughout the fine-grained matrix.

In thin-section, the texture is intersertal. Because of alteration, however, the texture is commonly "messy", and individual minerals are difficult to identify. The basic mineralogy is plagioclase, pyroxene, amphibole, calcite, and iron ore. Plagioclase occurs in slender lathes, which are intensely zoned, and show a "fuzzy" twinning. The anorthite content is in the andesine/labradorite range. Pyroxene shows the typical dispersion and birefringence of titanaugite, and occurs as small, stubby granules. The amphibole, which is in slender needles as well as granules,

shows a low extinction angle and deep orange to brown pleochroism, suggesting that it is barkevikite. Small crystals of iron ore are scattered throughout the matrix in considerable quantities. Calcite, and to a lesser extent, serpentine make up the ocelli, although both these minerals are also found in the groundmass. Serpentine may be, in part, after olivine.

CHAPTER 3

TECTONIC STRUCTURES

Definition of Structural Elements

There is some disagreement among structural geologists of various countries regarding certain nomenclature. For example, usage of the term "foliation" is different in America than in Britain. Hence, I feel it is worthwhile briefly to consider the various structural elements observed, and to define at least in the less obvious cases, how the terms have been used in the following pages.

The term foliation is used to describe the compositional layering or banding in the metamorphic rocks (see discussion in Wilson, 1961, p.458). In the psammites and some types of semi-pelite, the foliation is most probably of sedimentary origin, whereas in pelites and the other types of semi-pelite, the foliation is of metamorphic origin. In calc-silicate granulites, a combination of sedimentary and metamorphic processes has produced the foliation, while in the amphibolites, it is mainly a metamorphic feature. Igneous processes may, however, be responsible for some part of the planar features in the amphibolites.

Various structures may be grouped under the term

cleavage; schistosity, strain-slip cleavage, and fracture cleavage, among others (see Knill, 1960; Wilson op. cit. p.457-464). The term schistosity is here used to indicate a planar structure in the rock defined by the alignment of platy minerals. The schistosity and foliation are readily distinguishable in the hinge area of minor folds, where they are mutually oblique; when minor folds are absent, however, these two planar structures are distinguishable only in the pelitic gneiss, and appear to be essentially coincident in the other rock types.

Though an axial plane schistosity is nearly always present in the minor folds of the earlier phases of folding, crumpling is a common feature of the later stages of folding. The crumpling is very similar to that described by Fleuty (1957, p.113-114), who points out that "these structures bear a family resemblence to the 'herringbone structure' described by Richey (1952), and to slip-cleavage well known in pelitic rocks of the Dalradian and Appalachians (e.g. Clough 1897, White 1949)". The term crumpling, therefore, is here used as a general term which embraces this "family" of structures, where the use of such terms as strain-slip or fracture cleavage would be inaccurate and misleading.

Although folding occurs on all scales, the term minor fold and major fold are used in the following contexts:

minor folds are folds whose geometrical features are not of sufficient size and continuity to be recorded in scale on the 6 inch map; major folds are folds whose geometrical features are of sufficient size and continuity to be recorded in scale on the 6 inch map.

Lineations of various types are common structures throughout the area. The axes of minor folds are the most common type, while the intersection of schistosity/foliation and crumpled mica/foliation are also widespread. Locally, weathering may have eroded most of the mica from a crumple, leaving only a quartzo-feldspathic core with some seemingly elongated micas. At first glance, this type of lineation appears to be a recrystallisation phenomenon, when in fact it is largely mechanically produced. Quartzo-feldspathic and quartz rodding as well as quartzo-feldspathic striping (Plate VI) are found in pelitic and semi-pelitic rocks, and are not uncommon in the psammites. In the knotty semi-pelites, elongated kyanite-bearing knots form a distinctive lineation. Rarely in some of the calc-silicates and amphibolites, the amphiboles show a well-developed mineral orientation, with the long axes of the amphiboles forming the lineation.

As mentioned above, minor folds are common. In the field, wherever possible, the pattern of the minor folds has

PLATE VI

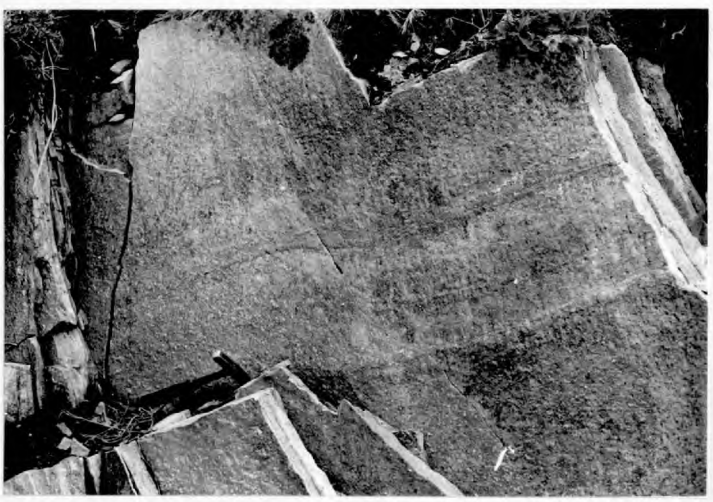
a. Quartzo-feldspathic rodding plunging to the west; north of Loch Choire a' Bhig.

b. Quartz rodding plunging to the south, east of Creag Feusag.

c. Quartzo-feldspathic striping plunging gently to the west; steep lineation is a crumpling of a later phase; west of Mullardoch Dam.







been noted so that they may be correlated with the geometry of the major folds. In the following pages, I shall speak of S, Z, and M folds; these terms refer to the fold pattern as it appears looking down the plunge. This terminology corresponds to the "sinistral" (S) and "dextral" (Z) of White and Billings (1951, p.668). Numerous authorities, including Ramsay (1958a, fig. 7)and Fleuty (1961, p.455-456), have clearly demonstrated the geometrical relations that should hold between minor and major structures of the same generation: S's and Z's are asymmetrical and are found on the appropraite limbs of the major folds, whereas M's are symmetrical and found in the hinge area. The terms symmetrical and asymmetrical are here used with respect to the geometry of the fold and not to its attitude (c.f. Billings 1954, p.40).

Among the major folds on the map, there are five basic types: anticline, syncline, antiform, synform, and neutral fold. Anticlines and synclines in the area are defined solely by sedimentary structures which declare the age relationships of the strata; these terms do not necessarily imply any special geometrical form. Antiform and synform (Bailey and McCallien 1937, p.81) are those structures which close upward and downward respectively; that is, the geometry but not necessarily the stratigraphic succession is

known. A neutral fold is a structure that closes sideways (Fleuty 1961, p.450). Since the rocks have been subjected to repeated folding, geometrical complexities arise whereby anticlines, as defined by sedimentary structures, have a synformal geometry, and vice versa. Hence, such terms as synformal anticline and antiformal syncline (Carey 1962, p.101) may be expected in the following pages[1].

General

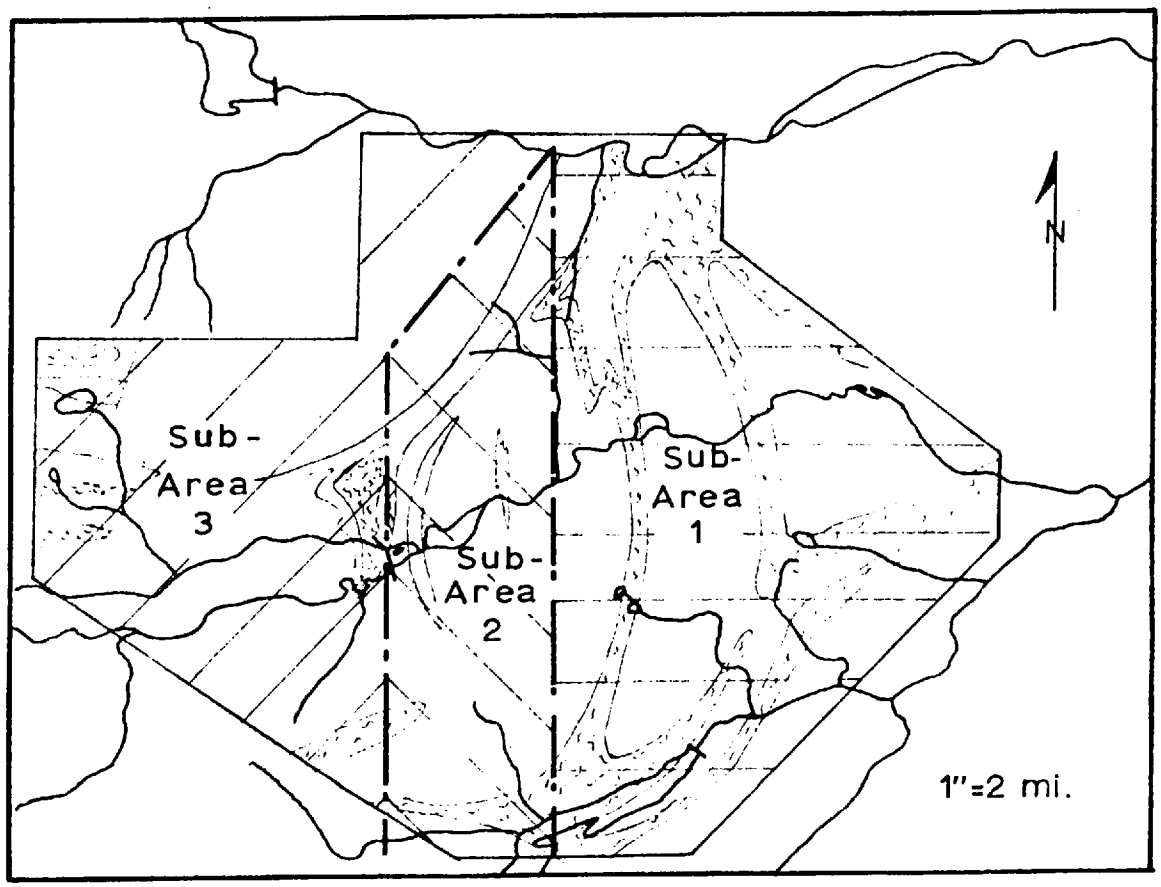
The structural geometry of the area is complex; I have therefore, divided it into 3 sub-areas in order to facilitate a clear presentation (Fig. 4). In describing the geometry of the rocks from each sub-area, I shall start with the earliest phase[2] of deformation as represented by major structures, and progress to the later phases in turn. I cannot overemphasize the fact that I have based the identification of the successive phases of deformation on refolding relationships. On this basis, it has been possible to build

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(1) Shackleton (1958) has introduced terms such as "downward facing anticline", which would correspond to the term "synformal anticline". I have preferred Carey's (ibid) nomenclature, because in two words, the term "synformal anticline" directly and succinctly defines the geometry and stratigraphical relationships of the fold in question.

(2) "Early Structures" = F-1, F-2; "Intermediate Structures" = F-3; "later Structures" = F-4, F-5.

FIG. 4 Sub-Area Distribution



up a sequence of phases in each sub-area. The sequence in the different areas have then been correlated by use of the following criteria: style of the fold, recrystallization accompanying the fold, and to a lesser degree, orientation of axial plane and axes of the folds. These correlations have led to the recognition of 5 phases of folding in the area, of which the oldest is F-1, and the youngest F-5. All phases are represented in each sub-area, except for phase 3, which is absent in sub-area 2. Generally, therefore, correlation of these phases between sub-areas presents no problem. The correlation of phase 3 between sub-areas 1 and 3 is established by indirect means. In each sub-area, F-3 folds refold F-2 minor folds and are being refolded by F-4 minor folds.

The identification of F-1 minor structures presents some difficulty, since both F-1 and F-2 minor folds and lineations are of similar aspect. I have classified a structure as F-1, therefore, only when it was possible to ascertain its age relationship to F-2 major or minor folds. There may be some misidentification between F-1 and F-2 minor structures over small areas, but this would not affect the interpretation of the major fold geometry. In every instance where I have deduced the geometry, etc. of a major F-2 fold by minor structures, it has been possible to demonstrate, either directly or indirectly, that those minor structures were of F-2 age.

Sub-Area 1.

Sub-area 1 is a north-south trending zone which covers most of the area east of an approximate line between Meallan Ohdar and Meall Mor. Generally speaking, the trends of the foliation and axial planes of the major folds are north-south, but in the south-east, the trends of the foliation and some folds are more towards the northeast. Half of this sub-area is occupied by the Glen Cannich "eye", an elongate structure trending north-south between An Soutar and Meallan na Ceardaich. The Loch Carrie Syncline lies to the west of this structure; to the east lie the Muchrachd Synform, and the Beinn a' Chairein, Benevean, and Dog Fall Neutral folds.

The Early Structures

The Glen Cannich Eyed Structure

The Glen Cannich Eyed structure which is of F-2 age, is considered to represent the earliest phase of folding that is recognizable on a major scale, since the stratigraphy as shown by sedimentary structures is in accord with the tectonic structures of this phase. There are refolded minor structures in the hinges of the major structure under consideration, and these minor structures are classed as F-1 age. I discuss the nature and significance of F-1 minor structures in the section on Structural Synthesis (page 195).

To facilitate a clear description, this eyed structure has been divided into two parts.

The Northern Part.

The northern part of the eyed structure is defined by lithologic boundaries, attitude of the foliation, schistosity/foliation relationships, and sedimentary structures. North of the River Cannich, the foliation of both limbs of the structure dips to the west at very high angles. The hinge of the fold is clearly defined by the swing in strike of the pelitic strata in the region of An Soutar, though it is poorly defined in the psammites. Unfortunately, exposure in this area is not very good, and later deformation has complicated the geometry, so that changes in orientation of the foliation may not always be a function of F-2 folding. Near Loch Carrie, however, the hinge is well-defined in the psammites, and the geometry is clearly that of a synform. South of the River Cannich, the synformal shape of the fold can be traced for about one mile farther to the south, and then the dips of the foliation on both limbs become parallel, with the dip to the east. Later folding, at least in part, is the probable cause of this tightening up of the synform. Well-preserved sedimentary structures, consisting predominantly of current-bedding and some slump structures, consistently face (Shrock 1948, p.17-18) away from the axial plane trace of

the fold. This relationship obtains from An Soutar to about one mile north of Meallan na Ceardaich in Glen Affric (Fig.3). Although the synform is not clearly defined by the foliation along its entire length, the schistosity/foliation relationships, which are common in both limbs of the fold, are in accord with the geometry of a synform plunging to the south, Fig. 5. It is seen, therefore, that for approximately 4/5ths of its length, the eyed structure is that of a synformal anticline.

The plunge of this fold, as determined by analysing the foliation orientation, is moderate to the south-southeast (Fig. 6a). Where later folding has tightened up the limbs and the synform is not recognizable as such, for example in the Loch na Gobhlaig area, the accompanying lineations indicate that the plunge is of the same trend and magnitude.

As can be seen from Fig. 6a, there is considerable scatter in the orientations of the F-2 lineations which accompany the fold. This is largely the result of the refolding of F-2 lineations by minor folds of a later phase, as well as the probability that a number of the lineation I have identified as F-2 may in fact be lineations related to F-1 folding. Generally speaking, however, I think that F-1 lineations are uncommon relative to F-2 lineations.

Minor folds associated with the synformal anticline

FIG. 5 Sketch Map Showing Schistosity/Foliation Relationship of F-2 Major Folds

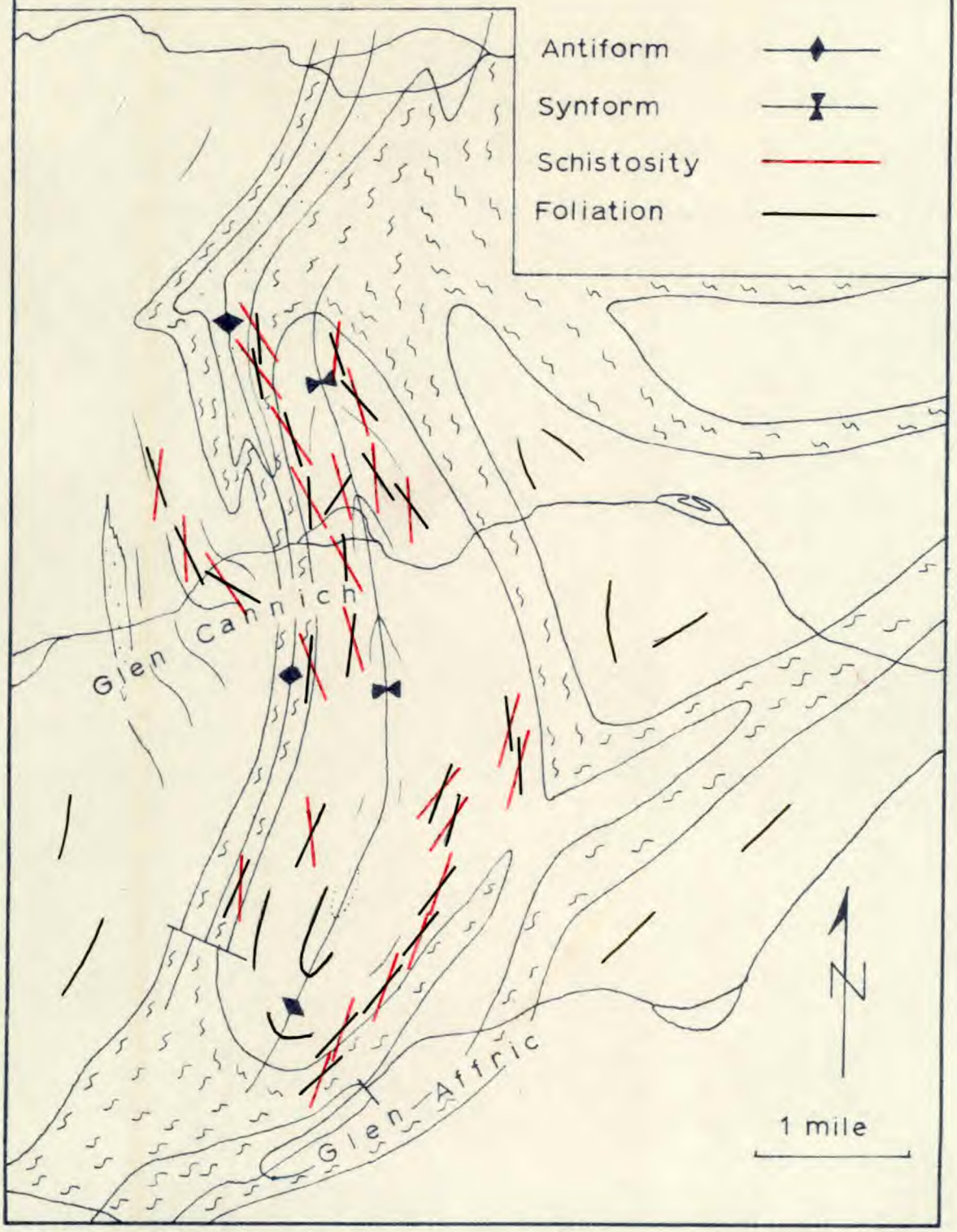
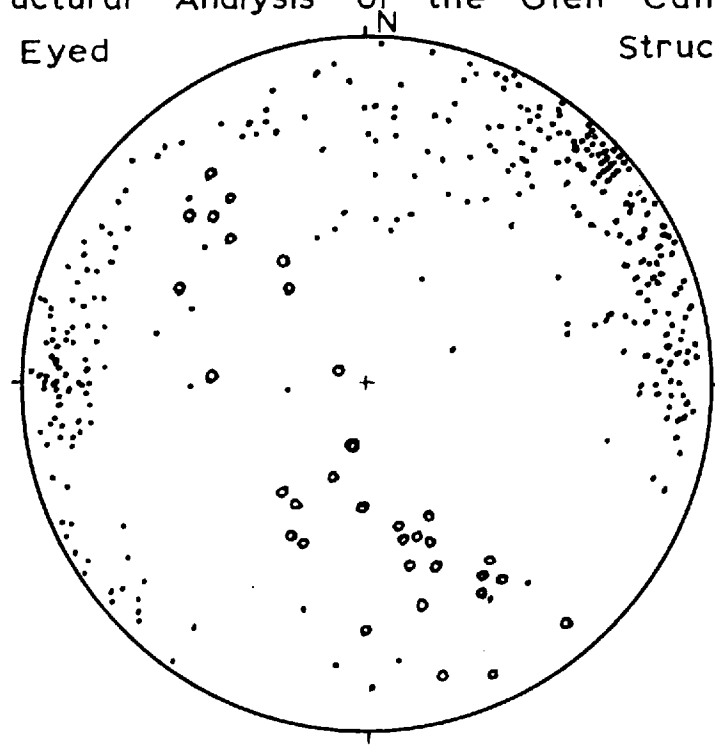


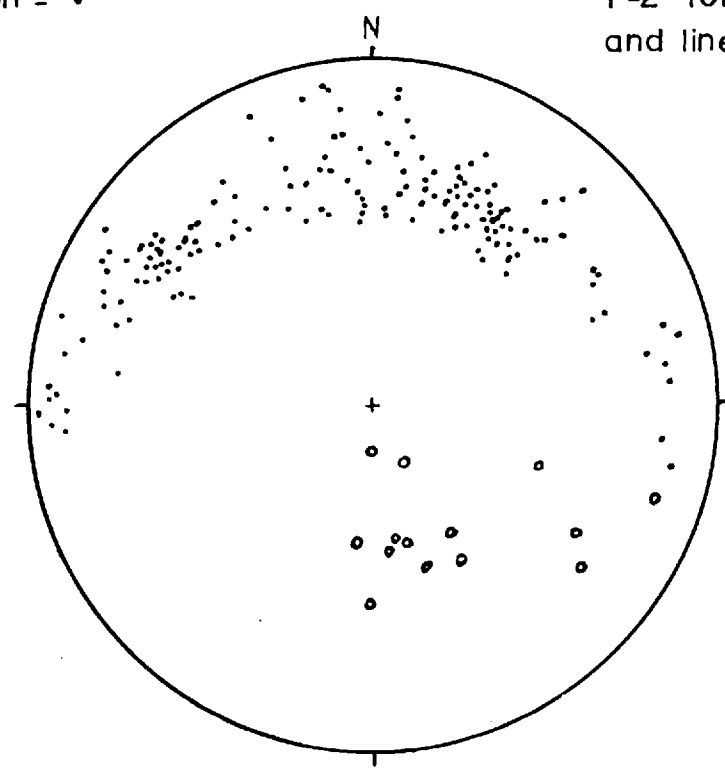
FIG. 6 Structural Analysis of the Glen Cannich Eyed Structure



a. Northern Part

π foliation = •

F-2 fold axes and lineations = o



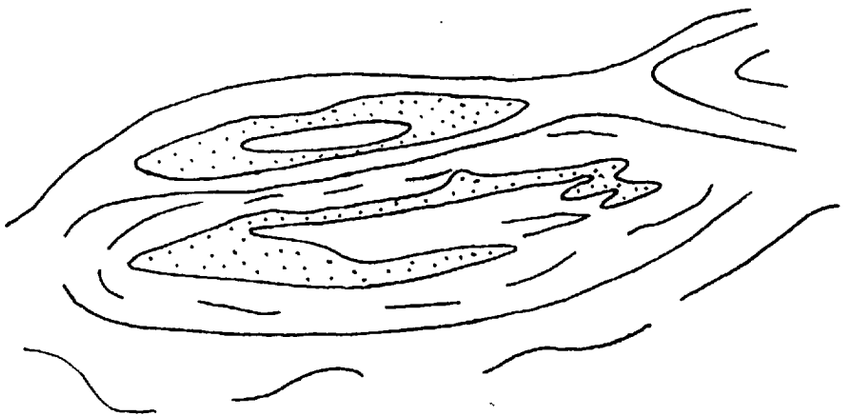
b. Southern Part

are not common, and when observed, their pattern is not always identifiable: typically the minor folds are very tight to isoclinal "V" shapes. Eyed minor structures as well as S, Z, and M shapes are sparingly present, however (see Fig. 7). They are rarely found in psammitic rocks, occurring most commonly in semi-pelitic types. Where the minor folds occur in other than pure psammite, they are accompanied by a well-developed axial plane schistosity. F-2 lineations in this area, aside from minor folds, consist predominantly of quartzo-feldspathic striping and schistosity/foliation intersections, with rodding and elongated knots occurring locally.

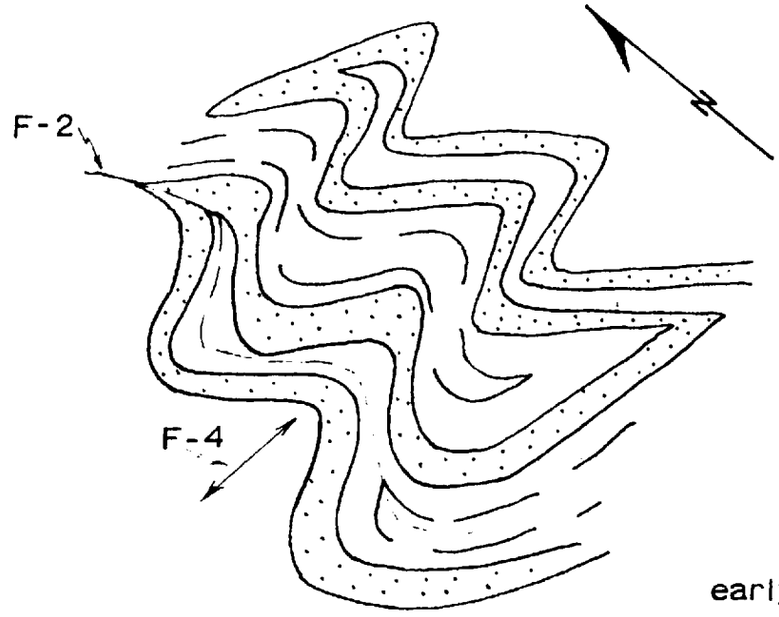
The Southern Part.

The geometry of the southern part of the eyed structure differs from that of the northern part. This difference begins to be evident about one mile north of Meallan na Ceardaich, where the swing of the foliation on the west limb of the structure is suggestive of the synformal closure. Exposures hereabouts are rare, however, and it is not possible to be sure if this is so. Further to the south along the axial plane trace, exposure is excellent and the structure is seen to be a very well-defined antiform. At the latitude where this transition from synform to antiform appears to take place, there is an abrupt change in the schistosity/

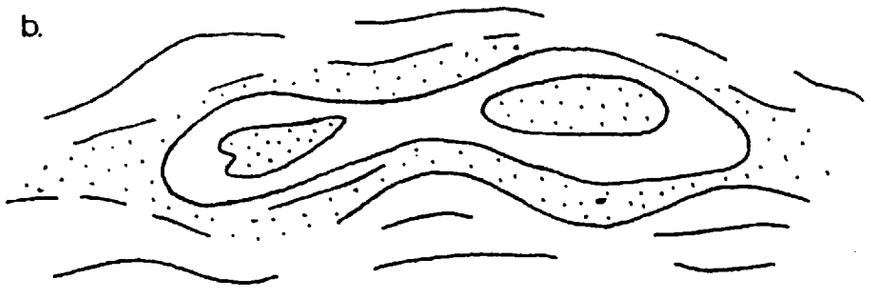
FIG. 7 Styles of Early Structures in Sub-area 1 Viewed ca. ⊥ to the Fold Axes



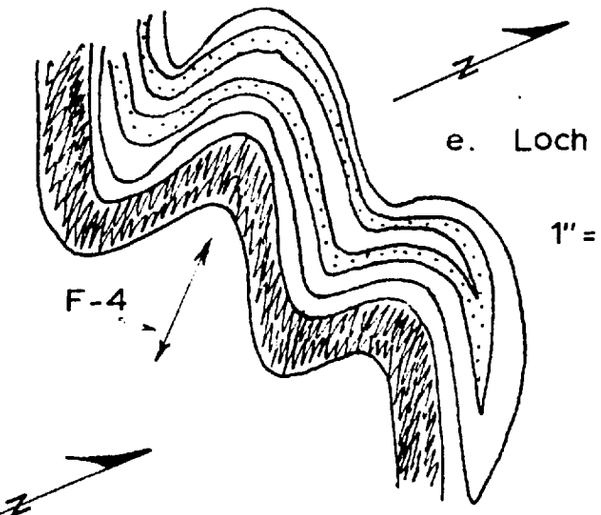
a. An Soutar 1"=6"



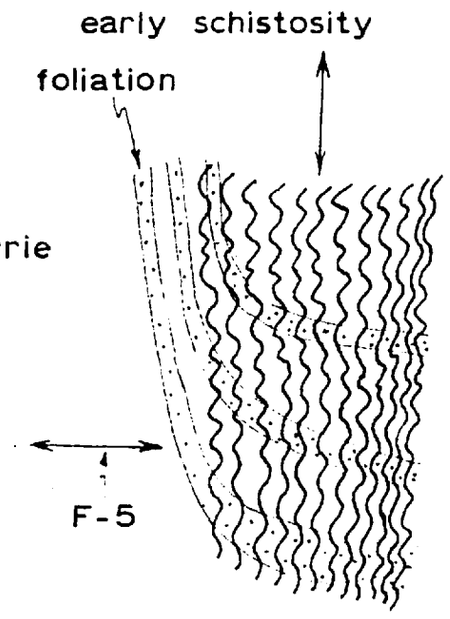
d. Glen Affric 1"=2'



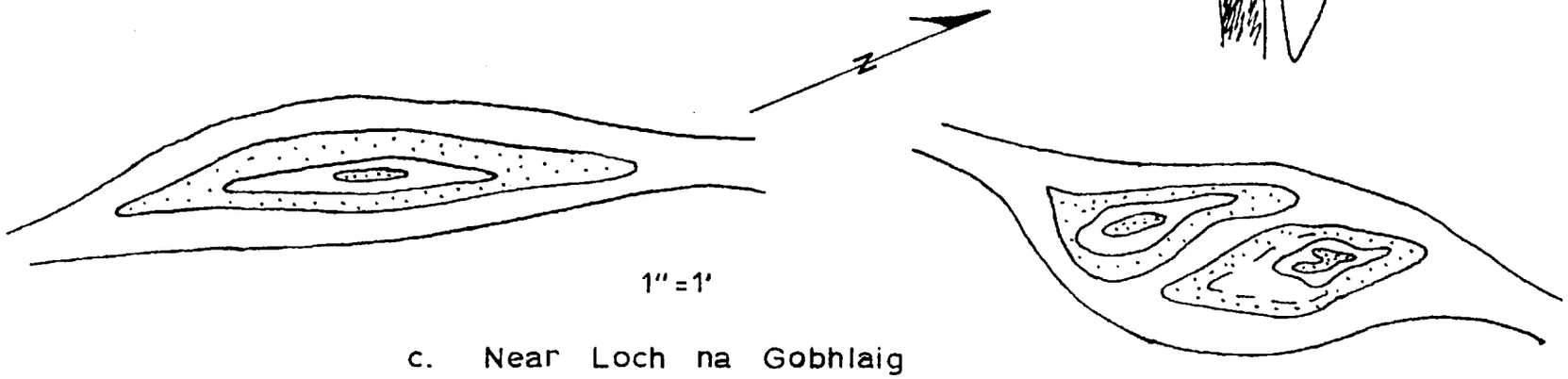
b.



e. Loch Carrie 1"=4'



f. An Soutar 1"=1'



1"=1'

c. Near Loch na Gobhlaig

foliation relationship: to the north it accords with the synformal geometry, and to the south it accords with the geometry of an antiform (Fig. 5).

The trend of the antiformal axis on Meallan na Ceardaich is southwards at moderate plunges, as found from the stereographic plot in Fig. 6b. Minor folds of F-2 age are absent from the fold core, but I have observed a few on the limbs. Their pattern is in accord with the major antiformal structure. F-2 lineations are almost as uncommon as minor folds, and where present are invariably quartzo-feldspathic rodding. The spread of lineation plots in Fig. 6b is mainly because of refolding by later phases of deformation, although it is possible that some of the lineations identified as F-2 may be of F-1 age.

Sedimentary structures have not been observed south of the latitude where the change from synform to antiform occurs, and hence it is not possible to be absolutely sure if the antiform is also anticlinal, although this is most probably the case. The axial plane trace of the antiform can be followed for about one mile from just north of Meallan na Ceardaich into Glen Affric proper, where it loses its identity. This is largely because of poor exposure coupled with the complex geometry that has resulted from post F-2 deformation.

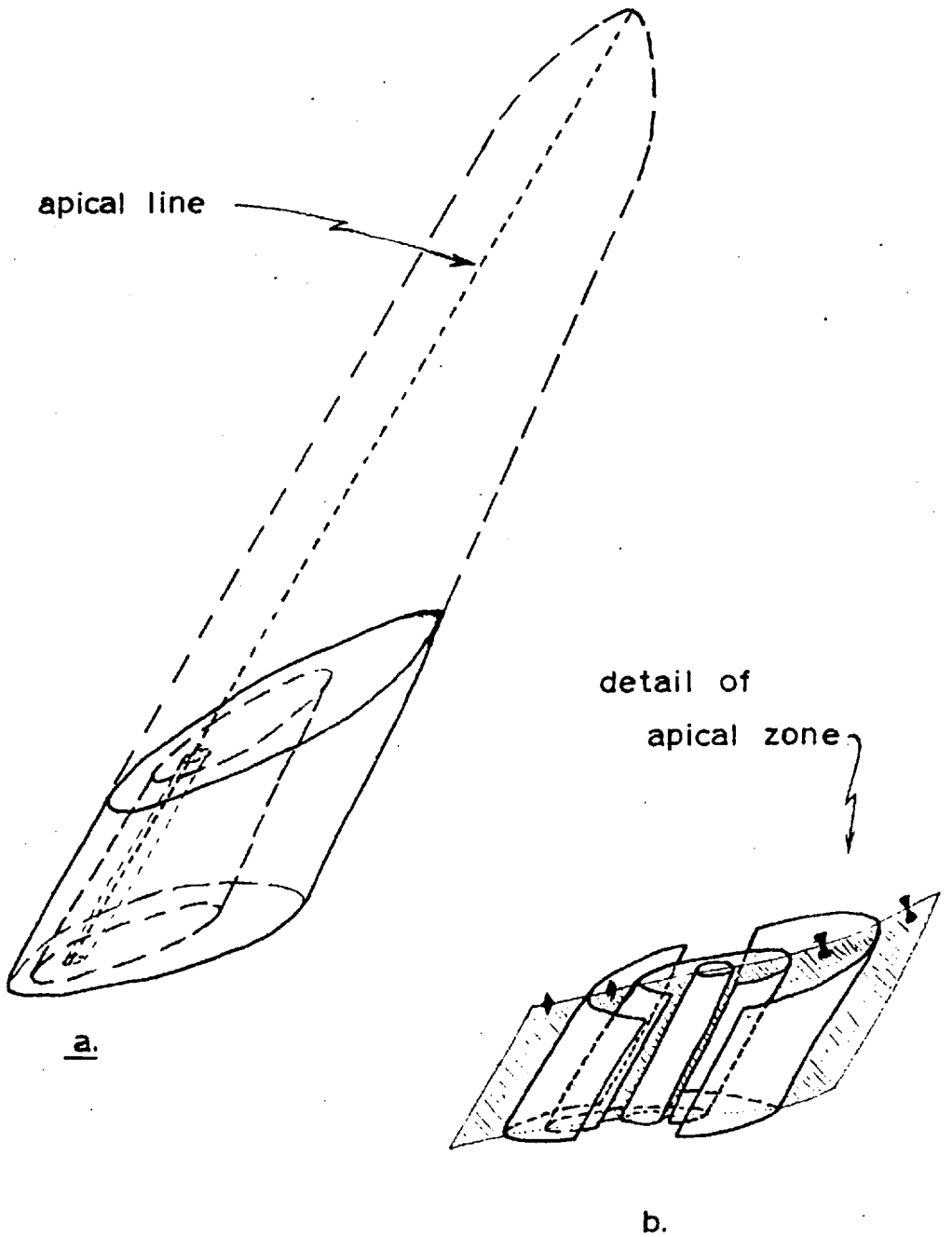
It is seen that the Glen Cannich Eyed Structure can be divided into two parts, whose direction of closure are opposed, and whose plunges are essentially parallel. It cannot be demonstrated, therefore, whether the plunges of the respective parts converge upwards or downwards. There is one source of indirect evidence to suggest that it is more probable that they converge upwards: stratigraphically, the eye is anticlinal. Tentatively, therefore, I suggest that the Glen Cannich eyed structure is an exceedingly elongated anticlinal dome, whose apical line is trending southerly at moderate plunges (Fig. 8a). The apex of the dome is just north of Meallan na Ceardaich, and is shown by the transition point where the synform changes into an antiform along its axial plane strike (Fig. 8b).

The Loch Carrie Syncline

This structure is the complementary syncline of the anticlinal dome described above, and is therefore considered to be of F-2 age. It is defined by sedimentary structures, schistosity/foliation relationships, and to a limited extent, by lithological boundaries. Its axial plane trace can be followed for six miles from Glen Strathfarrar to the area of Meall Mor in Glen Affric.

From Glen Strathfarrar to just east of Meallan Ohdar,

FIG. 8 Simplified Representation of the Glen Cannich Eyed Structure



the syncline is defined wholly on lithology, in that two units of pelite are separated by a semi-pelitic unit. Unfortunately exposure to the north and southeast of Meallan Odhar is sporadic, so that the exact boundaries of the pelite forming the western limb and the semi-pelitic core are not always clearly shown in the field. Further to the south along its axial plane trace, however, the boundaries are better defined; and at Loch Carrie, the pelitic units of the two limbs merge into one unit, thereby cutting out the semi-pelitic unit of the core. This defines the closure of the syncline. About one mile north and west of Loch Carrie, sedimentary structures are seen to face <u>toward</u> the axial plane trace of the syncline on both limbs.(1) This relationship holds from An Soutar to just north of Loch na Gobhlaig, a distance of about 2½ miles. South of the latter point for a little over a mile, no sedimentary structures were observed, mainly because of poor exposure. Just north of Meall Mor in Glen Affric, however, sedimentary structures reappear on the west limb, and still face toward the axial plane trace of the syncline. As mentioned in the last section, no undoubted sedimentary structures are present on the eastern limb in the Meall Mor area, which is the shared limb of the adjacent anticline.

The lineations accompanying the structure consist predominantly of quartzo-feldspathic rodding, schistosity/

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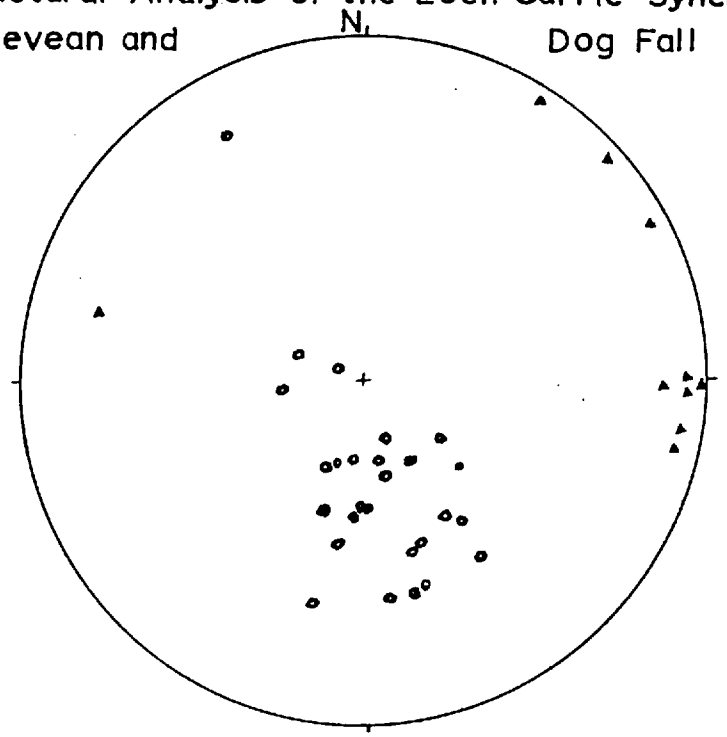
(1) See Fig. 3.

foliation intersection, elongated kyanite-bearing knots (rare), and occassional minor folds. They trend in a southerly direction, and their plunges are steep to moderate (Fig. 9a). The variations in orientation of the lineations and axial planes of minor folds seen in Fig. 9a are due mainly to refolding by later structures.

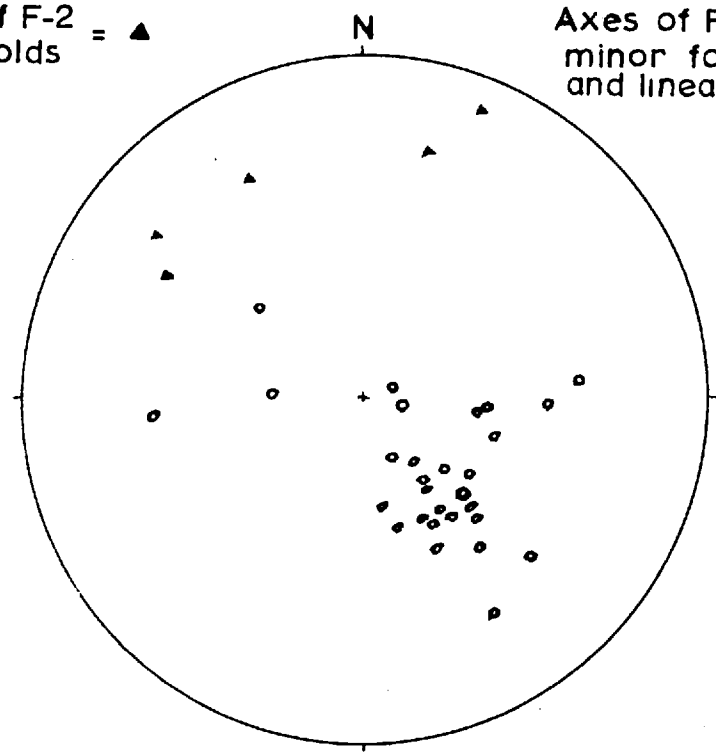
The geometrical form of this fold, as defined by the foliation, is elusive, although it may be indirectly determined. Since the plunge of this fold is southerly as deduced by lineations, and the closure is to the south as shown by the pelitic units merging at Loch Carrie, the geometrical form of the fold must be antiformal. And since sedimentary structures face toward the axial plane trace, the Loch Carrie fold, at least between River Cannich and Meallan Ohdar, is an antiformal syncline. Schistosity/foliation relationships bear out this geometry (Fig. 5). Between Meallan Ohdar, and Glen Strathfarrar, the synclinal trace must continue, since the pelitic units continue in a parallel manner; schistosity/foliation relations suggest that the antiformal geometry persists as well.

