Thesis submitted for the Degree of Ph.D.

in the University of Glasgow

THE STRUCTURE AND TECTONICS OF NORTH-EASTERN PERTHSHIRE

by

Frederick John Matheson

THE STRUCTURE AND TECTONICS OF NORTH-EASTERN PERTHSHIRE

CONTENTS

SUMMARY OF GEOLOGY

The Dalradian schists of North-eastern Perthshire range from the Blair Atholl Series to the Pitlochry Schist and contain epidiorite sills. From the "Flat Belt" to the Ben-y-Gloe Belt their structure has been interpreted by Bailey (1925) who suggested that the rocks were folded on N.E.-S.W. axes, but that folds belonging to various phases of the Caledonian orogeny could be recognised. He also invoked sliding to explain stratigraphical discordances. In few other parts of the Southern Highlands does a solution based on stratigraphic mapping present greater difficulties than in north-east Perthshire. This thesis shows that certain of these difficulties are resolved by the recognition of a complementary fold system on N.W.-S.E. axes. Evidence of this trend as well as the different types of folds on "Caledonoid" axes is given by the minor structures of the area.

Several episodes of igneous activity followed the folding. The earliest was the formation of the Duchray Hill Gneiss from part of the Ben Lui Schist. This was followed by the intrusion of the Glen Shee Diorite and the Carn Mor Granodiorite. Finally the metasediments were cut by suites of lamprophyre and felsite dykes.

I INTRODUCTION

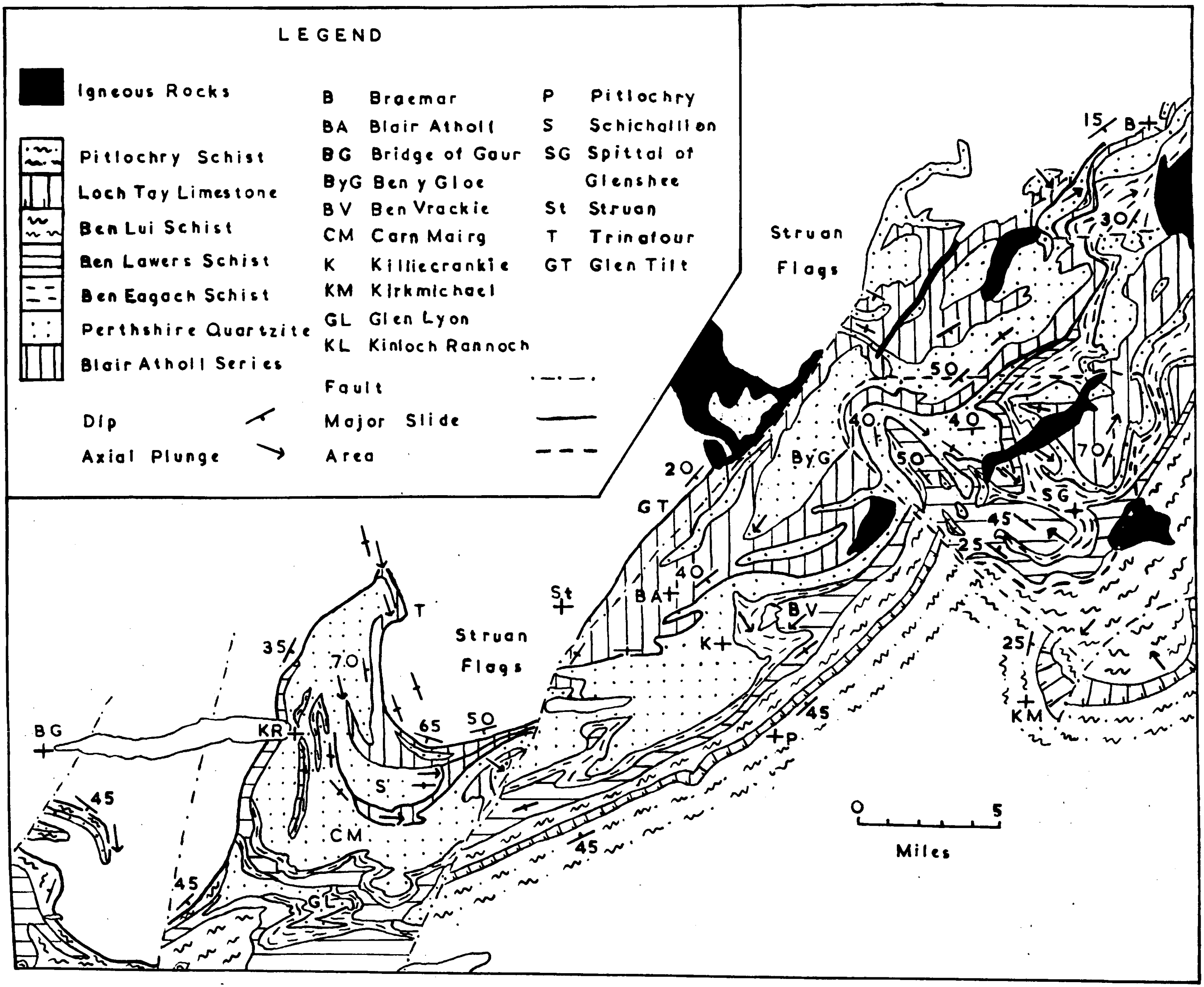
Location of Area

The area which covers about 55 square miles lies in the eastern part of the Grampian mountains and is centred about the Spittal of Glenshee (see Fig. 1).

Geologically the limits of the area are marked on the north by the southern flank of the Ben-y-gloe - Socach Belt of Quartzite from Loch Loch to Loch nan Eun and at the eastern end by the northern margin of the Cairnwell Quartzite. The northern limit of the area cuts across several intervening formations to link these two boundaries. The eastern march follows the eastern outcrop of Cairnwell Quartzite. From the south-eastern corner of the Cairnwell Quartzite the boundary cuts across the Ben Eagach and Ben Lawers Schists to the Glen Shee Diorite which it follows till it reaches the northern boundary of the Ben Lui Schist. It continues along the latter round the southern margin of the area as far as the Glen Fearnach Fault. The south-western limit of the area follows the fault for the rest of its length and then cuts across the Killiecrankie Schist to the southern end of Loch Loch.

Of major interest in the area is the fact that over the greater part of it the strike of the rocks trends at right angles to that normal in the Dalradians. This feature and the corresponding bulge of the Lower Dalradians towards the south-east into the Upper Dalradians of the "Flat Belt" are both rare enough in the Highlands to demand more detailed investigation than has hitherto been carried out.

FIG. 1. GENERALISED MAP SHOWING LOCATION of AREA.



Physical Features

As the area lies at the eastern end of the Grampian mountains it forms part of the less dissected Highland plateau where the only lochs are corrie lochs. Much of the high plateau remains as broad level moorlands cut into by deep glens and scarred by gigantic corrie cliffs. The relief ranges from 3,500 feet to 1,000 feet which is the lowest level to which the glens have been eroded.

The area can be divided into three parts according to the directions in which the rivers and mountain ranges run. In the north the grain follows the N.E.-S.W. trend common to the greater part of the Highlands. This part covers Glen Mhor and the Ben-y-gloe - Socach range. The grain of the eastern region, which comprises Glen Beag and the mountains to the east of it, follows a N.N.E.-S.S.W. trend and merges gradually into the N.E.-S.W. trend of the northern ground. The eastern and southern regions, however, which form most of the area, trend in a direction N.W.-S.E., which is at right angles to that usual in the Highlands. These differing trends are of course reflections of the control exerted on the local drainage by the strike of the formations which varies in a roughly corresponding manner.

The main rivers, the Shee and the Fearnach, flow south-east. They are probably original consequents on the Highland plateau but have no doubt been helped in their development by the trend of the rock formations in the south-eastern regions.

The topography of the less dissected plateau is disadvantageous geologically since exposures are poorer than in the more rugged country found further west. The hills are rounded with grassy slopes and the glens are floored by glacial deposits. Peat also covers large upland tracts. Even the corries are filled by rock debris and peat although cliffs often form their heads. Stream sections are generally poor but tend to improve towards the west. Exposures are generally sufficient to trace groups but not individual layers or the pitch of the larger isoclinal folds.

Methods

The area was mapped on the scale of six inches to one mile on the sheets of the Ordnance Survey. Aerial photographs on approximately the same scale were used, where possible, for the location of position. Particular attention was paid to the minor structures, both fold plunges and lineations being measured.

History of Research

Earlier work in the area has been scanty. Apart from incidental allusions by older writers such as Nicol and Macnair the first important work was carried out by the Geological Survey at the beginning of this century, when the whole district was mapped on the six-inch scale and the results published as sheets 55, 56, 64 and 65 of the one-inch map of Scotland. All the sheets except Sheet 56 are accompanied by explanatory memoirs.

G. Barrow was responsible for the mapping of all the present area.

His reading of the succession was accepted by A. Geikie (1891) and differs from that now generally accepted only in his assumption that the Blair Atholl Series were the youngest rocks and the Pitlochry Schist the oldest. He recognised that the Blair Atholl and Loch Tay Limestones were distinct and separate formations instead of being the same as had been thought for many years.

As regards structure Barrow believed that the major folding was of an open nature but explained tectonic thinning and thickening by a process which he called "Concertina Folding", in which each group was formed by repeated isoclinal folding of a single thin bed on itself like the bellows of a concertina. The process was accomplished without the neighbouring groups being affected because of decollement along the junctions. He arrived at this conclusion by observation of the omnipresent isoclinal minor folding but failed to realise that isoclinal folding could also explain the major structures. Nevertheless Barrow's contribution to Highland geology in general was very great and no praise can be too high for his lithological mapping except where he has been misled by his reading of the structure.

Cunningham-Craig and Grant Wilson (1905), who were colleagues of Barrow on the Survey, believed however that the Perthshire Quartzite was later than and overlay the other groups unconformably, and that the Ben Eagach and Blair Atholl Black Schists were one and the same formation. They held that all formations were folded openly and that the unconformity below the quartzite explained the juxtaposition of various formations.

Gregory (1910) realised that the Carn Mairg and Schichallion Quartzites were distinct formations though he failed to recognise that they were separated by the Killiecrankie Schist. Gregory also believed that the Ben Eagach Schist was part of the Blair Atholl Series and that the latter lay between the two Quartzites.

Bailey (1925 and 1928) furnished two valuable papers on the area after a few weeks rapid work. His approach was largely stratigraphical but based on the realisation that recumbent isoclinal folding on a Caledonoid axis was the main factor in controlling the distribution of the formations. He believed that the folding was accompanied by sliding which he had already postulated in the south-west Highlands to explain the cutting out and thinning of formations. Both the recumbent folds and the slides were later folded more gently on similar axes. Bailey also clarified the positions of the various groups, thus tidying up Barrow's mapping. He recognised the Killiecrankie Group where it was bounded by slides so that neither quartzite formation was present. He also subdivided the Blair Atholl Series into two groups, the Pale which is the younger thus coming against the Schichallion Quartzite and the Dark which is the oldest of the Dalradian rocks.

Since Bailey's work little has been done on the Dalradians but Williamson (1935) studied the formation of the Duchray Hill Gneiss from the Ben Lui Schist and also the intrusion and contract metamorphism induced by the Glen Shee Diorite. Wiseman (1934) also referred to the area in his paper on the epidiorites of the Dalradians.

II. THE DALRADIAN SEDIMENTARY SUCCESSION

Description of the Succession

The Dalradian sedimentary rocks have been divided into seven groups named from their dominant lithological components. The sequence is best established in eastern and central Perthshire which provide most of the locality names, but it can be recognised across Scotland and some members can be traced in the Dalradians of Ireland. Over such a wide area there are inevitable lithological and metamorphic variations and in the South-Western Highlands and Banffshire local names are frequently used to designate groups equivalent to some of those in Perthshire.

The succession is assumed to be a continuous sedimentary one because of the wide extent over which it holds, but the rocks have undergone such deformation that few, if any, of the contacts can be said to be sedimentary. Similarly tectonic thickening and thinning have progressed so far that estimates of the thicknesses of various groups can have little value.

In the past there has been widespread disagreement on the order of the Dalradian succession between the proponents of the "Tay" and "anti-Tay" orders. Briefly the Tay order was an ascending one from the Highland Border since at the northern side of the Flat Belt the Pitlochry Schist can be seen to dip under the Loch Tay Limestone and the latter in turn under the Ben Lui Schist. This also holds for various more southerly Dalradian groups such as the Leny and Ben Ledi Grits.

The believers in the "anti-Tay" order pointed out that the Dalradian group which rests on the Moine Flags was the Blair Atholl Series and so it is the oldest member with the Perthshire Quartzite following it. The actual junction between the Moines and Dalradians is nearly everywhere tectonic although this has often not been recognised till recently, e.g. by King at Braemar and Rast at Schichallion. The tectonic nature of the Moine - Dalradian boundary, however, does not alter the fact that the Dalradians nearly everywhere rest on the Moines and that the succession is a sedimentary one which has suffered movement during folding so that many points are not in contact with their original neighbours.

The contrasting hypotheses reflect the style of tectonics favoured by individuals. Those who believed that large scale inversions of the Dalradian sequence were impossible, such as Barrow, Geikie, Cunningham-Craig and Wilson, thought that the Tay order was correct, following the law of superposition. Bailey and his followers had already propounded the existence of large scale recumbent folds to explain the structure within the Dalradians so found no difficulty in accepting that the rocks of the Flat Belt were inverted.

For a long time there was no simple answer to this controversy until the use of current and graded bedding was applied. This demonstrated that the rocks of the Flat Belt form the inverted limb of an extensive recumbent fold with steeply packed folding. Bailey also showed by graded bedding that the Ben Eagach Black Schist is younger than the central Highland Quartzite.

In eastern Perthshire the only considerable variant from the standard succession of central Perthshire is that the Perthshire Quartzite is represented by the Cairnwell Quartzite which has certain characteristics which link it to both the Schichallion and Carn Mairg Quartzites. The Killiecrankie Schist, a quartzose garnetiferous mica schist, which is the central member of the Quartzite Series, is lacking altogether in the Cairnwell Belt which is at a higher structural level than that at which the Quartzite Series is normally seen. The Cairnwell Quartzite in places is separated by less than quarter of a mile across the strike from the Killiecrankie Schist which is the only representative of the main Perthshire Quartzite outcrop, the Schichallion and Carn Mairg Quartzites being cut out by slides. In the Ben-y-gloe Belt to the north the Schichallion Quartzite is the only member of the series present.

The full succession is:-

7. Pitlochry Schist
6. Loch Tay Limestone
5. Ben Lui Garnetiferous Mica Schist
4. Ben Lawers Calcareous Schist
3. Ben Eagach Black Schist
2. Perthshire Quartzite Series
    - c) Carn Mairg Quartzite
    - b) Killiecrankie Schist
    - a) Schichallion Quartzite

    Cairnwell Quartzite in East
1. Blair Atholl Series
    - Pale Group
        - c) Schichallion Boulder Bed
        - b) White Limestone
        - a) Banded Group
    - Dark Group
        - b) Dark Limestone
        - a) Dark Schist

1. Blair Atholl Series

There are two main outcrops of the Blair Atholl Series in the area. The first of these is the eastward extension of the main Blair Atholl Series outcrop which here outcrops in a narrow belt between the Killiecrankie Schist and the Ben-y-gloe Quartzite. The southern boundary of this outcrop of Blair Atholl Series has been recognised as a slide by Bailey since the Killiecrankie Schist comes against the Dark Group, though the latter is only differentiated in well exposed regions. The northern margin on the other hand is a normal stratigraphical one with the Schichallion Quartzite bounding the Pale Group.

The second outcrop is enclosed by the Cairnwell Quartzite of the Cairnwell Belt and in no place connects with the Blair Atholl Series of the main outcrop since the north-eastern end is cut off by the Lochnagar Granite. North of the latter relations are obscured by the Deeside Granites.

Bailey's Pale and Dark Groups can be distinguished fairly easily in the area but the further subdivision of the sequence, as established at Schichallion, is more difficult because of the gradual convergence of the differentiating characteristics outwards from the type area.

The Dark Schist is a soft, dark finely crystalline biotite muscovite schist in which graphite and iron ores vary greatly in quantity in the different bands. It can in places be black due to its graphite content and weathers rusty because of its content of pyrites. In the latter condition it is indistinguishable from much of the Ben Eagach Black Schist. It has a bright lustre on the planes of schistosity which often show minute puckering and crumpling, the intersection of various lineations and strain slip cleavage. It comes to outcrop only in a thin strip along the southern margin of the main outcrop and in a few small areas in the Cairnwell Belt.

The Dark Limestone is always coarsely crystalline over the whole of the area and is usually of a blueish-grey colour. In places such as the Limestone Quarry on the south flank of the Cairnwell it can be massive but is usually thin-bedded containing bands of impure calcareous schist which give a ribbed appearance to a weathered face and highlight the folding. It forms wide outcrops in the northern part of the Cairnwell Belt in the form of lenticles and occupies a thin strip along the southern margin of the main outcrop.

The Banded Group is a term, originally applied at Schichallion, that does not accurately describe the rocks assigned to it in this area, which are grey, rather quartzose and flaggy mica schists but are not sufficiently quartzose to give a true banded appearance. It corresponds rather to a paler variety of the Dark Schist and in places the two are separated more on their associates than on their own characters. It forms the central strip of the main outcrop and is spread throughout the Cairnwell Belt.

The White Limestone is a group term and covers several varieties of limestone, sometimes white saccharoidal marble or cream coloured with dark micaceous stripes ("Barrow's tiger rock") or pale grey and very impure and even mere calcareous schist. It forms the northern margin of the main outcrop and is the predominant limestone of the southern part of the Cairnwell Belt and is the only limestone of its eastern extension.

The Schichallion Boulder Bed is a massive very slightly calcareous quartzose mica schist containing pebbles or boulders of nordmarkite. It has been found in this district in one locality only, about a mile south-east of Cairnwell, where it is preserved in a fold at the eastern outcrop of the Cairnwell Quartzite. Here it is only represented by the matrix, a distinctive unbedded calcareous quartz mica schist which weathers in honeycomb fashion. Pebbles are much less frequent in the eastern outcrop of this bed which is generally accepted to be a tillite. Barrow records a similar outcrop in the Cairnwell Belt to the north of the area.

2. Perthshire Quartzite

The Perthshire Quartzite of the district occurs in three distinct belts - the Tummel, Ben-y-gloe and Cairnwell Belts. Correlation can only be made between the three when evidence from other districts is taken into account since each belt shows only one of the three possible rock types found where the Series is best developed.

The Ben-y-gloe Belt, as would be expected from its proximity to the Pale Blair Atholl Group, is represented by the Schichallion Quartzite which is a fine grained quartzite at its type locality but is more pebbly farther east. In spite of the lateral variation it is however appreciably less coarse than the typical Carn Mairg Quartzite, and Bailey correlates it with the Schichallion Quartzite because of its apparent stratigraphical contact with the Pale Blair Atholl Group and on its other side with typical Killiecrankie Schist on Ben-y-gloe itself. No Carn Mairg Quartzite is seen in the Ben-y-gloe Belt since that side of the quartzite which comes against the Ben Eagach Schist is never present.

The Tummel Belt is represented in eastern Perthshire by the Killiecrankie Group which is predominantly a quartzose garnetiferous mica schist with only a few isolated occurrences of quartzite. Both sides are bounded by slides, the Carn Mairg and Schichallion Quartzites, which are both present in the Loch Tummel area, being cut out by movement. Lenses of quartzite also appear in the group, notably on the eastern cliffs of Glas Tulaichean. The outcrops in the Glen Loch Burn are predominantly quartzose, and are considered by Bailey to be near the margin with the Carn Mairg Quartzite since a similar outcrop is found near the latter when it is present in the Tummel Belt.

The Killiecrankie Group was not recognised when the Geological Survey mapped this region so to render comparison possible with Sheets 55, 56, 64 and 65 it is necessary to explain how it was treated at that time. Barrow coloured the rock of the Glen Loch Section as quartzite, like the rocks at the head of Glen Fearnach, but he mapped the Glas Tulaichean region as undifferentiated schist. He identified the tongue running north-east from Glas Tulaichean, in common with the Ben Lawers Schist and Blair Atholl Series on either side of the Killiecrankie Schist, as Black Schist, but Barrow recognised that part of the outcrop as in fact calcareous (Memoir 65, p.28). He also realised that the Killiecrankie Group at Glas Tulaichean differed from other rocks of the Highland sequence and called it the Glas Tulaichean Schist but did not assign it to any precise stratigraphical position.

The third belt, the Cairnwell Belt, is known only in its type area except for some small outcrops on the south side of Glen Shee which are assigned to it. It contains rock types similar to those found in both the Schichallion and Carn Mairg Quartzites but is chiefly formed of a pebbly quartzite similar in character to that found in the Ben-y-gloe Belt which is equated with the Schichallion Quartzite by Bailey. The term pebbly quartzite as used in Scotland denotes a gritty rock rather than one containing pebbles. In it, however, grains of quartz and felspar are often more than quarter of an inch across.

At its outcrop the Cairnwell Quartzite lies between the Ben Eagach Schist, into which it passes by way of a striped transition group classed with the Ben Eagach Schist, and the Blair Atholl Series and so represents the whole of the Perthshire Quartzite Series although the Killiecrankie Schist of the Tummel Belt is in places only separated from it by a narrow outcrop of Ben Lawers and Ben Eagach Schists.

The question therefore arises whether the Cairnwell Quartzite is the equivalent of either one or both of the Schichallion and Carn Mairg Quartzites, the other members of the Perthshire Quartzite Series being cut out by sliding, or whether it represents the whole sequence in which the Killiecrankie Group is missing because of facies variation. Bailey (1925) has pointed out that there is no sign of a major discordance within the Cairnwell Quartzite although there are zones of shearing, and has favoured the view that facies variation is the more likely alternative. When the Quartzite series is followed westwards from central Perthshire similar changes of facies are found. In Islay for instance the series is continuous quartzite whereas in the north of Jura it includes a very large proportion of semipelitic flags, and the change can be traced coming on gradually in the intervening twenty five miles of the Jura exposures. Facies variation would explain the fact that in eastern Perthshire one of the belts into which the series is divided consists wholly of Killiecrankie Schist while the other two are almost entirely composed of quartzite. If sliding was the explanation it might well be expected that some remnants of each type would be preserved with the other.

3. Ben Eagach Black Schist

The Ben Eagach Schist of this area can be divided into two zones, which however have not been mapped. The part which normally lies next to the Perthshire Quartzite contains much intercalated quartzite so that it resembles somewhat the Banded Group of the Blair Atholl Series in central Perthshire. This portion is often missing from the outcrops but whether it has been cut out tectonically or is only locally developed is uncertain. It is present in great force on Ben Gulabin to the north of Glen Shee and in a thin strip along the eastern margin of the Cairnwell Belt.

The major constituent of the group, however, is a soft dark or black finely crystalline biotite muscovite schist weathering rusty because of its content of pyrites. The black colour is due to graphite and the rock as a whole is very similar to the Dark Schist of the Blair Atholl Group. In the south-western part of the area the schist has puckered planes of schistosity and carries numerous little garnets. Towards the north-east, however, beyond the Spittal of Glen Shee it is straight-cleared and relatively garnet-free as metamorphism increases.

4. Ben Lawers Calcareous Schist

This formation can be divided into three zones in the area. Near the Ben Eagach Schist it is characterised by conspicuous blades of actinolite and also by a brownish limestone, probably occurring in several beds. The actinolite is well developed in Glen Thaitneich especially on Creag Lamhaich, where, however, the limestone is not present, but where a band characterised by large impure garnets has been formed along the junction with the Ben Eagach Schist. The garnets occur in marginal portions of typical rocks of each group so the lateral transfer of various constituents must have been aided by movement near the boundary. The limestone is common in the south-western part of the area, however, in the Glen Fearnach region. It is similar in some occurrences to the Dark Limestone of the Blair Atholl Series but is usually coarser in grain and less well compacted. A small strip not previously mapped has been discovered on top of the Killiecrankie Schist between Glen Fearnach and Glen Loch.

