Frontispiece: Schichallion and Loch Rannoch.

# TECTONICS OF CENTRAL PERTHSHIRE

## (SCHICHALLION COMPLEX)

by:

N. RAST.

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# PART I.

# I. INTRODUCTION

## Location and Extent of the Area.

The area surveyed represents some 75 square miles of the ground between the villages of Kinloch Rannoch and Struan in Central Perthshire. It is bounded on the east partly by Loch Tay Fault and partly by an arbitrary, almost north-south line. The western boundary on the other hand is for the most part of geological significance in the sense that it has been drawn parallel and a quarter mile west of the line of main dislocation in the area. The southern and northern boundaries of the area are arbitrary east-west lines (Map 1).

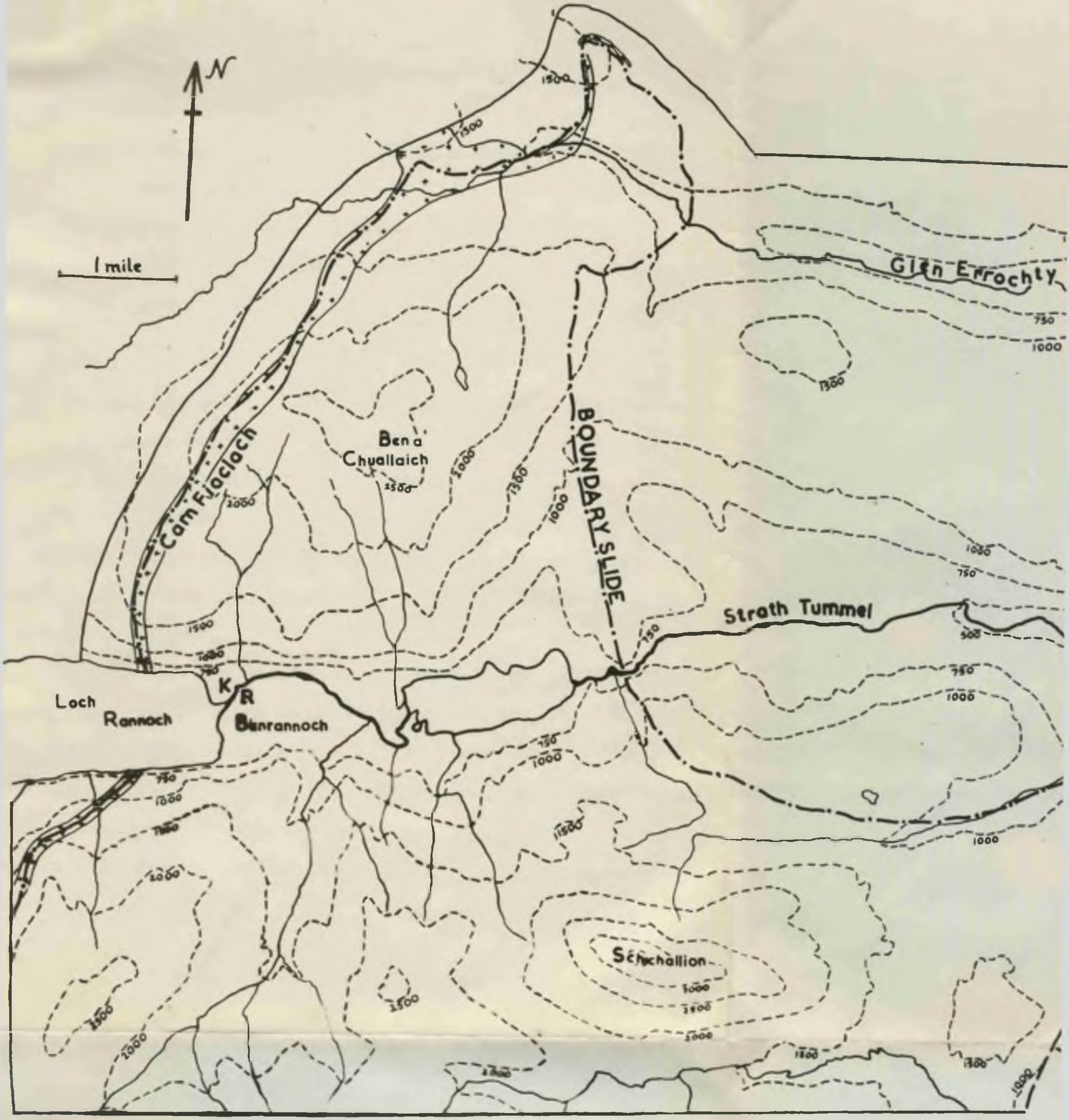
In general the western and southern parts of the area are mountainous rising up to and in the case of the peak of Schichallion above the 3000 ft. contour. The north east corner of the map forms lower ground, the hills not rising above 1600 ft. In addition traversing the ground from west to east there are two major valleys, Glen Errochty to the north and Strath Tummel to the south.

## General Geology

The solid rocks of this area consist largely of metamorphic rocks belonging to two systems :-

(a) Moine quartzo felspathic granulites
(b) Dalradian mica schists and quartzites.

The line separating the two is a fold-fault, which will be called the Boundary Slide. Of these the Moine granulites are by the general consensus of opinion the older formation. Intruded into them are the post-




**MAP 1 - BOUNDARIES OF THE AREA.**- Contours in feet above sea level. Cross ornament represents the extension of Carn Fiaclach sill. (KR= Kinloch Rannoch, K= Loch Kinardochy.)

orogenic minor igneous intrusions ranging in type from fairly acid felsites to diorite porphyries and lamprophyres. Such intrusions form relatively resistant topographical features of which the most conspicuous is the Carn Fiaclach ridge near the western boundary of the area.

Covering and in parts obscuring the solid geology are glacial morainic deposits and occasional boulder clay. In addition, fluvioglacial deposits are abundant in Bunrannoch, especially the part of the valley adjacent to Loch Rannoch, while the floor of Glen Errochty is mainly covered by drift. No special investigation of superficial deposits has been attempted

Physiography

The most outstanding single fact of physiographical significance is that the distribution of the two main metamorphic systems controls the topography. A glance on the Map 1 shows that the Dalradian rocks are those forming the high ground and the Moinian form the low ground. Evidently the reason is the resistance to the erosion shown by the Dalradian rocks, but is also supplemented by the existence of newer igneous intrusions at the Moine Dalradian boundary.

The influence of such intrusions is particularly well exhibited by the roughly triangular tongue of the Dalradian rocks projecting for some six miles northwards into the Moine country. This tongue will be called from here onwards the Dalradian Triangle and its western side is buttressed by the numerous intrusions of felsite and lamprophyre which form the high ridge of Carn Fiaclach. The eastern side of the Triangle is a wide outcrop of schists and limestones which form lower ground.

Within the Dalradian outcrops the topographic details are not by any means so simple. On the whole, however, when quartzite is massive, it is the most resistant rock and forms the high mountains of Schichallion (3454 ft.) and Ben a'Chuallaich (2925 ft.). However, when it is flaggy or develops a close jointing it seems to be less resistant than the adjacent schists, which are as a rule closely corrugated and do not develop a regular jointing system. When the flaggy quartzite is highly inclined its resistance to erosion is particularly low.

The larger rivers in the area do not show any particular relation to the underlying structure. Both Tummel and Errochty water flow in part parallel to the strike and in part across it. Minor streams, however, are to a greater or lesser extent adjusted to the structure flowing normally parallel to the strike. Some of the streams originate in certain high level lochs such is a stream which flows out of Loch Kinardochy, the latter being situated on a watershed (Map 1).

During the Ice Age the whole ground was covered by ice. The evidence for this is visible in glacial striae which are seen throughout the area, but especially well exhibited on the high quartzite peaks of Schichallion and Ben a'Chuallaich. Judging from the direction of these striae the movement over most of the area has been east to south-east.

<u>The Object of Study</u>.

The present work concerns itself almost exclusively with the ancient structure of the metamorphic rocks, as well as with the state and origin of their metamorphism. It is generally accepted that the deformation and metamorphism of Dalradian rocks is of Caledonian age and it is considered that the present study provides important additional data in interpretation of the geological history of the Caledonian Orogeny.

## II. OUTLINE OF THE PROBLEM.

### Previous Work

Apart from sporadic investigations of some special features of the area, such as Playfairs investigation of Schichallion quartzite (1811) and MacCulloch's comparison of the Schichallion Boulder Bed with the Port-Askaig Conglomerate of Islay (1819) no general work on the district was published until the beginning of the twentieth century. The first comprehensive account appears in the memoir of the Geological Survey of Great Britain for Sheet 55 (1905) where most of the area under examination was described by J.S.G.Wilson. A strip of about a mile wide and two miles long in the extreme south western corner is, however, included in Sheet 54, the memoir for which was not published until 1923.

The ideas in the Memoir for Sheet 55 were strongly influenced by the views of Cunningham Craig who envisaged a large scale unconformity within the Dalradian rocks. Such an unconformity was deemed necessary to explain the fact that the main quartzites of the Dalradian sequence were found to be adjacent to the various other members of the same sequence. This hypothesis was further strengthened by the presence of the Schichallion Boulder Bed, apparently at the base of the quartzite. The isolation of the outcrops of quartzite was interpreted in terms of isoclinal folding subsequent to the unconformity, each isolated outcrop becoming the core of a syncline. As a result of such a scheme the following succession of beds was proposed :-

Quartzite
Schichallion Conglomerate (Boulder Bed)
Unconformity
Blair Atholl Limestone
Black Schist
Ben Lawers Schist
Garnetiferous mica-schist (Ben Lui Schist)
Loch Tay Limestone
Pitlochry Schists
Green Beds
Ben Ledi Grits and Schists
Moine type.

These stratigraphical ideas were in conformity with the structural views advanced by Peter McNair (1903), whereby the structure of the Central Highlands was interpreted in terms of synclinoria and anticlinoria.

At the same time G.Barrow working to the east of this area conceived a different interpretation of the relations of the quartzite (1904). He suggested that the quartzite shows two "edges". One "edge" of the quartzite is associated with a black richly graphitic schist, which in turn is associated with a calcareous Ben Lawers schist. The other "edge" of quartzite is overlaid in an ascending order by the poorly graphitic Dark Schist and Blair Atholl Limestone. The "two edge" hypothesis of quartzite was further explored by E.B.Bailey and on his suggestion E.M.Anderson (1923) remapped parts of the present area. The succession established in his paper is essentially the one adopted by Bailey and McCallien in 1937, when the whole of the district was reassessed and mapping extended south to the slopes of Ben Lawers. However, certain minor modifications were introduced into the succession proposed by Anderson. Except for the removal of Becil Schist from Moine sequence, the present work does not show any justification for altering the succession advanced by Bailey and McCallien. This succession

Following p.6.

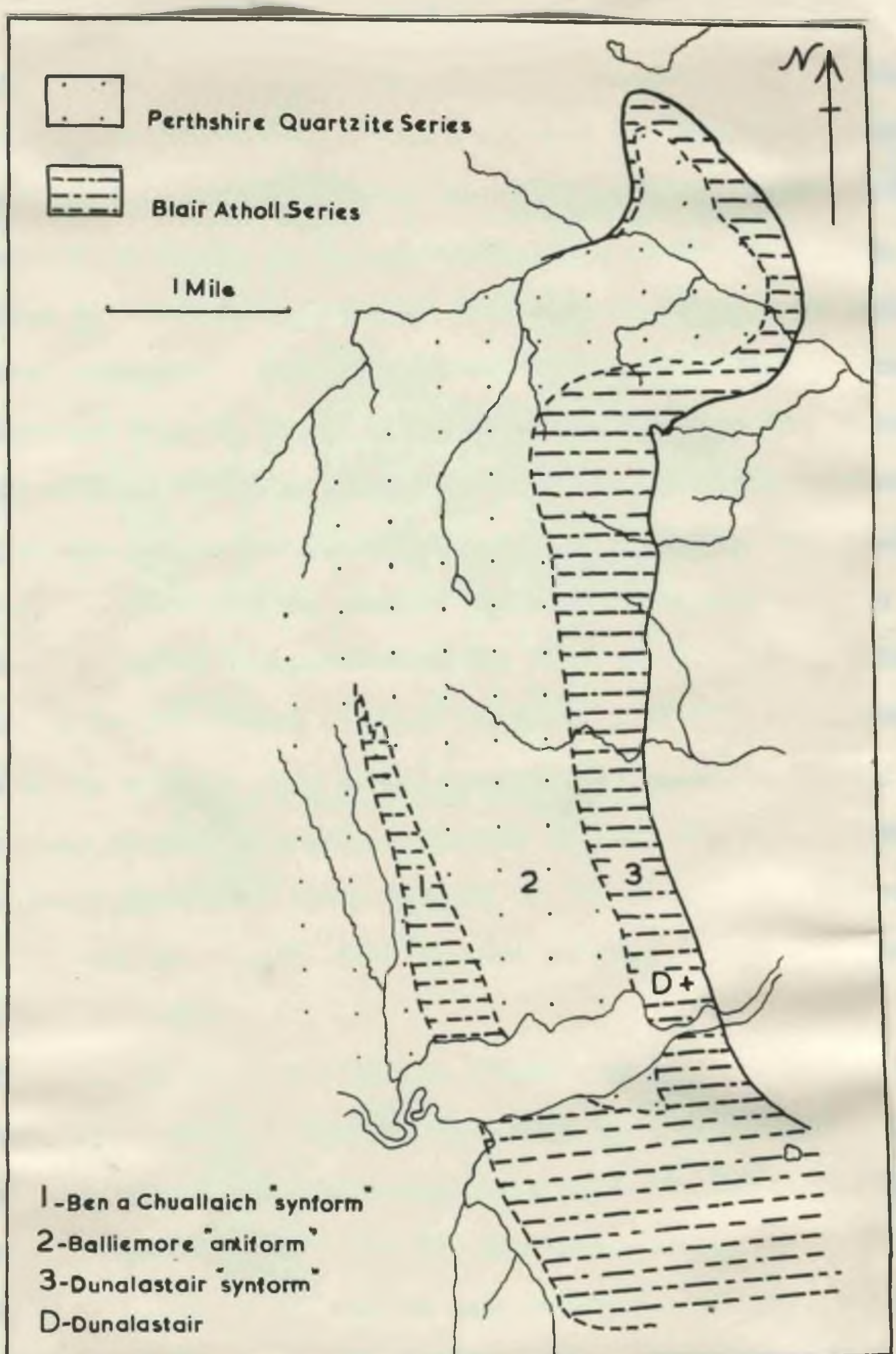
TABLE 1 - STRATIGRAPHICAL SUCCESSION

| Perthshire: Anderson 1923 | | Perthshire: Bailey & McCallien 1937 | Lithology (in Perthshire) | Islay |
|---|---|---|---|---|
| Ben Lawers Schist | | Ben Lawers Schist | Calcareous quartz mica schist with occasional thin quartzite and limestone bands. With the rise of metamorphic grade the impure calcareous bands are converted into a garnetiferous sedimentary amphibolite. | |
| Ben Eagach Schist | | Ben Eagach Schist | Dark graphitic schist, characterised by reddish weathering and submetallic lustre on fresh surfaces. | Jura Black Slates. |
| Carn Mairg Qte. | | Carn Mairg Qte. | Schistose quartzite which in parts coarse and pebbly and is generally less massive than the Schichallion Quartzite. | Main Quartzite. |
| Killiecrankie Schist | Perthshire Quartzite Series. | Killiecrankie Schist | Garnetiferous mica schist, which is in parts highly quartzose. | |
| | Perthshire Quartzite Series. | Main Schichallion Qte. | Massive slightly felspathic white quartzite. | |
| Schichallion Qte with intercalated Boulder Bed | Perthshire Quartzite Series. | Dolomitic Beds and the associated glometatic horizon. | The beds vary from dolomitic marbles to quartz, tremolite, phlogopite schists, and often have associated non-calcareous mica schists. The conglomerate is similar to the main Schichallion Boulder Bed, but is in general more quartzose | Dolomitic Beds.<br>Lower Quartzite. |
| | Perthshire Quartzite Series. | Schichallion Qte. | Massive greyish quartzite | ~~Port-Askaig Congl.~~ |
| Main Boulder Bed | Blair Atholl Series. | Main Schichallion Boulder Bed | A mixed series of conglomeratic lenticular bands, which in part are calcareous. Pebbles of pink nordmarkite are especially conspicuous | Port-Askaig Congl. |
| White Limestone | Blair Atholl Series. | White Limestone | Pale coloured dolomitic limestone with which there are some associated calc-mica schists. | Islay Limestone |
| Banded Group | Blair Atholl Series. | Banded Group | A group consisting of rapid alternations of bands of almost pure quartzite and schist | |
| Grey Limestone | Blair Atholl Series. | Dark Limestone | Grey marble with calc-silicate bands | |
| Grey Schist | Blair Atholl Series. | Dark Schist | Grey, slightly graphitic biotite schist | |
| Unrecognised | Moinian. | Beoil Schist ? | Very micaceous schist, with large porphyroblastic flakes of muscovite and biotite. Outcrops on the boundary between the Moine and the Dalradian rocks | |
| Struan Flags | Moinian. | Struan Flags | Flaggy quartzo-felspathic granulites. Variations in mineral composition are often obscured by the characteristic flagginess | |

together with general lithological descriptions of the rock types is shown on the table No.1.

Establishment of a succession in a structurally complex area does not by itself justify any inferences as to the order of deposition. Anderson (1923) argued that the order of deposition is such that the Blair Atholl Series is older than the Perthshire Quartzite Series. One of the main arguments was the existence of calcareous boulders within the Schichallion Boulder Bed. By itself an argument of this type is inconclusive. However, Bailey and McCallien were able to establish a very close correlation between the Dalradian succession of Perthshire and Islay, putting beyond any doubt the identity of the order of deposition in both areas. The low metamorphic grade and the comparative simplicity of structures on Islay allows an excellent preservation of original sedimentary structures such as current and graded bedding. Thus, there is a general agreement about the order of succession on Islay. Table 1 shows the correlation of Islay succession with Central Highland succession, and since the sequence on Islay is up from Port Askaig Conglomerate into Quartzite it is reasonable to suppose that the same applies to Perthshire.

Anderson proposed that the line separating the Dalradian from the Moinian rocks is a fold-fault. This was substantiated in detail by Bailey and McCallien who have called this particular structure the Boundary Slide. In the interpretation of the Dalradian tectonics, however, there was an important difference between the explanations advanced by Anderson on one hand




Map 2 - Ben a'Chuallaich and Dunalastair Cores.

and Bailey and McCallien on the other. Anderson suggested that the Dalradian rocks are overlying the Moinian in such a way that the structural succession is right way up. This implies that all the synclinal cores are composed of the younger formations and all the anticlinal cores of the older rocks. Bailey and McCallien on the other hand claimed that there is an important inversion of structural succession. Their argument was based on the inference drawn from certain exposures near the summit of Ben a'Chuallaich. According to Anderson when a core of Blair Atholl Series was traced to the top of the mountain, it was found to be surrounded anticlinally by quartzite. Bailey and McCallien on the other hand claimed that the pitch of the corduroy fluting which is abundant in the quartzite is parallel to the pitch of the fold, and since the inclination of the pitch which averages 30° trending 10-20° east of south is greater than the southern slope of the mountain, the structure must be a synform since the Blair Atholl core widens southwards (Fig.1). The term synform was used in a purely geometrical sense applying to the fold closing downwards. Since in this case the core is older than the envelope a large scale structural inversion must be postulated.

This synform was called the Ben a'Chuallaich synform. Another belt of Blair Atholl Series which is situated further to the east was called the Dunalastair synform and the intervening ground of the Perthshire Quartzite Series, the Balliemore antiform (Map 2). In addition Bailey and McCallien point out, that whereas on the western side of Dalradian Triangle the Dalradians for some distance overlie the Moinian rocks, to the south west of Trinafour the position is reversed. This according to Bailey and McCallien


Fig.1 - Contoured map and the topographical profile of Ben a'Chuallaich. Scale: 1in. = 1 mile.

implies a fairly large scale recumbent fold with a core of Dalradians and an envelope of Moines.

One of the most puzzling features of this area is a regional right angle bend of the strike; this Bailey and McCallien explain in terms of a subsequent twist. The development of the Boundary Slide was held to have been prior to the recumbent folding and twisting. Finally on the basis of a preliminary study of metamorphic zones the same authors were inclined to consider sliding as a post-metamorphic effect.

Problem to be Solved

Despite the fact that Bailey and McCallien's work was a considerable advance on the pre-existing knowledge of the district it owed much to the preceding publications of Wilson and Anderson. In a similar fashion the present study starts from the problems left over by Bailey and McCallien.

The most important problem of all is the nature and origin of the right angle deflection of strike, which in the general region further to the east, south and south-west is consistently west south west to east north east.

No satisfactory explanation has been advanced by any of the previous workers. Wilson suggested that the deflection was related to subterranean intrusions of hypothetical igneous bodies. He did not think that any post-folding movements could account for such a modification of the general Caledonoid strike. Indeed it is very difficult to envisage torsional movements of the type suggested by Bailey and McCallien which operated subsequent to the original folding. Anderson approached the problem very cautiously.

He pointed out that there is a general relationship between the dominant linear foliation, which he discovered in many parts of the area and the curvature of the strike. While, he thought, that the linear foliation is related to a flow of some kind he left the problem open.

The present work is centred round this particular problem which is not only of a local but of regional importance, since such right angled deflections of strike are noticeable features of the Grampian Highlands, occurring for instance in Tomintoul district of Banffshire, Ben Vrackie of Perthshire and Loch Creran of Argyllshire.

The theoretical aspects of the study are also of relevance to the question of the relationship between lineations and folds.

The other problem of regional importance is the relation between the structure and metamorphism. Bailey and McCallien's inferences about the time relations between the movements and metamorphism were based on relatively few observations, and a more detailed study was clearly desirable.

Apart from such regional aspects several local complications were left unsolved by the previous workers. One of these arose from the tectonic synthesis advanced by Bailey and McCallien, and apparently has escaped their notice. If the Ben a'Chuallaich fold is indeed a synform, then since according to the map produced by the authors there is no tectonic hiatus within the Dalradians of the Triangle the inversion of the sequence at Ben a'Chuallaich implies that the whole of the Dalradian sequence of the Triangle is structurally inverted and yet they overlie the Moine granulites at the western side of the triangle and underlie them at the eastern side.

Mapping leaves no doubt that the Ben a'Chuallaich structure is a fold, so the only explanation for such a situation is that two episodes of recumbent folding are represented. Clearly this possibility needed to be examined.

Another problem of considerable interest was the status of Beoil Schist which has been tentatively included in the Moinian sequence. The universal parallelism of the Schist with Boundary Slide implies simple structure in the Moines, which for a number of reasons is improbable.

Several approaches have been employed to solve these problems and before the proposed solution is advanced the methods used in this research are described.

## III. METHODS OF INVESTIGATION

### Mapping

The area was mapped geologically on 1/10560 (six inches to a mile) scale, though locally more detailed maps were constructed. The emphasis throughout was on metamorphic rocks, but major igneous masses were mapped as well. Because of the limitations of scale and time very small bodies of horn blende schist and epidiorite were not mapped. Some smaller igneous intrusions likewise have not been traced. The broader tracts of drift and alluvium are marked on the map, but no systematic delineation of all superficial outcrops has been attempted.

For most of the ground contours projected from the 1 inch topographical maps were used. These were found to be not entirely accurate in the western parts of the area and some approximate contouring using an Abney level has been done. Positions were determined on aerial photographs and frequently checked by compass readings.

### Structural Observations

Throughout the investigation it was considered that the minor structures would provide a clue to the major structures. Consequently the latter were especially investigated. All the minor structures could be divided into two major groups :-

(a) Planar structures (b) Linear structures.

Dip and strike measurements were made on planar structures which included bedding, foliation, schistosity and "flagginess". Some joints were also measured but no special investigation of jointing has been carried out. Altogether more than 4,000 observations on planar structures were recorded. A compass and a clinometer were used for this purpose.

Trend and plunge of the minor linear structures were recorded. The latter included folds, lineations of various kinds, which have been classified and differentiated, and occasional glacial striae. Most measurements were done using a compass and a clinometer. On steep overhanging surfaces the measurements were made using stereographic constructions as advocated by McIntyre (1951). Measurements of some three thousand minor structures were taken.

All structural measurements were carried out to the limit of $1^{\circ}$, though on the whole it is likely that such accuracy except in special cases is not warranted.

In addition in so far as folds were concerned a record was made of varieties of styles encountered in the field.

Mineralogical and Laboratory Studies.

In general mineralogy of the main rock types of the area is sufficiently simple to enable identification in the field. The existence of frequent pelitic bands enabled the author to produce a map ($S_3$) of metamorphic zones. This part of study was supplemented by some 400 thin sections, which were found especially useful in tracing the kyanite zone in the western parts of the area where the rocks have suffered a mild retrogressive metamorphism. In addition, the thin sections were used for deducing the relations between deformation and metamorphism as reflected in textural modifications.

Several petrofabric diagrams were constructed but no special study of petrofabrics has been undertaken. It has been assumed that unravelling of macro-structures on their own merit may provide a better basis for future petrofabric studies. On the other hand several orientated specimens were sectioned and used to supplement structural inferences.

Descriptive Arrangement of the Thesis.

While the ultimate significance of the minor structures depends on elucidation of the structural history of an area, there are several relatively simple geometrical relationships between the minor and the major structures that have to be presupposed before a major structure could be defined geometrically.

It has been found that the establishment of such geometric relationships can not be done on the sole evidence found in Central Highlands and data collected from other areas had to be used. In particular Clough's work on Cowal (1897) makes many structures intelligible. His observations supplemented by observations and deductions from Central Highlands form the basis for interpretation of major tectonic features of Schichallion complex. It seems thus justifiable to define and describe the minor structures found in the area separately from the main theme of the thesis. Such general account of minor structures and the methods of investigation based on them will be included in the remaining three sections of Part I.

In Part II the structure and tectonic history of the area will be described using the methods and results outlined in Part I.

Part III is reserved for the study of metamorphism and the distribution of metamorphic zones in the area, as well as their relation in space and time to the structural pattern described in Part III. Some related post-orogenic events will be also included in this part.

Abbreviations

To avoid the repetition of cumbersome phrases several abbreviations are introduced as follows :-

(a) From now on the area which has been mapped and is shown on the map $S_1$ in the folder, will be designated with a capital A and referred to as the Area.

(b) The tongue of Dalradian rocks projecting northwards into the Moines and characterised by north north west to south south east strike will be called the Dalradian Triangle or where a possibility of misinterpretation does not exist, the Triangle. Its most northerly point will be called the apex of the Triangle.

(c) In order that particular localities are simply and easily identified a locality map is prepared and is in the folder ($S_2$).

Any particular locality mentioned in the thesis usually has a bracketed code number attached to it. The initial letter and the first numerical after it refer to a grid square immediately identifiable on Map $S_2$. The two other numbers separated by commas refer respectively to horizontal and vertical co-ordinates within each individual square. Since on the scale at which the squares are drawn (1 in. side) it is difficult to do measurements of an accuracy higher than .01 of an inch, all the grid numbers are measured to this limit which in terms of actual distances on the ground imply an accuracy within fifty feet.

# IV. PLANAR STRUCTURES

## Introduction

The term includes planes of bedding, foliation, schistosity, "strain slip", "flagginess" and joints. The problem of the joints has not been investigated in any detail. The other structures and their relations to each other will be described in this section. In so far as the terminology is concerned as far as possible the common British use of the words is followed. The use of the term S- surface for planar structures, while has the advantage of being non-genetical, tends to hide the differences between the various structures and is in general unsuitable for description of macroscopic structures. In consequence, except where a reference is made relevant to the subject of petrofabrics the term is avoided.

## Bedding

In metamorphic terrains it can not be assumed a priori that the most conspicuous planes of lithological difference represent the original planes of bedding. Colour banding has been suggested to represent bedding in psammitic rocks. While possibly this statement is correct, unless some signs of primary sedimentary structures are present a final evaluation of such banding has been left sub-judice. The principal sedimentary structures that are helpful in this respect are :-

(a) Current bedding (b) Graded bedding (c) Slump bedding.

Of these, graded bedding if well developed is probably the most reliable. Current bedding unfortunately can be easily confused with certain types of sheared out folds and vice versa. Slump bedding is even less reliable as the possibility of confusion with tectonic folds is considerable.

It must be pointed out that even if the sedimentary structures are plain and unmistakable and prove a particular band to be a bed, it is not always safe to assume that its relations to the adjacent layers are necessarily stratigraphical, since as pointed out by J.F.N.Green (1931) close folding and a preferential elimination or thinning of limbs could account for an apparent succession of layers which is unrelated to stratigraphical order of deposition. According to the type of folding two cases may arise :-

(a) Lower limb is preferentially thinned and what appears as a succession is a pack of fragments of one and the same strati graphical layer (Fig.2a).

(b) Upper limb is preferentially thinned. Any relict sedimentary structures would indicate a succession in a reverse order from the original (Fig.2b).

Both types of folds were observed in the Area where in general they are devoid of minor sedimentary structures of any kind.

## Schistosity and Cleavage

The term schistosity is restricted here to the dominant planar orientation of conspicuous platy minerals such as micas and chlorites. Rarely amphibole bearing rocks are marked by planar rather than linear orientation of that mineral. In such cases the term schistosity is again

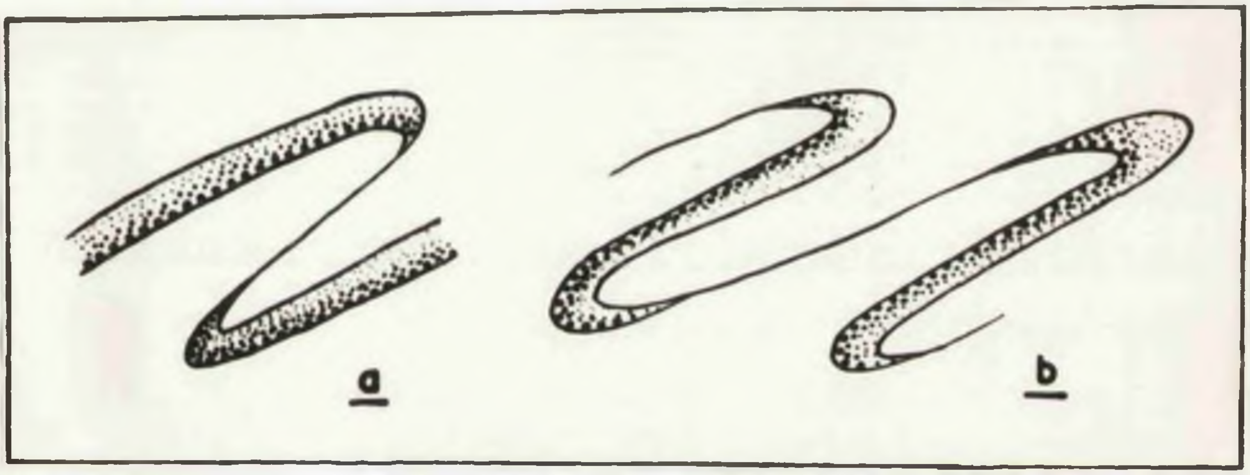



Fig.2 - Graded bedding in closely folded psammitic layers.

a - Preferential thinning of the lower limb.

b - Preferential thinning of the upper limb.

applicable. On the other hand all the cases of closely spaced fractures and joints are excluded unless such fractures are conspicuously lined by micaceous minerals.

American structural geologists such as Leith (1923) and Van Hise (1898) used the term schistosity and slaty or flow cleavage in the same sense. In common with Harker (1939) they distinguish two types of cleavage:-

(a) Slaty cleavage recognized by planar orientation of minerals.

(b) Fracture cleavage recognized as a system of closely spaced fractures.

Slaty cleavage and schistosity were assumed to have been produced by deformation by flattening. At least in so far as the unit represented by the fold itself is concerned the theory is widely applicable, since among other features it explains the dominant development of slaty cleavage parallel to the axial planes of folds. This direction is easily correlated parallel to the AB plane of the strain ellipsoid (Fig.3a).

The supposition that schistosity is universally a direct heir of slaty cleavage is untenable as the analysis of schist shows that the same fragment of rock often possesses several schistosities.

In the Area the most conspicuous schistosity at any point is almost invariably parallel to the axial planes of local minor folds when such are visible. This is most conspicuous where the general dip is high. Where the general dip of the formations is low schistosity at first sight appears to be subparallel or parallel to the compositional banding. Turner (1940) points out that an analogous case in New Zealand has to be explained by

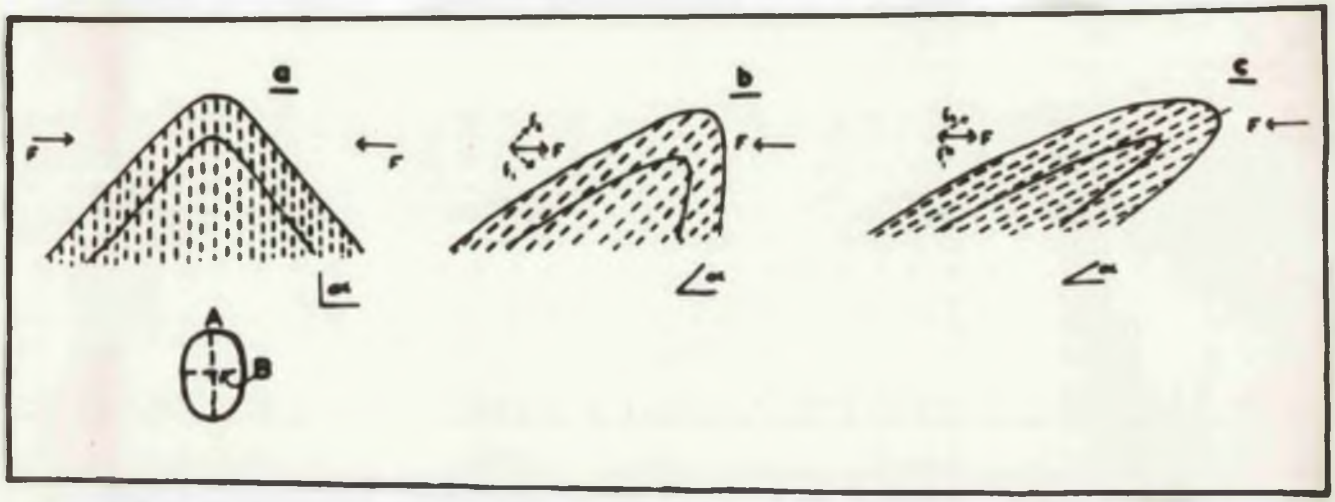



Fig.3 - Stages in evolution of cleavage in a fold

a - Development of cleavage in a symmetrical fold and at right angles to the compressive forces F.

b & c - Progressive recumbency is resulting in concentration of the shear component f.2 along the plane of cleavage.

F is assumed to be the regional force and $\alpha$ is the angle that such regional force makes with the cleavage of the fold. As the angle $\alpha$ decreases f.2 (shear component) increases.

recumbent folding and horizontal transport. He denies the probability of load metamorphism as advocated by Daly (1917).

As a general rule Turner's ideas are applicable to the Area, the apparent schistosity on bedding being axial planal to the isoclinal recumbent folds. Exceptionally, schistosity on bedding follows the closures of folds. Several cases of this phenomenon were observed in parts of Banded group where there are thin pelitic layers with dominant psammitic bends. Movement of flexure slip type accounts for such cases.

Where the schistosity is at low angles to the compositional banding it is often possible to see that it is also a plane of pronounced shear and the more recumbent the associated folds are the stronger is the shear.

Observations made on similar phenomena elsewhere have led to the main objection to schistosity being parallel to AB plane of the strain-ellipsoid. Suggestion was made by Becker (1893) that such schistosity corresponds to a plane of no deformation which is oblique to AB plane of the strain ellipsoid. It still remained necessary to explain why typically the most dominant plane of schistosity is a single plane, whereas there are two planes of no deformation in a strain ellipsoid, and why such schistosity is axial-planal. The relation between recumbency of folds and shearing on the axial planal schistosity tends to indicate that a two stage process could be envisaged in the case of such schistosity in the Area :-

1. Development of a symmetrical fold (Fig.3a) where schistosity is approximately parallel to the axial plane.

2. Progressive recumbency of the fold which causes concentration of shearing stress parallel to the planes of schistosity producing slip (Fig.3b).

Superficially the overturning of the fold can be visualized in terms of a rotating ellipsoid. Movement on a series of planes, however, can not be explained by appeal to the strain ellipsoid as deformation is much more akin to plastic. So even the simplest recumbent fold and the attendant schistosity have to be explained in terms of two phases. In the first the deformation was approximately elastic while in the second it was plastic. In the first phase the main process was the flexure of the band and in the second the shear of the same band.

The simplest case just described has more complex ramifications. If the planar structure which was folded is a pre-existing schistosity or more rarely a very close succession of very thin alternating bands of pelitic and psammitic material, the distance between each two planes of schistosity is of the same order as half of the wave length of the folds produced. This has been often called the strain slip cleavage (Fig.4). The space in between each two planes of such cleavage is packed with little puckers, and often it is possible to observe that as the folding proceeds to become recumbent shear concentrated on the planes of cleavage separates the equivalent puckers one from the other. Such puckers have been called "Totfalten" by Ampferer (1922) and have been admitted to be sheared flexure folds. Certain folds in Cowal show the existence of such "Totfalten" at the crests of larger folds the limbs of which show obvious shear parallel to the planes of schistosity (Fig.5). It is this observation (see King and Rast 1955a), which suggests the probability of at least some shear folds representing the last stage in evolution of flexure folds. In line with definition

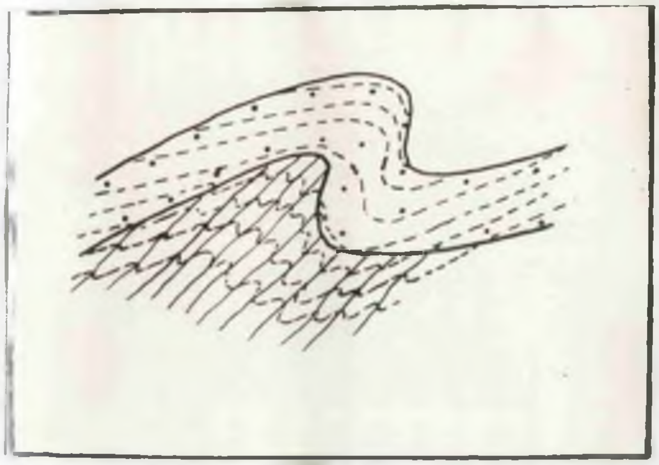


Fig.4 - Strain slip cleavage.

The broken lines indicate an earlier cleavage; the strain slip being represented by slightly irregular solid lines.

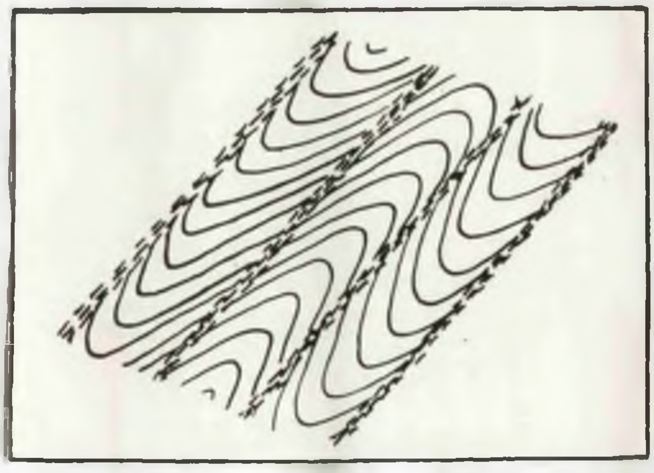


Fig.5 - "Tot falten"

A later stage in the evolution of strain slip cleavage.

of schistosity advocated in this thesis the strain slip cleavage if it is conspicuously lined with micas here will be called the strain slip schistosity. The development of "strain slip" schistosity is accompanied by fine crumpling of micaceous layers involved in folding. Such crumplings with their slightly irregular but essentially parallel elongation in the direction of axes of larger folds will be later on described more fully. They are normally closely folded planes of pre-existing schistosity. There is little doubt that such crumplings have been produced by compression and being typical of phyllites they can be called the phyllitic lineation.