South of the River Cannich into Glen Affric, the axial plane trace of the syncline is contained between the two boundaries of the pelitic unit; this is supported by facing directions of sedimentary structures. South of Meall Mor,

FIG. 9 Structural Analysis of the Loch Carrie Syncline and the Benevean and Dog Fall Folds



a. Loch Carrie Syncline



b. Benevean and Dog Fall Folds

the axial plane trace is lost in the poorly exposed and complex ground of Glen Affric proper. I discuss the probable overall geometrical form of the syncline in the section on Structural Synthesis (page 195).

The Glen Affric Folds

Two contiguous structures, both essentially neutral folds, are present in the area of Glen Affric. They are the structures which lie adjacent to the anticline and syncline described above, and are considered to be of F-2 age. These neutral folds are defined by lithology, pattern of minor folds, and schistosity/foliation relationships. The northwestern and southeastern folds of this contiguous pair have been termed the Benevean and Dog Fall Neutral folds respectively.

The Benevean Neutral Fold

Pelite forms the core of this northward closing isoclinal structure, and psammite forms the limbs. Along the northwestern limb, schistosity/foliation relationships and minor folds (Z's) are present; in the southeastern limb, minor folds (S's) are locally abundant. A limited number of M minor folds occur in the core of the structure. Both limbs dip to the southeast at moderate angles. The minor folds of both limbs and core as well as the schistosity/

foliation relationships in the northwestern limb are congruous with the geometry of the major fold.

The plunge of the Benevean Neutral Fold is well defined by minor folds and quartzo-feldspathic striping. The orientations of the lineations and axial planes of the accompanying minor folds, however, are variable on account of later deformations. As can be seen from Fig. 9b the trend of the linear structures is to the southeast, and the plunge is moderate. The pitch (Clark and McIntyre 1951) of the fold axis in the axial plane approaches 90°, and it is this quality which defines the fold as being neutral. The axial plane trace of the Benevean Neutral Fold can be followed to the southeast from one mile north of Dog Fall as far as the area of Benevean (Affric) Dam, a distance of about 1½ miles. West of this area, poor exposure and complex structure render further tracing of the fold impossible.

The Dog Fall Neutral Fold

This southwestward closing fold has much the same geometry as the complementary Benevean Fold. The limbs of the Dog Fall Neutral Fold are defined by pelitic units, and the core is occupied by psammite. Minor folds on the northwestern limb are S's, on the southeastern limb they are Z's, and in the core they are M's. Both limbs dip toward the southeast at moderate angles. The plunge of minor

folds and quartzo-feldspathic striping is to the southeast, and the pitch of the lineations in the axial plane is large (Fig. 9b). Hence, the Dog Fall fold is a neutral fold. The axial plane trace of this fold can be followed for about two miles from one mile north of Dog Fall to about one mile southwest of Benevean (Affric) Dam.

The Beinn a' Chairein Fold

This structure, which is probably the continuation of the Benevean fold (see page 102), is F-2 in age. It is defined primarily by the orientation of the foliation, and to a lesser degree by lithological boundaries. It can be seen on the map (in pocket) that the limbs of the Beinn a' Chairein fold are abnormally thickened. This thickening is mainly a result of later deformation by the Muchrachd Synform. Variation in the plunge of the axis of this synform combined with the present topographic surface has magnified the abnormalities (see page 109).

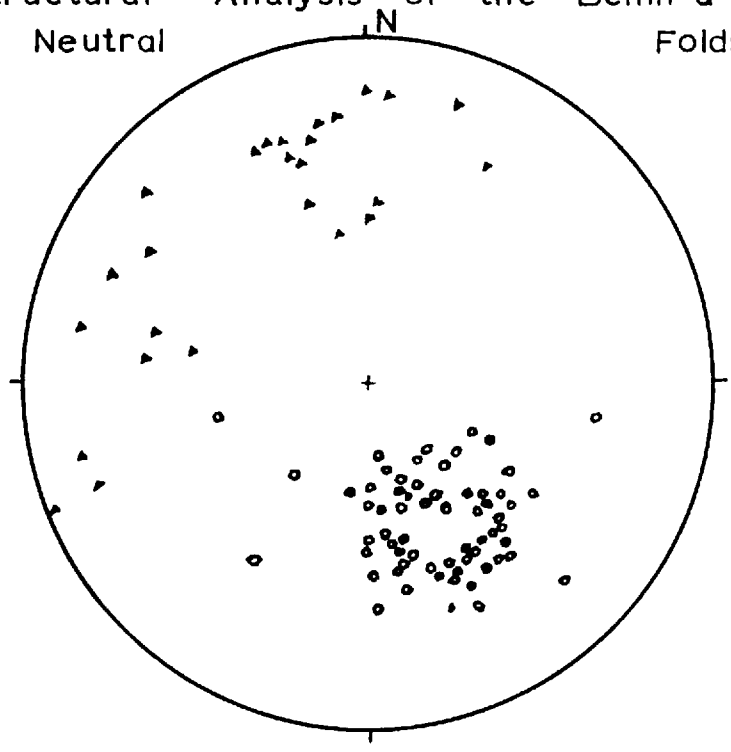
The axial plane trace of the Beinn a' Chairein fold, as defined by the orientation of the foliation, is apparent in the area of Meall Dubh. The orientation of the axial plane trace here is approximately east-west. As it is followed westward, it swings to the south through Lochan a' Mhuill Duibh, where it is crossed by the later synformal

trace, and continues in a southerly direction passing through the summit of Beinn a' Chairein. South of this summit, there is no exposure until the Lochan na Cuidhe area. Here, the orientation of the foliation, plus the fact that the pelite of the next stratigraphic unit is crossed, suggests that the axial plane trace probably continues to the south (see page 195).

The predominant lineation accompanying the fold is quartzo-feldspathic rodding. Minor folds are also present, as well as some occurrences of elongated kyanite-bearing knots, quartzo-feldspathic striping, and schistosity/foliation intersections. The dips of both limbs are moderate in a southeasterly direction. The predominant trends of the linear structures are also to the southeast, and their plunge is moderate (Fig. 10a). Since both the dip of the foliation and the plunge of the lineations are to the southeast, the pitch of the fold axis in its axial plane must be great. Hence, the Beinn a' Chairein fold is essentially a neutral fold, and this geometry is reflected in the minor folds which accompany it.

The sedimentary structures northwest of Muchrachd observed by Merh (1960) indicate that the Muchrachd Synform (= northwestern limb of the Beinn a' Chairein fold) faces southeastwards. Further, Merh's stratigraphical evidence

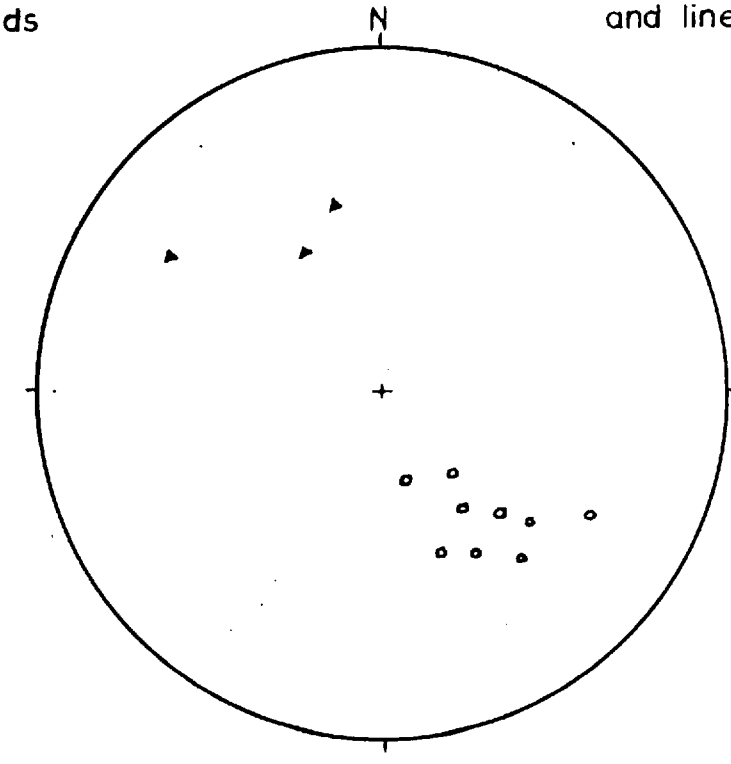
FIG. 10 Structural Analysis of the Beinn a' Chairein Neutral Folds



a. Main Fold

π ax. pl. F-2 minor folds = ▲

F-2 fold axes and lineations = o



b. Southern Fold

indicates that the rocks on the southern limb of the Beinn a' Chairein fold face northwestward. It seems likely, therefore, that the Beinn a' Chairein neutral fold may be synclinal.

One very important fact about the Beinn a' Chairein fold is that the patterns of minor folds supposedly synchronous with the major fold are not always congruous with the major fold geometry. In several localities in the core of the major fold, I have observed isoclinal minor folds whose axial planes are normal to the axial plane of the major fold. These minor folds are of F-1 age. Since both sets of minor folds (i.e. F-1 and the Beinn a' Cahirein set, F-2) are isoclinal, it is virtually impossible to identify them as separate phases except where one set is refolding the other. Hence, it is possible that a large proportion of the minor folds which have a pattern contrary to the geometry of the major fold are related to the F-1 folding.

From the map, it is seen that southwest of the River Cannich, the direction of closure of the Beinn a' Chairein fold is to the west or southwest. Just northeast of the river in Merh's area, however, the foliation strikes on either side of the axial plane trace appear to be closing toward the east. This suggests that the Beinn a' Chairein fold, when viewed in the light of its eastward extension

into Merh's ground, may be a very tight eyed structure, with its apex possibly just east of the River Cannich.(1)

The South Beinn a' Chairein Fold.

To the south of Beinn a' Chairein, the outcrop of the pelite defines a complementary fold, which is probably the continuation of the Dog Fall Neutral Fold (see page). Unfortunately, exposure in this area is poor, and it is difficult to directly ascertain the exact geometry of the fold. From the evidence available, however, the geometry appears to be similar to that of the Beinn a' Chairein fold. Both limbs of the South Beinn a' Chairein fold dip at moderate angles to the southeast. The fold hinge is exposed in one group of exposures south of Tombuie; and M shape minor folds of F-2 (?) age are found in this area. Lineations, which consist of quartzo-feldspathic rodding, schistosity/foliation intersection, and minor folding indicate that the pitch of the fold axis on its axial plane is great (Fig. 10b). The geometry of the minor folds conclusively illustrates this assumption. Hence, the South Beinn a' Chairein fold is also a neutral fold, whose axis trends to the southeast at a moderate plunge (Fig. 10b). The pattern of the observed minor folds is generally congruent with the major structure.

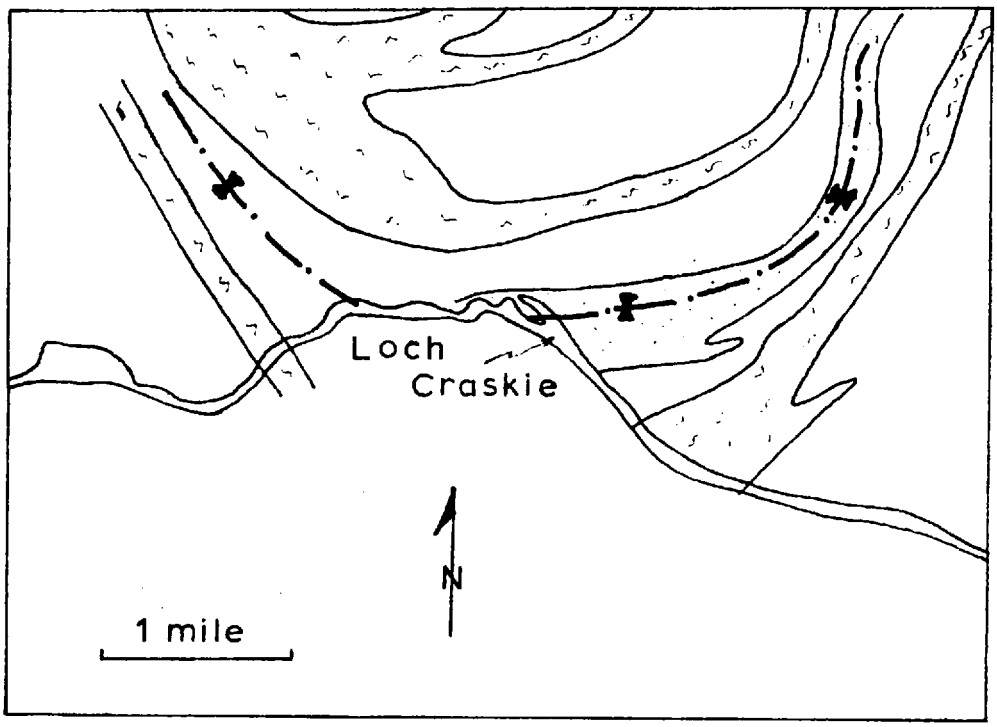
(1) See Fig. 35.

Intermediate Structures

The Muchrachd Synform

Merh (1960, p. 175), has used the name Muchrach Syncline to identify the synclinal (and synformal) fold northwest of Muchrachd. On a basis of stratigraphy, he suggested that the axial plane trace of the Muchrachd Syncline extends from northwest of Muchrachd through Craskie and continues to the east and northeast (Fig. 11). My mapping in this area shows that Merh's suggestion is untenable. Hence, the term Muchrachd Synform as I use it is only synonomous with Merh's usage of Muchrachd Syncline northwest of Muchrachd. The isoclinal fold recognized by Merh to the east and northeast of Craskie is probably the continuation of the Beinn a' Chairein fold. Since the Muchrachd Synform refolds the Beinn a' Chairein fold, the former fold northwest of Muchrachd is younger than suggested by Merh (see correlation chart, page 264). To justify my use of the term Muchrachd Synform, I must state that the synclinal nature of the fold around Muchrachd, as defined by sedimentary structures observed by Merh (ibid), results from the refolding of the northwest limb of the Beinn a' Chairein fold. In other areas along its axial plane trace, the synform is not necessarily a syncline.

FIG. 11 Sketch Map of the Loch Craskie Area after Merh (1960)

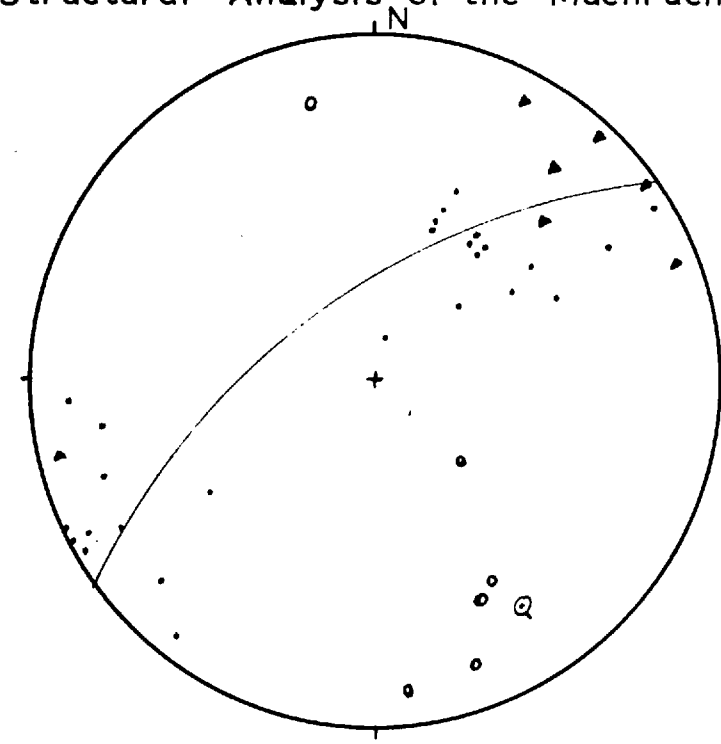


Syncline

The Muchrachd Synform, which is of F-3 age, is best seen in the area of Muchrachd, where lithologic boundaries and the orientation of the foliation clearly define the fold. Northwest of Muchrachd, near BM 2535, the fold is fairly tight, with a moderately dipping eastern limb and a steep to vertical western limb. The trend of the fold axis is southeast, and the plunge is gentle, as seen in Fig. 12a. As the fold is traced across the River Cannich, it becomes symmetrical and open, and although the trend is constant, the plunge steepens considerably (Fig. 12b). The axial plane trace continues to the southeast, and in the area of Lochan a' Mhuill Duibh, the synform is well-defined by the folded axial plane trace of the Beinn a' Chairein fold. Here the style of the Muchrachd Synform is symmetrical and very open. South of Lochan a' Mhuill Duibh, the axial plane trace is ill-defined. Indeed, it is doubtful whether the Muchrachd structure continues for more than a few thousand feet southeast of Lochan a' Mhuill Duibh, since just east of Beinn a' Chairein, the constant strike of the foliation indicates that the synform has died out.

In the Muchrachd area, the hinge of the synform is well-defined by the curvature of the foliation. In the area of BM 2535, however, which is northwest of Muchrachd, the hinge of the synform is not defined by the foliation, but

FIG. 12 Structural Analysis of the Muchrachd Synform



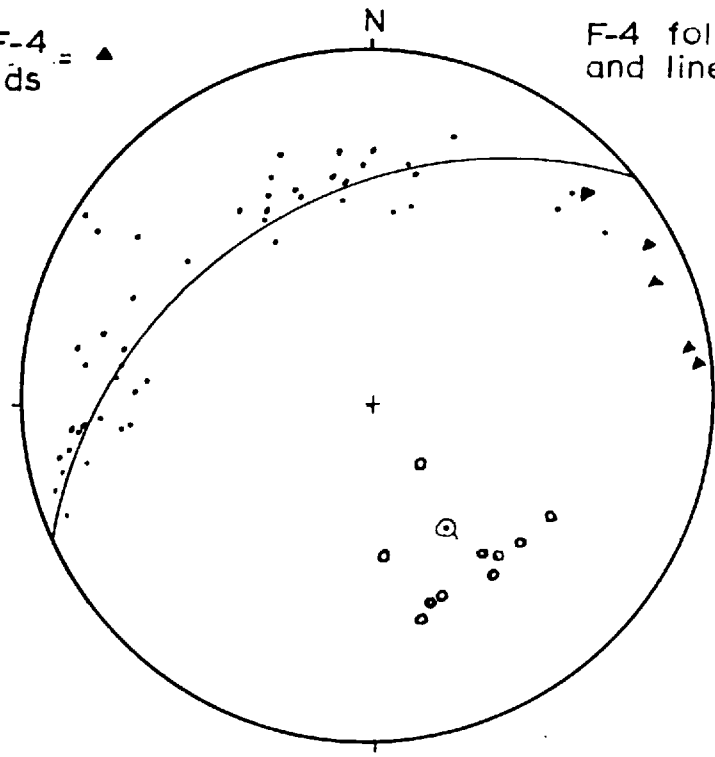
a. North part

π foliation = •

π ax. pl. F-4 minor folds = ▲

π to the girdle = ⊙

F-4 fold axes and lineations = o



b. South part

rather by a change in rock type from psammite to pelite. Some interdigitation of the two rock types occurs. It is not possible to prove that this interdigitation is structural, but it is suspected that this may be the case. North of BM 2535 in Glen Strathfarrar, the exact position of the axial plane trace of the synform in the pelite is difficult to place, since the dip of the foliation is steep, both east and west, indicating that the synform has become very tight. There is no doubt, however, that the synformal trace continues through the pelite to Glen Strathfarrar, because in the cliffed shore north of Loch a' Mhuillidh, the synform stands out boldly. Mukherjee (personal communication) has traced the synform for some distance further to the north. He notes that the fold has a moderately dipping eastern limb and a steep western limb, and that the plunge of the fold axis is very gentle to the south. Geological information from a tunnel driven by the Hydroelectric Board of Scotland indicates that in Glen Strathfarrar, the synform continues for a minimum of about 1000 feet below the present topographic surface. Furthermore, the synform is seen to control the stratigraphy and foliation dip for some distance on both sides of its axial plane trace. This synform, therefore, is undoubtedly a fold of major proportions in both Glen Strathfarrar and the

Cannich area.

It is very probable that the Muchrachd Synform is the complementary fold of the Combussory Antiform of Merh (1960). Mukherjee's findings north of the River Farrar substantiate this supposition. This pair of folds, then, is seen to originate to the north of the River Farrar in Mukherjee's ground, and can then be traced to the south into Merh's and my areas. Merh (ibid), however, did not project the axial plane trace of the Combussory Antiform as far as the River Cannich, probably because the hinge zone of that antiform is obscured by earlier folds. However, if the axial plane trace of the Combussory Antiform is projected in a southerly direction, it is seen to die out east of Beinn a' Chairein, in the same general region that the Muchrachd Synform dies out.(1)

One of the unusual features of the Muchrachd Synform is the apparent scarcity of related minor folds. Nowhere are there minor folds which could positively be demonstrated as genetically related to the major structure. Mukherjee (ibid) also notes this scarcity of minor fold related to the Muchrachd Synform as well as the Combussory Antiform. He has recorded a few occurrences of minor folds near the core of the latter fold north of the River Farrar which may be genetically related to it, but notes that the evidence for identifying their definite age is inconclusive. Near the

(1) See Fig. 42.

core of the same antiform south of the River Farrar, Merh (op. cit. p. 180) recorded "related" minor structures which "consist of small folds and crinkles" . From the evidene in surrounding areas, it is conceivable that these minor structures could be of F-4 age, as discussed below. Unfortunately, Merh did not record the style of these "small folds" on his map, and it is not known if they are congruent with the geometry of the major structure.

One of the difficulties in identifying minor folds that are genetically related to the F-3 major folds is that the axial plane trends of F-4 minor folds are locally sub-parallel to the axial plane of F-3 major structures. Furthermore, the patterns of F-4 minor folds northwest of Muchrachd are congruent with the geometry of the Muchrachd Synform. North of BM 2535, however, this congruent relationship begins to break down, as both S's and Z's are found on either limb of the synform, S's predominating. North of River Farrar, Mukherjee (ibid) observed that the pattern of F-4 minor folds occurring west of Combussory is constant irrespective of the major fold geometry of F-3 age: everywhere the pattern is an S. It seems, therefore, that even though the axial plane trend of F-4 minor folds and F-3 major folds is locally sub-parallel, it is highly improbable that the two are genetically related. Their congruent relationship

in the area of Muchrachd must be fortuituous in that their axial planes become parallel in that locality. Furthermore, it is seen in Figs. 12a, 12b, that the axis of the Muchrachd Synform does not correspond very well with the axes of F-4 minor folds. These facts further suggest that it is unlikely the major and minor structures in the Muchrachd are genetically related. It seems apparent, therefore, that the Muchrachd Synform and the Combussory Antiform are a pair of major structures of considerable size which are relatively devoid of genetically related minor structures.

Later Structures.

The later structures are represented by two phases of deformation, F-4, and F-5. Minor folds of these deformations are found throughout this sub-area. Generally speaking, F-4 minor folds are much more intense and more common than are those of F-5. In addition, a number of major folds of F-4 age are found in various localities, but no major folds of F-5 age have been identified.

Structures of F-4 Age.

Major Folds

Most of the major folds of F-4 age in this sub-area are continuous only for short distances along their axial

plane traces. This characteristic is also reflected in the accompanying minor folds.

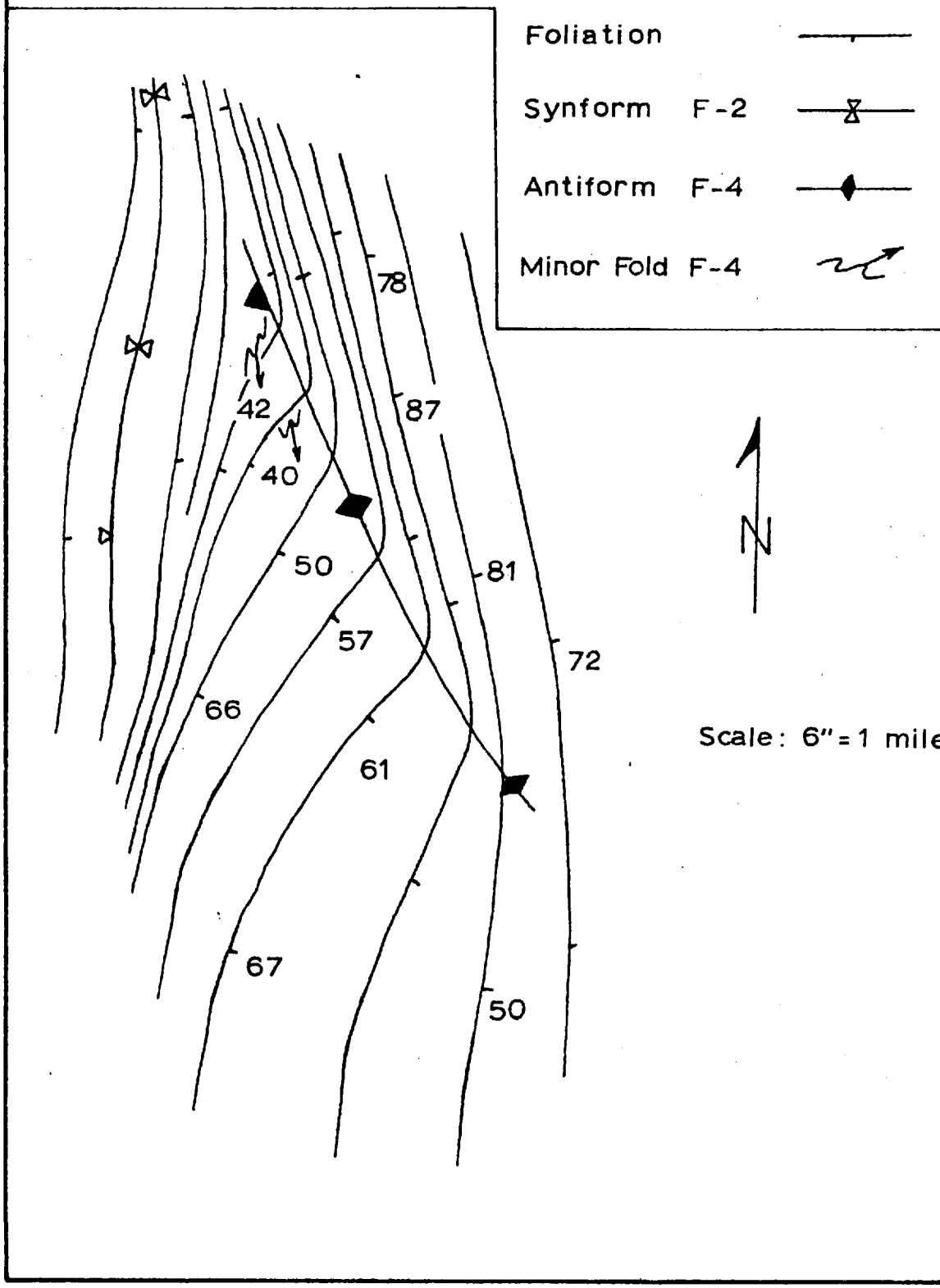
Coire Dubh Fold

This fold begins about one mile south-southeast of Loch Carrie, and continues for about two-thirds of a mile to the southeast, where it dies out. The fold has an unusual shape in that the orientation of the eastern limb is virtually parallel to the axial plane of the fold, whereas the western limb forms a high angle with it (Fig. 13). The axial plane of the major structure is essentially vertical. Minor folds appear to be absent except in the western limb, where they are rare. The plunge of the major fold is moderate to the south-southeast, as can be seen from Fig. 13. The minor folds trend south-southeast, and have a similar plunge as the major fold.

Allt Innis Folds

These three folds occur immediately to the west of Allt Innis an Droighinn in Glen Affric. They are defined by lithologic boundaries, orientation of the foliation, and the pattern of minor folds. The axial planes strike ESE-WNW, and have a very steep northerly or southerly dip; their axes have a moderate plunge to the east-southeast. The two northern folds are roughly symmetrical, and refold the axial planes of the Benevean and Dog Fall F-2 folds. The

FIG. 13 General Plan of the Coire Dubh Fold



remaining fold is similar to the Coire Dubh fold in that the northern limb is practically parallel to its axial plane, while the southern limb is at a high angle to it. The patterns of F_4 minor folds in the area are generally congruent with the geometry of the major folds. Subsidiary folding associated with the major folds, but too small to be mapped, is common. Hence the pattern of some of the minor folds may seem incongruent with a given fold, when in fact they are not directly associated with it.

The Achgate Synform

The present exposure in this area does not yield enough evidence to define the Achgate Synform. However, the Geological Survey of Scotland mapped the reservoir site prior to its flooding in 1952, and they kindly released this information to me. By combining this information with the mapping I have done, the nature and extent of the synform becomes evident. It is defined by the orientation of the foliation, lithologic boundaries, and the pattern of minor folds; it extends from about one mile just to the south of Achgate. The axial plane of the synform strikes WNW-ESE, and the dip is very steep to the north. The axial trend of the major structure is easterly, and judging from the plunge of accompanying minor folds, the major fold plunge is probably variable. The pattern of minor folds is

essentially congruent with the major fold geometry.

The Meall Mor Folds

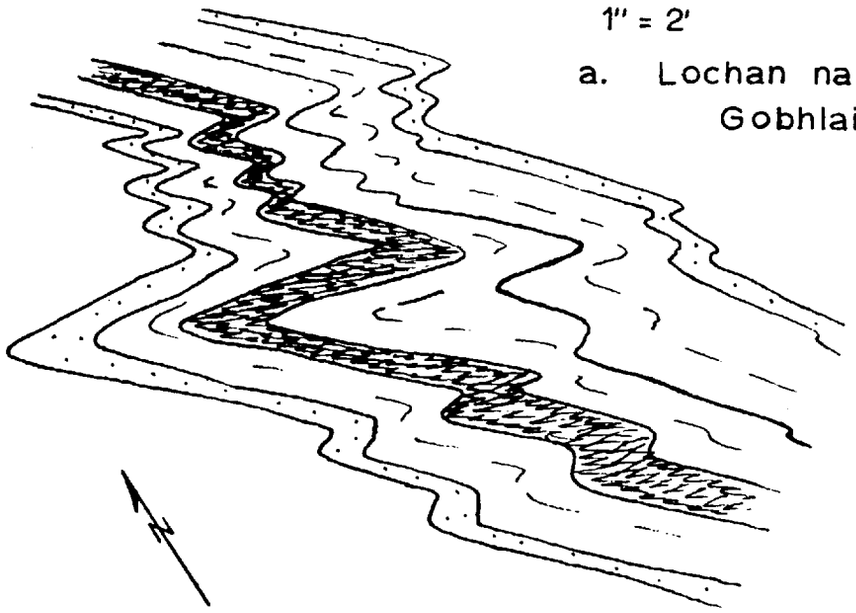
This pair of folds is traceable for about two-thirds of a mile through rather poorly exposed ground. The folds begin just south of Meall Mor in the pelite, and disappear into the unexposed ground to the southwest. The axial planes of the major folds strike ENE-WSW, and have steep dips of variable direction. The plunge of their fold axes, as indicated by the dip in the hinge area, is steep to the south-southwest. Related minor folds are virtually absent. From the available exposure, the geometry of the folds appears to be that of a very open structure which dies out along its axial plane strike.

Minor Folds

Although there are a number of major folds of F-4 age as described above, it is more typical of this phase of deformation to be represented only by minor folds.

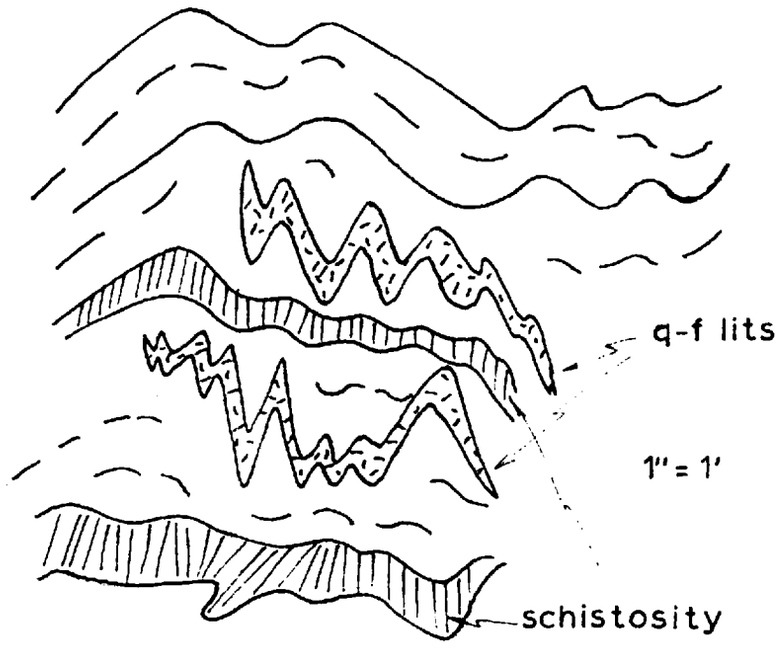
The pattern of the minor folds is variable, and S and Z shapes are common; M patterns are also present in some areas. The style of the folds tends to be moderately closed, but it is not uncommon for folds to become very tight in the pelite and semi-pelites. Some of the variations in style of the F-4 folds are illustrated in Fig. 14 and Plate VII.

FIG. 14 Styles of F-4 Minor Folds in Sub-area 1 Viewed ca. ⊥ to the Fold Axes

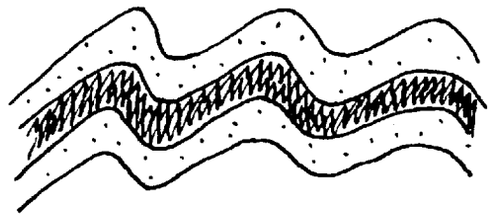


1" = 2'

a. Lochan na Gobhlaig area

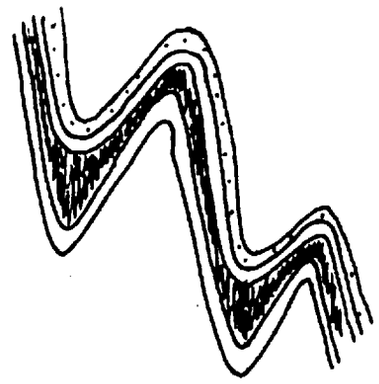


b. North of Meallan Ohdar



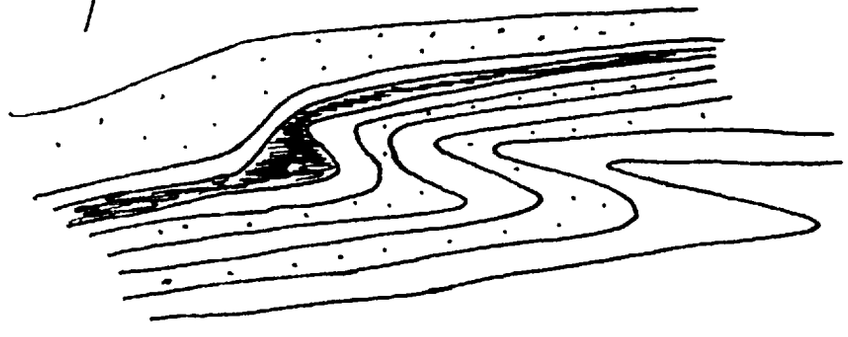
c. Near An Soutar

1" = 5'



d. Loch Carrie

1" = 2'



1" = 3'

e. Glen Affric

PLATE VII

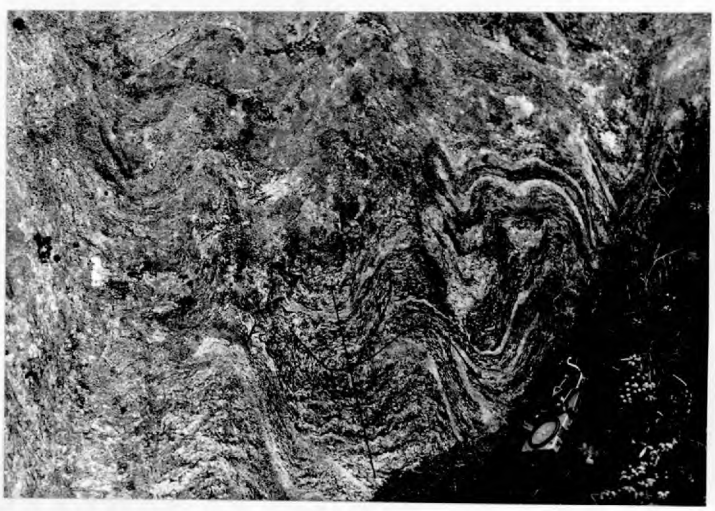
a. Interference on a minor scale of F-4 and F-5; long axis of dome-basin structures in F-4 axial plane trace; larger fold is F-5. South of Beinn a' Chairein in Glen Affric.

b. Typical style of F-4 minor folds in Glen Affric; plunge is to the northeast; near Achgate.

c. A style of F-4 minor folds west of An Soutar in Glen Cannich. F-4 fold is refolding an early minor fold in bottom right hand corner of the photograph.







Except in the far northwestern corner, F-4 minor folds in sub-area 1 are invariably accompanied by a crumpling parallel to the axial planes (Plate VIII). This crumpling can vary in intensity from a well-developed slip-strain cleavage (see White 1949, fig. 1; Wilson 1961, fig 28) to the "herringbone structure" illustrated by Richey (1952, plate X). In many folds where a band of pelite is sandwiched between bands of psammite, the crumpling in the core of the fold is so tight that it gives the impression of an axial plane schistosity, since many of the micas lie sub-parallel to the axial plane of the fold.

One of the most noteworthy variations of structural elements throughout the sub-area is the systematic swing in strike of F-4 axial planes and axes. In sub-area 1, the variation of axial plane strike from north to south is as follows: N-S in Glen Strathfarrar to NW-SE in Glen Cannich to WNW-ESE in Glen Affric. The axial planes are everywhere steep, dipping either easterly or westerly. The trends of the axes of the minor folds show a similar variation from Glen Strathfarrar to Glen Cannich: that is, south to south-east to east-southeast, although there are local areas where the trend is northerly.

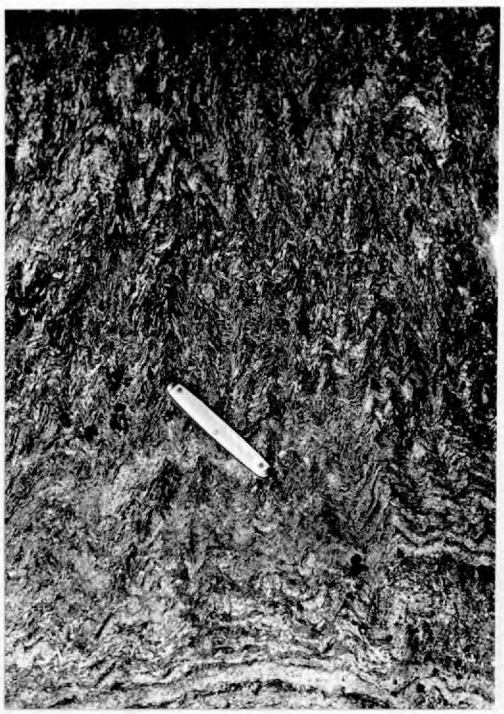
Immediately to the west of Meallan na Ceardaich, it is seen that the axial planes of F-4 minor folds (and major

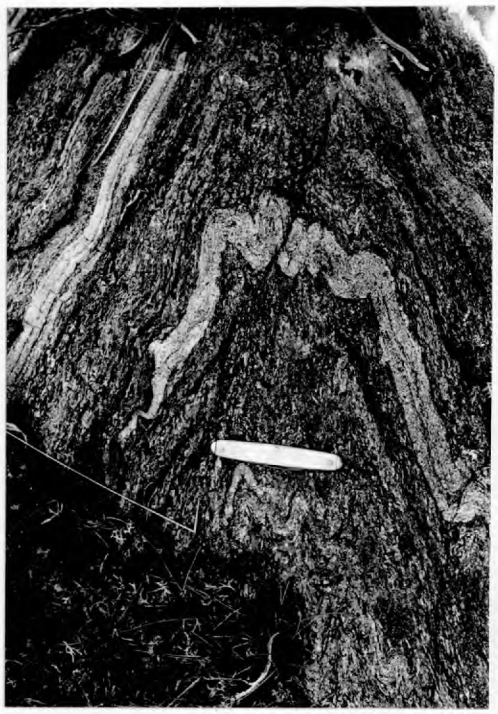
PLATE VIII

a. Typical axial plane of crumpling associated with F-4 minor folds in the pelitic rock. Knife is 4 inches long; west of Loch a' Mhuillidh in Glen Strathfarrar.

b. Same as above.

c. Typical crumpling of F-5 folding; east of An Soutar.



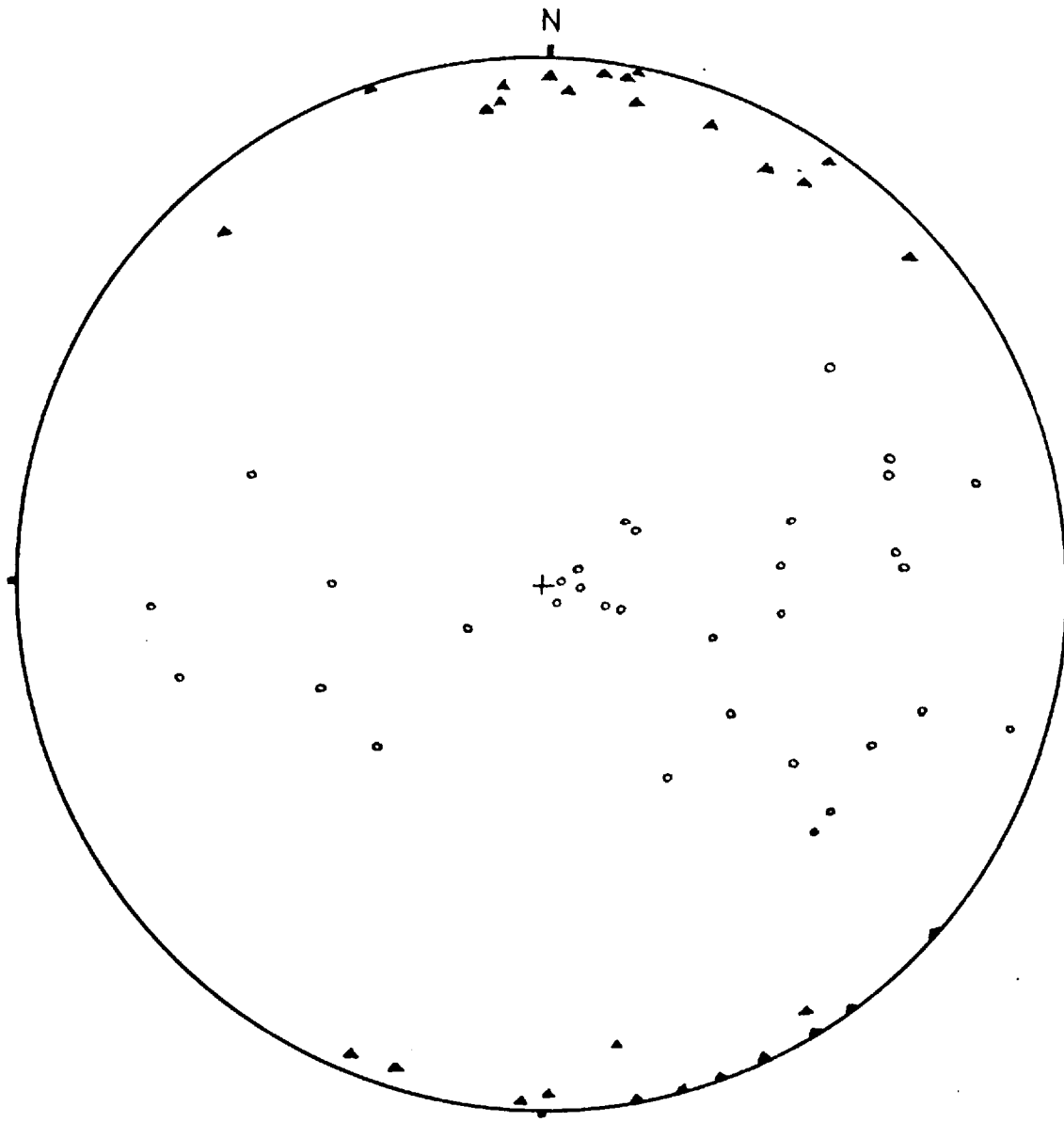




folds) swing toward a NE-SW trend rather than an ESE trend as they do elsewhere in sub-are 1. Judging from the trends of F-4 axial planes further to the west (sub-area 2), the Meallan na Ceardaich-Achgate area is a locality where the axial plane orientation of the F-4 minor folds diverges into two different directions. This zone of divergence extends to the north, and is oriented roughly north-south between Meall Mor and Meallan Odhar-An Soutar. The possible significance of this divergence together with the variations in axial plane trends of F-4 minor folds in the other sub-areas is discussed in a later section (page 206).