The main part of the Ben Lawers outcrop consists of extremely contorted soft mica schist containing numerous quartzitic beds or lenticles, usually pitted with small rusty cavities due to the weathering out of ferruginous carbonate. Muscovite is the chief mica. The rocks contain a band of limestone near Dalhenzean, less pure than those found lower in the sequence but quarried in the past probably because of its accessibility.

In two crags on either side of Glen Shee the group shows an exceptional metamorphic facies probably due to hornfelsing by the nearby Glen Shee Diorite. The hornfels extends farther than the normal contact metamorphism produced by the diorite so that the latter probably extends farther laterally below the surface. The rocks appear flinty, finely crystalline and laminated but still contain a considerable proportion of carbonate.

The part of the group nearest to the Ben Lui Schist is less calcareous but is still sufficiently calcareous to be distinguishable from the younger formation.

In Glen Shee Bailey (1925) divided the Ben Lawers Schist into two belts separated by a band of Ben Eagach Schist and Cairnwell Quartzite which he thought formed the core of a N.E.-S.W. recumbent fold in an envelope of the Ben Lawers Schist. This fold, which in Bailey's sections displays an extremely complicated and sinuous course, does not in fact exist and the outcrops are much more easily explained by a downfold on a N.W.-S.E. axis. In addition the minor structures give ample evidence of a fold of this kind (refer to pages 47-48). The northern boundary of the Ben Lawers Schist is formed nearly everywhere by the Killiecrankie Schist since the Ben Eagach Schist is cut out by sliding except on the western side of Glen Fearnach.

Epidiorite sills abound in the group.

5. <u>Ben Lui Garnetiferous Mica Schist</u>

This group is composed of a grey garnetiferous mica schist which is often distinctly quartzose and sometimes carries quartzite bands.

From Ben Vrackie to Glen Doll it acts as host rock to the Duchray Hill Gneiss.

6. Loch Tay Limestone

This formation only enters the area on the south-western side of the Glen Fearnach Fault and has only been mapped to show the displacement of the fault. It usually consists of well-bedded rather quartzose, calcareous schist but includes bands of fairly pure blueish-grey limestone which are often thick enough to work. In Glen Fearnach little limestone is present but at Dalrulzion just south of the area there are extensive quarries.

7. Pitlochry Schist

This also occurs only on the south-western side of the Glen Fearnach Fault and is a quartzose mica schist which is often garnetiferous.

III THE EPIDIORITES

The epidorites are especially abundant in the Ben Lawers Group but also occur in the Killiecrankie Schist and occasionally in the Blair Atholl Series and Ben Eagach Schist. A large outcrop forms the boundary between the Ben Eagach and Ben Lawers Schists on the eastern side of the Cairnwell Belt and can be traced across Glen Shee. Another follows the junction between the Ben Lui and Ben Lawers Schists in the south-western part of the area but also cuts right across the Ben Lawers outcrop on Meall Uaine. This may be due to intrusive linking with another running along the centre of the Ben Lawers outcrop, or alternatively to repeated folding. Other large masses occur on the south-western side of Glen Shee and along the ridge between it and Glen Fearnach. In the head of Glen Fearnach the north-eastern slope is cut by a series of sills and a large mass at the head of the Ben Lawers outcrop has been folded with its host rocks.

In the Killiecrankie Schist the epidiorite sills are especially abundant in those parts which have undergone deformation: they may well have been intruded after the recumbent folding but before the later open folding. They are well seen south of Loch nan Eun where they are thin and follow the schistosity. At the head of Glen Fearnach they are thicker and are involved in the later folding since they follow the schistosity. They are rich in unrotated garnets as are the other formations in this region. The two types of epidiorite,differing both in size and relation to the structures of their host rock, strongly suggest formation during two different periods of intrusion, one before the recumbent folding and the other after it but before the refolding. Petrographically the two kinds are similar so their original igneous natures were probably similar although they may have converged in character because of the metamorphism.

In their centres the thicker epidiorites often bear a close resemblance to normal dolerite but at their margins they grade into a hornblende schist. This is because the original igneous material has been shredded out during folding - a feature more apparent in epidiorites within the Ben Lawers Group than in the Killiecrankie Schist. It is especially well displayed on Creag Loiogte and in the lower part of Glen Fearnach. A consequence is that areas larger than the original intrusions may have been mapped as epidiorite because of their epidiorite content.

The epidiorites are recognised as sills rather than lavas because of their tendency to cut across various horizons. Contact phenomena are present on both top and bottom of the sheets.

Contact phenomena occur but are obscured by the shredding already described. They are confined to hornfelsing of the schists for short distances ranging up to a few feet according to the size of the intrusion. The effect is to reduce the amount of schistosity produced in these zones. The zones are also characterised by biotite and garnet crystals larger than those normal in the schists so these may well have originated during the thermal metamorphism.

The epidiorites are essentially plagioclase amphibolites. In the garnet zone of regional metamorphism, into which the area falls, they can be divided into two groups, according to whether or not garnet is present as described by Wiseman (1934). These can be further subdivided when either biotite or epidote or both together are present.

IV MAJOR STRUCTURES

The basic structure of the area was produced by the Caledonoid recumbent folding, which caused repetition of several formations from north-west to south-east. The key formation in the structure, the Perthshire Quartzite Series, has been particularly affected by repetition, so that it outcrops in three belts, the Ben-y-Gloe, Tummel and Cairnwell Belts.

The Tummel Belt, which in north-eastern Perthshire consists entirely of Killiecrankie Schist, is the lowest structurally, although it outcrops between the other two. It rests on the Blair Atholl Series to the north-east and forms part of the lower limb of the Ben Lui recumbent syncline. The Killiecrankie Schist is bounded on both sides by slides which cut out the flanking quartzite members of the Series.

The Tummel Belt passes to the Ben-y-Gloe Belt farther north-west by an isoclinal anticline of which the Blair Atholl Series forms the core. Across the nose of the anticline the Perthshire Quartzite Series changes in facies so that the Killiecrankie Schist is replaced by the Ben-y-Gloe Quartzite. The change, however, cannot be traced since the nose of the anticline has been eroded. The Ben-y-Gloe Belt itself forms an isoclinal synform with an envelope of Blair Atholl Series; its axial plane dips to the south-east.

From the Ben-y-Gloe Belt the Perthshire Quartzite Series passes round the nose of the Ben Lui recumbent fold to reappear in the Cairnwell Belt which lies on the upper limb of the Ben Lui Syncline. In doing so the Series passes above the exposures of the Tummel Belt. In the Cairnwell Synform the Blair Atholl Series overlies the Cairnwell Quartzite.

The Ben Lui Syncline lies above the Killiecrankie Schist of the Tummel Belt. Its core consists of the Ben Lui and the Ben Lawers Schists and its envelope of the Ben Eagach Schist and older formations. Except where the Ben Lawers Schist outcrops round the Cairnwell Synform, the core rocks trend N.W.-S.E. in contrast with the N.E.-S.W. trend produced by the Caledonoid folds. The N.W.-S.E. trend has been caused by later folds on this axis, which are superimposed on the earlier, Caledonoid folds. The N.W.-S.E. folds are chiefly found in the south-western part of the area where their axial planes usually dip to the north-east at 40°. In the south-west the Ben Eagach Schist and the Cairnwell Quartzite were brought down by synforms and the Killiecrankie Schist brought up in antiforms on the N.W.-S.E. or crossfold axis. In many of the cross folds the Ben Eagach Schist was eliminated by sliding.

In Glen Fearnach the main outcrop of Killiecrankie Schist in the Tummel Belt was affected by the cross folding so that it trends N.W.-S.E. and forms a synform, of which the Ben Lawers Schist forms the core. The axial plane of the Glen Fearnach Synform dips to the north-east at 50°; its plunge is to the south-east. On the south-western side of Glen Fearnach the main outcrop of the Ben Eagach Schist was preserved in the lower limb of the Ben Lui Fold, whereas in other parts of the area it was eliminated by the slide on the southern side of the Killiecrankie Schist.

The cross folds are ubiquitous throughout the area on the minor scale, but in the north and east they only modify the Caledonoid trend of the formations. Later Caledonoid folds are also present throughout the area on the minor scale and have most effect on the major structure in the Cairnwell Synform, where isoclinal folds cause repetition of the members of the Blair Atholl Series. The axial planes of the later isoclinal folds in the Cairnwell Synform dip to the south east at 70°; their plunge is to the north-east at low angles. The later Caledonoid folds are contemporaneous with, or slightly later than, the cross folds.

Except for the relations between the Belts of the Perthshire Quartzite Series, the generalised section across the area agrees with Bailey's sections (1925) across central Perthshire. Bailey thinks that the Ben-y-Gloe Belt forms an isoclinal antiform and so links it with the Tummel Belt by a synform, of which the Blair Atholl Series outcropping between the two belts forms the core. The Tummel Belt has then got to join the Cairnwell Belt round the apex of the Ben Lui Fold. Pantin's work on Ben-y-Gloe, however, suggests that the Ben-y-Gloe Belt is a syncline, and the small part of it in the present area also suggests that it is a syncline because of the plunge of the isoclinal folds which make up the Belt.

The synclinal interpretation of the Ben-y-Gloe Belt also agrees with Rast's interpretation at Schichallion (1957), where the refolding of Caledonoid recumbent folds by later cross folds was suggested to explain the structure. The position of the Ben Lui Syncline on top of isoclinal folds of the Blair Atholl Series and the Perthshire Quartzite Series is not affected by the relations between the various belts of quartzite.

In north-eastern Perthshire Bailey (1925) suggested that the N.W.-S.E.

trend of formations in Glen Shee could be explained by a series of Caledonoid recumbent folds which were uptilted by pitch. The recognition of the N.W.-S.E. fold system, however, provides a simpler alternative, in which the structure produced by the Caledonoid recumbent folds is similar to that of central Perthshire, and that the recumbent folds, the Ben-y-Gloe Syncline and the Ben Lui Syncline, were refolded on the N.W.-S.E. trend by the cross folds.

Recent work by Harris and Start in central Perthshire suggests that the Ben Eagach and Ben Vrackie Folds can also be explained by cross folds. Bailey, on the other hand, believes that the Ben Vrackie and Glen Fearnach Folds are parts of the same Caledonoid recumbent fold which has been uptilted by pitch between these two areas.

At Braemar the structural level is lower than in the present area so that nappes containing the Perthshire Quartzite, Blair Atholl Series and the Moine Flags are found.

The major structures can be conveniently considered in two groups. The first group consists of structures formed by the early Caledonoid recumbent folds which produced a strong axial plane schistosity. The second group of structures was developed by the later cross folds on the earlier schistosity. The later Caledonoid folds are subsidiary. These groups are approximate only for the effects of the different folds overlap in nearly every structure. For instance the structures formed by the recumbent Caledonoid folds have been modified in detail by the later movements.

The Caledonoid structures fall into four main groups according to their geographical locations and tectonic positions. From north-west to south-east and also from the bottom to the top of the structure they are:-

a) The Ben-y-Gloe Syncline

b) The Tummel Belt

c) The Ben Lui Fold

d) The Cairnwell Synform.

The cross fold structures fall into two main groups which are:-

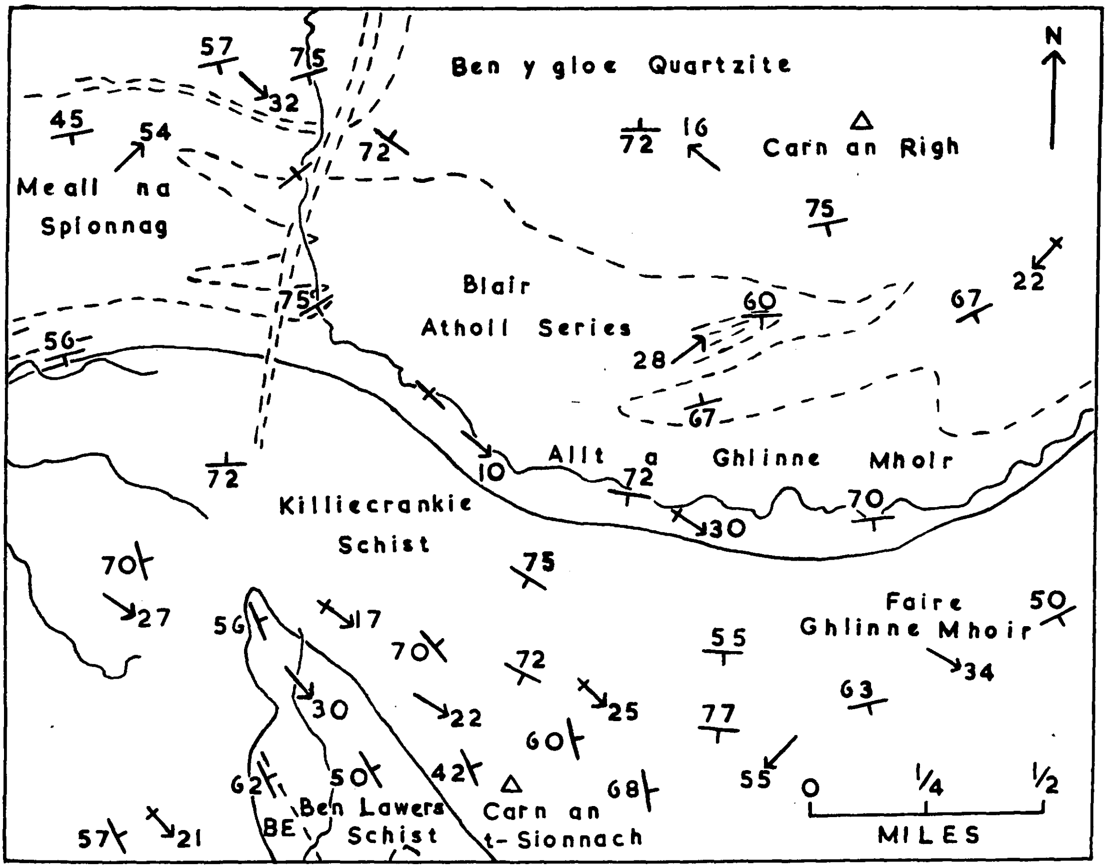
a) The South-Western Folds

b) The Glen Fearnach Synform.

The Ben-y-Gloe Syncline

The Ben-y-Gloe Quartzite is bounded on all sides by the Blair Atholl Series, with which it is in stratigraphical contact as mentioned in the section on stratigraphy. The Ben-y-Gloe Quartzite dips under the Blair Atholl Series at steep angles along most of its south-eastern boundary except on the western side of Carn an Righ, where the relations between the two formations are reversed. The dip of the Blair Atholl Series under the Ben-y-Gloe Quartzite is shown by graded bedding in the quartzite to be the original one, so that the Ben-y-Gloe Quartzite is the younger formation. The fact that most of the outcrop is overturned can be explained by assuming that in this area the two groups form the upper limb of a recumbent fold of which the Ben-y-Gloe Quartzite is the core. The Ben-y-Gloe Quartzite is relatively undeformed in this region so that observations on graded bedding are reliable in evaluating sequence. The later folding is dominantly Caledonoid and is gentle; its effects on a large scale can be

FIG. 2. MAP of GLEANN MOR.



Geological Boundaries	- - -	Strike and Dip	50
Major Slide	——	Axial Plunge	→30
Ben Eagach Schist	BE	Lineation	25

seen in the outcrops of Ben-y-Gloe Quartzite interdigitating with the Blair Atholl Series south of Carn an Righ. The recumbent Caledonoid minor folding plunges gently N.60°E or S.60°W approximately, with the direction varying. The cross folding is subordinate in this region and its chief effect is a strong lineation amounting to rodding in places running N.W.-S.E.

The outcrop of the Ben-y-Gloe Quartzite narrows considerably where the Allt Ghlinne Mhoir flows across it. Mapping reveals that the Ben-y-Gloe Belt is formed, not by one large fold, but by a series of isoclinal folds, originally recumbent but now with their axial planes dipping steeply to the south-east or south-west. The quartzite forms synforms which plunge N.60°E on the Carn an Righ side of the glen and N.60°W on the Ben-y-Gloe side; in both cases the plunge is at low angles. These plunges of the folds cause the underlying Blair Atholl Series to outcrop in the bottom of the glen except for one thin strip of quartzite connecting the Ben-y-Gloe and Carn an Righ outcrops. Stratigraphical or tectonic thinning has not affected the thinning of the outcrop because the plunge of the folds reveals that the quartzite would be present at higher levels corresponding with the outcrops on hill tops if the river had not eroded down to its present level.

South of Carn an Righ a band of limestone in the Blair Atholl Series forms an antiform which plunges N.60°E as does the synformal quartzite tongue to the south of it which forms the southern limb of the antiform.

The folds plunging N.60°E are early Caledonoid folds while those plunging at N.60°W are in the cross fold direction. The latter, however, from their style and nature appear to be similar to the Caledonoid folds and are probably Caledonoid folds which have been bent round by the later cross folding associated with the Glen Fearnach Synform. The cross folding is chiefly represented in this region by buckling and a strong lineation running N.W.-S.E. and plunging south-east which is superimposed on the earlier folds. Therefore the evidence in this small region points to the fact that the Ben-y-Gloe Belt is a synform and not an antiform as assumed by Bailey.

Throughout the rest of its outcrop towards the north-east the Ben-y-Gloe Quartzite dips under the Blair Atholl Series. The commonest structural feature is a strong rodding developed on the cross fold axis which plunges down the banding at S.45°E; corresponding folds run in the same direction but are less frequent. The Caledonoid folds, which are less frequent than the cross folds, plunge gently to both north-east and south-west.

The Tummel Belt

The Killiecrankie Schist, which forms the Tummel Belt, is bounded on both sides by major slides i.e. those which cut out formations. That on the north cuts out the Pale Blair Atholl Group all along its length although exposures are not everywhere sufficient to distinguish the subdivisions of the Blair Atholl Series. Indeed the latter formation can often only be traced through peaty hollows with sparse outcrops between the mountains formed by its neighbouring formations of the Perthshire Quartzite Series. Within the Quartzite Series itself the

Schiehallion Quartzite is missing because of sliding although in this region it forms the whole of the Ben-y-Gloe Belt which in places is only a few hundred yards away on the other side of the Blair Atholl Series.

The southern slide everywhere cuts on to the Carn Mairg Quartzite which disappears north of Ben Vrackie which is six miles to the south-west of this area. For the greater part of its length it also cuts out the Ben Eagach Black Schist which is preserved only on the south-western side of the Glen Fearnach Synform.

This lessening of the effect of a Caledonoid structure, the slide, in a cross fold which is essentially later is a curious phenomenon which calls for comment. It can best be explained on the supposition that the site of the Glen Fearnach Synform was occupied by a downwarp during the Caledonoid recumbent folding. This downwarp may have been formed by gentle folding at the very outset of the Caledonian orogeny or more likely it was a depression in the actual nappes as found in the Alps. The Ben Eagach Schist would then be protected from the main part of the shearing during the formation of the recumbent folds by its position in the downwarp. Alternatively the slide reached its maximum intensity in Glen Fearnach and cut through the Ben Lawers Schist to come in contact with one of the downfolds of the Cairnwell Belt so that the position of the main Ben Eagach outcrop is now taken by the downfold. This latter explanation appears unlikely as will be shown more fully in the section on the Glen Fearnach Synform since the minor structures in the Ben Eagach Schist indicate that this group is part of the sequence from the Killiecrankie Schist of the Tummel Belt to the Ben Lawers Schist and not a downfold terminated at either end by the plunge of the crossfolds.

The large amount of movement produced by the sliding is indicated by the fact that the Killiecrankie Group is everywhere sheared. This shearing causes the quartz crystals to break down into smaller grains while mica appears as small laths throughout the rock rather than as wide bands along the schistosity. These laths are well orientated because of the shearing and have not been refolded while all earlier structures have been destroyed. Shearing is especially developed along the northern margin and is well seen in the Allt Easgaidh which is the burn running down from Loch nan Eun to Glen Thaitneich. Here the Killiecrankie Schist is represented by a narrow belt so that the two slides are close to each other. As this belt is approached from the south signs of shearing become progressively greater through the Ben Lawers and Ben Eagach Schists until the climax is reached at the slide. As noted by Bailey, shearing and crushing are also well developed on the north-eastern side of Glen Fearnach. In the wide outcrop extending south-east of Glas Tulaichean, however, shearing is less pronounced.

The same cross fold lineation seen in the Ben-y-Gloe Belt is also well developed in the Killiecrankie Schist but is accompanied by more folding as would be expected from its less competent nature. The plunge is generally south-east. Caledonoid folding is fairly frequent in the north-eastern belt but is less so in the Glas Tulaichean outcrop and rare round Glen Fearnach especially at the head. The plunge of the Caledonoid folding is variable since there are several isoclinal crossfolds within the Glas Tulaichean outcrop while there is an open synform to the south-west. The Glen Fearnach Synform is an isoclinal syncline with its axial plane dipping north-east at 50° so here the few Caledonoid folds plunge down the dip to the north-east.

The several isolated outcrops of Killiecrankie Schist to the south-west will be treated under the section on cross folds.

The Ben Lui Fold (see Fig. 43)

This fold cannot be seen directly in north-eastern Perthshire but its presence is extrapolated from the type area to explain the stratigraphy. The Blair Atholl Series and the Killiecrankie Schist, if the complications produced by the later folds on both Caledonoid and cross fold trends are ignored, generally dip towards the south-east. South-east of the Killiecrankie outcrop but separated from it by the southern slide comes the Ben Lawers Schist, except on the south-west side of Glen Fearnach where the Ben Eagach Schist intervenes. The Ben Lawers Schist also dips south-eastwards at approximately the same angles as the Killiecrankie Schist and so passes under the Ben Eagach Schist of the Cairnwell Belt. In the south of the area, however, the Tay order prevails with Loch Tay limestone dipping under Ben Lui Schist under Ben Lawers Schist under Ben Eagach Schist. The dip increases along this north-westward traverse from 20° to the north-west until it passes through the vertical to reach 70° to the south-east.

The structure is best seen where the various groups dip under the Cairnwell Synform since the rocks of the whole south-western part of the district now lie on the cross fold trend. The key to the Caledonoid structure is given by the strip of Ben Eagach Schist preserved between the Killiecrankie Schist and the Ben Lawers Schist in Glen Fearnach. This association is similar to that of the main Ben Eagach outcrop in central Perthshire which is cut out towards the east by the southern slide. In the rest of the region this strip has been cut out by this same slide. The lenticles of quartzite contained in it are "tectonic fish" isolated during the sliding and may represent the Carn Mairg Quartzite.

The succession from north-west to south-east is therefore:- Killiecrankie Schist, Slide (usually cutting out Ben Eagach Schist), Ben Lawers Schist, Ben Eagach Schist, Cairnwell Quartzite. As all these formations dip to the south-east they must therefore form a fold with the youngest, the Ben Lawers Schist, forming the core so that the structure is synclinal. The constancy of dip on both sides of the envelope show that the fold is isoclinal and its wide extent indicates that it was essentially recumbent but in this region has been upturned by later folds.

The direction of closure of this fold is uncertain but it appears likely that it is to the north-west and the actual nose has been removed by erosion. One reason for believing this is that the core rocks, the Ben Lawers Schist, are present in great strength in the south-eastern part of the fold while only a narrow outcrop is found in the north-west. The next youngest group, the Ben Lui Schist, is never found in the north-western part of the region but covers a wide area in the south-east. The Ben Lui Schist which must form the core of a syncline within the Ben

Lawers Schist is found only in the south-east and so the closure of the fold would be expected to lie to the north-west where the oldest envelope rocks are found. The fact that the Ben Lui Schist is involved in a recumbent syncline closing to the north-west brings to mind that the Ben Lui Fold itself is a similar structure which can be traced across the Highlands to eastern Perthshire. The part of the fold found over most of the Glen Shee area is one involving older rocks than at Ben Lui, with Ben Eagach Schist closing round Ben Lawers Schist instead of the latter closing round Ben Lui Schist.