Schists and phyllites with a well developed planar structure often develop another structure which in cross section could resemble the phyllitic lineation. The structure has been called the strain band and occasionally confused with strain slip schistosity. The band is a monoclinal double buckle (Fig. 6), which has an unusually long linear dimension parallel to the axis of buckling and in this respect differs noticeably from strain slip crumples. The strain slip crumples typically show the ratio $a/l = 1/10$ where a is the amplitude of the crumple and l is its elongation parallel to the axis. The strain band buckles measured in the Beoil schist had the ratio of $a/l$ of the order of 1/100 to 1/500 and no doubt, even more extreme cases exist. The deformation along strain bands only occasionally ends by production of simple monoclines. In the field they are often found to show eventual overturning and a concentration of shearing soon takes places at the apecies of the buckles giving rise to schistosity, since the planes of shearing are almost inevitably lined by micas. In psammitic rocks the stage

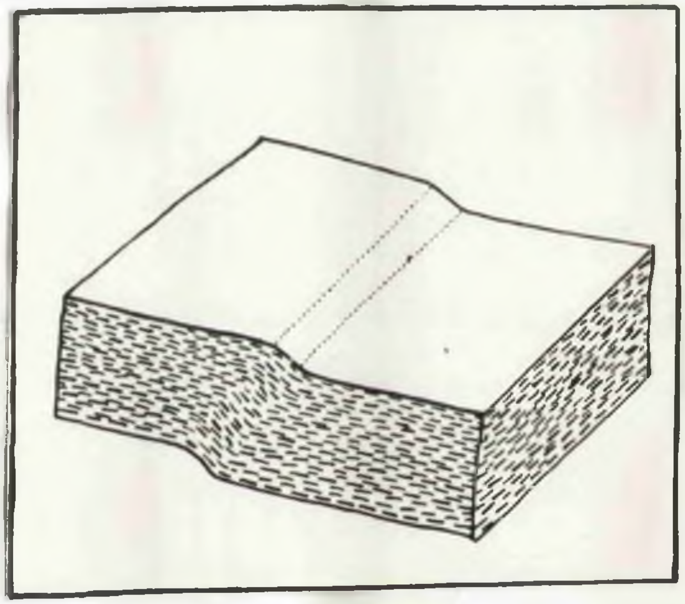


Fig.6 - Diagrammatic representation of a strain band.

at which overturning occurs does not develop easily and instead the rock fractures through a system of closely spaced faults parallel to the axial planes of strain band buckles. This is evidently the fracture cleavage of Harker and others. The possible mechanical cause to be suggested for the initial phase of formation of the strain bands is shearing. Indeed such an explanation is demanded since as the Fig.7 shows points such as C and D have moved towards each other in a horizontal sense and away from each other in a direction oblique to the planes of schistosity or bedding in the rock. Evidently as suggested such shear does not take place parallel to the AB plane of strain ellipsoid. The evolution of strain bands can be again explained in terms of two phases.

(1) An essentially elastic stage resulting in formation of buckled monoclines.

(2) Provided the rock is capable of plastic deformation, overturning occurs and a schistosity develops which has a different geometric relations to the buckled material from that characteristic of strain slip (Fig.8). This will be called the strain band schistosity. If, however, the work is psammitic it behaves as a brittle substance and fractures supersede the development or initial buckles.

In all the cases discussed the schistosity in its ultimate character can not be compared with either slaty or false cleavage proposed by Harker (1939, pp.152-162), since the initially different processes give rise to ultimately similar structures, once the concentration of shear promotes the growth of platy minerals. The development of such minerals

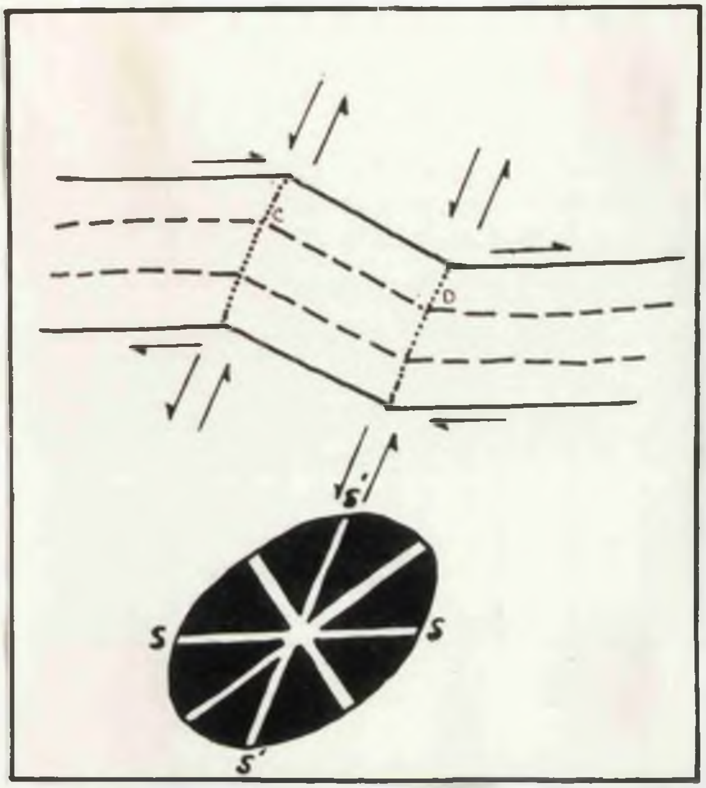



Fig.7 - Relations of a strain ellipsoid to a strain band. Arrows represent shear stresses. SS and S'S' are the surfaces of maximum shear.

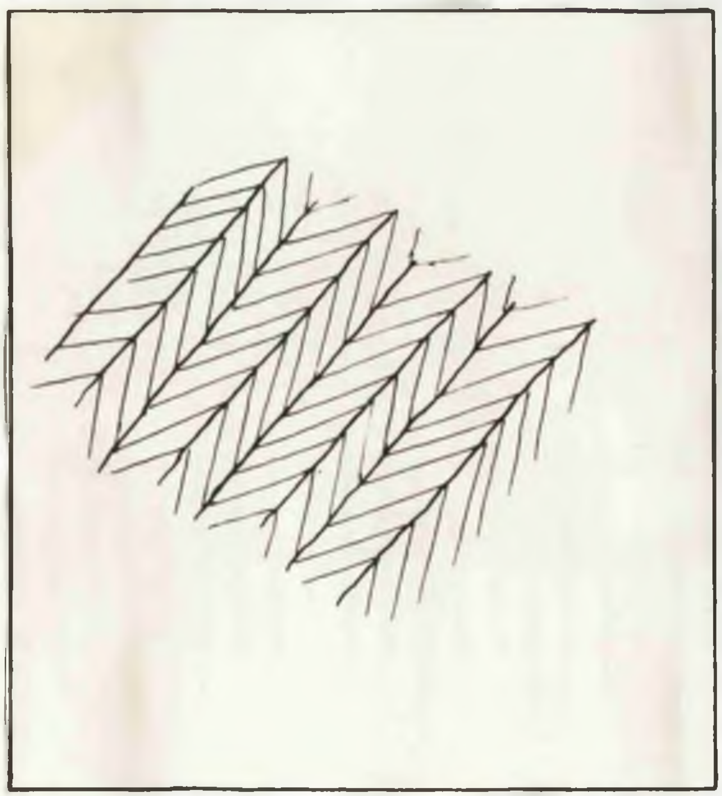


Fig.8 - Strain band schistosity, represented by thick lines.

during the plastic phase is in a sense mimetic, since they utilize the planes of shear predetermined by a preceding phase of deformation. If, however, by mimetic one implies the type of growth which is entirely post-tectonic then the term as a general rule is not applicable. The tendency of thickenning of schistose layers with deformation and shear clearly indicates that deformation and mineral reconstitution go hand in hand. In this respect there is considerable evidence presented by Clough from Cowal (1897, p.26). He points out that the development of the planes of strain slip and the growth of minerals on them finally give rise to a type of banding which is far more prominent than the relicts of bedding seen here and there in the shape of less deformed resistant psammitic bands and sheared out lenticles between the planes of schistosity; which by then have been so thickened with accumulated mica as to achieve the status of foliation. Such pseudo-bedding could after careful examination be differentiated from the actual bedding in the relatively low grade metamorphic rocks of southern Cowal. With the increase in metamorphic grade which occurs northwards the last relicts of bedding disappear, leaving foliation which has been produced on the planes of schistosity masquerading as bedding.

Multiple Schistosities.

In the account of development of schistosity so far as important simplification has been introduced. The recumbency of a particular set of flexure folds or strain band monoclines has been treated as a final result of deformation. Throughout the Area there is considerable evidence that such is not the case. Again the understanding of the observed phenomena has been gained via structural considerations put forward by Clough (1897 pp.9-29) from Cowal. Clough noticed that the initial schistosity can be folded again and affected by strain slip. Eventually the strain slip gives rise to a new schistosity, but even this schistosity does not represent the last stage in deformation, as it gets folded twice more, each new episode being associated with a new schistosity. All four episodes of deformation in Cowal are attributable to a continuous maintenance of more or less uniform regional forces, as the strikes of all schistosities are approximately the same and parallel to the Caledonoid direction, and as each episode proceeds to recumbency there is a final correspondance in dip values as well. These observations provide one of several explanations for the existence of multiple planes of schistosity or the S- surfaces of writers on petrofabrics. For instance starting from the simplest possible case of axial planal schistosity with no micas on the bedding plane we can detect IS surface (Fig.9a), but if this S surface is in itself folded and a new schistosity develops, two extra S surfaces are produced (Fig.9b). In Central Perthshire the metamorphic grade is high and the schists have been subjected to strong recrystallization often loosing the evidence of bedding hence dating of schistosities is not so simple as in Cowal. It is a common field experience, however, that micas, even where the megascopic plane of schistosity is pronounced, do not have an absolutely planar orientation; instead, they show a complex sub-rhomboidal arrangement. On close inspection

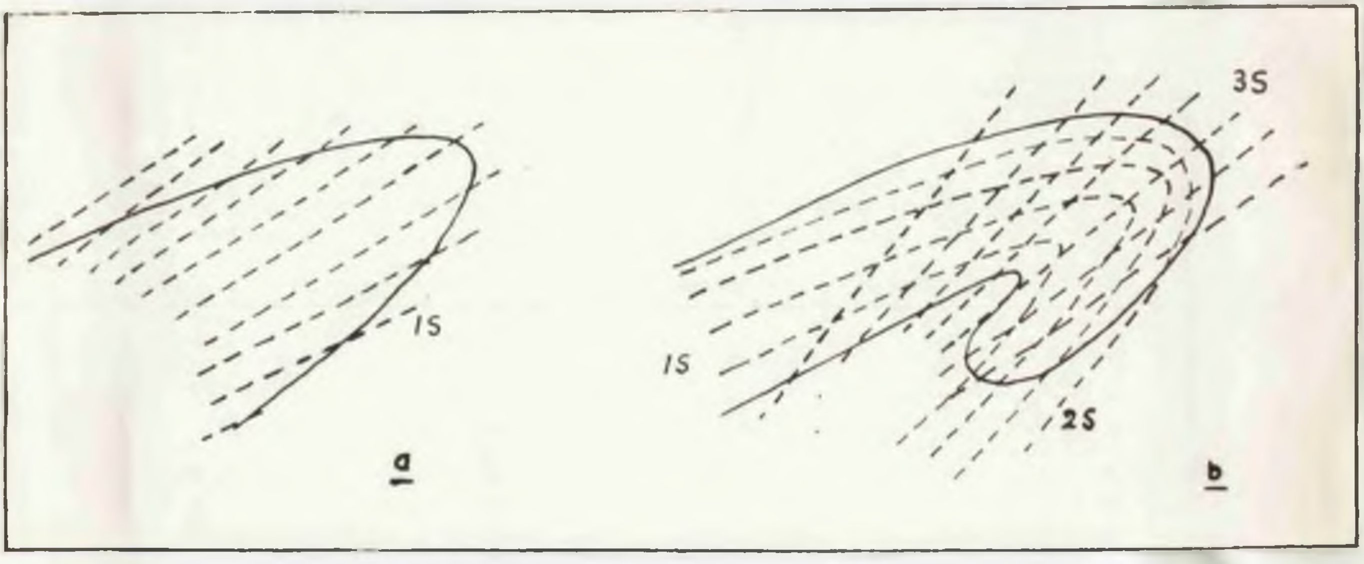



Fig.9 - The evolution of multiple schistosities.
On refolding of the original schistosity IS (a) two additional schistosities 2S and 3S come into existence.

of the polished orientated specimens several planes of inclination of micas were found. It is probable that the present orientation of the micas in such schists is the result of several episodes of a continuous series of deformations. In such a case the present schistosity is a compromise effect of these deformations and may be called after Turner (1945, p.280), the "compromise schistosity". For instance a specimen of Killiecrankie schist collected from Meall Dearg (Pt.B7,56,77) shows on superficial examination only one pronounced plane of schistosity. A composite petrofabric diagram of the same schist reveals the presence of at least 6S surfaces (Fig.10) of which three intersect at small angles on the axis b and the three other less important S surfaces intersect on the axis b. It is very probable that the explanation lies in the hypothesis of multiple foldings, which has been outlined on the preceding pages.

Foliation.

The term foliation is used here in the sense normally applied by British geologists. It implies compositional banding and as such is different from schistosity. Foliation can not be everywhere distinguished from bedding, but two main types of foliation can be in general recognised in Central Highlands.

(1) Bedding foliation, which either reflects the original bedding or represents planes of mineral segregation that occur parallel to the bedding.

(2) Schistosity foliation, which is localised on the pre-existent planes of schistosity. As pointed out in the preceding pages such foliation depends largely on the tectonic control.

Following p.26.

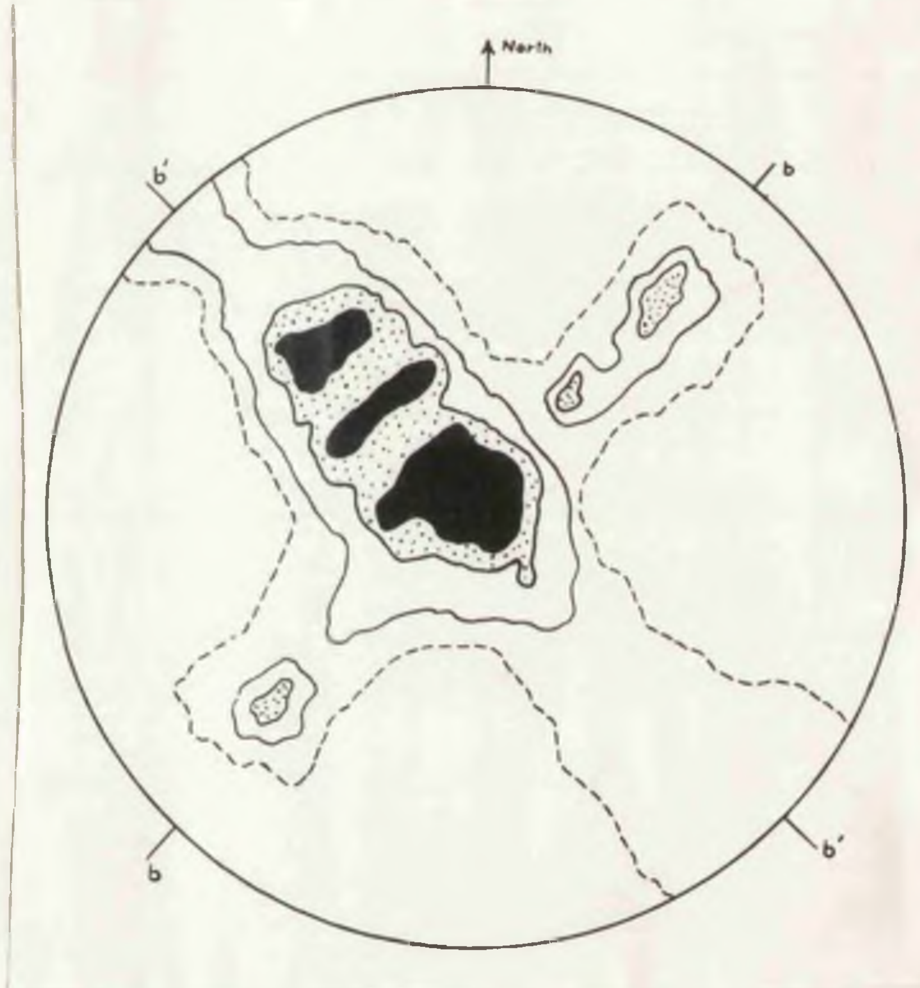



Fig.10 - Petrofabric diagram of Killiecrankie Schist
from Meall Dearg.
Biotite, poles of (001) for 300 flakes.
Contours 12%, 6%, 1%, 0.5%, per 1% area.

In high grade gneissose rocks other types of foliation evidently exist and mechanisms such as permutation by magmatic solutions, lit par lit injection, differential melting and diffusion have been suggested responsible for their origin.

Schmidt (1932) advocated purely mechanical processes responsible for foliation in low and medium grained schists. However it seems likely that the most successful mechanism in these rocks is metamorphic differentiation due to metamorphic diffusion. Such mechanism was suggested by Turner (1941) for the low grade schists of New Zealand. Clough (1897, p.22) long before pointed out that the growth of micas on the planes of strain slip "must imply a molecular change throughout".

Relations between Bedding, Schistosity and Foliation.

Whereas in the sequence of upright isoclinal folds of weakly metamorphosed rocks the discrepancy between schistosity and bedding is common the reverse is not infrequent in schists. Several factors bringing this position about have been already pointed out, but at this stage it is convenient to systematise them under two general sub-headings.

1. Masking effect of "compromise schistosity" - The size of micas in schistose rocks is often of the order of thickness of laminae of bedding or a weak foliation. Since lithological differences between such laminae are often slight they are masked by the much more conspicuous orientation of micas and are not normally detectable except on very smooth polished surfaces. This applies especially to semipelitic types of Moine granulite. Bedding is

seen as a rather inconspicuous colour banding only where the rocks have been polished by the action of water. An especially good example of this phenomenon is seen on the northern shore of Loch Rannoch, 1 mile west of Kinloch Rannoch (Pt. A6,75,94). On the beach, the water-worn surfaces of the rocks show a most intricate folding with dominant schistosity being parallel to the "flagginess" of the granulite. A few yards above these, in the rough granulites by the roadside no other structure, except "flagginess" can be detected. Similar conditions prevail in Dalradian schistose quartzite and micaschists east of this locality. These rocks in the field often do not appear to possess any structure except a uniform flagginess, yet frequent folds can be seen in cross-sections cut in the laboratory. Such folds are recumbent in style and do not fold the flaggy layers themselves.

2. Shearing out of limbs and apicies of folds. - It has been already pointed out that one of the effects of progressive recumbency is concentration of shear on the planes of schistosity giving rise to an eventual foliation. On the very small scale of the "Totfalten" this shearing takes place on both limbs of overturned folds simultaneously, since each plane of schistosity is a plane of equivalent shear. With strain bands two alternative possibilities occur as follows:-

(a) Shear concentration on both buckles of the monocline, a state of affairs already illustrated on Fig.8. This case is especially characteristic of single monoclines.

(b) Shear concentration on lower buckles of the monoclines (Fig.11). This type frequency occurs where there are many monoclines one after the other. The apices of such corrugations are usually very much sharper than of those associated with strain slip schistosity.

Fig.11 - Shear concentrated on the lower bands of the strain bands.

At a stage in deformation when the evidence of schistosity indicates a pronounced shearing the effect of it is not confined to the very small scale structures. Larger folds also show the evidence of shearing, and give rise to the following styles :-

(a) Concertina folding with sheared out limbs of harder units - Banded group south of Lassintullich often show this type of deformation (Fig.12a). At this extreme stage of deformation the succession tends to be of the same order of thickness as previous to the folding.

(b) Extension shear folding when the lower limb of the fold is preserved. Many cases of this style are known from Killicrankie Schists south-west of Kinloch Rannoch. In this, as in the previous case the dip of schistosity closely approximates the dip of the formation as a whole (Fig.12b).

(c) Schistosity shear folding when the shear has concentrated on the closely spaced planes of schistosity as in Fig.6.

(d) Shearing out of both limbs of the unschistose member of a succession. For example a sheared out fold of amphibolite from Allt Mor near Kinloch Rannoch (Pt.B5,97,47) (Fig.12c).

The extreme style of shearing is evidently associated with the last stages of deformation involving an appreciable recumbency. Throughout the Central Highlands this type of deformation becomes dominant as the Moine-Dalradian boundary is approached and is characterised of the Moines themselves. (See King and Rast 1955b). It gives rise to a characteristic flagginess of the rocks near this boundary. Barrow has coined the term "Moine phase" as an expression of this style. However, the term shear tectonics seems to be more appropriate despite its genetical connotations. The areas characterized by shear tectonics show more or less platy schistosity which is often of a "compromise" type. These areas also show numerous sheared out folds and where shearing is less intense the folds are clearly recumbent with the average dip of schistosity, bedding and foliation being the same.

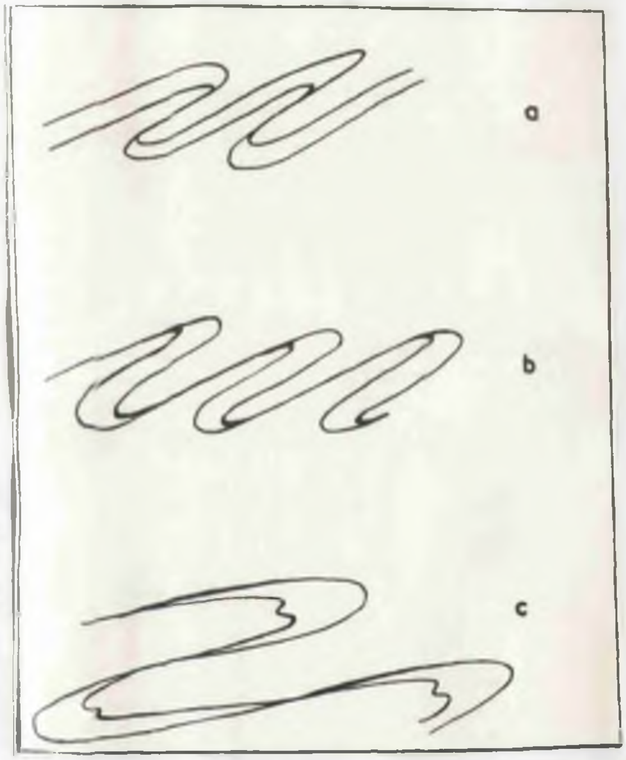



Fig.12 - Styles of systems of recumbent folds.

a - Lower limb eliminated.

b - Upper limb eliminated.

c - Both limbs eliminated.

# V. LINEAR STRUCTURES

## Introduction

The most important linear structures are minor fold, but since the explanation of their geometrical variety depends largely on theoretical considerations it is convenient to remove them to another section. In this section the main varieties of lineations will be described bringing in the examples noticed in the Area.

## Lineation and its Types

While the term lineation according to Cloos (1949, p.1) includes all the linear structures irrespective of their origin in this thesis the main concern is obviously with the lineation produced by structural deformation in metamorphic rocks. In the same memoir Cloos has devised a comprehensive scheme of classification of lineations. The scheme is largely genetical and includes some 15 different types. Since, however, the origin of some of the lineations met with in metamorphic rocks is still in dispute, it seems advisable to sub-divide the lineations encountered in the Area according to their morphological characteristics. Such a sub-division is necessarily just a working field classification.

Apart from the minor folds seven types of lineations have been recognized in Central Perthshire. They are as follows :-

1. Preferential elongation of minerals
2. Stretched pebbles
3. Phyllitic lineation
4. Intersections of planar structures
5. Grooves and slickensides
6. Mullions
7. Boudins and Tectonic inclusions.

Preferential Elongation of Minerals.

Growth of acicular minerals in such a way that a majority of individual crystals point in the same direction is a very common phenomenon in metamorphic rocks. In the Central Highlands hornblende schists of a presumed igneous origin show this par excellence. The degree of parallelism varies with mineral content, but also probably with type of deformation. Presence of porphyro blasts of garnets usually disturbs the regularity of orientation and the acicular hornblendes tend to wrap round the equi-dimensional garnets. Such irregularity is even more pronounced when these garnets show signs of rotation contemporaneous with growth, which are seen in the development of S trends of inclusions within the garnets.

Presumed sedimentary hornblende schists as a rule behave differently. The calcareous Ben Lawers schist is especially prone to develop sedimentary amphibolites, which at first appear as a "Garbenschiefer" type of rock in which actinolitic amphiboles form laths of up to 3-4 cms. long. The individual laths in these rocks grow on planes of schistosity and do not show any preferred linear orientation. The groundmass in such rocks consists of quartz, calcite, epidote, chlorite, plagioclase and accessory zoisite and sphene. Micas and ores also occur frequently. With the increase in metamorphic grade these minerals are usually converted into some more hornblende and almandine garnet, the final product being a coarse hornblendic rock in which the amphiboles still possess a lath shaped habit and do not develop a specially conspicuous lineation.

Apart from hornblende schists few other rock types show this type of lineation. A porphyroblastic scapolite schist near Lassintullich (Pt.E6,50,20), however shows a similar type of growth of scapolites. In this rock scapolites up to an inch in length have a surprisingly regular orientation.

When these minerals form the bulk of the rock the lineation is invariably parallel to the minor folds if such are to be found at or near the exposure. On rare occasions sparce growth of small crystals of amphibole has been observed to occur on the inter-faces of quartzose or amphibolitic layers when such are folded into upright folds (Fig.13). In such cases the hornblendes are found to be orientated at right angles to the axis of the fold. It must be emphasised that the inter-faces of these layers are in effect joints and bear all the characters of late movement. They are found particularly near Creag Varr.

Micas at times show elongated habit especially on the jointed surfaces of Moine granulites. Their direction of elongation is at right angles to the trend of minor folds which are Caledonoid in most localities. Those minor folds with axes at right angles or nearly so to the local Caledonoid trend usually show the elongated micas parallel to their axes. Evidently there is a difference in origin of such lineations occurring on the joint surfaces and the overall reorientation of minerals in metamorphic rocks. This lineation seems to be later than the main movements and belongs to that stage of deformation which could be loosely described as brittle.

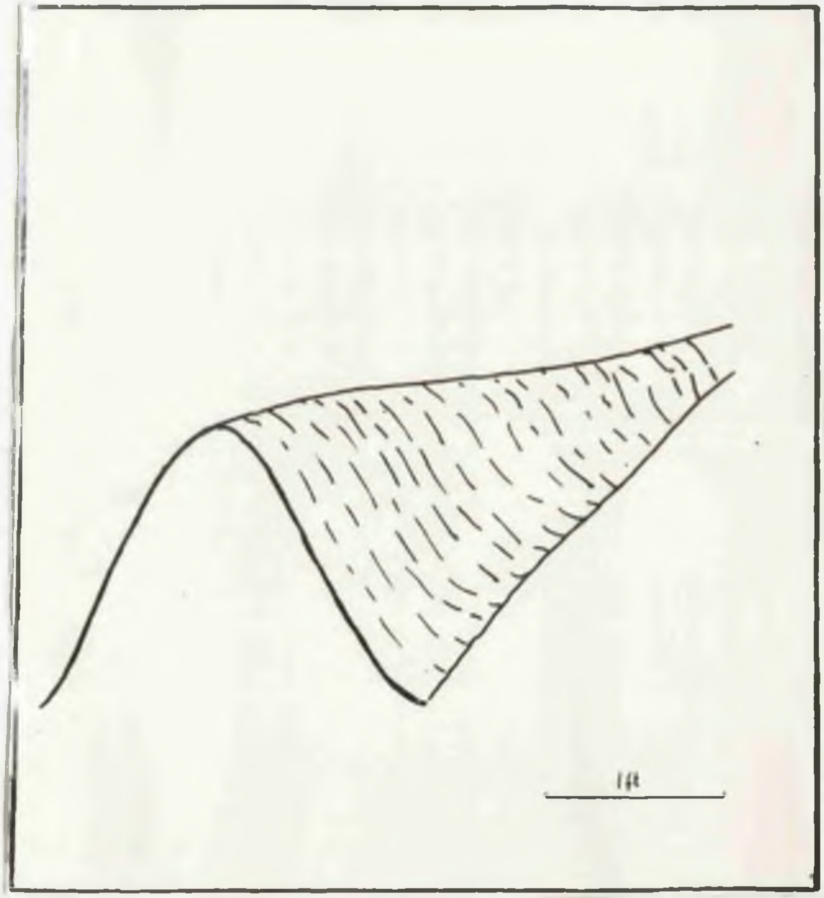


Fig.13 - Lineation of amphiboles on the surface of quartzose layers of a fold from Creag Varr.

Elongation of Pebbles

The district of Schichallion is rather favourable for the study of elongated pebbles, since the occurrence of the Schichallion Boulder Bed affords a good opportunity. The author has seen the lineated conglomerates of Norway described by Kvale (1945) but no comparable phenomena have been observed in Central Perthshire, where the deformation is evidently much weaker, at least in so far as the conglomerates are concerned. Three main types of pebbles and boulders occur in Schichallion Boulder Bed:

(a) Granitoid (b) Quartzose and phyllitic (c) Calcareous

Granitoid pebbles are generally equidimensional and do not appear to have been appreciably deformed or indeed preferentially orientated. Some quartzose pebbles are also equidimensional and again little signs of deformation have been found.

A fair proportion of the quartzose and all phyllitic pebbles, however, are elongated. Usually it is difficult to say whether this elongation is primary or tectonic. Probably all these pebbles were originally elongated, but also subsequently modified by movements. The rather abnormal dimensions of certain fragments indicate the high probability of post depositional deformation of the pebbles. About 50 measurements were made on the pebbles from Cnoc an Fhithich (Pt. E7,90,82 ) and Allt Mor, 1 mile west of Glengoulandie. In some cases the dimensions were definitely abnormal such as 10 cm. x 1 cm. x .75 cm. The majority, however, were on average of the order of 3 cms. x 1 cm. x 0.5 cm. A certain proportion on the other hand were larger and equidimensional. While a sample of 50 is not adequate for statistical analysis it can be said that the moderately elongated fragments formed 75% of the sample.

The elongated pebbles are invariably parallel to the axes of local minor folds or at least to one of the trends if more than one are present. Calcareous pebbles are invariably elongated again parallel to the axes of minor folds. Quartzose and granitoid pebbles tend to be more or less equidimensional. Those parts of Boulder Bed which are calcareous tend to contain more equidimensional granitoid and quartzose pebbles, than the more quartzose portions of the same formation. It seems that the following hypothesis would explain adequately the above observations.

(a) Pebbles of different lithology show different powers of resistance to deformation.

(b) Granitoid pebbles are most undeformable while calcareous pebbles are most deformable. The quartzose pebbles are in between.

(c) Originally equidimensional pebbles have suffered less deformation than those possessing primary elongation.

(d) Competence of the matrix is an important factor in deformation of pebbles.

Phyllitic Lineation

Plications of the amplitude comparable to the distance between each two planes of schistosity are not included here in the definition of the minor folds. Such plications have already been mentioned in the last section under the terms of phyllitic lineation and strain bands. The former structure is much more widespread and consequently more important. Normally it is a small scale crumpling of schistose foliae of a schist. Often the crumpled schistosity appears to be subparallel to the bedding and the conclusion may be reached that the bedding has been crumpled.

Such appearances are due to the fact that crumpling does not appear until a pronounced schistosity characteristic of shear tectonics has been formed. Though the effect of shear tectonics is to produce a statistical parallelism of lithological bands and schistosity there are as a rule to be found some discrepancy where the closures of folds have been preserved. Once such a succession is refolded the phyllitic lineation appears and is parallel to the axes of new folds. The old closures of the folds are generally difficult to recognize especially if refolding occurs on analogous axes. Here the phyllitic lineation is useful in recognition of two episodes of folding since its direction of plunge will not be absolutely parallel to the plunge of the closures of the older folds. The relevant observation is that the trend of phyllitic lineation is cut abruptly by the lithological continuity of the older closure. These conditions have been actually encountered in Central Perthshire and a very good example from the Moine Granulites north of Glen Errochty will be described in Section XII.

Intersection of Planar Structures

Lineations of this type result from the intersection of cleavage or schistosity and bedding or foliation, and since cleavage and schistosity are usually axial planal, trace of cleavage on bedding or bedding on cleavage is parallel to the direction of plunge of the fold. Unfortunately, in high grade or medium grade schistose rocks these criteria are rarely applicable in practice, as conspicuous intersections of schistosity and bedding are often lacking.

Such intersections especially if at a small angle are very difficult to observe in the field. However, Fig.10 shows such a case as a result of a petrofabric study, where the recognized axes b and b can be matched by minor folds in the field.

Grooves and Slickensides

On the whole slickensiding except in the neighbourhood of Loch Tay Fault has not been found to be widespread in the Area. Usually it represents the result and indicates the direction of the latest displacements on a plane. On vertical surfaces subparallel to Loch Tay Fault slickensiding is often subhorizontal and parallel to the fault, though other directions exist as well. However, the quartzose rocks adjacent to the fault at and north of Glengoulandie are broken up by numerous joints and whatever the overall direction of movement, on the joint it was conditioned by local orientation of the joint plane.

Other types of grooves exist in association with mullions and boudinage and will be discussed under those headings.

Mullions

A variety of structures has been included under this title. In a recent paper Wilson (1953) has described these structures from the type locality at Oykell Bridge and has differentiated them into:-

1. Bedding or fold mullions.
2. Cleavage mullions.
3. Irregular mullions.
4. Roddings.

According to Wilson mullions are composed of country rock, whereas rodding is synonymous with quartz-rods derived from segregations of silica during movements. Both of the two structures have been recognized and are widespread in the Area.

Cleavage mullions have been observed in Allt Mor west of Glengoulandie (Pt. K9,19,41) and consist of prisms of quartzite derived from the intersection of closely parallel joints and bedding at the closures of folds.

As regards the other two types of mullions a variety of structures has been recognized and will be described .

(a) Corduroy fluting - The term was introduced by Bailey and McCallien (1937) and is probably more or less synonymous with irregular mullions of Oykell Bridge. The mullions are pencils of psammitic material separated by rather irregular joints. Such structures are invariably parallel to the direction of local minor folds. South east from Schichallion, in Allt Mor these structures appear to be especially associated with the cores of tight folds and are in the nature of joints to the extent of possessing a sparce coating of muscovite-mica; in this respect resembling flagginess of the Moinian granulites. Bailey and McCallien have especially reported them from a hill known as Meall nan Eun north of the summit of Ben a'Chuallaich (D3,55,25). These exposures have been now re-examined and two distinct structures were found.

1. Mullions of irregular type.

2. Grooves produced on recrystallized quartz veins. Such quartz veins are nearly planar and cover joint planes. These grooves, thus, are analogous to slickensides and almost certainly are late structures. They are parallel to the irregular mullions on Meall nan Eun and plunge at 20°-30° trending 10°-20° east of south.

Such grooves do not seem to be analogous with the grooves which are occasionally associated with boudinage, where it occurs in quartzose formation; in which case the edges of the boudins are grooved.

The quartzose portion of Banded group exposed in Errochty Water near Trinafour (Pt.F2,90,54) shows this phenomenon very well.

The common association of irregular mullions with cores of folds suggests that their origin may be related to relaxation experienced by the rock after release of pressure. During the period of movements the rock in the core of a fold experiences a high compressive stress. On release of pressure, so called "released fractures" will occur giving rise to the irregular joints which form the surfaces of the mullions. (Fig.14).

(b) Whale back mullions - The irregular mullions of the Area are often on the scale of 1-3 cms. across each individual pencil. Whale back mullions have been so called by the author because they have the shape of broad elongated humps often several feet across. Quartzite, especially where it is adjacent to schistose formations is prone to show this structure. Numerous observations indicate that these mullions are recumbent folds (Fig.15) of an unusual character, the broad hump of the mullion being the uninverted limb of the fold. The steep eastern slope of Creag on Ffithich shows these structures very well.

(c) <u>Organ Pipes</u> - The term was introduced by J.S.G.Wilson in the Geological Survey Memoir for Sheet 55 (1905) for rather peculiar elongated structures which have the appearance of organ pipes. The type locality is the bed of river Garry two miles north-west of Struan, Perthshire. These structures are again folds, owing their particular shape to the combination of original

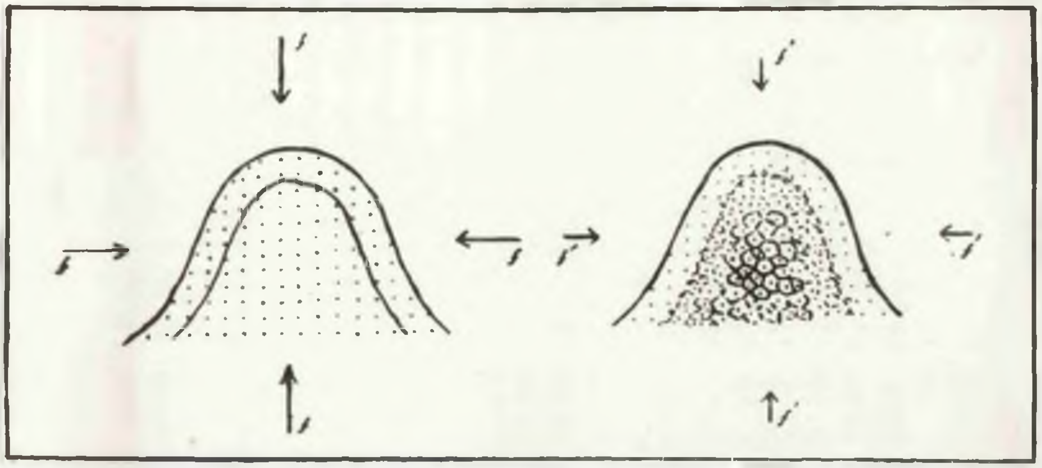


Fig.14 - The origin of irregular mullions due to relaxation of compression from f. to f'.

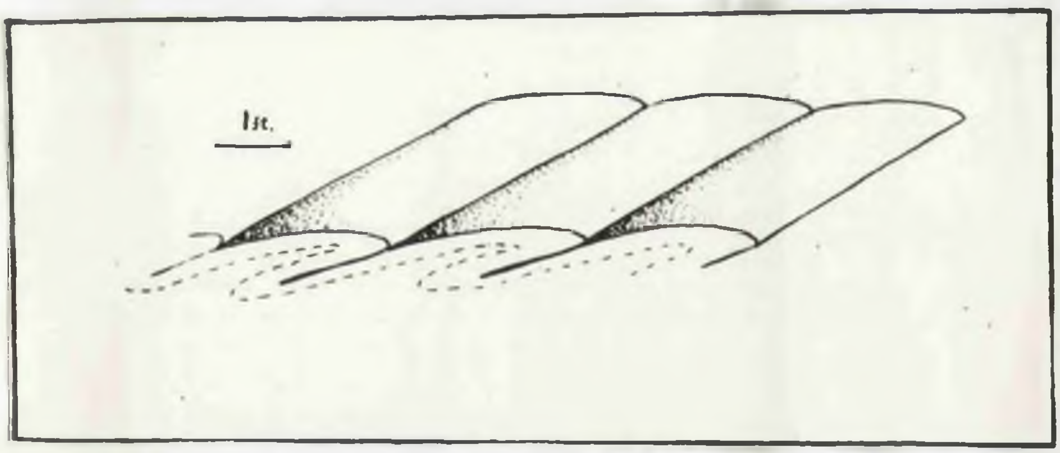



Fig.15 - Whale back mullions - (western slopes of Ben a'Chuallaich).

geometry and modification by erosion (Fig.16). Similar though less extreme structures are present in the bed of Allt Mor, north of Kinloch Rannoch (Pt.B5,95,57). These structures are of the same order of magnitude as whale back mullions.

(d) Pseudoripple mullions - These are normally of moderate dimensions of a few centimeters across and in appearance resemble ripple marks. Their non-sedimentary origin is obvious as they are almost invariably associated with crests of folds. All the appearances suggest that they are compressional structures, but there is no actual evidence as to whether they are in fact flexure folds or not. Such mullions are common throughout the quartzose rocks of the Area (Fig.17).