In the area to the south and southwest of Meallan na Ceardaich, the changes in trend and plunge of F-4 minor folds are extreme (Fig. 15). The orientations of the axial planes also show some variation. Despite the poor exposures, it is apparent that these variations of the F-4 structural elements result from the superposition of F-5 minor folds on F-4 minor folds, and possibly to a lesser degree, the superposition of F-4 minor folds on earlier structures. It is exceedingly difficult to determine which event was responsible for the greater part of the variation of F-4 fold axes. Near Benevean Dam, one can see folds interfering in a pattern such as illustrated in Fig. 16a, suggesting that deformation during F-5 is largely responsible

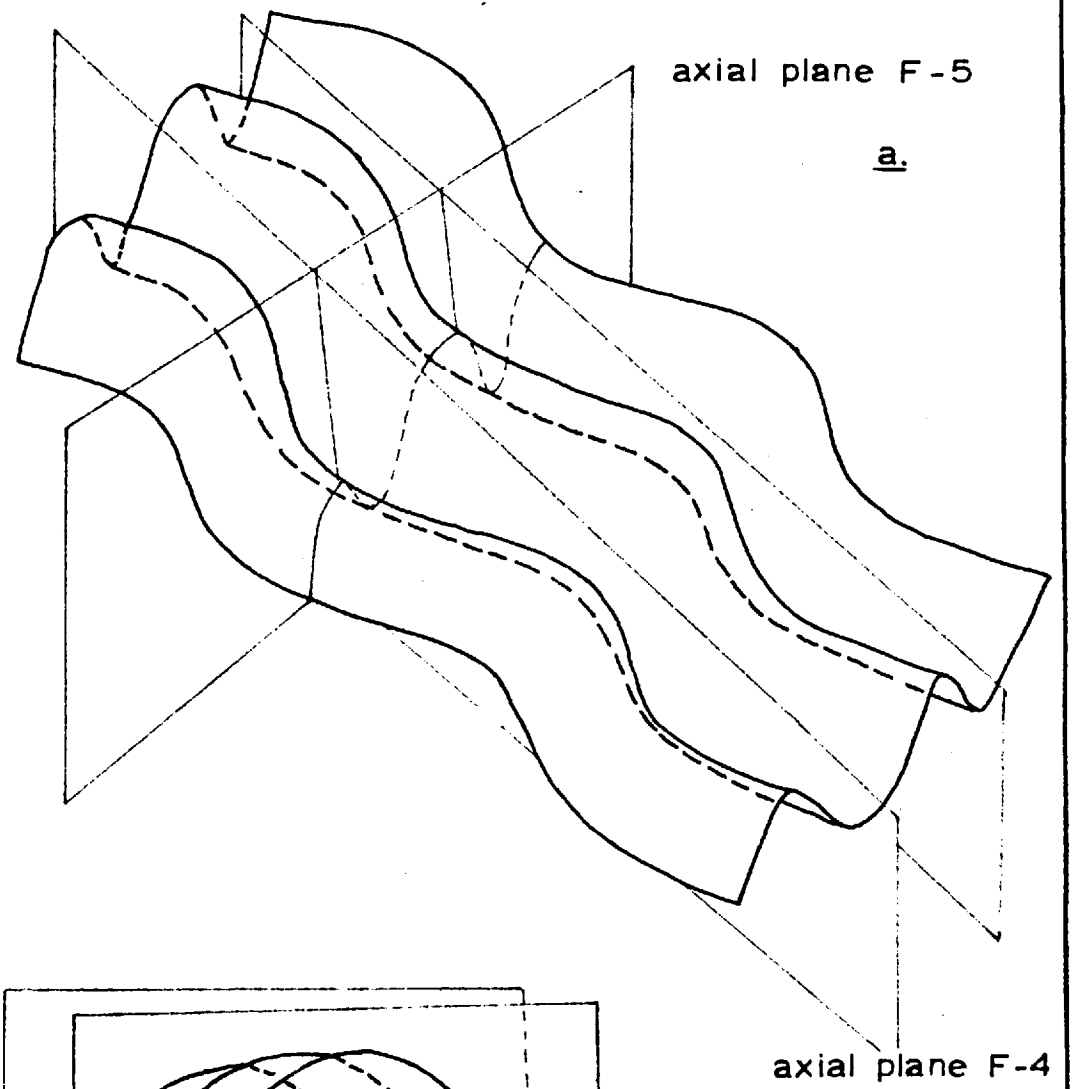
FIG. 15 Variation in Orientation of F-4 Minor Folds in Glen Affric Proper

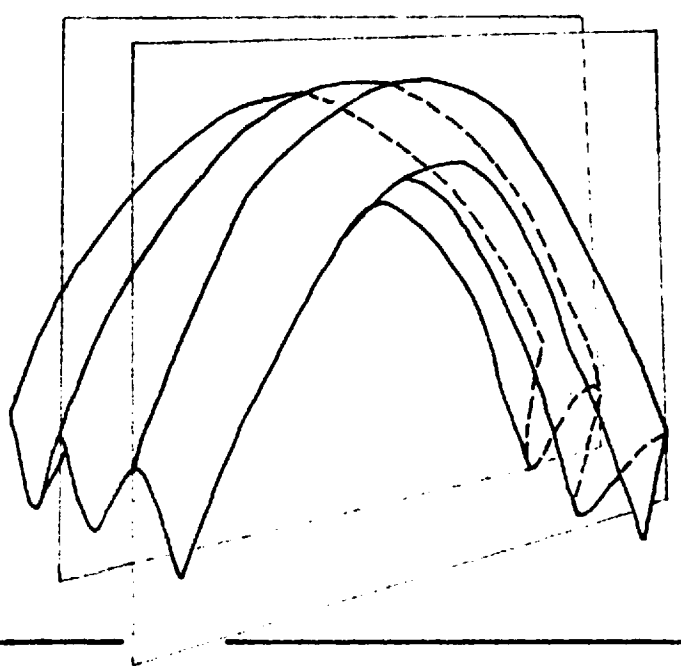


⏜ axial plane F-4 minor fold = ▲

axis of F-4 minor fold = o

FIG. 16 Variations in Plunge of F-4 Fold Axes





for F-4 variations. Again, further west of Achgate, the geometry illustrated in Fig. 16b is common on a minor scale. In both examples illustrated, the axial plane of F-4 is essentially undeformed, Plate IX. There are, however, a number of localities where the axial plane of F-4 can be seen to be refolded by F-5 minor folds (Plate VIIa and IXc). Crumpling by F-5 is frequently seen to be superposed on the F-4 folds where the axes of the latter vary; hence, it is probable that much of the variation in F-4 fold axes is a result of deformation by F-5.

Structures of F-5 Age.

This generation of folding is expressed as warpings of the foliation, crumpling in the pelitic layers, and in some areas, gentle folding. Large scale folding of this generation has not been identified. In Glen Affric, as described above, F-5 locally becomes more intense than is characteristic of that phase of deformation in other parts of sub-area 1.

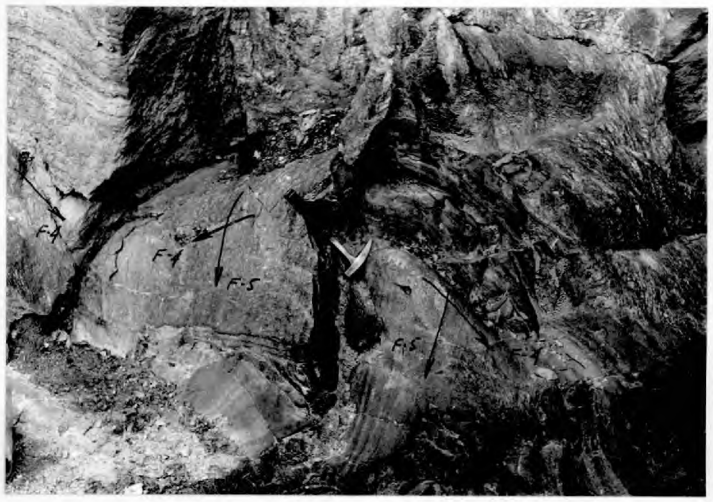
The axial planes of F-5 folds are steeply dipping northerly or southerly; the plunge of their axes is also steep. The trend in orientation of the axial plane strike of F-5 shows a systematic variation from north to south: in Glen Strathfarrar, it is east-west, in Glen Cannich NE-SW, and

PLATE IX

a. Variation in axial orientation of F-4 with no deformation of its axial plane; F-5 lineation is a crumpling. West of Affric Dam on road, Glen Affric.

b. Same as above.

c. Same as above except F-5 is deforming the axial plane of F-4 (not pronounced).


F-4
F-4
F-5
F-5


F-4


F-5
F-4

in Glen Affric, NNE-SSW. The plunge of the fold axes is toward the west or southwest. There are numerous exceptions however, where the plunge is to the east or northeast as a result of the original dip of the foliation being in that direction.

In some localities among the pelitic rocks, the axial plane of crumpling varies in orientation over very small distances (i.e. within a few feet). In others, the axial plane orientation is extremely regular over similar distances. The style of crumpling is moderately tight and typically an M (Plate VIIIc), though examples of S and Z patterns have been observed.

Sub-Area 2

General

Sub-area 2 is a north-south trending zone which lies between the western boundary of sub-area 1 and an approximately north-south line passing through Doire Tana and Mullardoch Dam, Fig. 4. The general trend of the foliation and axial planes of major folds is north-south, except in the region of Doire Tana, where it is roughly east-west.

The Early Structures

No positively defined early structures have been identified in sub-area 2, but one possible major fold exists south of the River Cannich along the ridge of Doire Tana. It is defined by a pelite which suddenly ends about 2000 feet to the east of the main cairn of that ridge (BM 2884). Although exposure is poor in that area, the change in strike of the psammites to the east of Doire Tana suggests the presence of a fold hinge. It is possible, therefore, that the pelite may lie in the core of an isoclinal fold. Minor folds are essentially absent, but one minor fold with an M pattern in the proposed hinge area was observed. Its plunge is nearly vertical. If the fold, as defined by the pelite, does exist, the orientation of the foliation and the plunge of the minor fold indicate that the dip of the axial plane

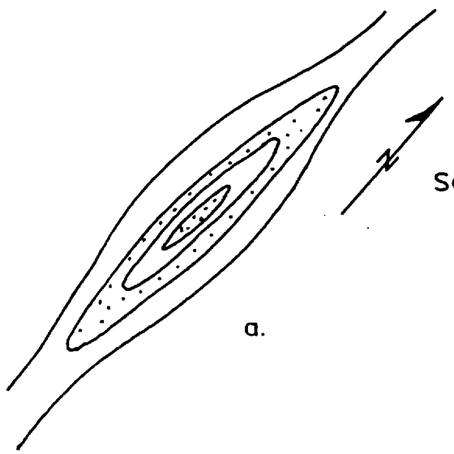
and the axial plunge are both very steep.

Between the River Cannich and Meallan Odhar, there are a number of localities where the sedimentary structures face towards the west, whereas the usual direction is to the east, Fig. 3. As there are no major folds of a later deformation in those areas, it is probable that the reversal of facing direction is a result of isoclinal folding.

Minor structures of F-2 (and F-1 ?) are common throughout sub-area 2. In many exposures, they have an S, Z, or M pattern, and usually show an axial plane schistosity. Just as common, however, are V patterns. A number of eyed structures on a minor scale also occur, Fig. 17. Linear structures are not uncommon, and consist of quartzo-feldspathic rodding and striping, elongated kyanite-bearing knots, and schistosity/foliation intersections. Only one occurrence of mineral orientation was observed, and that was shown by the ferromagnesian minerals in pyroxene-albite bands.

One of the peculiarities of sub-area 2 is that northwards from the River Cannich, the width of the outcrop of the Loch Carrie Psammitic Group decreases considerably along its strike. At the River, the apparent thickness is over 12,000 feet, but to the north in the area of Meallan Odhar, it thins to a few hundred feet. This abrupt decrease in

FIG. 17 Styles of the Early Minor Folds in Sub-area 2 Viewed ca. ⊥ to the Fold Axes



a.

1" = 1"

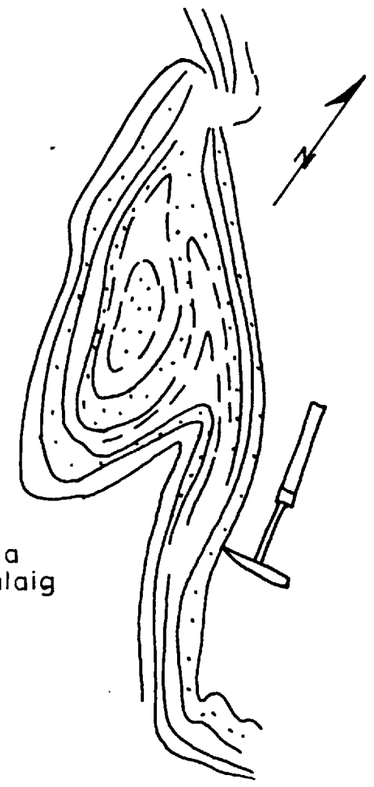
Southwest of Loch Carrie



b.

1" = 6"

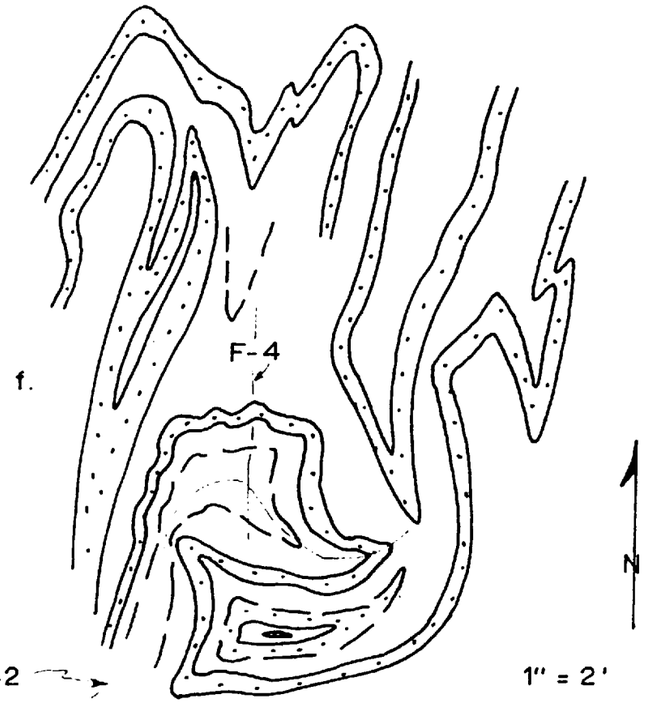
North of Boat Ho, Glen Cannich



d.

Loch na Gobhlaig

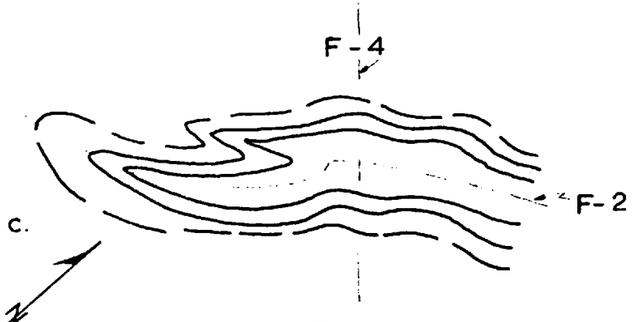
d. & e. after photographs



f.

1" = 2'

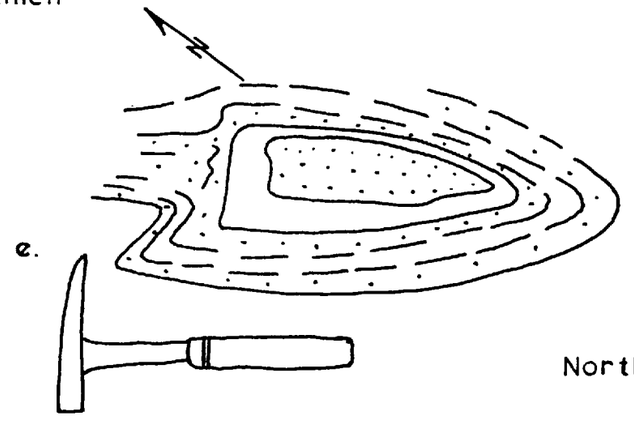
Northwest of Boat Ho



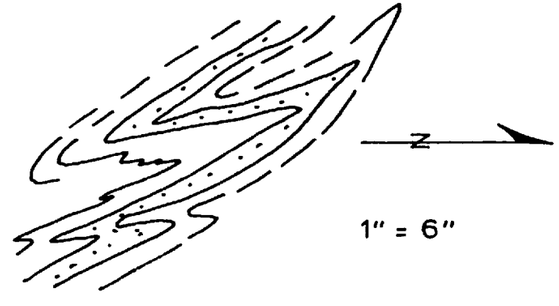
c.

Northwest of Boat Ho

1" = 1'



e.



g.

1" = 6"

North of Boat Ho

thickness, which is of considerable magnitude, takes place within a remarkably short distance along the strike of the psammitic group. This might be explained by

1. a change originated during sedimentation,
2. a major (F-2) fold or folds, and/or
3. a slide.

These possibilities are considered:

1. It is possible to produce a rapid decrease in thickness of a rock unit under certain deposition conditions. A trough, for example, formed by a downfaulted basement, might receive a large volume of sediments, while the upfaulted side receives none. Such is the case in Switzerland, where the thickness of lower Lias on one side of a syn-depositional fault is virtually nil, whereas on the other side, it approaches 9000 feet (Kuhn-Schnyder and Vonderschnitt, 1953). As there is no evidence for such a fault in the contiguous stratigraphic groups, a depositional relationship of this type is not a likely explanation for the thinning of the psammite. Furthermore, the Moine Series is characteristic of deltaic or estuarine deposition, and in such an environment, rock thicknesses will not show abrupt variations of the magnitude mentioned above (Prof. Gill, personal communication). Hence, it is most unlikely that

the thinning of the Loch Carrie Psammitic Group north of River Cannich is an original sedimentary feature.

2. A fold closure of a major (F-2) fold, perhaps similar in aspect to the Glen Cannich Eyed Structure, might account for an apparent thinning of the psammitic group. Eyed minor structures (of F-1/F-2 age ?) are known to be present in a number of localities in sub-area 2 (Fig. 17); but neither the direction of facing of sedimentary structures nor schistosity/foliation ~~on~~ relationships suggest that there is any one big F-2 fold in this area. Unfortunately, poor exposure and the presence of major F-4 folds at Meallan Odhar obscures the area where the hinge of an F-2 fold as defined by lithologic boundaries of the pelite would occur. It is possible that instead of one major F-2 fold, the 12,000 foot thickness might have resulted, at least in part, from repetition by a series of smaller isoclinal major folds, whose hinges are unrecognizable. The hinges of the Benevean and Loch Carrie Folds in sub-area 1 are of this nature; but there the folds are defined by their pelitic boundaries, without which their presence might have gone undetected, because the foliation orientation does not outline their geometry. In any case, the evidence for the thinning of the psammitic group toward the north as a result of pre

F-4 folds remains inconclusive.

3. Since (1) and (2) above cannot satisfactorily account for the change in thickness of the psammitic group, it seems probable that the most reasonable explanation is the presence of a slide[1]. Firstly, however, it should be realised that sliding and the folding discussed above are not mutually exclusive, and that both may account for some part of the change in thickness of the psammitic group.

The evidence for the slide is as follows:

a. the abrupt thinning of the psammitic group in the vicinity of Meallan Odhar,

b. a change in axial plane orientation of F-4 minor folds on either side of the line of the slide, and

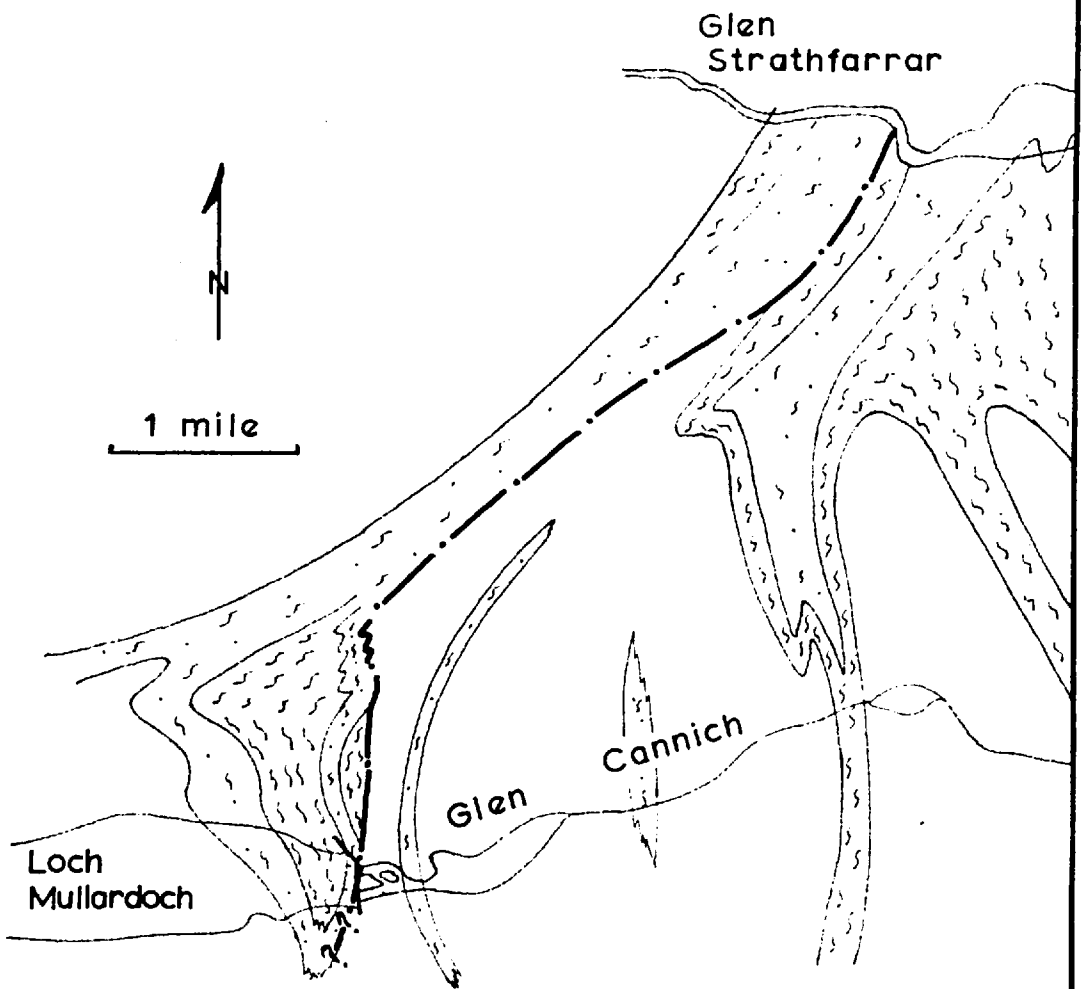
c. a suggestion of discordance of foliation on either side of the line of the slide along part of its trace.

The exact locality of the slide is difficult to ascertain from the field evidence, but the general line shown on the map in Fig. 18 seems the most probable, and its continuation is recognizable further north in Mukerhee's area (personal

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[1] M.J. Fleuty has suggested that the meaning of the term "slide" (Bailey, 1910) may be refined. I use the term as Fleuty proposes: "A slide is a fault formed in close causal connection with folding, which is broadly conformable with a major geometric feature of the folding, and which results in the thinning and/or excision of major members of the rock-succession affected by the folding".

FIG. 18 Sketch Map of the Area North of River Cannich



Probable position of the Slide = —·—·—

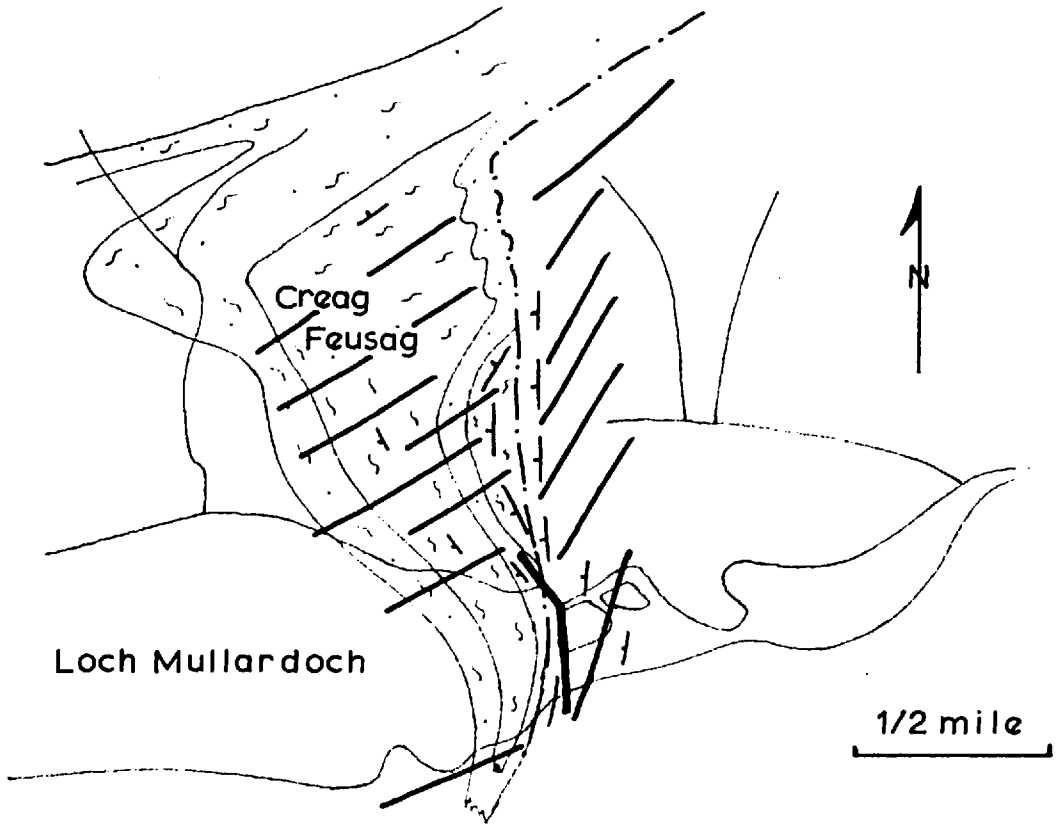
communication, D.M.). The continuation of the slide south of the River Cannich cannot be drawn because of the lack of exposure.

In the field, mylonite or crushed zones that might indicate its presence have not been observed; nor does any flagrant discordance of foliation strike occur within any one exposure. Except for one locality north of Mullardoch Dam, the strike of the foliation on both sides of the proposed slide is essentially parallel. However, slides which are concordant with the foliation for at least some distance along their strike have been described by Bailey 1910, Rutland, 1959, and Fleuty, 1961.

A suggestion of discordance of foliation strike and of lithologic units on either side of the line of slide does occur north of Mullardoch Dam, Fig. 19. In this area, the strike at both ends of a pelitic lens is toward the slide on its western side, yet this rock type is absent to the east: hence, the eastern margin of the pelitic lens appears to be cut off by the slide.

The age of the slide is not known. It must have been initiated before F-3, however, because it is folded by the Combussory Antiform (F-3) in Mukherjee's ground in the north (personal communication). Movement was probably reactivated along parts of its strike during later deformations. The

FIG 19 Sketch Map of the Creag Feusag Area Showing Change in Strike of F-4 Axial Planes



Strike of F-4 axial planes = ———

Foliation strike = —

Slide = —·—·—

abrupt kink in the axial plane strikes of F-4 minor folds just north of Mullardoch Dam is indicative of such a reactivation (Fig. 19). Apparently, the slide acted as a plane of décollement in that locally, the rock bodies on either side of it could fold on differently oriented axial planes in response to the same forces.

Intermediate Structures

No major or minor structures in sub-area 2 have been identified as Intermediate Structures.

Later Structures

F-4 Structures

Major Folds

Major folds of this phase of deformation occur in and to the south of the Liatrie and Lubguish areas in Glen Cannich, but their areal extent is limited. These folds are somewhat similar to the "pod-folds" of Mendelsohn (in Wilson, 1961, p. 508), in that their axial plane traces join at either end where, as a pair, the folds die out.

The Liatrie fold pair begins two-thirds of a mile north of the River Cannich and continues for about two miles to the south of that River. The axial planes are steeply dipping and strike roughly north-south; their fold axes trend to

the south at moderate to steep plunges (see map). The geometry of the folds varies along their axial plane traces. North of the River Cannich, the folding of the pelitic unit has resulted in the fold being very tight, and the plunge of the folds here is essentially vertical. As one traces the fold southwards into the psammites, the style becomes more open with broad hinges, and the plunge is now moderate to the south. The synform which forms the eastern unit of the fold pair, is considerably tighter than the antiform. The folds appear to die out west of Loch na Gobhlaig, although lack of exposure makes it impossible to know precisely where. Minor folds associated with this major fold pair are not common; where they have been observed, however, their pattern is concordant with the major fold geometry.

Although the exposure is poor southwest of Lubguish, another fold pair is traceable from just south of that locality for about 1½ miles further in that direction, where it dies out. The folds appear to have a similar geometry to the Liatrie folds south of the River Cannich, with the synform being tighter than the antiform. Their axial planes dip steeply, and their strike is also roughly north-south. The fold axes trend to the south at moderate plunges (see map, Fig. 45).

Both the fold pairs just described are refolding

earlier structures. In the case of the Liatrie folds, sedimentary structures on the limbs of the antiform face towards the axial plane trace, and on the limbs of the synform, face away from the axial plane trace. Hence, the antiform is synclinal, and the synform is anticlinal. This fact plus the presence of refolded minor folds and schistosity suggests that the Liatrie folds are refolding one limb of an early structure.

The Meallan Odhar Fold Pair

This pair of F-4 folds is reasonably well-defined by lithologic boundaries, foliation orientation and pattern of minor folds. The axial plane of the fold pair strikes NE-SW, and dips steeply. The plunge of the fold axes is very steep to the northeast (see map). The general appearance of the fold pair on the surface is an S-shape, with a very short shared limb. Minor folds show a Z-shaped pattern on the shared limb, and on the outer limbs the pattern is S-shaped. Exposure outside the immediate area of Meallan Odhar is very sparse, so it is not possible to determine the exact longitudinal extent of the two structures. Judging from the few available exposures, however, the fold pair must die out along its axial plane strike within $\frac{1}{2}$ mile on either side of Meallan Odhar.

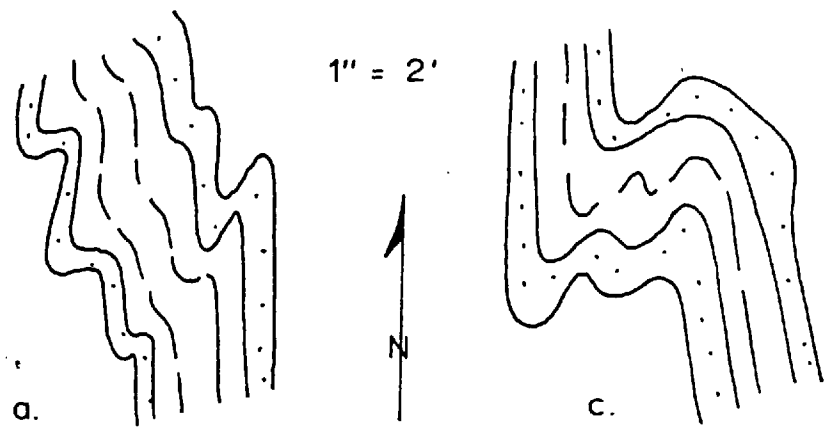
Minor Folds

Minor folds of this phase of deformation are common throughout the sub-area, but are usually not associated with any major fold structure. The asymmetry of these minor folds is typically S-shaped, although Z and M patterns are sparingly present (Fig. 20, Plate X). F-4 lineations, other than minor folds, are restricted to the lines formed by crumpled micas on foliation surfaces.

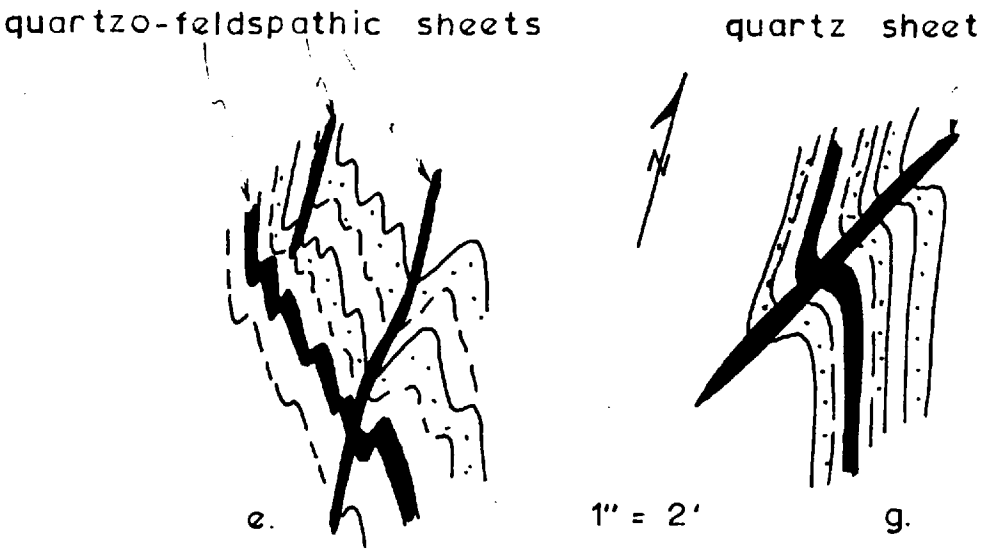
South of the River Cannich, the average axial plane strike of the minor folds is north-south, as far as the area of Doire Tana, where the strike swings into an ENE-WSW orientation. The trends of the minor fold are southerly, and swing to WSW in the area of Doire Tana; their plunge is moderate to steep.

North of the River Cannich, between Liatrie and Mullardoch Dam, the average axial plane strike of the F-4 minor folds is north-south, although farther to the north, it is NE-SW; the axial plane dip is westerly, moderate to steep. Within this area, there is a systematic variation in the trends of the F-4 minor fold axes. This variation occurs in a series of zones, each of which contains a generally uniform direction of plunge, and which are roughly parallel to the strike of the regional foliation. These zones are shown in Fig. 21, and each has been given a

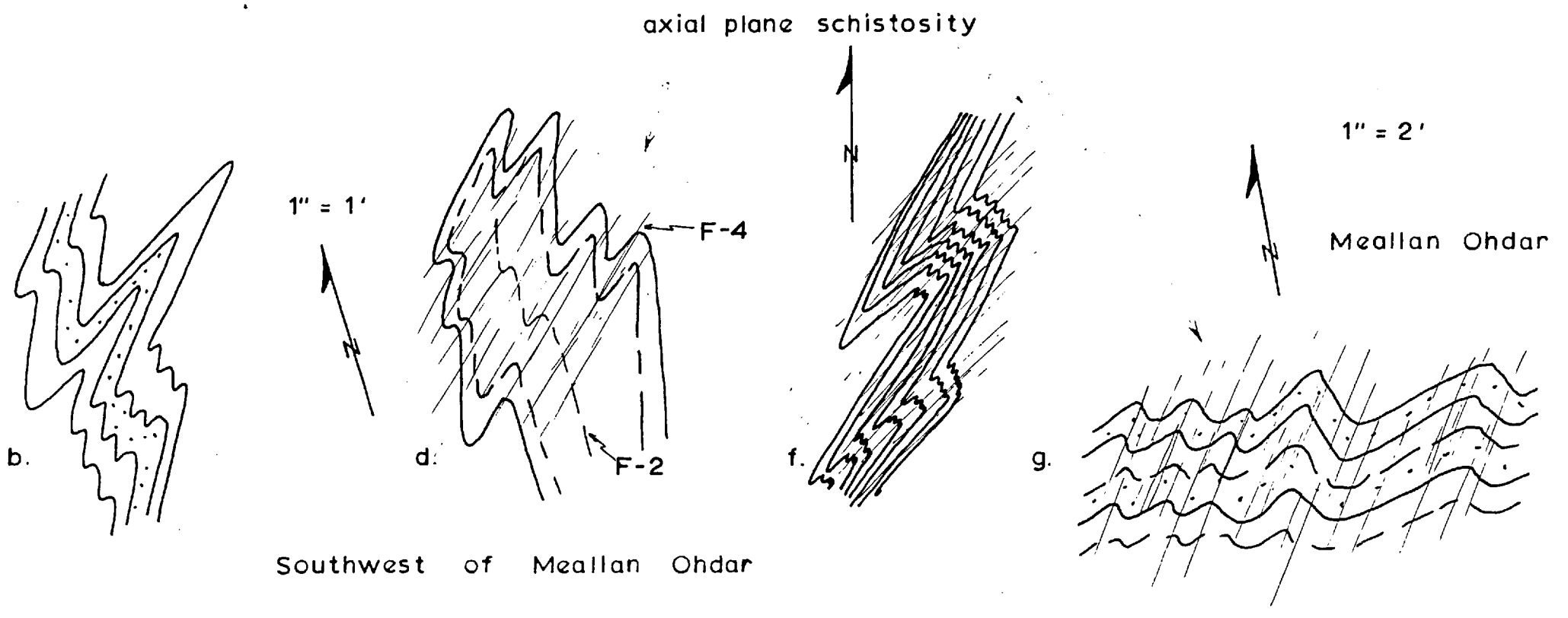
FIG. 20 Styles of F-4 Minor Folds in Sub-area 2 Viewed ca. ⊥ to the Fold Axes



North of Liatrie, Glen Cannich



Quarry at Mullardoch Dam



Southwest of Meallan Ohdar

PLATE X

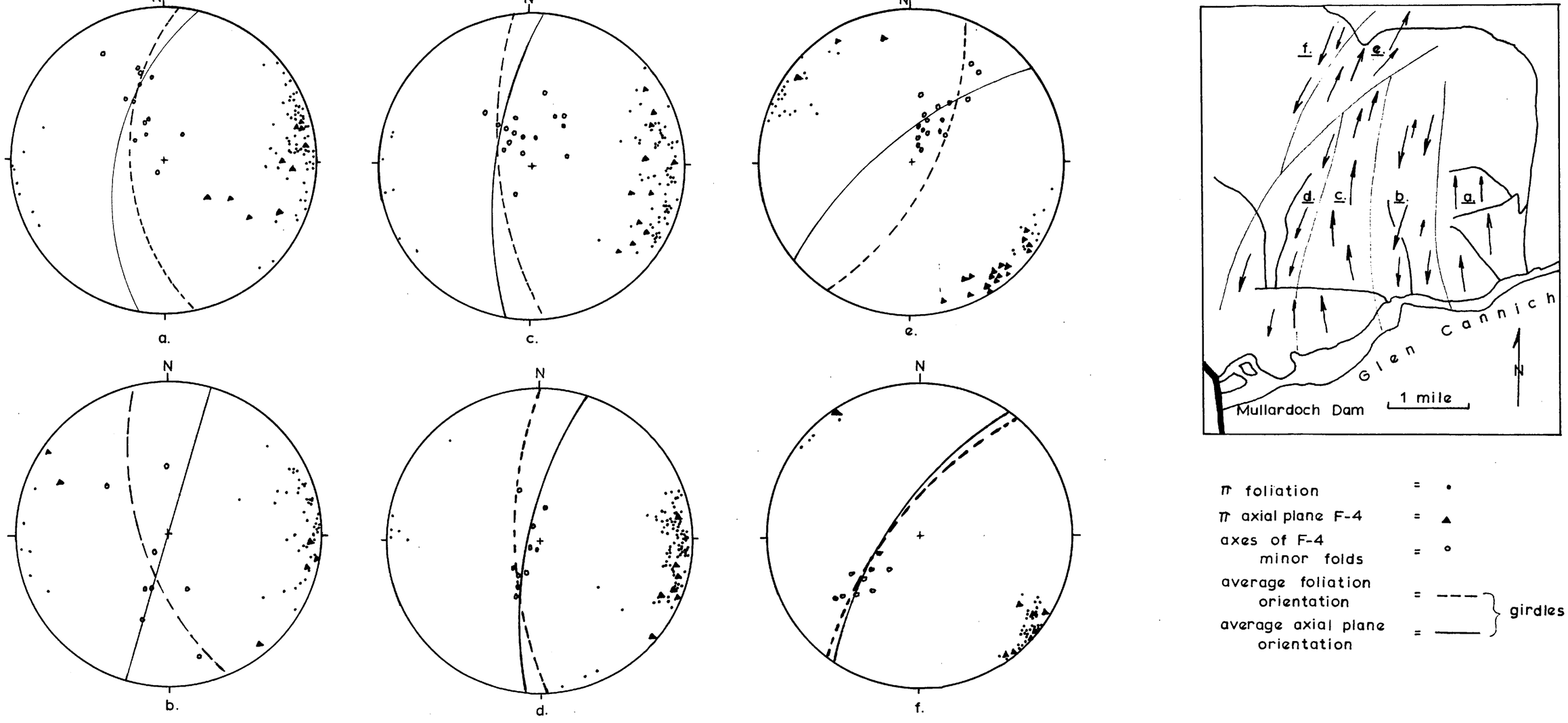
a. F-4 minor folds 1 mile SW of Meallan Odhar. The F-4 folds in this area have an axial plane schistosity.

b. Eyed structures associated with F-4 (?) minor folds. Just west of Mullardoch Dam. Knife is 4 inches long.