The earliest folds seen in the minor structures of the area are recumbent folds which correspond to the Ben Lui Fold. These often show signs of sliding on the lower limb which is similar to the cutting out of the quartzitic members of the Perthshire Quartzite Series and the Ben Eagach Schist in the lower limb of the Ben Lui Fold.

The nose of the Ben Lawers Schist is much more elongated than that of the Ben Lui Schist when judged by extent of outcrop. In places it is very thin as can be gauged by the close juxtaposition of the Killiecrankie Group and Cairnwell Belt outcrops between Glen Shee and Glen Fearnach.

The Cairnwell Synform

This structure is unique in the Central Highlands in that the Blair Atholl Series is found detached from the main outcrop. The Cairnwell Quartzite which forms the envelope of the Blair Atholl Series is also found in no other region. The Ben Eagach Schist should also be considered as part of the Cairnwell Synform since it lies above the

Ben Lawers Schist which forms the core of the Ben Lui recumbent syncline. The structure is termed a synform because it takes the form of a downfold but is in fact an inverted anticline since the oldest rocks present, the Blair Atholl Series, form the core. The synform itself is formed by a series of isoclinal late Caledonoid folds, both synforms and antiforms with several cross folds complicating the outcrop.

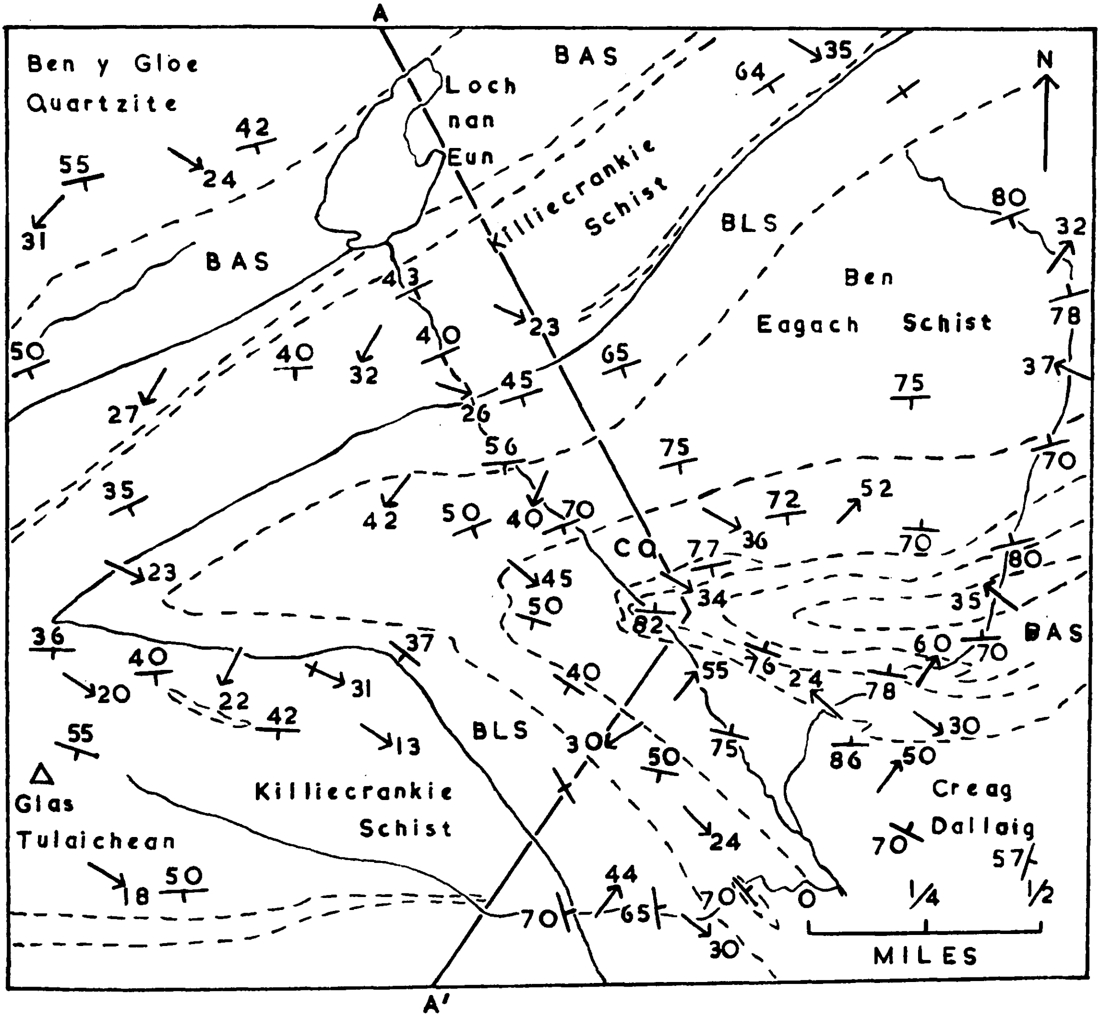
The fold is bounded on its eastern side by narrow belts of Ben Eagach Schist and Cairnwell Quartzite which dip at approximately 70° to the east-south-east. That this dip has been overturned relative to that of the Flat Belt can be deduced by a traverse towards it from the south-east over younger groups. As the Flat Belt is itself inverted this overturning of the dip means that the rock succession is now the right way up. Starting at the south-eastern boundary of the Ben Lawers Schist the dips are as low as 20° to the north-west. The dip rapidly steepens so that at the north-western boundary of the Ben Lawers Schist it reaches as much as 70° to the north-west. A belt of epidiorite then intervenes and the dip in it passes through the vertical so that the following Ben Eagach Schist generally dips at 70° to the east-south-east, although there are still some dips to the north-west. This variation is caused by isoclinal folding of late Caledonoid type which causes the direction of dip to change gradually over a wide area. Fold axes generally plunge north-north-east to north-east at low angles with a corresponding "b" lineation. Cross folds also with a "b" lineation plunge steeply down the dip.

The phenomenon of a series of steep isoclinal folds forming a structure, which like the synform is essentially flat on the larger scale, is similar to Barrow's concertina folds but in fact affects all the groups present though their behaviour varies according to their competence. The isoclinal folds can be seen to refold recumbent folds whose axial planes are coplanar with the schistosity.

The minor structures show the same relations on the north-western side of Glen Beag as far as the Carn Mor granitic intrusion which cuts across the Cairnwell Synform. North-west of the granite the outcrop of the fold trends on N.W.-S.E. axis as far as the western side of Glen Thaitneich. Here the rocks of the Cairnwell Synform have been folded together with the underlying Ben Lawers Schist and Killiecrankie Group.

The structure in this region has been shown by Bailey to be a synform on his recognition of the Killiecrankie Schist as a separate Group and his tracing of the Ben Lawers and Ben Eagach Schists round the nose of the Cairnwell Quartzite at the head of Glen Thaitneich. The Geological Survey had previously linked the Blair Atholl Limestone exposed in the Allt Easgaidh with the Ben Lawers Schist found north of the summit of Glas Tulaichean, thus cutting through the Cairnwell Quartzite and Ben Eagach Schist. Both the latter, however, are poorly exposed because of a thick covering of peat. The connection of the two calcareous groups was presumably made because all the formations dip to the south at angles ranging from 40° on Glas Tulaichean to near vertical in the Allt Easgaidh. Bailey, however, showed that the two calcareous outcrops were distinct lithologically and could easily be

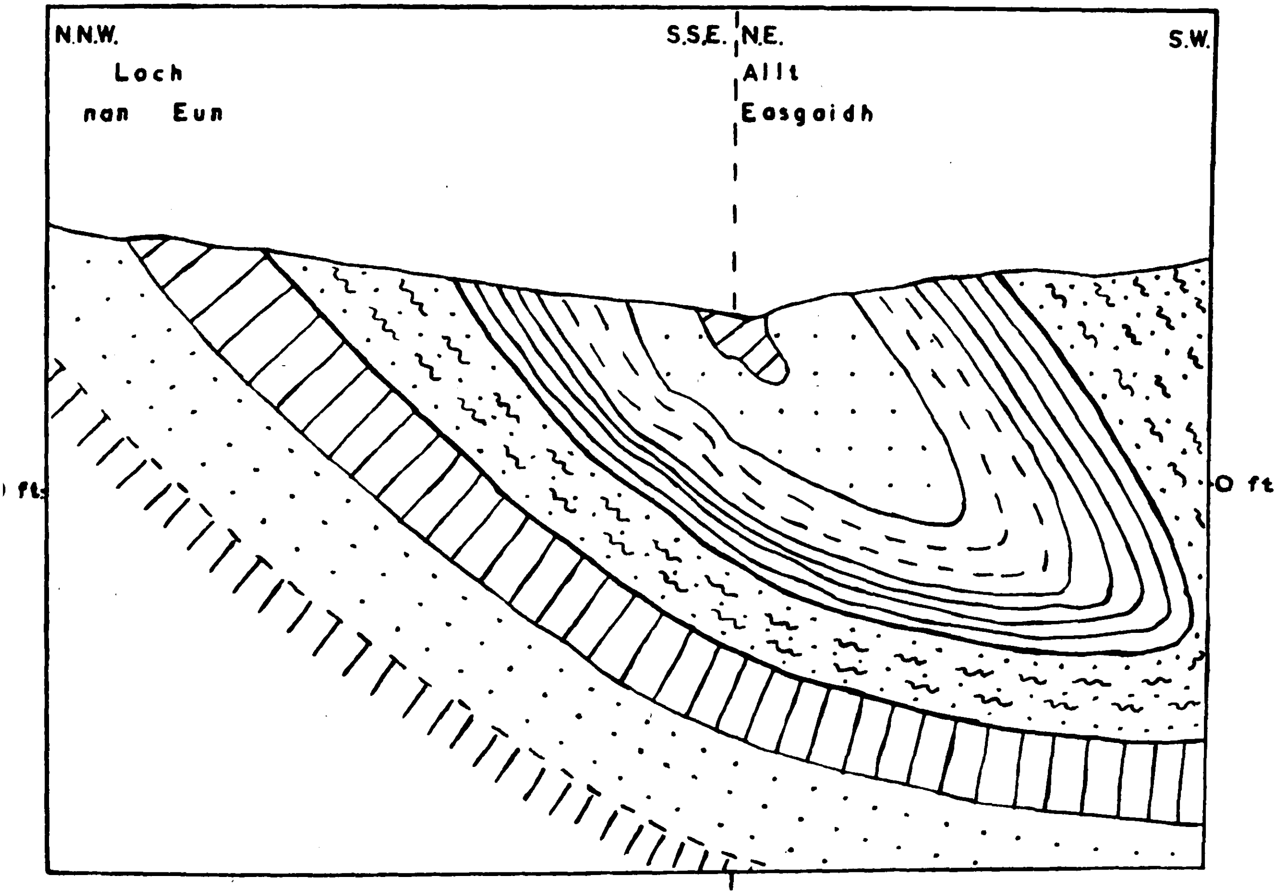
FIG. 3. MAP of GLAS TULAICHEAN.



Geological Boundaries	- - -	Strike and Dip	50
Major Slide	——	Axial Plunge	30
		Lineation	25

Ben Lawers Schist	BLS
Cairnwell Quartzite	CQ
Blair Atholl Series	BAS

FIG. 4. SECTION of GLAS TULAICHEAN SYNFORM along A–A'.



LEGEND for ALL SECTIONS.

Igneous Rocks
Hornblende Schist

Ben Lui Schist
Ben Lawers Schist
Ben Eagach Schist
Killiecrankie Schist
Cairnwell and Ben-y-Gloe Quartzites
Blair Atholl Series

Geological Boundaries
Major Slides
Faults
Inferred Boundaries

Horizontal Scale 1 in.=2000 ft.
Vertical Scale 1 in.=2000 ft.

assigned to their respective horizons.

The trend of the cross folds is consistently near 120° but the plunge steepens with the dip from 20° on Glas Tulaichean to 50° in the Allt Easgaidh. The late Caledonoid folds likewise vary from 30° to 70° but their plunge is usually towards the south-west. In the Allt Easgaidh both sets of folds developed contemporaneously in that one does not refold the other and one cannot be unfolded to leave the other undisturbed. Both however fold recumbent folds whose axial planes are parallel with the schistosity.

The main trend of the synform is on the cross fold axis but swings in the distribution of the formations show that Caledonoid folding has also played a part, so that the trend of the synform is more E.-W. than N.W.-S.E. The combination of south-westerly plunging Caledonoid folding and east-south-easterly plunging cross folds has produced subsidiary synforms and antiforms within the major structure. These form gentle culminations and depressions but lead to the lensing of individual outcrops e.g. the central limestone of the Blair Atholl Pale Group found in the Allt Easgaidh. The distribution of formations produced by these sets of folds shows that on the major scale they are contemporaneous although they may have persisted for different periods in different areas and so one or other may be dominant in a particular sector of the synform. Both, however, are always found on the minor scale.

The subdivisions of the Blair Atholl Series cannot be traced across the Carn Mor Porphyry to the main outcrop of the Cairnwell Synform because exposures on either side of the intrusion are extremely poor.

On the north-eastern flank of the Cairnwell Synform, the angle of dip in the northern part of the Ben Eagach Schist remains fairly constant at 50°, but swings to south-south-east. In the southern part of the schist and in the Cairnwell Quartzite, however, the dip steepens and overturns so that on Carn a' Geodh, where the outcrop widens considerably, the quartzite overlies the Blair Atholl Series.

At the Cairnwell the northerly dip persists except at the eastern end where the dip swings to the west at 40°. Variations in the dip across the Cairnwell outcrop show that the quartzite has been affected by isoclinal folds on the W.N.W.-E.S.E. trend. The plunge of the cross folds is at approximately 40° to the west-north-west so the Cairnwell is a subsidiary synform on the W.N.W.-E.S.E. axis overlying the Blair Atholl Series of the main Cairnwell synform. Nearly the whole outcrop forms the southern limb of the subsidiary synform with the northern limb represented by a narrow belt linking it to the sinuous outcrops of quartzite round Loch Vrotachan.

The thickening of the quartzite outcrop on Carn a' Geodh and the Cairnwell is probably due to movement during the recumbent folding. Much of the narrow outcrop which forms the main part of the belt has been thinned tectonically; that sliding has occurred can be seen by the juxtaposition of the Cairnwell Quartzite with different members of the Blair Atholl Series both in Glen Beag and at the head of Glen Thaitneich.

North-eastwards the Cairnwell Synform persists until it is truncated by the Lochnagar Granite but it fails to reappear on the far side of that intrusion.

To the south-west the Cairnwell Synform is terminated by the combination of an antiform of the cross fold axis and the north-easterly plunge of the Caledonoid folds. The Caledonoid plunge is most effective east of Glen Beag and is reflected by the shape of the outcrops. The plunge is 20° to the north-north-east while the dip varies between 50° and 70° to the east-south-east. On the western side of Glen Beag, however, the dip is 25° to the north-east while the Caledonoid plunge remains the same as on the eastern side. The cross folds plunge to the east-south-east at 10° to 15° whereas farther east they plunge steeply down the dip at 50° to 70° to the east-south-east. The same dip to the north-east persists right across the Ben Eagach Schist outcrop on the south-west side of Glen Shee but increases to 40°. That the antiform is in fact formed of several isoclinal bands is shown by the repetition of downfolds of quartzite found on top of Ben Gulabin. These plunge to the east-south-east and the ones disconnected from the main quartzite outcrop are terminated by the cliffs on the south-eastern side of the hill. The largest is connected to the main outcrop by a similar downfold on the Caledonoid trend. Here again we have the effects of both sets of later folds combining to produce complicated outcrops.

Proceeding north-eastwards to Creag Lemhaich on the east side of Glen Thaitneich the dip has steepened to 50° to the north-east and the cross folds plunge east-south-east at 20° - 30°. This plunge carries

FIG. 5. MAP of CREAG LAMHAICH.

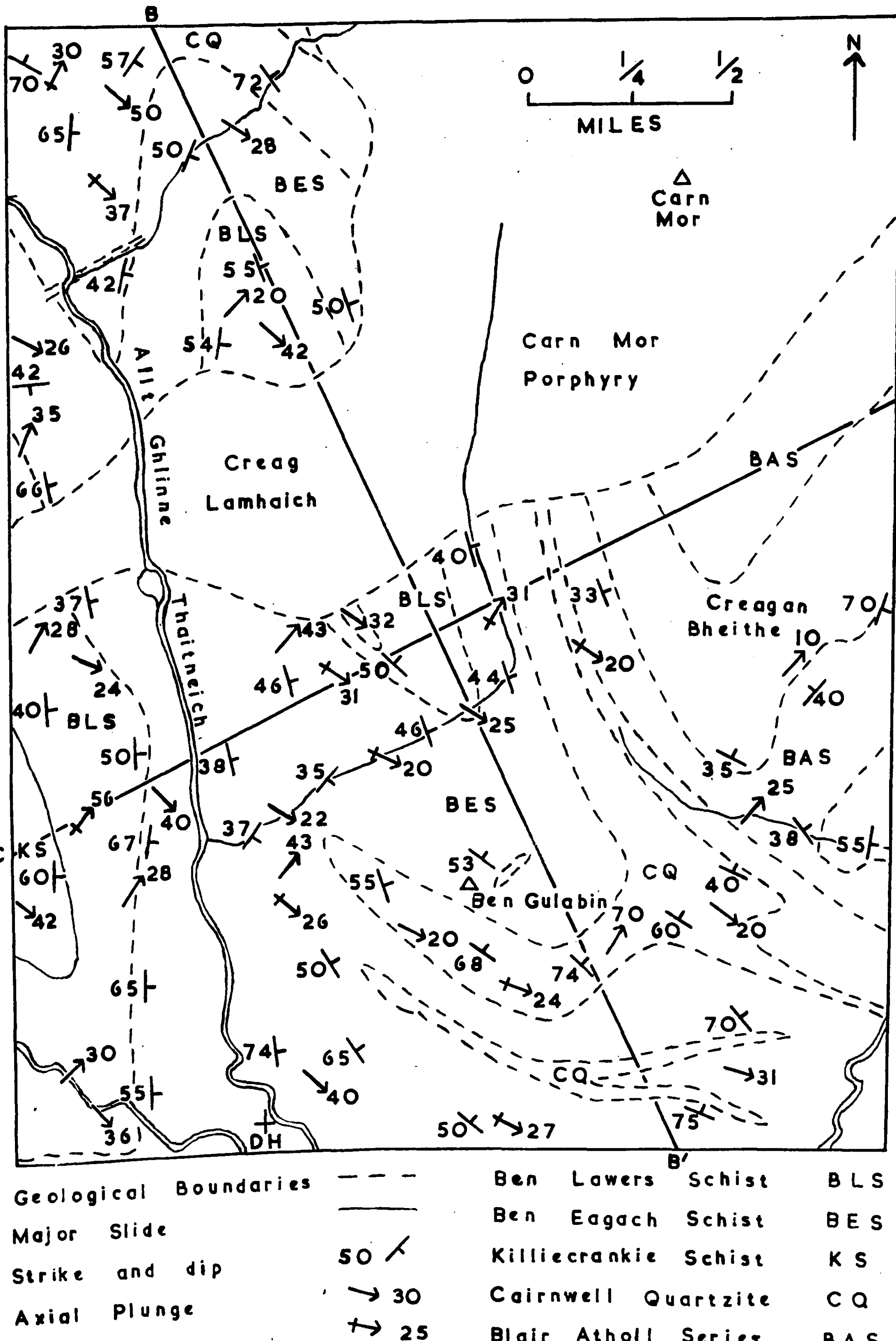


FIG. 6. N.W.–S.E. SECTION of CREAG LAMHAICH along B–B'.

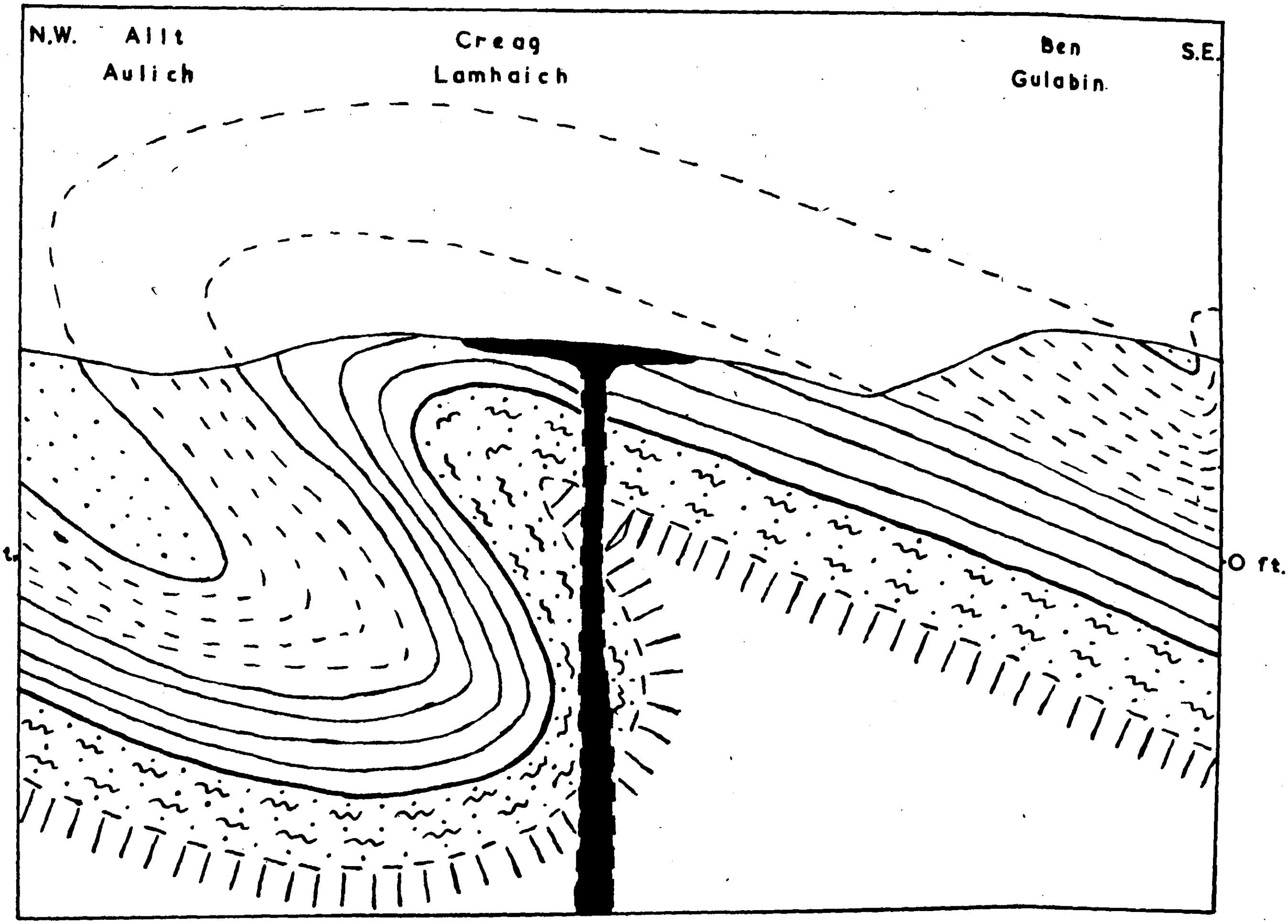
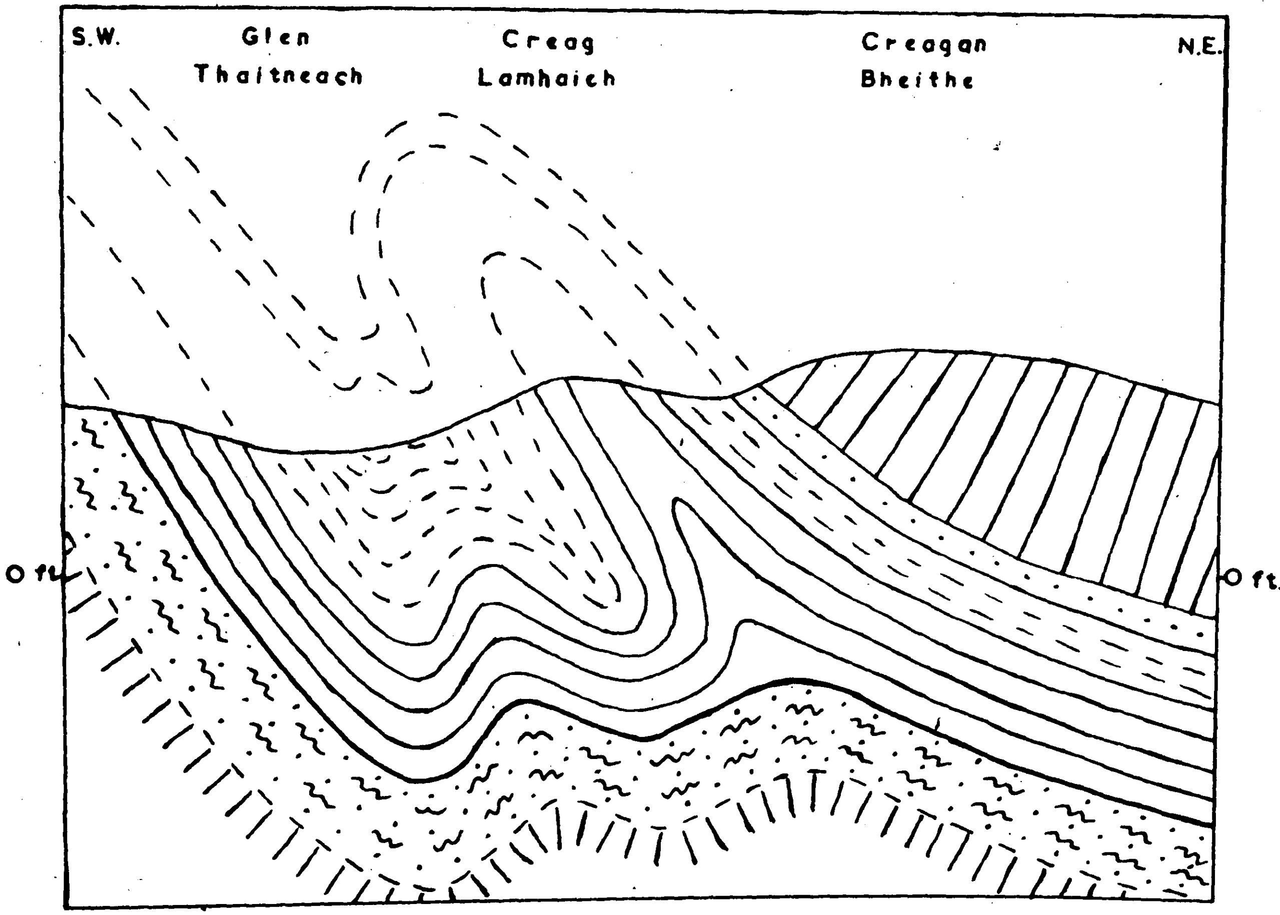