Boudinage

Boudinage is here used for the structure described by Lohest (1909) from Belguim and redescribed by Wegmann (1932) and Cloos (1947). The structure consists of a series of parallel, disjointed, elongated segments which in cross section appear as a series of sausages (boudins) of a usually more competent rock surrounded by a less competent medium. The segments are normally quartzose or amphibolitic and the medium schistose.

The geometry of these segments implies that they have been originally a continuous layer and owe their deformation to tensional forces (Fig.18a).

In addition to this type, which is characterised by the barrel shaped cross-sections of boudins, in formations such as Banded Group there exists a different type of structure with segments having a losenge shaped cross-sections. Again the segments are elongated at right angles to the cross-

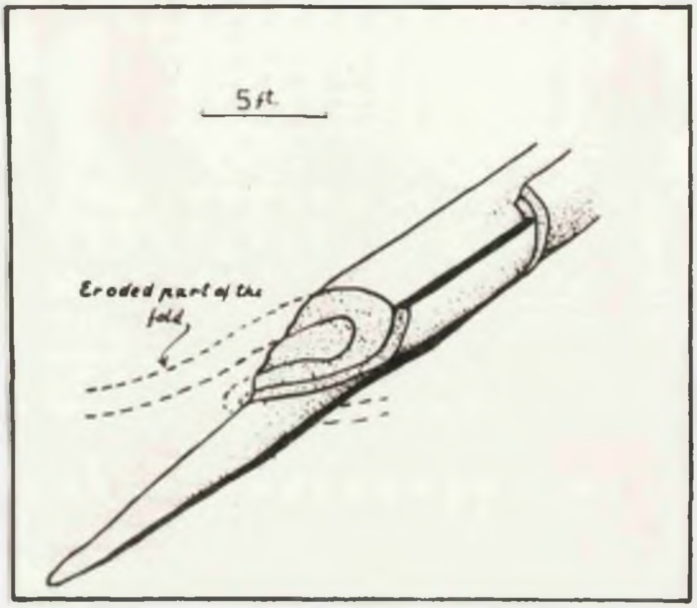



Fig.16 - A sketch of organ pipe structure - River Garry.

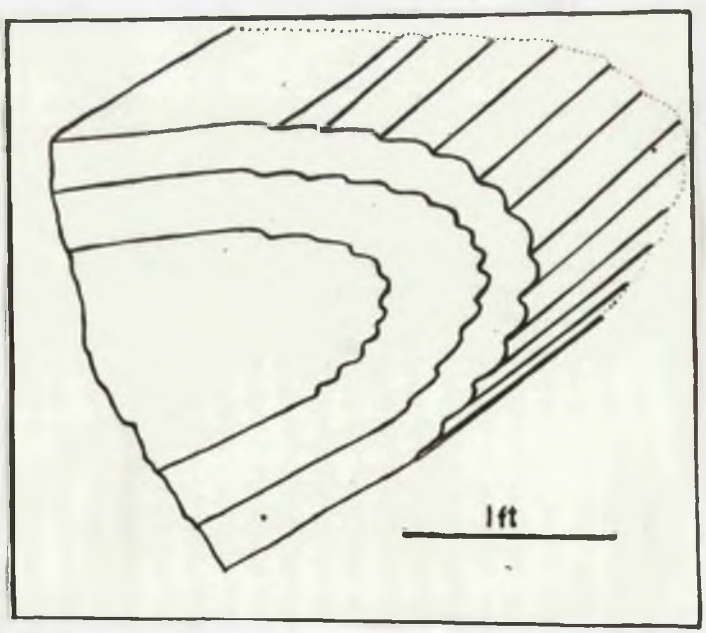



Fig.17 - A sketch of pseudoripple mullions $\frac{1}{8}$ mile north east of Kinloch Rannoch.

section (Fig.18b). An explanation of such geometric diversity could be sought in the mechanics of deformation of the relatively competent materials. In the case of barrel shaped boudinage the competent layer starts yielding by plastic deformation first and only later the two segments get separated. In the case of lozenge shaped boudinage there is no plastic stage preceding fracture. All the stages of transition from one type to the other can be seen in the Area.

Normally boudins are elongated parallel to the axes of local folds. Cases have been observed, however, where the barrel shaped boudins have an elongation oblique to the axes of local folds. (Pt. B5, 92, 70).

Since boudinage is produced by tension affecting and disrupting the harder layers, the results obtained by metallurgical experiments with sheets of mild steel subjected to tension are of interest (Nadai 1951, pp.316-327). These experiments show that depending on the thickness of the sheet failure can happen on a zone either perpendicular or oblique to the direction of principal stresses. It is not unlikely that layers of rock will behave in a similar way. In other words boudins with axes oblique to the axes of folds may originate due to the impact of the same set of stresses as were responsible for the folds themselves.

Conclusions

With the exception of slickensides, oblique boudinage elongation of hornblendes and occasional micas on the interfaces of layers of quartzite and amphibolite, all other lineations described in this section are parallel to the axes of local minor folds. This implies that the structural problem of relations between the minor and the major structure can be approached by examination of mechanics style and kinematic significance of folding.

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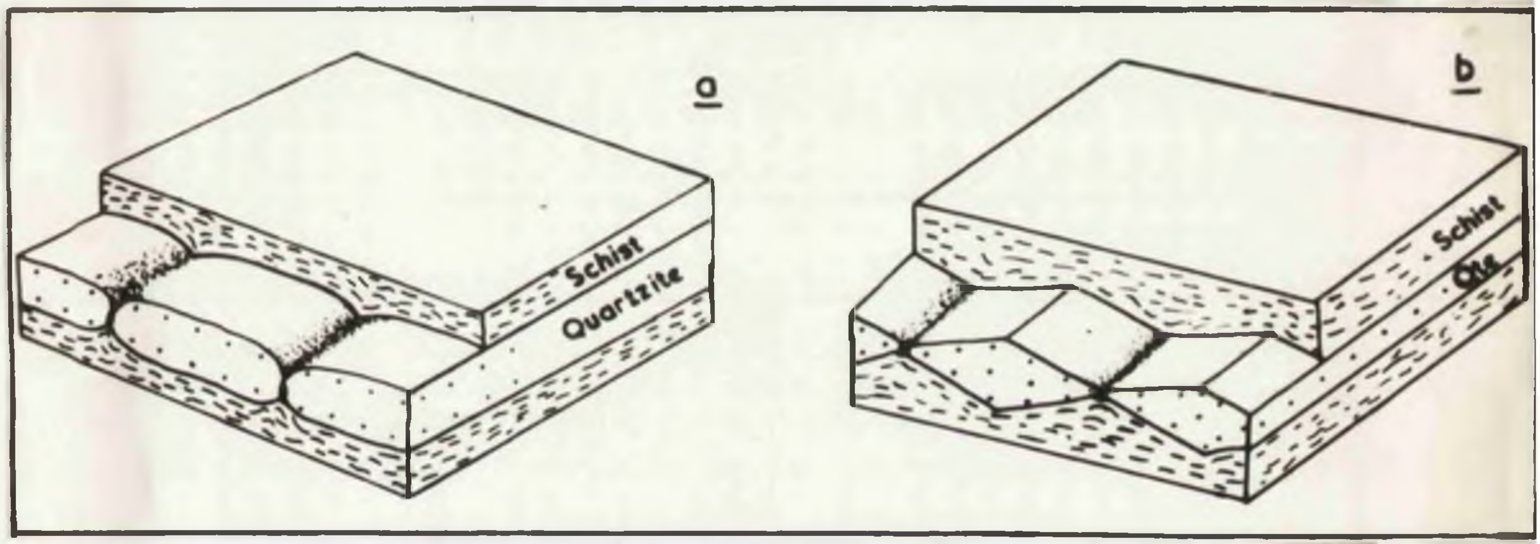


Fig.18 - Boudinage.

a) Barrel-shaped.

b) Lozenge-shaped.

## VI. FOLDS AND REFOLDING

### Introduction

Minor folds and lineations of the Area show such a diversity of geometric forms that no all embracing mechanism is applicable. Geometrically, most of the minor folds in the Area can be classified into two major groups:

1. Nearly symmetrical folds
2. Strongly overturned folds.

Though transitional cases exist, on the whole they are not very frequent.

The Symmetrical folds are not difficult to interpret as there is a general acceptance that in most cases such folds have originated by buckling; nevertheless, the common association with phyllitic lineation must be explained.

The overturned folds on the other hand present several features which merit special considerations. In the Area three important styles of such folds have been recognized.

1. Those folds that are characterized by a reduced or eliminated lower limb.
2. Those folds in which the upper limb is thinned, while the lower limb is preserved.
3. Closures of the folds with both limbs thinned out.

In addition to the diversity of styles the minor folds show a diversity of structural relations to the major folds. Some folds affect many layers at the same time, while others affect only one layer; yet another set of folds refold the pre-existent flexures.

To explain such features a number of mechanisms has been advanced and are available in the literature. For instance a comprehensive review by Tromp (1937) gives a summary of various mechanisms of which four can be advocated to explain most of the folds in the Area. The four mechanisms are as follows:-

1. Buckling mechanism.
2. Pushing mechanism.
3. Drag mechanism.
4. Shear mechanism.

Buckling Mechanism

If a horizontal layer is subjected to horizontal compressive forces two possibilities can be envisaged.

1. Shearing strength of the layer is smaller than buckling limit, resulting in the fracture of the layer.
2. Shearing strength of the layer is larger than buckling limit and the layer will buckle.

Neither operation involves any external bending moments, while such undoubtedly operate internally. Since, geologically speaking, in the deeper parts of the orogenic belts confining pressures are high the shearing strength is also high and buckling is the normal process of relief of accumulated stress.

The physical properties of buckled material were investigated by Smoluchowski (1909). Under conditions of high stress he has indicated that in a buckled layer $\lambda = ch^{3/4}$

Where: = wave length of undulation
c = constant
h = thickness of the layer

The equation applies to elastic substances, but can be used in a general way for plastic deformation.

The above equation indicates that folds with small wave length require a very small thickness of the layer. This fact is of a geological significance since it explains the origin of phyllitic lineation. Bedding planes in which continuous thin micaceous layers do not exist are not likely to give rise to small scale corrugations. On the other hand the surfaces of slaty cleavage or axial plane schistosity if subjected to a subsequent episode of deformation will give rise to corrugations with very small wave length. In other words the first phyllitic lineation will in normal circumstances be subsequent to the first schistosity.

In the Central Highlands the phyllitic lineation, being in the nature of small scale crumpling, is undoubtedly associated with movements which have folded pre-existent schistosity. Such can be sometimes proved in individual exposures where refolded folds are to be seen.

The other important feature arising from studies of physical causes and effects of buckling and recognized by engineers is that any sheet of material subjected to compressive forces exceeding buckling limit, will buckle simultaneously on two sets of axes. The main fold with a small radius of curvature will be formed with an axis at right angles to the direction of pressure, while the cross-fold will be formed with an axis parallel to the direction of pressure (Fig.19). Denoting the larger radius of curvature R and the smaller radius of curvature r it has been found by Koenigsberger (1924) and Hungurer (1922) that the ratio $r/R$ decreases with the increasing thickness of the layer, provided the other dimensions of the layer are kept constant. Or more explicitly the cross-fold becomes more pronounced in thicker layers. In addition, the cross-fold increases in amplitude relative to the

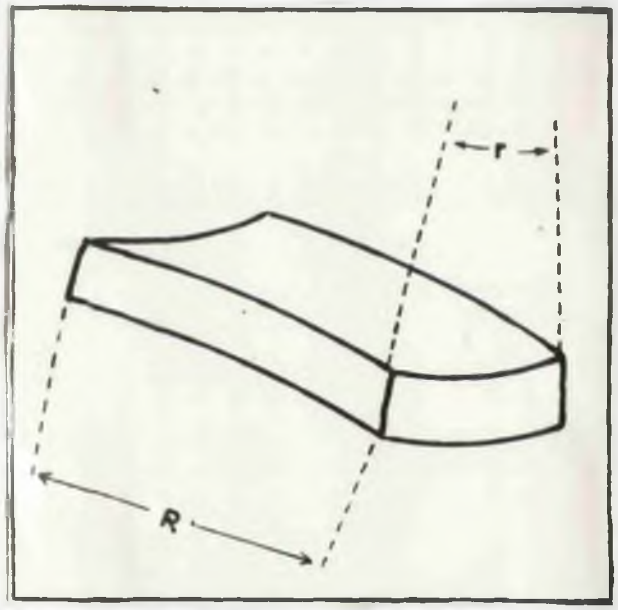


Fig.19 - Relations between the main and the cross-fold in a buckled layer. The radius of the main buckle (r) is smaller than the radius of cross-buckle (R).

main fold with the increase in plasticity. Hungurer (1922) suggested that this is the appropriate mechanism for the origin of culminations and depressions in the Alps. Evidently such "automatic" cross-buckles will become more intense with overturning of the main buckle and if, in the process of overturning the main buckle experiences a lateral resistance the cross-buckle will become quite an important structure. In other words, the development of a cross-buckle always lags behind in relation to the main fold. It is submitted that these considerations are especially applicable to thick geosynclinal prisms and folded regions where cross-folding of this type can be expected.

A fold evolving due to the operation of buckling will gradually overturn. This is essentially a reflexion of internal friction within the material whereby the compressive forces are dissipated with distance and the points nearer to the locus of incidence of force will tend to override the more distant points. If compression continues still further a rupture will develop and a thrust will form at the base of the recumbent fold. Such a sequence of events is portrayed on the Fig.20, the implication being that folds with thinned lower limb have developed by a buckling mechanism. This is not to be taken as meaning that the great overfolds with exceedingly large amplitudes have their origin solely due to this mechanism. It is, however, very likely that they have began as buckles.

Pushing Mechanism

This mechanism is directly related to the problem of bending. A horizontal layer if pushed vertically at any particular point, while its edges are kept down, will bend and form a fold. There is no definite evidence

Following p.44.


Fig.20 - The evolution of a recumbent fold.

that such pushing is common the superficial parts of the earth crust. However, it is very likely to occur in the area characterized by larger recumbent folds. It is a known fact that the internal friction in the rocks is such that force can not be transmitted for a long distance. A possible explanation, however, is available assuming that material is squeezed into the cores of the folds pushing them actively forward. The recumbent folds with thicker lower limbs can be interpreted in terms of this mechanism. The explanation involves two stages (Fig.21):-

1. Formation of an overturned fold with subsidiary drag folds by buckling and drag mechanisms or pushing mechanism.

2. Recumbency by pushing mechanism.

As a result of this mechanism a total extension of the envelope of the fold takes place, but this extension is especially concentrated on the limbs. The belt of Killiecrankie Schist both north and south of Kinloch Rannoch shows numerous folds of this type.

Drag Mechanism

The easiest illustration of this mechanism is afforded by drag folds which are of a frequent occurrence on the limbs of larger folds, the normally accepted explanation being that buckling of the layers of any thickness promotes subsidiary shearing stresses (Fig.22). On a major scale the mechanism has a very probable application in the formation of overfolds with basal thrusts. To be more explicit, at first a buckle formed by compressional forces will have a vertical axial plane. As the movement proceeds and the buckle overturns shear component of compressive force becomes more

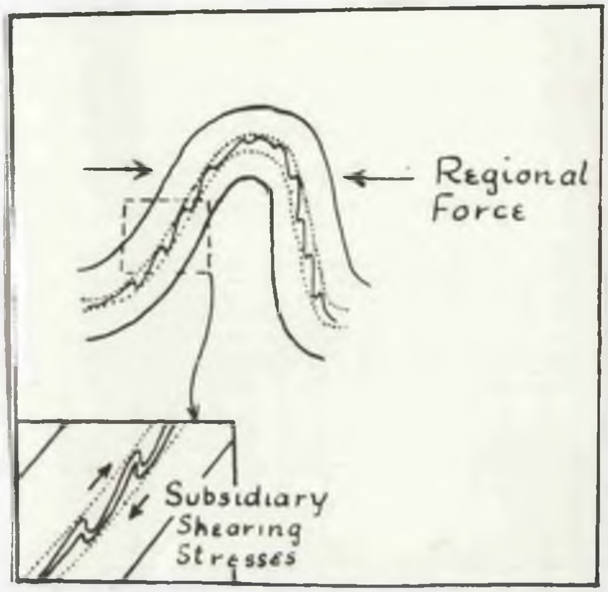


Fig.21 - Subsidiary shearing developed during buckling.

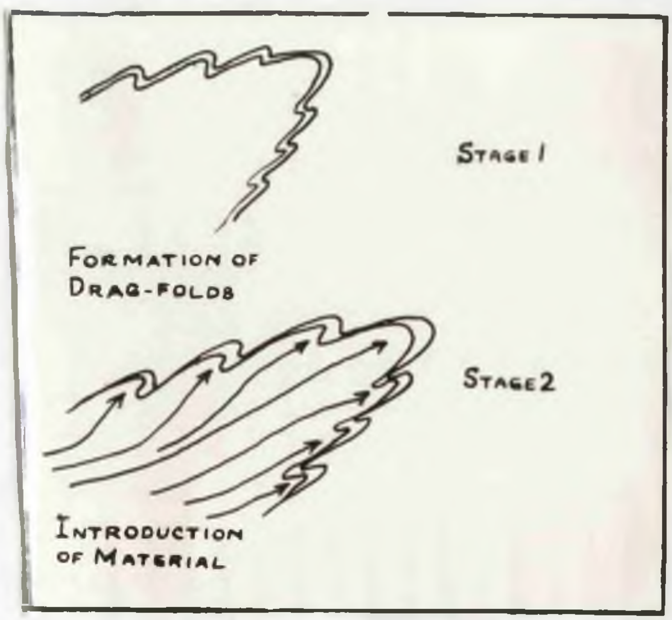


Fig.22 - The origin of folds by pushing.

and more concentrated on the underside of the buckle and further movement will take place by drag.

In so far as the minor folds are concerned, it is rather difficult to differentiate between the drag folds and overturned small scale buckle folds unless the way that the folds are packed one upon the other can be observed for some distance. Moreover a fold with strongly unequal limbs, especially if it is within a particular layer is in general a drag fold. On the other hand, if many layers are involved it is probably a buckle fold.

Like the buckle folds, the drag folds are characterized by basal thrusts.

Shear Mechanism

This mechanism involves interpenetrative movements of layers. It seems likely that frequently such movements take place only after the production of buckles.

On a very small scale "Totfalten", but also larger fold-closures with sheared out limbs owe their origin to the operation of interpenetrative movements.

Refolding

Whatever the mechanism of folding, the resultant folds are sometimes clearly refolded. Clough in his work on Cowal (1897) introduced two sets of criteria for recognition of refolding.

1. He argued that under normal circumstances small recumbent folds will suffer from elimination of the lower limb. If, however, the folds show elimination of the upper limb alone, this circumstance is due to overturning subsequent to the origin of the normal fold. While this criterion is inapplicable in the Central Highlands, inferences drawn from it seem to explain the structure of Cowal satisfactorily.

2. Clough recognized a series of folded schistosities and also folded strain slips. This second argument is decisive in the sense that the folding of the schistosity must happen after the episode of movement responsible for production of the first schistosity. Actually, the third and most important criterion of refolding is present in Cowal, as well as in the Central Highlands, but was not described by Clough. It is that minor folds can be themselves folded; such a criterion can be called the geometric criterion of refolding. Three possibilities exist :-

1. The first and the second axes of folding are parallel to each other (Fig.23a).

2. The first and the second axes of folding are at right angles to each other (Fig.23b).

3. The first and the second axes of folding are oblique to each other (Fig.23c).

All these cases have been recognized in the Area and will be described subsequently. At this stage it is more appropriate to examine some general implications of refolding.

Obviously, any second episode of refolding will not affect materially the trend of the previous folding so long as it is either parallel

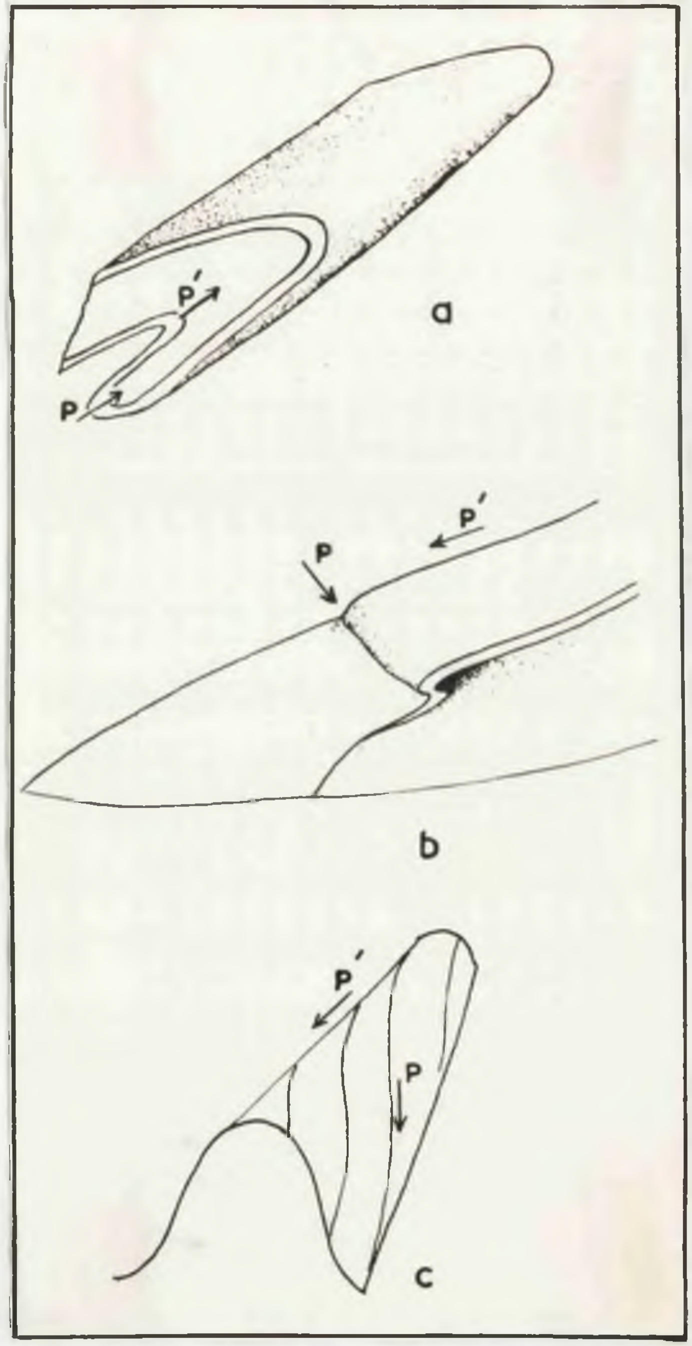


Fig.23 - Refolding.

a - The axis P of the earlier fold is parallel to the axis P' of the later fold.

b - The axis P of the earlier fold is at right angles to the axis P' of the later fold.

c - The earlier and the later axes of folding (P and P') are oblique to each other.

See p. 139.

or at right angles to that trend. In the latter case, however, the degree and direction of plunge of the previous axes and the associated lineations will be altered (Fig.24a). If the refolding axes of the second episode of folding are associated with a more or less symmetrical folds, again the previous oblique axes will show a deviation in the degree and direction but not the trend of their plunge. On the other hand if the refolding folds are overturned an appreciable scattering of the previous axes and lineations is expected. This is obvious and can be easily verified by drawing a line on a sheet of paper and folding it obliquely to the line. (Fig.24b). The geological implications of this fact are important in the areas where more than one episode of folding is suspected, since the apparent scatter of the older set of axes will be due to the subsequent folding and not to their original irregularity. Nevertheless a second episode of refolding especially if it happens on axes trending across the first set of folds should a priori be less regular than the first one. This phenomenon is the result of the fact that in any process of folding any irregularities of the pre-existing structure will tend to influence the distribution of subsequent stresses, and inevitably structures will be formed which show the effects of compromise between the original structure and the subsequent folding. Such structures have been recognized in the Central Highlands.

Continuous and Discontinuous Refolding

Theoretically two distinct regional causes may activate refolding of earlier structures :-

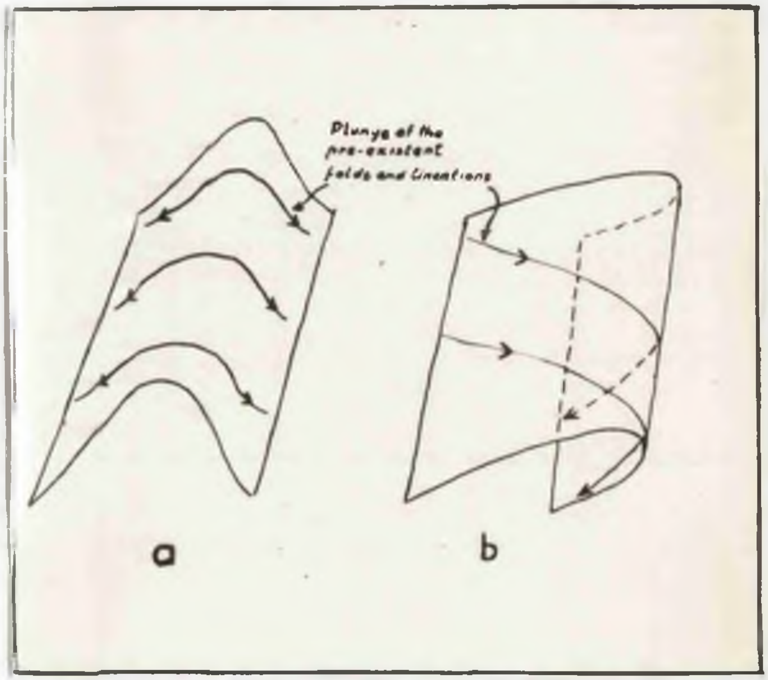


Fig.24 - Relations between the folded lineations and folds.

a - Pre-existent folds and lineations at right angles to the new trend.

b - Pre-existent folds and lineations oblique to the new trend.

1. An episode of folding entirely later than the first episode of folding, such as the effects of an entirely separate orogenic episode or even a later orogency.

2. Continuity of movements producing refolding of earlier structures. For instance as already argued the effects of simultaneous cross folding may appear in strength only when the main folding has been sufficiently evolved; so that the culminations and depressions will form major lines only late in the process of orogency. This is the inference drawn from the studies of Hungurer (1922). Even several refoldings on the same axis may be the result of continuous movements necessitated by the interplay of several mechanisms of folding.

While any single or compound episode of folding may result in final overturning, recumbent folding and shearing giving the rocks an aspect of shear tectonics, it may be arrested at a relatively early stage of symmetrical or nearly symmetrical folds. Such folds have a widespread phyllitic lineation associated with them and they are responsible for upturning of any previous structures. While minor drag folds are frequent there is no appreciable shearing on either planes of schistosity or the lower limbs of the structures. Such a style of tectonics will be called from here onwards flexure tectonics, and in the Central Highlands the areas characterized by flexure tectonics show all the signs of late folding. However, this will emerge from the detailed study of the structures in the Area.

With these remarks in background such detailed description can be now attempted.

PART II.

# VII. DISTRIBUTION OF FORMATIONS

## Introduction

A comparison of the map $S_2$ with the map produced by Bailey and McCallien (1937) shows that at least in so far as the distribution of the Dalradian outcrops is concerned there is a large measure of agreement between the present work and theirs. In fact, in this respect the main difference is in the mapping of Ben Eagach Schist in the western part of the area.

Again, all the slides, which have been recognized by Bailey and McCallien, have been substantiated in this work; and since the present study is a successor to theirs, as far as possible the same terminology has been used to denote particular structures.

## Main Lithological Belts

Leaving aside for the time being the subject of the Moinian rocks, all the Dalradian rocks can be divided into two parts according to their structural significance.

1. Perthshire Quartzite Series.
2. The Blair Atholl Series stratigraphically lower and Ben Lawers and Ben Eagach schists stratigraphically higher than the Quartzite Series.

The second group makes a series of belts divided by the Perthshire Quartzite Series. Altogether there are four important belts of Blair Atholl Series of which the most easterly has a subsidiary core which is cut obliquely by the Loch Tay Fault (Map 3).

These four belts are restricted to the eastern parts of Dalradian outcrops. In addition there are three belts of Ben Eagach and Ben Lawers schists restricted to the western parts of the Dalradian outcrops. All these seven belts are evidently cores of large scale folds.

Of the four Blair Atholl cores two are seen to show right-angled deflections of strike and in this respect, at least for descriptive purposes it is convenient to separate them from the other two cores. In other words it is convenient to describe the Area, sub-dividing it into three sectors shown on the map 3. The three sectors can be called :-

1. The Central or Dunalastair Sector.
2. The Western or Dalhosnie Sector.
3. The Eastern or Kinardochy Sector.

The Dunalastair sector includes the two Blair Atholl cores with right-angled bends. The Dalhosnie sector includes the three cores of Ben Lawers and Ben Eagach Schist. The Kinardochy sector includes the two eastern cores of Blair Atholl Series. Of these three sectors the central sector of Dunalastair provides the key to the district and it will be described first. The Moinian rocks of the Area will be treated in a later section.

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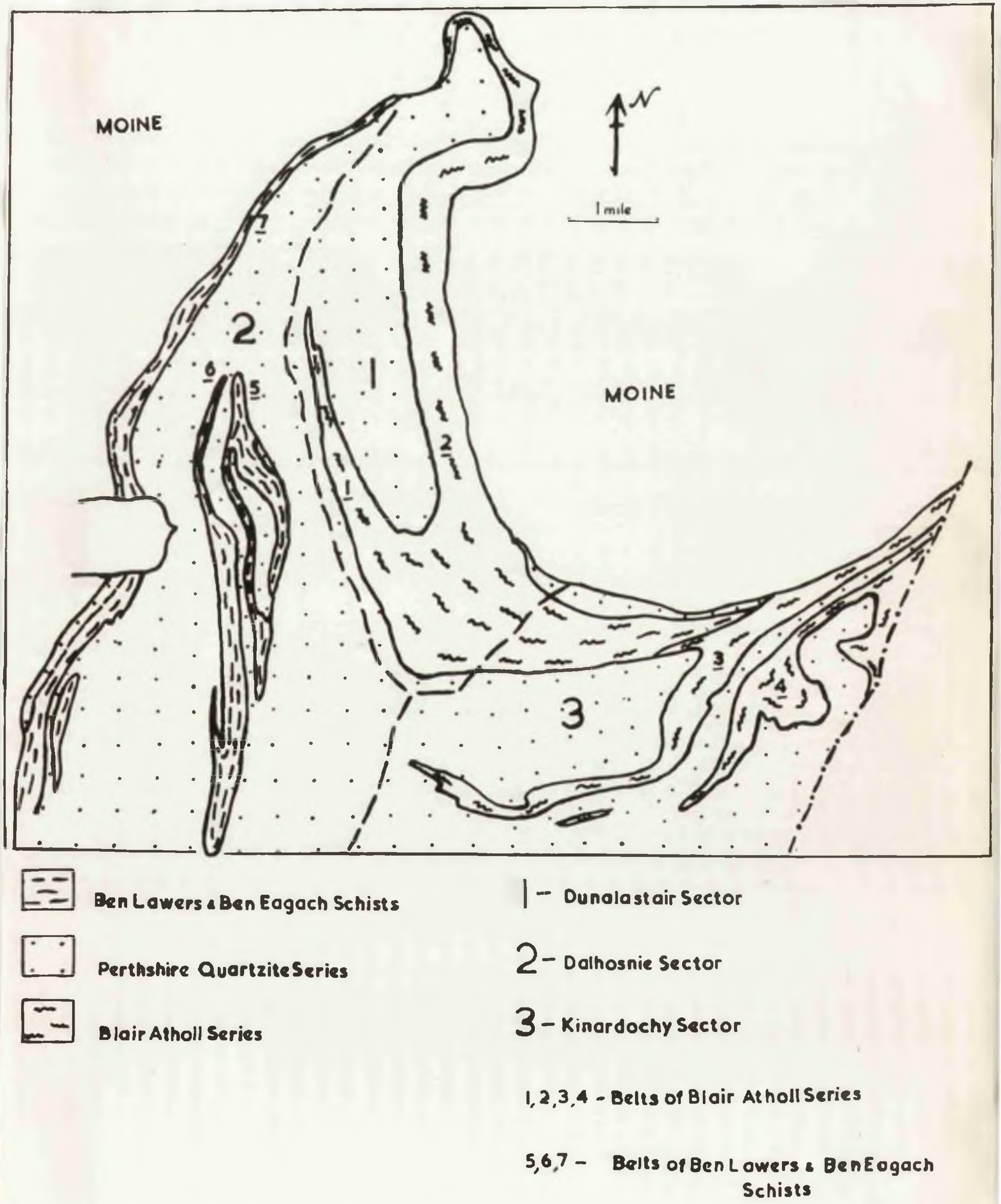



Map 3 - Major features of the Area.

## VIII. DUNALASTAIR SECTOR.

### Stratigraphy and Lithological Variations

Rocks of two metamorphic series, the Perthshire Quartzite and the Blair Atholl, exist in this sector, the former being stratigraphically higher. The general lithology of the sub-divisions of these two series has been summarised in Table 1. However there are numerous local lithological modifications that will require description.

Within the Blair Atholl Series apart from minor and haphazard lithological variations there is a tendency for a systematic variation which can be ascribed to the influence of Boundary Slide. Such systematic variations are summarized in the following table :-

| Stratigraphical level | Normal Lithology | Lithology near the slide |
|---|---|---|
| White Limestone | Crystalline marble with associated calc-tremolite schist | Tremolite rich schist. |
| Banded Group | Distinctly banded series of quartzite and schist layers | Granulitic quartz mica schist, slightly banded. |
| Dark Limestone | Dark slightly impure marble | Often tremolitic schist with some marble |
| Dark Schist | Slightly graphitic mica schist | Dark biotite schist with little graphite |

In this sector the Dark Schist has normally a high proportion of mica the flakes of which are as a rule corrugated giving the schist a lineated aspect, which has been termed by Anderson linear foliation. The thin sections and polished hand specimens leave no doubt that this is in fact a rather extreme type of tightly packed phyllitic lineation. Occasionally these schists

become highly quartzose, but remain dark due to the presence of many inclusions of finely disseminated graphite. Often a rather curious corrug-surfaces are frequently lined with intermittent flakes of biotite elongated parallel to the direction of corrugation. Such flakes are possibly mimetic.
parallel to the direction of corrugation. Such flakes are possibly mimetic.

The Dark Limestone as a rule is a massive rock only occasionally showing conspicuous ribbing due to the presence of calc-silicate bands. Sometimes these ribs get closely folded and sheared out producing small sigmoidal fragments dispersed throughout the rock. Some of the ribs show small, very sharp corrugations which were found to be useful in working out the direction of folding in otherwise featureless massive rock. Such corrugations have been for convenience called "ribbing" lineation; in fact they are miniature folds.

The Banded Group almost everywhere has its characteristic banding, but occasionally becomes dominantly quartzose as near Ballintium (Pt.E5, 95, 25) or south of Lassintullich (Pt.E7,29,87). On the other hand at times the group is rather uniformly schistose as near Lochan Daim (Pt.F7,57, 86) Near Cnoc an Fhithich (Pt.F7,39,44 ) a curious facies of the Banded Group shows a rather unusual growth of porphyroblastic micas showing monoclinic form. In the same general locality books of up to two inches across are seen in association with irregular veins of pegmatite. A flaggy modification of Banded Group can be seen north of Lochan Daim (Pt.F6, 58, 01) where rather slaty fine grained rocks show banding on a very much smaller scale than usual, with the thickness of each band not exceeding a few millimeters.

The White Limestone generally bears some tremolite. In places west of Lassintullich (Pt.E6,78, 01 ) it shows a quartzose modification with numerous rosettes of tremolite. North west of this locality the limestone is associated with a porphyroblastic scapolite schist. Scapolitization also affects the adjacent Schichallion Boulder Bed and to a certain extent parts of a large body of hornblende schist intruded into these rocks.

The Schichallion Boulder Bed is the most variable formation in the sector. In general it is calcareous at its margin with the White Limestone, the passage from one to the other being through a calcareous schist with weathered out calcite. This rock has been called by Wilson (1905) the honey-comb rock. Next to the Schichallion Quartzite on the other hand the Boulder Bed is highly quartzose and often develops stratigraphical intercalations of quartzite. In addition it shows all types of variations from a rather schistose matrix to a very hard one which is almost hornfelsic in appearance. There is no comparative variation in the types of pebbles except that calcareous varieties in general increase towards the margin with the White Limestone.

The highly quartzose rocks of the Perthshire Quartzite Series show much less variation than the Blair Atholl Series. Even then, several varieties of Killiecrankie Schist can be recognized. Normally the schist is a more or less uniform containing both biotite and muscovite. It is occasionally richly garnetiferous and frequently shows quartzite bands. The size of micas is variable. For instance the schists near Auchtipart (Pt. E5.16,07) are characterized by small micas and resemble the more micaceous varieties of Moine granulites. On the other hand in Glen Errochty (Pt.F2,50,93) these schists are much coarser in grain; they are strongly corrugated and have abundant thin psammitic bands which show signs of several stages of deformation by refolding.

Dolomitic Beds

Stratigraphically the Dolomitic Beds are so important that they should be described separately. Anderson (1923) mistook them for members of Blair Atholl Series and indeed they resemble the White Limestone closely. Bailey and McCallien (1937) have recognized three important outcrops of these beds:
(a) The outcrop stretching from the neighbourhood of Trinafour to a point several hundred yards south of Allt na Moine Bhuidhe. Near this stream the beds are associated with a scapolite rich hornblende schist very dragnostic in hand specimens since scapolites appear as white porphyroblasts 1 to 3 mm. across. The origin of this rock is doubtful, as except for the abundance of scapolite it appears to be indistinguishable from the other hornblende schists in this area, which are clearly of igneous origin.
(b) The Dolomitic Beds of Tempar burn where the beds are associated with dark biotite rich flaggy schists. This as well as the aforementioned exposures of Dolomitic Beds has been accepted in this thesis to be a two sided stratigraphical intercalation within the Schichallion Quartzite.
(c) The Dolomitic beds occurring in a wide belt along the eastern flank of Schichallion are in a separate category and will be discussed subsequently (p. 82 ).

Hornblende Schists and Epidiortes

These rocks are very numerous in the Area, but their treatment is more conveniently reserved for a separate section (p.124 ).

Distribution of Outcrops

The structure of this sector is dominated by the two main cores of Blair Atholl Series, which unite west of Lochan Daim (Map 3). The western of the two cores has been called by Bailey and McCallien (1937) the Ben a'Chuallaich synform and the eastern the Dunalastair synform. A close examination of the details of the cores shows that they cannot be explained as synforms. The reasons are as follows :-

(a) Near the summit of Ben a'Chuallaich it is possible to see an anticlinal upfold of calcareous honeycomb rock surrounded by Schichallion Quartzite. "Ribbing" lineation associated with the rock plunges $10^{o}$ west of north at $15^{o}$. The disposition of the upfold indicates that such is the plunge of the upfold as well, and while it is not the main closure of Ben a'Chuallaich core it nevertheless indicates a right way up structural succession, whereas Bailey and McCallien (1937) maintain that the succession is inverted.