FIG. 21 Variations in Direction of Plunge of F-4 Minor Fold Axes and their Relation to F-4 Axial Plane and Foliation Orientation



letter, a to f. Such variations of plunge may be explained in two ways:

1. The dip of the foliation remains constant, while the dip of the fold axial planes is steep but undulating, so that in one zone it is steeper than the foliation, and in the next more gentle. The strike of the foliation and the axial planes are subparallel throughout, such that the pattern of the minor folds are practically always S-shaped.

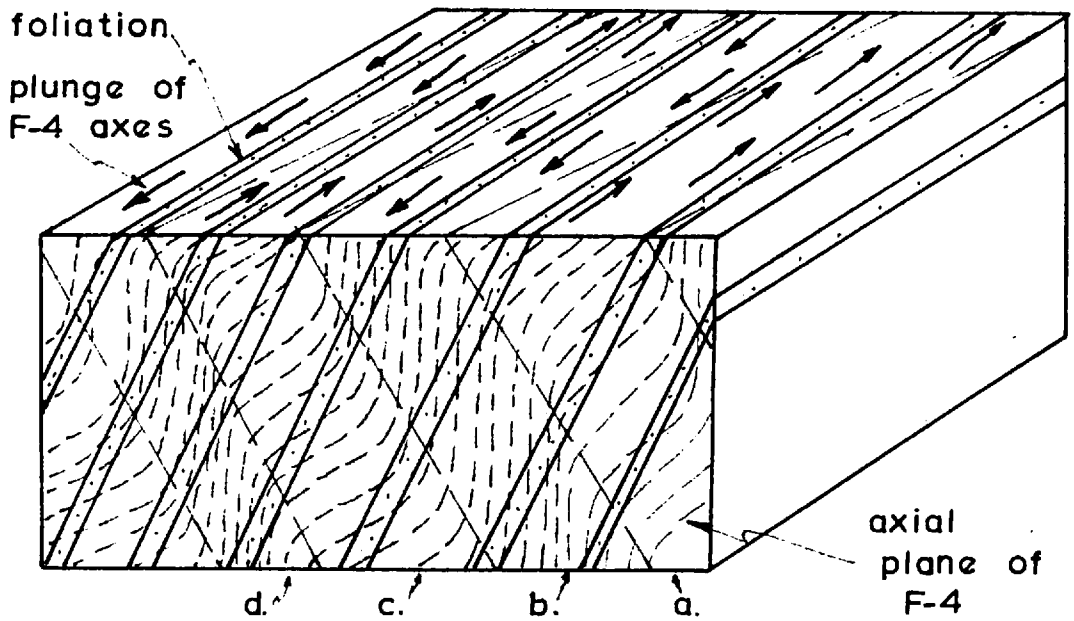
2. The dip of the foliation is undulating, but that of the F-4 axial planes is constant, so that again in contiguous zones the intersections of the two planes plunges in opposite directions. The strike of the foliation and the F-4 axial planes are as above (1).

The zones a - d of Fig. 21, the foliation dip is predominantly to the west, and hence explanation (1) above is applicable. The relationship is diagrammatically illustrated in Fig. 22. From the stereographic plots in Fig. 21 (a - d), it is seen that where the average[1] axial plane dip is more gentle than the average foliation dip (a & c),

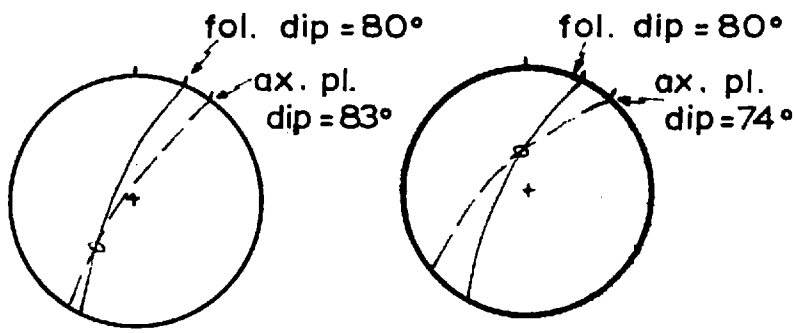
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[1]The spread of the poles to the axial planes in Fig. 21 (a - d) is a reflection of the swing in the axial plane strike of the F-4 folds along the length of the zones. The azimuth of the "average" axial plane orientation was judged from the scatter of poles, and its dip by the dip of the plane containing the spread of poles.

FIG. 22 Idealized Diagram Showing Relation Between Axes & Axial Planes of F-4 and the Foliation

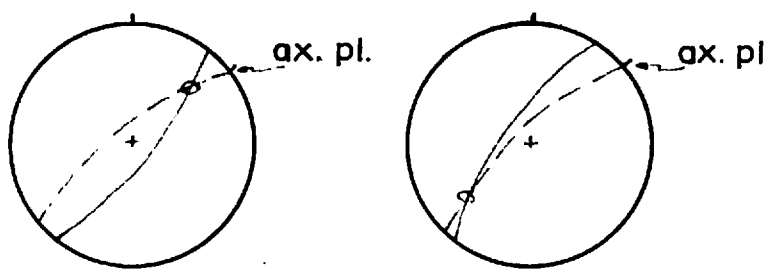


zones of different ax. pl. dip



zones b. & d. zones a. & c.

Case 1: foliation dip constant, ax. pl. dip varies



zone e. zone f. see FIG.

Case 2: ax. pl. dip constant, foliation dip varies

the axes of F-4 minor folds plunge northerly; and where the planar dips have a reversed relationship (b & d), the plunge of the F-4 minor folds is to the south. The strikes of the foliation and axial plane of F-4 are close to each other, and hence the trace of the zones of differing axial plane dip appears roughly parallel to the foliation.

In zones e and f, explanation (2) is the primary reason for the varying plunge of the F-4 minor folds: in zone e, the dip of the foliation is to the east, and the plunge of F-4 minor folds is northerly; in zone f, the dip of the foliation is to the west, and the plunge of F-4 minor folds is southerly. What the change in dip of the foliation in zones e and f represents is open to question. It is doubtful that it represents an early fold, because the lithology is not repeated on both sides of the dip change.

F-5 Structures.

This phase of deformation is present in the form of warping, gentle folding, and crumpling of the foliation. The axial planes strike ENE-WSW on the average, and the dip is steep. The trend of the fold axes is westerly, with a steep plunge. The style of the folding generally tends to be symmetrical.

Sub-Area 3

General

Sub-area 3 lies west of sub-area 2, Fig. 4. The general strike of the foliation and axial planes of the major and minor folds is east-west, except in the northeastern part of the sub-area, where it is NE-SW. The important structures in the area are the Mullardoch Eyed structures and the Creag Feusag Antiform, which are northwest of Mullardoch Dam; and the Creag a' Bhaca and Toll Creagach Synforms, which are southwest of the Dam. Structures of lesser importance occur between Loch Tuill Bhearnach and Loch Mullardoch.

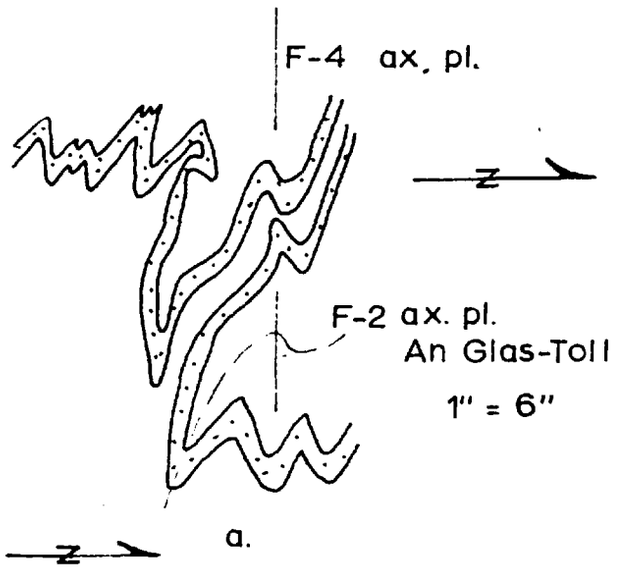
The Early Structures.

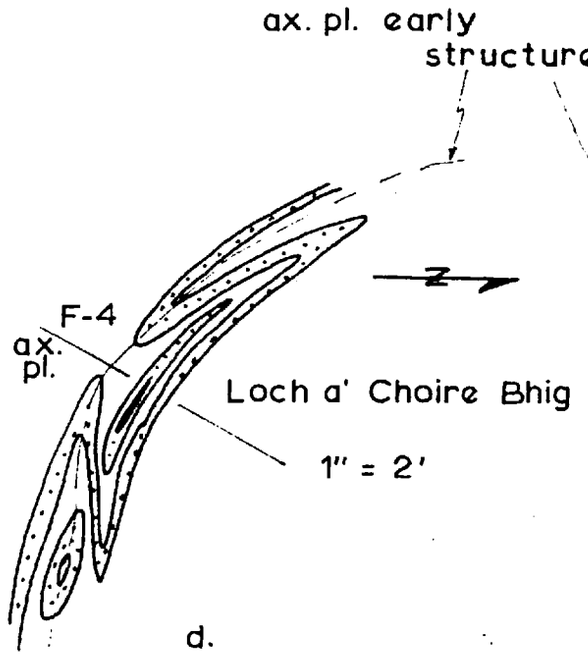
The early structures in this sub-area are not uncommon on a minor scale, Fig. 23. On a major scale, however, they are not well-defined, except for the Creag a' Bhaca Synform.

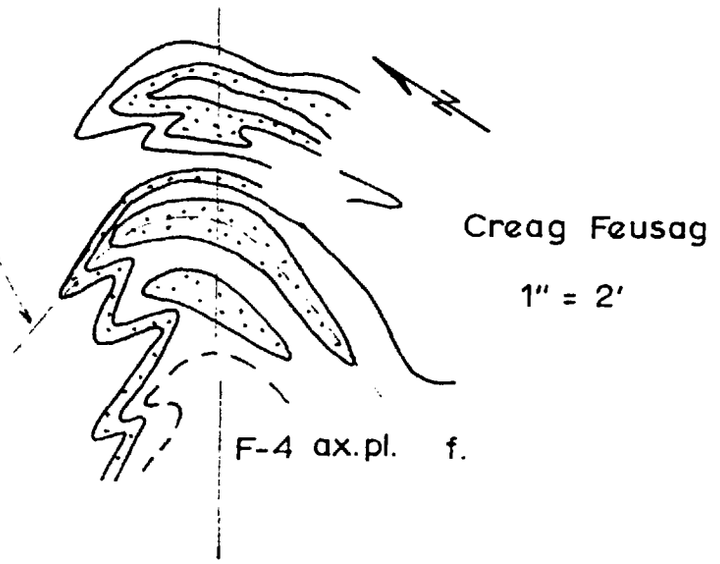
The Creag a' Bhaca Synform

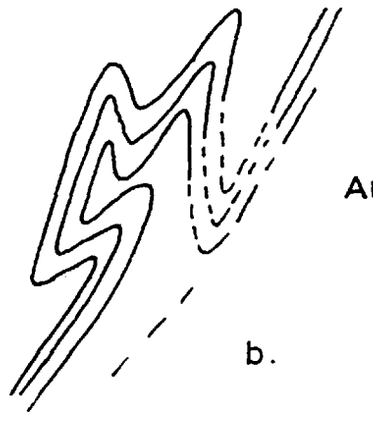
This fold is considered to be of F-2 age. The axial plane of the synform strikes NW-SE, and dips at moderate angles to the southwest, as do both its limbs; the synform, therefore, is overturned to the northeast. The fold axis trends west to northwest at moderate plunges (see map Fig. 45).

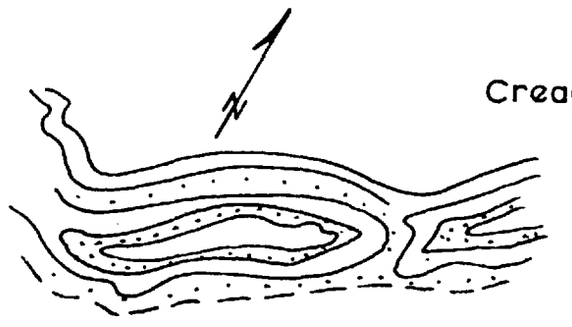
FIG. 23 Styles of Minor Folding of the Early Structures in Sub-area 3 Viewed ca. ⊥ to the Fold Axes

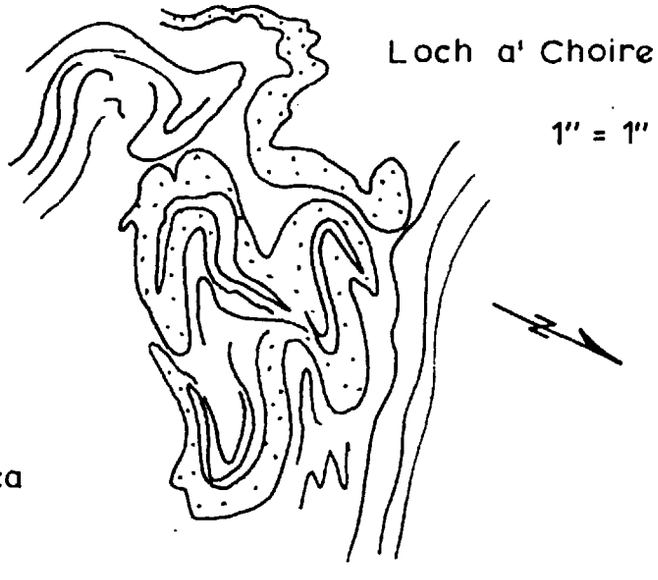


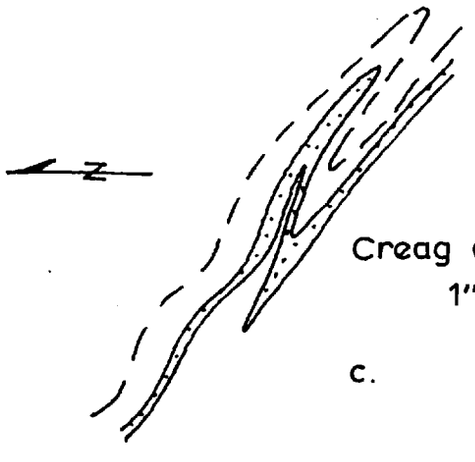


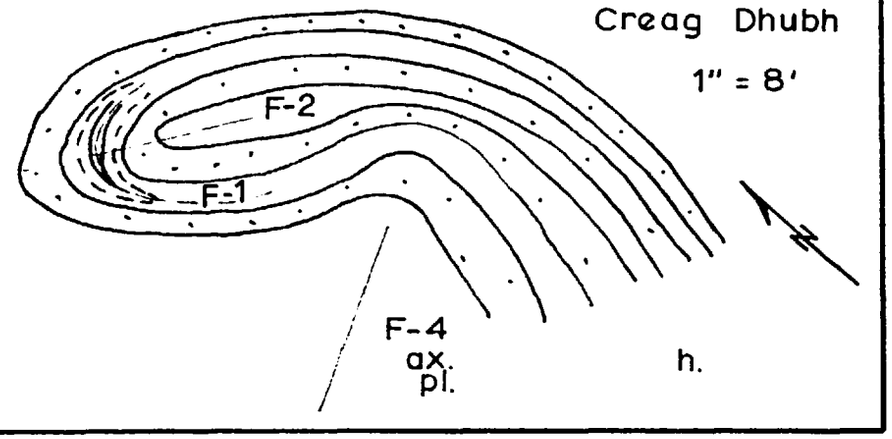












The geometry of the synform, which is essentially isoclinal, is clearly shown by the strike and dip of the foliation, the pattern of minor folds, and schistosity/foliation relationships. On the west limb, minor folds have an S pattern, on the east limb a Z pattern, and in the core they are M's. Lineations, apart from minor folds, consist predominantly of quartzo-feldspathic rodding.

Within the well-defined hinge of this fold, one can recognise isoclinal minor folds whose axial planes are parallel to the foliation. These minor folds are F-1 age. Further evidence for the presence of F-1 folds in this general area may be seen on the north shore of Loch Mullardoch, where very tight isoclinal minor folds of F-2 age are refolding isoclinal minor folds of F-1 age, Plate XI. The F-2 folds in this exposure have the same axial orientation and are accompanied by rodding in the same way as the minor folds associated with the Creag a' Bhaca Synform.

It is possible to follow the axial plane trace of this major synform from Loch Mullardoch for about 3000 feet to the southeast, but beyond this point there are no exposures.

The Mullach na Maoile Syncline

A rigorous definition of the Mullach na Maoile Syncline is impossible, mainly because of poor exposure. In fact, only in the immediate area of Mullach na Maoile is it

PLATE XI

a. Recumbent F-2 minor fold plunging to the NW at about 8°; edge of Loch Mullardoch, about 2 miles west of Mullardoch Dam. Plane of photograph is about normal to the fold axis.

b. F-1 minor folds being refolded around axial plane of recumbent F-2 (above); same locality, but about 25 feet to the left of the above picture.

c. F-4 minor folds interfering with F-2 structures; The lineation parallel to the longer axis of the compass is F-2. F-4's trend WSW, F-2's trend NW. Same general locality as above but about 300 feet to right of (a) above.




F-1
F-2


F-1
F-2

possible to demonstrate that such a structure exists.

The syncline, which is also synformal, is defined by two factors: the dip of the foliation, and the facing directions of sedimentary structures. In general, the fold itself is very tight, with very steeply dipping limbs; therefore the axial plane must also dip steeply. That the eastward dipping foliation is right way up is shown in two localities by sedimentary structures along the western flank of the syncline. Sedimentary structures at several localities also show that the westward dipping rocks are right way up.

Minor folds that could positively be identified as being related to the syncline have not been observed. There are suggestions of minor folds whose axial planes are parallel to the foliation, however. Unfortunately, it was not possible to measure the attitudes of axes of these minor folds; and because later folding has reoriented the foliation, it is not possible to determine the trend of the synclinal axis, either directly or indirectly.

The axial plane trace of this syncline can be followed for about 2000 feet. Its strike is NE in the north, changing to south as it swings around the hinge of a later antiform, but it disappears in unexposed ground towards Loch Mullardoch.

The Mullardoch Eyed Structure.

The structural geometry of the rocks in the Creag Feusag area is exceedingly complex; minor structures that are related to four different periods of deformation have been observed, and these are defined by refolding relationships.

The dominant lithologic feature in the immediate area is a large mass of pelite, surrounded by semi-pelite, which in turn is flanked on three sides by psammite (see map)Fig.44. Both ends of the outcrop of pelite appear to be fold closures. Later folding, however, has substantially reoriented the foliation, so that the closures are not well-defined by its present orientation. Unfortunately, it has not been possible to substantiate the exact nature of these fold closures by using the pattern of related minor folds, because:

1. the early geometry has been badly distorted by later folding;
2. the rare isoclinal minor fold of F-1 age are not always distinguishable from F-2 isoclines;
3. minor folds associated with F-4 locally become isoclinal in the semi-pelitic rock.

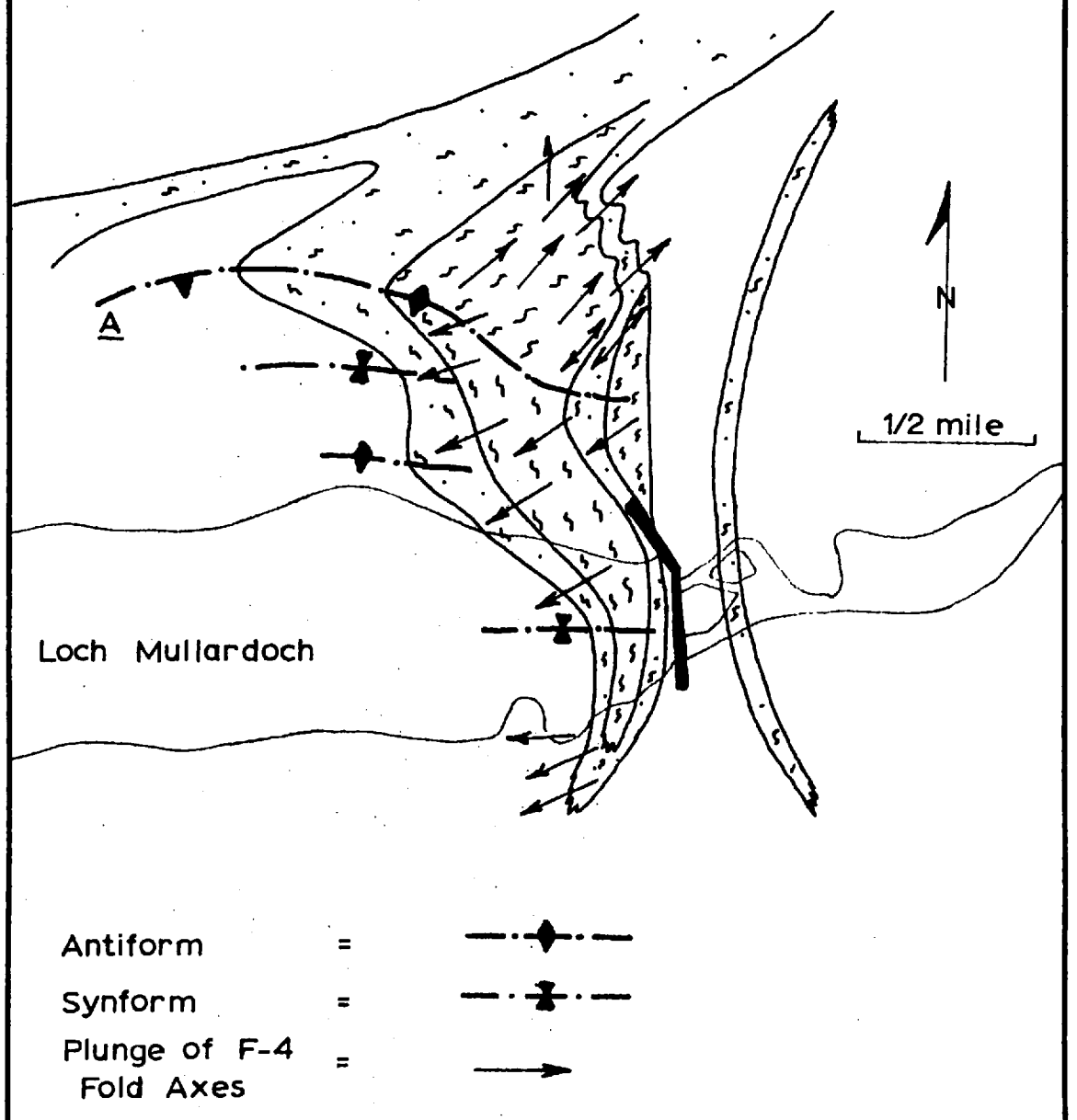
It is possible, however, to suggest the probable geometry of the Mullardoch structure on the basis of the

outcrop pattern of the pelite, and from interference patterns and orientation of minor folds.

Since the pelite closes both to the south and north, its outcrop defines what is essentially an eyed structure. The orientation of the minor folds and lineations associated with this structure indicates that the northern half of the eye plunges to the north or northeast, and is therefore antiformal; the southern half of the eye plunges to the WSW, and is also antiformal. Because the opposite ends of the eye trend away from each other at steep plunges, and the limbs of both antiforms dip to the west, it is reasonable to suggest that the eyed structure is an acute dome overturned to the east. In many parts of the immediate area, the geometry of the interfering minor structures reflects the eyed geometry of the major structure.

One of the principal problems in understanding this dome is to determine what two phases of deformation have brought about its formation. As seen in Fig. 24, the dome is being refolded by a later structure, the Creag Feusag Antiform (antiform A in the figure). Since the minor folds and lineations of the dome generally plunge in opposite directions on either side of the axial plane trace of this antiform, one might assume that the antiform is responsible for the doming. There are two lines of evidence which

FIG. 24 Sketch Map of the Creag Feusag Area



suggest that this interpretation is not satisfactory:

a. the interference pattern of minor structures;

b. theoretical considerations concerning the formation of eyed folds.

a. It is common in the Creag Feusag area, especially in the semi-pelitic rock, to find individual eyed minor structures (Plate XII) which are not easily interpreted in terms of the patterns described by Weiss (1959), Ramsay (1962b), Carey (1962), or O'Driscoll (1962). That is, the axial plane of only one phase is visible.

It might be possible to form individual eyed structures by local differential movement similar to the diapiric action of a salt dome. Nicholson (1963) has described eyed minor folds in a marble, which do not follow the patterns of Ramsay, etc., and has suggested that they were produced during one phase of movement by "non-cylindroidal deformation of the marbles and differential movement within and along the axial plane of the folds" (op. cit. p.67). It seems unlikely that the mechanism suggested above is applicable to the eyed folds in the Creag Feusag area, because the environment of the eyes is unlike that described by Nicholson.

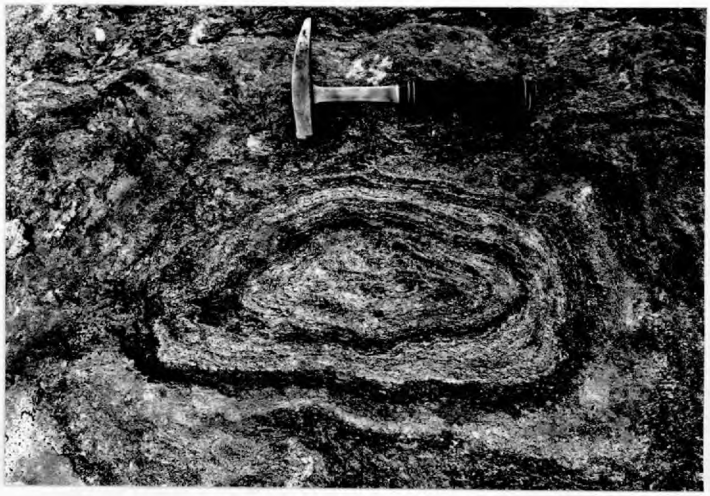
It is also possible that eyed F-2 minor folds may have been formed without leaving obvious evidence for the later

PLATE XII

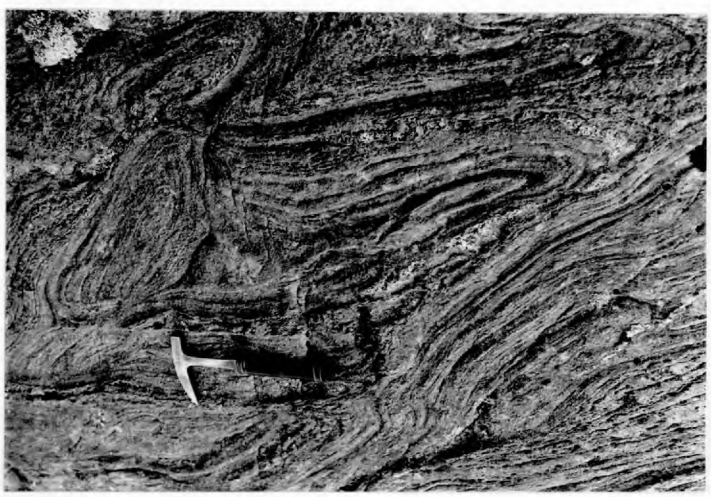
a. Eyed structure in pelite; west of Mullardoch Dam.

b. Eyed structure in semi-pelite; eastern edge of Creag Feusag; pencil is 4 inches long.

c. Eyed structures in pelite; eastern edge of Creag Feusag.







phase which produced them. In such a case, the following conditions must have been satisfied:

1. the later deformation contained a considerable component of shear;

2. the axial plane of F-2 minor folds was absolutely parallel to the foliation during that deformation;

3. the "a" direction of the later deformation lay in the foliation (Ramsay, 1960, 1962b). The nature of the later deformations suggests that it is improbable that all these conditions were satisfied simultaneously. The majority of the eyed minor structures, therefore are probably genetically unrelated to post F-2 deformations.

b. To form eyed structures by the interference of two phases of deformation, a number of geometrical conditions must be satisfied (see Ramsay 1962b). One condition which CANNOT obtain is that the two interfering phases be co-axial. Throughout the Creag Feusag area, the axes of F-2 minor folds and F-4 minor folds are nearly always parallel. The few exceptions are found locally on the east side of Creag Feusag (see Plate XIII), and there the earlier structures involved may be of F-1 age. Although crumpling etc. by F-5 occurs on different axes from the other phases, it is clear that intensity of this folding in the area is not

PLATE XIII

a. Eyed structure produced by the interference of F-2 (?)/F-4 minor folds; eastern edge of Creag Feusag.

b. Eyed structure folded by an F-4 minor fold; since F-2 and F-4 are co-axial in this area, either the eye is a result of F-1/F-4 interference, or an F-1/F-2 eye refolded by an F-4 minor fold.


F-4



sufficient to form the eyed structures under consideration. It is most significant, however, that where F-1 lineations have been observed in this area, they show a considerable divergence from the axes of F-2 as well as from all the other phases of deformation, Plate XIV. Hence it is probable that many of the eyed minor structures, such as those illustrated in Plate XII, have resulted from the interference of F-1 and F-2 minor folds. The sporadic occurrence of the eyes reflects the relative lack of minor folds of these two phases, combined with the necessary condition that to form an eye, a minor fold of each phase must have formed at the same locality (except under the conditions stated in a. above).

Since F-2 minor folds and the Creag Feusag Antiform are essentially co-axial (Fig. 25a), at least on the southern limb of the antiform, it is improbable that the Mullardoch Dome has formed by the interference of these two phases. And because many of the eyed minor structures in the area appear to be a result of F-1/F-2 interference, it is suggested that the Mullardoch Dome is a result of F-1/F-2 interference on a major scale. The geometrical conditions obtaining during formation of F-1/F-2 interference patterns are discussed in the section on Structural Synthesis.

PLATE XIV

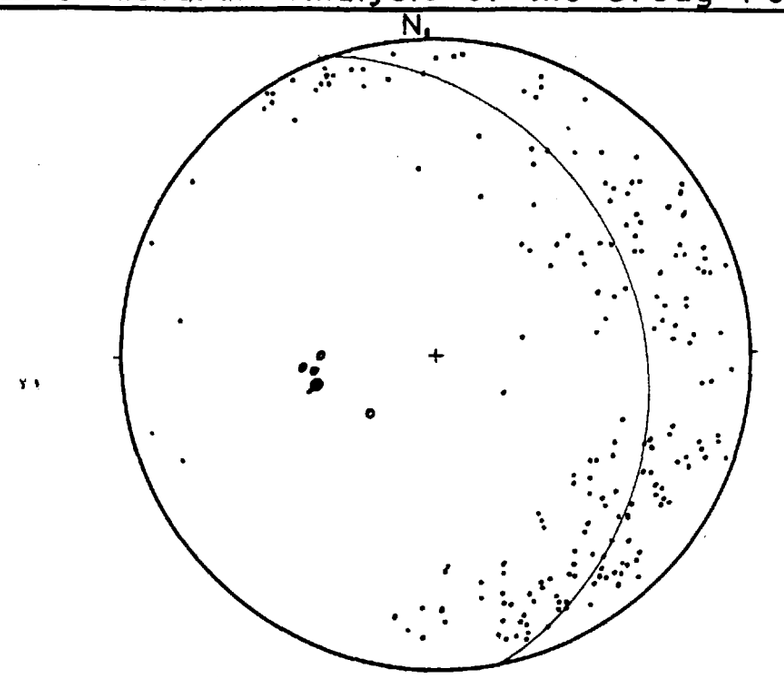


a. F-2 minor folds co-axial with F-4 minor folds (not shown), plunging to the west. Photo is in a plane approximately normal to the fold axis; west of Mullardoch Dam.

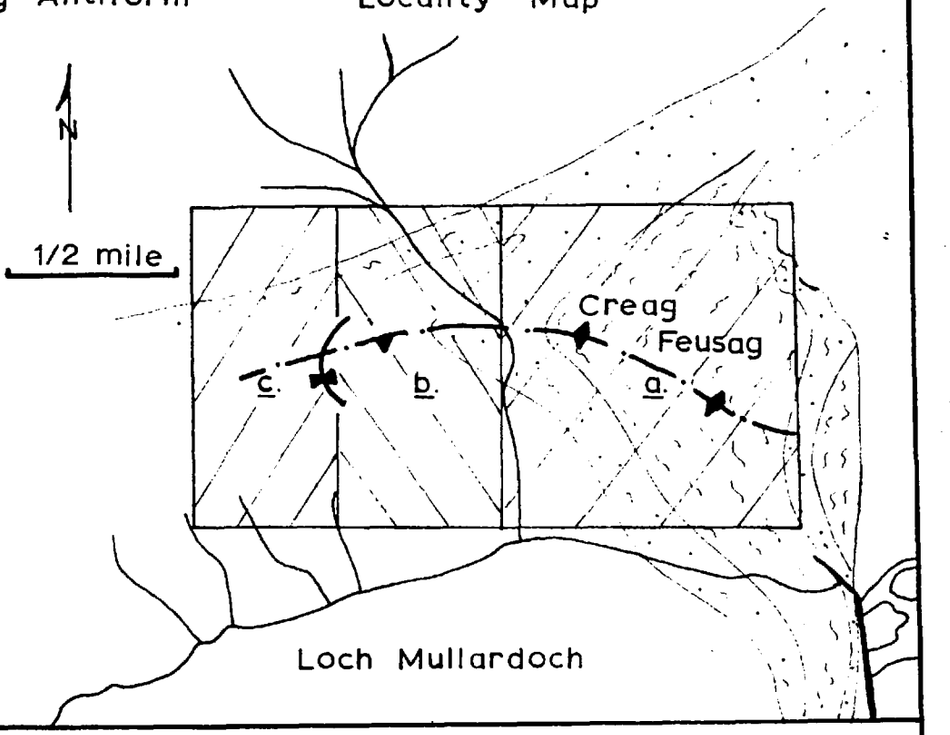


b. F-1 lineation (feldspathic striping and rodding) being refolded by F-4 minor folds (co-axial with F-2); same exposure as above (a), looking in opposite direction (east).

FIG. 25 Structural Analysis of the Creag Feusag Antiform



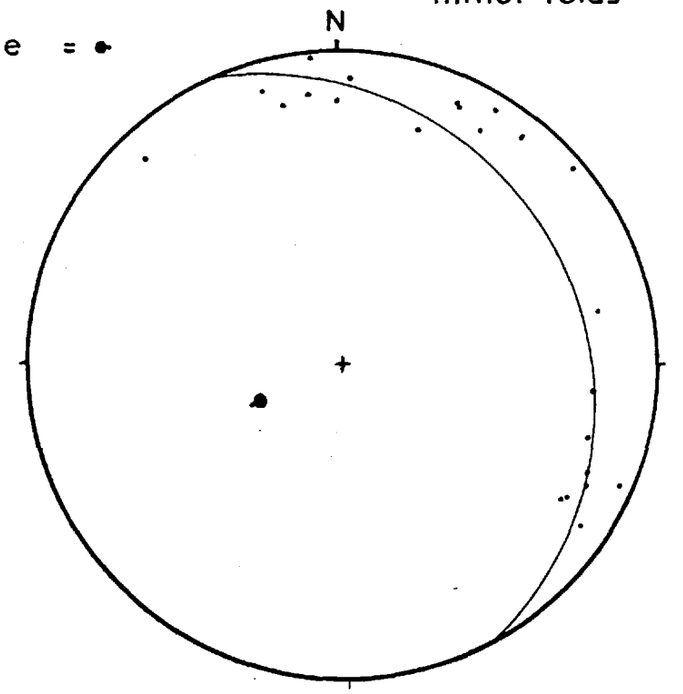
Locality Map



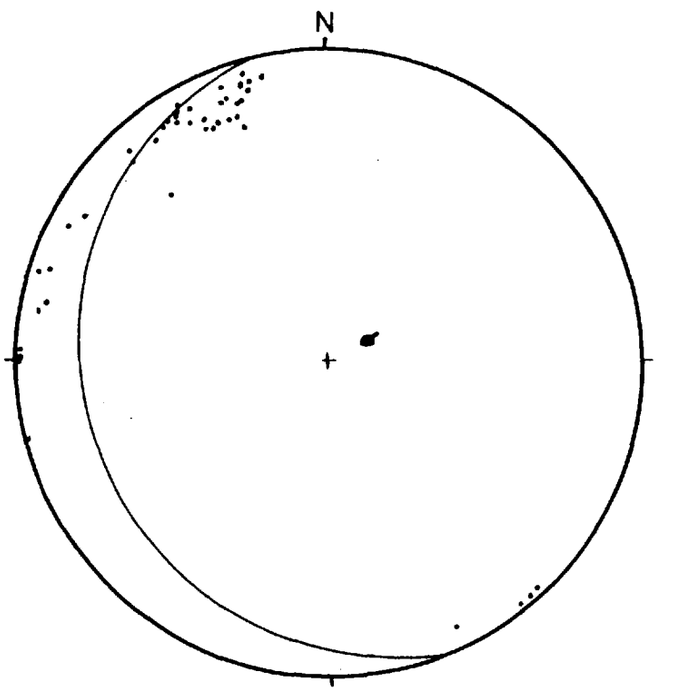
π to foliation = ·

π to girdle = •

a. axes of F-2 minor folds = ∘



b.



c.

Intermediate Structures

The intermediate structures of sub-area 3 are not always well-defined geometrically. Furthermore, the age of the major structures can only be inferred from the relations between them and later structures (i.e. F-4), but the incongruity of F-4 minor folds with respect to the major fold geometry suggest that the major structures are earlier than F-4. Some of the characteristics of the F-4 minor folds are discussed in this section, since they are necessary in determining the nature of the intermediate structures.

The Creag Feusag Antiform

The Creag Feusag Antiform has two well-defined limbs, dipping northwest and southwest on opposite sides of the axial plane. The axis plunges westerly at moderate to steep angles, Fig. 25a, and the axial plane strikes approximately WNW-ESE and dips very steeply to the south. The swing in strike of the axial plane in the area of Creag Feusag is probably a result of later folding.

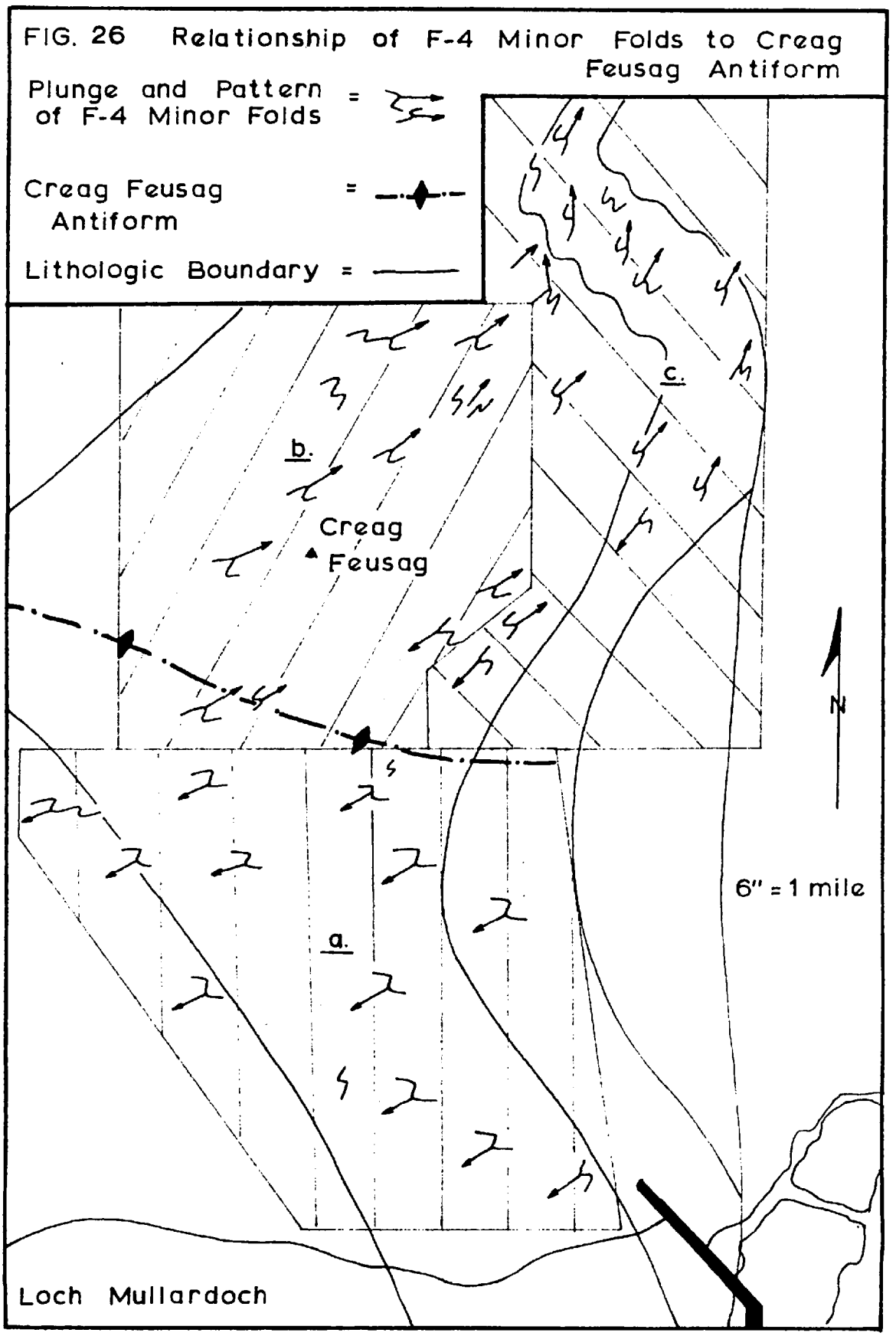
The geometry of the fold is that of a normal antiform on the east side of Allt Mullardoch, but on the west side of that burn the northern limb becomes overturned to the north. The structure is then an overturned antiform

plunging to the west, and this geometry continues along its axial plane trace toward Mullach na Maoile until the F-2 syncline is crossed. At this point, the antiform becomes a synform plunging to the east, Fig. 25b,c. West of Mullach na Maoile, the exposures are virtually absent; but judging from observed strike directions, the antiform appears to die out before it gets to Allt Taige, because no evidence that the fold exists could be found in that burn.

F-4 minor folds abound in the Creag Feusag area. One might assume that they are related to the Creag Feusag Antiform as their axial planes appear to be sub-parallel to the major fold axial plane. It will become apparent in the following paragraphs that the Creag Feusag Antiform must be earlier than the F-4 minor folds.