FIG. 7. N.E.–S.W. SECTION of CREAG LAMHAICH along C–C'



the outcrop of Ben Lawers Schist on top of the hill under the Ben Eagach Schist which forms the greater part of its surface. The Caledonoid folds plunge north-north-east at 40^{o}. At the northern end of the Ben Lawers outcrop, across the Carn Mor Porphyry, the same structures are seen but neither set of folds can cause either the termination of the Ben Lawers outcrop or the swing of the Cairnwell Quartzite to a position in the Allt Ghlinne Thaitneich, to the west of, and 1,000 feet below the Ben Lawers Schist of the Creag Lamhaich outcrop.

An isoclinal cross fold would imply that the Ben Lawers Schist forms a "tectonic fish" since the south-easterly plunge would carry it above the Ben Lawers Schist at the north-western end and below it in the south-east. The cross folding, however, does not appear to have been strong enough to produce that type of structure. A later Caledonoid fold would have caused the strikes to assume Caledonoid trend but they are dominantly N.W.-S.E. Therefore the only possibility left is a Caledonoid fold connected with the recumbent folds but not necessarily itself recumbent. This structure, formed as a drag fold below the Cairnwell Quartzite, would account for the relative positions of the various groups and would agree with the minor structures which show recumbent Caledonoid folding refolded by cross folds. Late Caledonoid folds take the form of gentle buckles. The cross folding on the major scale then folded the early Caledonoid fold into an isoclinal antiform to give the enclosure of the Ben Lawers outcrop by the Ben Eagach Schist, carrying it under the Ben Eagach Schist to the south by an east-south-east plunge. That the drag fold is local is shown by the fact that no trace of it can be seen in the outcrop of Ben Lawers Schist on the west side of Glen Thaitneich.

The South-Western Folds

Although cross fold structures have been considered with the Cairnwell Synform the south-western area is almost exclusively formed by the superposition of cross folds on the recumbent Caledonoid folds. The region is one of isoclinal cross folds which bring up the Killiecrankie Schist of the lower limb of the Ben Lui Fold in the cores of antiforms and bring down the Cairnwell rocks of the upper limb in the cores of synforms. Over the greater part of the region the Ben Lawers Schist outcrops, forming the extended core of the Ben Lui Fold. The Killiecrankie Schist appears only in the more northern part of the region while the Cairnwell rocks predominate in the south but also extend into the north.

The Killiecrankie Schist of the Glas Tulaichean outcrop, as shown earlier, dips to the south and south-east in its northern part. Farther south it continues to do so for the greater part of the outcrop but is modified towards the boundaries of the group in Glen Thaitneich and Glen Lochsie.

In Glen Thaitneich the dip of the Killiecrankie Schist together with the overlying Ben Lawers and Ben Eagach Schists is to the east or east by north at 55° though locally it may range down to 30° and up to 70°. The Caledonoid plunge is approximately 30° to the north-east and the cross fold plunge 40° to south-east by east. The dip and

FIG. 8. MAP of SOUTH-WESTERN FOLDS of KILLIECRANKIE SCHIST and CAIRNWELL QUARTZITE.

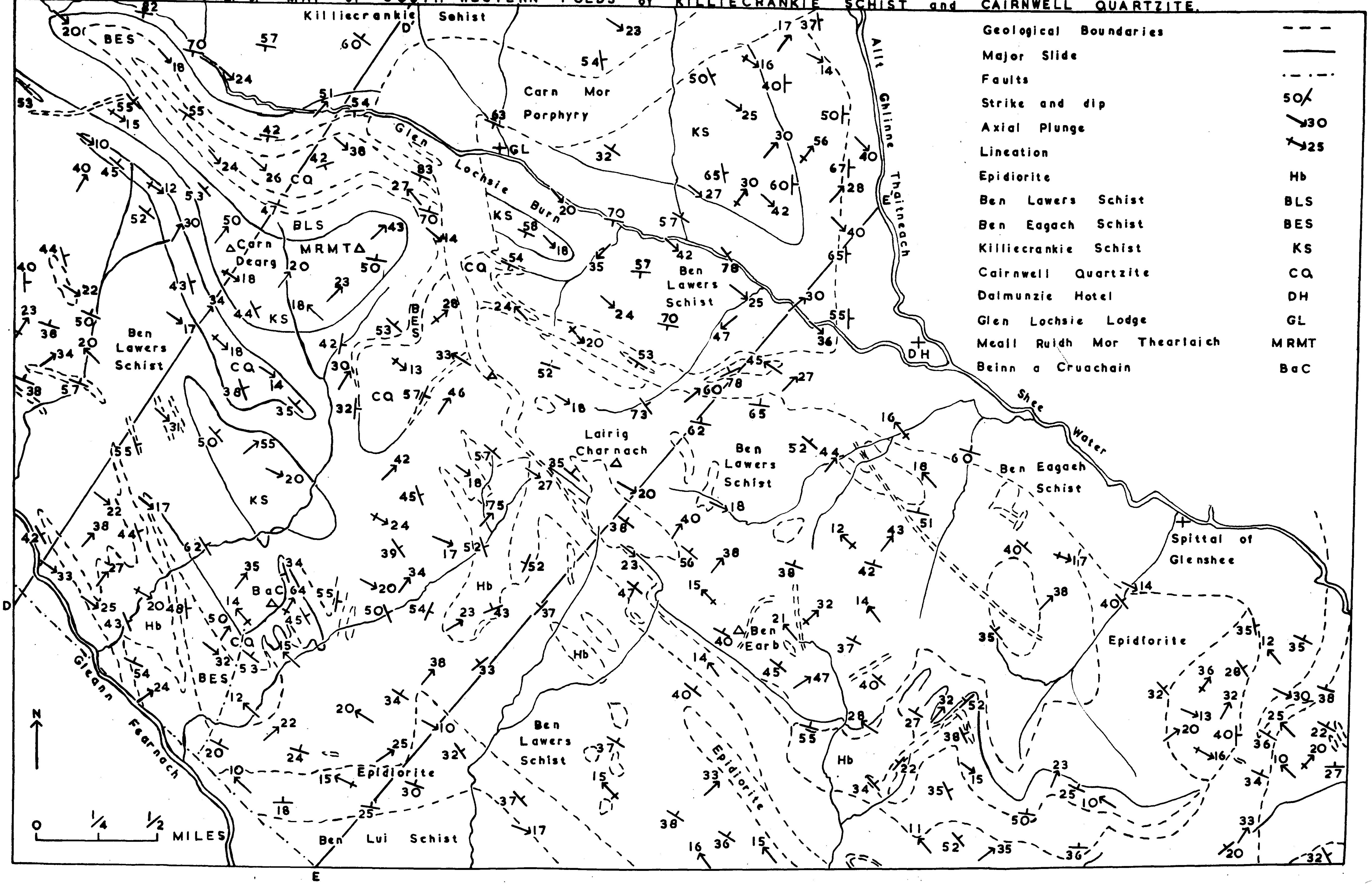


FIG. 9. N.E.–S.W. SECTION of SOUTH-WESTERN FOLDS along D–D'.

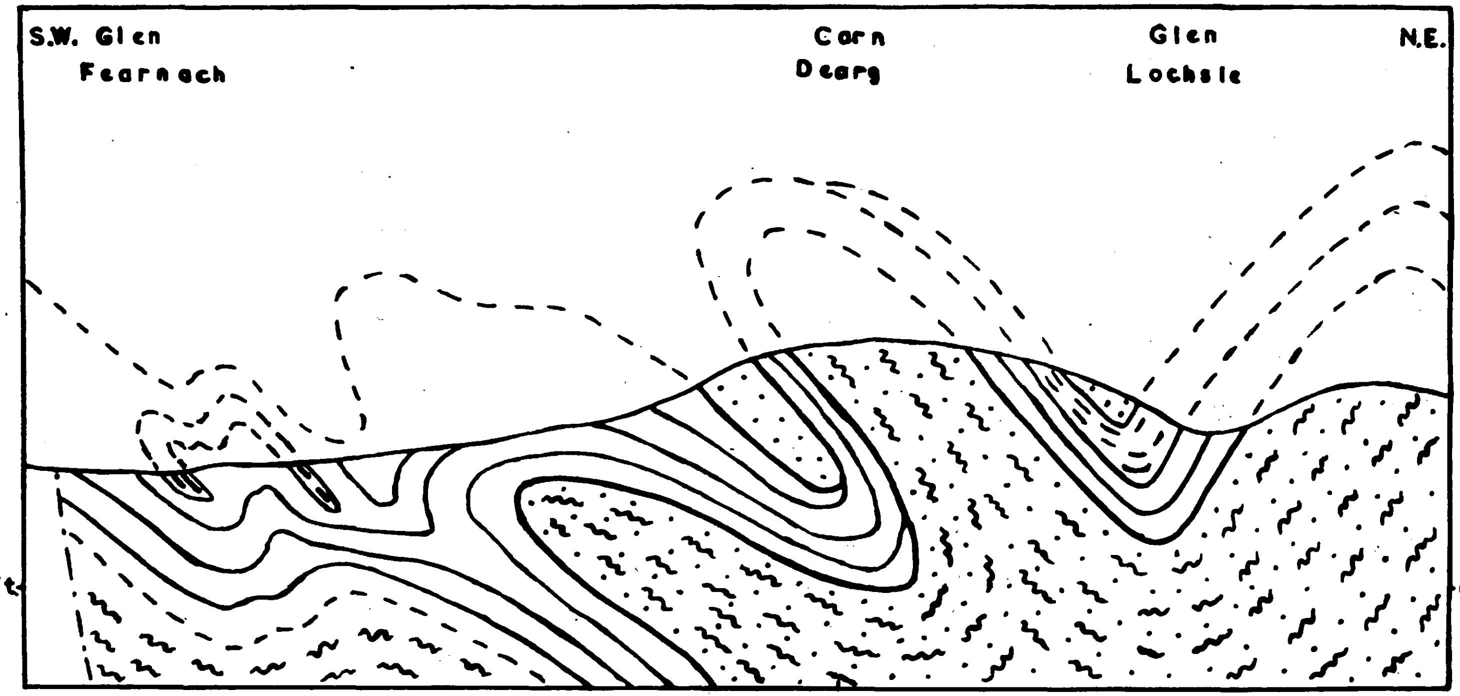
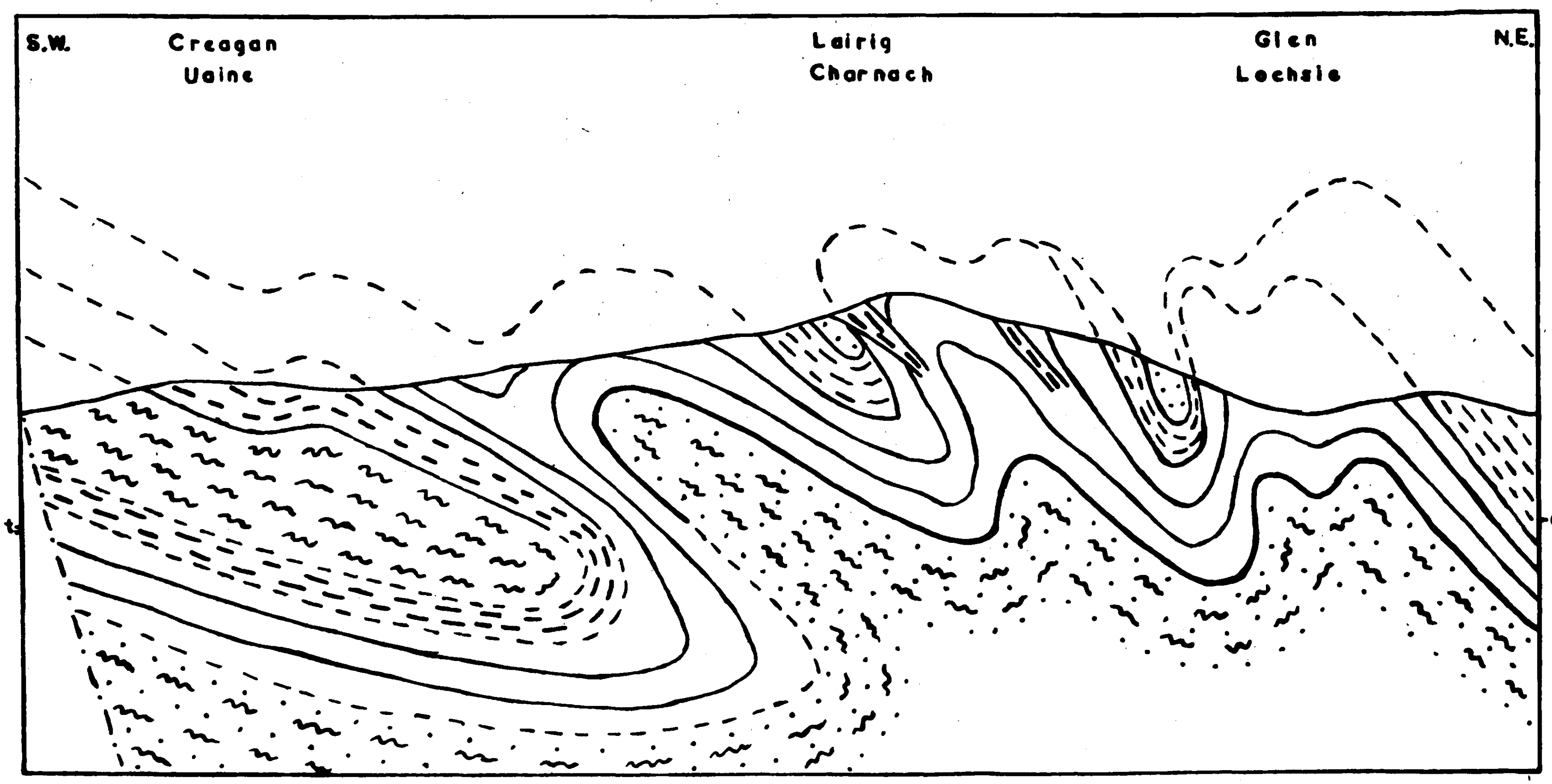


FIG. 10. N.E.–S.W. SECTION of SOUTH-WESTERN FOLDS along E–E'.



plunges hold over most of the nose of the Killiecrankie Schist on Creag a' Chàise and the cross fold plunge is responsible for carrying the group under the Ben Lawers Schist. On Creag Bhreac just to the north-west the strike swings round to N.W.-S.E. so that the dip is now 50° to the north-east. The Caledonoid plunge runs approximately down the dip while the cross fold plunge is at 15° - 20° to the south-east by east. It may be even less where the dip is less. This low plunge is partly responsible for the wide extent of the Killiecrankie Schist outcrop in this region but repetition by recumbent Caledonoid folds probably also plays a part. West of Creag Bhreac the dip is 45° to the south with Caledonoid plunge 35° to the south-west and cross fold plunge 20° to the south-east by east. The charge in dip and Caledonoid plunge indicates that there must be an antiform within the Killiecrankie Schist with a complementary synform to the north to bring the northerly dip back to the general southerly dip found in the synform at the head of Glen Thaitneich. This in turn means that there must be an isoclinal antiform between these two synforms. All these folds are on N.W.-S.E. axis approximately. The Ben Lawers Schist on the west side of Glen Thaitneich dips under the Ben Eagach Schist at 50° - 65° to the east or east-north-east with cross fold plunge at 25° to the south-east. This structure is also found in the marginal parts of the Killiecrankie Schist.

Towards Glen Lochsie the southerly dip of the Killiecrankie Schist steepens through 70° to the vertical to bring down the overlying Ben Lawers Schist in the floor of the glen. The cross fold plunge is

25° - 30° to the east-south-east and the Caledonoid 50° to the south-west. West of the Carn Mor Porphyry the dip once again diminishes in the Ben Lawers Schist and succeeding Ben Eagach Schist and Cairnwell Quartzite until it is 35° - 40° while the cross fold plunge also drops to 20° but is still to the east-south-east. On the southern margin of the quartzite, however, the dip is 50° to the north-north-east so that the Ben Eagach, Ben Lawers and Killiecrankie Schists reappear to form an open synform. To the north-west the exposures are very poor but the nose of the fold can be traced and here the dips steepen to 50° - 70° on both sides of the fold. The steepest dips are once again found in the envelope but the cross fold plunge remains at 20° to form the closure of the fold by the Killiecrankie Schist. The synform, however, can be traced farther north-west by the dips within the Killiecrankie Schist. Towards the south-east also the dips in the fold increase to 70° and and the predominant cross fold plunge is 15° - 20° to the west-north-west thus indicating closure in that direction, but the actual nose of the synform is cut off by the extension of the Carn Mor Porphyry.

East of the intrusion the southerly dip in the Ben Lawers Schist continues farther south so that an isoclinal antiform of Killiecrankie Schist outcrops on Creag Chreumh. This outcrop dips to the south-south-west at 55° with Caledonoid plunge at 45° to the south-west. The cross fold plunge is 20° to the south-east by east and this carries the Killiecrankie Schist under the Ben Lawers Schist to the east.

South-west of the Killiecrankie Schist appears a small isoclinal synform of the Ben Eagach Schist and the Cairnwell Quartzite, which in turn is succeeded to the south-west by an open synform similar to that of Upper Glen Lochsie. The dip is 55° to the north-north-east at the southern boundary of the Ben Eagach Schist which therefore overlies the Ben Lawers Schist to the south-west. The Cairnwell Quartzite fails to the south-east because of cross fold plunge at 20° to the west-north-west but the belt of Ben Eagach Schist continues to join the main Glen Shee outcrop just west of Dalmunzie. There is a small lenticle of quartzite enclosed in the Black Schist outcrop on the north-east slope of Meall a' Choire Bhuidhe half way between the previous locality and the main Ben Eagach outcrop.

Just before the belt of Ben Eagach Schist reaches the main outcrop in Glen Shee the belt widens and in it is enclosed another larger lenticle of quartzite whose sinuous outcrop shows that it has been affected by both cross and Caledonoid folds.

The dips rangs from 70° to the vertical chiefly to the south-south-east on the northern side and north-north-west on the southern side although the strike swings to W.N.W.-E.S.E. in the middle of the outcrop because of folding. The structure is therefore a syncline with a vertical axial plane. The outcrop terminates to the east with a crossfold plunge to the north-west at 40° and to the west with Caledonoid plunge to the north-east at 30°.

To the south-west of this open synform of Cairnwell rocks all the formations dip to the north-east with dips ranging from 40° to 65°. The strike also swings slightly. On Meall Ruidh Mor Thearlaich and Carn Dearg to the south-west of the synform in Upper Glen Lochsie an outcrop of Killiecrankie Schist dips north-east at 50° with a Caledonoid plunge of 40° to the north-north-east. This outcrop connects with the main outcrop of Killiecrankie Schist round the nose of the Glen Lochsie Synform. The cross fold plunge of 30° to the south-east carries the Killiecrankie Schist under an outcrop of Ben Lawers Schist brought down by a Caledonoid synform in which the Cairnwell rocks reappear. Near the boundary some of the Killiecrankie Schist also dips in the same direction as the cross fold plunge.

The Caledonoid downfold causes the quartzite outcrop to swing from N.W.-S.E. along Glen Lochsie to run south-west through Carn Tarmachain. Here the dip is 50° to the north-north-east with the Caledonoid plunge 30° to the north-east and the cross fold plunge 20° to the south-east. On the south-eastern side of the fold the dip is 65° to the north-west and the cross fold plunge 40° to the west-north-west so that the fold is open. South-westwards towards the nose of the fold the Ben Eagach Schist fails. At the nose the dip on the western side is east-north-east at 35° and the cross folds plunge 20° to the south-east, but on the south-eastern side the dip is 55° to the east-south-east. The beds on the south-eastern side are therefore overturned so that the fold becomes nearly isoclinal. The Caledonoid plunge remains 25° - 30° to the north-east. Bailey (1925) continued the Cairnwell outcrop of Carn Tarmachain to the south to link up with that found on Ben a' Gruachain, but no evidence can be found in support, although there are no exposures just north of Ben a' Cruachain because of peat. The northern part of Bailey's continuation, however, consists of well developed Ben Lawers Schist with no trace of quartzite or Black Schist.

The Geological Survey on the other hand linked the Carn Tarmachain outcrop with the quartzite of Carn Dearg on the other side of Allt Ruidh nan Eas. These outcrops would appear to be linked because of the low south-easterly pitch of the Carn Dearg outcrop, but the valley descends to a low structural level so that only Ben Lawers Schist is exposed in it.