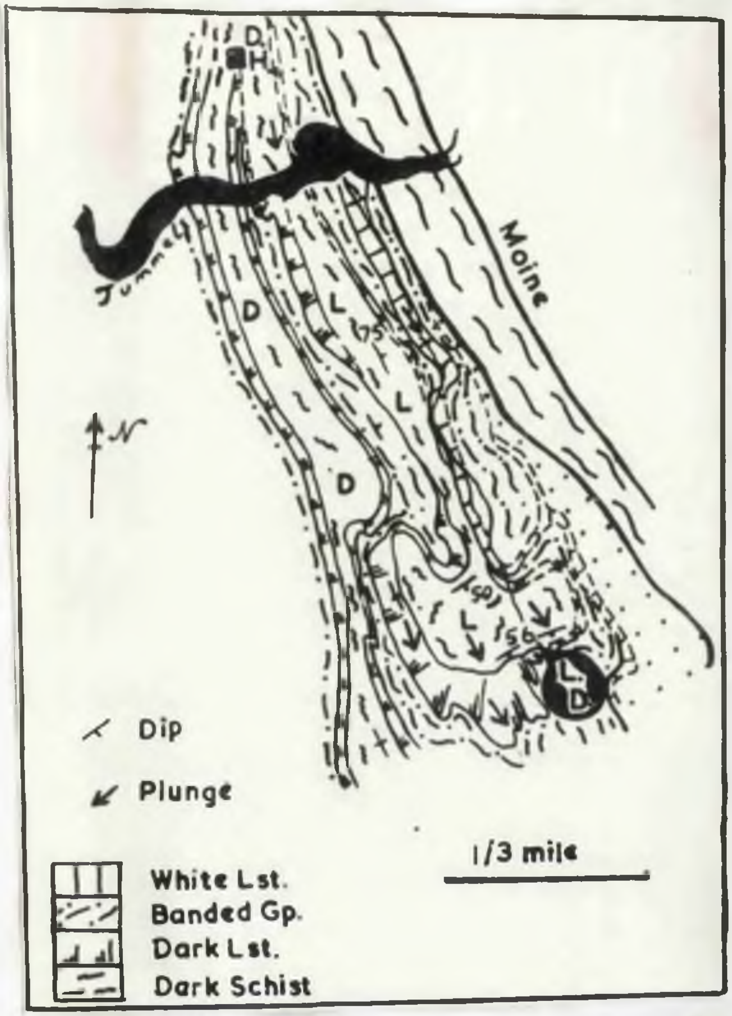
(b) The Dunalastair core branches into two at Dunalastair house. The main branch continues north of Schichallion to the western boundary of the sector and beyond. The subsidiary branch to be called Lochan an Daim fold closes by the shores of the Lochan. Map 4 shows that all the local minor folds and lineations plunge south south-eastwards and this is also the plunge of Lochan an Daim structure as is shown by the distribution of dips. This implies that the fold is an antiform, and since it possesses a core of the oldest Dark Schist the succession is uninverted, whereas the supposition that the Dunalastair core is a synform implies that the succession is upside down.

(c) A similar case is apparent in the southern part of the Ben a'Chuallaich core where the strike changes abruptly (Map 5). Here an obvious antiform of Dark Limestone is surrounded by Banded Group and again locally the succession is normal.

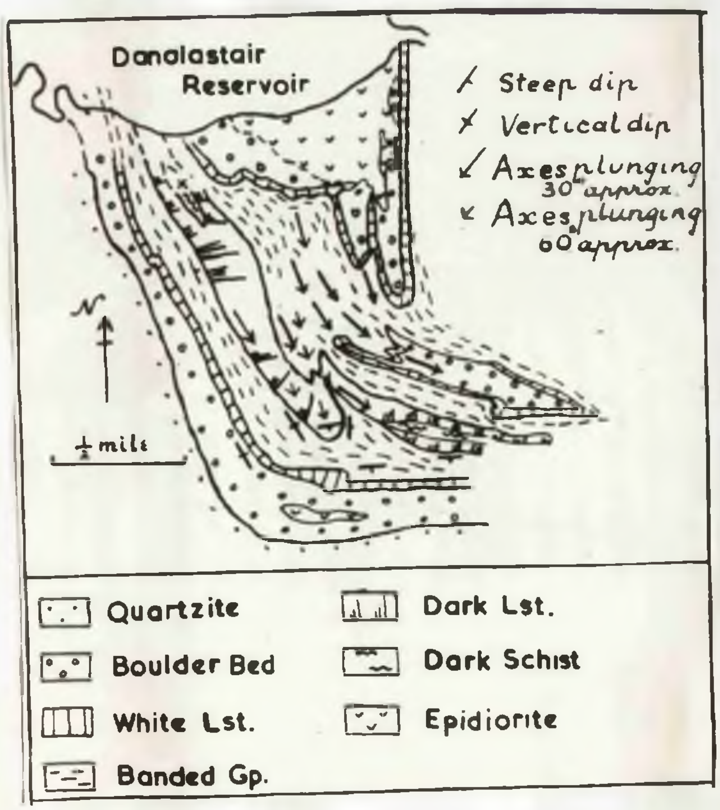
The position is not alleviated if following Anderson it is assumed that both Ben a'Chuallaich and Dunalastair folds are antiforms, since in that case the quartzite intervening between the two Blair Atholl cores will have to be a synform. This is impossible as the plunge of minor folds at and near the closure of this structure (Map 6) indicates that it is an antiform.

While in relation to the structures of intermediate size such as Lochan an Daim fold there is a direct proof that the plunge of the minor folds directed $10^{\circ}$-$30^{\circ}$ east of south indicates their plunge, since the distribution of dips confirm it, there is no such proof for the major structures such as Ben a 'Chuallaich fold. Herein lies the explanation of the apparently anomalous behaviour of these folds. It is proposed that the plunge of the minor folds and lineations in this sector generally represents the effects of the latest episode of deformation superimposed on the cores of pre-existing folds.

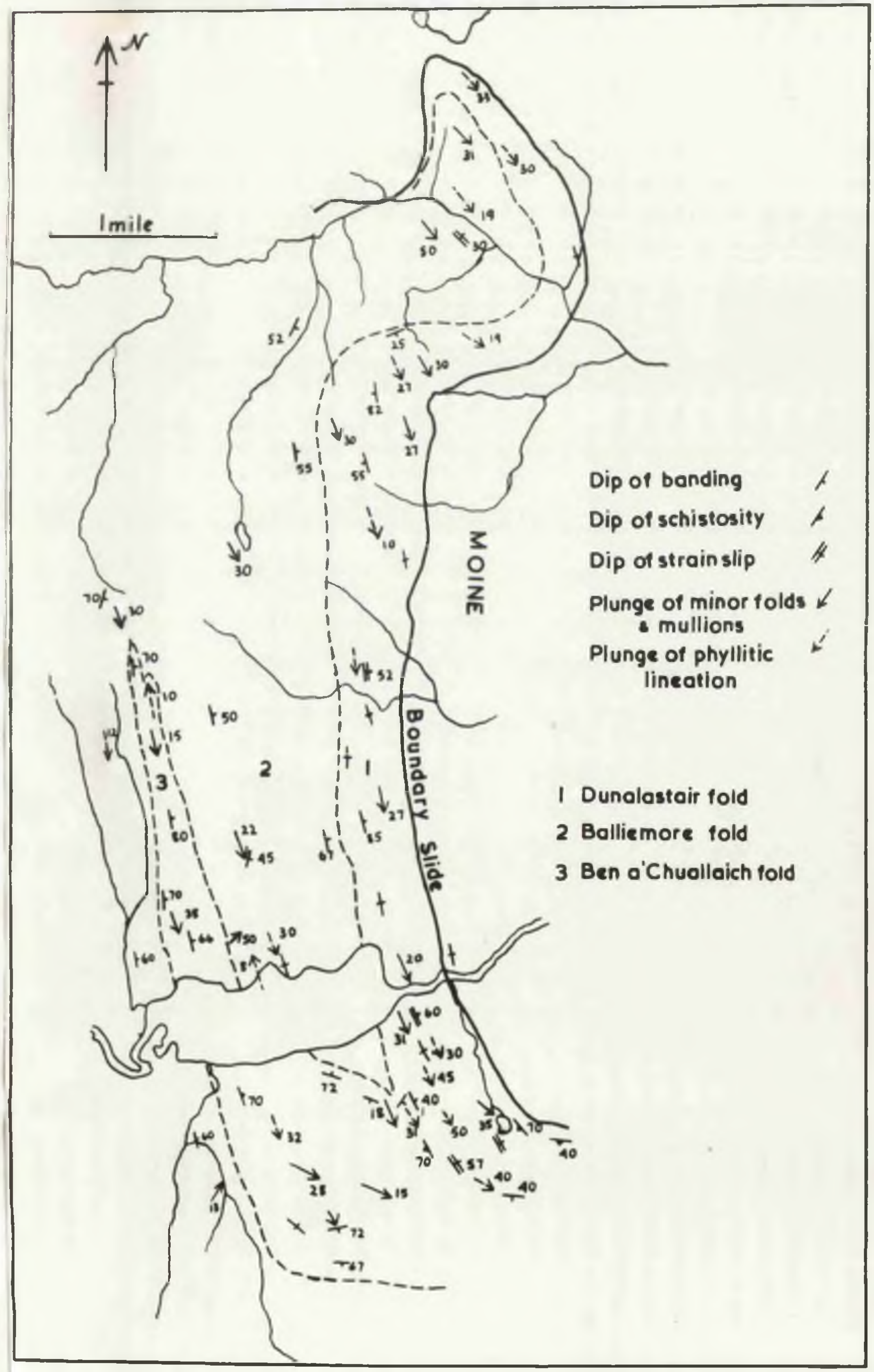
The present north-south elongation of the Ben a'Chuallaich and Dunalastair cores is the reflection of such late movement. However, the closures




Map. 4 - Loch an Daim fold.




Map. 5 - Southern part of Ben a'Chuallaich core.




**Map 6** - Structural map of Dunalastair Sector (Minor Structures)

Blair Atholl cores (1 & 3) are separated by a quartzite core (2)

of both folds are at the northern extremities of the two Blair Atholl cores and no amount of refolding can influence the position of the closure of a tight fold at any one point, provided the fold-axes of the second episode of folds are at right angles to the axes of the first folding. The right angle bend suffered by the two cores is also evidently the result of refolding, implying that the axes of the first folding were approximately at right angles to the later direction. In short, the original, unrefolded cores of Ben a'Chuallaich and Dunalastair also closed to the north.
If the second episode of folding is responsible for the north-north east-south south west trend of the Ben a'Chuallaich core north of the Tummel, it is reasonable to suppose that the east north east-south south west trend of the Blair Atholl cores north east of Schichallion corresponds approximately to the trend of the first folding, which must have been Caledonoid. In such a case the right angle bend of the strike of the cores implies that the folds of the first episode of folding were Caledonoid nappes, which closed to the north. Such an analysis carried out on the evidence of the map is confirmed by the observations made on the character and distribution of minor structures.

Minor Structures of Ben a'Chuallaich Core (North of the Tummel).

The general dip of the formations is at $50^{o}$-$70^{o}$ to the east or $10^{o}$ north of east. This is also the general dip of schistosity which where it is well developed has associated with it a pronounced phyllitic lineation. The most revealing exposures occur just north of Auchtipart (Map 7).

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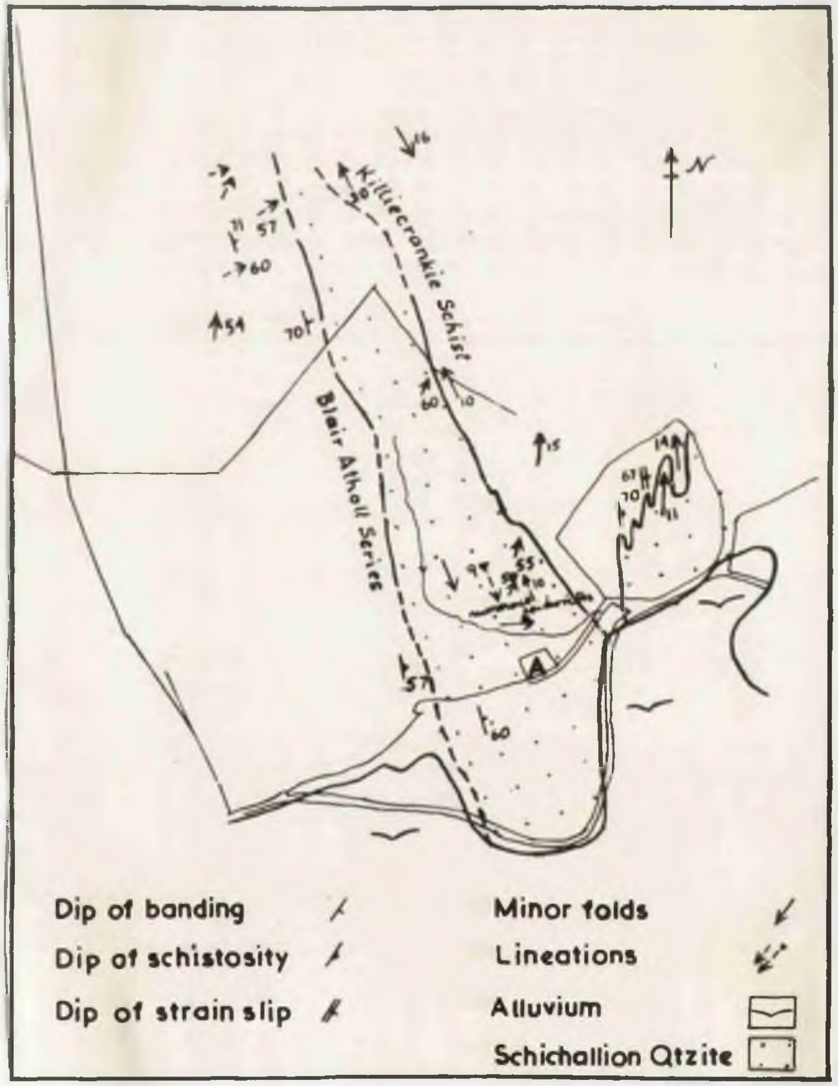



Map 7 - Structural map of Auchtibart (A) sector.

Here a relatively thin remnant of Schichallion Quartzite, which shows some folded relict sedimentary structures such as current bedding, contains unfolded into it sheets of epidiorite. In general most of the folds present are small antiforms and synforms with rounded closures. Such folds are normally almost symmetrical and are frequently associated with small scale local slides. At the junction with the Killiecrankie Schist bands of quartzite alternate with mica and hornblende schists and show numerous pseudoripple mullions. The plunge of the mullions and the axes of the synforms and antiforms varies from $10^{\circ}$ east of south at $20^{\circ}$ to $10^{\circ}$ west of north at $15^{\circ}$.

In addition there are a number of earlier recumbent folds with steep axes directed down the dip of the formations. These folds plunge $20^{\circ}$-$30^{\circ}$ east of north at $50^{\circ}$-$60^{\circ}$. Apart from these folds there are numerous fine lineations that could be observed on the eastern flank of Ben a'Chuallaich and which on average have the same direction and degree of plunge. Such lineations are often very recumbent phyllitic crumples, but also on occasions directions of elongation of acicular minerals. The recognition of these axes and lineations with a general Caledonoid direction as associated with the dominant $10^{\circ}$ east of south axes is important, since this fact supports the contention that the Ben a'Chuallaich core is a folded fold. The dominant trend is evidently the trend of cross-folding.

That the direction of the earlier axes is more northerly than that of the average Caledonoid trend of the Central Highlands which is $20^{\circ}$-$40^{\circ}$ north of east to $20^{\circ}$-$40^{\circ}$ south of west, is attributable to the fact that the local cross fold trend is not precisely at right angles to the Caledonoid trend. It has been pointed out that such a circumstance results in deflection of the pre-existing lineations and folds (see p. 60).

The cross-folds of Ben a'Chuallaich core while maintaining a uniform trend frequently show variations of plunge. Very fine exposures occur just west of Torr nan Cabar (Pt.D5, 80, 42) where the pseudoripple mullions are seen to follow closures of folds which show frequent reversals of plunge. The Blair Atholl Series of the Ben a'Chuallaich core show numerous reversals of plunge of the cross folds as well. By comparison with the ground further to the west it has been concluded that this phenomenon is essentially later than cross folding (see p. 39). Such variations in the plunge of cross folding die out north of the summit of Ben a'Chuallaich.

While no special study of the joints has been undertaken, it is clear in most exposures that the a c joints of the cross-folds are the most frequent.

Minor Structures of Ben a'Chuallaich Core (South of the Tummel).

The main core can be detected south of the Tummel where it continues south south westwards towards Schichallion and swings sharply into the east-west trend (Map 6). The interesting point is that the majority of minor folds and lineations also follow this swing. These folds and lineations have a plunge of $20^{o}$-$30^{o}$ which swings from $20^{o}$ east of south to practically east. However, numerous observations show that there is also a number of steeper axes and lineations which do not swing at all. In fact right at the bend they plunge down the dip of the rocks as shown on the map 6. The distribution of dips indicates that this is the plunge of the comparatively large antiformal core of limestone, which plunges 50°-60° south of east at a relatively high angle.

The existence of two cross-fold axial directions in this area must be explained. It is suggested that the swinging trend of the minor folds has resulted from the influence of the mass of Schichallion Quartzite parallel to which there are axes to the south of the mountain as well. On the other hand east of Schichallion normal cross-fold axes with a plunge of 20°-30° trending 20°-30° south of east reappear again. A few Caledonoid folds are again visible, for instance in the Dolomitic Beds of Tempar burn (Pt. D7, 94, 55). These beds have been protected by the thick quartzite on the either side of them, and on minor scale have not suffered appreciably from the effects of refolding. In consequence the associated fine grained biotite schists are platy and do not show appreciable crumpling. On the other hand the schistose formations of the main Blair Atholl cores do not show this platy schistosity, but an extensive small scale crumpling and phyllitic lineations. Even in these occasional signs of the first folding are present. For instance the quartzose bands of the Banded Group are often sheared into tectonic inclusions which are in addition folded on cross-fold axes. Unfortunately there are no adequate exposures where the plunge of the pre-cross-fold closures can be read clearly. In addition the tectonic inclusions and indeed the continuous quartzite bands of the Banded Group show frequent signs of lozenge-shaped boudinage, which on local evidence is either post-cross-folding or roughly contemporaneous with it.

The biggest and the most spectacular tectonic inclusion within the Blair Atholl cores occurs at the southern end of the Balliemore fold. The inclusion consists of a completely disconnected closure of the Balliemore fold and is almost a mile in length and up to 300 yds. in width. Lithologically it consists of Boulder Bed with a discontinuous selvage of White Limestone surrounded everywhere by Banded Group (Map 5).

The Ben a'Chuallaich core south of the Tummel attains in parts an almost vertical dip of lithological units. Its schistose parts, however, often show strain slip schistosity dipping at moderate angles of $40^{\circ}$-$50^{\circ}$ to the east or east northeast, which indicates the general inclination of the axial planes of the local cross-folds.

Minor Structures of Dunalastair Core.

South of the Tummel, as shown on the Map 6, minor structures conform with those of Ben a'Chuallaich core. There are, however, differences north of the river where the rocks of Dunalastair core are in general more squeezed and show the influence of shear to a greater extent. For instance in Allt na Moine Bhuidhe (Pt.E4,91, 32) the Banded Group of the western limb of the Dunalastair core shows a very regular banding with sharp closures of the cross-folds and a preferred elongation of the quartz and felspar grains parallel to the fold axes.

Again the Dark Schist of the inner core, which south of the Tummel has a characteristic lineated appearance due to crumpling assumes a progressively more planar aspect towards Allt na Moine. Further north at

Croftnagowan where in the closure of the fold the Dark Schist expands again it regains its lineated character. Such variations in aspect are to be attributed to the influence and proximity of the Boundary Slide. This does not mean that sliding is necessarily entirely contemporaneous with cross-folding, since the Beoil Schist shows a strong phyllitic lineation on the cross-fold axes.

The significant swing of strike at Croftnagowan does not deflect the axes of minor folds. Bailey and McCallien (1937) have demonstrated that this swing is due to the existence of a recumbent fold which has refolded the Dunalastair core. That this is so is obvious from the relations of the minor structures to the swing as is shown on the Map 6.

<u>Trinafour Core</u>

A mile north east of Croftnagowan a closure of another core of Dark Schist can be recognized and it is in fact the continuation of the limestone involved in this core that is seen to continue round the apex of the Dalradian Triangle. The core can be traced southwards to Allt na Moine Bhuidhe where incomplete portions of it have been found and still further south near Lochan Beoil Chaidhaiche portions of it can be seen. Here as well as in Allt na Moine Bhuidhe this core is separated from the Dunalastair core by a strip of Perthshire Quartzite Series. This core, which being adjacent to the Boundary Slide, has suffered more deformation than the other Blair Atholl cores will be called the Trinafour core (Map 8).

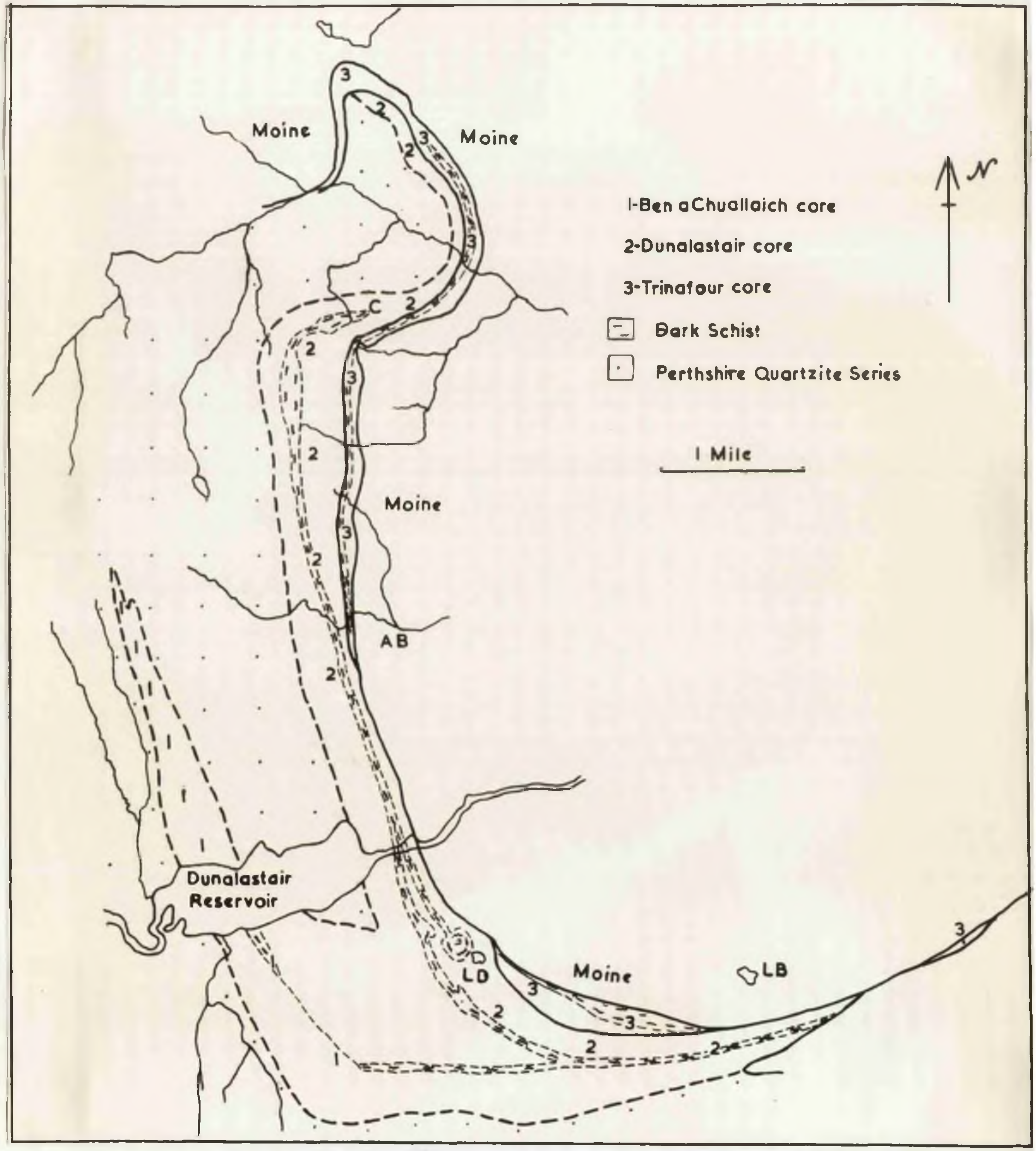



Fig.8 - Trinafour core.

The Nature of the Blair Atholl Cores

It has been already shown that the cores of Blair Atholl Series in this sector are incompatible with the hypothesis of them being either synforms or antiforms. It has been tentatively suggested that they may be the upturned cores of recumbent folds of large magnitude. The minor structures indicate that at least two episodes of folding have affected these cores. The first episode of which little is known nevertheless has left relicts in the shape of minor folds with Caledonoid axes. It seems, thus possible to make an inference that the first episode of movement also produced the large scale folds on Caledonoid axes.

The second episode which is responsible for upturning of the Caledonoid axes, and which has refolded the pre-existing schistosity of the schists into numerous corrugations imparting thereby a characteristic phyllitic lineation, was related to axes approximately at right angles to the Caledonoid direction. Most of the minor folds and lineations of this sector have been produced by this second episode. The trend of the Blair Atholl cores has been determined partly by such cross-folding and partly by the original attitude of the cores.

The closures of the three cores are the upturned closures of the first episode of folding, whereas the major deflection of the strike at Trinafour is the effect of the second episode, which has also produced a recumbent fold. From this it is possible to show that the first movement is more profound, since from the closure of the Dunalastair fold to the closure of the complementary Balliemore fold the distance is $5\frac{1}{2}$ miles implying a corresponding measure of recumbency during the Caledonoid episode of deformation. On the other hand, the measure of recumbency due to the cross-fold movements is only about 2 miles near Trinafour. Moreover, recumbency of this order of magnitude on cross-fold axes appears to be exceptional.

At this stage, to simplify the description, the two movements which are associated with Caledonoid and cross-fold axes may be given the specific titles of the Caledonoid Movements and the Cross-fold Movements respectively.

## IX. DALHOSNIE SECTOR

### Stratigraphy and Lithological Variations

Rocks of the Blair Atholl Series are not found in this sector; the meta sedimentary rocks consisting of the Perthshire Quartzite and Ben Lawers and Ben Eagach schists. The lithological varieties will be described in a stratigraphical order.

As in the Dunalastair sector the Schichallion Quartzite is a white + saccharoidal quartzite with a small proportion of felspar of mainly albitic composition. Current bedding is occasionally seen as in the band of quartzite east of Creag Varr (Pt. C5,93, 27), but as a rule it is absent. The quartzite is sometimes of a flaggy character and occasionally shows schistose bands as on the crags south west of Dalhosnie (Pt.D7,20, 80).

The Killiecrankie schist in this sector again shows considerable variations, and when it is quartzose it is very hard to distinguish it from the schistose varieties of Carn Mairg Quartzite.

Some varieties seem to be pebbly, with pebbles appearing as elongated spindles, the direction of elongation being parallel to the fold axes. These are easily confused with varieties which show isolated porphyroblast i.e. augers of felspar, usually microcline. At one locality east of Creag Varr (Pt.D5, 15,67) a very curious quartzose garnetiferous variety with sheared out plications of thin strings of amphibolite was collected. In general although occasionally slightly graphitic the Killiecrankie Schist is easily distinguishable from the other schist formations in the sector, that is Ben Eagach and Ben Lawers by being non calcareous and non graphitic.

The Carn Mairg Quartzite is a very variable formation which consists of coarse schistose and granulitic quartzites. Where massive, the Quartzite is much coarser than the Schiehallion Quartzite. On the margins of Ben Eagach schist, Carn Mairg quartzite is slightly carbonaceous. As traced northwards from the neighbourhood of Carn Mairg the quartzite becomes progressively more schistose and granulitic resembling Moines in its flaggy aspect. One of the distinguishing features of the quartzite is the occasional presence of sedimentary amphibolites. Such, for instance, are sporadically found in the bed of Allt Mor near Kinloch Rannoch. These are very rich in quartz of which they have up to 25%, otherwise they can be mistaken for epidiorites. The quartzite bordering the southern shore of Loch Rannoch is often extensively felspathized. The felspars are both albite and microcline and are obviously post-sedimentary as progressive alteration can be observed ultimately resulting in replacement of practically all the quartz. Some iron and calcium have been also introduced resulting in development of magnetite in the quartzite and a tendency for micas to be replaced by amphiboles and epidote. The residual mica flakes, in fact, show an unusually dark colour. The quartzite have several sills of post-meta morphic felspar porphyries intruded into them. It is unlikely that such minor intrusions are responsible for the afore-mentioned metasomatic effects as the bulk of the material introduced is disproportionately large. The metasomatized rocks are well displayed in a small quarry south of Loch Rannoch (1 mile south west of Kinloch Rannoch).

The Ben Eagach Schist is a carbonaceous schist which is fairly uniform in composition, but frequent variations in the proportion of mica and pale green amphibole of tremolite-actinolite series reflect the fact that it was originally more or less calcareous. In fact, there are varieties of schist in which the proportion of the amphibole is so high that the rock becomes a carbonaceous amphibolite, as on the western slopes of Creag Varr. On the top of Creag Varr such calcareous bands have been altered into a quartzose amphibolite commonly known as Garbenschiefer. Sporadic thin bands of quartzite are not uncommon in the Ben Eagach Schist of Creag Varr.

The Ben Lawers Schist of this sector is on the whole rather different from the calcareous muscovite phlogopite schists and Garbenschiefers of the type locality (Ben Lawers). The muscovite bearing schists still persist, but are generally subordinate to the coarse garnetiferous amphibolites, which contain but little felspar and are of a sedimentary rather than igneous origin. These amphibolites are evidently high grade equivalents of the calcareous Garbenschiefers. When such rocks are associated with meta-igneous amphibolites it is often impossible to trace the margins of the intrusion. There are two important outcrops of Ben Lawers schist in this section. The first occurs on the western margin of the Dalradian Triangle and is separated from the Struan Flags by the shear zone of the Boundary

Slide. It is possible to map this outcrop of the Ben Lawers Schist as a separate entity. The other outcrop which occurs in the core of the fold which will be called the Creag an Fhithich synform. Here the schist is often inextricably mixed up with Ben Eagach Schist, both having been broken up into a complex melange.

Distribution of Outcrops

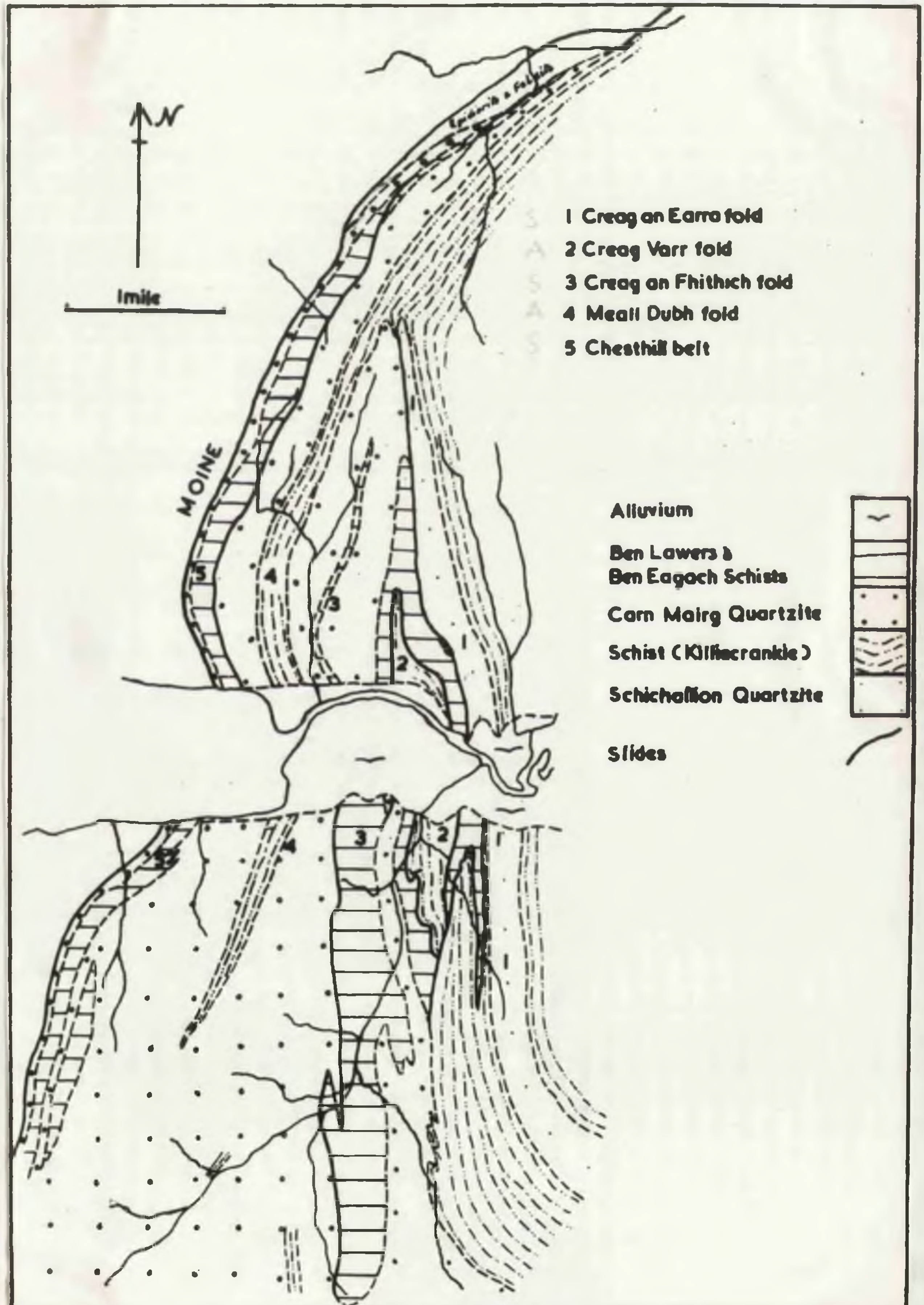
Three types of lithological belts are characteristic of this sector :-

1. To the east two belts of Killiecrankie Schist, separated by a belt of quartzite conform to the pattern of outcrops formed by the Blair Atholl cores of the Dunalastair sector. South of Schichallion the quartzite is in fact associated with a broken Blair Atholl core. There is little doubt that this structure is analogous to the recumbent fold described in the previous section. Bailey and McCallien (1937) realizing the analogy have called it the Creag an Earra synform. It is proposed to call it the Creag an Earra recumbent fold or nappe (Map 9).

2. Immediately west of the Creag an Earra fold there are two folds involving Ben Eagach and Ben Lawers schists. They are tending north-south and neither is following the great recumbent folds. Considerations of minor structures, to be discussed, show that:-

(a) The eastern fold is a broken antiform to be called the Creag Varr antiform.

(b) The western fold is a broken synform to be called the Creag an Fhithich synform.




Map 9 - General Map of Dalhesnie Sector.

These folds have a different mode of origin from Dunalastair, Ben a'Chuallaich and Creag an Earra recumbent folds.

(c) West of Creag an Fhithich synform there is a marked change of strike, and the trend instead of being north south becomes 30° east of north - 30° west of south. In this ground there are two folds, the first of relatively minor significance has Killiecrankie Schist in the core. This is the Meall Dubh antiform. The second one with a core of Ben Lawers Schist further south widens to the Chesthill belt of Glen Lyon, which according to Bailey and McCallien (1937) corresponds to the Ben Eagach fold which Bailey (1925) has identified south of Loch Tummel.

The above generalizations can be substantiated only with the help of minor structures which will now be considered.

Distribution of Minor Structures

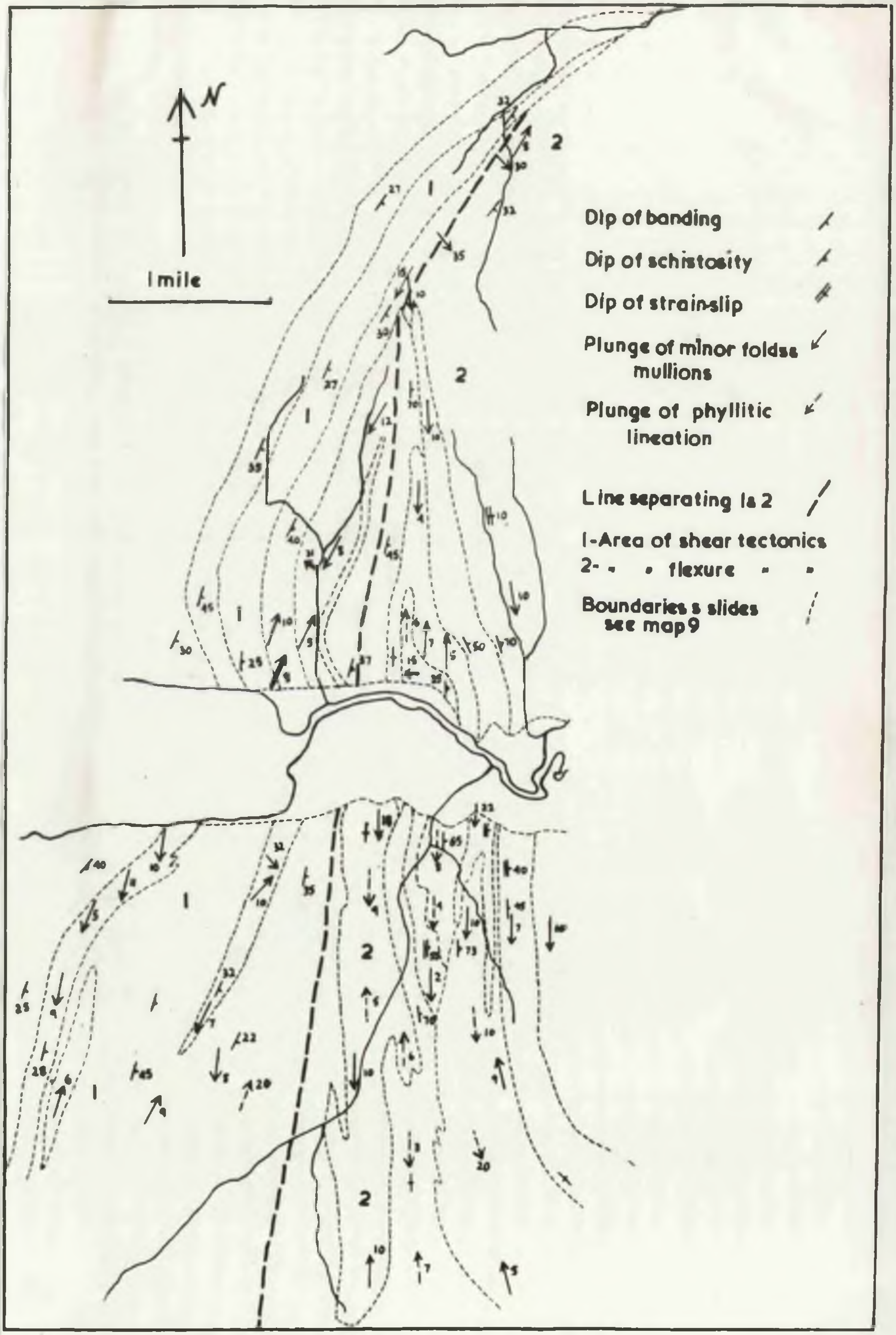
It has been shown that the area affected by the cross-folding in the Dunalastair sector is characterized by flexure-tectonics. This effect is not so noticeable on the western margin of the Ben a'Chuallaich fold; nevertheless, it persists through and is especially apparent around the Creag Varr and Creag an Fhithich folds where even quartzose portions of Killiecrankie Schist show a strong puckering. To the west of these two folds, however, a remarkable change takes place. The Carn Mairg Quartzite, the Killiecrankie Schist and the Ben Lawers Schist of Meall Dubh and Chesthill cores exhibit all the characteristics of shear-tectonics. Puckering and phyllitic lineation disappear. On the other hand, sheared out closures of folds and tectonic inclusions become abundant and boudinage is prevalent, the rocks assuming all the peculiarities associated with the "Moine phase". This change takes place at the same time as there is the general change in strike. In other words the line of Creag an Fhithich fold corresponds to a rapid change in tectonic style and the axial plunge of folds.

All the areas in which the flexure tectonics prevail are characterized by folds with north-south to north-west-south east trend, all of which are the result of the cross-fold episode of movement. On the other hand the area characterized by the shear tectonics as shown on the map 10 show axes trending $25^{\circ}$-$35^{\circ}$ east of north to $25^{\circ}$-$35^{\circ}$ west of south. The absence of phyllitic lineation on Cross-fold axes implies the absence of the effects of the Cross-fold Movements. In other words the rocks west of the Creag an Fhithich line did not suffer from Cross-fold Movements and have been affected only by the preceding Caledonoid Movements.

The Killiecrankie Schist outcrop south of Loch Rannoch which shows minor folds on cross-fold axes may appear to be inconsistent with this generalization. These folds, however, show a significant difference from the cross folds of say Creag an Fhithich synform, for they are recumbent folds showing a measure of recumbency similar to the folds trending $30^{\circ}$ east of north. In addition the latter folds have a common plane of schistosity with the recumbent cross-folds, a circumstance, which indicates that the two are contemporaneous or nearly so.