As is seen in Fig. 26, the changes in direction of plunge of F-4 minor structures roughly coincide with the axial plane of the major antiform. To the north of this axial plane, the F-4 minor folds plunge to the northeast; to the south, they plunge southwest. Furthermore, the area can be divided into three smaller areas, a, b, and c, where Z's plunge to the SW, Z's plunge to the NE, and S's plunge to the NE, respectively, Fig. 26. These changes in plunge and pattern of F-4 minor folds are the expression of the angular relationship between the orientation of the axial

FIG. 26 Relationship of F-4 Minor Folds to Creag Feusag Antiform



plane and the foliation upon which they were superposed. In area a of Fig. 26, the foliation/F-4 axial plane relation produces minor folds whose pattern in congruous with the major antiform. However, in area b, F-4 minor fold patterns remain the same, yet their plunges are now to the NE. This implies that the foliation must have been dipping to the north before F-4 was superposed. The latter implication plus the fact that the change in plunge of F-4 minor folds roughly coincides with the axial plane of the Creag Feusag Antiform strongly suggest that the two limbs of the Antiform were in their present general orientation before the superposition of F-4. In addition, the fact that the trends of axial plane strike of F-4 minor folds cut across the axial plane of the major Antiform in one locality(Fig. 26), definitely suggests that the Creag Feusag Antiform is pre F-4 in age; and because this Antiform refolds an F-2 structure, it must be of F-3 age.

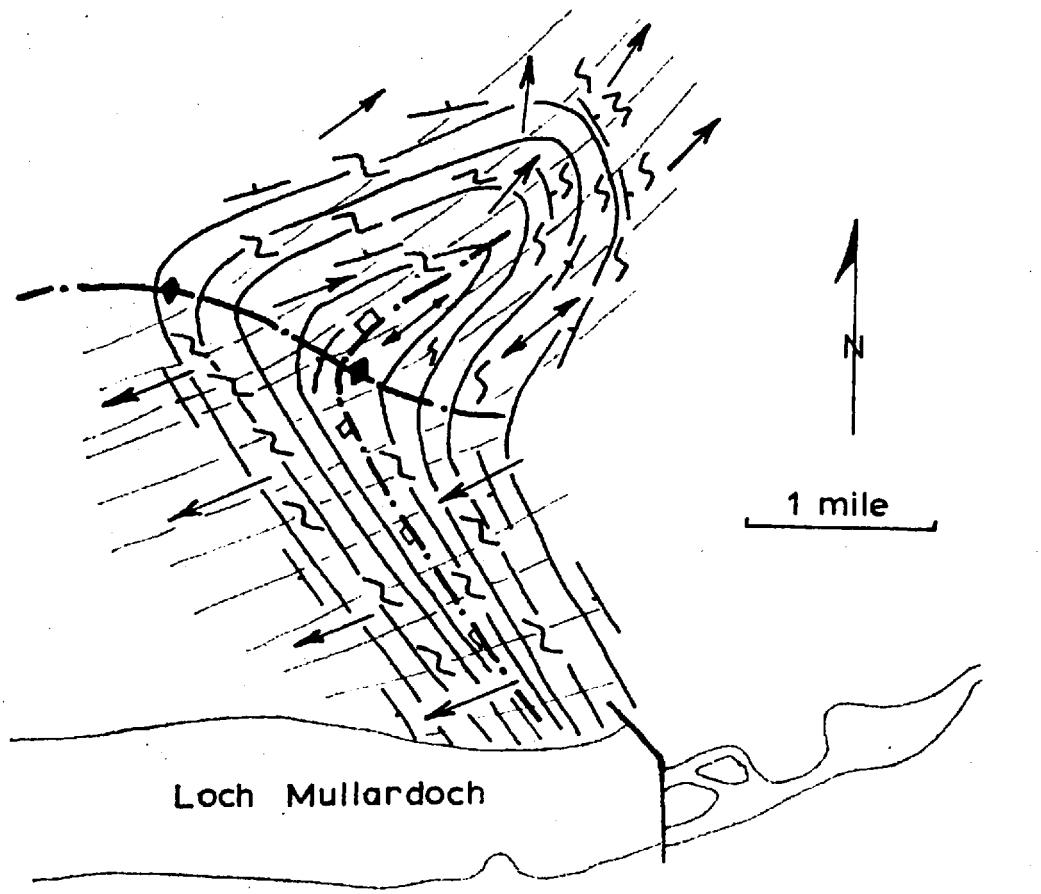
In area c of Fig. 26, the plunge of F-4 minor folds is predominantly NE, but contrary to the minor folds in sections a and b, the pattern is an S, and locally becomes M. Because the axial plane orientation of F-4 is reasonably constant in that immediate area, the pattern and trend of the F-4 minor folds implies that the foliation in area c was oriented roughly north to northwest and dipped

eastward before superposition of F-4. This change in foliation orientation represents the northern hinge of the Mullardoch Dome; the relationship is diagrammatically illustrated in Fig. 27.

Though minor folds related to the Creag Feusag Antiform appear to be absent, one finds in the area of Mullach na Maoile F-4 minor folds which are congruous with the geometry of the Antiform; but because the Creag Feusag Antiform and F-4 minor folds are distinctly separate phases in the Creag Feusag area, their concordance in the Mullach na Maoile area is probably fortuitous, that is, the axial planes of the two phases are locally brought into parallelism in that area. Renewed movement of the Creag Feusag Antiform during F-4 folding may in part account for the tendency for these two phases to be concordant in the Mullach na Maoile area.

Directly to the south of the Creag Feusag Antiform is a complementary synform which has a geometry very similar to the fold described above. The axial plane trace of the synform begins in the semi-pelite on the western edge of the large pelitic mass of Creag Feusag. The extent of this synform, therefore, is not as great as its antiformal counterpart. Further to the south still, are an antiform and a synform of limited extent. Their axial planes strike approximately east-west, and dip steeply; the plunge of

FIG. 27 Diagrammatic Illustration of the Relation of F-4 Minor Folds to Pre-existing Major Fold Geomety in the Creag Feusag Area



their axes is to the west (see map), Fig. 45.

Structures between Sgurr na Lapaich and Loch Mullardoch

The general strike of the foliation between Sgurr na Lapaich and Loch Mullardoch is east-west. If one were to walk on a north-south line between these two localities, the following lithologic units would be crossed:

Pelite
Lewisianoid
Muscovite Psammite
Semi-pelite with calc-silicate lenses
Psammite with calc-silicate lenses
Pelite
Psammite
Semi-pelite
Psammite
Pelite
Psammite
Semi-pelite

It is necessary to mention briefly the nature of these lithological units in order for the reader to fully appreciate the difficulties inherent in interpreting the structures. Only one of these units can be traced along its strike for more than one mile, and that is the muscovite psammite, which can be followed all the way to Glen Strathfarrar. The Lewisianoid unit appears to end at a small fault, while the eastern ends of the two pelites south of Loch a' Choire Bhig disappear into peat bogs at or near Allt Taige. The pelite which lies closer to the Loch appears to become less

pelitic toward the east. All the semi-pelitic units are discontinuous, and it is virtually impossible to draw meaningful contacts that are valid for over 1000 feet between semi-pelite and psammite.

By observing the dips and strikes of the foliation alone, three structural zones appear to exist. The most northerly of these borders Loch Tuill Bhearnach, the next to the south passes through Loch a' Choire Bhig, and the third lies just north of An Glas-Toll. All these structural zones strike east-west. In defining these structures, it will be necessary to discuss some of the characteristics of F-4 minor folds, which otherwise would have been discussed in the section on Later Structures.

The Loch Tuill Bhearnach Area

There are no clearly defined major structures in this area. The pattern of variations in orientation of F-4 minor folds, however, suggest that pre F-4 structures exist.

Since the style of folding, orientation of axial plane of minor folds, and degree of recrystallisation (i.e. axial plane schistosity) is constant throughout this area, it is most probable that the majority of non-isoclinal minor folds with E-W axial planes constitute one phase of folding. By analyzing the variation of orientation of this phase, which is

F-4, it is possible to detect original zones of variation in the foliation which may be the result of pre F-4 folding. In area 1 of Fig. 28a, for example, two significant facts are brought out: firstly, there are three contiguous zones of folds with a Z pattern plunging in opposite directions; and secondly, the plunge of the mappable folds in zone (c) steepens abruptly in the plunge direction, i.e. easterly, over a small area. These facts may be explained as follows: the change in trend and magnitude of plunge of F-4 minor fold axes in the Loch Tuill Bhearnach region is the result of superposition of these minor folds upon a foliation whose direction of dip was varying, and the orientation of the plunge reflects the original dip of the foliation. Also, the strikes of the foliation and axial planes of F-4 minor folds are close to each other yet they maintain a constant angular relationship; hence, it is clear that superposition of F-4 minor folds on a foliation whose strike is slightly askew to that of the fold axial planes would result in a change in trend of the fold axes as opposite dips of the foliation are encountered, though a constant fold pattern would still be retained, Fig. 28b. This is similar to that described from zones e and f of Fig. 21, in sub-area 2. Unfortunately, it is not possible to demonstrate whether the change in dip of the pre F-4

FIG. 28a Variations of F-4 Minor Folds in the Loch Tuill Bhearnach Area

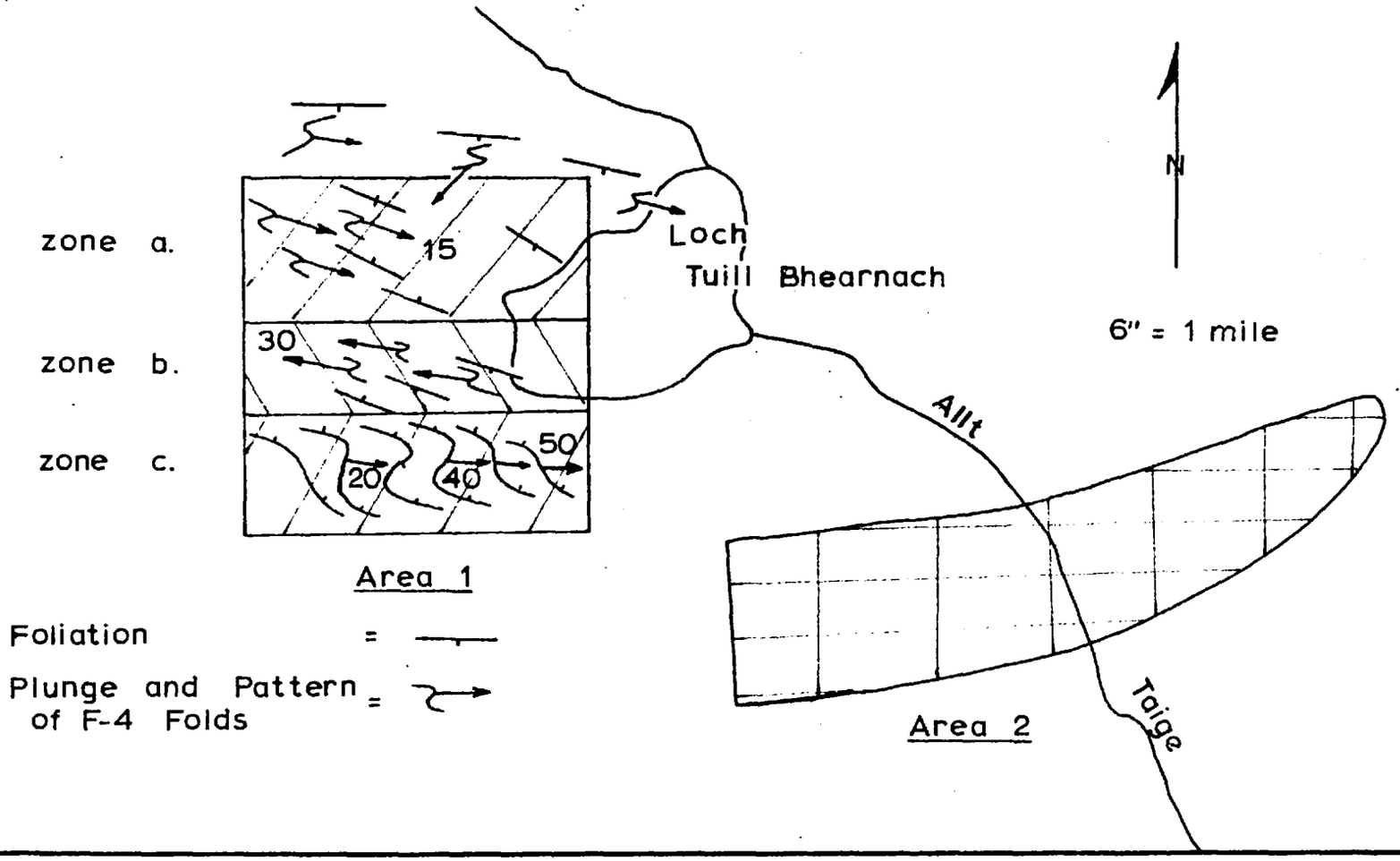
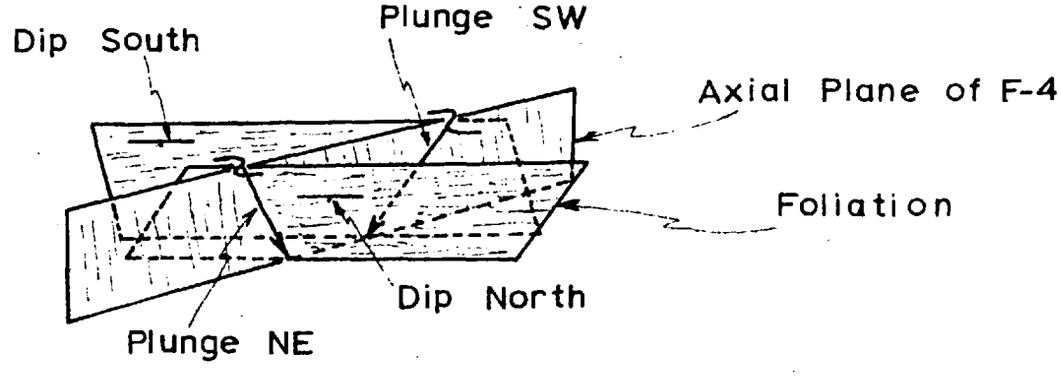


FIG. 28b Three Dimensional Diagram Illustrating the Change in Plunge of F-4 Minor Fold Axes While Folds Maintain a Constant Pattern



foliation in the Loch Tuill Bhearnach area is due to early major folds, or merely a localized warping.

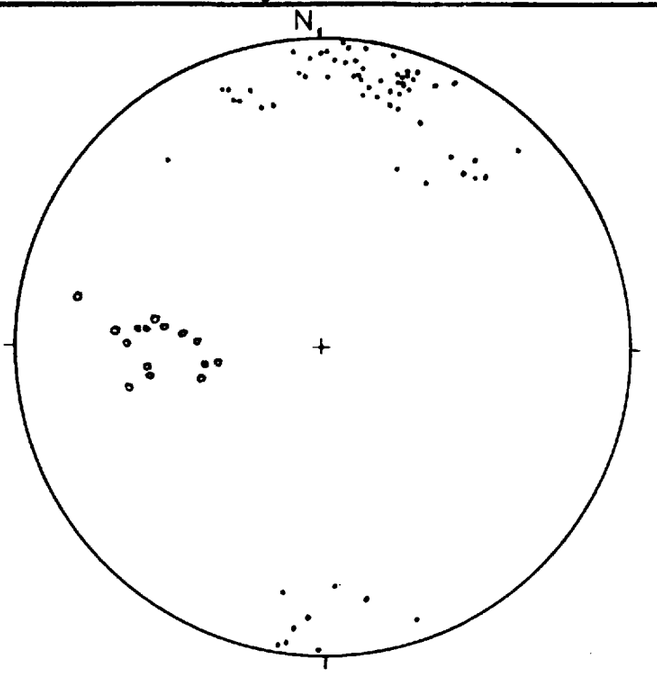
The Choire Bhig Structure

This fold is defined by the inward dip of the foliation and its strike, which converges to the east. Its axial plane trace passes through Loch a' Choire Bhig. Although the dips on both limbs are generally toward the axial plane, suggesting that the structure may be synformal, dips away from the axial plane are not uncommon, Fig. 29a,b. Two other facts must be mentioned; firstly, whereas on the northern limb of the structure, the minor fold pattern and its direction of plunge is usually concordant with a synformal geometry, on the southern limb, they are nearly always discordant; and secondly, the pelite on the south side of the axial plane trace is not repeated on the north side. Two possible hypotheses can be invoked to explain the facts:

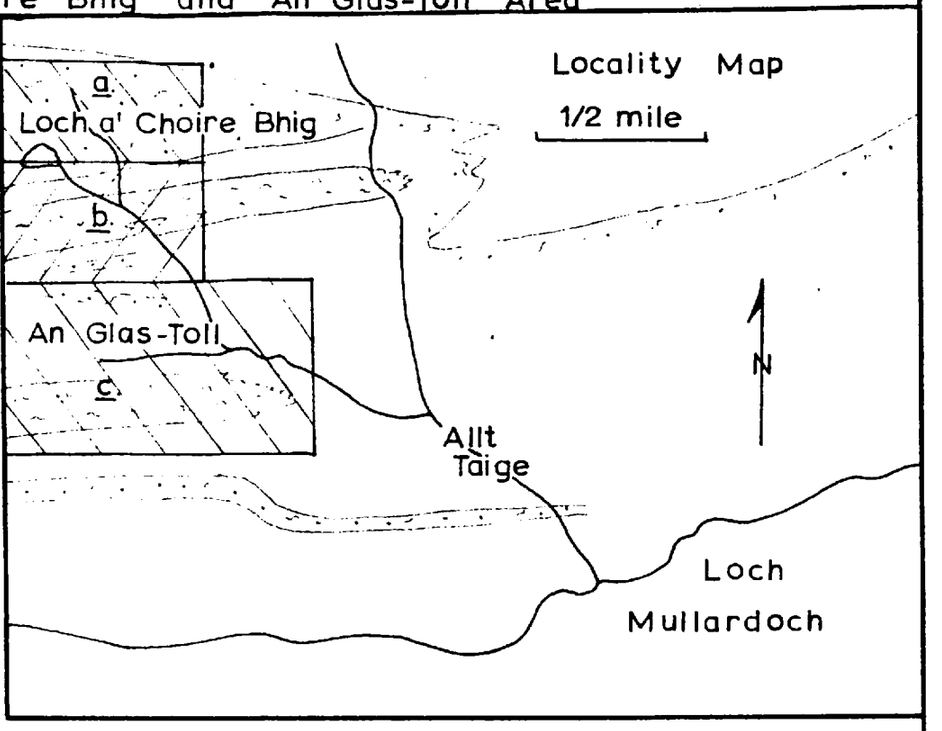
Hypothesis 1.

As the lithology is not repeated on both sides of the axial plane, a warping as pictured in Fig. 30 might well account for the observed facts, and observations suggesting that such warpings do occur in this area have been made. Because the rocks contain abundant minor folds, however, it is difficult to assess the extent of the warping, that is,

FIG. 29 Structural Analysis of the Loch a' Choire Bhig and An Glas-Toll Area

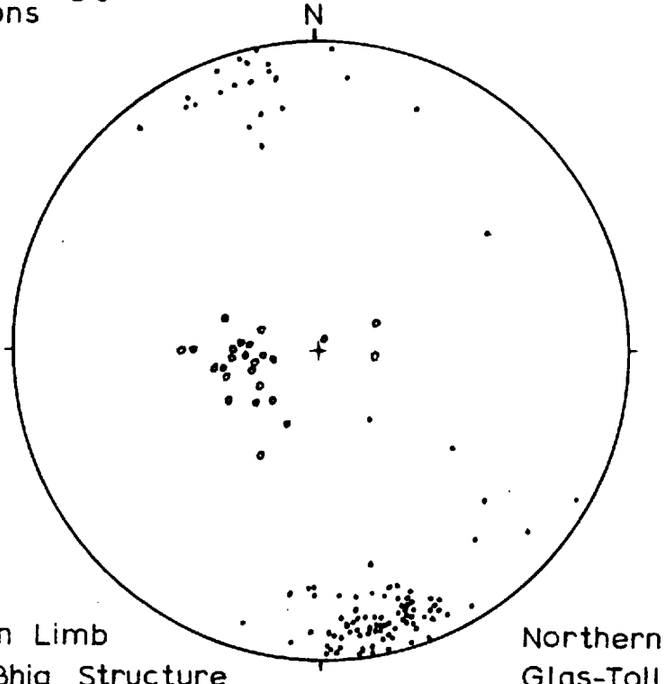


a. Northern Limb Choire Bhig Structure



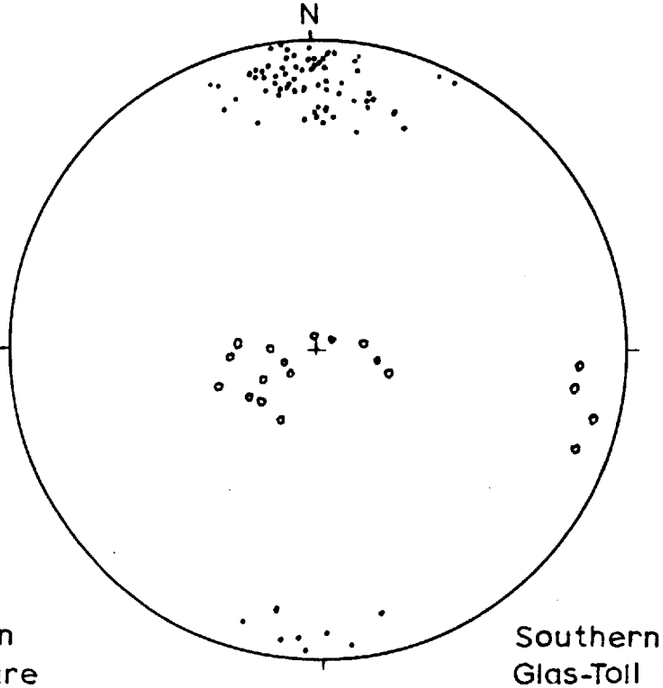
π to foliation = •

F-4 fold axes and lineations = ○



Southern Limb Choire Bhig Structure

b.

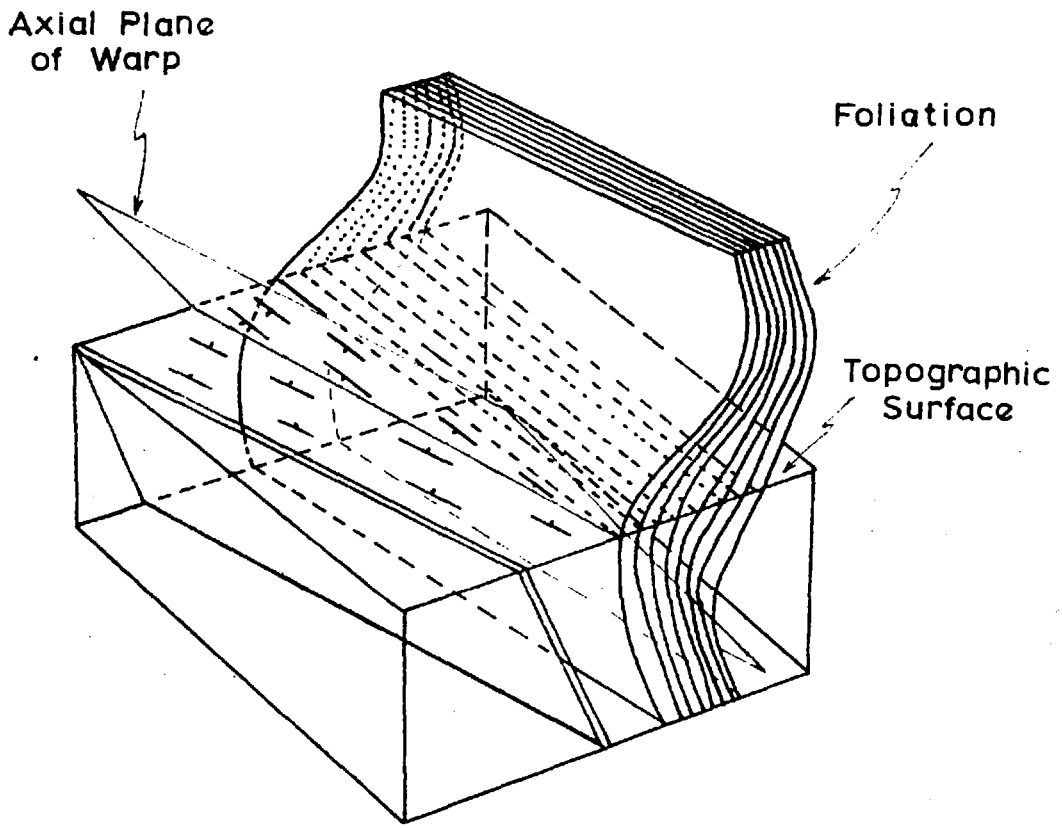


Northern Limb An Glas-Toll Structure

c.

Southern Limb An Glas-Toll Structure

FIG. 30 Block Diagram Illustrating Warping



Intersection of axial plane with topographic surface is trace of the apparent synform

whether it occurs on a large scale over a large area.

Hypothesis 2.

If the structure is a synform, it is certainly pre F-4 since F-4 minor folds on the southern limb generally show a pattern contrary to the proposed major fold geometry: i.e. the majority of minor folds have a Z pattern on both limbs of the fold. Furthermore, if the proposed synform is assumed to be F-3 age, which would not be unreasonable, the fact that the pelitic unit does not appear on both sides of the axial plane could be explained as envisaged in Fig. 31. Here it is suggested that the pelite is in the core of an early fold that is being refolded by the synform. The pelite along parts of its strike, in fact, is characterized by early isoclinal folds which have been strongly refolded by F-4 minor folds (Plate XV), which may indicate that the unit itself is part of a pre F-4 structure.

Whether the Choire Bhig structures is as pictured in Figs. 30 or 31, unfortunately, remains open to question.

The An Glas-Toll Structure

Difficulties similar to those described above are encountered in attempting to elucidate the geometry of the An Glas-Toll structure. It is defined by the convergence of strikes of the foliation towards the west, while the

FIG. 31 Diagrammatic Cross-section Normal to the Plunge of Later Major Folds

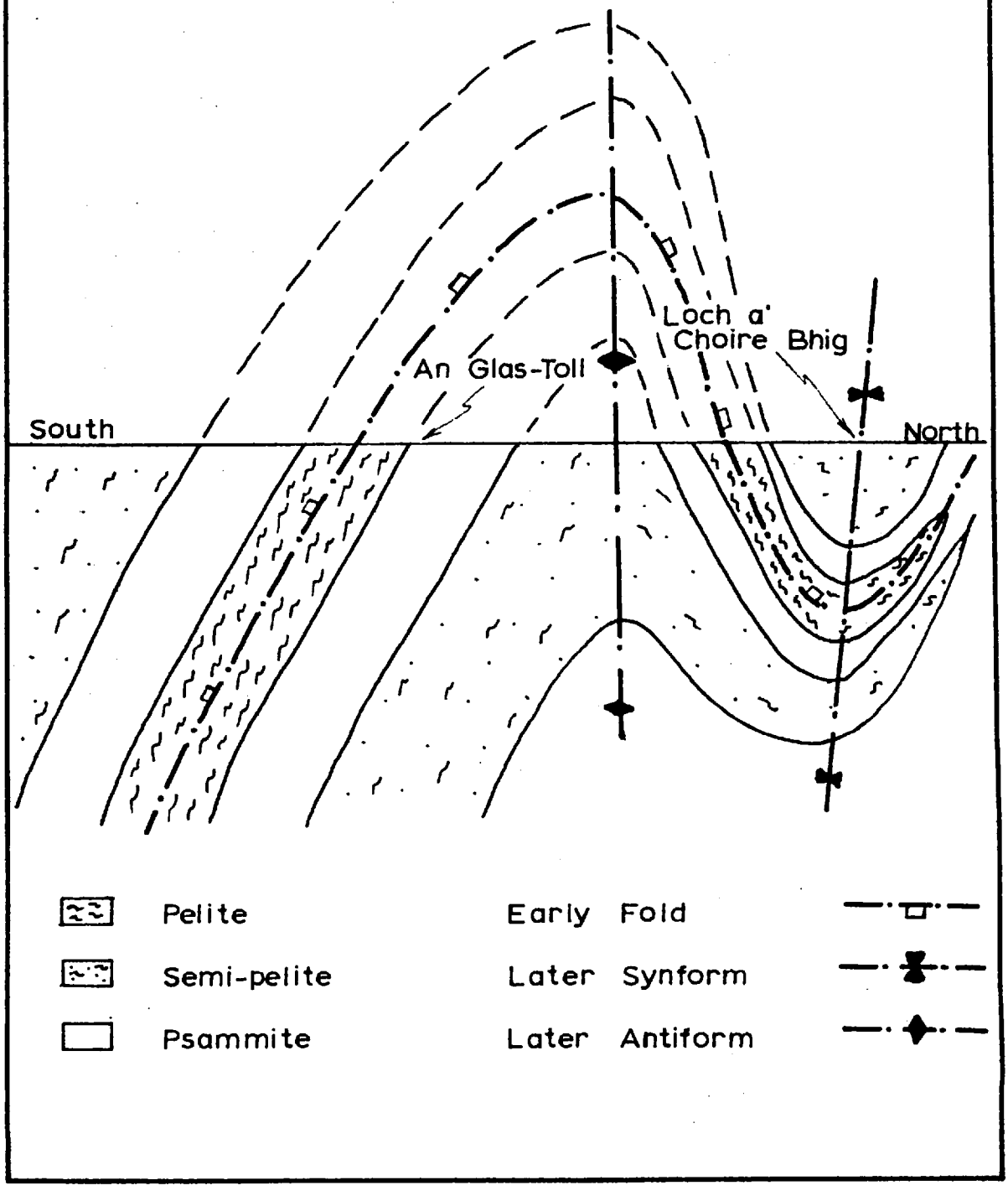
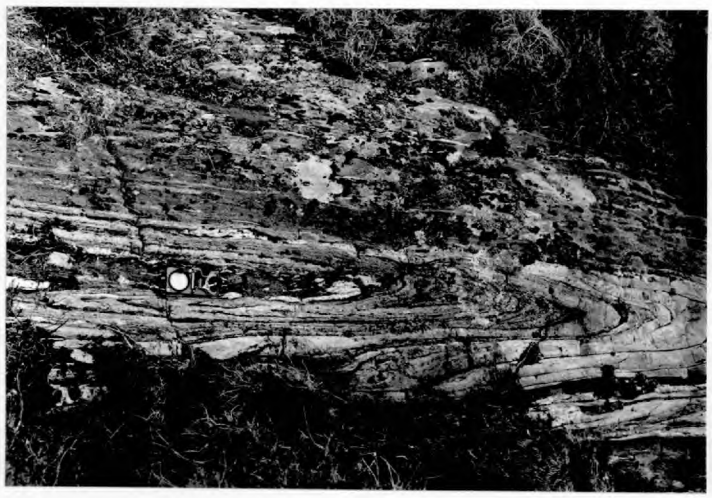


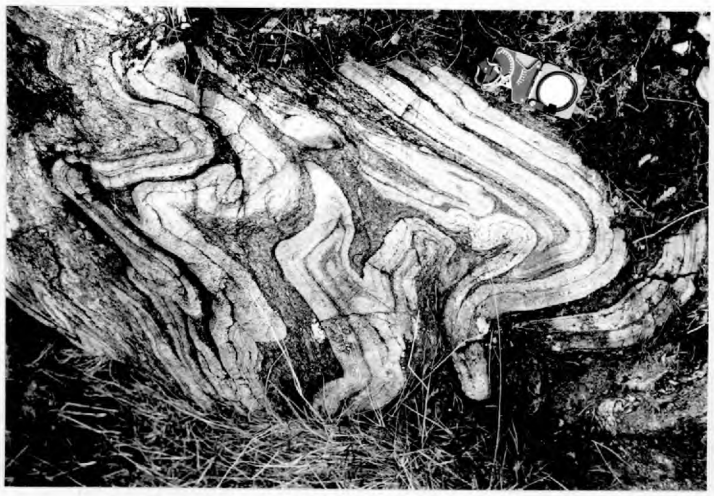
PLATE XV

a. Isoclinal fold refolding an isoclinal fold (F-2/F-1 ?); earlier fold is immediately below the compass; in An Glas-Toll area.

b. F-4 minor fold refolding an earlier phase minor fold; just to the south of Loch a' Choire Bhig.

c. Same as (b) above.







dips are generally away from the axial plane; hence, it appears to be an antiform. This interpretation is strengthened by the fact that here the lithologic units are repeated on both sides of the axial plane trace. The pattern of the minor folds, however, are incongruous with such a major fold geometry: Z patterns predominate on both limbs of the antiform. The minor folds are undoubtably of F-4 age; hence, the antiform must be pre F-4.

One puzzling feature of the lithology is the abruptness with which the pelite of both limbs suddenly ends at Allt Taige. Admittedly, exposure is poor in this area, but where there are exposures to the east, there is no indication whatsoever that the pelite continues along its strike; neither is there evidence to suggest that a fault has offset the pelites. The abrupt ending of the pelitic units to the east, therefore, must be accounted for either by a facies change, or they may be forming the core of an early fold which closes at both ends as a result of interference on a major scale (c.f. the Mullardoch Eyed structure). There is no conclusive evidence to support either of these suggestions, however.

Neither the Choire Bhig or An Glas-Toll structures are traceable for more than 3000 feet. Although inadequate exposure accounts for part of this, the nature of the

structures also adds to the difficulty.

The Toll Creagach Synform

The axial plane trace of this overturned synform lies about 1½ miles southwest of Mullardoch Dam, between Toll Creagach and Loch Mullardoch. Its strike is east-west, and it dips steeply to the south. Both limbs also dip to the south, hence the synform is overturned to the north. The hinge of the fold is sharp and well-defined, and its fold axis trends to the WSW at moderate plunges (see map). Just to the east, the hinge appears to broaden out. Though it is possible that this fold may be of F-3 age, the fact that rare F-4 minor folds are congruent with the major fold suggests that it could be of F-4 age.

Exposures are absent to the east along the projection of the axial plane of this fold until Creag a' Bhaca is reached. Here again is a synform, but in this case with a very broad hinge. Both limbs dip toward the axial plane, which strikes east-west and appears to be steeply dipping. That this structure is not a simple synform, but is folding a group of rocks which were already folded is suggested by the complex pattern of foliation strikes near Creag a' Bhaca; by the fact that locally the sedimentary structures face in opposed directions; and by the presence of early minor folds

whose axial planes are folded by the later major structure. Although lack of exposure renders a rigorous defining of the geometry in this area impossible, it is probable that the two synforms just described are one fold, and that it is probably refolding the Creag a' Bhaca Synform, which is of F-2 age (page 150).

Later Structures

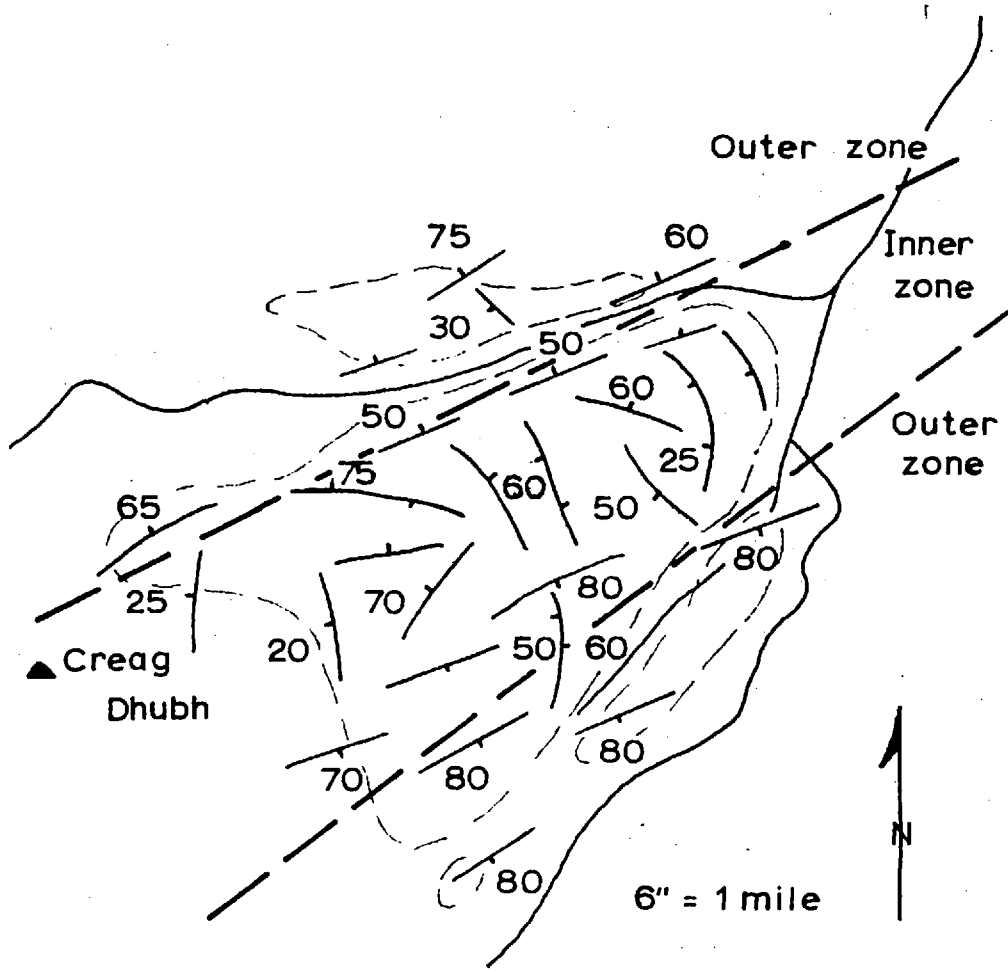
The later structures of sub-area 3 consist predominantly of minor folds of F-4 and F-5 ages, with the possible exception of the major fold described above. Also, in the Creag Dhubh area, an ill-defined major structure, which is discussed below, has been recognised. Near Loch Tuill Bhearnach, a phase of folding between F-4 and F-5 was noted, but it is of restricted occurrence.

The Creag Dhubh Area

Minor folds from four phases of deformation, F-1, F-2, F-4, and F-5, are present in the Creag Dhubh area. This age sequence is based on the mutual interference of these minor folds as seen in the field.

As can be seen from Fig. 32, the foliation is arranged in three zones. In the two outer zones, the foliation strikes are parallel and roughly NE, and their dips are

FIG. 32 Map Showing Generalised Foliation Orientation in the Creag Dhubh Area



Generalised Orientation of Foliation = 50

Generalised Boundary of Exposure = ----

Zone Boundary = — — —

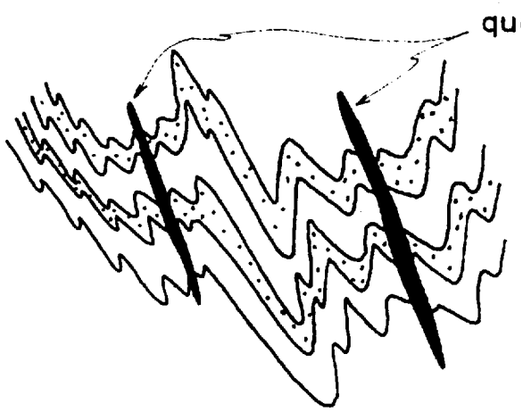
outwards in opposite directions. The strike of the foliation in the inner zone is variable, but tends to be at high angles to the strikes of the outer zones, and the dips are erratic in direction and magnitude. Unfortunately, the rock type in this area is wholly psammite, and the complete lack of marker horizons makes it impossible to deduce the geometry of major structures, because the joining of the foliation strike lines between the individual exposures has infinite possibilities. If minor fold interference reflects the major fold geometry, however, the nature of the major structures in this area is undoubtably complex.

F-4 Minor Structures

Most of the essential characteristics of F-4 minor folds in sub-area 3 have already been described in the sections on early and intermediate structures. A few remaining points are dealt with below.

The style of the F-4 minor folds are reasonably constant. Some examples are illustrated in Fig. 33 and Plates XIc, XIIIc, XVc and XVI. Their pattern is variable, but Z's whose upper hinge closes to the northeast predominate. This implies that the axial planes have a more northerly strike than the general trend of the foliation. It is seen, also, that if one follows the foliation from Glen Strathfarrar

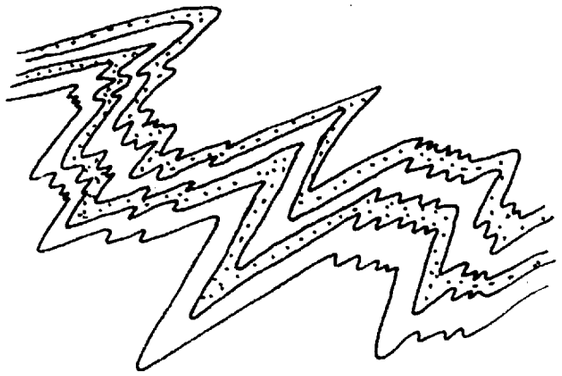
FIG. 33 Styles of F-4 Minor Folds in Sub-area 3 Viewed ca. ⊥ to the Fold Axes



Mullach na Maoile

1" = 3'

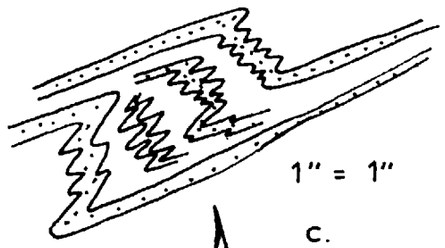
a.



Loch a' Choire Bhig

1" = 1'

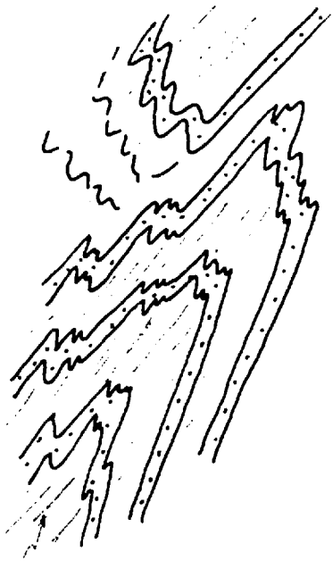
b.



1" = 1"

c.

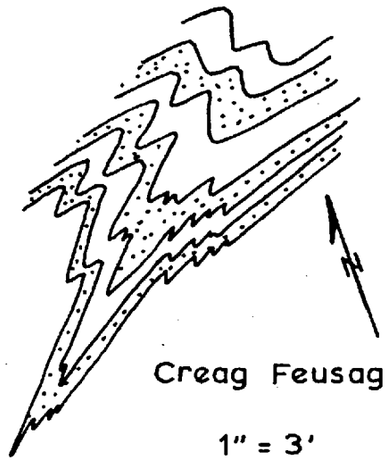
Loch
Tuill
Bhearnach



Creag Feusag

1" = 1'

e.