On Carn Dearg the Cairnwell Quartzite which forms an escarpment dips at 35° - 40° to the north-east with the Caledonoid plunge running down the dip. The cross fold plunge is at 10° - 15° to the south-east by east and terminates the outcrop to the south-east where the level of the quartzite has been cut through by the Allt Ruidh nan Eas. At the north-west end the same plunge causes the outcrop to rise above the Ben Lawers Schist, the Ben Eagach Schist being cut out by a slide all round this outcrop. Another small lenticle of the quartzite is found on the next hill slope to the north-west across a small intervening burn which has eroded through the quartzite to the Ben Lawers Schist. The cross fold plunge at 12° to the south-east also causes this outcrop to fail to the north-west.

The extreme attenuation of the Ben Lawers Schist in the upper part of Glen Fearnach is shown by its close proximity to the Killiecrankie Group which is only fifty yards away from the quartzite. The Ben Eagach Schist has been removed by sliding between the Ben Lawers Schist and both of the Perthshire Quartzite Groups. South-west of and below the Carn Dearg escarpment of Cairnwell Quartzite there is another patch of poorly exposed Killiecrankie Schist with similar minor structures.

Just above Glen Fearnach stands the mountain of Ben a' Cruachain which is yet another area formed of downfolds of Cairnwell rocks. They are well exposed so that several minor synforms can be distinguished. The Ben Eagach Schist is well developed on the south-western side of the outcrop but is missing on the north-eastern inverted limb of the synform, probably due to the greater amount of movement there during the cross folding. It is also preserved in one of the antiforms between two synforms of quartzite.

The Ben a' Cruachain outcrop is divided into two parts by a curving north-north-east fault which only causes slight displacement of the stratigraphical groups. The part to the north-west of the fault consists of one synform of Cairnwell rocks which can be traced north-west across the Allt Ruidh nan Eas. The dip is 60° to the east-north-east with the Caledonoid folds plunging to the north-east at 40°; the cross folds plunge at 15° - 20° to the south-east and cause the outcrop to terminate to the north-west. On the south-eastern side of the fault, however, the strike has swung to W.N.W.-E.S.E. so that the cross folds are now plunging at 15° to the north-west causing the outcrop to rise above the Ben Lawers Schist to the south-east. The quartzite outcrop does not reach the crest of the hill so the south-easterly plunge again controls the outcrop to bring up the Ben Lawers Schist on the north-western slope. The straight north-western boundary between the Ben Lawers Group and the quartzite hints at a N.W.-S.E. synform. The repetition of folds causes variations in dip; all the dips are steep, generally to the north-east; but the most easterly fold is open so that the eastern margin of the quartzite dips to the west-south-west. The dip soon, however, returns to the north-east on the far side of an antiform of limestone within the Ben Lawers Group. To the east of this limestone there is another lenticle of impure quartzite.

Bailey(1925) connected the north-western end of the Ben a' Cruachain outcrop of quartzite by a loop with the Carn Dearg outcrop. This link would need to run obliquely to the strike of and cut through limestones developed in the Ben Lawers Group and in fact no quartzite is to be found in the region.

The ridge between Glen Shee and Glen Fearnach is formed of a belt of Cairnwell Quartzite with Ben Eagach Schist on its south-western margin. The Ben Eagach Schist has been cut out by sliding to the north-east but a belt of it runs from the south-eastern end of the quartzite outcrop to link with the Cairnwell outcrop well developed in Glen Shee. There are also a few lenticles of Blair Atholl limestone enclosed in the quartzite. The dip is generally between 40° and 50° to the north-east with the Caledonoid plunge at 30° - 40° to the north-east by north. The cross fold plunge may be locally to the north-west but is generally to the south-east at low angles; it causes the outcrop to terminate in the north. The major structure is therefore a synform on N.W.-S.E. axis with south-eastern plunge; the Ben Eagach Schist and Cairnwell Quartzite form the core and the Ben Lawers Schist the envelope. The structure is similar to that found farther north-west but is less complex in outcrop. The dip and minor structures are similar in the

Ben Eagach outcrop running down to Glen Shee, which is an open synform on the Caledonoid axis, preserving the overlying Ben Eagach Schist within the Ben Lawers Group. The cross fold plunge is at low angles to the south east on its north-western side and to the north-west on its south-eastern margin. The north-western plunge combined with the Caledonoid plunge to the north-east causes the termination of the outcrop of Cairnwell rocks to the south-east. If the belt were part of a recumbent Caledonoid fold the rocks would strike N.E.-S.W.

In the south-east of this region the Ben Lui Schist dips at 20° to the north-west with the Caledonoid plunge running north-north-east at low angles and the cross plunge in a direction somewhat more westerly than the dip. In the Ben Lui Schist of Glen Fearnach the dip swings round so that it is north-east with the Caledonoid plunge approximately down the dip and the cross folding gently to the east-south-east. Between these two areas while the strike swings round, the cross fold plunge is north-westerly so that on both dip and plunge the Ben Lui Schist is carried under the Ben Lawers Schist. The beds are therefore inverted similar to those described at the corresponding tectonic level on the south-east of the Cairnwell Synform.

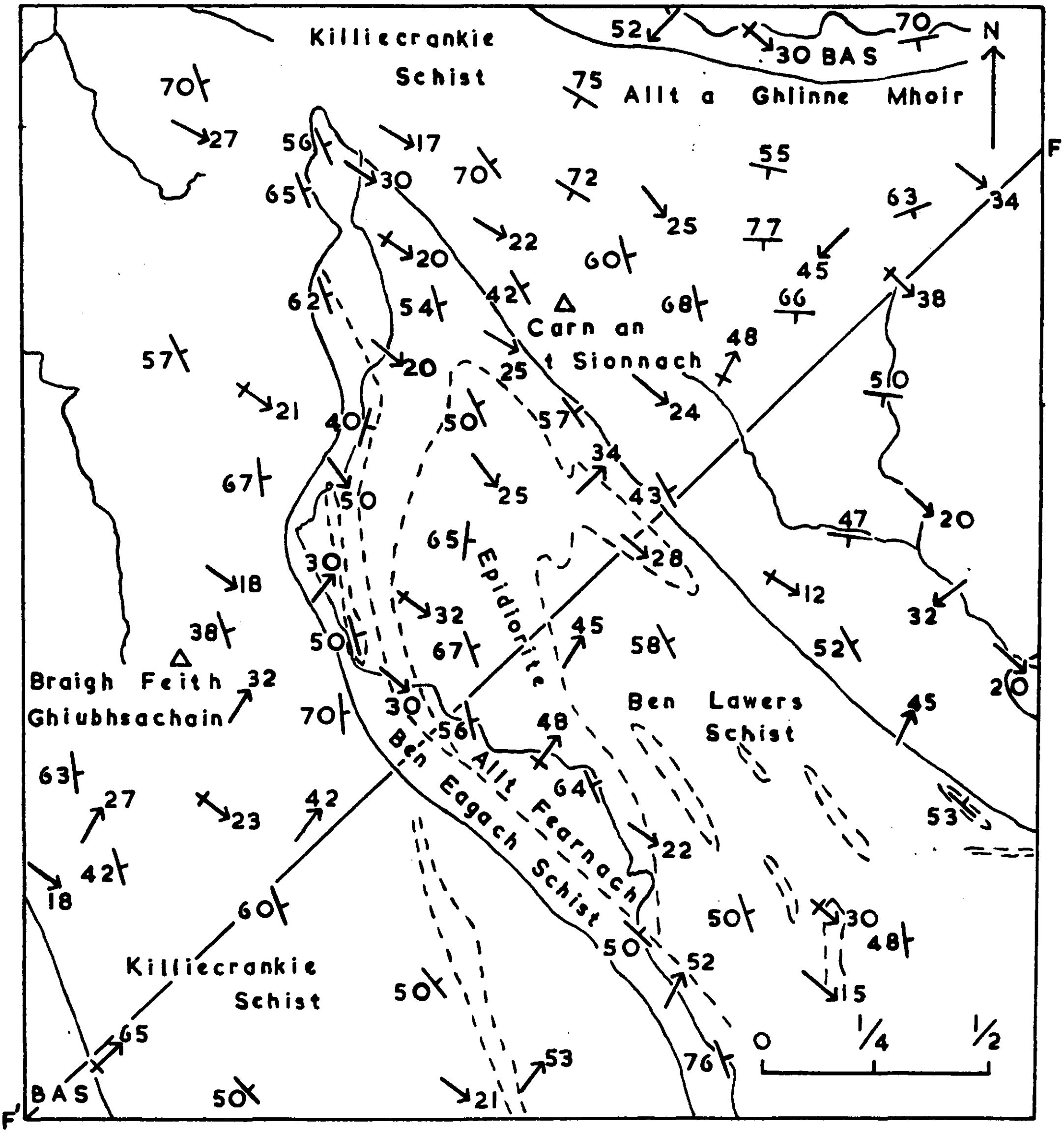
Just south of Ben a' Cruachain the strike of the Ben Lui and Ben Lawers Schists swings to W.N.W.-E.S.E. and the dip is 30° to the north-north-east. The Caledonoid plunge is 20° to the north-east and the cross folds plunge at 10° - 15° to the north-west. The north-westerly plunge is similar to that seen in the Cairnwell rocks on Ben a' Cruachain itself and also at the most southern outcrop of the Ben

Lawers Schist. The swing in strike occurs just before the Glen Fearnach Fault is reached and is probably the beginning of a greater swing to join up with the formations on the south-western side of the fault which dip at 35° to the north-west. The actual swing cannot be traced because of the fault.

The Glen Fearnach Synform

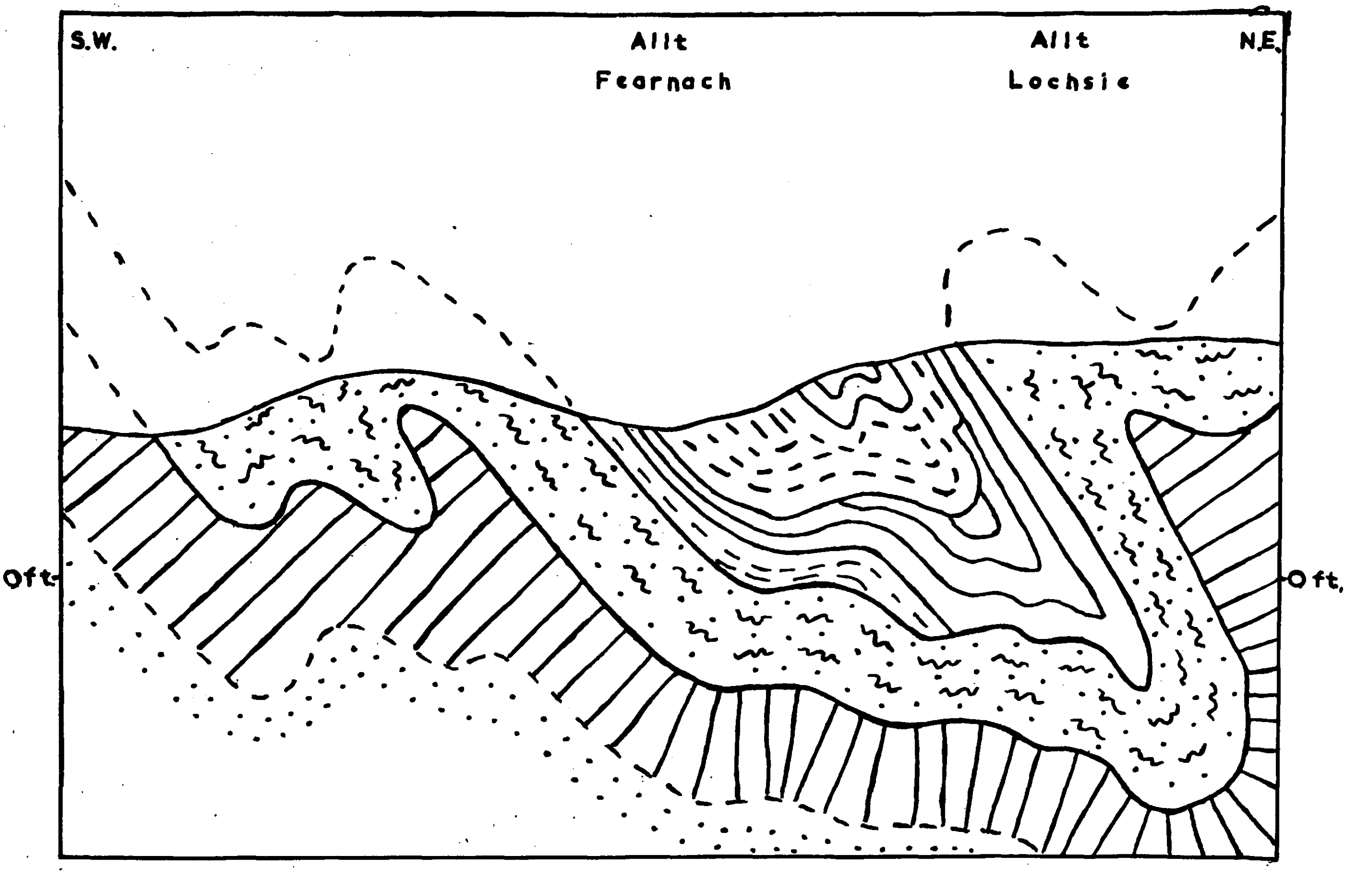
At the head of Glen Fearnach the Killiecrankie Schist of the Glas Tulaichean outcrop which lies to the north-east of the Ben Lawers Schist of Glen Fearnach swings round so that it also outcrops to the south-west of the Ben Lawers Group. The dip is everywhere at about 50° to the north-east although it may range from 30° - 70° and its direction may also vary considerably. The Glen Fearnach Synform also affects the underlying Blair Atholl Series which outcrop to the north and west of the Killiecrankie Group. As shown in the section on the Tummel Belt Series, the Blair Atholl Series to the north dips steeply to the south-east or south under the Killiecrankie Group. On the northern slope of Carn an t-Sionnach and in that part of the Allt a' Ghlinne Mhoir to the north of it, however, the dip swings to the south-south-west at 70°. The cross folds plunge at 20° to the south-east and the Caledonoid at 50° to the south-west. To the south-west, however, the dip rapidly changes to 50° to the east-north-east but still with cross fold plunge at 20° to the south-east while the Caledonoid plunge is 40° to the north-east. These structures persist in the Ben Lawers outcrop and also across the Killiecrankie Group found to the west of Glen Fearnach and into the Blair Atholl Series still further west. The latter group is specially

FIG. 11. MAP of GLEN FEARNACH.



Geological Boundaries	- - -	Strike and Dip	50⊢
Major Slide	——	Axial Plunge	→30
Blair Atholl Series	BAS	Lineation	⟼25

FIG. 12. N.E.–S.W. SECTION of GLEN FEARNACH along F–F'.



well developed at Loch Loch where it dips at 35° to the east-north-east with Caledonoid plunge of 25° to the north-east and cross fold plunge of 10° to the south-east. The Blair Atholl Series which outcrops between Loch Loch and Glen Mor and the nearer part of the Killiecrankie Schist swings in strike with the formational boundaries so that the dip is usually in the normal direction of south-south-east for these formations, at about 50°. The cross fold plunge is 35° to the south-east and the Caledonoid 20° to the south-west. The Killiecrankie Schist which lies nearer the Ben Lawers, however, reveals the same structures as in the younger group.

In the core of the fold the Ben Eagach Schist outcrops between the Ben Lawers Schist and the Killiecrankie Schist but the slide is still present between the latter and the Ben Eagach Schist since the Carn Mairg Quartzite is missing. Enclosed within the Ben Eagach Schist, however, are two lenticles of quartzite which may represent Carn Mairg Quartzite detached during the sliding associated with the formation of the Caledonoid recumbent folds. Both outcrops have similar minor structures to the surrounding Ben Eagach Schist and cannot be explained by dip or plunge to overlie the Ben Eagach Schist. The Ben Eagach Schist fails to the south just north of Daldhu; in the north it fails near Creag Gama' Choire where the boundary of the Killiecrankie outcrop swings to N.E.-S.W. for a short distance. This swing and another farther south are not reflected in the strike of the formations except for one or two isolated patches. These swings are probably due to the south-easterly plunge of several cross folds which make up the whole synform.

The cross fold plunge between 20° and 30° to the south-east is dominant over the whole region and increases towards the nose where it obliterates nearly all other structures. This dominant structure therefore produces the Glen Fearnach Synform on N.W.-S.E. axis. Caledonoid folding is less frequent and is usually at 40° to the north-east. Some variations in dip occur within the fold e.g. to the south of Creag Dubh where the dip is 45° to the north-north-east and the cross-fold plunge is 15° to the north-west. To the west in the Ben Eagach outcrop in the Allt Fearnach the dip is 60° to the east-north-east with cross fold plunge at 30° to the south-east. The dip and plunge are similar in the lower part of the Allt Glen Loch.

On the crest of the ridge between Glen Fearnach and Glen Loch, to the south-east of Sron Chrion a' Bhacain a thin strip of limestone not previously described outcrops among the Killiecrankie Schist. Lithologically it resembles the Ben Lawers limestones more than those of the Blair Atholl Series; the dip in common with the Killiecrankie Group is 50° to the north-east. The Caledonoid plunge is 45° to the north-north-east with the cross fold plunge at 20° to the south-east in the north-western end of the outcrop and horizontal running N.W.-S.E. in the south-eastern part of the outcrop. The horizontal plunge carries the limestone above the Killiecrankie Schist, which outcrops on a lower part of the ridge farther south-east. This outcrop therefore appears to be the remnant of a cross fold synform parallel to the Glen Fearnach Synform.

V MINOR STRUCTURES

Minor Structures in Rocks of Different Kinds

a) Quartzites

Bedding is best preserved in quartzites in which strings of pebbles (usually flattened) and graded beds can be recognised. Current bedding is however extremely rare in the area. The explanation for the preservation of bedding is probably that the massive quartzites were not intensely folded during the recumbent folding, movement being taken up in bands in which a platy layering obscures the original structures. Intervening strata show only gentle folding which can be referred to the later superimposed folds. The quartzites responded to the Caledonoid recumbent movements by tectonic thickening and thinning on a major scale rather than by the production of minor folding. The intensity of folding increases towards the margins of the quartzite outcrops. Both the Ben-y-Gloe and the Cairnwell Quartzites are characterised by a strong rodding on N.W.-S.E. axis which is often accompanied by mineral elongation. The rodding, however, is best developed in the Ben-y-Gloe Belt. On the N.E.-S.W. axis lineations take the form of small striations which are often bent by rodding.

b) Limestones

These are particularly instructive about tectonic style especially where they contain thin siliceous layers. This is because the siliceous layers are partly preserved from deformation by the effectively plastic behaviour of the limestones. Similarly calcareous formations deform more plastically than other groups on the major scale, so that the Blair

Atholl Series and calcareous Ben Lawers Schist form long attenuated folds. When siliceous bands are present they show less extreme deformation by folding whereas in the limestone the fold may be partly or completely destroyed by shearing. The siliceous layers gradually lose their continuity until they are only represented by tectonic inclusions which are often recognisable fold closures. The limestones show much more exaggerated folds, the closures of which may be lost through shearing. The final stage of shearing gives what appears to be a uniformly bedded limestone but the fact that the layering is not depositional in origin is indicated by isolated fold closures and obliquely convergent layering somewhat similar to current bedding in quartzites. Intense folding in more competent adjacent formations also shows that the apparently simple structure in the limestones is not original. The limestones in the Ben Lawers Group show the same structures as are found in the Blair Atholl Limestones.

Early Caledonoid folds, which are isoclinal in form, are rarely found in the limestones because of the intensity of deformation but are represented by the closures mentioned above. Schistosity parallel to the banding is in fact axial plane schistosity related to these closures and in its turn is folded openly by the later Caledonoid and cross folds.

c) Schists

The most common planar structure seen in the schists is a well developed schistosity on which the later folds were formed on both Caledonoid and cross fold axes. Associated with both sets of folds are strong lineations on the same axes which usually take the form of wrinkles on the surface of the schistosity but also appear as mineral orientations along a N.W.-S.E. trend. This schistosity is normally parallel to bedding but when the apex of a Caledonoid recumbent fold is seen the schistosity cuts through the bedding and is sub-parallel to the axial plane of the folding. The schistosity is therefore an axial plane schistosity produced during the recumbent folding.

In the graphitic Ben Eagach Schist there are also small gentle undulations on the schistosity along the trend of both fold axes. These are probably to be regarded as intermediate stages between lineations and the larger more pronounced folds on whose limbs they develop. The lineations express themselves as several sub-parallel striations produced at various stages in the one movement. The striations do not cut each other but the later ones cause the earlier to fade out. The latest of these lineations is parallel to the present "b" axis of the fold although the earlier were probably parallel to the "b" axis at the time of their formation. Also in the Ben Eagach Schist the lineations belonging to the later Caledonoid and cross folds cut each other indiscriminately so that sometimes one is later, sometimes the other. This can be observed within a few feet and so points to the fact that both sets of folds were essentially developed contemporaneously although locally one may be later than the other.

New axial plane schistosities of strain slip type may develop in association with the later folds on both axes but they are of local extent only and have little significance with regard to the major structures. For example the most extensive and significant of these later schistosities occurs on Ben Gulabin where the dominantly N.E.-S.W. folds of the Cairnwell Synform are truncated by the N.W.-S.E. folds which align the formations to the south-west along this trend. The schistosity belonging to the Caledonoid recumbent folds has been upturned by the cross folds and cut through by their axial plane schistosity. In the apices of the cross folds their schistosity cuts through the Caledonoid schistosity but on the limbs it runs parallel to the earlier schistosity.

Later shear bands develop on both axes in the schist especially the quartzose Killiecrankie Schist. These are shown in Fig. 13. These represent the last stages of adjustment to the tectonic forces and have little effect on the distribution of formations.

Boudinage

Boudinage is not well developed in the area since the prerequisite of hard bands with adjacent softer layers is rare. For instance the Banded Group of the Blair Atholl Series is a uniform grey schist lacking the quartzite bands of the type area in central Perthshire, but the Blair Atholl Limestones show some development of boudins where siliceous bands are present. The Ben Eagach and Ben Lawers Schists are usually too uniform to contain boudins, but boudins are found where siliceous bands are present. Some good examples, however, are found within the epidiorites in which some bands are harder than others.