Minor Structures and Creag Varr Fold

Bailey and McCallien (1937) working north of the Tummel realized that Creag Varr represents a large upfold of Killiecrankie Schist plunging under the cover of Ben Eagach Schist. Quite apart from the evidence of




Map 10 - Structural Map of Dalhosnie Sector (Minor structures). - Regions of different tectonic style are indicated.

mapping it is apparent that all the minor folds of the Killiecrankie core are plunging at a small angle northwards, thus implying an antiformal shape to the fold.

The junction of Ben Eagach Schist and the Killiecrankie Schist can be mapped very precisely and in places small portions of Carn Mairg Quartzite are still present in between the two. Movements on the junction have been very strong so that in parts recumbent folds of quartzite and amphibolite have been folded recumbently again. Following northwards the plunge gradually reverses and yet the outcrop of Ben Eagach Schist thins out. Such a relationship means that the Creag Varr fold is not just a simple antiform but a more complex structure. Considering the eastern boundary of the Ben Eagach Schist on Creag Varr part of the explanation becomes immediately apparent as there the Schichallion Quartzite core of Creag an Earra fold is seen to occur next to the schist with only sporadic slices of Carn Mairg Quartzite and Killiecrankie Schist in between. Evidently a slide separates the core of Creag an Earra fold from the Ben Eagach schist of Creag Varr. This slide is no doubt partly responsible for the disappearance of the Ben Eagach Schist northwards. In fact the slide eliminates the Ben Eagach Schist from the eastern limb of the Creag Varr upfold. On the western limb of Creag Varr upfold the Ben Eagach Schist is on either side adjacent to the members of Perthshire Quartzite Series, which implies that the Schist is synformal on this limb. Now, if the slide on the eastern limb of the structure is held responsible for the cutting out of Ben Eagach Schist, on the western limb the schist will plunge out northwards in any case. Such an interpretation accords well with the fact that on independant grounds it is possible to prove that the Creag an Fhithich fold is a synform. It must be separated by an antiformal core of Carn Mairg Quartzite from the synformal limb of the Creag Varr structure. In fact this is the case.

The continuation of Creag Varr structure can be seen south of the Tummel. The western limb of Ben Eagach schist continues normally for another two miles, but the eastern limb of the antiform is more complex as here it has been subjected to a most violent deformation. Throughout the schist isolated bodies of Carn Mairg Quartzite and discontinuous masses of a highly garnetiferous hornblende schist are dispersed as tectonic inclusions. The trend of the minor folds and phyllitic lineations, however, indicates that a very broken synform is present in which the Killiecrankie Schist is occupying the core.

A strip of Killiecrankie Schist separates the Ben Eagach Schist from the Creag an Earra belt of Schichallion Quartzite. This strip is a tectonic position which is consistent with the explanation advanced here. This very tight synform of Ben Eagach Schist tends to converge towards the western limb and undoubtedly would have met it about a mile south of Dalhosnie (Pt.C7, 80,39 ) but for the intervention of a slide. This slide is the continuation of the slide described from the western limb of Creag Varr structure north of the Tummel and which may be called the upper Creag Varr Slide. The convergence of the two limbs of Ben Eagach Schist is due to the fact that south of the Tummel the plunge of the cross-folds changes from a few degrees to the north to a few ($3^{\circ}$-$20^{\circ}$) to the south in consequence of which the Craig Varr antiform shows a closure occurring 1 mile south of Dalhosnie. Throughout the Creag Varr structure the attitude of schistosity, which is normally of strain slip type is $40^{\circ}$-$70^{\circ}$ to the east, indicating a westerly overturning.

Minor Structures and Creag an Fhithich Synform

It has been demonstrated that the Craig Varr antiform is a highly complex structure. Similarly the Creag an Fhithich synform shows a considerable complexity. The synformal character of the fold is obvious if the plunge of all the minor structures at its two closures is considered. The northerly closure which is some 2 miles north of Kinloch Rannoch occurs in the region of south south westerly plunge. On the other hand the southern closure is in the area of northerly plunge. The most complex area is however the central part around Creag an Fhithich where dividing lines between the Ben Eagach and Ben Lawers Schists as well as the junctions with Carn Mairg Quartzite practically disappear and all three formations are thrown into a melange of disconnected masses which are nevertheless characterized by a more or less uniform plunge of folds and lineations which is $4^{\circ}$-$10^{\circ}$ south.

On the assumption that the schistosity agrees with the axial plane it can be said that the fold has a vertical axial plane south of Pt. 07, 30, 04. it is variable in the neighbourhood of Creag an Fhithich and it is inclined to the east north of Kinloch Rannoch. Immediately west of Creag an Fhithich the distribution of dips indicates a subsidiary antiform overlain by Carn Mairg Quartzite. The structure has evidently a westerly inclination of the axial plane. Such local variations in regional dip of isoclinally folded series may be due to the existence of a large intrusion of epidiorite almost immediately to the west.

That the Ben Eagach Schist margining the synform and the surrounding Carn Mairg Quartzite are frequently interfolded is obvious on considering some exposures in a stream immediately east of Allt Mor (Pt. C5, 15, 15). Here at the junction of the two formations recumbent folds of quartzite and the infolded schist can be seen. The infolds of quartzite possess Caledonoid trend and form upfolds projecting into the schist indicating that at this point the structural succession is right way up.

North of the Tummel, in so far as Creag an Fhithich fold is concerned the effects of the Cross-fold Movements become very much less pronounced. The phyllitic lineation is inconspicuous and most folds trend 25°-35° east of north to 25°-35° west of south. In effect what was a Cross-fold synform south of the Tummel becomes a Caledonoid fold north of the river. Such a case could easily arise when the two trends are not separated by too great an angle.

Meall Dubh "Antiform" and Minor Structures.

West of the Creag an Fhithich synform the most notable structure is the Meall Dubh belt of Killiecrankie Schist flanked on the either side by Carn Mairg Quartzite. This belt continues northwards joining the main belt of the Killiecrankie Schist which runs along the western side of the Creag an Earra fold. Southwards the last exposures of the Meall Dubh belt are seen near the summit of Meall Breac, two and a half miles south west of Kinloch Rannoch. Lineations and axes of folding indicate that locally the disappearance of the belt can be explained by plunge, which is at a few degrees 30°-35° west of south.

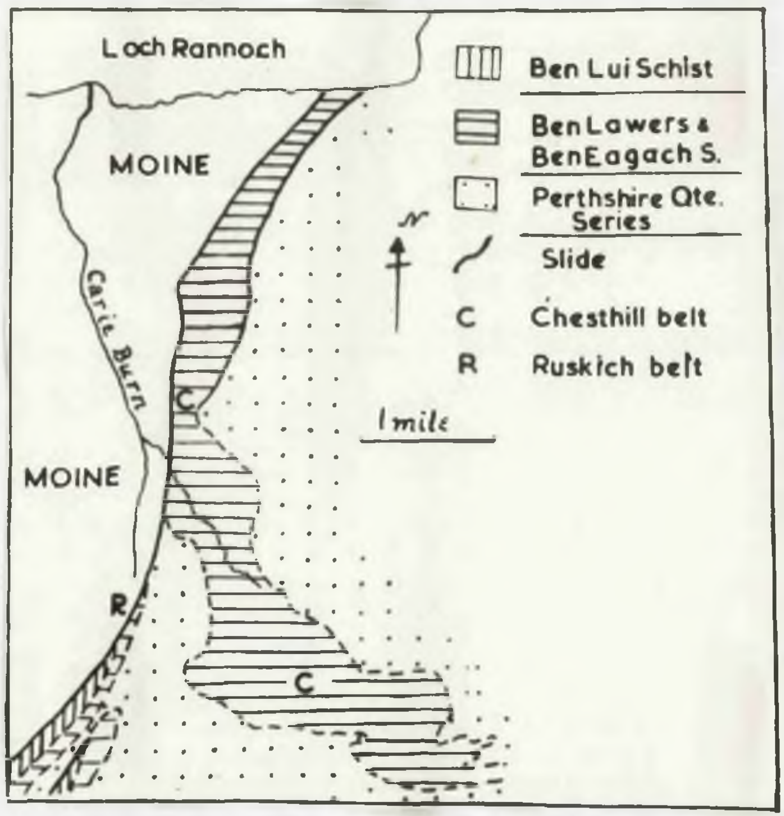
A puzzling feature, however, is that the plunge changes its direction just a few hundred yards further to the south, where numerous exposures of quartzite, Ben Eagach Schist and Ben Lawers Schist show minor folds with an average plunge being 25° east of north at 10°, and yet the Killiecrankie Schist fails to reappear. In fact, the exposures of the Killiecrankie schist described above are the most westerly exposure recorded in the Area, despite the fact that the Pebbly Quartzite, which is equivalent to Carn Mairg Quartzite has been mapped at numerous localities to the west. The failure of the Killiecrankie Schist is possibly primarily stratigraphical although local tectonics are probably a contributory factor. There is also indirect evidence in support of this contention. Several discontinuous belts of a quartzose garnet mica sheet have been found by Bailey and McCallien within the great area of Carn Mairg Quartzite situated between the Creag an Fhithich and Chesthill belts of Ben Lawers and Ben Eagach schists. The one immediately to the west of the Creag an Fhithich fold is well exposed. It can not be connected to any major structure in the area and seems to be more in the nature of a stratigraphical intercalation and may represent the final manifestation of this particular sedimentary facies.

After the above discussion it is obvious that the evidence favouring an antiformal character for the Meall Dubh belt is inconclusive, but in a district where belts of Ben Eagach and Ben Lawers schists appear to be synformal, a belt of Killiecrankie Schist with Carn Mairg Quartzite on the either side is reasonably interpreted as antiformal.

Chesthill Belt of Ben Lawers Schist.

Separating the western outcrop of Carn Mairg Quartzite from the Boundary Slide is a belt of Ben Lawers Schist which has been traced by Bailey and McCallien (1937) all the way to Glen Lyon and called the Chesthill belt. In Glen Lyon the core of the belt consists of Ben Lawers Schist bounded on either side by Ben Eagach Schist and Carn Mairg Quartzite. Sporadically all these formalities have now been traced on the either side of the belt in the sector under consideration. On the western side of the core for most of the distance Ben Lawers Schist is directly adjacent to the slide zone, while on the eastern side of the core Ben Eagach Schist continues as a thin band intervening between the Ben Lawers Schist core and the flanking Carn Mairg Quartzite right up to the southern shore of Loch Rannoch (Map $S_1$).

Except that this belt of schist structurally underlies the Carn Mairg Quartzite no generalization can be safely made until the country south of the Area is re-examined. The Ben Lawers Schist having been traced to the upper reaches of Carie burn seems to continue further south towards Creag Ard (Map 11). However, as the map shows Bailey and McCallien have continued the outcrop between the Chesthill and Ruskich belts. They point out that such a continuation can not be proved on the basis of local exposures. Whatever the precise structure of the Chesthill belt it appears to be largely




Map 11 - Chesthill and Ruskich belts.
(According to Bailey & McCallien)

sheared out by the Boundary Slide.

While in the Dunalastair sector the rocks adjacent to the Boundary Slide have not suffered appreciable post-metamorphic deformation, in this sector occasional patches of mylonite are to be seen (Pt.C3, 75,69) and the microscopic examination of thin sections indicates quite widespread effects of retro-metamorphism. This subject will be returned to later.

Summary

The conclusions reached in this section may be summarized as follows:-

(a) The continuation of the quartzite closure of the Creag an Earra nappe has been recognized in this sector.

(b) West of this belt of quartzite there occur two major cross-folds, the Creag Varr antiform and the Creag an Fhithich synform.

(c) West of Creah an Fhithich synform the trend is Caledonoid.

(d) The cross-folds of this sector are oblique to the Caledonoid trend.

## X. KINARDOCHY SECTOR

### Stratigraphy and Lithological Variations

In this sector the metasedimentary rocks range stratigraphically from the Dark Schist of the Blair Atholl Series to the Killiecrankie Schist of the Perthshire Quartzite Series. Variations in rock types are just as considerable as in the other sectors.

The Dark Schist on the whole is similar to the Dark Schist of Dunalastair sector, especially east of Schichallion. It usually possesses a linear rather than planar foliation and associated with it occur sheared out discontinuous bodies of garnetiferous amphibolite. It has been already noted that in the Area this kind of structure is associated with dominant cross-folding and indeed immediately north of Schichallion where the effects of cross-folding are not as strong as elsewhere in the sector the Dark Schist of a fragment of the Trinafour nappe has a good planar schistosity (Map 8 ). The same schist develops large porphyroblasts of kyanite and hornblende. An associated calcareous schist is very rich in tremolite and is presumed to be Dark Limestone.

The Dark Schist of the Creag an Earra core is associated with numerous calcareous bands and layers of limestone as seen in a series of streams flowing into Allt Kynachan. It is impossible to say whether stratigraphically one or all of these limestones are equivalent to the Dark Limestone. In several localities these rocks show layers of a curious very dark fine grain quartzite, which is extremely splintery on fracture and is charged with graphite. While no definite statement can be made about the origin of this rock, the author is inclined to think that this is probably a metamorphosed sedimentary chart. At one point it outcrops by the roadside (Pt.L7, 20, 02).

South and west of Loch Kinardochy where a series of intrusions of metadolerite and hornblende schist occur limestones show the development of large blades of highly coloured actinolite and a strongly plaeochroic epidote implying metasomatic introduction of iron. Both Dark and White limestones of the Blair Atholl Series have been affected.

The Banded Group has the same general lithology as elsewhere in the Area.

White Limestone apart from occasional enrichment in tremolite and phlogopite does not show any outstanding variations. Grading through honeycomb rock it passes almost imperceptibly into Schichallion Boulder Bed. On Schichallion itself the Boulder Bed is repeated. As in the Dunalastair sector the second horizon of the boulder bed is generally more quartzose than the main horizon and is characterized by smaller pebbles. Though granitic pebbles exist they seem to be less abundant than in the Schichallion Boulder Bed proper. An exposure of this rock occurs a hundred yards south of Braes of Foss.

A few yards east of the latter exposure the Dolomitic Beds of Schichallion make their appearance. Here they are represented by calcareous schists with occasional thin bands of limestone bearing pale green tremolite. Bands of tremolite rock also occur, one of the bands being composed of highly packed spherulites of radrating blades of tremolite.

The Dolomitic Beds increase considerably in width when traced on to the eastern slope of Schichallion, where they are associated with a considerable mass of biotite schist and flaggy schistose quartzites.

The bulk of Schichallion quartzite of Schichallion is a massive rock very occasionally showing evidence of bedding. Some exposures show folded current bedding. The Killiecrankie Schist is again a variable formation of schists and schistose quartzites.

Distribution of Outcrops.

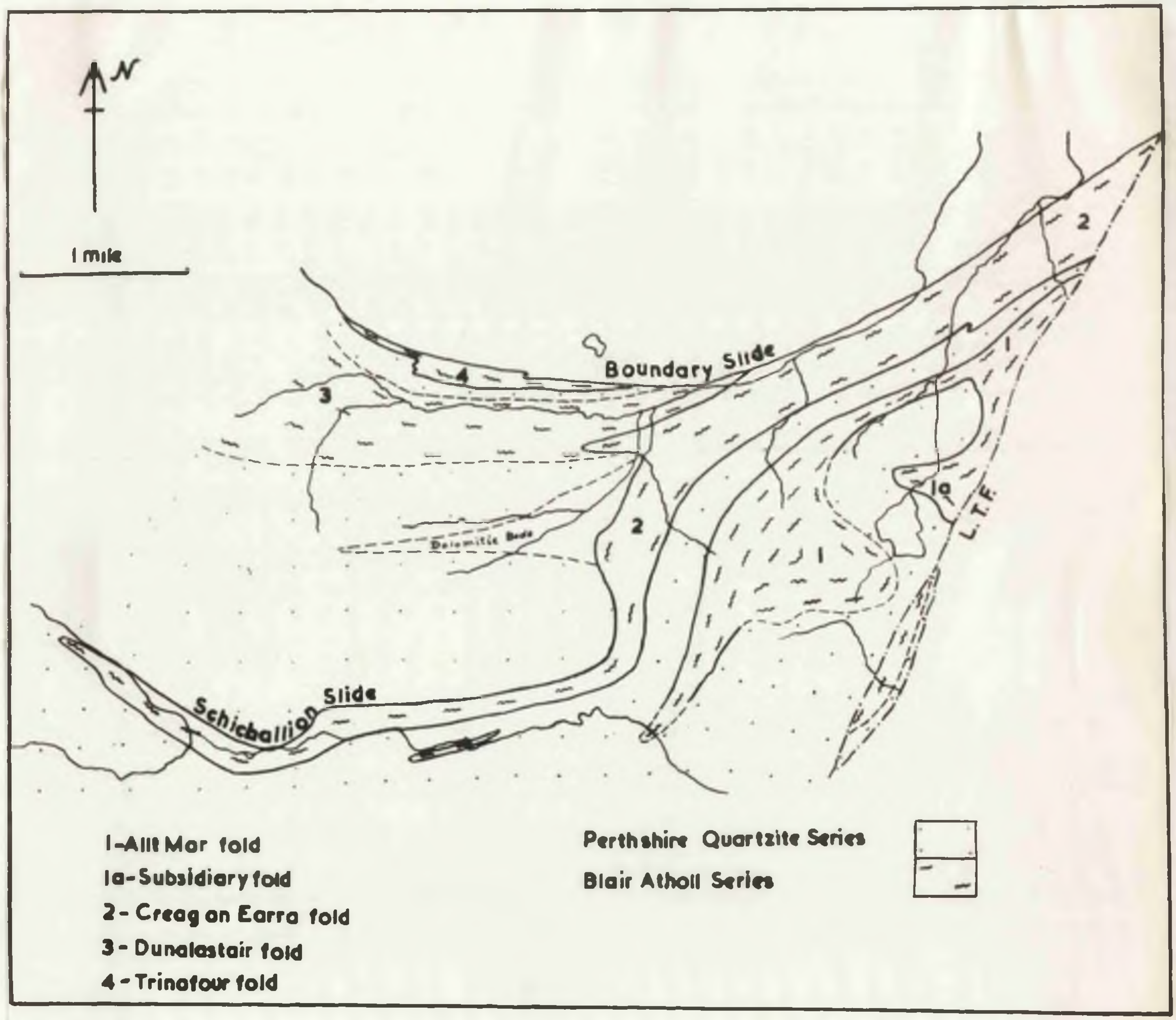
The existence of three Blair Atholl cores is obvious from the map 12. Of these the two most important are :-

1. The Creag an Earra core which continues into Dalhosnie sector south west from Schichallion and which truncates the remnants of the Dunalastair and Ben a'Chuallaich cores in the Kinardochy sector.

2. The Allt Mor core with a subsidiary core next to the Loch Tay fault.

Separating the Creag an Earra core from the Allt Mor core there is a fold of Killiecrankie Schist intermittently flanked by Schichallion Quartzite.

The Creag an Earra core is extremely broken. On the northern limb of this core the flanking quartzite is seen only in one or two very small exposures south of Schichallion (Pt. F9, 60, 30). On the southern flank again the quartzite has been subjected to strong movements and is cut out altogether when the core is traced north-eastwards. A complex structure occurs




Map 12 - General map of Kinardochy Sector.

on the eastern slopes of Schichallion where the calcareous Dolomitic Beds are truncated by the Creag an Earra core. This is shown by Bailey and McCallien as due to the operation of Schichallion Slide.

The Dolomitic Beds and the associated biotite schists of Schichallion reach an unusual width of some 500 yds. across the strike. The beds are quite strongly folded and show all the signs of deformation and yet the original thickness of the horizon must have been considerable. Some duplication by folding is suspected, since the subsidiary horizon of boulder bed is repeated twice across the strike from the Dolomitic Beds to the Boulder Bed proper.

South of the Creag an Earra core in Allt Mor there are several exposures of limestone occurring on the boundary of the Creag an Earra belt of quartzite and the Killiecrankie Schist to the south. The limestone is evidently a part of the Creag an Earra fold though the connection with the main core is nowhere seen.

Two other problematical calcareous outcrops occur wholly within the Killiecrankie Schist south of the two main cores. The first is an actinolite rich rock with sub-spherical small bodies of zoisite and calcite.

The second is a very small patch of a pale limestone situated on the eastern slope of Dun Coilich (Pt. K9,78,66). It is conceivably a glacial eratic, but the minor folds have exactly the same plunge as those in the surrounding Killiecrankie Schist, namely $10^{\circ}$ south of east at $20^{\circ}$-$25^{\circ}$.

The Allt Mor core forms a highly complicated outcrop which can not be adequately examined until the minor structures are described.

Distribution of Minor Structures[x]

It should be observed that this is the most complex sector of the Area and though the minor structures demonstrate conclusively the existence of at least two and possibly three episodes of movements, the direction of the axes of the first movement are suggested only tentatively. However, comparison with other sectors provides the explanation of the local complexities.

The difficulties of interpretation arise from two factors :-

1. Dominant cross-folding on axes varying from due west to $45^{\circ}$ south of west. - This movement is attested by all the usual criteria of refolding such as folded-folds, extensive phyllitic lineation and the occasional development of strain bands.

2. The influence of the Schichallion mass of quartzite, resulting in the axes of minor folds swinging into parallelism with the boundaries of the quartzite. Although the strongly deflected folds are local in distribution the presence of Schichallion may be partly responsible for the more westerly trend of cross-folding in the greater part of the sector.

The extent of the influence of cross-folding in terms of major tectonics can be seen from the general distribution of the strike of the various formations. Two important cross-folds are seen at the western part of the sector. Both have the cores of Blair Atholl Series, but whereas the combination of dips and plunges proves beyond any doubt that the fold south of Loch Kinardochy is plunging under the quartzite, the one north of Loch

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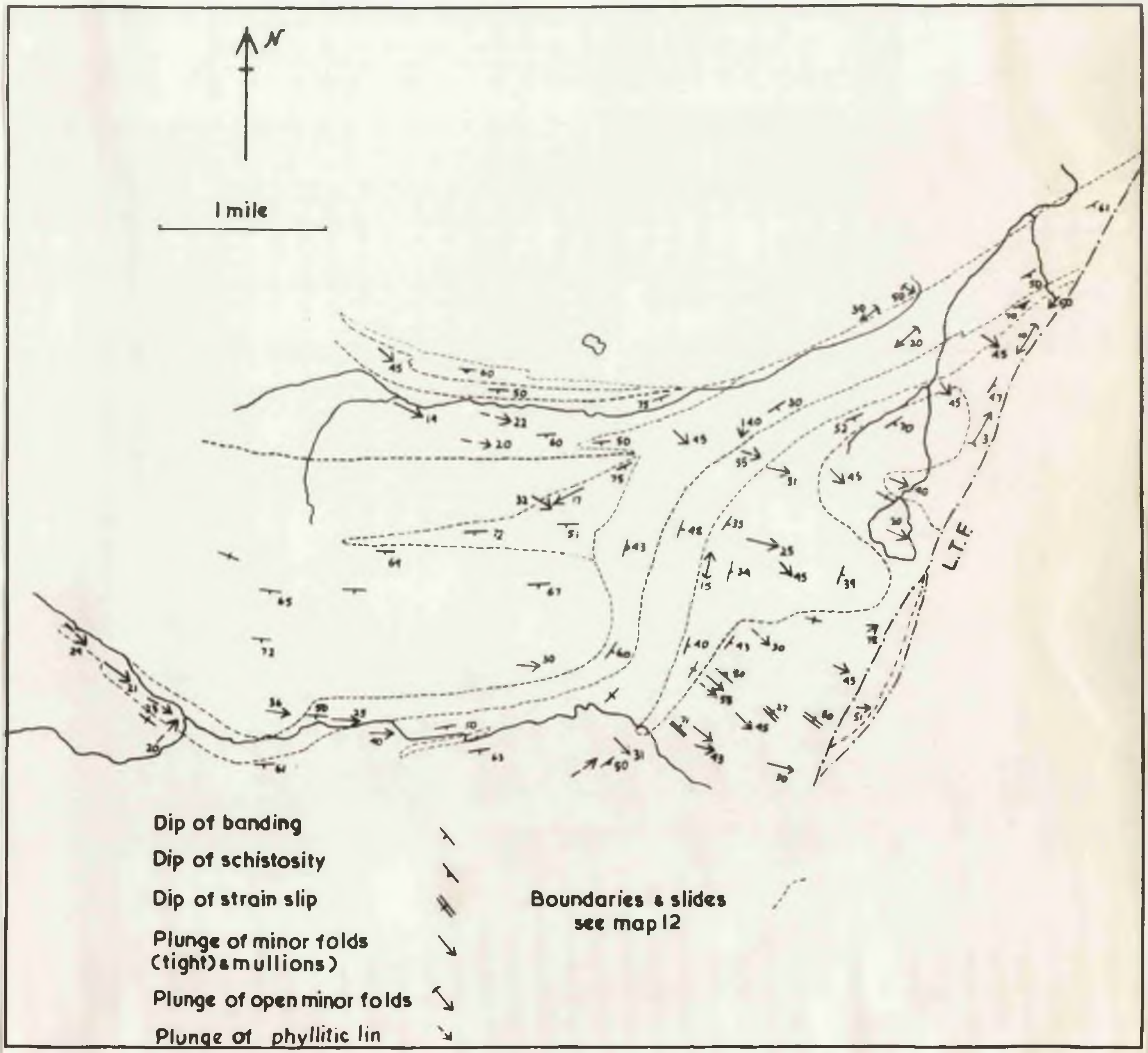
[x]See Map 13.




Map 13 - Structural map of Kinardochy Sector.

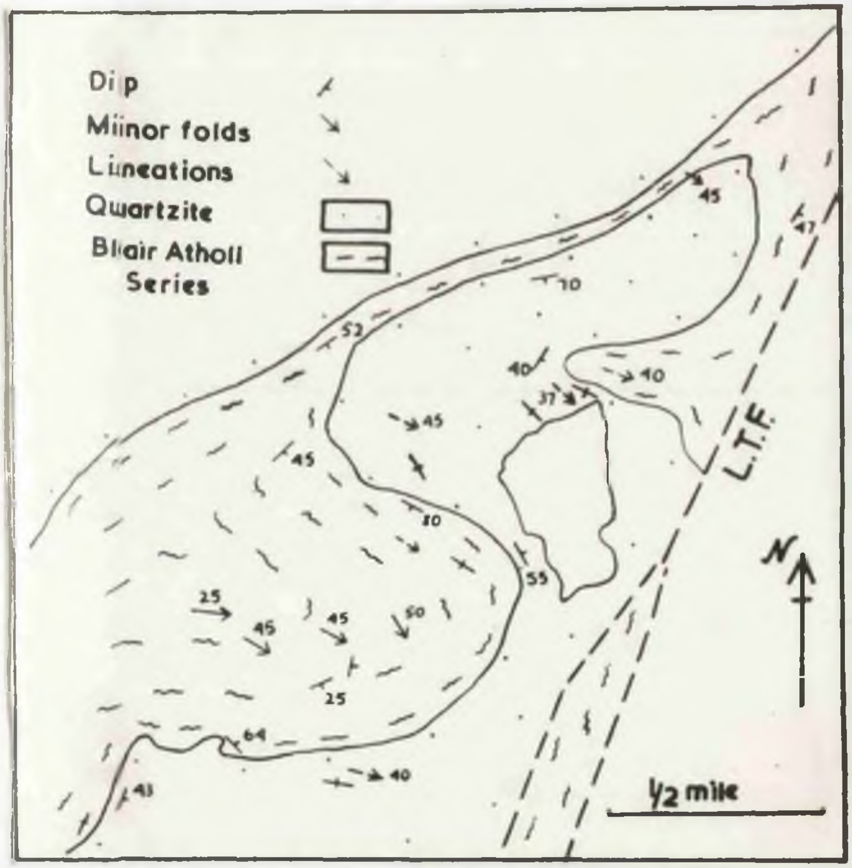
Kinardochy is plunging off the quartzite (Map 14). This means that from west to east a sequence consisting of a layer of Blair Atholl Series overlain by the quartzite which is in turn overlain by another layer of Blair Atholl series has been folded on axes which trend down the regional dip in this sector. In other words two cores of Blair Atholl Series and the intervening quartzite have been refolded on cross-folds.

South of the southern of the two major cross-folds the outcrop of Killiecrankie Schist on Dun Coilich has been strongly affected by these movements producing strong crenulation and in places the development of strain slip schistosity. In all the cases examined (153) the inclination of the strain-slip schistosity is towards north-east, which is the same in the Killiecrankie Schists west of Trinafour.

Such coincidence of the vergence of axial planes suggests that the cross-folds of Kinardochy sector belong to the same general movements which have affected the rocks of the other two sectors and which have been already called the Cross-fold Movements.

In this sector the amplitude of the major cross-folds increases south eastwards towards the Loch Tay fault. In fact the Creag an Earra fold and the western limb of the Allt Mor core are not appreciably affected by the major cross-folding.

Relatively weak post-Cross-fold Movements are indicated by the occurrence of a phyllitic lineation trending on east-west axes. Such lineations are seen on numerous surfaces within the Killiecrankie Schist of Dun Coilich. The low inclination of these lineations and the fact that they are not




Map 14 - Loch Kinardochy folds.

deflected by the cross-folds suggests that they are later, and they may be connected with the easterly plunging folds in the ground south of west of Loch Kinardochy. Such folds usually possess a smaller angle of plunge ($5^{o}$-$20^{o}$) than the cross-folds proper which plunge $25^{o}$-$45^{o}$. These folds may be the enfeebled representatives of the east-west folds associated with the Schichallion mass, which themselves may be slightly younger than the Cross-fold Movements.

So far pre-Cross-fold Movements have only been implied. The strongest evidence for their existence is that the major cross-folds refold more than one Blair Atholl core at the same time, in effect using the pre-Cross-fold folds as layers; the earlier folds being isoclinal thus constitute the layers involved in the later folding. Moreover, the shape of the Allt Mor Blair Atholl core suggests that it is of the same series of structures as the Dunalastair, the Ben a'Chuallaich and the Creag an Earra recumbent folds. The general strike of the Blair Atholl Series on the western limb of Allt More core is Caledonoid and as it has been already suggested this limb has not been appreciably refolded by the Cross-fold Movements, it is clear that the pre Cross-fold Movements were Caledonoid.

Unfortunately the original plunge of the Blair Atholl Caledonoid cores can not be prooved conclusively, although the evidence of the minor folds is suggestive. All the Caledonoid minor folds of the sector can be classified into :-

(a) The open flexures (b) The recumbent folds (Map 13).

A few open flexures plunge $10^{o}$-$35^{o}$ west at small angles ($0^{o}$-$15^{o}$)

It is fairly certain that these represent the very latest episode of mild deformation and are responsible for the slight fluctuations of plunge of the earlier folds. The open flexures are not accompanied by a schistosity.

Sharp and recumbent folds on Caledonoid axes have been noticed in several localities. These generally plunge $20^{\circ}$-$40^{\circ}$ west of south, north of Loch Kinardochy and $20^{\circ}$-$45^{\circ}$ east of north, south and west of Loch Kinardochy. The implication of the plunge north of Loch Kinardochy is that the quartzite separating the main Allt Mor core from the subsidiary core next to the Loch Tay fault is synformal. If so, then the Allt Mor core is antiformal and the change on Caledonoid plunge which occurs just south of Loch Kinardochy is due to the influence of the cross-fold acting as a culmination of plunge. It also implies that the closure of Allt Mor core occurring just south of Allt Mor is also antiformal the Caledonoid plunge having undergone another reversal of direction.

The above inferences can be supported by the obvious analogy which exists between the Allt Mor fold and the major Blair Atholl cores of Dunalastair sector. It has been argued that both the Ben a'Chuallaich and the Dunalastair folds are in the nature of recumbent antiforms with the Blair Atholl Series in the core. The Allt Mor core is evidently analogous to them and therefore is another recumbent antiform separated by a synform of quartzite from yet another recumbent core of Blair Atholl which occurs adjacent to the Loch Tay fault.

<u>Conclusions</u>

Structural features of the Kinardochy sector show the same movement picture as those of the Dunalastair sector. The rocks have been affected by two major movements producing :-

(a) A series of recumbent folds with Blair Atholl core closing to the north.

(b) Two major, almost symmetrical cross-folds, which refold the recumbent antiforms.

## XI. GEOMETRIC SYNTHESIS OF DALRADIANS

Recapitulation

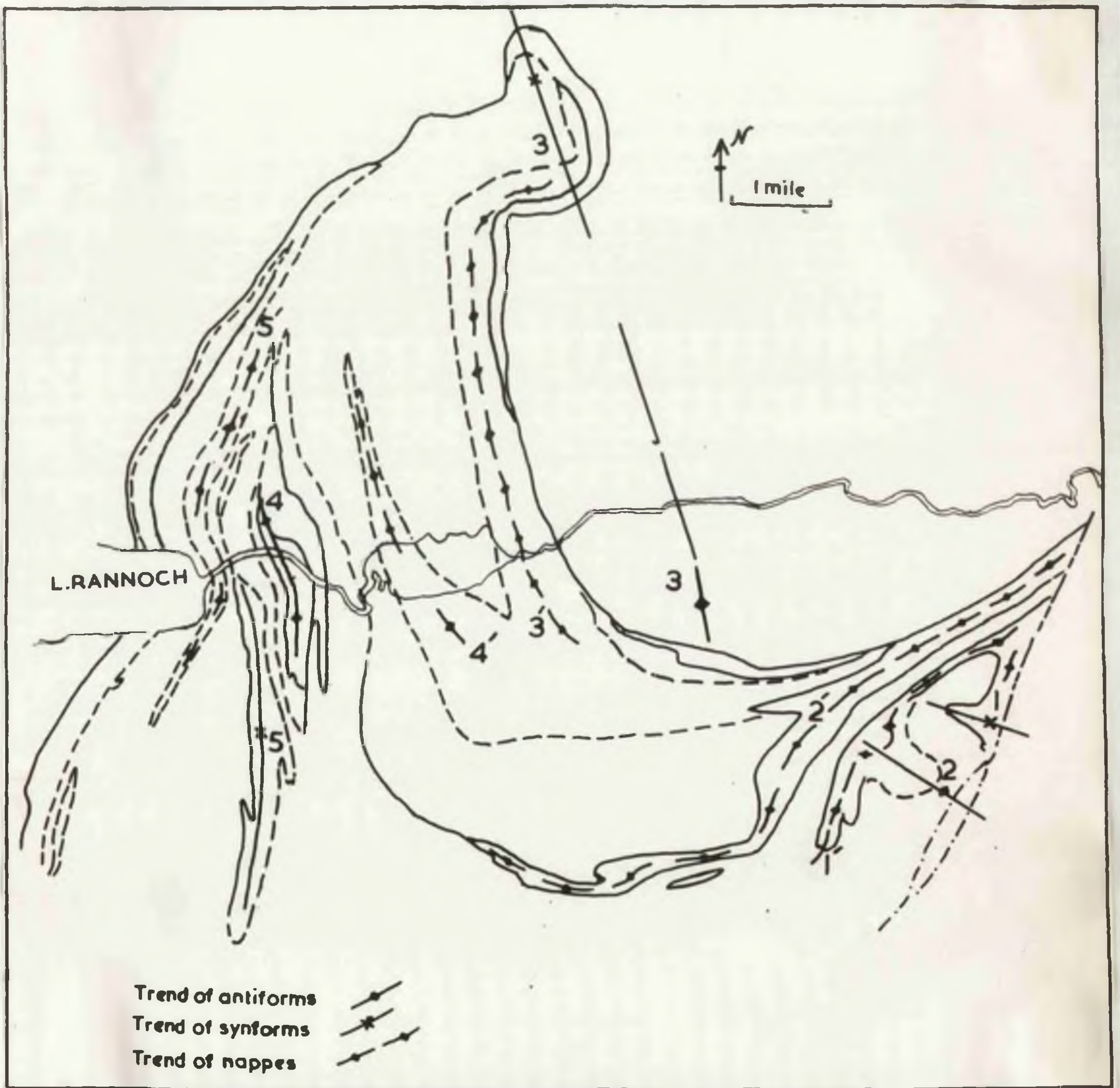
At this stage it is possible to summarise the main features produced by the orogenic deformation of the Dalradian rocks in the Area, as follows :-

(a) All the rocks have suffered at least two important phases of deformation; the first being responsible for production of the large recumbent folds up to five and a half miles in amplitude and possessing Caledonoid trend. The second episode is responsible for cross folding of varying intensity on a major scale, being practically negligible in the extreme western part of the Dalradian Triangle and strongest at the apex of the triangle, where a recumbent cross-fold with an amplitude of almost 2 miles is found.

(b) The cross-folds do not possess an absolutely constant trend, but vary from north-south in the western to 10°-20° south of east in the eastern part of the Area.

(c) From east to west five important cross-folds have been recognized (Map 15).

1. Synformal core north-west of Loch Kinardochy.
2. Antiformal core south-west of Loch Kinardochy.
3. The great recumbent fold at Glen Errochty, where it consists of a recumbent antiform and a complementary synform.
4. Creag Varr antiform, attended by two tight synforms.
5. Creag an Fhithich synform.




Map 15 - Structural lines in the Area.
1, 2, 3, 4, 5 are cores of cross-folds; $\dot{1}$, $\dot{2}$, $\dot{3}$, $\dot{4}$, $\dot{5}$ are cores of Caledonoid nappes. See text.

(d) The main Caledonoid Movements were responsible for production of four major recumbent folds with cores of Blair Atholl Series and an over-riding recumbent fold with a core of Killiecrankie Schist. The folds again from east to west are as follows :-

1. Allt Mor fold with a subsidiary smaller core to the east.
2. Creag an Earra fold.
3. Dunalastair fold with an adjacent incomplete Trinafour core.
4. Ben a'Chuallaich fold.
5. Meall Dubh "antiform" which is the only one with a core of Killiecrankie Schist showing the original Caledonoid trend, though more northerly than usual.

These five antiformal cores are associated with intervening synformal cores.

The core of Ben Lawers and Ben Eagach schists outcropping west of Meall Dubh antiform, again possesses a general Caledonoid trend, but its exact status will depend on future investigations in Glen Lyon.

(e) The plunge of the cross-folds is $30^{\circ}$-$60^{\circ}$ in Dunalastair and Kinardochy sectors, where it is dominantly due south-west to south south-west.

In Dalhosnie sector the plunge of the cross-folds is generally low ($0^{\circ}$-$20^{\circ}$), and fluctuates locally from south or south south east to north or north-west. The plunge is at $10^{\circ}$ east of south at the extreme northern part of the sector, while it trends at a few degrees north to north north-east at Creag Varr. Crossing the Tummel the plunge is again southwards and it reverses to northwards in the southern parts of the sector. The Caledonoid axes of Meall Dubh "antiform" show similar fluctuations in plunge. Such zones of culmination and depression of plunge trend approximately east-west and may be related to the east-west post-Cross-fold Movements detected in Kinardochy sector.

(f) The boundary between the Dalradian and the Moinian rocks is a slide, which has been called the Boundary Slide by Bailey and McCallien (1937). A number of other slides exists within the Dalradian rocks and can be recognized from mapping.

From the above structural relations a geometric form of the Dalradian rocks may be deduced. Each lithological unit involved in the re-folded cores of Dunalastair Ben a'Chuallaich and Creag an Earra forms a series of almost right angle bends. The map ($S_1$) shows that the northern part of each belt dips approximately east-wards or east north-eastwards at its northern extreme in conformity with the general dip of the overturned part of the Dunalastair core. However, once traced southwards all the belts approach verticality near the right angle bend. In fact that vertical portion of the Creag an Earra fold is of quite a considerable extent. As each re-folded Caledonoid core is traced from the eastern part of the Area to the bend it becomes at first vertical, and further to the north it overturns. Bearing these facts in mind, it is convenient to start the reconstruction of the geometry by trying to reconstruct the form of the Boundary slide.