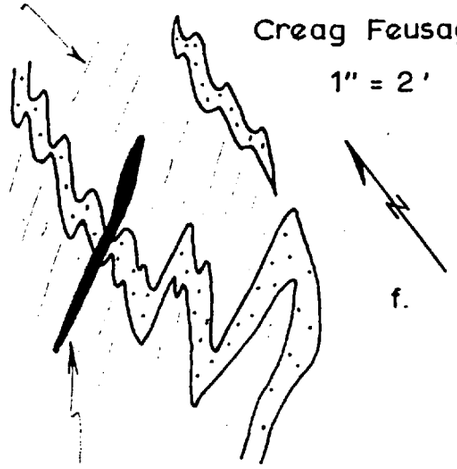


Creag Feusag

1" = 3'

g.

flattened axial plane crumpling



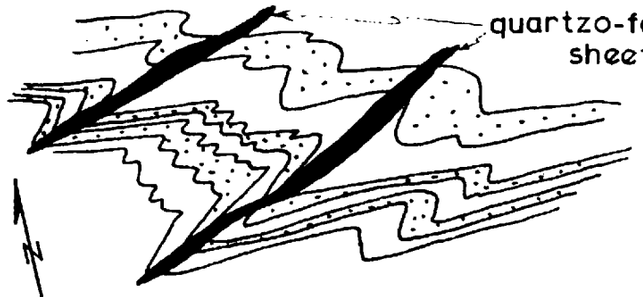
Creag Feusag

1" = 2'

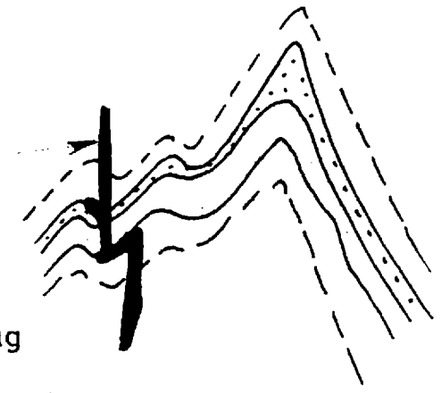
f.

Toll Creagach

1" = 1'



d.

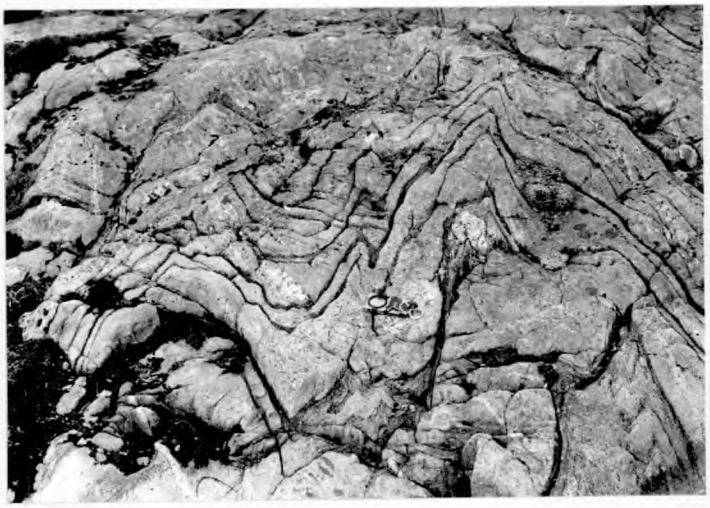


Creag Feusag

1" = 1'

h.

PLATE XVI



a. F-4 minor fold in the Loch a' Choire Bhig area; this fold has "wavy" schistosity.



b. F-4 minor folds on the south side of Loch Mullardoch, near Dam; knife is 4 inches long.

in the north to Sgurr na Lapaich in the west, the strike gradually changes from NNE-SSW to east-west. The axial planes of the F-4 minor folds, which dip steeply, make a similar swing from SW to WSW to west, as do the trends of their axes. There are areas, however, where the axial trend is to the east or NE, but this is a result of local variation in the orientation of pre F-4 foliation.

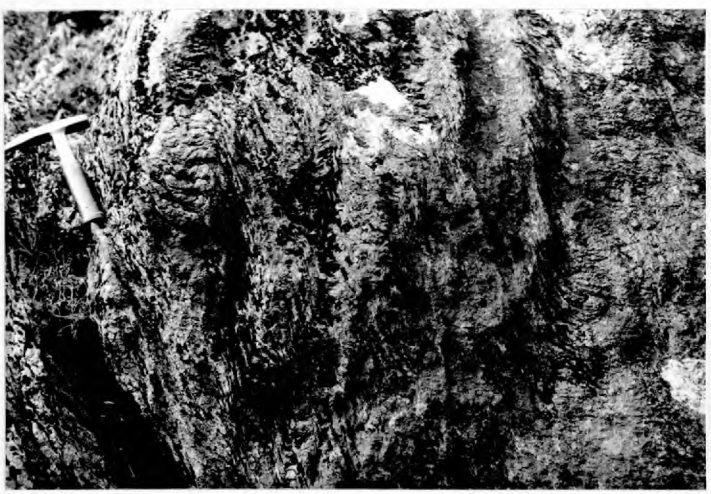
The recrystallization which accompanies the folding increases markedly from southeast to northwest. In the area of Mullardoch Dam, for example, a flattened crumpling typically accompanies the minor folds; whereas in the Creag Dhubh area, the crumpling has developed into an intense schistosity, Plate XVIIa. This axial plane schistosity is commonly "wavy", as if it had been further deformed after the recrystallization of the mica had ceased. Although distinct F-5 crumplings locally refold the schistosity, there are areas where the "wavy" schistosity is unaccompanied by evidence of F-5 movements. Hence, the "waviness" in not considered to be a result of F-5 folding. The problem is discussed in the section on post F-4/pre F-5 structures below.

Another interesting and perhaps significant fact is that while an F-4 axial plane schistosity may develop in the semi-pelite or mica-rich psammite, in adjacent pelites, the F-4 minor folds are accompanied only by a crumpling. This

PLATE XVII



a. F-4 schistosity/foliation relationship in the Creag Dhubh area; foliation is parallel to hammer handle, schistosity parallel to hammer head. Note "waviness" of the schistosity.



b. F-4 schistosity being refolded by pre F-5/ post F-4 minor folds; south of Loch Tuill Bhearnach.

phenomenon can be observed in various localities from Glen Strathfarrar southwards to Meallan Ohdar and Creag Feusag, as well as in the Sgurr na Lapaich - Loch Mullardoch area.

Post F-4/Pre F-5 Structures

South of Loch Tuill Bhearnach, the F-4 cleavage is being refolded by later crumples over a narrow zone (see area 2 of Fig. 28a, and Plate XVIIb). These crumples are everywhere co-axial with F-4 minor folds, and are intimately mixed with them. For example, in some localities within this narrow zone, there is a gradation over a short distance (15') from the typical "wavy" schistosity associated with an F-4 minor fold to later crumples refolding the schistosity. Futhermore, in one exposure it is possible to see that though the pattern of the F-4 fold is a Z, the later crumple is an S, Fig. 34.

The age relationship of the F-5 and post F-4/pre F-5 crumples can be clearly demonstrated in an exposure south of Loch Tuill Bhearnach, where the F-5 crumples can be seen superposed on minor folds which are refolding the F-4 schistosity (Plate XVIIb). The latter minor folds, therefore, are obviously post F-4 and pre F-5. In thin section, Plate XVIIIa, especially in the hinges of the pre F-5 crumples, the following holds true:

1. the micas are bent and show a strained extinction;

FIG. 34 The Relation Between Schistosity and Minor Folds of F-4 and Pre-F-5/Post-F-4 Crumpling Viewed Normal to the Fold Axis

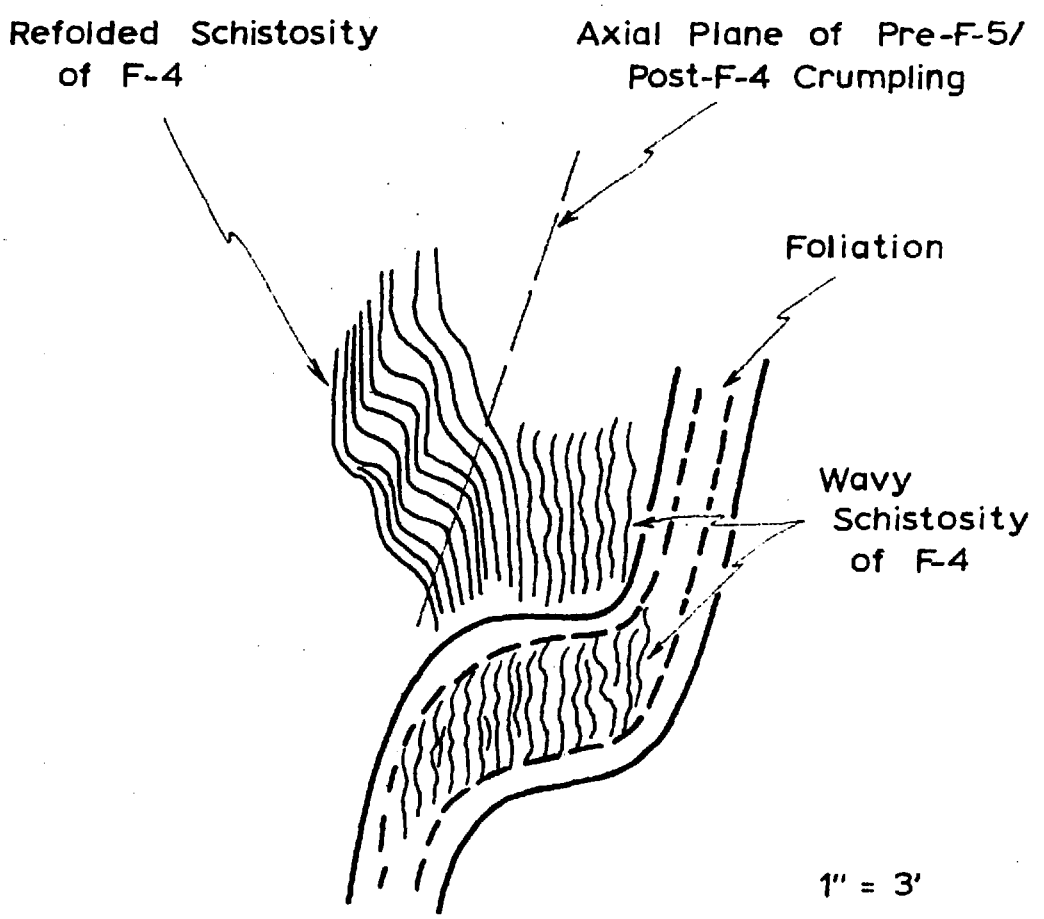
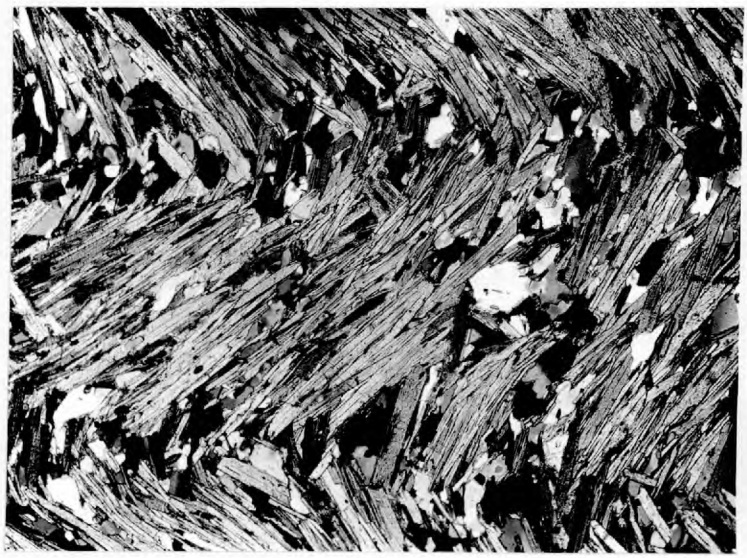


PLATE XVIII



a. Photomicrograph of a pre F-5/post F-4 crumple; mica is muscovite; remainder is quartz. Note strained extinction in both the mica and quartz, and the serrated edges of the quartz crystals. South of Loch Tuill Bhearnach. x 25



b. Photomicrograph of an F-5 crumple. Mica is biotite and muscovite. Note lack of strained extinction in the mica. NW of An Soutar. x 25.

2. the quartz is intensely strained and has serrated edges. It is clear from this evidence that at least the last stages of pre F-5 crumpling are essentially post-metamorphic. The movement apparently did not generate enough energy to effect local recrystallization of the micas (or quartz ?), as it did during F-5 phase of deformation, Plate XVIIIb. In addition, because F-4 and pre F-5 foldings are co-axial and virtually co-planar, it is reasonable to suggest that the post F-4/pre F-5 folding is a last stage activity of F-4. This is most obvious and intense in the zone described above (Fig. 28a area 2), where the axial planes of F-4 and pre F-5 are slightly askew. Hence, we can conclude that a late stage of the F-4 movement was responsible for refolding its own cleavage (c.f. Ramsay 1958a, p.293). More commonly, however, the post F-4/pre F-5 activity did not have sufficient energy to refold the F-4 schistosity, and the pre-existing axial plane of F-4 was utilized to dissipate the energy of the deformation; this resulted in the formation of the "wavy" schistosity which is so typical of F-4 minor folds in sub-area 3.

F-5 Structures

The F-5 movement phase is represented by crumples in the pelites, very gentle folding with crumples in the

semi-pelites, and warpings in the psammite. The general strike of the axial planes is NNE-SSW, and their dips are steep. The trend of F-5 axes is to the southwest at moderate plunges. In the area around Creag Dhubh, Loch Tuill Bhearnach, and Loch a' Choire Bhig, as well as on the north shores of Loch Mullardoch just west of the Dam, the F-5 structures are reasonably well-developed. In other parts of sub-area 3, F-5 is uncommon, although its apparent absence may be in large part because of poor exposure coupled with the presence of massive psammitic rocks which have not responded to the deformation.

STRUCTURAL SYNTHESIS

General

In the preceding pages, the geometry of the individual fold structures from each sub-area has been deduced from the facts gathered in the field, and correlation of the folds in the sub-areas has been kept to a minimum. In this section, an attempt is made to combine some of the observed facts into a coherent picture, and to discuss the more important structural phenomena and their possible implications.

Review of the structural sequence.

The major structures which control the stratigraphy and outcrop pattern of the main lithologic groups of the Glen Cannich area are known to be early in age, and have been classified as F-2, because they can be seen to fold a still earlier group of minor structures, F-1. The F-2 folds include the Glen Cannich Eyed Structure, the Loch Carrie Syncline, and the Benevean, Dog Fall, Beinn a' Chairein, and South Beinn a' Chairein Neutral Folds. One major fold, the Muchrachd Synform, deforms one of the F-2 structures, and is considered to be of F-3 age. The F-4 movement has produced mappable folds of limited extent and many minor structures, which are co-axial with the F-2

minor folds, but cut across F-3. F-5 structures, which vary from a crumpling to minor folding is widespread over the whole area, and affects all the previous structures.

For purposes of discussion the Area as a whole has been divided into two halves, the eastern and western.

The Structural Pattern of Early Folds in the Eastern Half of the Area.

The eastern half of the area embraces sub-area 1 and the eastern half of sub-area 2, Fig. 35. The general structure is characterized by the complex outcrop pattern of the An Soutar Pelitic Group (see Stratigraphic Map, p.251). This pattern, as will be shown below, is the result of the interference of F-1 and F-2 folds on a major scale. A brief review of the evidence for F-1 folding is presented first.

F-1 Folding

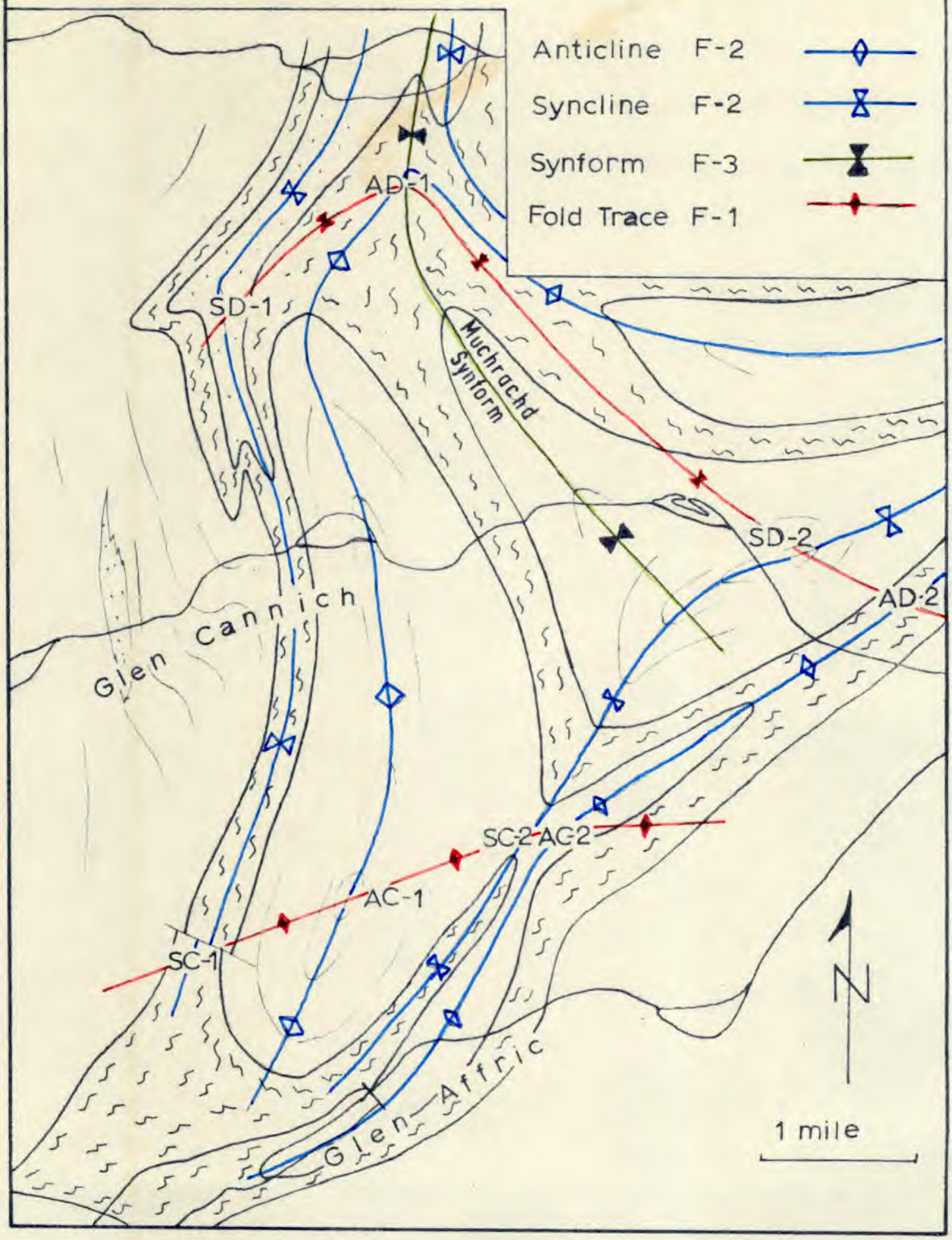
There are a number of localities where F-2 structures are seen refolding earlier folds and deforming lineations. The latter structures are classed as F-1, and consist of isoclinal minor folds, quartzo-feldspathic rodding and striping. These structures may be found in the following localities:

1. In the hinges of the Beinn a' Chairein, Glen Cannich, and Creag a' Bhaca major F-2 folds, where isoclinal minor folds are seen to be refolded by the major F-2 structures;

FIG. 35 Sketch Map of Eastern Half of Area

SD = Synclinal Depression AD = Anticlinal Depression

SC = Synclinal Culmination AC = Anticlinal Culmination



2. At Mullardoch Dam, where undoubted F-2 minor folds are refolding a quartzo-feldspathic lineation;

3. The north shore of Loch Mullardoch, where F-2 minor folds are refolding isoclinal minor folds;

4. East of Beinn a' Chairein near River Cannich, where F-2 minor folds are refolding isoclinal minor folds;

5. Creag Dhubh, where pre F-4 minor folds, which are most probably F-2 age, are refolding isoclinal minor folds.

It is seen, therefore, that F-1 folding is represented in the sub-areas only as minor structures, and the reason for the apparent absence of F-1 major structures is explained below.

The Interference Pattern of F-1/F-2 Foldings.

The interference of F-1 and F-2 folds on a major scale has produced a series of basins and domes, as outlined by the An Soutar Pelite. Subsequent deformation has modified the already complex three-dimensional form, however, so that its pre F-3 geometry is not immediately apparent. In Fig. 36a and 36b, an idealized case of dome-basin formation developed by refolding of an earlier set of folds is presented to clarify the sequence of events involved.

Several authors, for example de Sitter (1956, p.314 - 322), Weiss (1959), Carey (1962, p.99-115) and O'Driscoll (1962a, 1962b), have discussed the patterns which result from the superposition of two phases of (similar) folding;

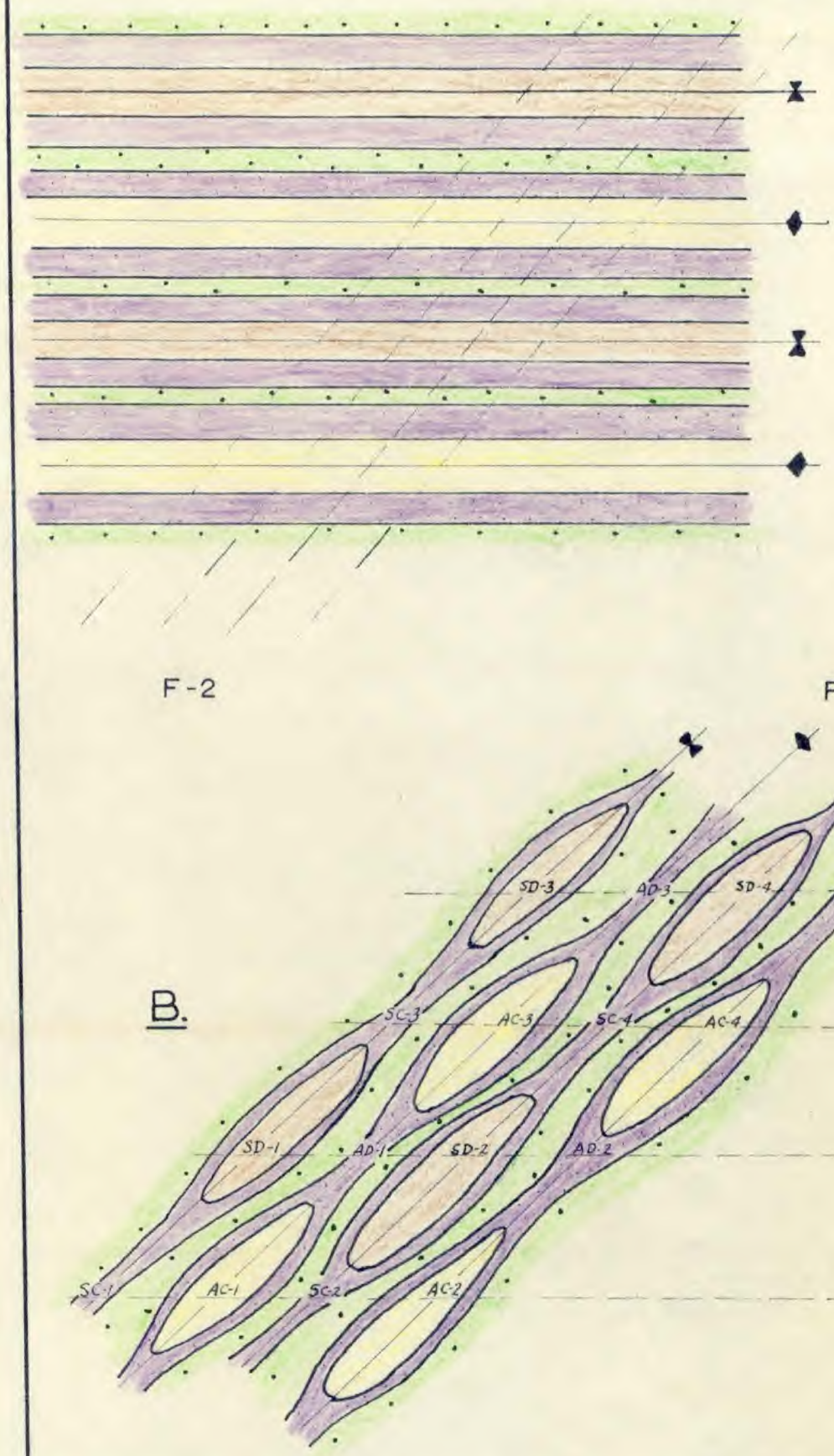


FIG. 36 Idealized Diagram

Illustrating Dome-Basin Formation with Subsequent Deformation

SC = Culmination of Synclinal Axes

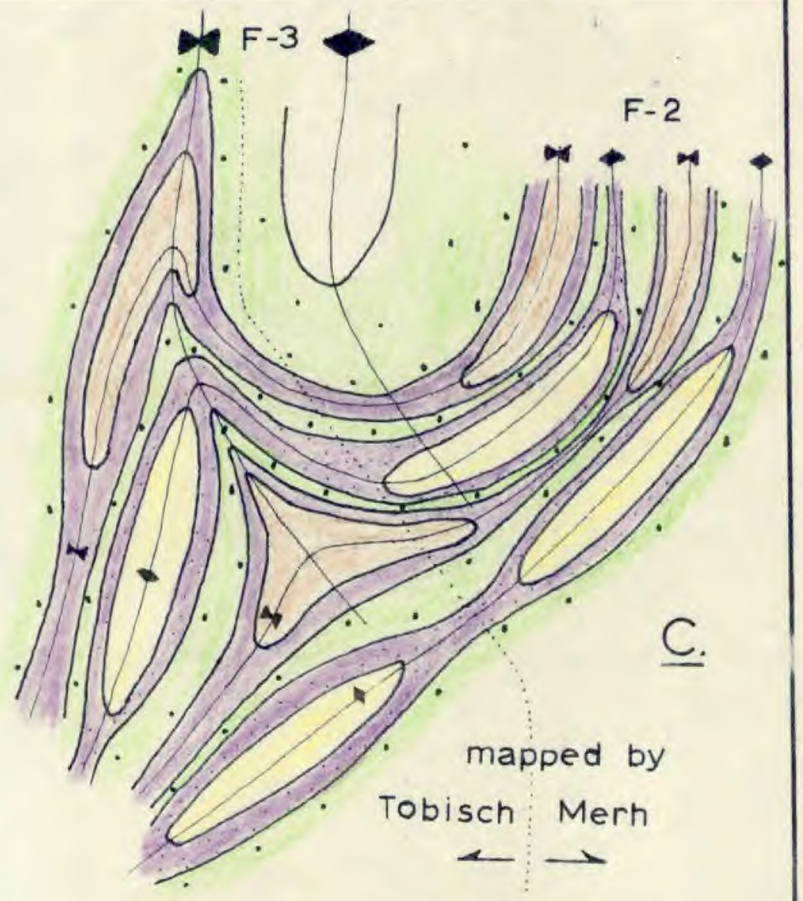
SD = Depression " " "

AC = Culmination of Anticlinal Axes

AD = Depression " " "

Antiform

Synform



and Ramsay (1962b, p.467 - 473) has outlined the three fundamental types of interference patterns and the geometrical conditions which must obtain during their formation. The idealized case represented in Fig. 36 b, is Type 1 of Ramsay (loc. cit.) "where the 'a' direction of the second folds lies close to the axial plane of the first folds". Whether the domes and basins produced in this type of interference are round, oblong, or elliptical (etc.) depends on a number of factors (c.f. Ramsay, ibid; Carey,ibid). If, for example, the wave lengths and amplitudes of the interfering folds are equal, and their axial planes are mutually perpendicular, the resulting domes and basins will have equal dimensions in both fold directions. If, however, the amplitude of the second folds is greater than the amplitude of the first folds, given equal wave lengths, the resulting domes and basins will be elongated in the direction of the second folds. Or if the folds of both phases had equal wave lengths and amplitudes, but there was a large component of flattening parallel to the axial plane of the second folds, the domes and basins would also tend to be elongated in the direction of the second folds. A pattern such as shown in Figs. 36 b could be produced by the resulting fold interference as illustrated in the last two instances cited above. As can be seen from the figure, the first set of

folds can only be inferred from the pattern of the domes and basins, and the precise geometry of any given F-1 major fold is obscurred because of the pronounced elongation in the direction of the F-2 structures. Furthermore, the facing direction of sedimentary structures in the Type 1 interference pattern of Fig. 36 b, would conform entirely to the seond structures, leaving no trace of a previous folding history. The last two points, it should be remembered, are directly applicable to the Glen Cannich structures.

Now if, for example, a subsequent deformation (F-3) were superposed on the interference pattern shown in Fig. 36b, the result could be as pictured in Fig. 36c. In a <u>very qualitative</u> way, then, one can apply the idealized interference pattern shown in Fig. 36b to what probably was the initial interference pattern resulting from F-1/F-2 interference **in Glen Cannich;** and that shown in Fig. 36c, to represent the subsequent deformation of F-1/F-2 by the Muchrachd Synform (F-3). Fig. 35 shows the possible positions of the culminations and depressions of the antiformal and synformal axes of the folds in the Glen Cannich region, so that they may be related to the more simplified and idealized pattern represented in Fig. 36c. It should be noted that in Fig. 35, the indicated positions of: AC-1, SC-2, and SD-2 are reasonably accurate; those of SC-1 and AC-2 are

probable; and those of AD-1, AD-2, and SD-1 are possible. Though the possibility of a large error in placing some of these positions is fully realized, I have suggested in Fig.35 possible traces of the F-1 folds by joining up the depressions and culminations of the F-1/F-2 structures; the orientation of the resulting F-1 traces, however, is meant to be a qualitative estimation.

The position of the F-3 synform in Fig. 35 roughly coincides with the depressions in the axes of the Glen Cannich and Beinn a' Chairein folds, and one is at first sight tempted to assign the formation of the basins and domes to an F-3/F-2 rather than an F-1/F-2 interference. On closer examination, however, it is seen that the position of the F-3 synform is not genetically related to the basin and dome formation. Some of the evidence is as follows:

1. the F-3 synform ends at Beinn a' Chairein, yet the Glen Cannich 'eye' continues for 3 miles further to the south from this latitude;
2. the direction of closure of the Beinn a' Chairein fold (F-2) does not change as it crosses the axial plane trace of the F-3 synform, which it should do if the later fold had been responsible for the production of the basin.

It is obvious from the information presented in the sections on sub-area 1, 2, and 3, that the basin and dome

structures in the Glen Cannich area do not fit into an ideal model, such as represented in Fig. 36. The linear elements associated with them, for example, do not plunge away and toward each other in the domes and basins respectively, but plunge essentially parallel to each other. The domes and basins, therefore, must be visualized as being very acute cones whose apical lines are inclined to the horizontal (see Fig. 8). It has not been possible to determine whether the acute cones were originally formed as such during superposition of the two phases (F-1/F-2), or whether a more gentle dome and basin pattern was first formed, and then was later distorted to its present geometry by subsequent folding.

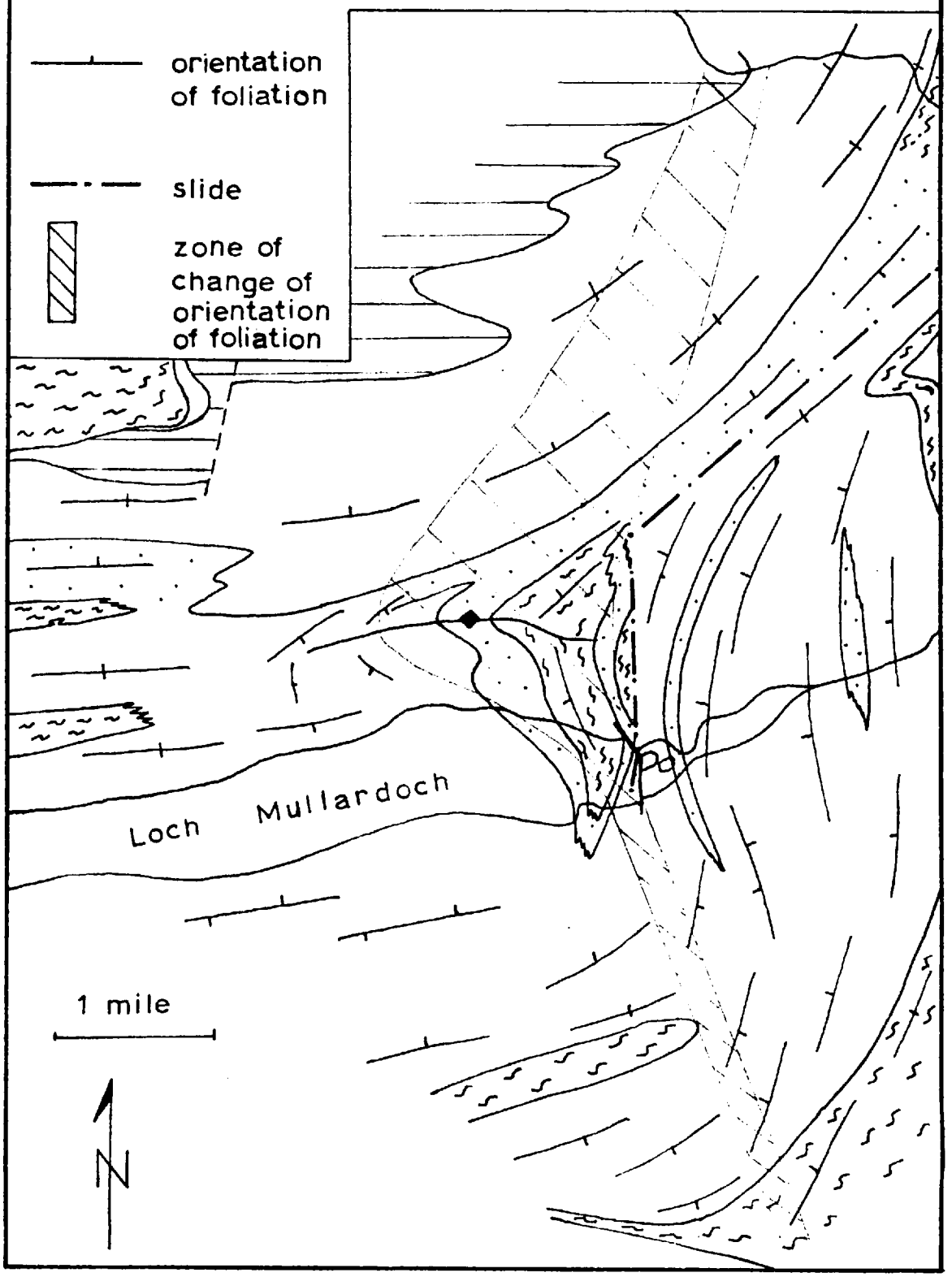
Some Aspects of pre F-4 Structures in the Western Half of the Area.

The western half of the area consists of sub-area 3 plus the western half of sub-area 2, Fig. 37.

F-1/F-2 Interference Pattern

It was shown in the section on sub-area 3, that the Mullardoch 'Eyed' Structure is an acute dome that has resulted from the interference of F-1 and F-2 major folds (page). The geometrical conditions which controlled its formation were probably very similar to those described above (i.e. Type 1 of Ramsay, 1962b). Why the dome should be isolated

FIG. 37 Sketch Map of Western Half of Area



instead of being one of a series of domes and basins, as in the eastern part of the area, is not entirely clear. Its isolation from the domes and basins to the east might be accounted for by the presence of the slide immediately to the east of the Mullardoch Dome. Similar structures to the west of that structure might exist, but poor exposure and a lack of reliable marker horizons make their presence uncertain.

The Major Change in Foliation Strike

One important structural phenomenon in the area shown in Fig. 37 is the sharp bend in the trend of the foliation strike. A zone has been drawn which approximately divides the area shown in the figure into two parts: to the west of it, the strike is east-west; and to the east it is north-south.

In the northern part of the figure the change in strike of the foliation is gradual, and appears to be the expression in this Area of the southern limb of the Loch Monar Synform (Ramsay 1958a). In the central part of the figure, to the east of Creag Feusag, the foliation is north-south; but on the western side of the slide (see page136), the strike of the foliation changes, indicating the influence of the Creag Feusag Antiform. This continues towards the west until that fold dies out, and thence the foliation strike is east-west. In the southern part of the figure, a similar deflection of

strike occurs, but here it is confined to a relatively narrow zone.

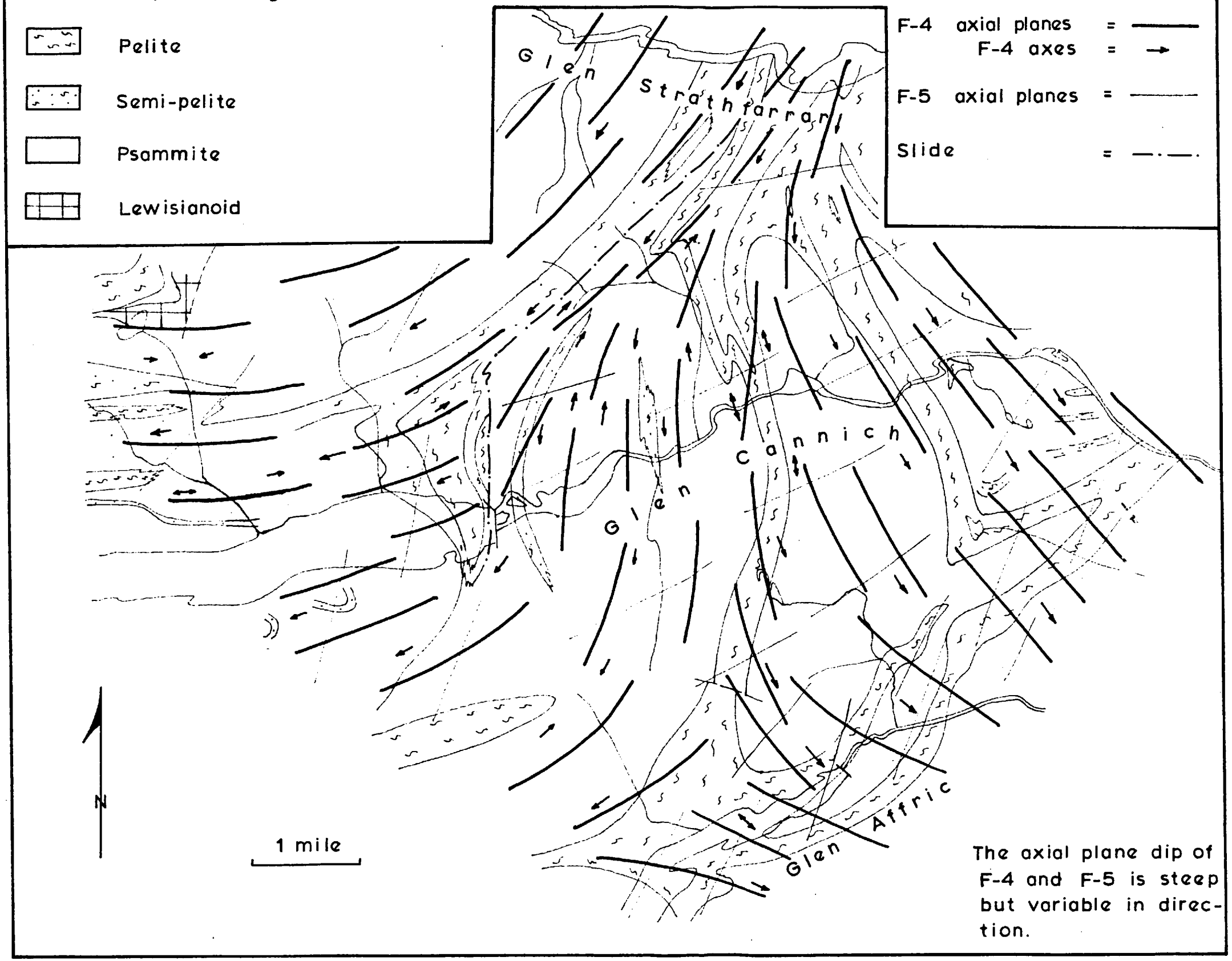
It is reasonable to assume that this bend in the foliation occurred simultaneously throughout the area. As the bend in the northwest is probably the expression of the Loch Monar Synform, so it is possible that the Creag Feusag Antiform formed in response to the same forces, and the slide east of Creag Feusag acted as a steeply dipping plane of décollment.

Trends of F-4 Minor Folds

In the sections on the individual sub-areas, it was noted that the trend of axes and of axial plane strikes of F-4 minor folds varied systematically. These trends for the entire Area are plotted in Fig. 38. It can be seen that the trend of the F-4 minor folds changes from roughly NNE near Glen Strathfarrar in the north to E-W in the western and southwestern regions and to NW-SE in the southeastern regions of the map.

Ramsay (1958a, p. 292-293) and Fleuty (1961, p.465-468) have reported systematic variations in the axial plane orientation of their later structures which are comparable to folds of F-4 age in this area. Both authors were able to relate this variation to the presence of earlier major folds. They suggested that a tightening up of the earlier folds during

FIG. 38 Map Showing Generalized Strikes of Axial Planes of F-4 and F-5 Minor Folds



The axial plane dip of F-4 and F-5 is steep but variable in direction.

the later movements were responsible for the present variations in orientation of the later axial planes. In the Glen Cannich area, however, the variations of F-4 axial plane orientation do not appear to be directly related to the presence of individual early folds.

Unfortunately, there is some disagreement among various workers as to the significance of the axial plane of a fold in its relation to the principle axes of the deformation ellipsoid. Flinn (1962, p.425), for example, maintains that the axial plane does not "bear any special relation to the axes of the deformation ellipsoid" (see also Ramberg, 1959). Most other workers, however, assume that the axial plane of a fold (other than those of a conjugate fold) is the plane containing the major and intermediate axes of the deformation ellipsoid (the ZY-plane), which is normal to the direction of maximum shortening (X). Experimental work on folding has shown that this assumption is generally valid for the folds produced in the laboratory (c.f. McBirney and Best, 1961; Patterson and Weiss, 1962). If the latter assumption is applied to the F-4 minor folds in the Glen Cannich region, it is obvious from Fig. 38 that the axes of the deformation ellipsoid of the F-4 folding must have systematically changed their orientations in space from one part of the area to the other. This might be interpreted

in the light of Flinn's (op.cit., p.427) comment: "Inhomogeneity ... tends to simplify structure by rotating the stress axes, and hence the deformation ellipsoid, into a more symmetrical position relative to the layering and other structures already present". It is possible, therefore, that the overall stress applied to the rocks of the area during F-4 was "distributed", so to speak, to facilitate the easiest "path" for the release of the energy involved. More specifically, the axes of the stress and resulting strain ellipsoids at any given locality have different orientations as a result of accommodating to the local inhomogeneities already present in the rock. In this manner, despite their swing of strike, the axial planes of F-4 folds could still have been formed in coincidence with the ZY plane of the local deformation ellipsoid (i.e. normal to the direction of maximum shortening), which is in keeping with the experimental work mentioned above. This would, however, require a large variation in the axial orientation of the deformation ellipsoid from one part of the area to another; but because the inhomogeneity of the pre F-4 geometry is so pronounced, such a large variation may be reasonable.