Isolated fold hinges are not treated as boudins since they are formed by compression and shearing during the folding while true boudins

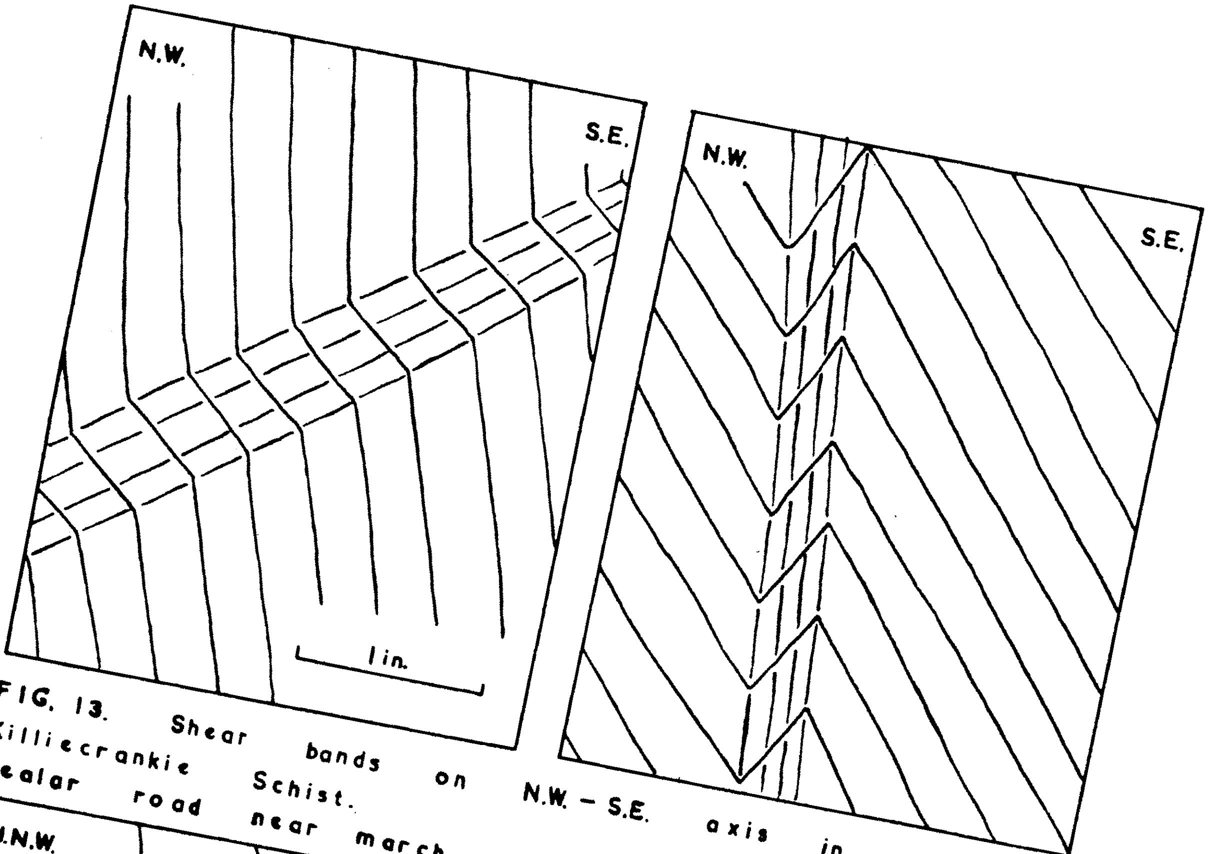


FIG. 13. Shear bands on N.W. – S.E. axis in Killiecrankie Schist. Fealar road near march.

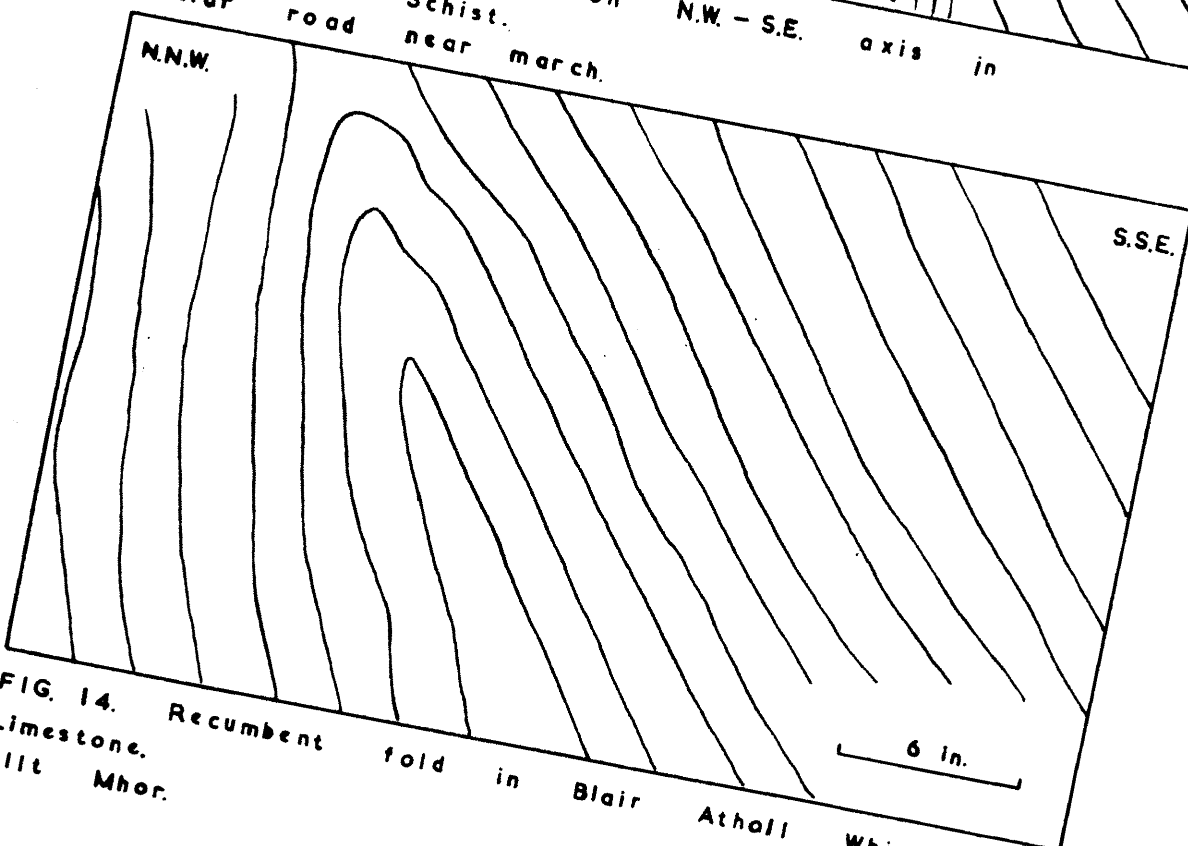


FIG. 14. Recumbent fold in Blair Athall White Limestone. Allt Mhor.

are formed by tensional separation of a sheet of original hard material.

Styles of Minor Structures in Different Areas

a) The Ben-y-Gloe Syncline

In the quartzite, Caledonoid recumbent folds are not seen and the later folds are only simple flexures. The cross fold direction is delineated by mineral elongation and rodding and the late Caledonoid by striations. The Blair Atholl Series in the Allt Mor, Allt Feith Ghuibsachain, and Creag an Loch are much more revealing, although at first sight they seem to be evenly banded. Within the layers isoclinal recumbent folds are present on the N.E.-S.W. axis. They have been upturned by later movement and are illustrated in Figs. 14 and 15. The example from the Allt Mor, if flattened, would close to the north, but this is a reflection of the effect of the later folding on the trend of the recumbent folds.

Later folds in the Blair Atholl Series take the form of simple undulations on both N.E.-S.W. and N.W.-S.E. trends. In the Blair Atholl outcrop on the north side of Meall na Spionag (north of the Ben-y-Gloe Belt), a later schistosity is developed on the axial plane schistosity produced by the recumbent folds, which dips south at 50° to 80°. The newer schistosity dips east-south-east at 30° and is associated with the development of later Caledonoid folds, of which it is the axial plane cleavage. It is of the strain slip type and is illustrated in Fig. 16.

b) The Cairnwell Synform

Isoclinal Caledonoid folds, whose axial planes are parallel to the regional schistosity, are well seen in the Cairnwell Synform. An

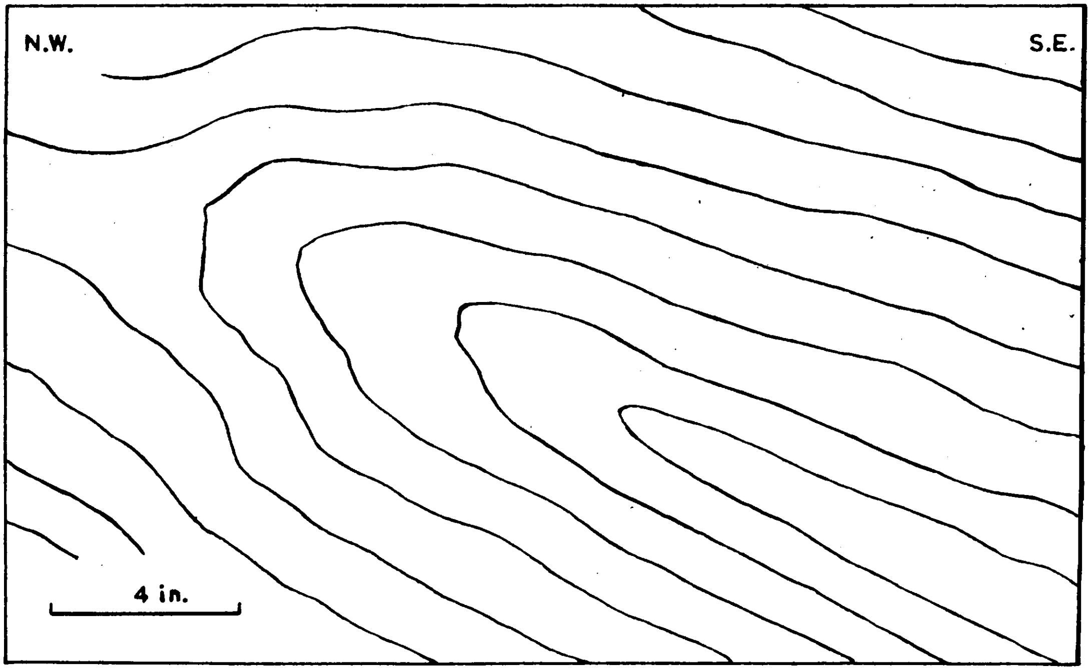


FIG. 15. Recumbent Caledonoid fold in Blair Atholl White Limestone.
South of Creag an Loch.

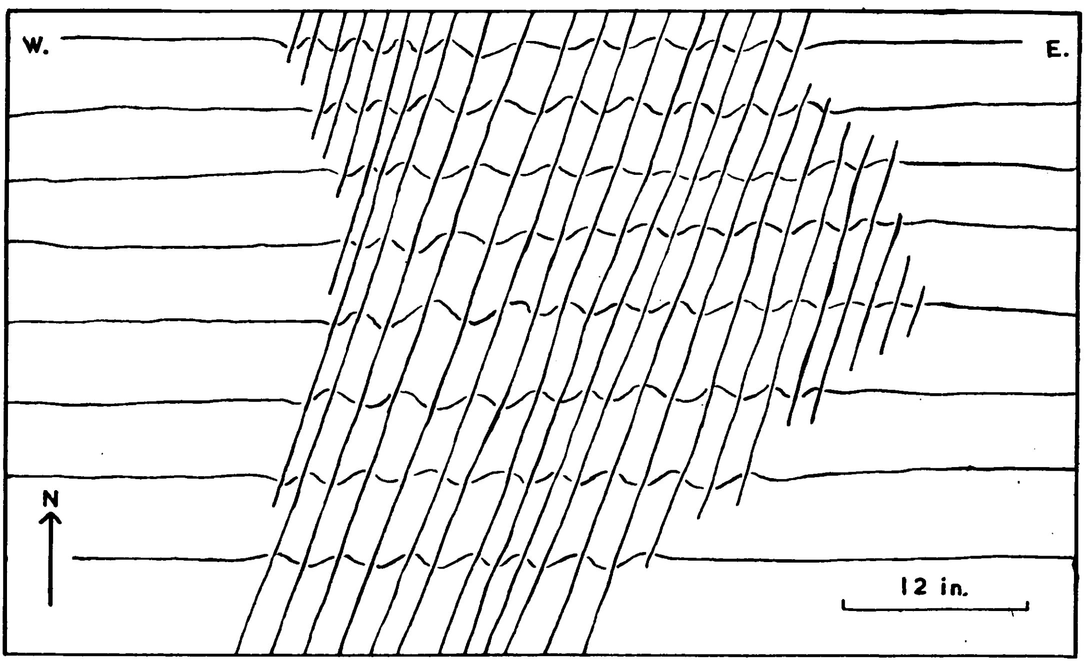


FIG. 16 Plan of Blair Atholl Dark Limestone shows E.-W. bedding dipping South at 50° cut by N.N.E.-S.S.W. cleavage dipping E.S.E. at 30°. Meall na Spionag.

example in the Ben Eagach Schist is shown in Fig. 17; in this fold the axial plane schistosity is the dominant structure, while the isoclinal fold is picked out by a band which is more siliceous than the usual schist. At the apex of the fold the siliceous band has been cut through by the axial plane schistosity produced by the fold. Fig. 18 illustrates similar folds in the Banded Group of the Blair Atholl Series. In this group there is more variation in composition between the pelitic and psammitic members than in the Ben Eagach Schists, so that the axial plane schistosity cuts through the earlier pelitic banding at the apex of the fold, but not through the psammitic. In both Figs. 17 and 18 the axial plane schistosity associated with the folds is parallel to the earlier banding at the apices of the folds. The banding in the Blair Atholl White Limestone is often isoclinally folded but it can be shown that it itself is formed of earlier isoclinal folds, which have been extremely attenuated. Fig. 19 is an example in which the limbs of isoclinal folds themselves split into limbs of the earlier isoclinal folds. Fig. 20 shows isoclinal early Caledonoid folds in the Allt Easgaidh, picked out by siliceous bands, which do not develop axial plane schistosity. The banding in the limestone, however, runs parallel to the axial planes of the folds, but is not actually an axial plane schistosity. It represents the limbs of folds similar to those in the siliceous bands but whose apices have been sheared out.

Late Caledonoid folding, which refolds the schistosity of the recumbent folds in the Blair Atholl Series of the Cairnwell Synform,

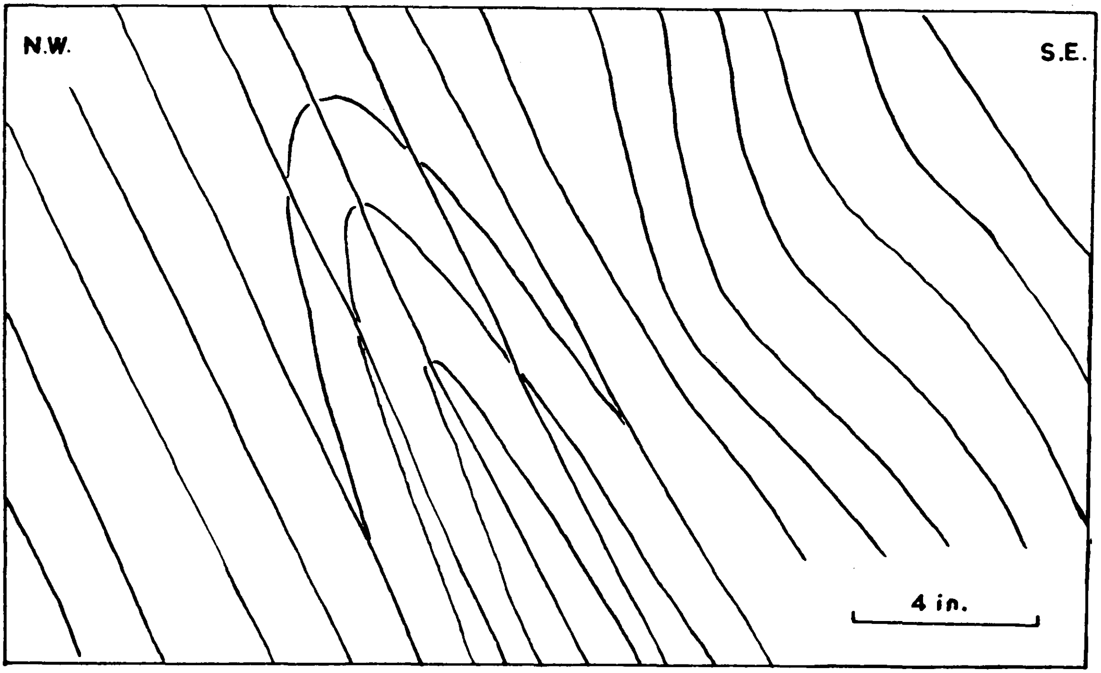


FIG. 17. Early Caledonoid recumbent fold in Ben Eagach Schist.
Crag above Shenaval

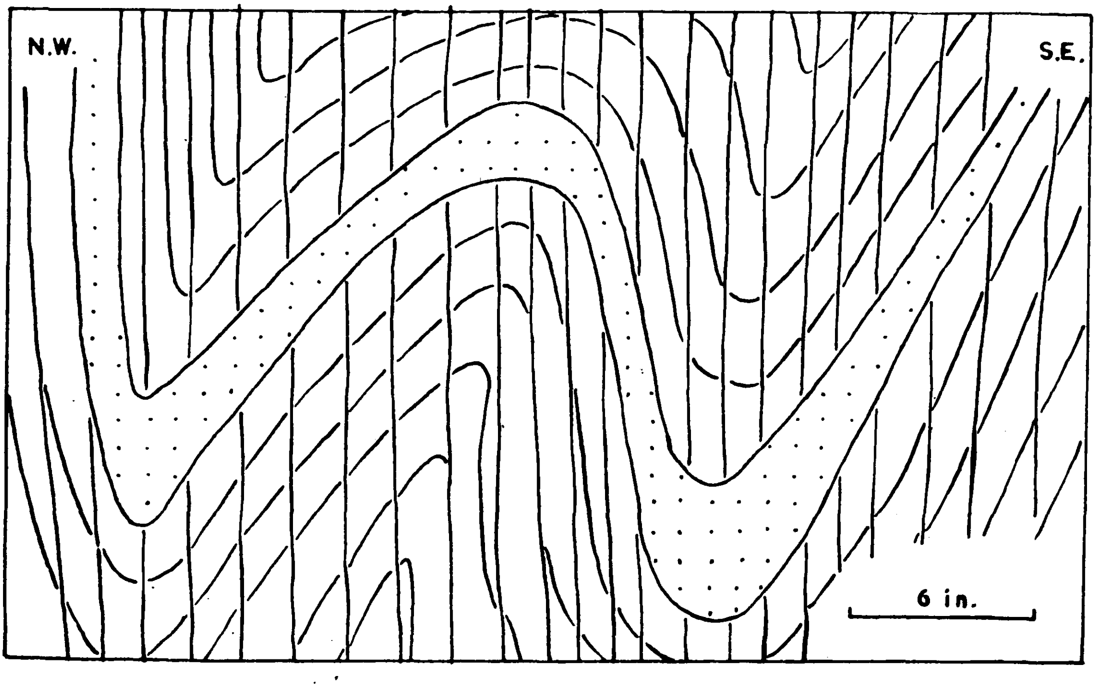


FIG. 18. Early Caledonoid folds in Blair Atholl Banded Group.
West of Moine Glac an Lochain.

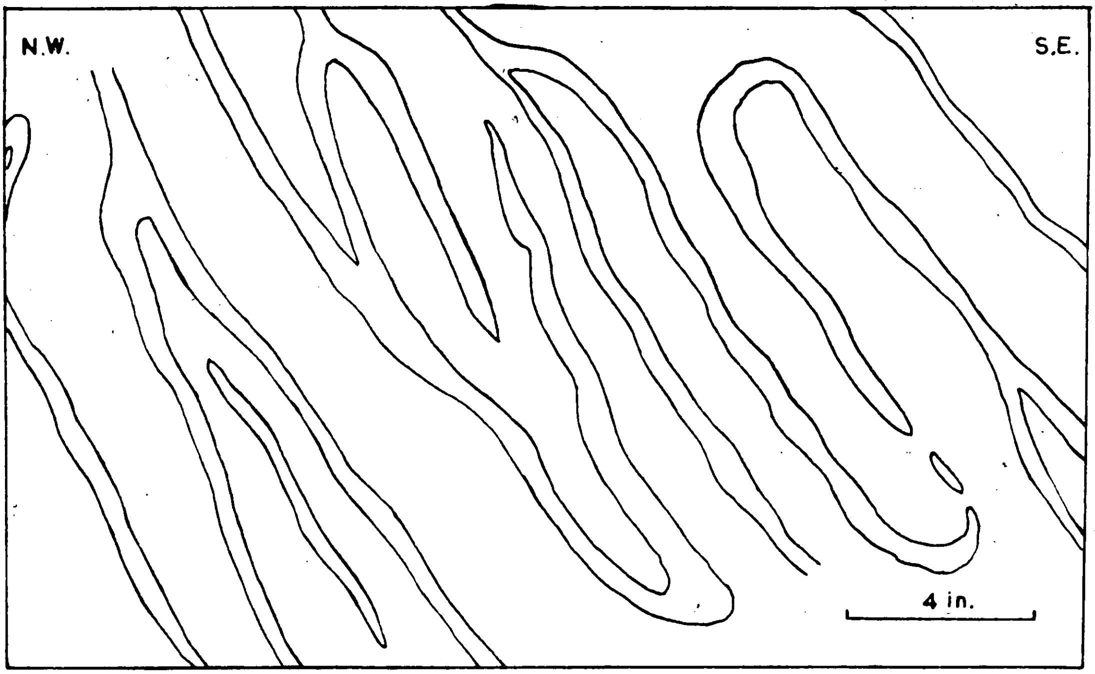


FIG. 19. Caledonoid folds in which the limbs are attenuated recumbent folds in Blair Atholl White Limestone. Creag nan Eun.

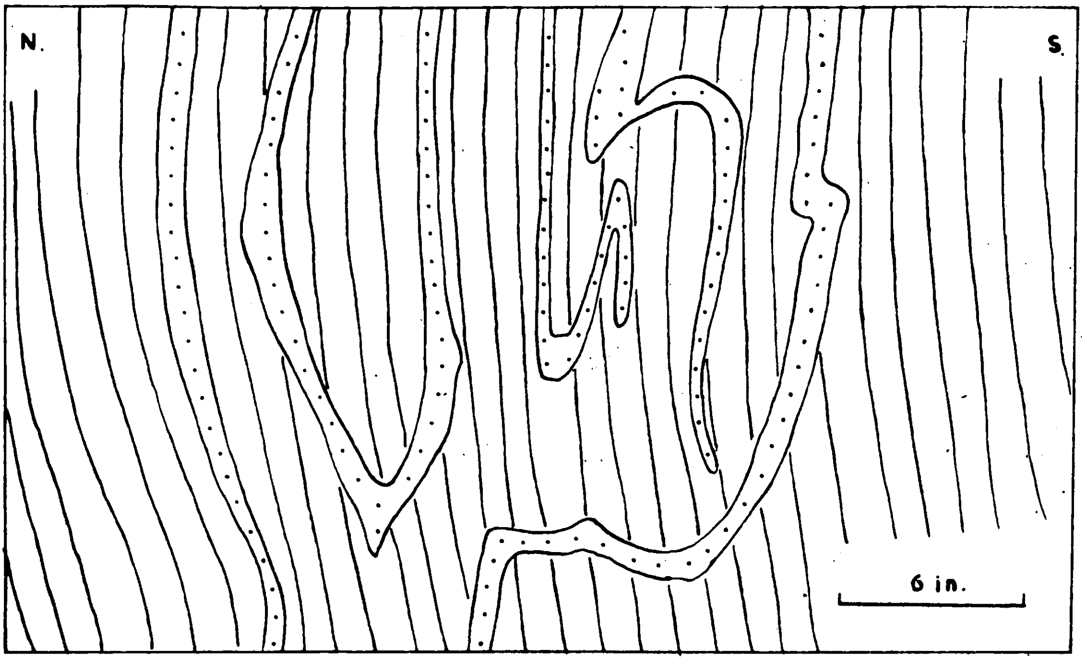


FIG. 20. Early Caledonoid recumbent folds with axial plane schistosity in Blair Atholl White Limestone. Allt Easgaidh.

is isoclinal in style and so is responsible for the repetition of formations. It is accompanied by a "b" lineation, which consists of crumples on the planes of schistosity.

Folds on the N.W.-S.E. axis are rarer in this region, but are also isoclinal; Fig. 21 is an example from the Ben Eagach Schist, in which a new axial plane schistosity is developed. This new schistosity is of the strain slip type, and differs from the axial plane schistosity of the recumbent folds in that the new micas developed do not cut across the earlier layers, of which the fold is formed. In other words the strain slip schistosity is not so strong as that produced by the recumbent folds. A "b" lineation, which takes the form of crumples on the planes of schistosity, and also mineral elongation is associated with the cross folds.