Reconstruction of the Boundary Slide

At the western part of the Dalradian Triangle the slide is inclined west south-eastwards with the general dip of the Dalradian rocks varying from $45^{\circ}$ in the south to $25^{\circ}$ in the north. From Lochan Beoil

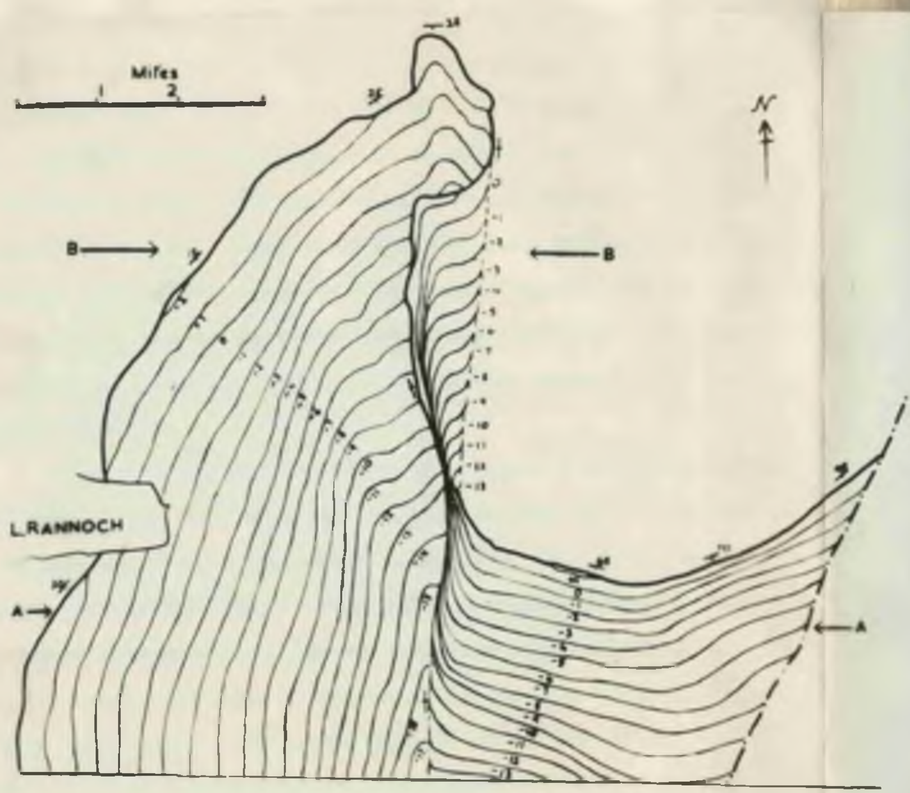
Chathaiche to the Loch Tay fault the average inclination of the rocks is $65^{\circ}$ southwards or south-eastwards. These are the parts where the slide is Caledonoid in trend and essentially conformable to the Caledonoid folds, as the outcrops of the Dalradian formations trend parallel to it. Ignoring for the moment the corrugation of the slide by the cross-folds, it is fairly evident that from Lochan Beoil Chathaiche up to Trinafour and round the apex of the Dalradian Triangle until the Errochty Water has been reached again the slide is conformable to the recumbent folds with Blair Atholl cores. However, over the three miles of ground which separate Colrig from Errochty Water the slide is evidently oblique to the Caledonoid structures, cutting off the Killiecrankie Schist apices of the Caledonoid folds and transgressing from Trinafour fold to the bottom of Chesthill belt. From the western boundary of the Dalradian Triangle to Lochan Beoil Chathaiche, the conformable slide has been folded by the Cross-fold Movements. The Cross-fold Movements have not disturbed this essential conformity,since they have folded the sheets of recumbent folds and the attendant conformable slide together.

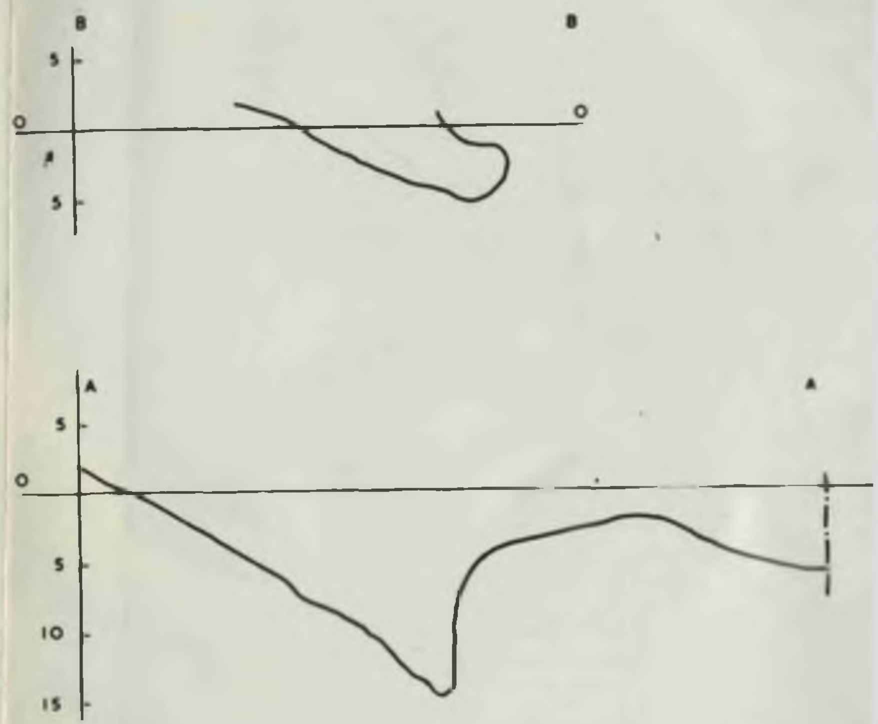
A corrolary of this deduction is that where the cross-folds are at right angles to the Caledonoid folds the plunge of the cross-folds indicates the pre Cross-fold inclination of the slide, provided that there has not been any appreciable post-orogenic tilting. This would mean that where the cross-folds are oblique to the Caledonoid folds the plunge of the cross-folds will be less, as indeed is the case with the Creag Varr and Creag an Fhithich folds.

The persistence of the vertical belt near the bends of the cores of Blair Atholl Series has to be re-examined from a different standpoint. The recumbent cross-fold at Glen Errochty possesses quite a high plunge of $25^{\circ}$-$30^{\circ}$. Such a fold can not continue indefinitely at depth. Moreover, whereas this plunge indicates the inclination of the synformal part of the cross-fold, where the antiformal part is encountered the plunge is evidently steeper. Since the axis of the antiformal part of the cross-fold trends almost at right angles to the trend of the Dalradian formations between Lochan an Daim and Lochan Beoil Chathaiche, the local steep dip of $60^{\circ}$ is equivalent to the local plunge of the antiformal part of the cross-fold. This means that unless the whole of the cross-fold bends downwards the common limb of the synformal and the antiformal parts is dying southwards. In other words the cross-fold alters in style. Evidently, in the process of disappearing the common limb first becomes vertical, giving rise to the relatively persistent vertical belts near the bend of the cores. It was found that such a deduction helps in the drawing of the structural contour diagram (Fig.25) of the Boundary Slide. The diagram was drawn by sketching in the contours of the Caledonoid segments of the slide, in the first place, and by extrapolating these contours in the cross-fold by bearing in mind the implications of the cross-fold plunge just described.

Geometric Shape of the Nappes

Fitted into the complex trough formed by the slide there are the refolded nappes whose axial planes follow the geometric form of the slide.




Structural Contours of Boundary Slide. ~ Contours at 1000 ft. intervals below and above sea level. Vertical scale of the sections is expressed in 1000 feet.

Fig.25.

In Kinardochy sector the nappes are overlying the upper limb of the antiformal part of the Glen Errochty cross-fold and are in the same position as in the pre-Cross-fold times. Here it is obvious that the Trinafour nappe is the lowest, followed tectorically upwards by a combined core of Dunalastair and Ben a'Chuallaich folds, which are in turn covered by the Creag an Earra and Allt Mor folds (Map $S_1$). Here the exposures on the ground represent a section essentially parallel to the closures of the folds (Fig.26a). On the other hand in the Dunalastair sector the ground surface approximates to a cross-section (profile) of the Caledonoid nappes, which have been upturned by the cross-fold movements (Fig.26b).

In Dalhosnie sector another cross-section of a nappe (Creag an Earra fold) is seen. West of it the effects of the Glen Errochty cross-fold die out abruptly, although two smaller cross-folds (Creag Varr and Creag an Fhithich) are seen refolding a Caledonoid nappe wholly composed of the members of Perthshire Quartzite Series and Ben Lawers and Ben Eagach schists. The upper or probably both limbs of this nappe form the Carn Mairg belt of pebbly quartzite which overlies much of the southern belt of the Killiecrankie Schist, which covers the upper limbs of the Creag an Earra and Allt Mor folds. The southern part of this belt of quartzite is outside the Area, but its limits are shown on the map 16. The quartzite evidently forms a cover to the nappes which possess cores of Blair Atholl Series. This interpretation of the structures is portrayed in the block diagram and is further illustrated by the serial sections across the Dalradian rocks. (See $S_4$ in the folder.)

# XII. MOINIAN ROCKS OF THE AREA

## Introduction

The Moinian rocks underlie the Boundary Slide where it is Caledonoid and form an envelope round the Dalradian core. Owing to their generally uniform lithology they provide only limited structural data. Nevertheless in a number of ways their study has supported and supplemented the conclusions reached from the study of the Dalradian rocks.

Beoil Schist, which has been classified as a Moinian Schist by Bailey and McCallien, presents a rather novel problem and will be treated in the section of slides.

## Stratigraphy and Lithological Variations

An effective stratigraphy of the Moines can not be established from available data. The rocks of the Area, which are locally known as Struan Flags are generally psammitic rocks but contain occasional bands of pelite. Where the exposures are adequate as they are south of the Tummel and round the apex of the Dalradian Triangle it is possible to differentiate and map various bands, although the boundaries are more or less ill-defined. Elsewhere, Moinian rocks are generally only sporadically exposed and are usually covered by peat, or glacial deposits. An additional difficulty is introduced in places where the rock is abnormally rich in felspar, especially microcline, some of which forms distinct porphyroblasts. In such cases it is difficult to discover whether the present character of the rock reflects its original composition or is due to a subsequent introduction of felspar.

Though "flagginess" is an almost ubiquitous feature of the Moines of the Area, it is especially pronounced near the Boundary Slide. It has been already noted that such flagginess is largely tectonic in origin.

The flags occasionally show a grading texture but it is impossible to ascertain whether or not this represents graded bedding as the rocks have been recrystallized extensively. At one locality near Struan (Pt. M2,35,54). well preserved current bedding is seen to be overturned. Such original structures are frequently seen in the type of granulite known as "salt and pepper Moine" in which micas are relatively small and do not possess a very pronounced orientation. These rocks are massive rather than flaggy and the preservation of the original structures probably implies that the "salt and pepper" type represents a less disturbed portions of the Moine sequence.

Mineralogically the Moinian rocks are quartzo-felspathic granulites with varying amounts of mica. Both plagioclase and potash felspar are present and normally in the Area potash felspar is more abundant. Under the microscope it is possible to see, that whereas potash felspar is normally quite fresh, the plagioclase felspar shows extensive micaceous alteration products. Moreover the potash felspar texturally lobes into other minerals. While the criterion of lobing does not in all the cases imply the late origin of the lobing mineral, it is virtually certain that the larger crystals of microcline formed in the Moines of the Area are late, since they are seen to interrupt and cut across micas (Fig. 28a). The proportion of potash felspar to plagioclase varies quite considerably. Exceptionally there are varieties which are poor in potash felspar such as to the south of the Tummel.

The proportion of micas in the Moines is variable, but only occasional thoroughly pelitic portions have been noticed.

Highly quartzose Moines occur on Creag Kinachan south of the Tummel. In fact Wilson (1905) has included these rocks into Perthshire Quartzite Series. At the other extreme highly felspathic Moines are known from the neighbourhood of Trinafour (Pt. F1,89,50). Coarseness in these rocks may be indicative of degree of recrystallization as well as a reflection of original lithological character. However, a band of very coarse Moines which surrounds the apex of the Dalradian Triangle is undoubtedly a lithological unit, as the micas are small (Map 18b). On the other hand the coarsely felspathic gneisses with large biotites and occasional garnets, which occur south of Glen Errochty (Pt. K3,32,80.) are evidently intensely metamorphosed rocks and resemble the Moine Gneisses of the injection complexes.

A puzzling feature of the Moinian rocks is an almost complete absence of hornblende schists and epidiorites which are so abundant in the Dalradian rocks, despite the evidence to be presented (p.128) that at least some of the epidiorites are later than the main movements.

Structure

The virtual impossibility of recognising specific horizons within the Moines makes the elucidation of structural pattern a matter of considerable difficulty, but two features are readily apparent :-

1. The regional distribution of dips round the Boundary Slide in general confirms the structural relations inferred within the Dalradians. To the west of the Dalradian Triangle the sheet dip of the Moinian rocks carries

them under the Dalradian. To the east of the Dalradian Triangle, where the slide possesses a Caledonoid strike the Moines again dip under it. They dip off the Dalradian rocks adjacent to the Glen Errochty cross-fold (Map $S_1$).

2. Vertical belts with strikes in agreement with the axial direction of the cross-folds exist in several localities within the Moines, showing that these rocks have been affected by the Cross-fold Movements. The most conspicuous of these belts occurs at the apex of the Dalradian Triangle. It continues for 3 miles in north-westerly direction.

Another belt occurs near Bohespie; its continuation being uncertain as the exposures fail both to the south and to the north. The rocks here have a north-south strike.

Another nearly vertical belt can be detected on the southern slope of a hill known as Sron Choin (Pt.D1,39,99). In all these belts the characteristic "flagginess" of the Moinian rocks is folded. If as has been suggested this "flagginess" is at least in part tectonic in origin its development must have preceded visible cross-folding. In other words there is a parallelism between the tectonic histories of the Moines and the Dalradians.

There are indeed many indications that the tectonic pattern of the Moines is one of extreme complexity, as may be seen from a detailed study of the Moines exposed on the northern slopes of Glen Errochty west of Struan. The lower reaches of Errochty Water as well as the hills immediately to the north show several exposures of generally massive Moine granulites. In the river (Pt.M2,95,55) while the bulk is uniform psammitic granulite some semipelitic portions occur. At one point especially very intricate folding is seen (Fig.27). The dip of schistosity which is axial-planal is about 30°, 25° south of east and the axes of folding plunge 35° north of east at 10°. The dip and strike of schistosity corresponds to the average dip and strike of "flagginess" of the surrounding rocks. Half a mile west of these exposures on the brow of a hill (Pt.M2,35, 54 ) current bedded psammitic granulites again show a schistosity dipping 30°-40° in south westerly direction. The average dip of bedding is 20°-25° east south-east and the evidence of current bedding is that the granulites are overturned. If the movements producing overturning have also produced schistosity, then the criteria are conflicting, for whereas the current bedding proves the rocks to be upside down the relations of schistosity to bedding indicate that the formations occur in the upper limb of a fold. The only possible conclusion is that the rocks are showing the evidence of two movements. The schistosity appears to be of a "strain slip" type, the plunge of the crinkles produced trending 25° north of east at 15°-17°, so the second movement is Caledonoid. The dip of schistosity here is higher than the general "flagginess", whereas in the exposures in Errochty Water it corresponds to the "flagginess". It seems reasonable to suggest that the latter rocks have been deformed only by one set of movements which are Caledonoid. On the hill, however, the rocks have suffered a second episode of movements which is also Caledonoid. Here, therefore is an example of refolding on the same set of Caledonoid axes, the first folding having been strong enough to produce recumbent folds. Judging by the style of the plications the second Caledonoid movement has produced relatively open

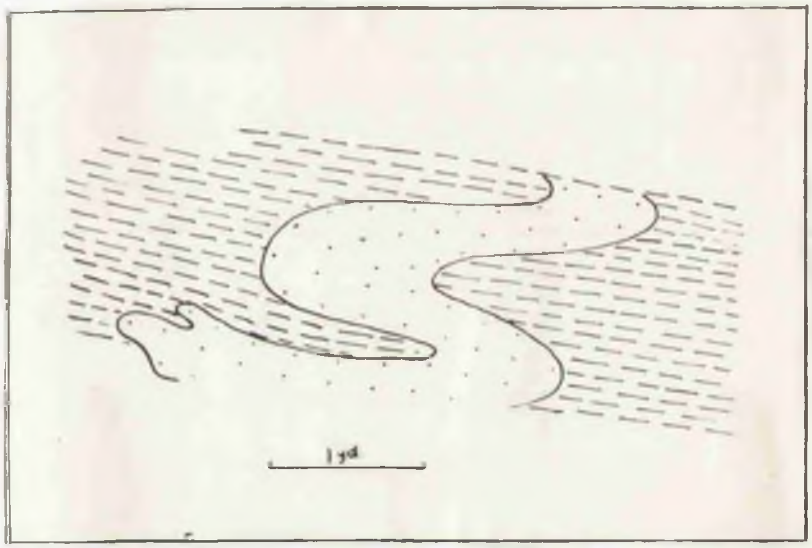



Fig.27 - Style of folds from Glen Errochty.
Psammitic band, stippled; pelitic band,
dashes.

overturned folds the direction of overturning being to north-west.

One mile and a quarter to the east in a stream several exposures of a very flaggy granulites show a general dip of $40^{\circ}$-$50^{\circ}$ at $10^{\circ}$-$20^{\circ}$ south of east. This may be a belt of later cross-folding but exposures are poor.

A further half a mile to the west, a prominent series of crags shows a belt of steeply dipping Moines striking $20^{\circ}$ north of east, and the inclination varying from $20^{\circ}$ west of north at $70^{\circ}$-$80^{\circ}$ east of south at $80^{\circ}$. The "flagginess" here is folded on relatively open folds with the axial planes inclined south west at $25^{\circ}$. Those open folds are obviously of the same character and belong to the same movement as the "strain slips" of the second Caledonoid movement. Their plunge is $15^{\circ}$-$25^{\circ}$ trending $20^{\circ}$ north of east (Pt. K2, 62, 36).

Similar considerations apply to the rocks of a small quarry $\frac{1}{4}$ mile to the south. The Caledonoid folds continue for another $\frac{1}{4}$ mile westwards where they are interrupted by a belt of cross-folding. The relatively even variation of strike on the map gives the erroneous impression that there is a swing of Caledonoid folds into cross-folds. The cross-folding is accompanied by a well-marked phyllitic lineation which is seen to crinkle the axial plane schistosity of the Caledonoid folds. The axial plunge of the latter has simultaneously been changed from north-easterly to westerly. This belt of cross-folding continues south of Glen Errochty as is obvious from the distribution of dips (Map $S_1$).

If the above inferences are correct the tectonic history of the Moines in this Area can be summarized as follows:-

(a) Recumbent folding on Caledonoid axes.

(b) Open folding on Caledonoid axes.

(c) Open refolding on cross-folds, which here trend 20°-35° south of east and plunge at 30° in the same direction.

Late Movements

Four miles north of Trinafour and outside the Area there is some evidence of yet later movements, inducing a considerable amount of strain banding on approximately east-west axes. This strain banding is well-displayed under the Dalnacardoch bridge. In places this movement gives rise to a series of closely spaced faults (fracture cleavage). Whereas all the other movements do not affect the metamorphic state of the rocks retrogressively, these latest movements are responsible for the replacement of biotite by chlorite. However, this phase of deformation evidently forms part of the main orogenic cycle as there is no granulization of quartz or felspar and while in places actual breccias of Moine fragments are produced these breccias (Fig.28b) are parallel to the "flagginess" and the quartzo-felspathic elements of neither fragments nor the matrix show any strain shaddows.

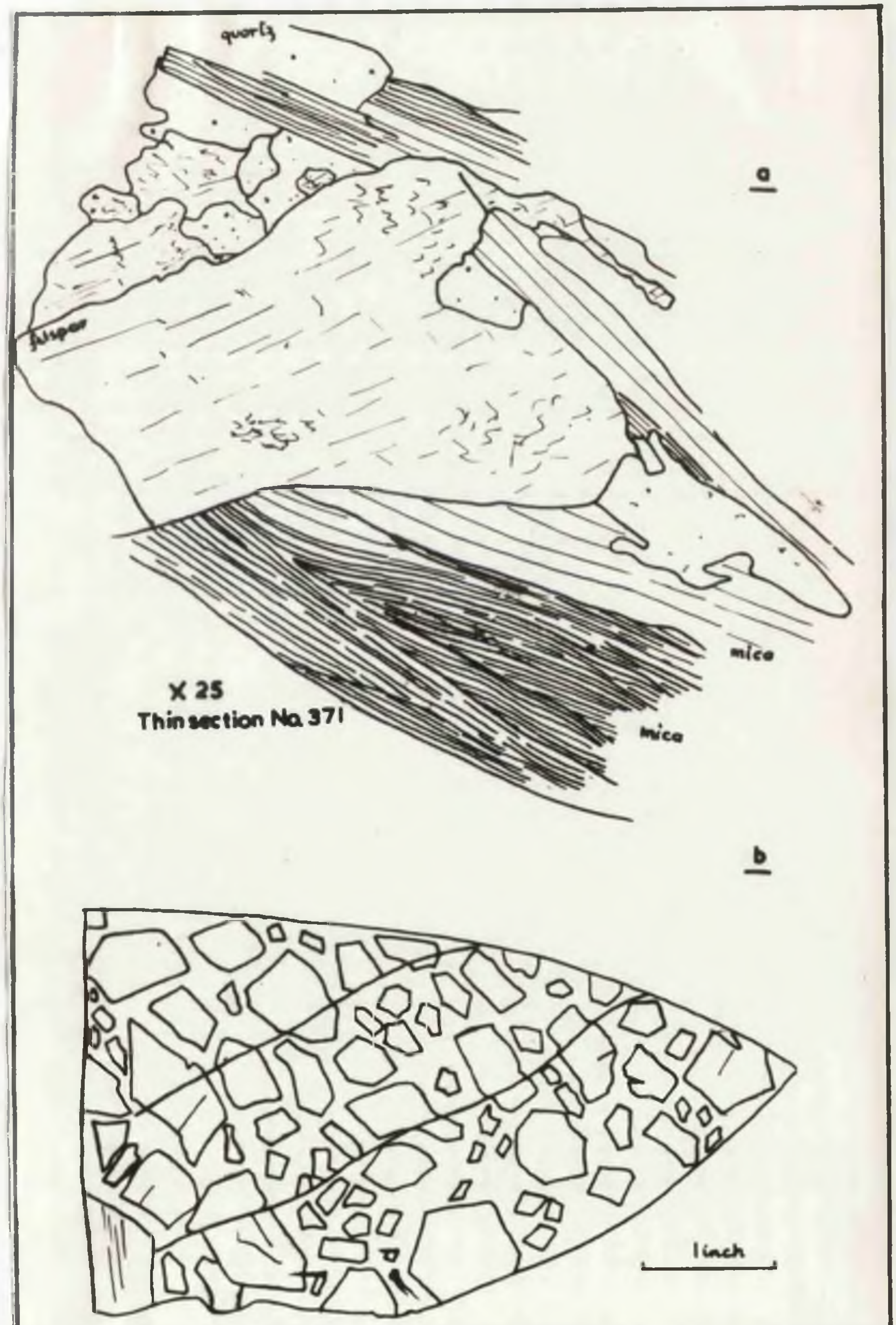



Fig.28 - Structures in the Moines.-

a. Porphyroblast of microcline intersecting flakes of mica.

b. A sketch of a breccia from the Moines of Glen Garry.

# XIII. SLIDES

## Introduction

The term slide was initially introduced by Bailey (1910) to denote a fold-fault without the necessity of reference to thrusts and lags. It was soon realised that slides often exhibit a style which is sympathetic with the major folding in a particular district.

While a slide can originate via thrusting or lagging and be folded subsequently it can also originate in the process of folding. Obviously it is important to distinguish between the two types and some progress in this direction has been made in Schichallion area.

The largest of the slides in the Area is the Boundary Slide which conforms to the pattern of the Dalradians in many places, but cuts sharply across them north east of Colrig.

## Tectonic History of Boundary Slide.

The fact that along the western boundary of the Dalradian Triangle which is Caledonoid in trend there is a relatively sharp truncation of formations indicates that the slide has probably originated either simultaneously with or entirely later than the folding of Caledonoid nappes. Since none of the nappes contains a core of Moinian rocks it is likely that sliding continued after the cessation of the main Caledonoid Movements intersecting a series of nappes obliquely. At this time the slide was evidently in the nature of a basal plane underlying the nappe complex.

The oblique intersection of formations by the slide seems to be related to cross-folding, since when the slide is viewed down the direction of the Glen Errochty cross-fold it is seen that the shearing out of the Caledonoid nappes is most marked on the lower limb of the synformal and the upper limb of the antiformal parts of the cross-fold and is negligible on the common limb (Fig. 29). This suggests that the cross-fold has originated by a mechanism of pushing (see p. 44 ). If so the oblique intersection of the Caledonoid nappes was achieved during the Cross-fold Movements. Shearing was probably more intense towards the apex of the Dalradian Triangle, while it weakened southwards where the overfolding of the Glen Errochty cross-fold disappears. This circumstance would explain the more northerly Caledonoid strike in the western parts of the Triangle. This also implies that merely by flattening out the present Boundary Slide and elimination of the cross-folds it is not possible to reproduce precisely the pre-cross-fold surface, since during the Cross-fold Movements that surface was stretched more towards the north than south.

The push has evidently originated from a north-easterly direction producing a thinning of the north eastern or eastern limbs of the cross-fold antiforms, such as Creag Varr and the southern of the Loch Kinardochy folds, and reducing the western limb of the cross-fold synforms such as Creag an Fhithich. Thus the attendant slide in these localities have been originated by the Cross-fold Movements.

Pre-Cross-fold Slides.

Examination of the Caledonoid nappes with cores of Blair Atholl Series on the map $S_1$ shows that all of them are characterized by a reduced lower limb. It has already been suggested that they close north-westwards, which supports the idea that the slides are the basal thrust-planes of the Caledonoid nappes. These slides coincide closely with formational boundaries in the Caledonoid nappes and may be assumed to have been contemporaneous with

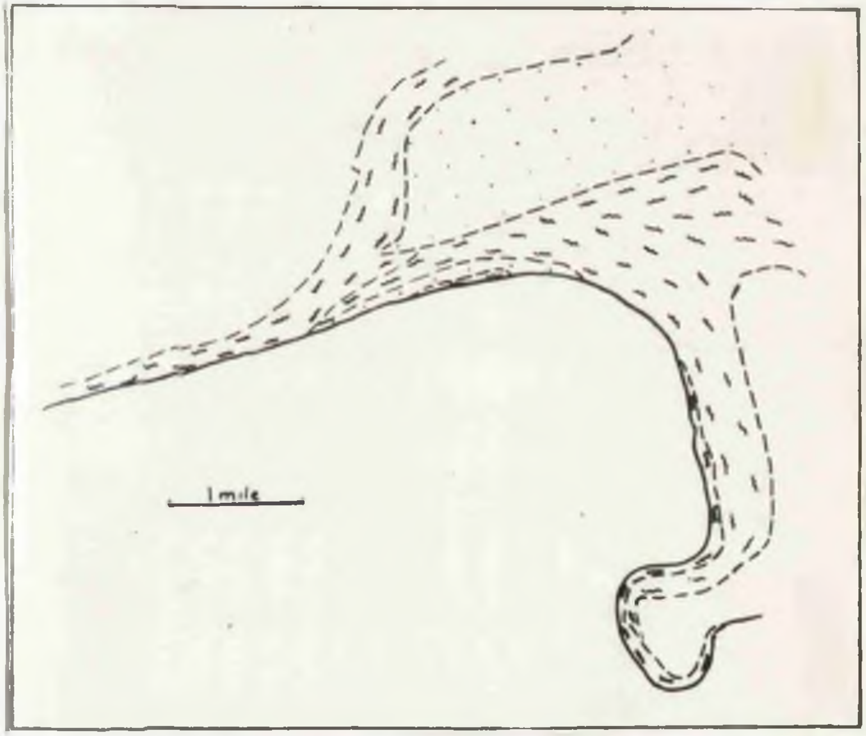


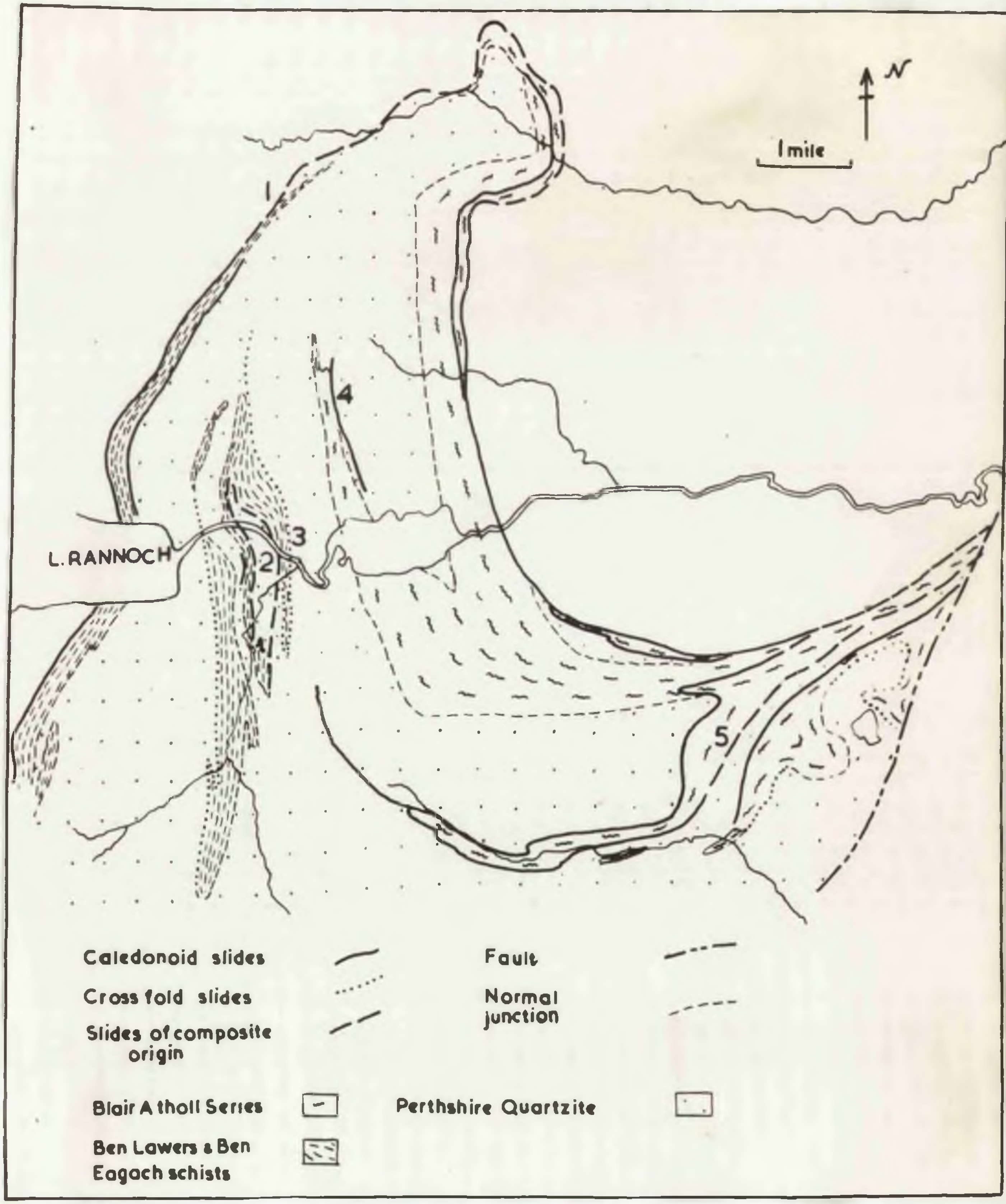

Fig.29 - The profile section of the Glen-Errochty Cross-fold.
Quartzite, stipples; Blair Atholl Series ~ .

the main Caledonoid Movements. Evidently, these slides have been produced by drag mechanism (see p. 45 ). It is mainly in these slide zones that the Caledonoid folds have been found to indicate the tectonic nature of the Blair Atholl cores. This in itself implies that the basal slides of the Caledonoid nappes owe their origin to the Caledonoid Movements.

The lower slide of Creag Varr is of a puzzling origin, since though it is folded on a cross-fold, there are a number of Caledonoid lineations near the slide. Moreover the Ben Eagach Schist at the junction with the underlying Killiecrankie Schist shows frequent refolded folds. On the other hand the slide was probably active even subsequently to the Cross-fold Movements, since the hornblende schists adjacent to its western vertical part are broken into a type of melange indicative of brittle movements. The problem is not easier if a solely post-Caledonoid origin of the slide is assumed as then the question arises as to what has happened to the Carn Mairg Quartzite, which has disappeared leaving the Killiecrankie Schist adjacent to the Ben Eagach Schist. In short it appears necessary to postulate that both Caledonoid and Cross-fold Movements participated in the evolution of the slide. Such a composite origin appears necessary for several other slides shown on the Map 17.

## Degree of Deformation on the Slides

The degree of deformation associated with the lower of the Creag Varr slides is unusual. In general Caledonoid slides show the obvious signs of deformation in the sense that the adjacent formations are broken into a series of discontinuous lenticular bodies, which are often closures of folds.




Map 17 - Slides in the Area. 1. Iltay Boundary slide; 2. Lower Creag Varr slide; 3. Upper Creag Varr slide; 4. Ben a'Chuallaich slide; 5. Schichallion slide.

Such can be seen near Schichallion slide east of Schichallion, and to a lesser extent near the Ben a'Chuallaich slide, which shows exceedingly deformed and folded quartzite. The slide junction of Carn Mairg Quartzite and Ben Lawers Schist of Chesthill belt north of Loch Rannoch again is of the same type as Schichallion slide. It is at first sight a puzzle that the major Boundary Slide does not appear to be associated with any striking signs of deformation,and indeed its recognition on the western side of the Dalradian Triangle was not easy in view of the occurrence there of an apparently continuous passage from the rocks of Moine type into those of Dalradian type. On the western side of the Triangle the presence of the Chesthill belt of Ben Lawers Schist made possible the accurate location of the Boundary Slide (Bailey and McCallien, 1937). The presence of post-metamorphic felsites and porphyries which follow the slide in this part of the Area tends to obscure the position of the slide in the critical area of near Colrig. However, after a detailed re-examination of the ground a solution has been found. In fact, an understanding of the tectonic significance of the Beoil Schist has thrown new light on the problem of the deformation involved along the Boundary Slide.

Beoil Schist.

As a separate entity the Beoil Schist was first recognized by Bailey and McCallien from the type locality Lochan Beoil Chathaiche. The schist there is a muscovite biotite rich rock containing quartz, albite and microcline as the other main minerals. It has occasional garnets which rapidly increase in abundance and size in proximity to boudins of amphibolites which are locally well represented. Simultaneously adjacent to the amphibolites the proportion of micas decreases as the garnets appear.

In typical Beoil Schist the large and porphyroblastic micas give the rock its very diagnostic aspect. Bailey and McCallien (1937) have mapped the schist from a point a mile and a half east of Lochan Beoil Chathaiche round the apex of the Dalradian Triangle and continued it as far as Errochty Water (Map 18a). It has been found possible to recognise the schist through intermittent exposures to Colrig and thence in a zone immediately continuous with the Dalradian rocks right to the south-western boundary of the Area. In this ground the schist is sandwiched between two sills of felsite as far as Loch Rannoch and from then onwards it overlies one of the sills, the upper one failing. Here as well as on Colrig the schist has been evidently included by Bailey and McCallien with Ben Lawers Schist into the Chesthill belt. That this is not so is clear as in parts a flaggy granulites indistinguishable from local variants of Carn Mairg Quartzite intervenes between the Beoil Schist in the rocks of the Chesthill belt.

On the eastern side of the Dalradian Triangle Beoil Schist is clearly unrelated to the Dalradians and has been therefore included as a member of the Moines (cf. Bailey and McCallien 1937). Now the schist not only has been detected in the western part of the Area, but mapping of the Moinian rock types indicates that it has transgressive relations to the Moines as well as to Dalradian rocks. On the other hand the Schist is unmistakably related to the Boundary Slide (Map 18b). This indicates that the origin of the schist is bound up with tectonics rather than stratigraphy. The schist is a tectonic schist (see King and Rast 1955b).

The development of large porphyroblastic micas, which are diagnostic of the Bcoil Schist, was recognized by Suess (1931) as of tectonic significance. In other respects there are wide variations from place to place reflecting local lithological variaties in the adjacent Moines. This alone disposes of the possibility that the schist has any stratigraphical identity.

Such cases of mechanical convergence on and adjacent to the lines of tectonic dislocation have been reported by Read from Unst (1934). There, however, the production of a tectonic schist is accompanied by retrogressive metamorphism.

Conclusions

The contents of this section can be summarized as follows :-

(a) Obvious mechanical effects of deformation appear on the relatively minor slides.

(b) The main Boundary Slide is accompanied by the presence of a tectonic schist.

(c) It is possible to assign a tentative time sequence to the slides.

(d) Both the Caledonoid and the Cross-fold Movements participated in formation of certain slides such as the Boundary Slide.

## XIV. TECTONIC HISTORY OF OROGENIC DEFORMATION

### Relations between the Caledonoid and the Cross-fold Movements.

Throughout the preceding account a clear cut distinction has been made between the Caledonoid and the Cross-fold Movements; and indeed on the scale of the Area alone such a distinction is very useful, as it provides a basis for geometrical representation of the major structures. This, however, need not indicate that in fact the two movements were separated by a considerable interval of time. If erosion had removed the recumbent part of Glen Errochty cross-fold the structure would have appeared to be more in the nature of an axial depression. Belts of axial culminations and depressions occur throughout the Highlands, sometimes attaining the stature of major cross-folds. In the section on folding it has been indicated that these culminations and depressions are possibly direct by-products of the main, in this case Caledonoid folding. While a culmination attains a noticeable amplitude only after the primary folds are already established, theoretically it originates at the same time as the main folding.

It is a matter of observation that a schistosity does not develop until folding has attained a considerable intensity, marked by recumbency or compression of folds. Thus it is possible to recognize in some localities the condition in which a schistosity has developed in agreement with the axial planes of the main folding, but none has yet formed in relation to the complementary culminations or depressions. When such a schistosity does form it is superimposed on the main schistosity and so appears as an entirely later structure. It is in such a way that the relations between the Caledonoid and the Cross-fold Movements appear to be best explained. Such a hypothesis provides an interpretation of those slides which reflect the action of both Caledonoid and Cross-fold Movements. Moreover, important evidence on a regional scale beyond the limits of the present area also points to an intimate relationship between Caledonoid and Cross-folding :-

(a) Throughout the Grampian Highlands major cross-folds are rarely recumbent and when they are the recumbency is much less than that of Caledonoid folds.

(b) The cross-fold belts do not persist across the strike of Caledonoid folds for any long distance. On a relatively minor scale this can be seen in relation to the Kinardochy fold.

(c) The main Cross-folds are at right angles to the Caledonoid trend and as recumbency is achieved the plane of cross-fold schistosity becomes sub-parallel to the Caledonoid schistosity, implying the operation of a similar set of external forces.

(d) Cross-folds earlier than the local Caledonoid folds have been recorded on a major scale from the Dalradian rocks of Donegal (see: Holmes and Reynolds, 1954). On a minor scale cross-folds with a common schistosity with Caledonoid folds have been observed in the Area. In Cowal four alternating episodes of Caledonoid and cross-folding can be seen (see King and Rast 1955a). Since it is hardly conceivable that the direction of main orogenic forces fluctuated in a corresponding fashion, the more plausible explanation is that the apparent alternation of movements is due to the differences in the rate of evolution of main and cross-folds.