Observations on Interfering Phases Worthy of Note.

F-4/F-2

One of the most noteworthy characteristics of F-4/F-2 interference on a minor scale is that in practically every instance of refolding, the two phases are co-axial. Mukherjee (personal communication) and Merh (1960) report a similar phenomenon. The significance of this phenomenon is not known at present. Where minor folds of the two phases interfere, however, it seems apparent that the axis of the early fold in some way controls the axis of the later fold.

F-5/F-4

In contrast to the parallelism of axes of F-4 and F-2 folds interference, minor folds of F-5 always have differently oriented axes relative to the pre-existing structures. Of further interest is the fact that the trend in axial plane strike of F-5 minor folds tends to be at a high angle to the trend in axial plane strike of F-4. The variations in strike of F-5 frequently accompany variations in strike of F-4 axial planes, such that the axial planes tend to remain at a high angle, Fig. 38. It was noted, however, that locally in individual exposures, the angles betweenthe axial planes of F-4 and F-5 were not invariably as large as might be suggested by the simplified trend map (Fig. 30).

MECHANISMS OF FOLDING

The Geometry of F-4 Minor Folds

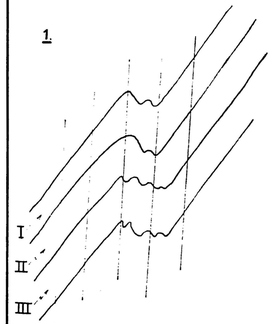
A study of the F-4 minor folds has been carried out because these structures are widespread throughout the area and because they, unlike the earlier folds, can be seen in an essentially undeformed state. This geometrical analysis has been made by measuring the thicknesses of individual bands around the fold normal to the foliation and parallel to their axial planes. Ramsay (1962a) has summarized the principles that apply in determining the geometry: i.e., whether a fold is of concentric or similar type. In brief, these principles are as follows: the bands forming a concentric or parallel fold will be of equal thickness around the fold when measured normal to the banding, or will show a decrease in thickness at the hinge of the fold when measured parallel to its axial plane. The bands forming a similar type fold will be of constant thickness when measured parallel to the axial plane of the fold, or will show an increase in thickness at the hinge if measured normal to the bands. Ramsay (ibid) also suggests mechanisms by which such folds may have been formed, as deduced from their geometry. The brief study presented here should not be considered as a rigorous application of the methods outlined by Ramsay.

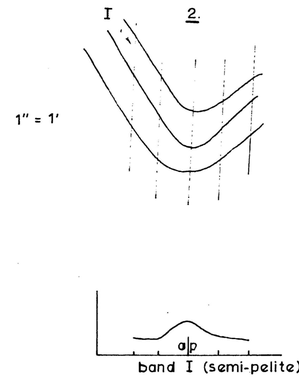
Minor folds at seven localities which are scattered throughout the area (see Fig. 3) were selected for investigation, and at these points the following conditions hold true: the minor folds were known to be of F-4 age; the three-dimensional geometry of each minor fold could either be directly or indirectly determined; and the thicknesses of the bands of the minor folds could be measured in a plane that was known to be essentially normal to the axis. At each locality in the field, the fold to be measured was sketched as accurately as possible, and then the thickness of one or more bands was measured parallel to the axial plane of the fold, Fig. 39. In one fold (no. 4), however, the measurements were made normal to the foliation to ensure a maximum accuracy, since the shape of the fold rendered measurements parallel to its axial plane difficult. It should be noted that the sketches of the folds shown in Fig. 39 are primarily intended to show the appearance of the fold and the locality of each measurement relative to the fold. The variations in thickness of any one band as shown on the graphs may not always be readily apparent from the sketch.

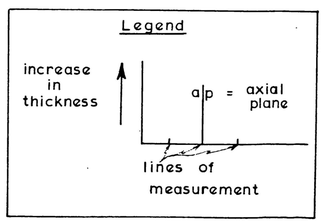
The thicknesses of different bands have been plotted on rectangular coordinates; the abscissae represent individual lines of measurement, the ordinates give the actual thicknesses measured. From these plottings, the geometry of each

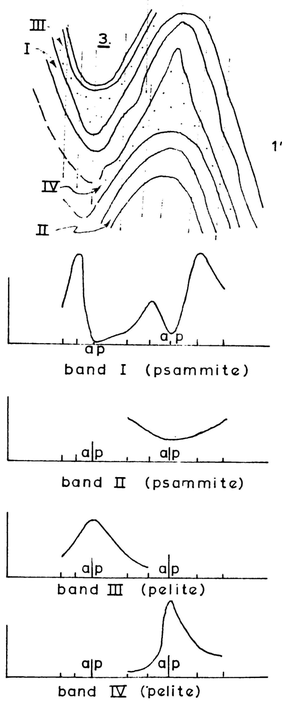
FIG. 39 Sketches of F-4 Minor Folds Showing Style, Lines of Measurement Relative to Fold, and Thicknesses of Individual Bands as Shown on Graphs; All Measurements Except 4. Made Parallel to the Axial Planes of the Folds

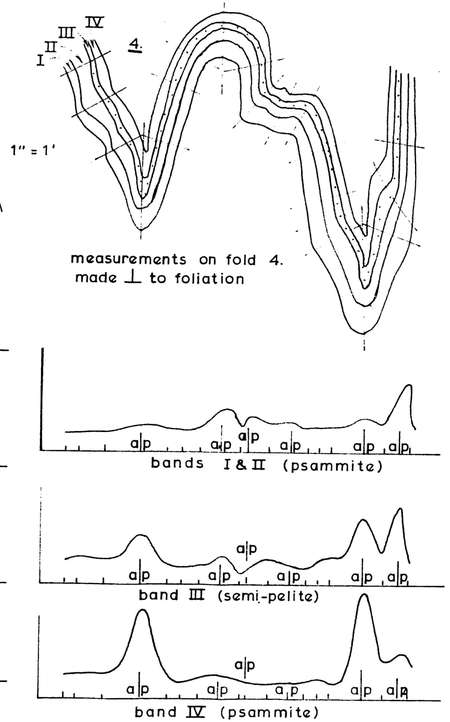
F-2 Minor Fold

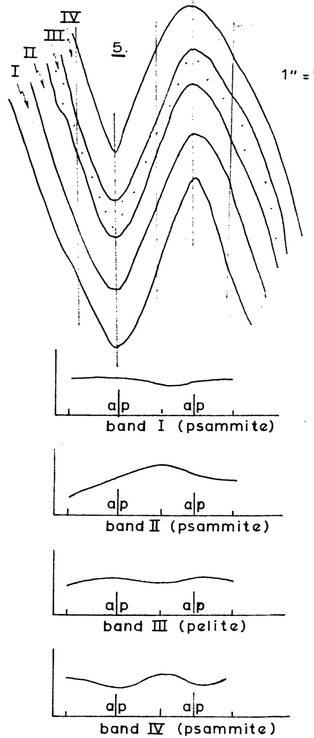


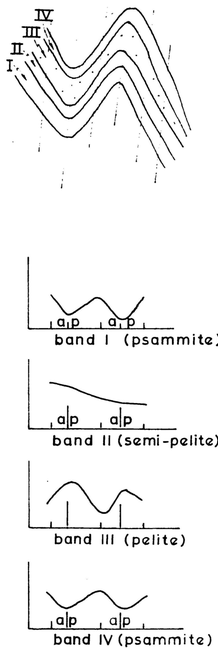


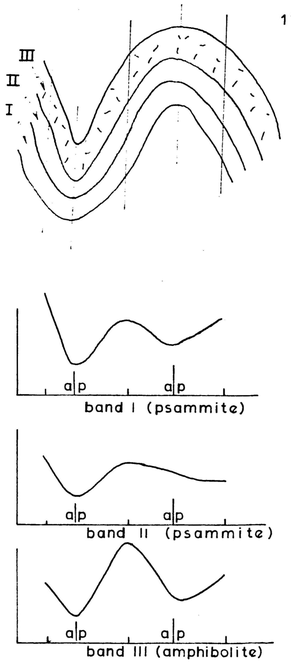


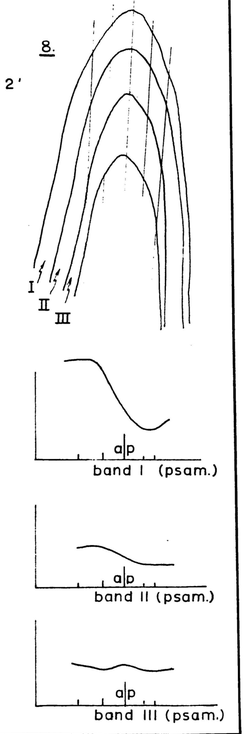












fold was determined, and the structure classified as concentric, similar type, or a modification of one or both:

Fold 1.
Similar type: variation in thickness of band II is probably original.

Fold 2.
Concentric: as shown by band II (psammite).

Similar type: somewhat modified, as shown by band I (semi-pelite).

Fold 3.
Concentric: as shown by bands I and II (psammite) with some original variation.

Similar type: greatly modified by flattening, as shown by bands III and IV (pelite).

Fold 4.
Concentric: with modifications by flattening.

Fold 5.
Similar type: with some concentric component, as shown by band IV.

Fold 6.
Concentric: shown by bands I and IV (psammite).

Similar type: band II (semi-pelite) with an original variation; band III (pelite) modified by flattening.

Fold 7.
Concentric.

Except for examples 1 and 5, which come from near the northwestern boundary of the area, all the folds defined by

the competent bands (psammitic) have a concentric geometry. The less competent bands (semi-pelitic and pelitic), however, show a geometry which is more like that described as "similar". Both concentric and similar type geometries have been modified to varying extents by flattening, by which the limbs, especially in the immediate vicinity of the hinge zone, have been squeezed together. In folds 1 and 5, the basic geometry is a similar type. In fact, most of the F-4 minor folds observed in the northwestern quarter of the area resemble the similar type geometry of specimens 1 and 5. These folds are accompanied by an axial plane schistosity; in the other folds cited above, the axial plane structure is one of crumpling of the micas.

Mukherjee (personal communication), who has mapped the area immediately to the north of my ground, has made accurate measurements on a number of minor folds of the same age as F-4 structures by the methods suggested by Ramsay (1962a). In all his folds, the axial plane structure is a crumpling, which in some examples is remarkably flattened. Many of the minor folds measured by Mukherjee consist of thinly-banded semi-pelite, which have essentially the same competency when considered in units of, for example, 6 inches or 1 foot. Yet some of the minor folds in this lithology have a concentric geometry, and others sometimes within a few feet

of the former, have a similar type geometry. Furthermore, he has found that within some folds, a unit of thinly-banded semi-pelite might have a similar type geometry, yet one band of psammite from that unit has a concentric geometry. It seems, therefore, that the transition from concentric to similar type geometry of these minor folds in the two areas is not a sharp one.

The following deductions can now be made:

1. In the southwestern three-quarters of the area, the mechanism of folding of the F-4 minor folds was dominantly a combination of flexure and flattening, with a component of simple shear obtaining in the pelite bands; the simple shear component parallel to the axial planes, however, did not penetrate into the competent (psammitic) bands.

2. In the northwestern quarter of the area, the F-4 minor folds were probably initiated by the same mechanisms as described above (1), but as recrystallization intensified, and the rocks became more plastic, pure and simple shear components entered into the folding, becoming increasingly more penetrative, until they became important mechanisms in the formation of the folds.

The Geometry of F-2 Minor Folds

Measurements of the thicknesses of individual strata have been made in one F-2 minor fold. The methods and conditions for measuring the thicknesses were the same as those used for the measurement of F-4 minor folds.

The geometry of this fold is essentially of similar type, as can be seen from Fig. 39. Band I, however, shows a variation in thickness across the fold which may be original.

Mukherjee (ibid) has made accurate measurements on 18 of his F-1 (equivalent to F-2 folds in the Glen Cannich Area) minor folds from his ground. He has found that though four of the minor folds show an almost perfect similar type geometry, individual bands in the other 14 folds show concentric characteristics which have been greatly modified by other processes, especially flattening.

Because later deformation has undoubtably altered the original F-2 minor fold geometry, it is not possible to deduce the mechanism of F-2 folding from the information available.

BRITTLE STRUCTURES

Faults

As mentioned in the Introduction, a major fault is considered to lie in Strath Glas (Hinxman 1901, p.102), which forms a part of the southeast boundary of the area. Apart from this structure, there is little evidence of faulting on a major scale within the area. There are, however, numerous prominent topographical features indicating planes of weakness in the rocks, along which movement may or may not have taken place. These features usually appear on the hill-sides as deep, narrow gullies, which trend roughly east-west or north-south, the former being more common. The gullies are usually occupied by streams; but in other localities, planes of weakness are indicated by slumping and breaking away of large blocks of rock from otherwise stable slopes.

In most occurrences, the planes of weakness are not accompanied by fractured or brecciated rock, slickensides, gouge, or other evidence for movement on the plane. One exception to this is in Allt Coire Eoghainn (northwest of Mullardoch Dam), where slickensides, fractured rock, and some gouge in one locality have been observed in the stream bed. The comparison of the rocks on either side of the fault does not indicate a horizontal displacement, but suggests that if

there was movement on the plane, either the vertical component was predominant, or the amount of movement was negligible.

A fault probably cuts off the end of the Lewisianoid outcrop in the region of Loch Tuill Bhearnach. This is suggested by the fact that many exposures of psammite west of the fault line contain Lewisianoid rock types, whereas the exposures of psammite east of it do not. Since the exposure is poor in this area, and some exposures west of the line do not contain Lewisianoid rock types, the presence of a fault here has to be based on circumstantial evidence.

Just north and northeast of Meallan na Ceardaich in Glen Affric, a fault is indicated by the apparent offsetting of the pelite. Although exposure is poor, gullies line up with the apparent offset. Furthermore, the topographical features continue into Glen Cannich, where information from a tunnel (Hydroelectric Board of Scotland) shows a 100 foot wide zone of broken and slickensided rock exactly in line with them. The sense of displacement along the fault plane is dextral, and the probable magnitude of the horizontal component is a few hundred feet.

Joints.

Generally speaking, the rocks in the Glen Cannich - Glen Affric area are well-jointed, especially the psammitic

rocks. In some localities, e.g. Fraoch-Choire (southwest of Mullardoch Dam), jointing is intensely developed in at least two, if not three or more directions. However, the main objective in the field study was to gain an understanding of the geometry of the folding, and the joint patterns were not seriously investigated.

CHAPTER 4

METAMORPHISM

General

The maximum grade of metamorphism reached during the main progressive metamorphism was effective throughout the entire Glen Cannich - Glen Affric Area. This was followed by retrogressive metamorphism, and the mineral assemblages of some rocks show a lower grade than that which generally holds for the area as a whole. In the pages which follow, the grade of metamorphism attained during the main progressive metamorphism is first discussed, and the typical mineral assemblages from the Moinian rocks are listed. Local variations and their possible significance are then considered. The mineral assemblages of the Lewisianoid rocks are discussed in a later section.

Mineral Assemblages of the Moine Rocks

The mineral assemblages listed below are typical of their respective rock types:

Psammite

(1) Quartz-oligoclase/andesine-K feldspar-(biotite-muscovite±epidote±garnet).

Semi-pelite

(2) Quartz-oligoclase/andesine-K feldspar-biotite-muscovite-(garnet).

(3) Quartz-oligoclase/andesine-biotite-muscovite-garnet.

(4) Quartz-oligoclase/andesine-biotite-muscovite-garnet (kyanite)

Pelite

(5) Quartz-oligoclase/andesine-biotite-muscovite-garnet (tourmaline)

(6) Quartz-oligoclase/andesine-biotite-muscovite-garnet (kyanite±tourmaline).

Amphibolite

(7) Hornblende-andesine/labradorite-quartz-zoisite-(biotite).

(8) Hornblende-andesine/labradorite-quartz-garnet-biotite.

(8) Hornblende-andesine/labradorite-(biotite-clinozoisite).

Calc-silicates

(10) Quartz-andesine-hornblende-biotite-epidote+zoisite-garnet-(sphene-clinozoisite).

(11) Quartz-andesine-hornblende-biotite-epidote-K feldspar-(sphene-clinozoisite).

(12) Quartz-andesine-hornblende-epidote+clinozoisite-garnet-(sphene).

(13) Quartz-anorthite-diopsidic pyroxene-garnet-(amphibole-clinozoisite-calcite).

Pyroxene-Albite Rocks

(14) Quartz-Sodic diposide-albite-amphibole-epidote-(sphene).

Grade of the Main Progressive Metamorphism

The mineral assemblages in the psammite, semi-pelite pelite, and amphibolite indicate that the maximum temperature-pressure conditions reached during the main progressive metamorphism correspond to those of the Kyanite-Almandine-Muscovite Subfacies of the Almandine Amphibolite Facies (Turner and Verhoogen, 1960). This is equivalent to the kyanite zone in the Barrovian sequence of progressive metamorphism (Barrow, 1893).

Many of the assemblages listed above are also stable in other subfacies of the Almandine Amphibolite Facies (Turner and Verhoogen, op.cit. p.545-550). Furthermore, it has been pointed out by the above authors (loc. cit.) that kyanite is stable in the Staurolite-Almandine Subfacies in rocks rich in Al_2O_3 and low in alkalis. Since kyanite in the Glen Cannich rocks occurs only in knots, one is tempted to suspect that the knots may in fact be rich in Al_2O_3 and low in alkalis. If this were so, the presence of kyanite in the knots would not be diagnostic of the Kyanite-Almandine-

Muscovite Subfacies for the surrounding rocks. However, the mineralogy of the knots is essentially muscovite-(kyanite-quartz-feldspar). The bulk chemical composition of this assemblage is not only high in Al_2O_3, but is also high in alkalis; hence the special composition conditions stated above are not applicable to the rocks in question. The appearance of kyanite in the knots, therefore, is indicative of physical conditions obtaining in the Kyanite-Almandine-Muscovite Subfacies, and assemblages (4) and (6) may be considered diagnostic.

Kennedy (1949) has outlined the mineralogical changes that may take place in calc-silicate granulites with an increase in temperature. He equates those changes in the calc-silicates with comparable changes in pelitic schists, such that his (a) zoisite-biotite, (b) zoisite, (c) anorthite-hornblende, and (d) anorthite-pyroxene zones correspond to the (a and b) garnet, (c) kyanite, and (d) sillimanite zones originally proposed by Barrow (1893; 1912). Assuming that those correlations suggested by Kennedy are correct, the mineral assemblages of the calc-silicates listed on page [illegible] suggest a variance in the metamorphic grade. Assemblages (10) and (11), which are of widespread occurrence, suggest a middle garnet-zone grade; assemblage (12), which is found in Glen Affric, suggests and upper garnet-zone grade; and

assemblage (13), which is found near Loch a' Choire Bhig, suggests a sillimanite-zone grade (for sample distribution, see Fig. 3).

It seems possible, therefore, that the calc-silicates may be more sensitive to temperature-pressure changes than the other rock types. Whereas the other types generally retain the mineralogy of the highest metamorphic grade attained the calc-silicates only show relics of this grade (assemblage (13)), and have adjusted themselves to conditions which prevailed at a later stage in the metamorphism, as shown by assemblages (12), (11), and (10). It is suggested, therefore, that assemblage (13) represents an approximation to the original mineralogy of the calc-silicates (i.e. pre-retrogression), and that this assemblage is roughly in accord with the metamorphic grade as indicated by the psammite, semipelite, pelitic, and amphibolitic rocks.

Pyroxene-Albite Rocks

The genesis of the pyroxene-albite rocks in Glen Cannich is not altogether clear. Rock and mineral textures in field exposures and in thin-section suggest that metasomatic processes may have been active. Also, because the ferromagnesian minerals in at least one locality are oriented parallel to the local F-2 lineation, these

minerals appear to have crystallized during the main progressive metamorphism associated with F-2 folding. Yet the albite, which is unaltered, appears to be in stable co-existence with epidote, and even calcite! The pair albite-epidote appears to contradict the grade of metamorphism as shown by the mineral assemblages in the majority of the rocks throughout the Glen Cannich area (see page 222). It seems more probable, therefore, that though these rocks formed during the main progressive metamorphism co-eval with F-2 folding, compositional conditions obtaining in their immediate area were very different from those prevalent in the surrounding rocks; i.e. there must have been a <u>local</u> permeation by solutions rich in Na_2O in the ground where the pyroxene-albite rocks are found. The mineral assemblage (14) which formed, therefore, was largely controlled by the bulk composition of the rock plus the presence of permeating solutions. Since the present composition of the rock as suggested by the assemblage (14) represents an atypical rock-type relative to those outlined by Turner and Verhoogen (1960) and Kennedy (1949) for the determination of physical conditions during metamorphism, the assemblage cannot be used to determine the metamorphic grade of the surrounding rocks.

Retrogressive Metamorphism

Evidence for a retrogressive metamorphism, which followed the main progressive metamorphism, is found in most parts of the area. The retrogression is shown by the following mineralogical changes:

In pelitic and semi-pelitic rocks:

(1) Kyanite → sericite/muscovite.

This is a very common change observed in rocks from all parts of the area. It is commonly expressed by knots or segregations of sericite/muscovite which, in a limited number of instances, include crystals of kyanite. More commonly, however, all the kyanite appears to have altered to the mica.

(2) biotite → chlorite.

A rare transition. Biotite is nearly always free of alteration.

(3) garnet → biotite.

A very rare transition. Of the 153 thin-sections examined, the garnet is fresh in all but a few.

In calc-silicate granulites:

(1) diopsidic pyroxene → hornblende

(2) anorthite (An_{92}) → andesine (An_{40})

Pyroxene and anorthite have only been observed in one

thin-section. In the others cut from calc-silicate granulites, these two minerals appear to have been converted entirely to hornblende and andesine, respectively, although relic textures to substantiate this suggestion are evident in one slice only.

(3) hornblende → biotite

An uncommon transition. The hornblende and biotite usually appear to be co-existing stable phases.

In amphibolitic rocks:

(1) hornblende → biotite

A very rare transition. The hornblende is nearly always unaltered.

In pyroxene-albite rocks:

(1) sodic diopside → amphibole.

An uncommon transition. Most of the sodic pyroxene is unaltered.

In psammitic rocks:

(1) biotite → chlorite

An uncommon transition. The biotite is usually unaltered.

(2) oligoclase/andesine → albite[1]

Though the plagioclase of the pelites, semi-pelites, and amphibolites does not appear to have been affected by the retrogression (except for alteration to sericite?), the mineral assemblage in 6 out of 33 thin-sections of psammite is as follows:

(15) Quartz-albite-K feldspar-(biotite-muscovite)± epidote-garnet-chlorite)

The reaction albite + epidote = plagioclase + water is one of the main criteria for defining the transition from conditions which obtain in the upper Greenschist Facies to those which obtain in the lower Almandine Amphibolite Facies (Fyfe, Turner, and Verhoogen, 1958, p.218; de Waard 1959, p. 561). It is seen from assemblage (15) that the pair albite-epidote is present in these rocks, and that its presence probably reflects a change in temperature-pressure conditions from those defined by the oligoclase-bearing rocks. Because the localities of the six specimens with assemblage (15) are found in widely separated parts of the area (Fig.3), it is reasonable to suggest that those temperature-pressure

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(1) The albite in the psammite is always altered, in many slices very strongly. This is contrasted with the albite in the pyroxene-albite rocks, which is invariably unaltered. Hence, I think that the genesis of the albite in these two rock types is different.

conditions which produced the pair albite-epidote obtained throughout the entire area. This being the case, it is not clear why the oligoclase/andesine → albite + epidote transition took place in only one-fifth of the psammite specimens, and in fact has not been observed at all in the pelitic, semi-pelitic, and amphibolitic rocks. It seems probable that the slow rates of reactions from high to low temperature equivalents might account for this persistence of the higher grade minerals as metastable phases (Fyfe et al., op. cit. p.96-98).

From the information given above, coupled with the fact that garnet and hornblende are essentially unaltered, it is possible to suggest two alternatives concerning the physical conditions which may have prevailed during retrogressive metamorphism:

(1) If the oligoclase/andesine, albite, garnet, and hornblende are considered as being essentially stable phases during the retrogressive metamorphism, then the physical conditions which prevailed were probably in the range of the transition between the Greenschist and Almandine Amphibolite Facies, as suggested by the transition oligoclase → albite + epidote.

(2) If the oligoclase/andesine, garnet, and hornblende are considered to be meta-stable phases during the

retrogressive metamorphism, then it is not possible to determine the physical conditions which prevailed. The growth of sericite and possibly muscovite from the kyanite suggests that at least the sericite may have been a stable phase.

On the evidence available, it cannot be stated which of these two alternatives is the more probable.

Post-Retrogressive Recrystallization

Some recrystallization of the rocks has taken place after the retrogressive metamorphism. This is evident in many thin-sections, that groups of small crystals, or large, strained prophyroblasts of muscovite appear to be growing within knots of sericite. In some specimens, the muscovite porphyroblasts are not accompanied by sericite; these might be interpreted as examples where all the sericite has re-crystallized. The longest dimension of the muscovite porphyroblasts are typically at random angles to the foliation.

Another possible indication of post-retrogressive recrystallization can be seen in the garnets from two specimens of pelite. Here, cores of garnet which are essentially free of inclusions are surrounded by rims of garnet that are loaded with inclusions. In some of the garnets, fractures are abundant in the core, but die out where the inclusion-

loaded rim begins, and vice versa (Plate IVa); and in at least two garnet crystals, a difference in refractive index between core and rim is evident. This clearly suggests that the core and rim of the garnet are of a different composition, and that they probably crystallized under different physical or chemical conditions. Whether the conditions which changed during crystallization were pressure and/or temperature, or the composition of ion-bearing fluids, is open to question. Jones (1962, p.472) has suggested that differences between core and rim in garnets, such as described above, could be accounted for merely by a slight change in the composition of the fluids from which the garnet was absorbing ions. In such a situation, the compositional difference between core and rim would NOT necessarily indicate: (1) a time break, or (2) a change in temperature-pressure conditions separating the crystallization of the core rim, respectively. Garnets of the type described here are rare in the Glen Cannich - Glen Affric Area, although Merh (1960, p.161) reports similar phenomena in the adjacent ground to the northeast. In view of the hypothesis of Jones (ibid), the significance of the core/rim relationship of garnets from the area under consideration remains inconclusive. They may indicate a second period of garnet crystallization. It is entirely possible, however, that ion-bearing solutions

may have been changing composition from place to place in the area. In some localities, this change may have been considerable enough to affect a noticeable difference between core and rim of the garnet. This process could quite possibly have taken place during one continuous period of crystallization as defined by gross temperature-pressure conditions.

Lewisianoid Assemblages

Because Lewisianoid rocks are restricted to one small corner of the area, their mineral assemblages would not be representative of the metamorphic grade for the area as a whole; hence, they are considered separately from the Moine rocks.

The Lewisianoid body in the area consists essentially of calc-silicate rocks very similar to those described by Ramsay (1954, p. 89-90). These calc-silicates, however, should not be considered equivalent to the Moinian calc-silicate granulites described in the previous sections. The mineral assemblages of the Lewisianoid rocks are as follows:

(1) Quartz-diopsidic pyroxene-tremolite/actinolite-epidote-(oligoclase or K feldspar).

(2) Quartz- K feldspar-biotite-muscovite-epidote-(tremolite/actinolite).

(3) K Feldspar-diopsidic pyroxene-tremolite/actinolite-epidote-(biotite-andesine).

(4) Quartz-andesine-hornblende-(epidote-sphene).

(5) Quartz-epidote-iron ore.

Since the mineral assemblages of the rocks do not correspond with any one of the main categories as outlined by Turner and Verhoogen (1960) or Kennedy (1949), it is difficult to determine precisely the metamorphic grade. The presence of essentially unaltered diopsidic pyroxene and andesine in some assemblages, however, suggests that these minerals were stable phases during the main progressive metamorphism. Textural evidence indicated by some crystals of pyroxene altering to amphibole, however, suggests that retrogressive metamorphism effected some of these rocks; and Ramsay (ibid), has described calc-silicates immediately to the north, which have been affected by migmatization, but there is no evidence to suggest that migmatization was active in the rocks in question.

Because the Lewisianoid rocks are at the very edge of one corner of the Area, and lie in deer forest country which was mapped during the last stages of field work, they have not been thoroughly investigated. From the work I have done, however, there is no conclusive field or laboratory evidence to suggest that they had a pre-Caledonian structural or metamorphic history.

Migmatization

Migmatization has profoundly affected the pelitic rocks, and the migmatitic material forms an integral part of that rock type throughout the area. Locally, the psammitic rocks are also migmatized, but not so commonly as are the pelites. Migmatization of the other rock types is essentially absent.

In both pelite and psammite, the migmatization takes the form of quartzo-feldspathic segregations and veinlets, which usually lie parallel to the foliation. Segregations are more common in the pelite, and lit-par-lit veinlets more characteristic in the psammite. In the western half of the area, sheets of quartzo-feldspathic material are seen to lie along the axial plane of F_4 minor folds, although this is not common. Rarely the migmatization has been so intense in the pelite that the rock may be classed as granitic. Such intense migmatization in the psammites is restricted to local occurrences in the northwest quarter of the area.

The difference in mineral assemblages (and therefore of chemical composition) of the segregations and veinlets in the pelites and psammites is of paramount importance in determining their source. In all the thin-sections of the two rock types that have been examined, the mineral assemblages of the quartzo-feldspathic material are as follows:

In pelite:

Plagioclase-quartz (never K-feldspar)

In psammite:

K feldspar-plagioclase-quartz

Micas in both rock types appear to be stable phases with respect to the migmatization; that is, there is no evidence of the micas breaking down and entering into the reaction that took place during migmatization.

The mineral assemblages of the segregations and veinlets, therefore, vary with the rock type in which they occur. This suggests that the quartzo-feldspathic materials were formed by anatexis of the host-rock, and that the composition of the latter has controlled their composition.

The experimental work of Winkler and Von Platen (1961) supports this conclusion. They have similated anatexis by subjecting greywackes and potassic clays to conditions near 700°C and 2000 bars P_{H_2O} and obtained the following results:

(1) The composition of the first melt to form is aplitic, and falls very near the cotectic line which separates the quartz from the feldspar field in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O (Bowen and Tuttle, 1958);

(2) After the first aplitic melt has formed, its composition becomes increasingly more tonalitic with only slight increase in temperature, until a tonalitic melt only is produced;

(3) Only during the stages of tonalite formation did the micas break down to release K20; (this suggests that in the Moinian rocks under consideration, K_2O, which went into the making of K feldspar in the melt, came from a source other than mica, namely pre-existing K feldspar);

(4) The final composition of the melt is fixed by the composition of the host rock.

As can be seen from the two assemblages given above (p. [illegible]) the presence or absence of K-feldspar defines the difference in their mineralogy. In the light of Winkler and Von Platen's experiments, it appears that during the anatexis of pelites in Glen Cannich the micas acted as stable phases, thereby withholding the only source of K_2O, since the rock contains no K feldspar. Hence, the migmatitic K feldspar could NOT be produced, and the anatectic product was plagioclase-quartz. In the psammites, however, K_2O was present mainly in the form of K feldspar, rather than in mica. During anatexis, the K feldspar in rock released K_2O to form K feldspar in the segregations, etc., and the anatectic product was K feldspar-plagioclase-quartz.

Since the knotty and speckled semi-pelites are commonly laced with quartz veins, it is possible that this material too is a result of anatexis connected with the migmatitic processes. However, metamorphic differentiation, as suggested by Turner (1948, p.148) might also account for such a phenomenon.

Age of the Migmatization

It is exceedingly difficult to place time limits on the migmatization. The following facts are of interest in this context: quartzo-feldspathic striping and rodding are lineations associated with F-1, F-2, and (rarely) F-4 structures; F-2 minor folds fold quartzo-feldspathic veinlets and very rarely have sheets of similar (?) material lying along their axial planes; F-4 minor folds also fold quartzo-feldspathic layers, and not uncommonly have sheets of the same material lying along their axial planes (Figs. 20 and 33). It seems reasonable to suggest, therefore, that migmatization was active during the tectonic phases F-1, F-2, and F-4. It is not possible to say whether this activity was continuous throughout these phases of deformation, or whether it was or was not active during F-3. If the Loch Monar Synform was contemporaneous with my F-3 (see under Structural Synthesis, p. 195), then it is possible that migmatization was active during F-3, because Ramsay (1958a) reports that migmatization accompanied the Loch Monar folding. In any case, there is no evidence to suggest that the migmatization continued beyond the later stages F-4.

Pegmatites

Pegmatite sheets and lenses are sparsely distributed

throughout the area. In some occurrences, they are intimately related to the migmatites, and are seen to merge with them. At least some of the pegmatites are probably outgrowths of intense migmatization. Elsewhere, however, they are found in completely unmigmatized rocks.

The timing of pegmatite emplacement is also difficult to ascertain. Most of the occurrences cross-cut the foliation, although some are parallel to it. A few examples of the concordant intrusions are seen to be folded by F-4 minor folds, and large muscovites in the pegmatites are aligned parallel to the axial planes of these structures. This suggests that some of the pegmatites were at least in a plastic condition during F-4. The actual time of emplacement, however, remains undefined.

Metamorphism as Related to Deformation

The metamorphic characteristics associated with minor folds related to the various phases of deformation give some idea of the relationship between metamorphism and deformation in the area. The following facts are relevant:

(1) F-1 minor folds have an axial plane schistosity, and are accompanied by lineations of quartzo-feldspathic striping and rodding types;

(2) F-2 minor folds have an axial plane schistosity,

and are accompanied by lineations which consist of quartzo-feldspathic striping and rodding, elongated kyanite-bearing knots, and oriented hornblende crystals;

(3) There are no minor folds which can positively be identified as being of F-3 age;

(4) F-4 minor folds have an axial plane schistosity in the northwestern quarter of the area, but lack it in the remaining three-quarters; axial plane migmatization sometimes accompanies the minor folds in the western third of the area. This suggests that during F-4 folding, metamorphism was more intense in the northwestern than the southeastern part of the area;

(5) In a thin-section from the post F-4/pre F-5 crumpling (Plate XVIIIa), many muscovite flakes are bent and strained, especially in the core of the crumples. The quartz grains show extreme strained extinction, as well as some serrated edges. This suggests that at least some movement took place parallel to the axial planes of those crumples after the metamorphism has ceased;

(6) Biotite from one thin-section of F-5 crumping (Plate XVIIIb) indicates that it recrystallized during formation of the crumples, since none of the biotite has a strained extinction. No biotite has been observed growing randomly across the foliation in any of the thin-sections,

hence this recrystallization of biotite is local, and is probably connected with the formation of the crumpling.

With the information available, it is not possible to construct a detailed time relationship between the metamorphism and folding. It is possible, however, to gain a general notion of their relationship, and the following deductions may be made from the facts listed above:

Metamorphism of at least biotite grade was initiated sometime during or before F-1 folding, and quartzo-feldspathic striping and rodding associated with this phase suggests that the metamorphic grade may have reached into the Almandine Amphibolite Facies. This grade of metamorphism either continued into F-2 folding, or it may have dropped off between F-1 and F-2. Undoubtably, however, metamorphism reached its peak during F-2, as shown by the formation of elongated kyanite-bearing knots and oriented hornblende crystals, as well as by the development of an axial plane schistosity of F-2 minor folds. This progressive metamorphism was followed by a phase of retrogressive metamorphism, which may have taken place:

(1) at the end of F-2 folding,

(2) during F-3 folding, or even possibly

(3) early during F-4 folding.

Recrystallization was subsequently reinitiated during F-4

folding, but was considerably more intense in the northwest than elsewhere. There the F-4 minor folds have an axial plane schistosity (biotite and muscovite). In the remainder of the area, the recrystallization during F-4 was restricted to formation of muscovite porphyroblasts from sericite, and possibly the growth of some new garnet. Biotite also crystallized to some extent, since the micas in the minor fold cores do not appear to have been bent. If one assumes that the F-4 movement was isochronous throughout the area, there must have been a metamorphic gradient which increased from southeast to northwest during this period of folding. Metamorphism then fell to the point of being negligible. This is indicated by the bent and strained micas seen in the post F-4/pre F-5 crumpling. Recrystallization during F-5 was restricted to the immediate areas of the F-5 crumpling, and was probably initiated by the energy connected with the folding.

CHAPTER 5

SEDIMENTARY STRUCTURES

Sedimentary structures are largely confined to certain horizons within the Loch Carrie Paammitic Group (see under Stratigraphy, p.250) in which they are beautifully preserved. The horizons which contain these structures have a very characteristics appearance; thin laminae of pale quartzitic rock alternate with films of dark minerals, so that the light coloured rock forms a marked striped appearance. It is easy to recognise such horizons in the field, and hence it is probable that most occurrences of sedimentary structures within the Area have been recorded.

The most common structure is planar cross-stratification (terminology after McKee and Weir (1953)), Plate XXb. It occurs in composite sets whose maximum thickness rarely exceeds 100 feet. Within some composite sets are co-sets which contain sedimentary structures that are in various stages of primary deformation (Plate XIX, XXa, Fig.40).

The undeformed structures are typically defined by thin laminae averaging about 0.4 cm. in thickness, and separated by exceedingly thin films of dark minerals, which in

PLATE XIX

a. Deformed sedimentary structures from the Carrie Psammitic Group just north of Loch Carrie. Knife is 4 inches long.

b. Same as above. The trace of the bedding plane is parallel to the long axis of the knife.

c. Same as above. The trace of the bedding plane is parallel to the pencil.



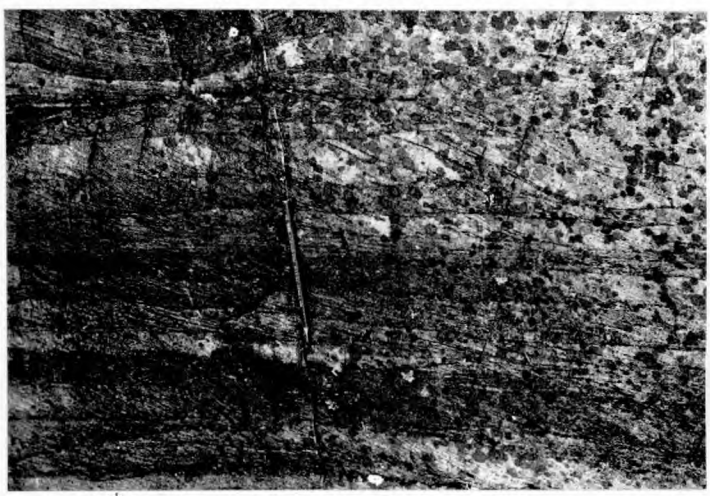




PLATE XX



a. Sedimentary structures from the Carrie Psammitic Group south of Loch Carrie. Slumping (and balling?) on left is pronounced; beds on right are only slightly deformed.

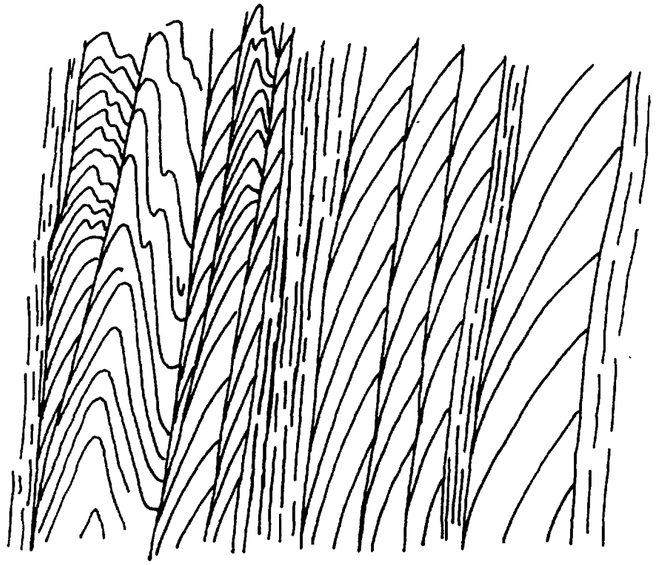


b. Sedimentary structures from the Carrie Psammitic Group north of Liatrie. Photograph illustrates typical cross-stratification found in this psammitic group. Note trough-like structure in upper left hand corner. Pencil is 6 inches long.

thin-sections are seen to consist of mica, epidote, garnet, and accessories in varying proportions. In the deformed structures, the laminae are considerably thicker, corresponding to "very thin-bedded" of McKee and Weir (ibid), and are seen to vary between 1 cm. and about 5 cm. The average thickness of a set of cross-strata is about 10 cm. (4 inches), and the maximum observed is about 30 cm. (1 foot). These thicknesses generally agree with those reported by Wilson, Watson, and Sutton (1953, p.378) and Richey and Kennedy (1939, p.33) for typical thicknesses of cross-strata in Moine psammites.

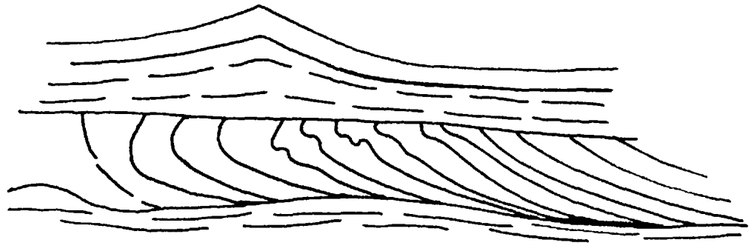
Deformed "sets" of strata within a given co-set were commonly observed, Plate XIX, XXa; Fig. 40. These are bounded above and below by beds in which the structures were undeformed, thereby implying that the deformation of a given stratum was confined to that stratum, and took place before or during the deposition of the overlying beds. This suggests that the deformation of the sedimentary structures was essentially primary , and this is supported by comparing these structures with primary deformed sedimentary structures in rocks that have not been subjected to tectonic movement (see especially Jones (1962, p.234-236), McKee et al (1962 p.158-159); Matthews (1961, fig. 3, p.61); Kuenen (1948)).