Fig. 22 shows that the competent Cairnwell Quartzite on Ben Gulabin develops simple late folds on the N.E.-S.W. axis, but Fig. 23 reveals that the hornblende schist farther south-east contains isoclinal folds similar to those of the Blair Atholl Series. In places a new axial plane schistosity is developed at the apices of the folds.

The cross folds in the extension of the Cairnwell outcrops in Glen Thaitneich and its tributaries are shown in Figs. 24 and 25. In Fig. 24 the folds in the Blair Atholl White Limestone are isoclinal in form, but do not develop a new strain slip schistosity parallel to their axial planes. The folds illustrated in Fig. 25, however, are from the striped part of the Ben Eagach Schist, in which both siliceous and pelitic layers are present. Accordingly a new strain slip schistosity

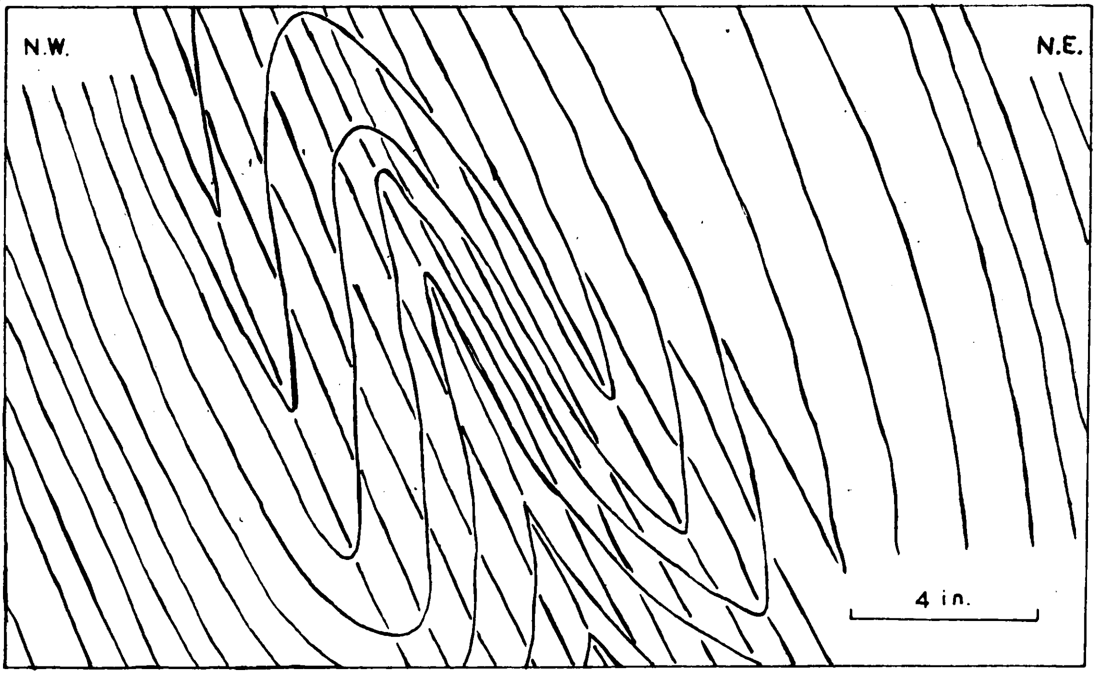


FIG. 21. Cross folds on axial plane schistosity of recumbent folds in Ben Lawers Schist. Bad an Loin.

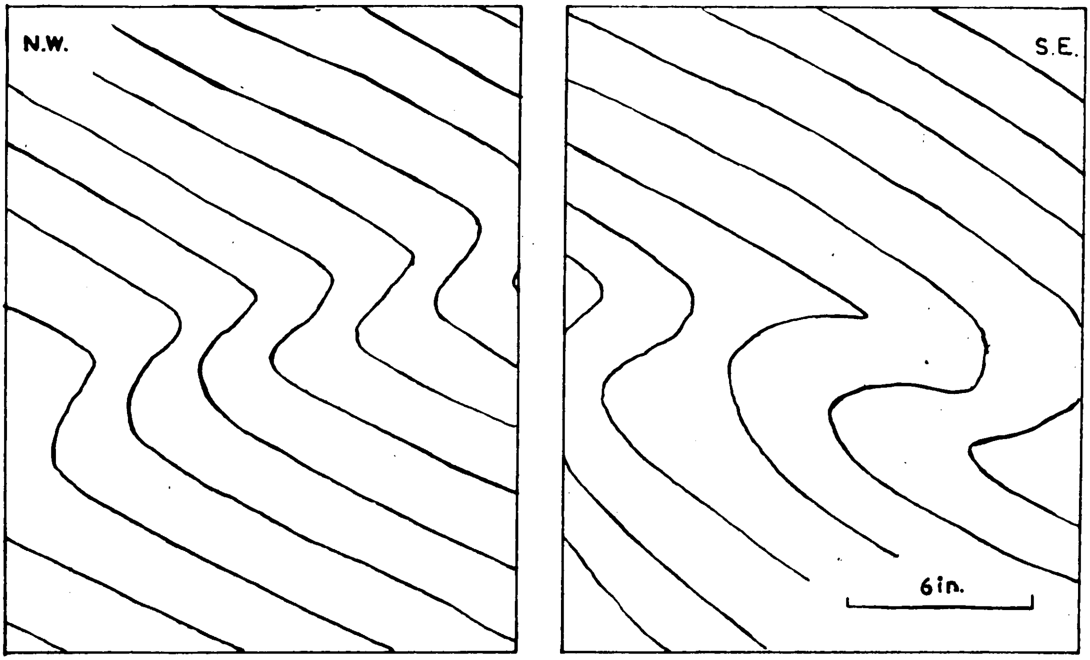


FIG. 22. Late Caledonoid folds in Cairnwell Quartzite. South-west side of Ben Gulabin.

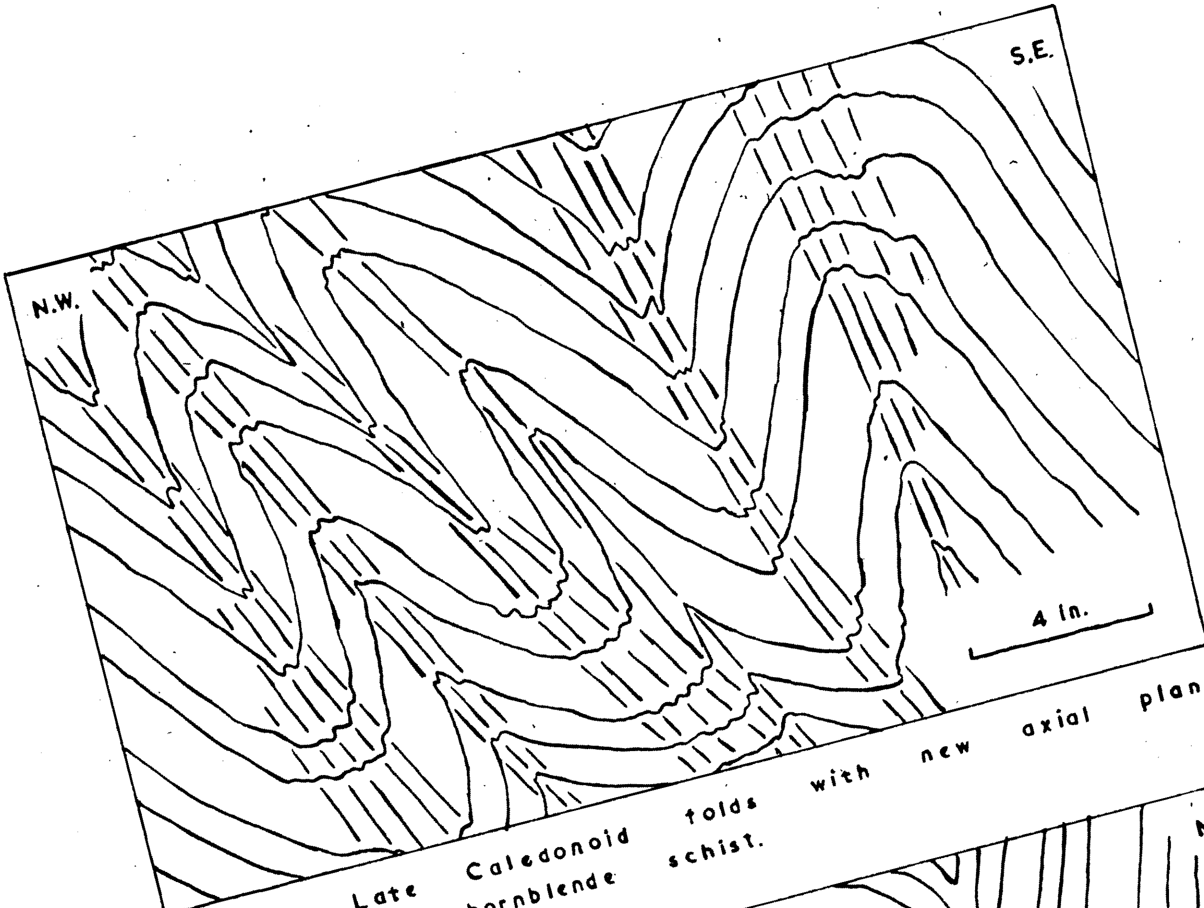


FIG. 23. Late Caledonoid folds with new axial plane schistosity in hornblende schist. Creag an Eich.

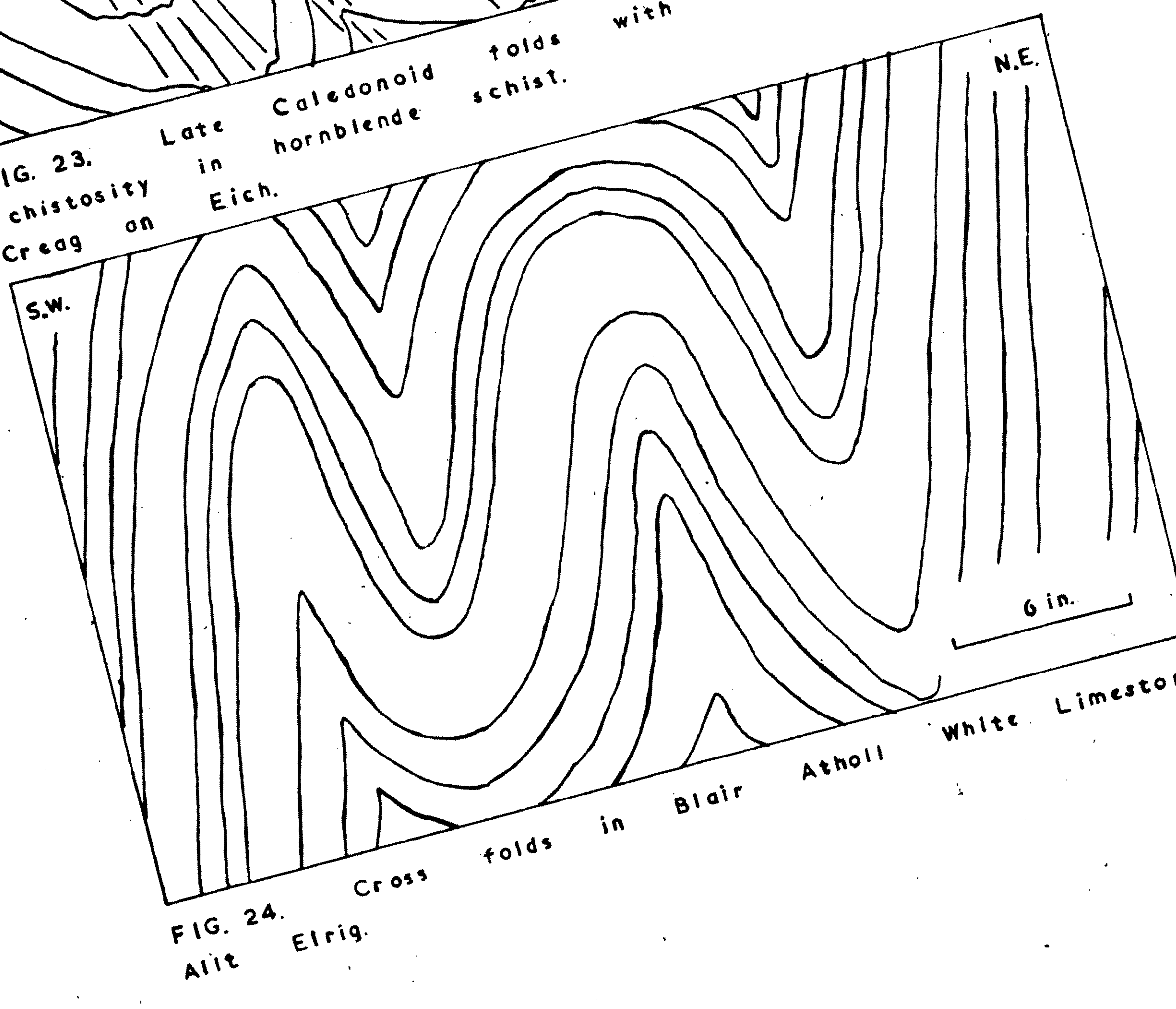


FIG. 24. Cross folds in Blair Atholl White Limestone, Allt Elrig.

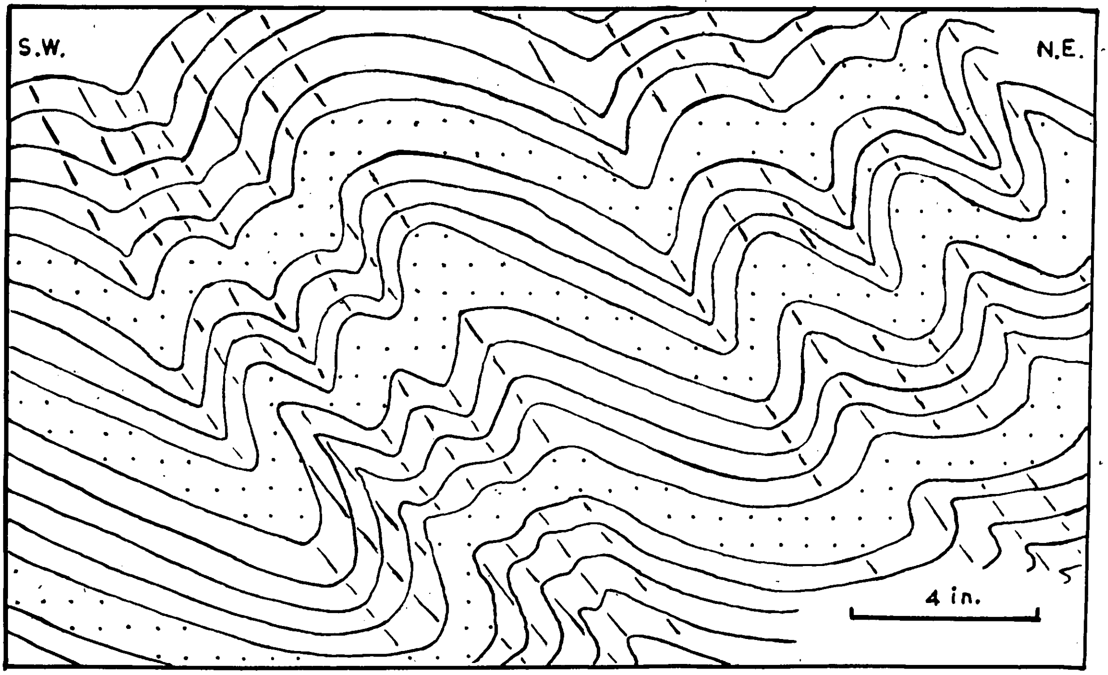


FIG. 25. Cross folds in Ben Eagach Striped Schist. Allt Aulich.

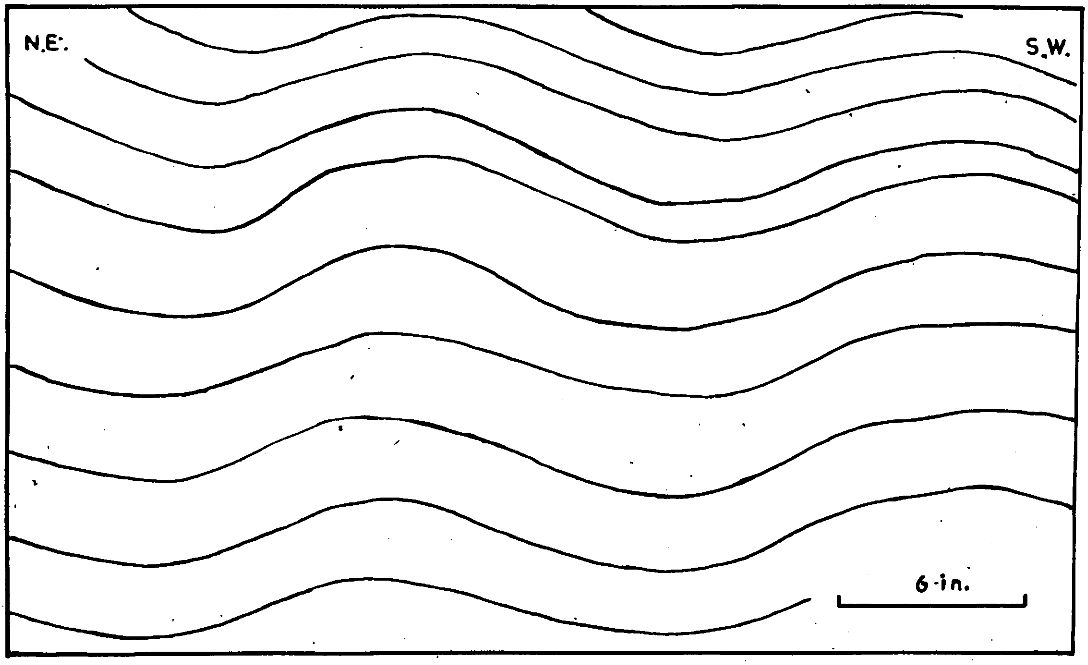


FIG. 26. Cross folds in Cairnwell Quartzite. Creag Dallaig.

developed in the pelitic layers, although the folds are more open than those in Fig. 24. The gentle cross folding found in the Cairnwell Quartzite of Creag Dallaig is exemplified by Fig. 26.

The various types of folds found on Creag Lamhaich are shown in Figs. 27, 28, 29 and 30. Fig. 27 is an example of the early Calédonoid folds, which control the distribution of formations. It is isoclinal in form, and its axial plane schistosity, which cuts through the pelitic banding at its apex, forms the regional schistosity. The fold is preserved in a siliceous band in the Ben Lawers Schist, but it can also be distinguished between the schistosity in the pelitic layers. Fig. 28 shows the later folds, also on the N.E.-S.W. axis, which refold the earlier schistosity. These folds are usually open in character, and do not form a new strain slip schistosity. Figs. 29 and 30 illustrate the cross folding, which is present throughout the outcrop and is isoclinal in character. Similar folds envisaged for the major structure would carry the south-east end of the Ben Lawers outcrop under the Ben Eagach Schist, because of the south-easterly plunge of the minor folds.

c) The South-Western Folds

The outcrop of Killiecrankie Schist between Glen Thaitneich and Glen Lochsie contains the early Caledonoid recumbent folds, whose axial plane schistosity is the regional schistosity. Fig. 31 illustrates these in the Ben Lawers Schist adjacent to the Killiecrankie Schist. This example is typical of the early Caledonoid folds in the south-western part of the area, where the cross folds are dominant, so that the early folds consist of sheared out limbs, and apices which transgress the

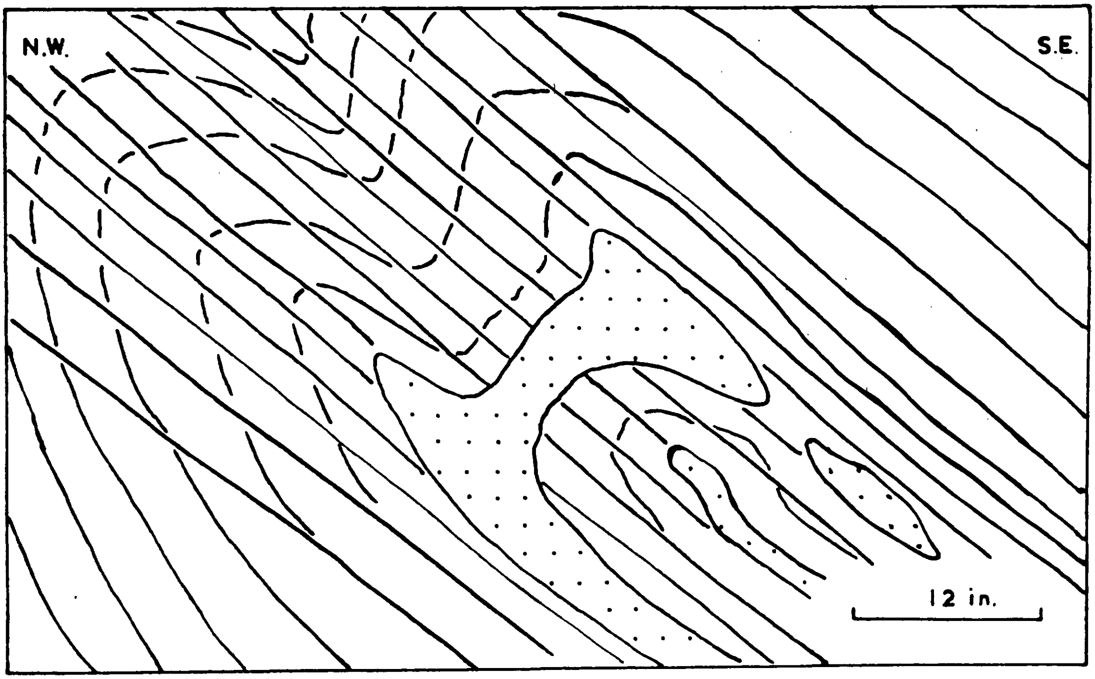


FIG. 27. Early Caledonoid folds in Ben Lawers Schist
North-west end of Creag Lamhaich.

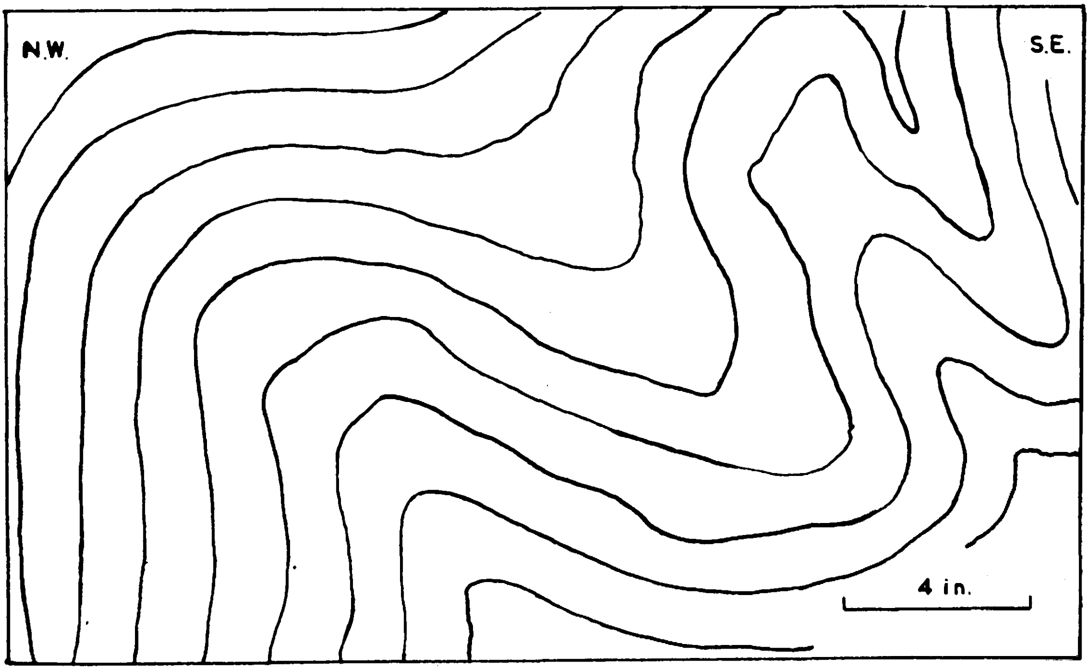


FIG. 28. Late Caledonoid folds on axial plane schistosity of early folds in Ben Lawers Schist.
North end of Creag Lamhaich.