History of Movements

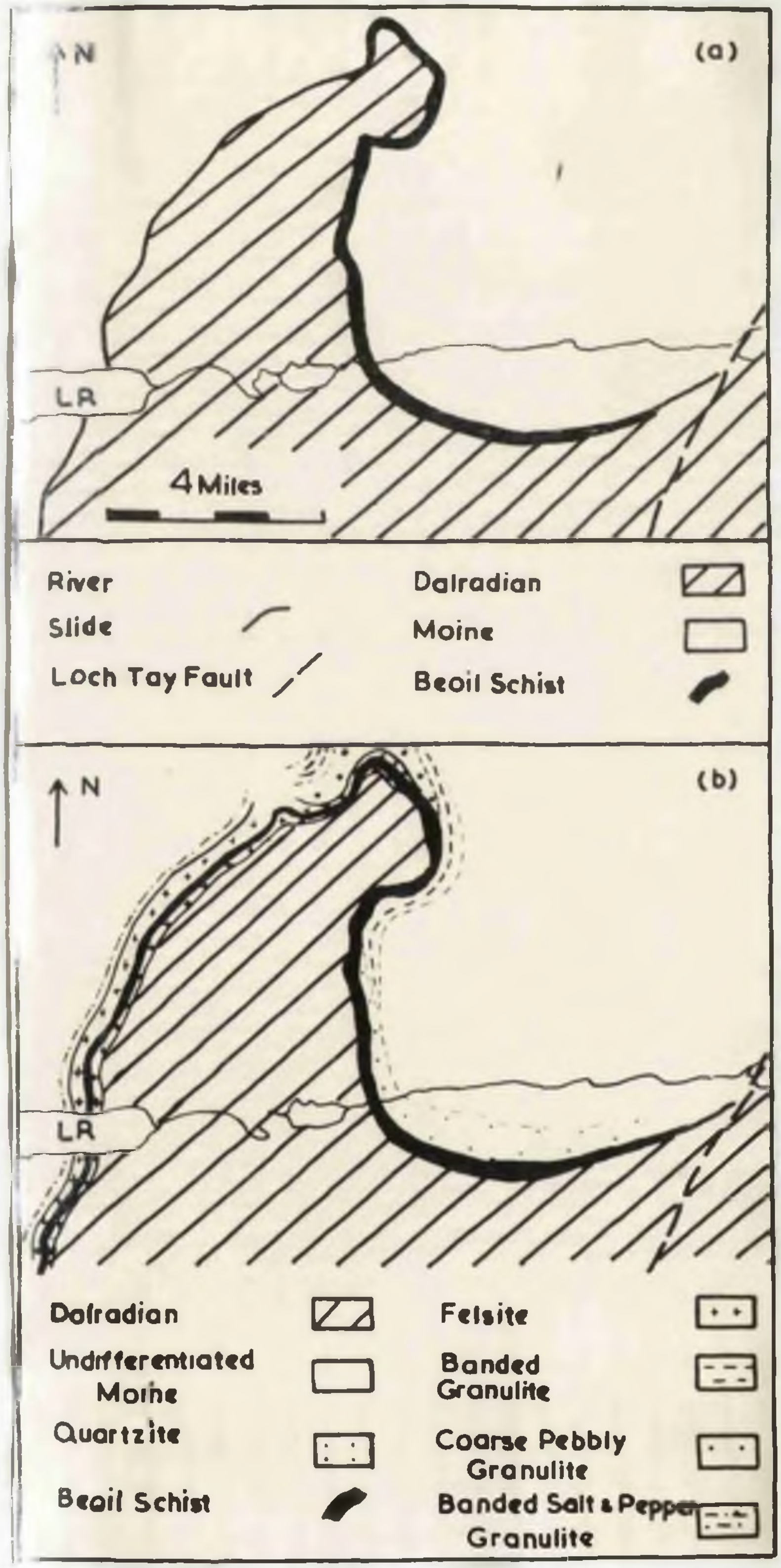
In terms of the foregoing conclusions the history of orogenic deformation resulting in the formation of the major structure of the Area appears to have been as follows :-

(a) Main Caledonoid Movements - Although the earliest structures that can be recognized are dominantly Caledonoid, some minor recumbent cross-folds, sharing the same axial-plane "compromise" schistosity have also been noted. The presence of such a schistosity in itself implies that the rocks even at this stage have undergone a complex, probably continuous deformation, and while in general cross-folding is contemporaneous, its progress to recumbency may have been earlier, later or simultaneous with the recumbency of some of the minor Caledonoid folds. These Movements produced major sliding characteristic of Caledonoid nappes.

(b) A subsidiary Caledonoid Movement is responsible for refolding of some of the Moine granulites. The effects of this movement were not appreciable in the Dalradian rocks of the Area.

(c) The major Cross-fold Movements responsible for refolding of large parts of Dalradians. Only limited recumbency is shown by the Glen Errochty fold. New slides directly related to these movements came into existence.

There are also contemporaneous or perhaps slightly later east-west folds, which are especially well developed around Schichallion but continuing sporadically both to the west producing slight culmination and depressions of plunge, and to the east giving rise to occasional phyllitic lineation.




Map 18 - Relations between the Beoil Schist and adjacent formations.
a - According to Bailey & McCallien.
b - According to Rast.

(d) Late Cross-fold Movements inducing strain bands in the Moine granulites and occasionally in the Beoil Schist. These movements were very weak but they may have been responsible for the brecciation of epidiorite on the western flank of Creag Varr.

# PART III.

# XV. DISTRIBUTION OF METAMORPHIC MINERALS AND ZONES

## Introduction

The following aspects of the present investigation have proved especially relevant in a consideration of the relations between structure and metamorphism :-

(a) Distribution of the metamorphic zones.
(b) Textural relations of the metamorphic minerals.
(c) Structural relations of the epidiorites and hornblende schists.

These aspects will be examined in the present and the two following sections.

## Influence of Original Composition and Metasomatism

While the mineralogical composition of metamorphic rocks depends on metamorphic intensity, two other factors are important, namely :-

1. The original composition 2. Metasomatism.

From the point of view of original composition all the metasedimentary rocks of the Area can be classified into three major groups :-

1. Psammitic 2. Pelitic. 3. Calcareous.

Of these pelitic rocks are especially useful in metamorphic studies. The frequently impure calcareous rocks are also useful, though in terms of mineralogical composition they are not entirely unambiguous in evaluation of the metamorphic grade of the rock. The psammitic rocks show practically no mineralogical variation with progressive metamorphism. For this reason grade of metamorphism is difficult to establish not only in the quartzose rocks of the Dalradians, but also in the prevalent rock types of the Moines.

The epidiorites and igneous hornblende schists show marked mineralogical changes in the lower grades of metamorphism, but no significant change is seen beyond the garnet grade. Thus although a considerable part of the Area is in the kyanite zone, the epidiorites found therein are not recognizably different from those of the garnet zone.

The possibility of a widespread metasomatic alteration of the rocks is difficult to assess since no chemical analyses have been carried out, but three relatively localized effects attributable to metasomatism have been established:-

1. Areas of Carn Mairg Quartzite sometimes show felspathization on quite a considerable scale. Both $Na^+$ and $K^+$ have been introduced giving rise to an almost quartz free albite-microcline rock. At the same time $Fe^{+++}$ and $Ca^{++}$ have been introduced, since the biotite rich partings of these rocks tend to develop very highly pleochroic epidotes and amphiboles, the latter obviously replacing biotite. Some magnetite also appears in the rock. The adjacent post-orogenic felsites are too small to have been responsible for these changes (Pt. B6, 44, 03).

2. Areas of scapolitization are found especially in proximity to certain epidiorites which have been emplaced into calcareous rocks. The main areas showing this modification have been already described (p.54 and p.55 ) and are shown on the map $S_3$.

3. Near Loch Kinardochy on the boundaries between limestones and epidiorites (Pt.K9,63,95 ) and (Pt. L8,50,97) another variety of metasomatic alteration occu[rs].

Here the marginal facies of limestone becomes highly charged with large porphyroblastic amphiboles showing intense plaeochroism from pale brown to dark green. They are associated with highly plaeochroic epidote and evidently some iron has been introduced into the limestone.

Metamorphic Zones

Two metamorphic zones have been recognized in the Dalradian rocks of the Area :-

1. Garnet zone 2. Kyanite zone.

The course of the isograd separating the two zones is often uncertain since west of Ben a'Chuallaich belts of quartzite and pelitic schist alternate. For this reason the isograd has been shown as passing through the quartzite, although the quartzite is of course free from kyanite.

The chief differences of the present map ( $S_3$ ) from the mapping of the metamorphic zones by Bailey and McCallien (1937) are as follows :-

(a) The recognition of the kyanite zone parallel to the Boundary Slide from the apex of the Dalradian Triangle almost to the shores of Loch Rannoch. The chief difficulty here was the fact that rocks of the Chesthill belt of Ben Lawers Schist have been affected by an episode of mild retrogressive metamorphism, which obscures the fact that they contain some kyanite. Usually the mineral is altered into an aggregate of hydromica, which under the microscope shows a curious trelissed texture. This is probably due to tendency of the mica flakes to grow along the cleavages of the crystals of kyanite.

(b) Between Dalhosnie and Tempar there are two belts of Killiecrankie Schist. While the western belt shows kyanite right up to the summit of Geal Charn, no kyanite has been detected in the eastern belt south of the Tummel.

(c) Staurolite has been frequently detected but always in association with kyanite, so that there is no justification for inserting a staurolite zone between kyanite and garnet zones.

Relations between Intensity of Structural Deformation and Metamorphic Minerals.

The distribution of the kyanite zone as represented on the map $S_3$ shows a marked correlation with the areas of most conspicuous sliding. Indeed, relationship between zones of shearing and metamorphic intensity is often obvious from the individual exposures. It is convenient to describe these effects by reference to specific minerals.

Quartz and Felspar - Although there are virtually no mineralogical changes to mark variations in grade in the psammitic rocks, certain textural changes may be recognized in aggregates of quartz and felspar. Quartzites whether pure or schistose near certain slides, such as the Creag Varr and the Boundary Slides, usually have a granulitic appearance. In addition felspars often segregate into augens (Fig. 30 ) which are elongated parallel to the axes of local folds.

Micas are evidently especially sensitive to movements. On the Boundary Slide the development of the conspicuously micaceous Beoil Schist has already been shown to be related to extreme shearing.

To a lesser extent this is true on the well exposed lower Creag Varr slide where at the junction of Killiecrankie Schist and Ben Eagach Schist, micas are especially large and in places a mixed rock is produced intermediate in character between the two schists.

Fig.30 - Augens of microcline elongated parallel to the axes of local folds.
Arrow indicates the trend of the fold axes.
Scale in inches.

Garnet - The dependence of size of the common almandine variety of garnet on the location of the rock with respect to the major shear zones is especially marked. Between Loch Rannoch and Dunalastair garnets, though widely found are generally inconspicuous, but near such major slides as the Boundary Slide and the Creag Varr slide ~~where~~ there is a rapid increase in the average size of garnets. Numerous exposures on Creag Varr show this phenomenon particularly well, where in the immediate neighbourhood of the slide there are certain bands in which the bulk of the rock is composed of garnets (Pt. C5, 60, 14). A certain exposure of epidiorite near the top of the crag shows garnets up to $\frac{1}{2}$ in. across; other smaller bodies of epidiorite on the top of the crag are also richly garnetiferous. Moreover certain rock types, from which garnet is normally quite absent, show the development of this mineral. The Ben Eagach Schist of Creag Varr has numerous small bodies of a slightly schistose micaceous quartzite, interpreted as relicts of Carn Mairg Quartzite which has been sheared out on the slide. In this particular location these rocks are appreciably garnetiferous, and moreover it is apparent that the garnets have developed largely at the expense of the micas. A sketch (Fig. 31) of a specimen of such a quartzite shows this effect most clearly since the garnets are surrounded by haloes of pure quartzite with no micas, whereas the bulk of the rock is evidently micaceous. At the same time thin calcareous bands in Ben Eagach Schist have been altered into a Garbenschiefer (Fig. 32).

Kyanite - The recognition of kyanite in the field is often inexpectedly difficult. On the one hand a tremolitic amphibole heavily clouded with graphite in the Ben Eagach and Dark schists ~~and~~ closely simulates kyanite; on the other hand crystals of kyanite, when wrapped in micas, as they often are,

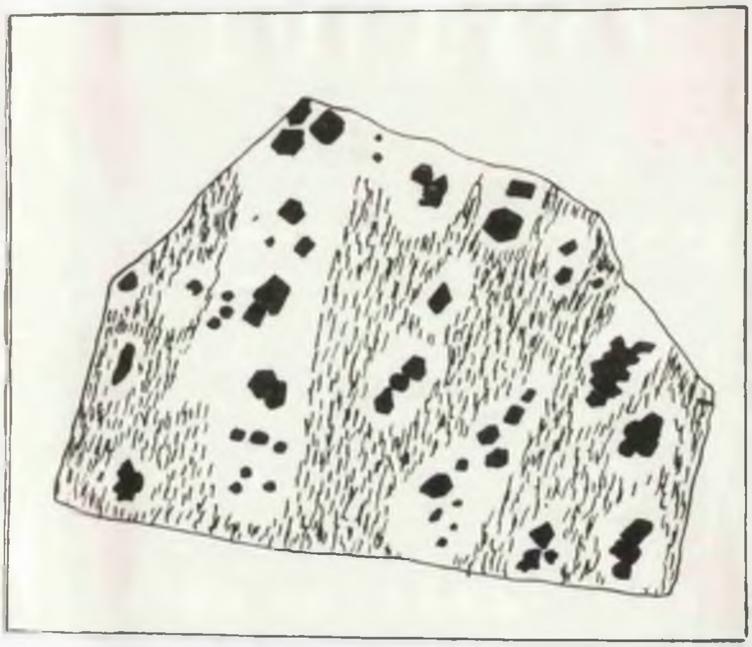


Fig.31 - A sketch of garnetiferous quartzite from Creag Varr (to scale).

Fig.32 - "Garbenschiefer" from Creag Varr.
Scale in inches.

are not easily recognized as such. However, many localities in the neighbourhood of the Boundary and Creag Varr slides (see Map $S_3$ ) show the development of kyanite in quartz and quartz-felspar veins. In such cases kyanite grows in large blades showing the characteristic blue colour.

Whereas metamorphic grade appears to be enhanced in proximity to slides there are locations in which the rocks appear to lag in metamorphic intensity by comparison with their general environment.

For instance the fine grained schists, often associated with Dolomitic Beds have been already commented upon (p.55). These vary from a light grey fine grained rock with an almost decussate arrangement of predominant white mica and sparing biotite, to dark brown biotite schist with green tourmaline. The former occur in Allt na Moine Bhuidhe, the latter in Tempar burn. Both types commonly contain abundant small cubes of pyrite. It is suggested that these rocks have been probably protected from deformation by the Schichallion Quartzite in which they form stratigraphical intercalations. Indeed where, as on the eastern shoulder of Schichallion the Dolomitic Beds have been cut abruptly by Schichallion slide they are much more strongly recrystallized.

The schists adjacent to the Ben a'Chuallaich slide and the Schichallion slide north east of Schichallion are not marked by the development of conspicuous porphyroblastic mica. The time-relations of the various slides probably provide the explanation for the differences in character of the associated schists the tectonic schists being more conspicuous on the Cross-fold slides.

Time Relations between Metamorphism and Sliding

It has already been suggested that the Creag Varr slides owe their origin and deformation both to Caledonoid and Cross-fold Movements (p.102). The quartz kyanite veins which occur near the slides are clearly later than these movements, since they often occur across the schistosity. This implies that the advance of metamorphism to the kyanite grade was later than the Cross-fold Movements. The development of garnets with S-shaped trends of inclusions (p.121) indicates that metamorphism was partly contemporaneous with deformation.

The Ben a'Chuallaich slide on the other hand, having been formed by the Caledonoid Movements which preceeded Cross-folding, does not affect the distribution of metamorphic zones and is probably pre-metamorphic.

Although there appears to be a relation between the Cross-fold zones of shear and the metamorphic grade, the relationship is by no means direct and simple, for the metamorphic "high" responsible for the formation of kyanite is evidently later than the actual shearing on the Creag Varr slides. This conclusion is evidently the reverse of that advanced by Bailey and McCallien (1937). They were impressed by the fact that the limits of kyanite zone are confined to the Dalradian formations, and that Beoil Schist which they included into the Moinian sequence is free from kyanite, though according to them it is similar lithologically to some varieties of kyanite bearing Killiecrankie Schist. Moreover, they argued that, though garnets do exist in the Beoil Schist they are small and sparce. This particular observation has been now investigated in some detail. The relevant exposures which provide the evidence are south and south-west from Lochan Beoil Chathaiche.

Here numerous disconnected strips of garnetiferous amphibolite are involved in the Beoil Schist. While the Beoil Schist away from the amphibolites is rich in porphyroblastic micas, the schist for a thickness of 1-3 ins. round the amphibolites is very poor in mica and has the appearance of semipelitic Moines, except for the fact that muscovite is absent in it and the rock shows large garnets up to $\frac{1}{4}$ in. in diameter. Moreover the garnets are clearly later than the biotite flakes as the latter are cut and interrupted by the former.

The inference is that garnet grew at the expense of muscovite by the addition of certain constituents from the amphibolites. Such addition could have happened only via metamorphic diffusion, the extent of diffusion being represented by the thickness of the garnetised band. In addition, it is also to be inferred that only where a body of amphibolite occurs in immediate proximity to the Beoil Schist, the necessary material for formation of garnets in the latter is available. In other words in the case of Beoil Schist controlling factor in this instance is the original composition and in particular the abnormal richness in muscovite. If this exceptional abundance of muscovite tends to prevent the development of garnet, it may well be that a similar compositional control is responsible for the absence of kyanite. That the muscovite-biotite assemblage is consistent with conditions under which the staurolite-kyanite subfacies of the amphibolite face is produced has been established by workers on metamorphic facies (Turner 1948, p.83).

At the margins of amphibolites the garnets transgress the planes of schistosity and are consequently post-tectonic.

# XVI. TEXTURAL EVOLUTION OF THE METAMORPHIC ROCKS IN THE AREA.

## Introduction

Interpretation of the textures of rocks is notoriously difficult, hence only the most clear cut and unambiguous relationships can be used in metamorphic studies. The graphitic schists are commonly the most informative since relicts of graphite-mica layers are commonly preserved at all stages throughout the metamorphic history.

In addition to the evidence of earlier fabrics provided by such inclusions, they often supply the proof that the growth of new minerals has been controlled tectonically.

## Growth of Metamorphic Minerals

Growth of the metamorphic minerals involves a variety of processes. In quartzites or limestones the dominant effect is probably recrystallization enhanced by lamellar gliding. In schists the redistribution of material and growth of porphyroblasts is satisfactorily accounted for by metamorphic diffusion. That no mechanical deformation is necessary to explain such growth is evident from the existence of "helicitic" inclusions in minerals such as kyanite and albite (Fig. 33). Similar inclusions may also be seen in tourmaline, in which it often happens that certain zones show preferential clearing of inclusions (Fig. 34). Sometimes a similar effect can be seen in garnets (Fig. 35 ) in which the inner zones tend to clear themselves of inclusions, whereas the outer zones still retain them. The growth of such garnets must have occurred at varying stages, being slower at first, so that the inner zones are cleared of inclusions.

Following p.119.

Fig.33 - Helicitic inclusions in kyanite,
X 25 P.P.L.

Fig.34 - Helicitic inclusions in tourmaline, X 25 P.P.L.

Fig.35 - Helicitic inclusions in garnet, X 25 P.P.L.

Amphiboles show different types of growth. In meta-sedimentary rocks they often form uniform reasonably euhedral crystals which show the undisturbed helicitic inclusions (Fig. 36 ), though sometimes poikiloblastic crystals with indefinite outlines have been observed (Fig. 37).

The hornblende schists of igneous origin usually show amphiboles with a good crystalline form and few inclusions. However, there are epidiorites in which relict cores of pyroxenes are detectable. In these the amphiboles form aggregates of numerous poikiloblastic individuals (Fig.38). Such a texture has not been observed in the meta-sedimentary rocks of the Area.

It has been suggested that the rate of growth of metamorphic minerals varies. There is also some evidence that during the growth of a mineral the rate of supply and the nature of the supplied material varies as well. This is especially evident in zoning, which is sometimes widespread. Examples of normal,reversed and oscillatory zoning in felspars have been found.

Dating of Minerals

The most useful minerals in interpretation of the geological history of rocks in the Area are :- micas, garnets, felspars and kyanites.

Practically every thin section of a schist shows numerous planes of oriented micas intersecting at varying angles. While it is practically impossible to date the earlier deformations, it is easy to recognize the latter deformations. The corrugations associated with the Cross-fold Movements are often recognizable under the microscope. Only rarely, however, are the cleavages of the individual crystals of mica actually flexed. Usually the micas are completely recrystallized and where each flexure is defined by a number of crystals of mica the individual crystals themselves show underformed cleavages (Fig. 39).

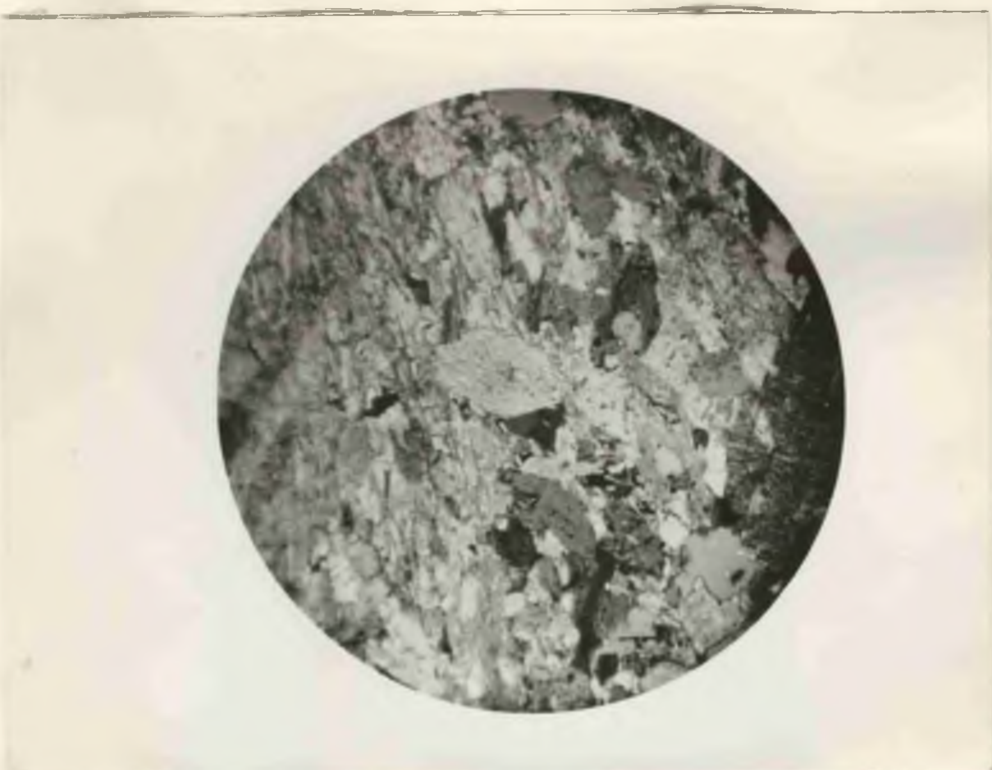


Fig.36 - Euhedral amphiboles in a sedimentary amphibolite;
X 25 C.P.L.

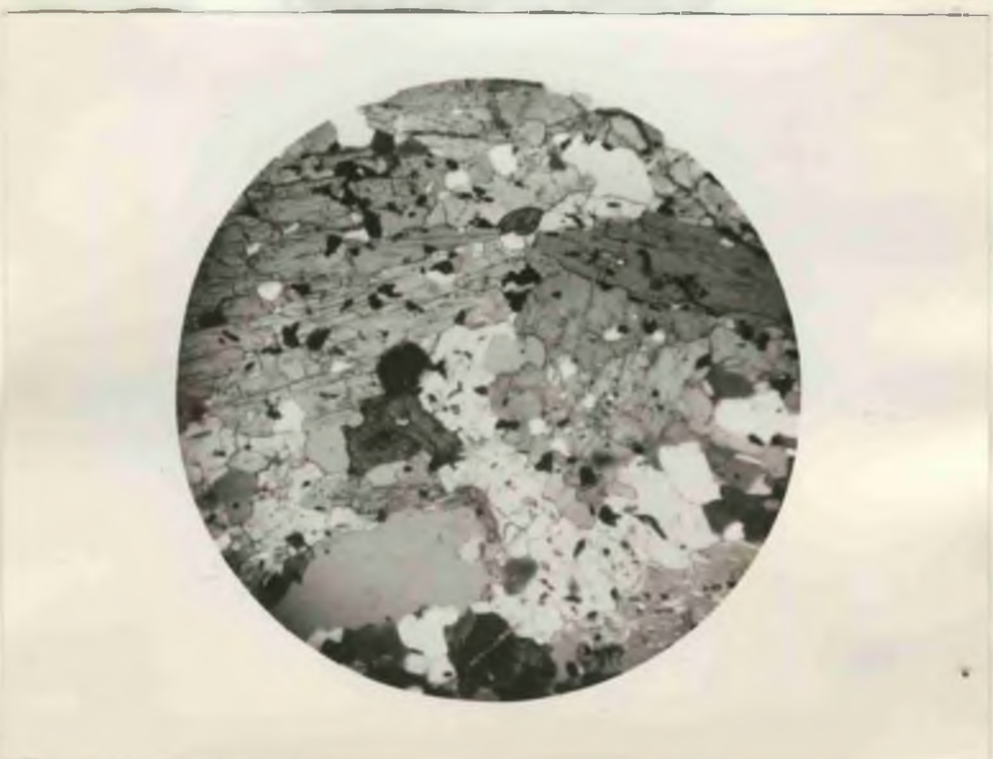


Fig.37 - Poikiloblastic amphiboles in a sedimentary amphibolite;
X 25 C.P.L.

Fig.38 - Granular epidiorite,
X 25 C.P.L.

The sequence of growth of kyanite, plagioclase and garnet are best illustrated by certain representative thin sections of rocks from Creag Varr. Here all three minerals are evidently of late development, as planes of graphitic inclusions pass uninterruptedly from one mineral to another (Fig. 40). These planes have manifestly been plicated prior to crystallisation of the enclosing kyanite and felspar. Kyanites sometimes enclose flexures incurred by mica flakes, the flexures having a Cross-fold axial direction (Fig. 33). Similar relations are shown by tourmaline (Fig. 34) which is pleochroic in shades of brown. In addition to the micas which follow the flexures, another episode of growth is represented by micas which are parallel to the axial planes of the flexures. A still later event is shown where the biotite has been strongly deformed and partly altered to chlorite. Slight retrogressive metamorphism of this kind is especially noticeable in specimens from the western slopes of the crag.

Other thin sections of Ben Eagach Schist from Creag Varr also show garnets with S type of inclusions and occasionally even "snow-balls" (Fig. 41). These garnets have evidently grown during the movements. Similar inclusions occur in the garnets of the garnetiferous quartzite from the top of the crag (Fig. 42). Study of oriented specimens shows that the axes of rotation of such garnets correspond to the local trend of the cross-folds (approximately north-south).

The contemporaneity of the growth of garnets and Cross-fold Movements may similarly be inferred from the Killiecrankie Schists of Dun Coillich, where "snow-ball" garnets are associated with the planes of strain slip schistosity.

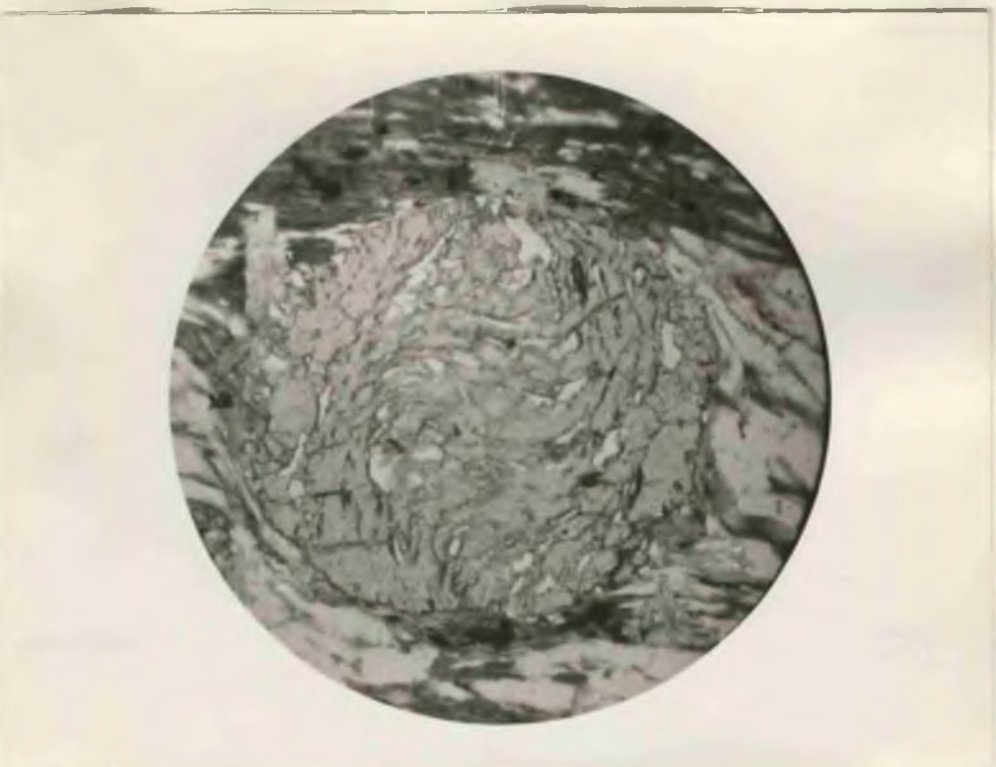


Fig.41 - Snow-ball garnets in the Ben Eagach Schist,

X 25 P.P.L.

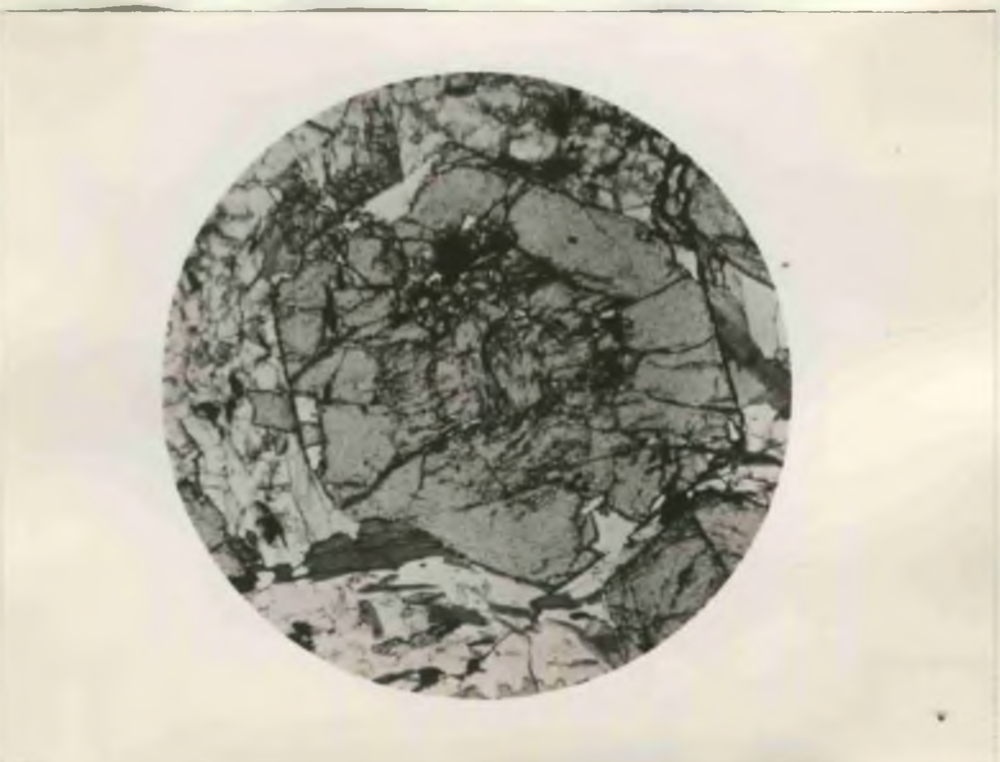


Fig.41a - Snow-ball garnets in the Ben Eagach Schist;

X 25 P.P.L.

Fig.39 - Undisturbed post-tectonic micas in a flexed layer; X 25 C.P.L.

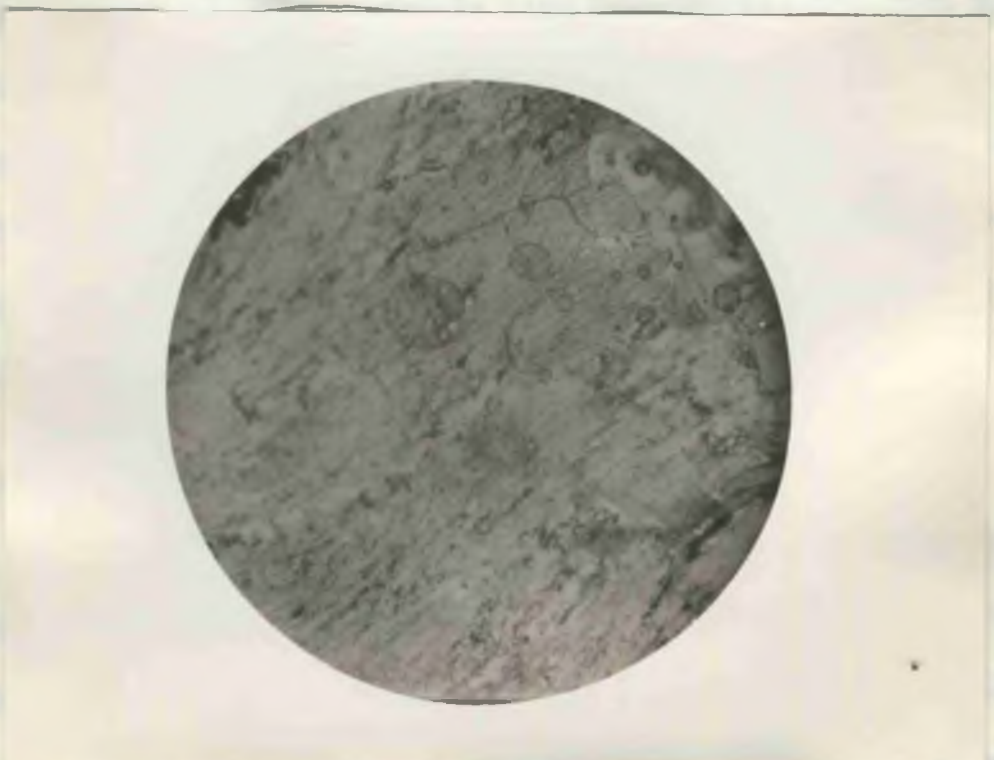


Fig.40 - Trends of inclusions passing through several mineral grains; X 25 P.P.L.

Many thin sections of the rocks from Creag Varr also show garnets which internally are full of oriented S type inclusions, while possessing a clear outer zones (Fig. 41a). The only explanation that appears consistent with all these cases, is that there have been two distinct stages in the growth of garnets.

1. Contemporaneous with Cross-fold Movements.
2. Subsequent to the Cross-fold Movements and showing no direct relations with any of the movements.

In broader terms this suggests that at least two stages are represented in regional metamorphism.

Similar conclusions are implied by the growth of microcline in the Killiecrankie Schists, which underly the Ben Eagach Schist at Creag Varr. These schists develop augens of microcline which are parallel to the axes or rather sharp recumbent folds (Fig. 30). The augens consist of very fresh microcline, the growth of which seems to have been contemporaneous with deformation. In thin sections there are also seen veinlets of microcline which cut across the general banding (Fig. 43). These are unattended by any draphthoretic effects. The first stage represented by the growth of augens is contemporaneous with tectonic deformation on Cross-fold axes; the second indicated by the veins is clearly post-tectonic.

Caledonoid Movements and Metamorphism

It is difficult to ascribe the formation of any metamorphic minerals to the Caledonoid Movements. Indeed in Chesthill belt garnets of the Ben Lawers Schist appear to be largely post-tectonic. This is shown by the fact that thin quartzose laminae often pass without deflection from the surrounding rock into garnets.

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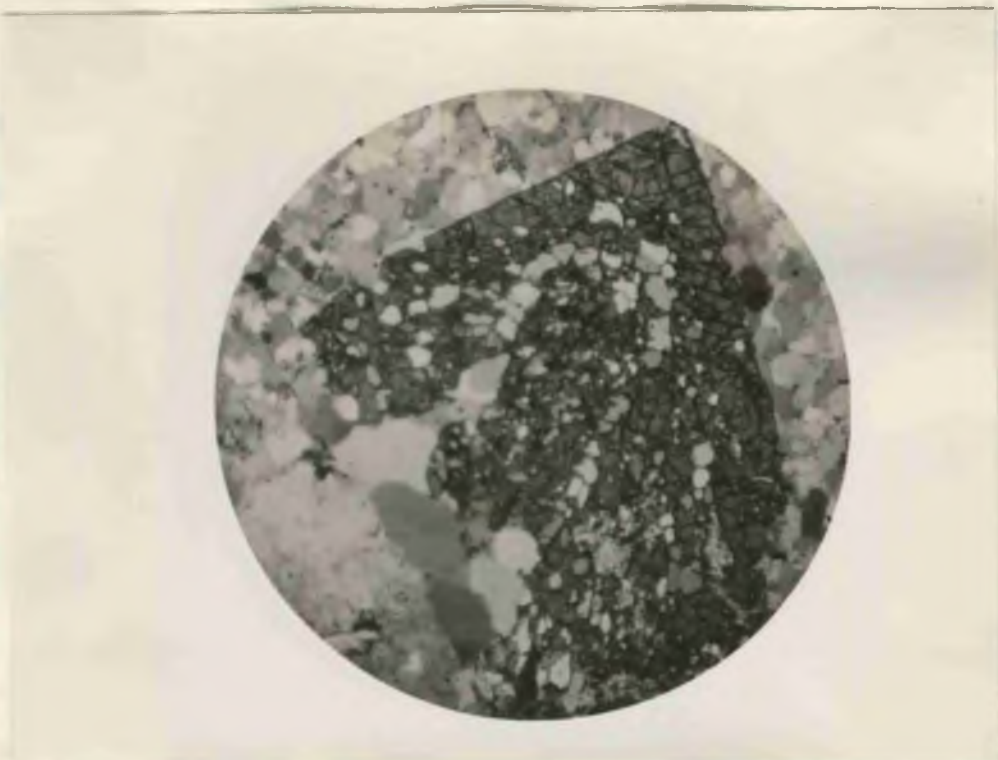


Fig.42 - Snow-ball garnets in the garnetiferous quartzite,
X25 C.P.L.

Fig.43 - Post-tectonic veinlets of microcline.
X 25 C.P.L.

However if as suggested the Caledonoid and the Cross-folds evolved broadly contemporaneously then at least a part of metamorphism is simultaneous with both sets of movements.

# XVII. EPIDIORITES AND HORNBLENDE SCHISTS

## Introduction

Both in mineral composition and in texture the epidiorites and the hornblende-schists show considerable variation. Their outcrops vary greatly in size, ranging from large masses up to half a mile in areal extent to very small bodies of a yard or two in length and several inches in width.