FIG. 40 Sedimentary Structures from the Loch Carrie Psammitic Group in Various Stages of Primary Deformation

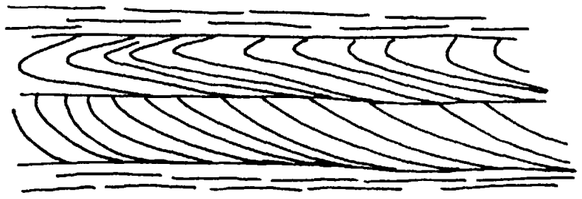


a. South of Loch Carrie

1" = 1'

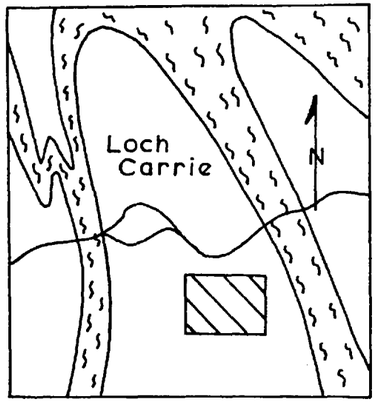


c. North of Liatrie

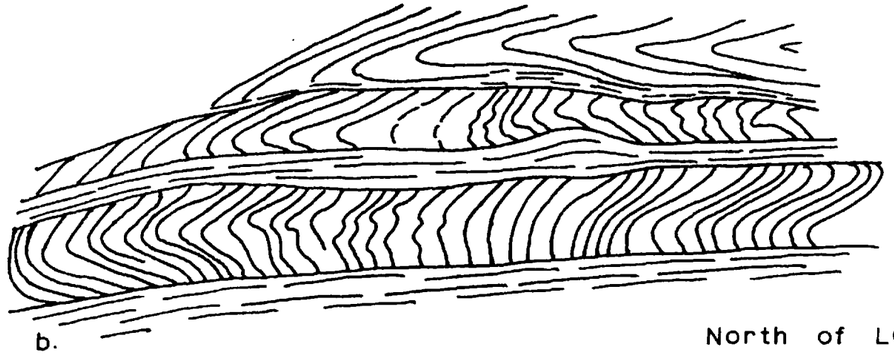


d. An Soutar 1" = 1'

locality of information for figure g.

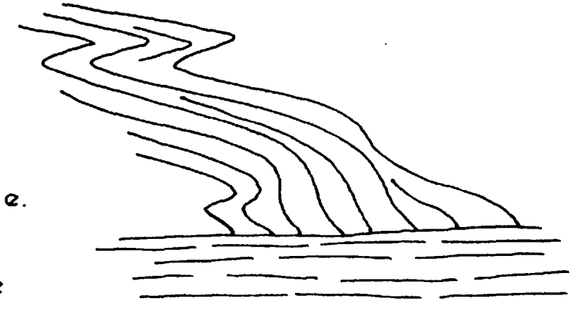


f.

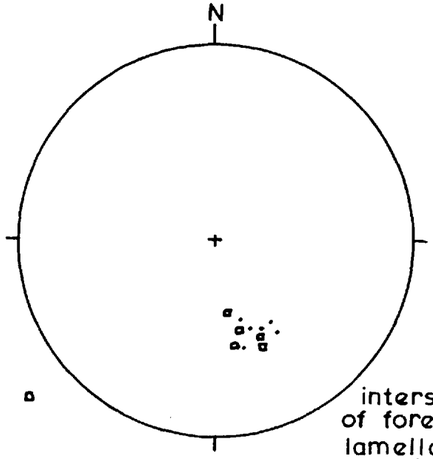


b. North of Loch Carrie

1" = 1'



e.



F-2 lineation = ▫

intersection of foreset lamellae and foliation = •

g.

Other workers have reported sedimentary structures from the Moinian rocks (Richey and Kennedy, 1939; Wilson et al., 1953, Sutton and Watson, 1954; Harker, 1956; Clifford, 1956; Ramsay, 1958b; Merh, 1960; Soper 1960). Richey and Kennedy (op.cit., p.31-35) described and figured such structures from the Moines at Morar. Many of these structures are deformed, and bear a striking resemblence to some of the deformed structures illustrated above. They attribute the deformation to "slumping of unconsolidated sediments" (i.e. primary deformation). Wilson et al (op. cit., p.379 - 380) have also reported such slump structures in the Moines from various parts of Scotland. In the area northeast of Glen Cannich, Merh (ibid) has recorded numerous occurrences of sedimentary structures, which come from the stratigraphic group that probably corresponds to the Loch Carrie Psammitic Group (see under Stratigraphy, p.). He mentions that he has observed slumping and deformed current bedding, but does not ascribe the two phenomena to the same cause. The "deformed current-bedding" of Merh (op. cit., plate 3) closely resembles phenomena from the Glen Cannich - Glen Affric Area discussed above. Merh, however, attributes the deformation of the sedimentary structures to tectonic processes rather than to primary deformation.

An interesting fact observed locally is that the

intersection of the foreset cross-stratified laminae with the bedding (foliation) plane forms a distinct lineation which plunges to the southeast. This phenomeon only occurs in a relatively small area about one mile southeast of Loch Carrie. Furthermore, this lineation, when plotted on a stereonet (Fig. 40), is essentially parallel to the F-2 lineation within that area. I have not found any exposures where the two types of lineations were observed on the same surface, and whether this linear parallelism is fortuitous or is indicative of some type of structural control is not clear.

Although the apparent current direction at each locality has been recorded wherever cross-stratification was observed, the directions of current for the area as a whole have not been calculated. This would necessitate knowing the orientation of the fold axis for every deformation at every locality where there was cross-stratification, so that accurate unrolling of the bedding (foliation) could be carried out. Furthermore, in areas of repeated deformation such as Glen Cannich, it would be necessary to know the mechanism of folding for each phase involved, and the extent to which each mechanism had entered into each folding (Ramsay, 1961, p.99).

CHAPTER 6

STRATIGRAPHY

General

It has not been possible to determine a stratigraphic succession which obtains throughout the entire area; nevertheless, a sequence of the groups in the southeastern two-thirds of the area can be established, as based on sedimentary structures. The three groups concerned are:

C. The Glen Affric Psammitic Group,

B. The An Soutar Pelitic Group, and

A. The Loch Carrie Psammitic Group.

The relative distribution of the groups is presented in the stratigraphic map of Fig. 41. From the map, it can be seen that the Loch Carrie Psammitic Group faces consistently toward the An Soutar Pelitic Group, indicating that the former is the older. In the area northwest of Muchrachd, the tops of the beds in the Glen Affric Psammitic Group face consistently away from the An Soutar Pelitic Group, indicating that the latter is the older. Hence, the stratigraphic succession, listed from youngest to oldest, is as stated above: C. → B. → A.

FIG. 41 Stratigraphic Map of the Glen Cannich Area

Pelite

Semi-pelite

Psammite

Lewisianoid

Glen Affric Psammitic Group C

An Soutar Pelitic Group B

Loch Carrie Psammitic Group A

no correlation possible

Creag Feusag Pelitic Group P

Glen Strathfarrar Hble. Group Q

Loch Beag Pelite Q_2

Lewisianoid Q_1

Glen Strathfarrar

Glen Cannich

Glen Affric

B??

N

1 mile

Lithologic Boundary =

Group Boundary =

Slide =

The remaining two groups to be considered are;

a. the Glen Strathfarrar Honblendic Group, which contains psammitic, pelitic, and hornblendic horizons, and

b. the Creag Feusag Pelitic Group.

A stratigraphic relationship of this pelitic group (b.) above, to the Loch Carrie Psammitic Group is not possible, because a slide separates them at least along part of their boundary. Furthermore, the boundary between these two groups is poorly defined in many areas, especially west of Mullardoch Dam, where it is exceedingly vague. This poor definition results from very poor exposure coupled with a complex structural geometry. In the Loch Mullardoch area, the central outcrop of psammitic rocks (Fig. 41) is correlated with the Loch Carrie Psammitic Group on the strength of the fact that both are psammitic and contain sedimentary structures. It is fully realised that the use of sedimentary structures as an "index fossil" is not sound practice, but in this situation, it seems to be the lesser evil. The boundary separating the Loch Carrie Psammitic Group from the Creag Feusag Pelitic Group west of Mullardoch Dam as shown in the stratigraphic map, therefore, is merely a line drawn on the strength of lithological differences between widely scattered exposures, and does not necessarily imply any definite geometrical form or true stratigraphical

boundary between the two groups.

The stratigraphical succession between the Glen Strathfarrar Hornblendic Group and the Creag Feusag Pelitic Group is unknown. The boundary between these two groups is well defined, but the dip of the foliation along it is essentially vertical; hence, not even the structural succession can be determined.

Description of the Groups

The Loch Carrie Psammitic Group

This psammitic group cropsout over a large area. It is the main unit within the Glen Cannich Eyed Structure, and is repeated to the west as far as Mullach na Maoile; to the southeast, it continues into the Doire Tana-Glen Affric area.

Psammite with rare calc-silicate lenses make up the greater part of the group, and various units within the group contain well-developed sedimentary structures. These sedimentary structures are especially common within and immediately to the west of the main eyed structure, and serve to indicate the presence of the early tectonic structures. To the south of Mullardoch Dam, by contrast, the psammite is so massive that no structures are measurable.

Patches of knotty, speckled, and sub-pelitic semi-pelites occur within the psammite. Rarely are these semi-pelitic types traceable for any distance along their strike. Notable exceptions are the unit just west of Mullach Tarsuinn, which is two miles long, and the unit passing through Liatrie, which is two miles long, and the unit passing through Liatrie, which is about one mile long. Both these units consist primarily of interbanded knotty semi-pelite and psammite, and end in unexposed ground. More common than the distinct units of semi-pelite are imperceptible gradations from psammite into semi-pelite and back into psammite. Most of the semi-pelites in this category are not mappable, because their bouhdaries are not sufficiently definite.

The An Soutar Pelitic Group

This pelitic group cropsout mainly in the eastern half of the area, but it has been repeated by tectonic structures, and its outcrop pattern is complex. The same rocks can be traced from Glen Strathfarrar through Glen Cannich into Glen Affric, and may even be followed further to the north-east (Merh, 1960).

The bulk of this group is composed of garnetiferous mica schist, but there are also subordinate thinly-banded

and sub-pelitic semi-pelites, as well as rare knotty semi-pelite. Traceable units of semi-pelite bordering the main pelitic unit are common. In two areas, namely An Soutar and Glen Affric, outcrops of psammite and semi-pelite occur in notable amounts within the pelite. It is not possible to be sure if all these outcrops represent facies changes within the pelite, or if some are tectonic infolds of different rock groups.

The Glen Affric Psammitic Group

The outcrop of this group is of limited areal extent compared to those described above. It occurs in the Glen Affric region along the eastern boundary of the area. Folding repeats the group in the eastern region of Glen Cannich, and once again repeats it in the area of Meallan Odhar and Glen Strathfarrar.

In the Glen Affric area, the rock is a relatively clean, white psammite, and is characterized by calc-silicate lenses and numerous sills of amphibolite. Semi-pelitic rock is rare on the whole, but in the eastern regions of Glen Cannich, the group south of the Glen contains a notable amount of semi-pelite, which is characterized by pink garnets and abundant quartz veins. Some coarse-grained pelite is [illegible] a purer psammite, similar to the white variety in Glen Affric.

Merh (1960) working to the northeast was able to divide the equivalent of this group into distinct psammitic and semi-pelitic groups. He found sedimentary structures in the psammitic group, but to the best of my knowledge, they do not occur south of the River Cannich. Apart from the area northwest of Muchrachd, where the psammite obviously corresponds (and in fact is) Merh's psammitic group, I have not been able to sub-divide the group in my area. However, much of the rock in the Beinn a' Chairein area probably corresponds to Merh's semi-pelitic group.

In Glen Strathfarrar and in the area of Meallan Odhar, a facies change in the group is evident, since the rock is now dominantly semi-pelitic; but lenses and thin units of a clean white psammite, which greatly resembles the group to the southeast, are not uncommon.

The Creag Feusag Pelitic Group

This group within the area of Creag Feusag is represented predominantly by a coarse-grained garnetiferous mica schist, which is surrounded by semi-pelite. Although exposure is poor along the strike of the group towards the northeast, the continuation of the rock type appears to be essentially a mixture of pelitic and semi-pelitic types. Near Glen Strathfarrar, large lenses of psammite also form a part of the group.

West of Creag Feusag, in the Mullach na Maoile and Loch a' Choire Bhig areas, the group consists predominantly of semi-pelite, psammite, and to a lesser extent, pelite. The semi-pelite contains abundant pink garnet, and locally, quartz rods and veinlets. Calc-silicate bands are common, especially at Loch a' Choire Bhig. The more psammitic facies enclose many discontinuous bands of semi-pelite, and in one horizon, again at Loch a' Choire Bhig, calc-silicate bands and lenses are abundant. The pelite, which crops out in the area of Loch a' Choire Bhig, is similar to the pelite in the Creag Feusag area, except that it tends to be finer-grained and contains more semi-pelitic material. Calc-silicate lenses are also found locally within the pelite.

The Glen Strathfarrar Hornblendic Group

In an effort to simplify correlation with the surrounding area, I have retained the name which Ramsay (1954, 1958a) gave this group, together with the names that he gave the subdivisions where they occur in my ground. The subdivisions of the group which crop out in may area are the Creag Dhubh Psammite, the Loch Beag Pelite, and the Lewisianoid.

The Creag Dhubh Psammite

This psammite may be traced for six miles from Glen

Strathfarrar in a southwesterly direction through Loch Tuill Bhearnach. Ramsay (ibid) was able to trace it north from Glen Strathfarrar for some distance. The rock is a feldspathic psammite with more epidote than the usual psammite, and containing rare lenses of calc-silicate. It also includes a slender horizon of pelite and semi-pelite near Carn nan Gobhar. In certain more micaceous bands, a whitish mica forms a very well-developed schistosity, which locally is the only planar structure visible in the rock. This is especially true in the area between Creag Dhubh and Loch Tuill Bhearnach. Hinxman (1906, p. 84) noticed the distinctive character of this rock unit, and commented on the "greenish-white" colour of the mica. He considered that the psammite represented "the lower siliceous zone which in many localities lies between the pelitic group of the Moine Series and the Lewisian complex". The psammite, in any case, forms the southeastern boundary of Ramsay's " 'Lewisian' " as well as of the Lewisianoid body which runs through Loch Tuill Bhearnach in my area.

The Lewisianoid Rocks

It is surprising that Hinxman did not map the piece of Lewisianoid that runs through Loch Tuill Bhearnach, since the body is one mile in length and close to 800 feet in its

broadest width. Ramsay (1958a) mapped the area immediately to the northwest, which joins the northwestern boundary of the Cannich Area. He describes rocks of similar aspect (i.e. Lewisianoid) which cover a significant part of the Loch Monar area[1]. Unfortunately, the ground between Ramsay's and my Lewisianoid rocks is poorly exposed, and it remains an open question as to whether the two outcrops are part of the same body.

The shape of the Lewisianoid body south of Sgurr na Lapaich is somewhat like a sausage. It emerges from below the rubble in the west as a slender prism (a few tens of feet wide), and rapidly widens in the east, where it finally ends along a fault contact. Exposures on the west side of the fault continue to show Lewisianoid rocks over a distance of about 3000 feet from north to south. Immediately to the south of one end of the sausage-like body, there is a lense of similar rock type. It is not traceable along its strike for more than a short distance (50 feet or so), because of rubble and unscalable cliffs; but about 200 feet to the east of this outcrop, the local psammites contain no trace of the Lewisianoid type, so it is presumed that this lens is of very limited extent.

---

[1]Although in his 1958a publication, Ramsay considered these rocks to be "an integral part of the Moine Series", in a later publication (discussion in Flouty, 1961), he (Ramsay) suggests that the rocks are not Moine after all, and in fact are probably Lewisian (personal communication).

The matrix, as it were, of the Lewisianoid body as a whole is a clean psammite. Within this matrix are scattered various types of Lewisianoid "inclusions". Some of these "inclusions" form lenses, but more commonly they are smeared out into the matrix to such an extent that it is difficult to ascertain where the "inclusion" ends and the psammitic matrix begins. Furthermore, the matrix and the ordinary Moine-type psammites that are in the area are identical. These facts coupled with poor exposures render the drawing of precise contacts between Lewisianoid and Moine rocks impractible.

Loch Beag Pelite

This pelite covers a very small area immediately around Sgurr na Lapaich. It consists predominantly of relatively fine-grained mica schist, with minor amounts of semi-pelite.

Correlation of Surrounding Areas

The stratigraphic succession established in the south-eastern two-thirds of the Glen Cannich - Glen Affric Area generally agrees very well with the succession that Merh (1960) found in the area to the northeast. The following correction is evident:

Tobisch	Merh
Glen Affric Psammitic Group	= Creag Dubh Psammitic Group Tombuidhe Semi-pelitic Group
An Soutar Pelitic Group	= Sgor na Doillaid Pelitic Group
Loch Carrie Psammitic Group	= Loch Meall a' Mhadaidh Psammitic Group.

In the southeastern corner of Merh's area, east of Creag Ruigh nah Uambach, his stratigraphic map indicates that his first three groups mentioned above are all present. I disagree with this interpretation, in that east of the outcrop of the Sgor na Doillaird Pelitic Group at this locality, only one stratigraphic group is represented, namely the Glen Affric Psammitic Group (= Creag Dubh Psammitic Group + Tombuidhe Semi-Pelitic Group of Merh). A reinvestigation of the geometry of the earlier structures in this part of Merh's area might resolve this difficulty in stratigraphic correlation.

The stratigraphic succession along the northern boundary of the Area agrees with that established by Mukherjee (personal communication). The following correlation is evident:

Tobisch		Mukherjee
Glen Affric Psammitic Group	=	Ardchulk Semi-pelite Mhuillidh Semi-pelite
An Soutar Pelitic Group	=	Ardchulk Pelite An Carnais Pelite Mhuillidh Pelite
Slide		
Creag Feusag Pelitic Group	=	Dubh Ghlac Pelite Rodha Semi-pelite
Glen Strathfarrar Hornblendic Group:		
Creag Dhubh Psammite	=	An Sithean Psammite

The correlation of the group along the northwestern boundary which joins with Ramsay (1954; 1958a) is straight forward, because our mapping overlaps, and the Glen Strathfarrar Hornblendic Group is common ground.

A table correlating the main stratigraphic groups from the surrounding areas with those from the Glen Cannich - Glen Affric Area is presented below.

Correlation Table of Stratigraphic Groups

Ramsay	Tobisch	Merh	Mukherjee
-------	Glen Affric Psammatic Gp. =	Creag Dubh Ps. Tombuidhe Semi-pelitic Gp.	Ardchulk Semi-Pel =Mhuillidh Semi-Pel.
-------	An Soutar =	Sgor na Doill-aid Pel. Gp.	Ardchulk Pelite =An Carnais Pel. Mhuillidh Pelite
-------	Loch Carrie Psammitic Gp. =	Loch Meall a' Mhadaidh Psam. Group ?=?	Carn ant Snath Semi-pelite
	----------SLIDE----------		
An Riabhachain Pelite ?=?	Creag Feusag Pelitic Gp.	==========	Dubh Glac Pelite Rodha Pelite
Glen Strath-farrar Hble. Group: Creag Dhubh Psammite	Glen Strath-farrar Hble. Group: Creag Dhubh Psammite	==========	(Glen Strath-farrar Hble. Group:) An Sithean Psam.
Upper Hble. Division ?=?	Lewisianoid	-------	--------
Loch Beag Pelite =	Loch Beag Pelite	-------	--------

CHAPTER 7

CORRELATION AND DISCUSSION

Fold Chronology

The table presented below relates the chronology of the successive phases of deformation from the surrounding areas to the succession in the Glen Cannich - Glen Affric Area.

Tobisch (1963)		Merh (1960)		Mukherjee (ms)		Fleuty (1957;1961)		Ramsay (1954;1958a)
F-1	=	uncertain	=	uncertain	=	---------	=	---------
F-2	=	F-1	=	F-1	?=?	F-1	=	---------
F-3	=	F-2*	=	F-2	?=?	F-2	=	F-1
F-4	=	F-3**	=	F-3	=	F-3	=	F-2
F-5	=	F-4	=	F-4	??=??	F-4	=	--------

*correlation valid only on a major scale; see text, p.
**correlation valid only in the northeastern part of Merh's area; see text, p.

Correlation with Ramsay

Correlation of folds on a major scale with those in the Loch Monar area mapped by Ramsay (1958a) presents no difficulties, since none of the major structures mapped by him are traceable into the Cannich area. Ramsay (op.cit.,

p.286), however, considered his first folds north of Creag Dhubh to be undeformed by the later structures comparable to my F_4 folds, whereas my mapping suggests that these later folds are indeed present on a minor scale, but have swung into parallelism with his first folds. Hence, some of the minor folds Ramsay classed as first fold age in that area may be the later structures (second folds, Ramsay's classification). There are also minor folds which are earlier than Ramsay's first folds as well as others which are post second fold age (Ramsay's classification) along the southeastern border of his area, as I mentioned in the previous section (p.25).

Correlation with Mukherjee

D. Mukherjee is at present engaged in investigating the area north of the River Farrar in Glen Strathfarrar (see Figs. 1 and 42), and I have had the opportunity of visiting parts of this ground in his company.

On the northern border of the Cannich Area, the Muchrachd Synform continues north of the River Farrar (= An Carnais Synform of Mukherjee), as previously mentioned (p.113). The Loch Carrie Syncline must also continue north of that River, although lack of exposure renders confirmation difficult (Mukherjee, personal communication). No other

LOCH MONAR

GLEN STRATHFARRAR

GLEN CANNICH

STRATH GLASS

LOCH MULLARDOCH

GLEN AFFRIC

N

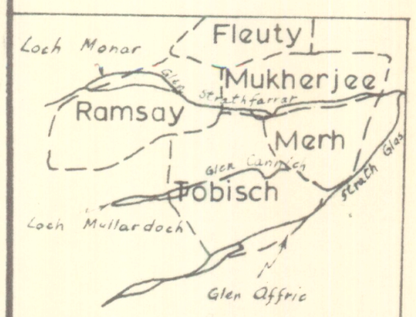


FIG. 42 REGIONAL GEOLOGIC MAP

Pelite

Semi-pelite

Psammite

Lewisianoid

Antiform

Synform

Neutral Fold

Foliation

1 mile

O. T. TOBISCH
Ph. D.
1963

major folds are present along the border of our respective areas, and we are in agreement with the correlation of minor fold chronology along the common border.

Correlation with Merh

The ground lying to the northeast of the River Cannich was mapped by S. Merh, whose unpublished thesis was completed in 1960 (see Figs. 1 and 42).

Major Scale

The relationship between Merh's Muchrachd Syncline (Fig. 11) and my Muchrachd Synform and Beinn a' Chairein folds has already been discussed (p.109). In addition, the possible extension of the dome-basin geometry from the eastern half of my area to structures which Merh (1960) had mapped is also suggested, Fig. 42. This interpretation should be viewed in conjunction with Fig. 37c. The reinterpretation of Merh's early structures, is, of course, only a hypothesis put forth in the light of the geometry of the Glen Cannich and Glen Affric rocks, and a reinvestigation of parts of Merh's area would be necessary to confirm or deny the hypothesis as applied to the early structures of Merh.

Minor Scale

There is some disagreement as to the age of certain minor folds along the border of Merh's area and the Cannich ground; these can be considered in two groups: early, and later structures.

Early Structures

Merh (1960) considered the isoclinal minor folds which accompanied his large isoclinal folds to be his first phase of folding. He suspected, however, that the present geometry of the early isoclinal structures might have come about by "more than one set of folding" (Merh, op. cit., p.204), which has proved to be correct, as I have demonstrated in the section on Structural Synthesis. It is likely that most of the minor folds which Merh assigned to his first phase are equivalent to my second phase (M-1 = T-2, Fig. 43). In parts of the area around Tombuie (Fig. 43), however, where it is possible to differentiate between my first and second phases (T-1 and T-2 of Fig. 43), it seems more likely that T-2 = M-3, and T-1 = M-1. In most of the region shown in Fig. 43, it is not possible to distinguish between minor folds of the first two phases in the Cannich ground or Merh's first and third phase, since their fold styles are essentially the same; this is indicated by T-1 + T-2 = M-1 + M-3 in Fig. 43.

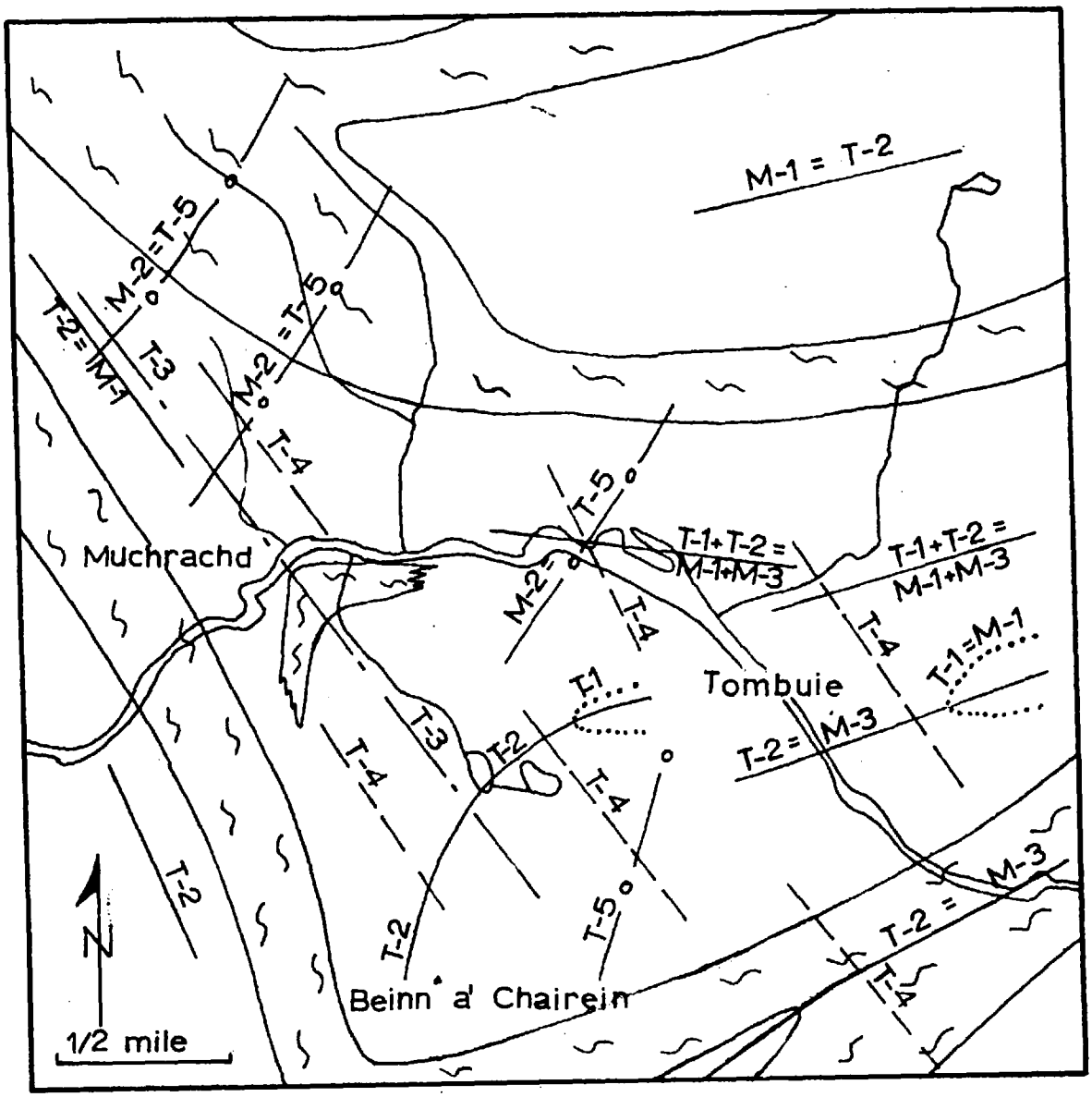


FIG. 43 Sketch Map Showing Minor Fold Trend in Area Adjoining Merh (1960)

Trends of Axial Plane Strike:

Merh's interpretation

M-2 = phase 2

Tobisch's interpretation

T-2 = phase 2

Pelite

Psammite

T-1 ····· T-2 ——— T-3 —·—· T-4 — — — — T-5 —o—o

Later Structures

The axial plane strike of Merh's third phase in Glen Strathfarrar is north-south, Fig. 42. Further south, very near Glen Cannich, Merh indicated that the trend swings to an ENE orientation, which is shown as M-3 in Fig. 43. Here I believe Merh erred in correlating the phases within his area. As mentioned previously, Merh's third phase near Tombuie is most probably an early phase (T-1 or T-2), and his third phase in Glen Strathfarrar, which trends north-south, most probably swings into a NW-SE position corresponding to T-4 east of Tombuie in Fig. 43. I have walked over the ground just north and east of Tombuie, and found that T-4 is indeed striking NW-SE. This is in harmony with the swing in axial plane strike of T-4 (F-4) from north-south near Glen Strathfarrar to NW-SE at Glen Cannich, Fig. 38. Hence, my F-4 (T-4) is equivalent to Merh's F-3 (M-3) in Glen Strathfarrar and part of the way toward Glen Cannich, but in the area east of Tombuie, because of Merh's confusion of earlier and later folds, the correlation is no longer valid.

Merh classed the Combussory Antiform as second phase. However, as the Muchrachd Synform is an F-3 fold (T-3) and the Combussory Antiform is the complementary structure[1],

---

[1] see Fig. 42; the axial plane traces of the Combussory Antiform and the Muchrach Synform pass through the second R and the first A in the word STRATHFARRAR, respectively.

his F-2 is therefore equal to may F-3. As seen from Fig. 42, the strike of the axial planes of this fold is north-south in the north, and swings around to NW-SE in the south. Merh, however, shows trends of minor fold axial planes of his second phase (M-2, in Fig. 43) as being NE-SW. Since the axial plane traces of the major and minor folds cut across each other at high angles, it is highly improbable that they are the same phase. Minor folds which I have classed as fifth phase in this area, have the same axial plane orientation as those that Merh classed as his second phase; hence, it is most probable that the minor folds of these two phases are equivalent (i.e. M-2 = T-5, Fig. 43). The final correlation of the Glen Cannich fold phases with those of Merh are summarized in the table on page 274.

BIBLIOGRAPHY

BAILEY, E.B., 1910. Recumbent folds in the schists of the Scottish Highlands. Quart. J. geol. Soc. Lond. vol. 66, pp 586-620.

BAILEY, E.B., and McCALLEN, W.J., 1937. Perthshire tectonics: Schichallion to Glen Lyon. Trans. roy. Soc. Edinb. v.59, pp 79-117.

BARROW, G., 1893. On an intrusion of muscovite-biotite gneiss in the southeastern Highlands of Scotland and its accompanying metamorphism. Quart. J. geol. Soc. Lond. v.44, pp.330-358.

BARROW, G., 1912. On the geology of lower Dee-side and the southern Highland border. Proc. Geol. Assn., Lond. v. 23, pp.274-290.

BILLINGS, M.P. 1954. Structural Geology. Prentice-Hall 514 p.

CAREY, S.W. 1962. Folding. J. Alberta Soc. Petrol. Geol. v. 10, no.3.

CLARK, R.H. and McINTYRE, D.B. 1951. The use of the terms pitch and plunge. Amer. J. Sci. v.249, pp.591-599.

CLIFFORD, P. 1956. The geology of the area around Loch Luichart, Ross-shire. Ph.D. thesis of the University of London.

CLOUGH, C.T. 1897 in The geology of Cowal. Mem. geol. Surv. Scot.

DEER, W.A., HOWIE, R.A., and ZUSSMAN, J. 1963. Rock Forming Minerals. vol. 2 Chain Silicates 379 p. Longmans.

de SITTER, L.U. 1956. Structural Geology. McGraw-Hill 552p.

de WAARD, D. 1959. Anorthite content of plagioclase in basic and pelitic crystalline schists as related to metamorphic zoning in the Usu Massif, Timor. Amer. J. Sci. v.257, pp.553-562.

FLEUTY, M.J. 1957. The geology of the Glen Orrin District, Ross-shire. Ph.D. thesis in the University of London.

FLEUTY, M.J. 1961. The three fold system in the metamorphic rocks of upper Glen Orrin, Ross-shire and Inverness-shire. Quart. J. Geol. Soc. Lond. v.117, pp.447-479.

FLINN, D. 1962. On folding during three dimensional progressive deformation. Quart. J. geol. Soc. Lond. v.118, pt. 4, pp.385-433.

FYFE, W.S., TURNER, F.J., and VERHOOGEN, J. 1958. Metamorphic reactions and metamorphic facies. Geol. Soc. Amer. Mem. no. 73, 259p.

HARKER, R.I. 1956. The stratigraphy and folding of some metamorphosed Moine sediments around the Carn Chuinneag and Inchbrae granitic gneisses. Geol. Mag. v.93, no. 1 pp.57-62.

HINXMAN, L.W.1901, 1902, 1906. in Summ. Progr. geol. Surv. G.B.

JONES, G.P. 1962. Deformed cross-stratification in Cretaceous Bima Sandstone, Nigeria. J. sediment. Petrol. v. 32 pp.231-239.

KENNEDY, W.Q. 1949. Zones of progressive regional metamorphism in the Moine Schists of the Western Highlands of Scotland. Geol. Mag. v. 86, pp. 43-56.

KING, B.C. 1942. The Cnoc Nan Cuilean Area of the Ben Loyal Igneous Complex. Quart. J. Geol. Soc. Lond. v. 98, pp.147-182.

KNILL, J.L. 1960. A classification of cleavages with special references to the Craignish District of the Scottish Highlands. Int. geol. Congr. Copenhagen. part 18, pp.317-325.

KEUNEN, PH.H. 1948. Slumping in the Carboniferous rocks of Pembrokeshire. Quart. J. geol. Soc. Lond. v. 54 pp.365-385.

* Jones, M.A. 1939. Inclusions in Garnet. Nature, Lond. 143, 1939 p.871

KUHN-SCHNYDER, E. and VONDERSCHMITT, L. 1953. Problems des Sudtessins. Ecl. geol. Helv. v.46, tafel 12.

MATTHEWS, P.E. 1961. Slump structures in the Table Mountain Series of Natal, So. Africa. Trans. Proc. roy. Soc. S. Afr. v. 64, pp.55-71.

McBIRNEY, A.R. and BEST, M.G. 1961. Experimental deformation of viscous layers in oblique stress fields. Bull. Geol. Soc. Amer. v.72 pp.495-498.

McKEE, E.D. and WEIR, G.W. 1953. Terminology for stratification and cross-stratification in sedimentary rocks. Bull. Geol. Soc. Amer. v. 64. pp.381-390.

McKEE, E.D., REYNOLDS, M.A., and BAKER, C.H.Jr. 1962. Experiments on intraformational recumbent folds in cross-bedded sand. Geol. Surv. Research; Geol. Surv. Prof. paper 450D U.S. Geol. Surv.

McLACHLAN, G.R. 1951. The aegerine-granulites of Glen Lui, Braemar, Aberdeenshire. Miner. Mag. no.212, pp.476-496.

MERH, S. 1960. The structural and metamorphic history of the area northwest of Cannich, Inverness-shire, Scotland. Unpub. Ph.D. thesis in the University of London.

MUKHERJEE, D. (ms). Caledonian structure and metamorphism in the eastern part of Glen Strathfarrar, Inverness-shire, Scotland. Ph.D. thesis in the University of London., Unpub.

NICHOLSON, R. 1963. Eyed folds and interference patterns in the Sokumfjell Marble Group, Northern Norway. Geol. Mag. v. 100 no. 1 p.59-68.

O'DRISCOLL, E.S. 1962a. Experimental patterns in Superposed similar folding. J. Alberta Soc. Petrol. Geol. v. 10 no. 3 pp.145-167.

O'DRISCOLL, E.S. 1962b. Models for superposed laminar flow folding. Nature, Lond. v. 196 (No. 4860), pp. 1146 - 1148.

PATTERSON, M.S. and WEISS, L.E. 1962. Experimental folding in rocks. Nature. Lond. v. 195 (N. 4846) pp. 1046-1048, Sept. 15.

PEACH and other 1913. The geology of Central Ross-shire Mem. geol. Surv. Scotld.

RAMBERG, H. 1959. Evolution of ptygmatic folding. Norsk. geol. Tidsskr. Bind 39 pp.99-152.

RAMSAY, J.G. 1954. The stratigraphy, structure, and metamorphism of the Lewisian "Inlier" and Moine rocks of Glen Strathfarrar, Ross-shire. Ph.D. thesis in the University of London.

" " 1955. A camptonitic dyke suite at Monar, Ross-shire and Inverness-shire. Geol. Mag. v. 92 no. 4 pp. 297-309.

" " 1958a. Superimposed folding at Loch Monar, Inverness-shire and Ross-shire. Quart. J. geol. Soc. Lond. v. 113 pp.271-308.

" " 1958b. Moine-Lewisian relations at Glenelg, Inverness-shire. Quart. J. geol. Soc. Lond. v. 118 pp.487-523.

" " 1961. The effects of folding upon the orientation of sedimentation structures. J. Geol. v. 69 no. 1 pp.84-100.

" " 1962a. The geometry and mechanics of formation of "similar" type folds. J. Geol. v. 70 no. 3 pp.309-327.

" " 1962b. Interference patterns produced by the superposition of folds of similar type. J. Geol. v. 70 no. 4 pp.466-481.

RICHEY, J.E. 1939. The dykes of Scotland. Trans. Edinb. geol. Soc. xiii, pp.393-435.

" " 1952. Pre-metamorphism cleavage in the Moine Schists of Morar, Western Inverness-shire. Trans. Edinb. geol. Soc. v. 14 pp.200-219.

RICHEY, J.E. and KENNEDY, W.Q. 1939. The Moine and Sub-Moine Series of Morar, Inverness-shire. Bull. geol. Surv. G.B. no. 2 pp.26-45.

RUTLAND, R.W.R. 1959. Structural geology of the Sokumvatn area, North Norway. Norsk. geol. Tidsskr. Bind 39 pp.287-337.

SHACKLETON, R.M. 1958. Downward-facing structures of the Highland Border. Quart. J. geol. Soc. Lond. v. 113 pp.361-392.

SHROCK, R.R. 1948. Sequence in Layered Rocks. McGraw-Hill 507p.

SOPER, N.J. 1960. A note on current-bedded Moines near Garve, Western Ross. Geol. Mag. v. 97 no.6 pp.504-508.

SUTTON, J. and WATSON, J. 1954. The structure and stratigraphical succession of the Moines of Fannich Forest and Strath Ban, Ross-shire. Quart. J. geol. Soc. Lond. v. 110 pp.21-54.

TRÖGER, W.E. 1956. Optische Bestimmung des gesteinbildungen Minerale. Stuttgart. 147p.

TURNER, F.J. 1948. Mineralogical and structural evolution of the metamorphic rocks. Geol. Soc. Amer. Mem. 30 342p.

" " and VERHOOGEN, J. (1951) 1960. Igneous and metamorphic petrology. McGraw-Hill (602p.) 694p.

WEISS, L.E. 1959. The geometry of superposed folding. Bull. Geol. Soc. Amer. v. 70 pp91-106.

" " and McINTYRE, D.B. 1957. Structural geometry of Dalradian rocks at Loch Leven, Scottish Highlands. J. Geol. v. 65 pp575-602.

WHITE, W.S. 1949. Cleavage in East-Central Vermont. Trans. Amer. Geophys. Un. v. 30 no. 4 pp.587-594.

" " and BILLINGS, M.P. 1951. Geology of the Woodside Quadrangle, Vermont-New Hampshire. Bull. Geol. Soc. Amer. v. 62 pp.647-696.

WILLIAMS, H., TURNER, F.J., and GILBERT, C.M. 1955. Petrography. W.H. Freeman. 406p.

WILSON, G. 1961. The tectonic significance of small scale structures, and their importance to the geologist in the field. Ann. Soc. geol. Belg. v.84 pp.423-548.

WILSON, G., WATSON, J. and SUTTON, J. 1953. Current-bedding in the Moine Series of Northwestern Scotland. Geol. Mag. v. 90 no.6 pp.377-387.

WINCHELL, A.N. 1951. Elements of Optical Mineralogy. John Wiley and Sons Part II. 551p.

WINKLER, H.G.F., and Von Platen, H. 1961. Experimentelle Gesteins Metamorphose V. Geochim. et cosmoch. Acta. v. 24 pp.250-259.

FIG. 3

Locality Map

Albite-bearing psammite = Ab

Calc-silicate assemblages (10)-(13) = (13)

Facing direction of sedimentary structures = good; questionable; m observed by Merh (1960)

Kyanite-bearing semi-pelite = Ky

Pyroxene-albite rock = Py

Measured folds = ①

Pelite

Semi-pelite

Psammite

Pyroxene-albite rock

Lewisianoid

Lithologic contact

Slide

Fold trace

Glen Strathfarrar

Creag Dhubh

Loch Tuill Bhearnach

Loch a' Choire Bhig

Mullach na Maoile 2482

Creag Feusag

Loch Mullardoch

Creag a' Bhaca

Toll Creagach 3452

Doire Tana 2884

Meall Mor

Meallan Odhar 2276

An Soutar

Liatrie

Loch Carrie

Loch na Gobhlaig

Meallan na Ceardaich

Muchrachd

Loch Craskie

Beinn a' Chairein 2119

Dog Fall

Glen Affric

Loch Beneveian

1 mile

O. T. Tobisch
1963
Ph.D. Geol.

GEOLOGICAL MAP OF THE GLEN CANNICH – FASNAKYLE FOREST AREAS, INVERNESS-SHIRE, SCOTLAND

LEGEND

- Pelite
- Semi-pelite
- Psammite
- Amphibolite
- Pyroxene-albite rock
- Dyke
- Lewisianoid

Lithological boundary:
- observed
- approximate
- conjectural

Orientation of the foliation

Fault

FIG. 44

Glen Strathfarrar

Loch a' Mhuillin

Meallan Odhar 2276

An Soutar 2118

2535

Glen Cannich Forest

Muchrachd

Loch Carrie

Meall Dubh

Lochan a' Mhuil Bhuibh

Tombuie

Beinn a' Chaisgein 2119

Coire Dubh

Loch na Dubhe

Loch na Gobhlaig

Allt Breighinn

Fasnakyle

Fasnakyle Forest

Sgurr na Lapaich 3773

Loch Tuill Bhearnach

Loch a' Choire Bhig

An Glas-Toll

3102 Creag Dhubh

3251 Carn nan Gobhar

2824

Creag Feusagach

2482 Mullach na Maoile

Allt Coire Eoghainn

Lubguish

Loch Seichheanich

Allt Mullardoch

Loch Mullardoch

CREAG A' BHACA

Toll Creagach 3451

2884

Meall Mor 2276

Meallan na Ceardaich

Achgate

Loch Benevean

Beinn a' Mheadhoin

57°20'

5°00'

MILES 0 1 2

KILOMETERS 0 1 2 3

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STRUCTURAL MAP OF THE GLEN CANNICH – FASNAKYLE FOREST AREAS, INVERNESS-SHIRE, SCOTLAND


FIG. 45

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