The five largest masses (Map 19) occur at :-

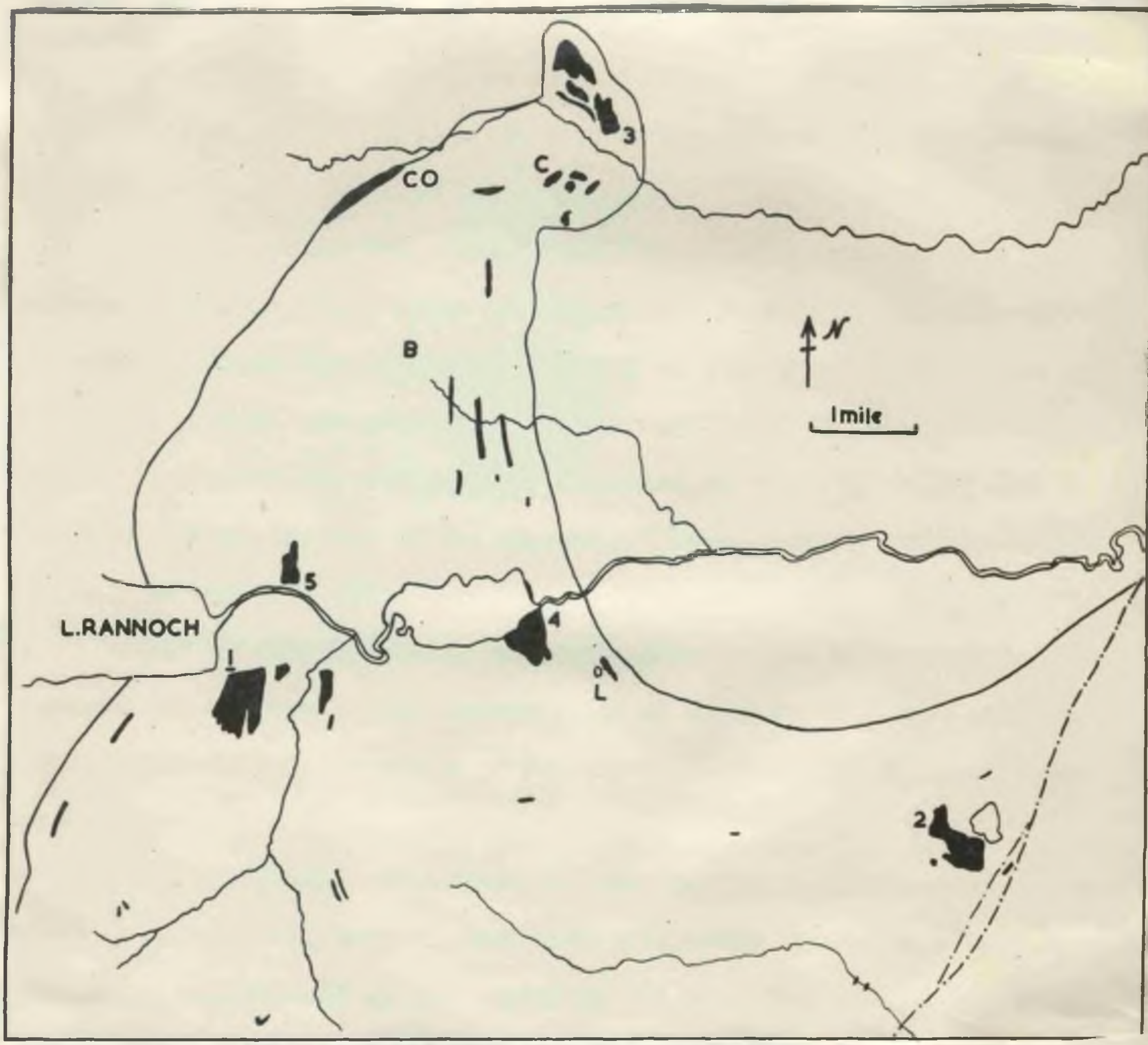
1. Meall Dearg
2. Kinardochy
3. Trinafour
4. Dunalastair
5. Creag Varr.

In addition there are very conspicuous intrusions at Croftnagowen and westwards at Colrig, as well as in the prominent crags on the eastern flank of Ben a'Chuallaich.

Even at the scale of hand specimens these rocks vary from hornblende schists to massive non-schistose epidiorites, both varieties representing meta-igneous rocks. Except in the Ben Lawers Schist where the meta-sedimentary and meta-igneous amphibolites occur side by side, it is as a rule relatively easy to distinguish between the two types, as meta-igneous hornblende-schists are generally the darker and the less garnetiferous of the two.

## General Petrography

The epidiorites of the Area vary petrographically according to grade of metamorphism and texturally. All were evidently basic igneous rocks and in some cases it is possible to show that they were originally dolerites. Thus a




Map 19 - Epidiorites and meta-igneous hornblende schists of the Area (Solid black).

1, Meall Dearg; 2, Kinardochy; 3, Trinafour; 4, Dunalastair; 5, Creag Varr. B, Ben a'Chuallaich; C, Croftnagowan; CO, Colrig; L, Loch an Daim.

specimen from Trinafour (Fig. 38 ) shows cores of partly altered pyroxene surrounded by small poikiloblastic crystals of amphibole, while traces of ophitic texture persist in the rock. In the case of many typical hornblende schists, however, no original textures remain.

Certain epidiorites, notably those near Loch Kinardochy, show abundant relicts of original phenocrysts of felspar. The interior of the phenocrysts is usually charged with rod-shaped crystals of zoisite and clinozoisite (Fig. 44 ). A small intrusion of epidiorite near Lochan an Daim shows not only relict phenocrysts but also original amygdales still partly filled with chlorite, though the bulk of the present infilling consists of pale green crystals of amphibole (Fig. 45).

Most of the epidiorites which show preservation of original igneous textures are confined to the eastern parts of the Area. West of a north-south line passing through the summit of Ben a'Chuallaich the hornblende-schists predominate.

Both the hornblende-schists and the granular epidiorites are garnetiferous. Garnets are, however, much more conspicuous in the hornblende-schists and are as much as half an inch across in the Creag Varr intrusions, a phenomenon that may be associated with shearing on the Creag Varr slides.

There is also textural evidence for this contention, since in the granular epidiorites garnets occur in small clusters commonly located at the margins between felspars and amphiboles (or pyroxene)(Fig.38) In hornblende-schists on the other hand garnets show an eyed structure with felspars (oligoclase to andesine) and hornblendes sweeping round them. These rocks frequently develop some biotite which also follows the outlines of the garnets (Fig. 46 ).

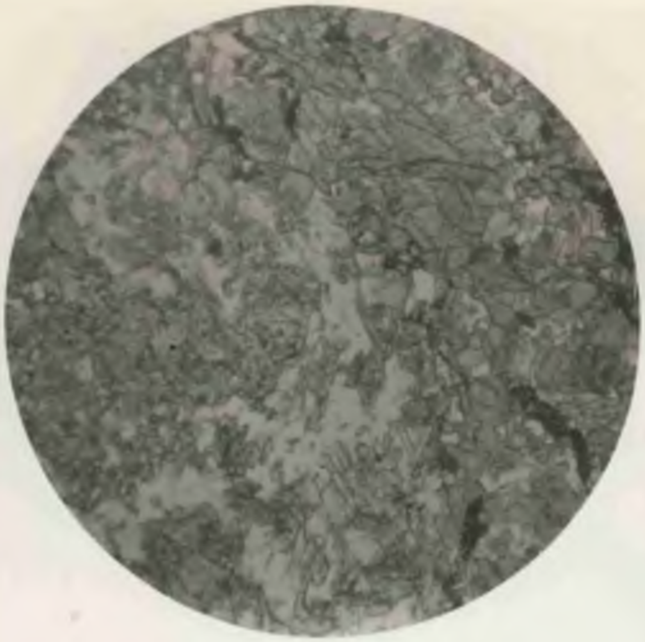


Fig.44 - Reconstituted phenocrysts in the epidiorite;

X 25 P.P.L.


Fig.45 - An amygdale in an epidiorite,

X $\frac{25}{2}$ P.P.L.

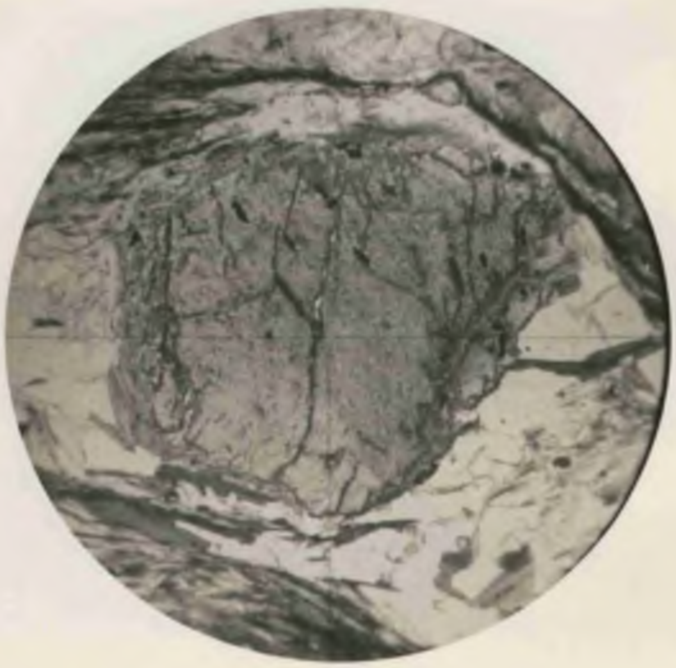


Fig.46 - Flakes of biotite conforming to the shape of a garnet,
X 25 P.P.L.

Apart from hornblende, plagioclase and garnet members of epidote-clinozoisite group and a certain amount of quartz, ores and sphene are common in the meta-igneous amphibolites of the Area. Minerals of the epidote-zoisite group are probably significant in gauging the metamorphic grade, for there appears in general, to be an inverse relationship between garnet on one hand and epidote, clinozoisite and zoisite on the other. For instance the epidiorites near Loch Kinardochy show few garnets but much zoisite and clino-zoisite and judging from the associated meta-sedimentary material they are in the garnet zone. On the other hand, the epidiorites of Trinafour though granular have an abundance of small garnets but are relatively poor in the minerals of epidote group.

This means that while on textural grounds a distinction can be made between the granular and schistose meta-igneous amphibolites, on mineralogical grounds the distinction is between the epidotic amphibolites of the garnet zone and the garnetiferous amphibolites of the kyanite zone. Such a mineral-ogical distinction does not apply to the meta-sedimentary amphibolites, which even in the garnet zone are prone to develop large garnets.

## Structural Features of the Epidiorites and Hornblende-Schists.

The hornblende-schists are as a rule structurally conformable masses. Locally exceptions to this rule occur, as near Auchtipart where the original igneous bodies were at least partly transgressive. The style of folding exhibited by these schists, however, conforms to the style of the folds in the surrounding meta-sedimentary formations.

Moreover, on occasions where some indistinct original banding is present it is possible to prove that the hornblende-schists have undergone folding of the same complexity as the meta-sedimentary rocks, with which they are associated. This may be seen, for instance, in the sheared out amphibolites of Allt Mor near Kinloch Rannoch (Pt.B5, 97, 50). Marginally some of the larger masses of the hornblende-schists which have been broken up and dispersed throughout the surrounding meta-sedimentary rocks. Examples of this are seen on the hills south of Dalhosnie.

The typically granular epidiorites, which are very well exposed on Croftnagowan and further to the west show an entirely different relations, and form a series of strongly transgressive sheets dipping south-westwards at relatively gentle angles. Marginally they show some shearing, but this is slight even by comparison with some of the post-orogenic felsites. Moreover they show hornfelsic selvages in which the invaded calcareous rocks are appreciably hardened. Internally these epidiorites never show much folding.

Farther north and especially north of Glen Errochty approaching the apex of the Dalradian Triangle both the granular epidiorites and the hornblende-schists occur together.

Age Relations of the Epidiorites

The granular epidiorites of Croftnagowan cut across the Dalnadran rocks which have been deformed by Cross-fold Movements. The preservation of ophitic texture internally and the occurrence of a fine grained chilled margin shows that the intrusions have not themselves been significantly deformed. Nevertheless the presence of garnets shows that they have attained a comparatively high grade of metamorphism. Thus three stages appear to be involved:-

1. Cross-fold Movements
2. Subsequent intrusion of dolerite sheets
3. Metamorphism

The hornblende-schists on the other hand have been strongly deformed by the Cross-fold Movements. More precise determination of the position of the hornblende-schists in the tectonic sequence is usually impossible. It may generally be suspected, however, that they were emplaced before the Caledonoid Movements. Thus the large intrusion south of Kinloch Rannoch which forms the eastern slopes of Meall Dearg is concordantly flanked by a tectonic passage zone of slices of Carn Mairg Quartzite and strongly schistose hornblende schist implying that both formations have been equally deformed.

Certain of the intrusions do not precisely conform to the two-fold classification into granular epidiorites and hornblende schists. The eastern shoulder of Ben a'Chuallaich shows several prominent crags which apparently represent sheets of epidiorite parallel to large scale joints - Both the joints and the epidiorites are evidently post-Cross-folding, but the epidiorites show a slight linear foliation and parallelism of hornblende crystals. Evidently certain movements have occurred contemporenously to the post-Cross-fold metamorphism.

A more important exception is represented by the Kinardochy epidiorites which will be described in some detail.

Kinardochy Epidiorites

South and south-westwards from the shores of Loch Kinardochy occurs a large and complex mass of epidiorite. Except at the margin the epidiorites are not strongly schistose, and in most parts are closely interfolded with the adjacent White Limestone and portions of Schichallion Boulder Bed. Much of the mass shows prominent phenocrysts of felspar and occasionally ophitic texture is revealed by the white weathering of the smaller felspars.

In detail the complex contains two types of epidiorite both porphyritic and mineralogically similar, but one type intrudes the other in a series of dykes, which have sheared margins but undisturbed interiors. Where the dykes of the second episode are thin they are much finer in grain and can be easily distinguished in the field since they weather in a lighter grey (Fig. 47). Thicker dykes again show fine grained margins, but internally they assume a speckled appearance owing to the presence of phenocrysts.

If it is assumed that the second episode of intrusion corresponds to that of the granular epidiorite of Croftnagowan, it is possible that the first episode corresponds to the hornblende schists of other localities. The epidiorites of the first episode are interfolded with the surrounding limestones. Relations between the epidiorites of the second episode and the limestones are difficult to ascertain.

No precise analogues of the extremely schistose hornblende-schists, which are so abundantly represented in the western parts of the Dalradians of the Area, are to be found among the small intrusions of this area. This may imply that owing to weaker pre-metamorphic movements, both the pre- and post-Cross-fold epidiorites have here the same general appearance. However,

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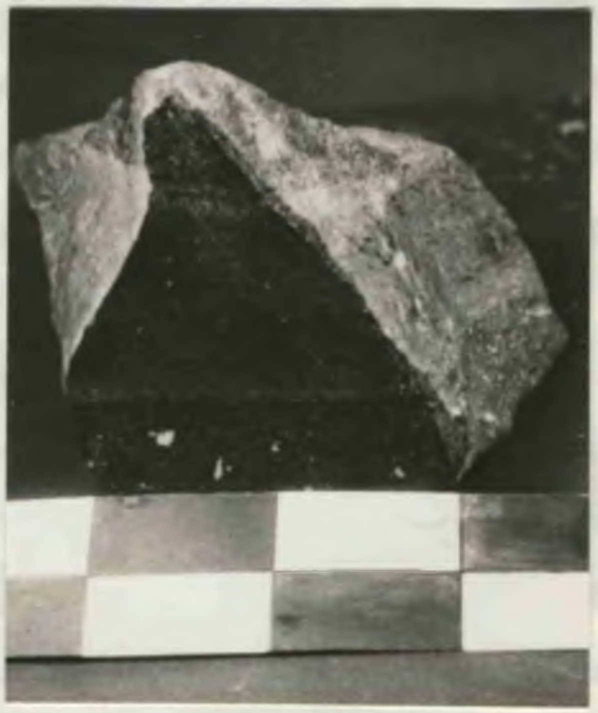

Fig.47 - A specimen of the older epidiorite cut by the younger one.
Scale in inches.

there were some movements post-dating the intrusion of the second episode of epidiorites.

Summary

(a) There were at least two episodes of intrusion of dolerites now metamorphosed to epidiorites. The first episode is pre-Cross-fold and probably pre-Caledonoid as well. The second episode is post-Cross-fold.

(b) The main episode of metamorphism is later than the second episode of intrusion.

(c) Weak post-intrusion movements are responsible for the development of a feeble lineation of hornblendes in some of the post-Cross-fold epidiorites.

(d) The evidence of the epidiorites confirms the conclusions reached on other grounds that an important episode of regional metamorphism has occurred later than the Cross-fold Movements. In fact a period of intrusion of dolerite has intervened between the Cross-fold Movements and the metamorphism.

# XVIII. POST-OROGENIC EVENTS

## Retrogressive Metamorphism

Three parts of the Area show the effects of retrogressive metamorphism. They are as follows :-

(1) The rocks in the immediate neighbourhood of the Loch Tay fault, where quite an extensive brecciation of quartzite and Killiecrankie Schist can be seen from Glengoulandie to the shores of Loch Tummel. The rocks have been transformed to a low-temperature assemblage principally represented by quartz, chlorite sericite and calcite. These effects die out rapidly west of the fault.

(2) The rocks at and near the Creag Varr Slide have suffered an episode of mild retrogressive metamorphism whereby some garnets tend to be transformed into chlorite, while kyanite shows alteration into hydromicas. This is evidently due to recurrence of post-metamorphic movements on the Creag Varr slides.

(3) Parts of the Chesthill belt of Ben Lawers Schist and the adjacent Moines show retrogressive metamorphism resulting in elimination of kyanite and a tendency for the garnets to be replaced by chlorite (Fig. 48 )

While it is difficult to date and indicate the causes of the late movements on Creag Varr, it is possible to explain and date the other two episodes. Of these Loch Tay fault belongs to the more recent movement. The retrogression in Chesthill belt is probably due to the presence of numerous igneous intrusions at the relatively slight deformation associated with them.

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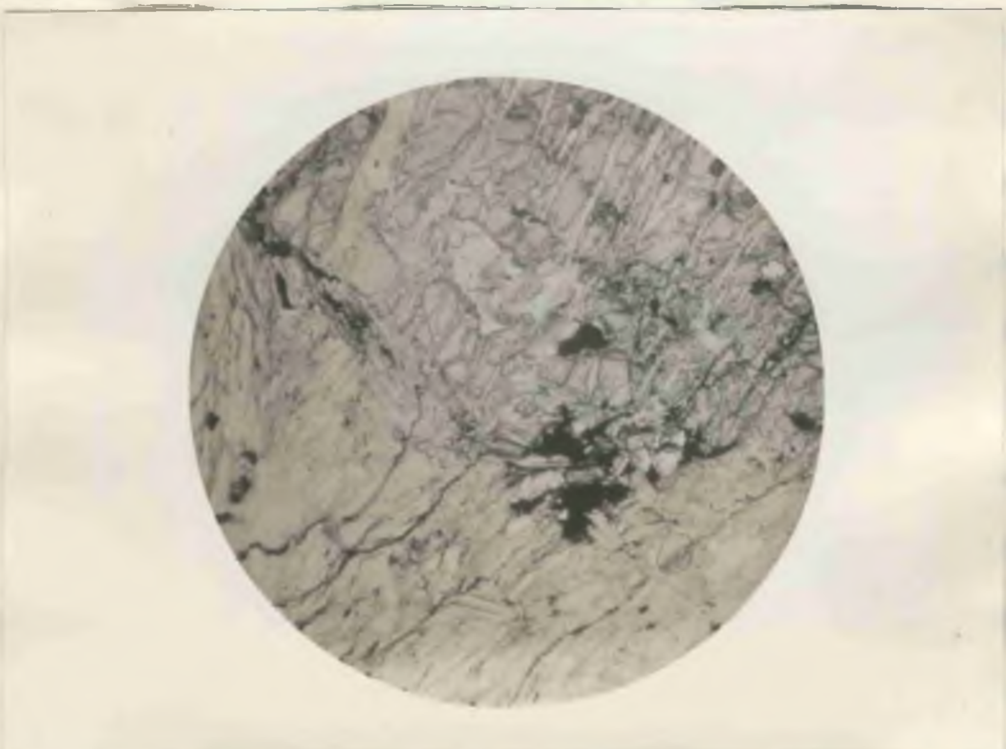

Fig.48 - Replacement of garnets by chlorite,
X 25 P.P.L.

The opinion expressed in the memoir for the Sheet 55 is that the igneous episode is connected to the intrusion of the newer granites. In fact it is later.

Evidence in this connection has been obtained from the dykes of felspar porphyry which are well exposed in the Garry north-west of Struan and near Cluns. Here the dykes contain a great variety of xenoliths, many of them of a pinkish granite (Fig.49) and a grey diorite. These xenoliths are similar to the types of rock occurring in the Glen Tilt and Glen Banvie intrusions and prove that the felsites are post-granite. A very strange circumstance is that some of the non-granitic xenoliths are of the type usually occurring in the Dalradian rather than the Moinian sequence. In particular xenoliths of a felspathic quartzite called by Barrow (1912) the porous quartzite has been noted. Similar dykes on a hill situated half a mile east of Struan and known as Creag Loigtse also contain xenoliths of a hornblende schist The poverty of the surrounding Moinian rocks in hornblende schists strongly suggests that the xenoliths are derived from a Dalradian assemblage.

If so it is likely that together with xenoliths of diorite and granite they have been brought up from depth. This evidence points to the probability that here at any rate Moines are underlain by Dalradians.

Petrography and Structure of Post-Orogenic Intrusions

The post orogenic intrusions vary from very acid quartz-felspar porphyries and felsites to rather more basic diorite porphyries. Numerous lamprophyres ranging from minettes to vogesites and kersantites occur as well. In the main these intrusions are more common in the area of the Moinian rocks,

Fig.49 - Xenoliths of a pink granite in porphyrite.
Scale in inches.

where they are chiefly dykes and follow the general Caledonoid grain of the country. South of the Tummel some of the dykes are seen to cut across the Boundary Slide, though here their trend is often irregular.

On the other hand at the western boundary of the Daradran Triangle the igneous intrusions form a series of sills which are in general parallel to the sheet dip of the rocks. Their intrusion has evidently been associated with considerable shearing as some of them show the effects of a mild metamorphism (Fig.50 ). It is evidently this shearing which accounts for the retrogressive effects noticed in the rocks of the Chesthill belt.

Elsewhere the intrusion of the late igneous masses has been accompanied by the formation of explosion breccias, which if traced laterally have their matrix replaced by the igneous material. One patch of such breccia is seen in the midst of the Killiecrankie Schist on the northern slopes of Gael Charn (Pt. D8, 44, 85).

While many of these intrusions are evidently related to joints, the series of sills parallel to the Chesthill belt has been influenced by the overall structure of the metamorphic rocks. Indeed it is no coincidence, that where as at Sron Choin the sills converge and thicken a quite a conspicuous belt of cross-folding exists within the Moinian rocks. Evidently the tectonic control of orogenically deformed rocks persisted into post-orogenic periods.

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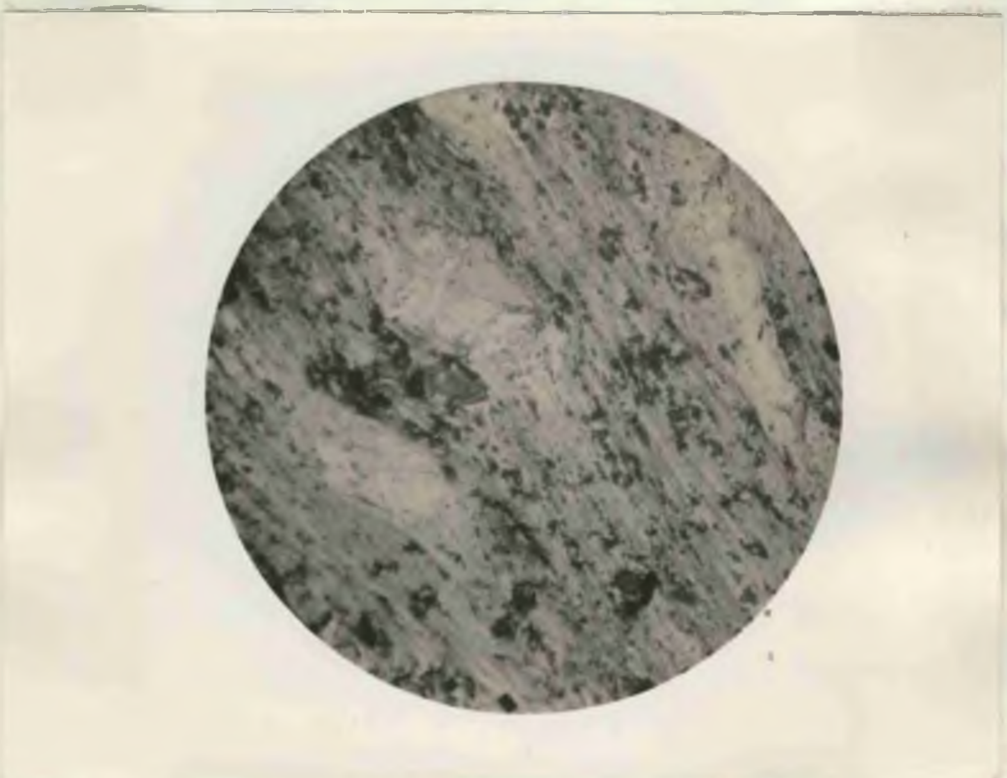

Fig.50 - Thin section of a sheared and metamorphosed porphyry;
X 25 P.P.L.

## XIX. STRUCTURAL AND METAMORPHIC HISTORY OF THE AREA

Sufficient data have been now gathered together to attempt a general reconstruction of the history of the Area. Obviously throughout the Orogeny there has been an inter-play of various forces giving rise to a complex picture of tectonic and metamorphic events.

The oldest tectonic and metamorphic events that are recognisable are not necessarily the earliest happenings in the evolution of orogeny. In fact the "compromise" schistosity of the earliest recognized movements is itself an indication of an earlier phase of deformation.

Again it is a tentative suggestion that the strongest earlier movements were associated with weaker metamorphism, the main metamorphism being essentially post-tectonic.

With these reservations the following sequence of events is inferred :-

(a) Sedimentation, intrusion of dolerite sills and dykes and some deformation.

(b) Caledonoid Movements - Recumbent folds were produced. These folds closed northwards and eventually became nappes with basal thrusts. Since the succession within these folds is structurally normal it is reasonable to assume that the movement was from south to north and the nappes were produced by drag mechanism.

(c) Weaker movements on Caledonoid axes were responsible for the relatively open folds in the Moinian rocks of Glen Errochty.

(d) Strong Movements (the Cross-fold) - The Caledonoid nappes were refolded on axes trending in general at right angles to the Caledonoid strike, though compromise-structures such as the Creag an Fhithich synform were also produced. These movements were responsible for a limited recumbency in the region of Trinafour and a very strong sliding on Creag Varr, Creag an Fhithich and Boundary Slides as well as on other minor shear zones. Metamorphism as high as garnet grade and responsible for the formation of "snow-ball" garnets was associated with these movements.

If as previously suggested the maximum of the Cross-fold Movements corresponds to and is contemporaneous with the weakening of Caledonoid deformation, then this metamorphism was also associated with the Caledonoid Movements. There is also some evidence of the slightly later east-west folds.

(e) Intrusion of dolerite sheets and dykes producing local contact metamorphism.

(f) Second episode of metamorphism, associated with some weak movements probably on cross-fold axes, since this is the direction of the plunge of lineation in the lineated hornblende-schists at Ben a'Chuallaich.

(g) Weak late orogenic movements giving rise to strain bands in the Moinian rocks, and probably the renewal of movements on the Creag Varr slides.

The orogenic history consists of two main events.

(h) The intrusion of porphyries, lamprophyres and felsites accompanied by weak movements producing some retrogressive metamorphism.

(i) Tear faulting resulting in the formation of Loch Tay Fault.

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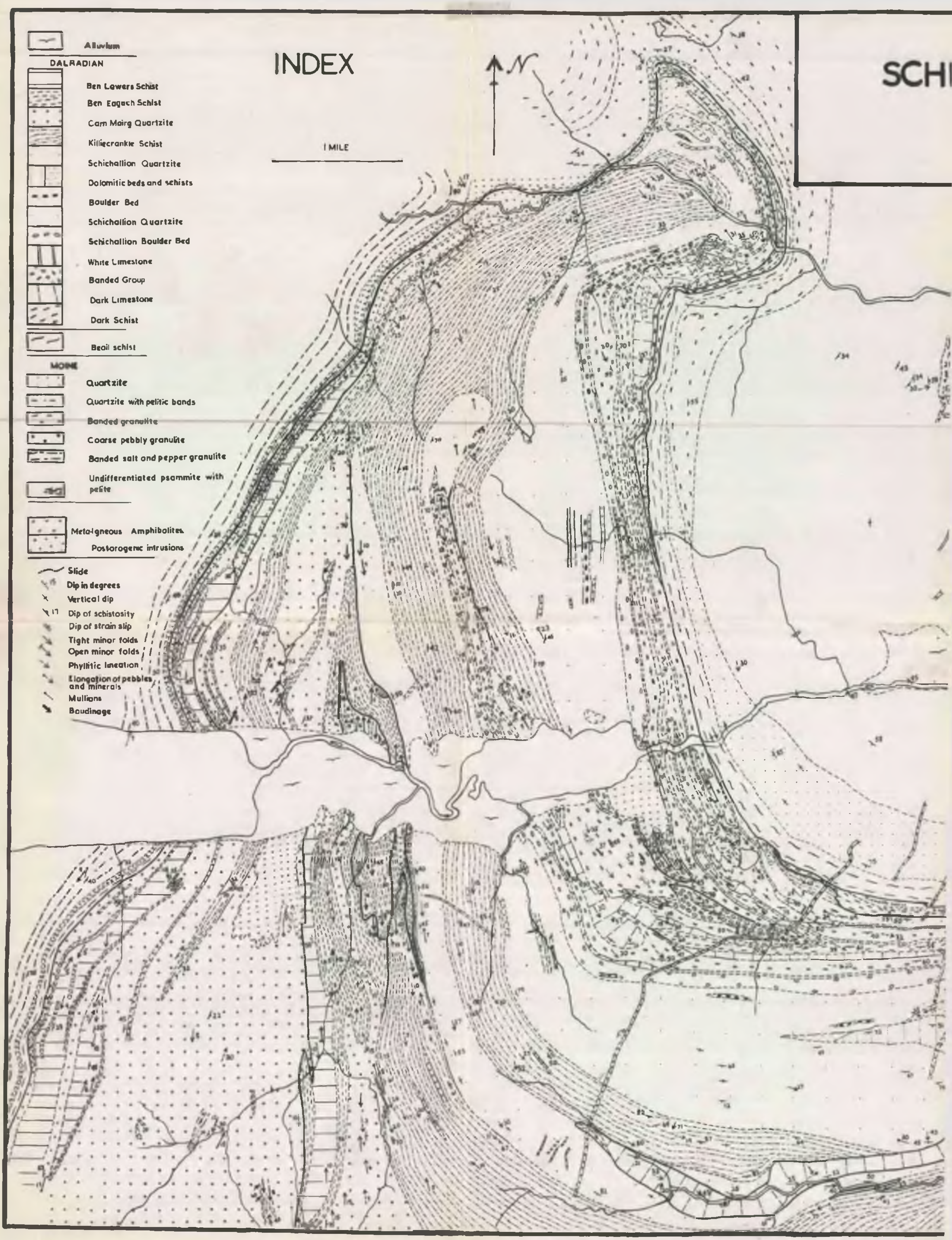
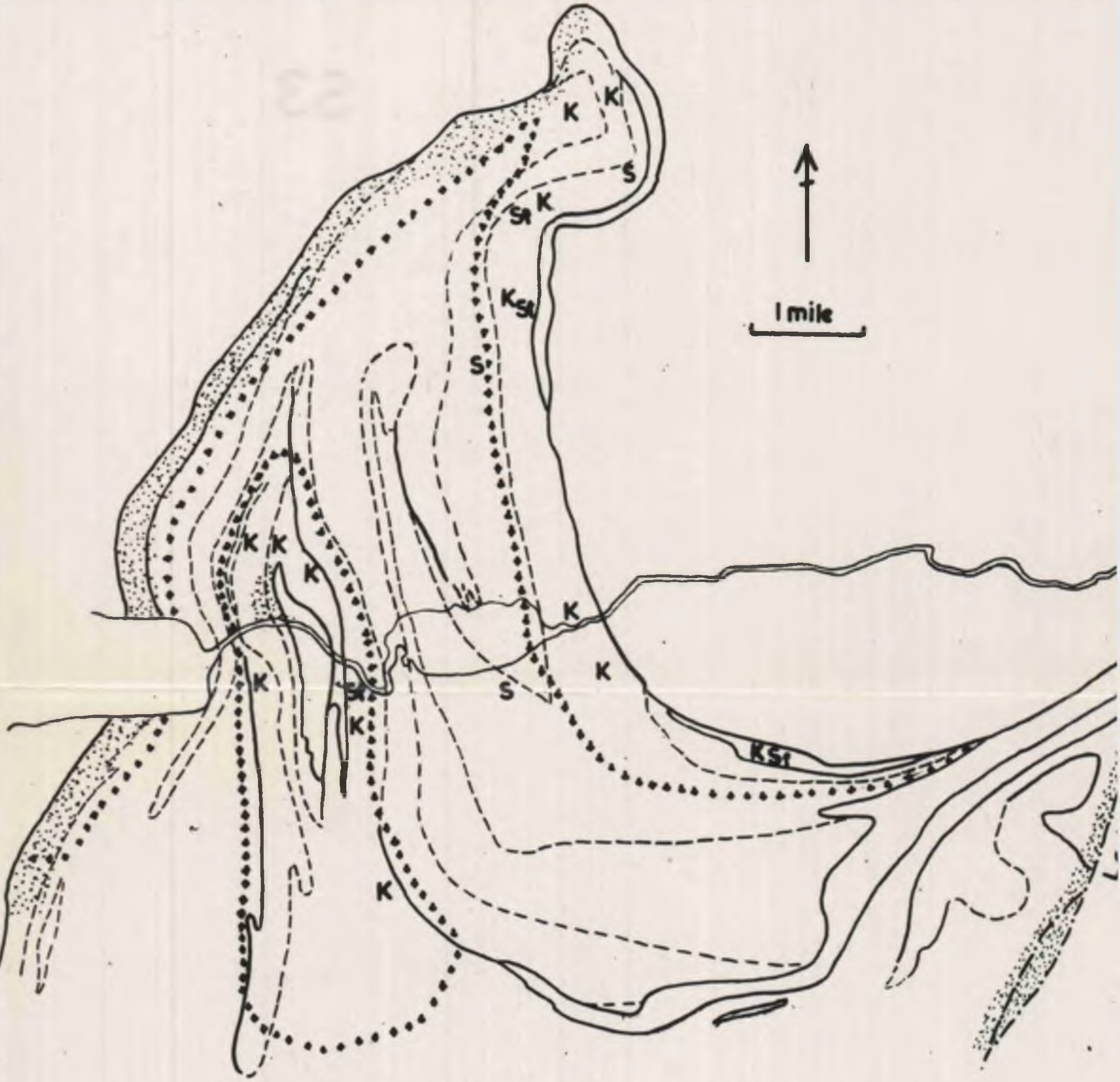
a - Parallel axes.

b - Axes at right angles.

c - Oblique axes, giving rise
to compromise structures

Fig.51 - Photographs of specimens of refolded folds. Scale in inches.

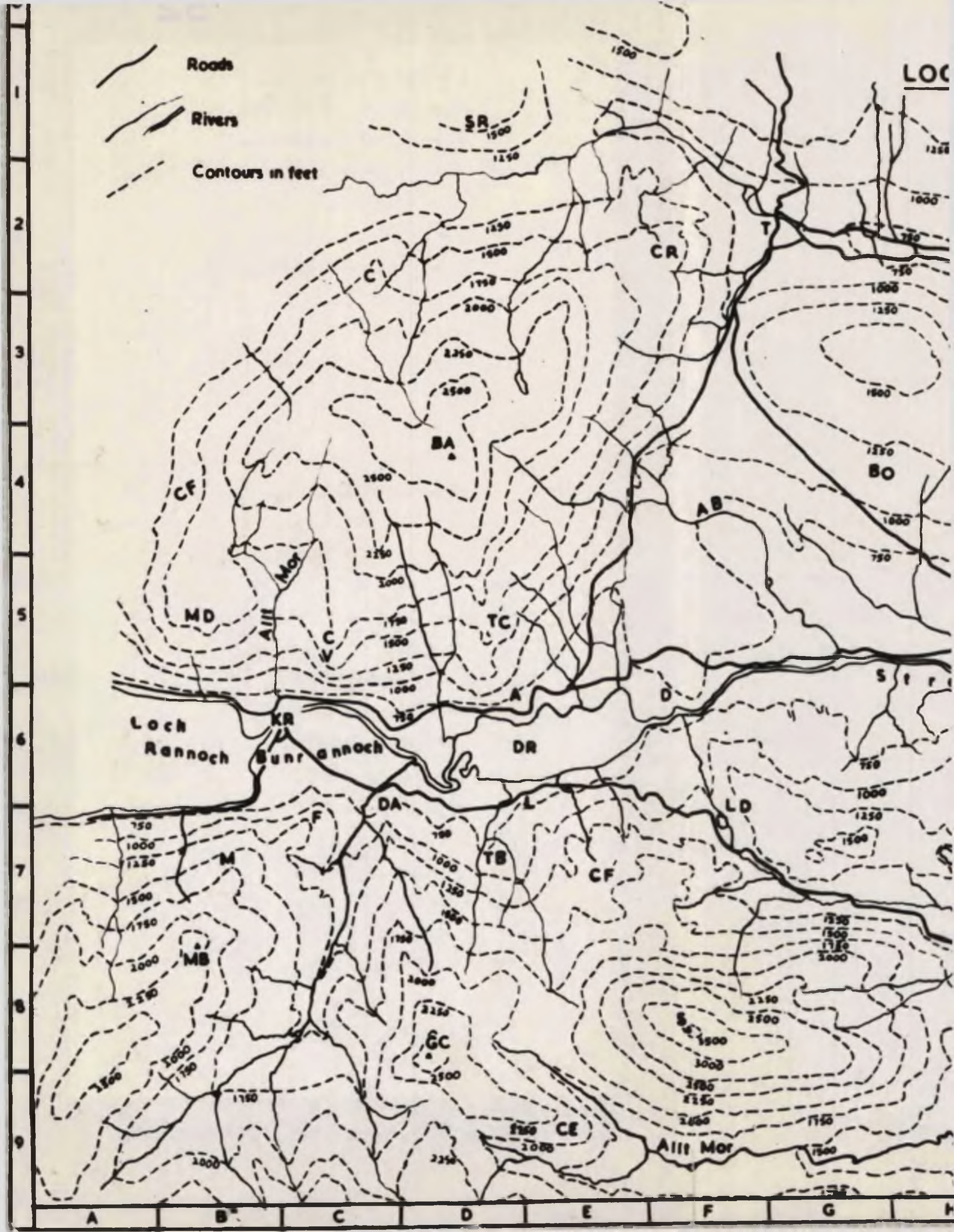

INDEX
N
1 MILE
SCHI
Alluvium
DALRADIAN
Ben Lawers Schist
Ben Eagach Schist
Carn Mairg Quartzite
Killiecrankie Schist
Schichallion Quartzite
Dolomitic beds and schists
Boulder Bed
Schichallion Quartzite
Schichallion Boulder Bed
White Limestone
Banded Group
Dark Limestone
Dark Schist
Beoil schist
MOINE
Quartzite
Quartzite with pelitic bands
Banded granulite
Coarse pebbly granulite
Banded salt and pepper granulite
Undifferentiated psammite with pelite
Meta-igneous Amphibolites
Postorogenic intrusions
Slide
Dip in degrees
Vertical dip
Dip of schistosity
Dip of strain slip
Tight minor folds
Open minor folds
Phyllitic lineation
Elongation of pebbles and minerals
Mullions
Boudinage




K - Kyanite in abundance
S - Scapolite " " " "
St-Staurolite " " " "

Kyanite isograd
Areas of retrometamorphism
Baundaries
Slides

Zones can not be mapped in the psammitic Moines of the Area



Roads
Rivers
Contours in feet
LOC
SR
CR
T
C
BA
BO
CF
AB
MD
Allt Mor
C
V
TC
A
D
S t r
Loch
Rannoch
KR
Bunrannoch
DR
DA
L
LD
F
M
TB
CF
MB
GC
S
CE
Allt Mor
A
B
C
D
E
F
G
H
1
2
3
4
5
6
7
8
9

A - Aucht
AB - Allt
BA - Ben
BF - Brae
BO - Bohe
C - Colri
CE - Crea
CF - Carr
CF´ - Cnc
CK - Crea
CR - Crot
CV - Crea
D - Dunal
DA - Dal
DC - Dun
DR - Dun
F - Crea
G - Glen
GC - Gas
K - Loch
KR - Kir
L - Luss
LB - Loc
LD - Loc
M - Meal
MB - Me
MD - Me
S - Sch
SR - Sr
T - Tri
TB - Te
TC - Tc