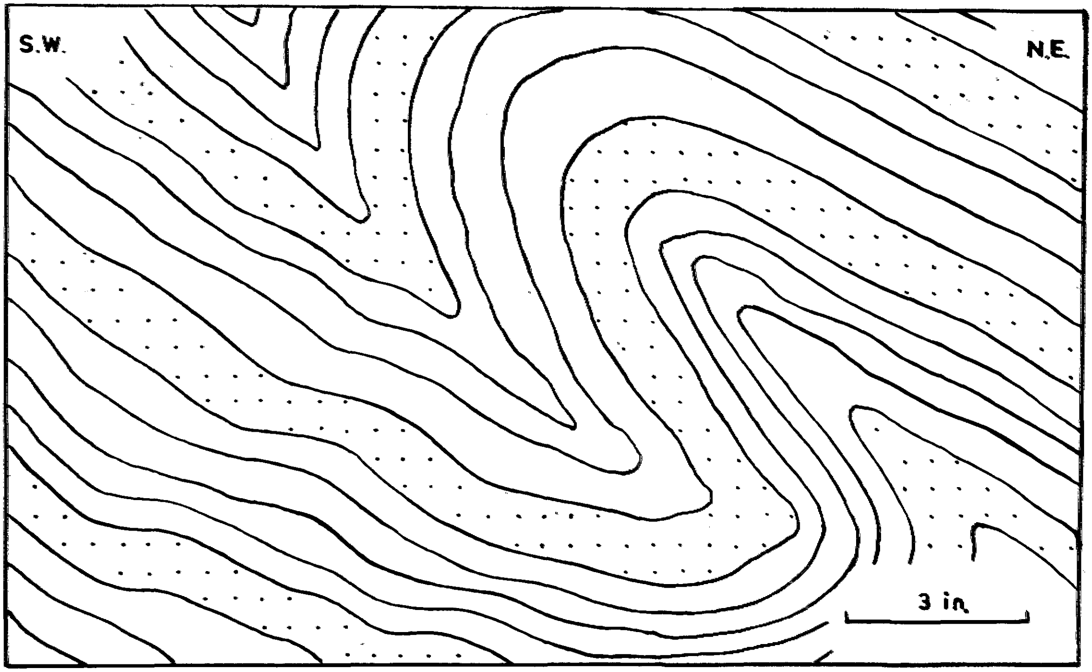


FIG. 29. Cross folds in Ben Lawers Schist. North end of Creag Lamhaich.

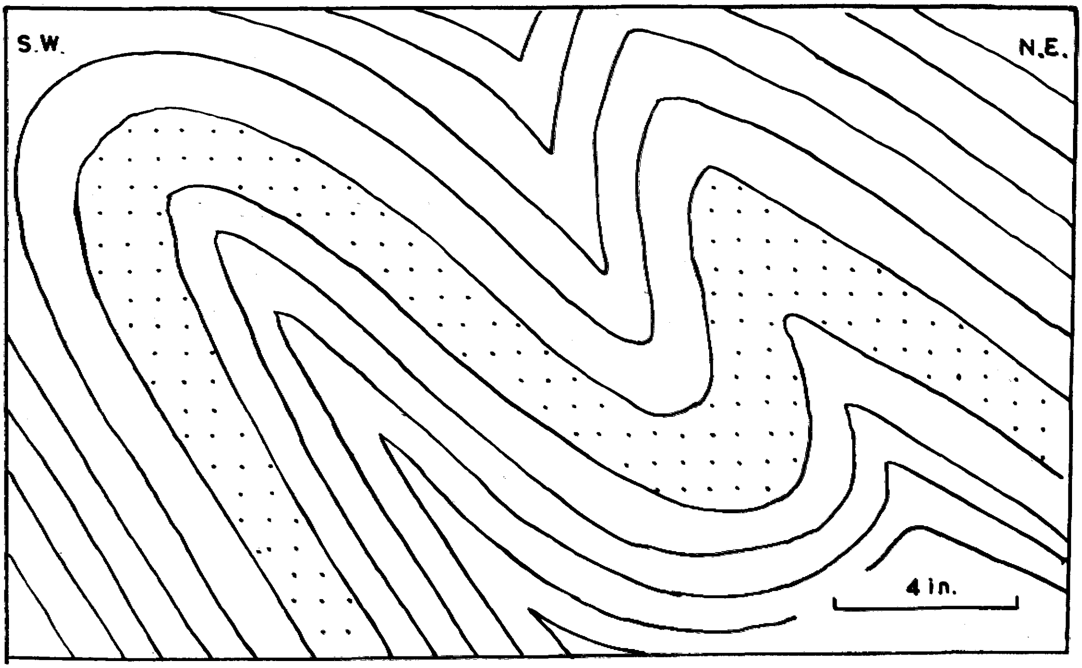


FIG. 30. Cross folds in Ben Eagach Schist. South end of Creag Lamhaich.

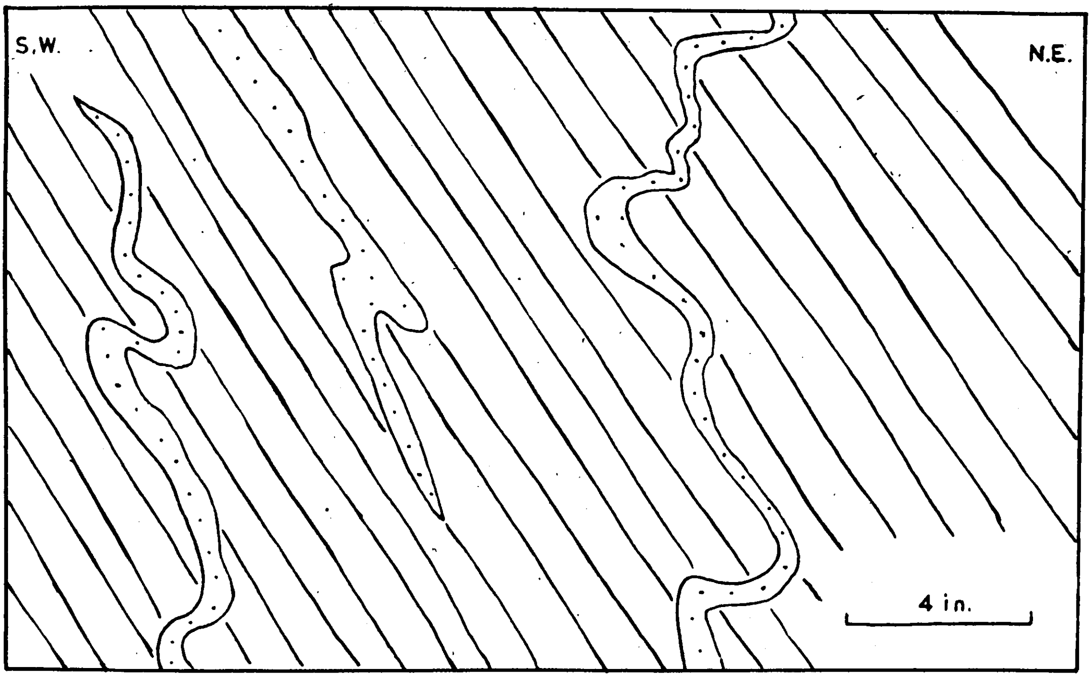


FIG. 31. Early Caledonoid fold remnants in schistosity of Ben Lawers Schist.
Creag Dearg.

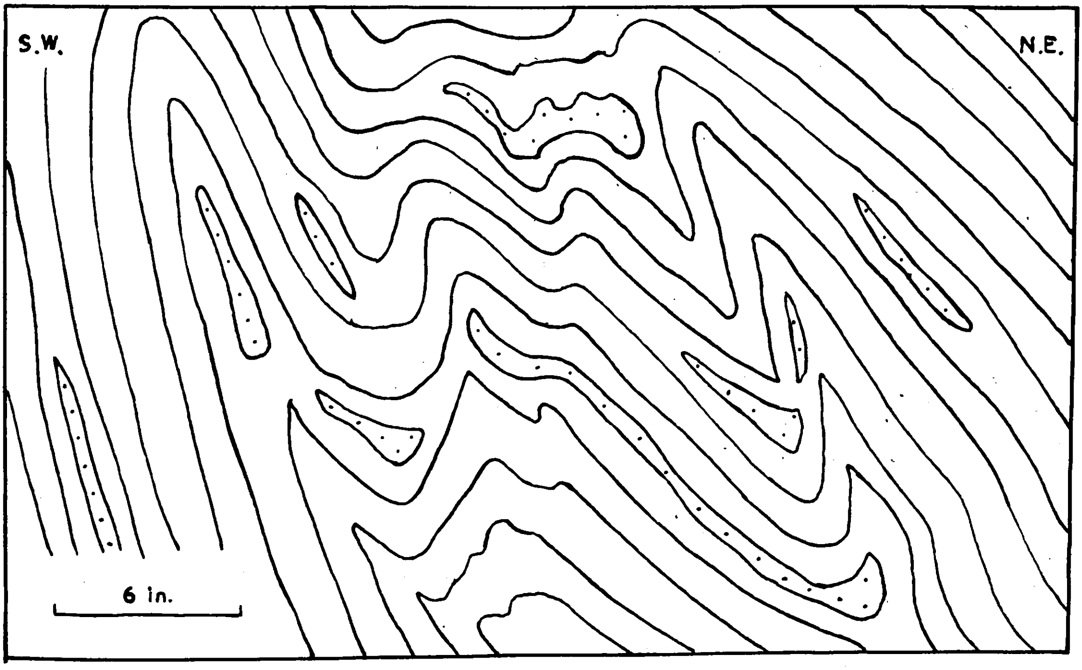


FIG. 32. Cross folds in Killiecrankie Schist. The siliceous lenticles are remnants of recumbent folds.
Creag a' Chaise.

regional schistosity. The fold style at the south-eastern end of the Killiecrankie Schist on Creag a' Chaise is shown in Fig. 32. At this locality the isoclinal cross folds on the regional schistosity plunge to the south-east to carry the outcrop under the Ben Lawers Schist. Isolated siliceous lenticles are remnants of early Caledonoid folds within the schistosity. A strong mineral elongation represents the "b" lineation of the cross folds. This lineation and the "b" lineation of the late Caledonoid folds also take the form of crumples on the planes of schistosity. The Caledonoid lineation cuts the one running N.W.-S.E.

South-west of the Glas Tulaichean outcrop of Killiecrankie Schist, the Ben Lawers Schist in Glen Lochsie reveals well developed minor folding since limestone bands are intercalated with the calcareous schist. Fig. 33 illustrates the recumbent Caledonoid folds which produce the regional schistosity and cause disruptions within the layers. They were refolded on the same axis by open folds, whose axial planes are at a considerable angle to those of the recumbent folds. Fig. 34 is an example of the cross folding which is superimposed upon the earlier Caledonoid folds. The cross folds are isoclinal and have developed a new strain slip schistosity in the pelitic layers between the planes of the regional schistosity.

The cross folds are the dominant minor structures south-west of Glen Lochsie and are nearly always isoclinal, with their axial planes dipping to the north-east. In some parts of the area, however, the late Caledonoid folds are the more powerful. Such a part is the outcrop

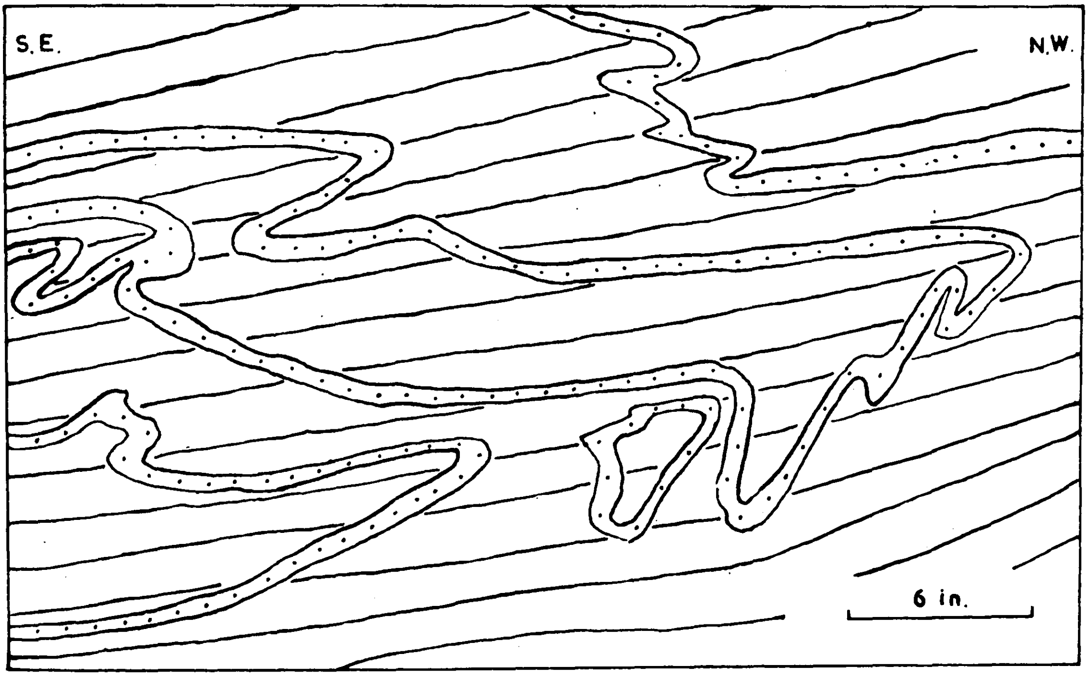


FIG. 33. Recumbent Caledonoid folds with axial plane schistosity in Ben Lawers Schist.
Clais Allt.

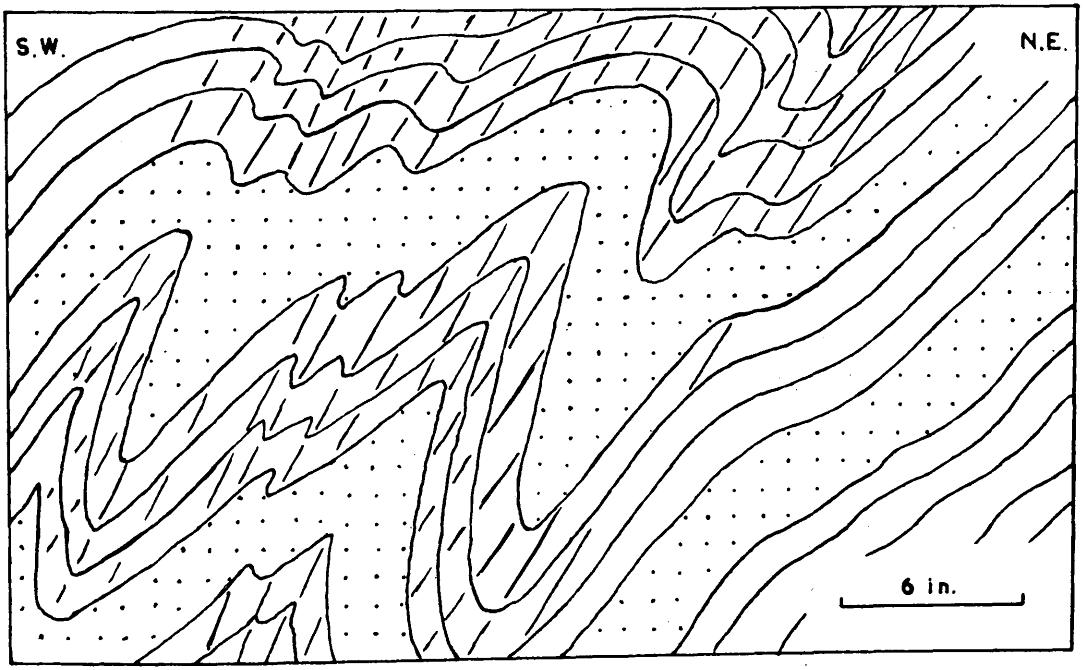


FIG. 34. Cross folds on axial plane schistosity of recumbent folds in Ben Lawers Schist.
Clais Allt.

of Cairnwell Quartzite which trends N.E.-S.W. through Carn Tarmachain. At the south-western end of the outcrop the late Caledonoid folds are isoclinal with their axial planes dipping towards the south-east, but farther north-east the folds become gentler and open in form. The major structure is of the same shape from the dips, as well as from the evidence of the minor structures.

Caledonoid folding also controls the trend of the Ben Lawers Schist on Sron Fearnach as shown by the outcrop of epidiorite found on that ridge. That the folding again is of open type is shown by the style of the folds in Fig. 35, and a new axial plane schistosity is developed in the pelitic layers at the crests of the folds. In some parts of the outcrop, however, the cross folding is dominant and is of the type shown in Fig. 36. The cross folds, which were formed on the regional schistosity, consist of a long and a short limb. A new strain slip schistosity cuts through the regional schistosity at the apices of the folds. In the localities where the cross folds are dominant the late Caledonoid folds take the form of simple undulations. This interplay of the two directions of later folding shows how the formations can outcrop over wider areas than might be expected from the direct measurement of plunge in any area.

South-west of Glen Shee there is a wide outcrop of Ben Lawers Schist before the Cairnwell rocks are again found. In this belt the minor folds on the N.W.-S.E. axis are characteristically isoclinal and are illustrated in Fig. 37. One limb is nearly always shorter than the other, and a new axial plane schistosity developed in the pelitic layers

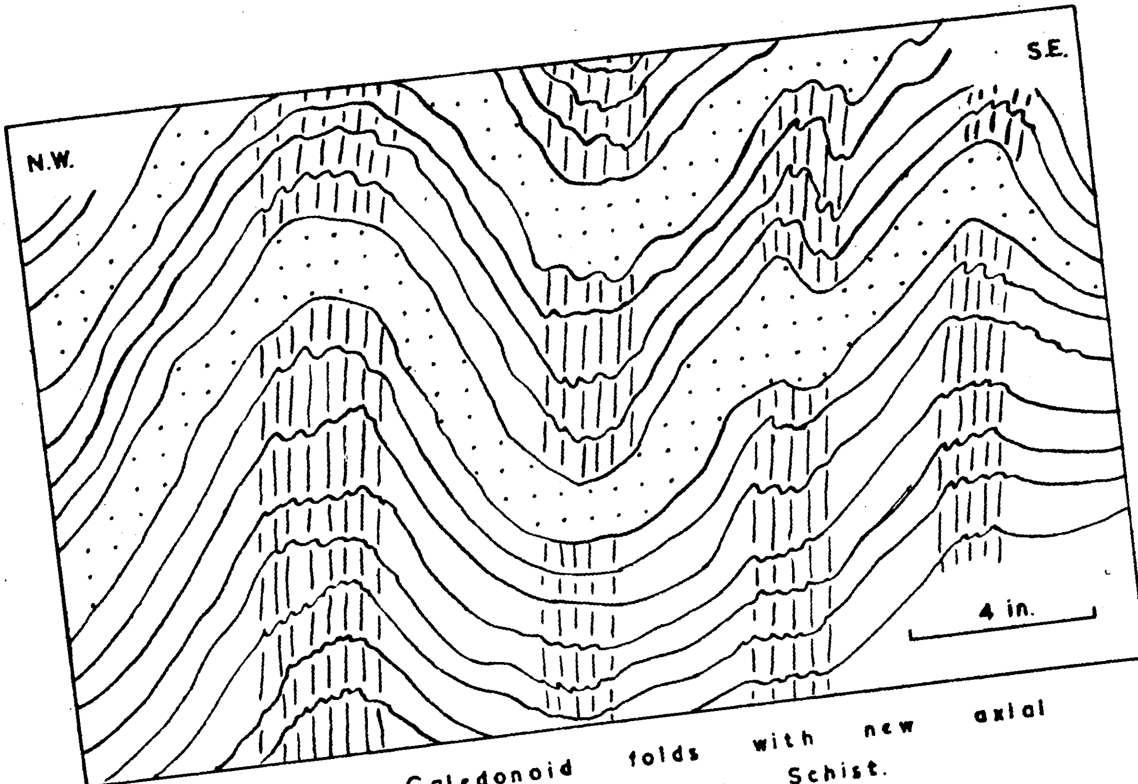


FIG. 35. Late Caledonoid folds with new axial plane schistosity in Ben Lawers Schist. Sron Fearnach.

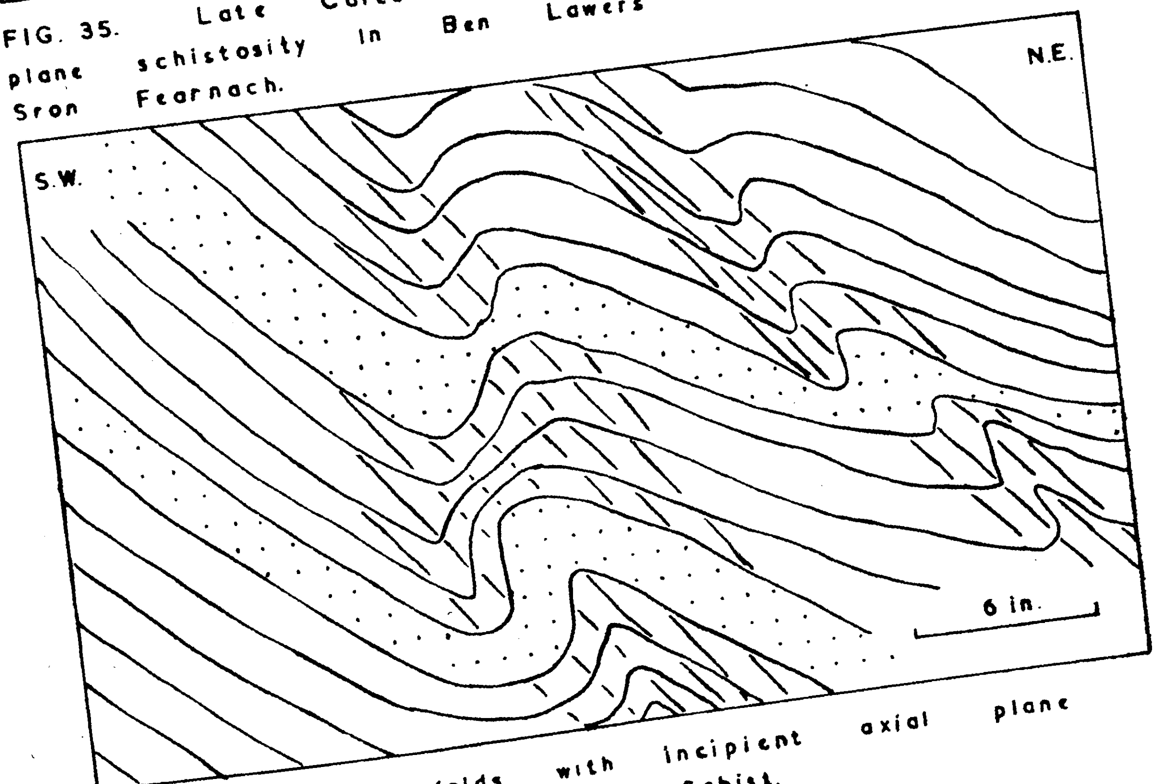


FIG. 36. Cross folds with incipient axial plane schistosity in Ben Lawers Schist. Sron Fearnach.

FIG. 37. Cross folds with new axial plane schistosity in Ben Lawers Schist.
Creag Beg.

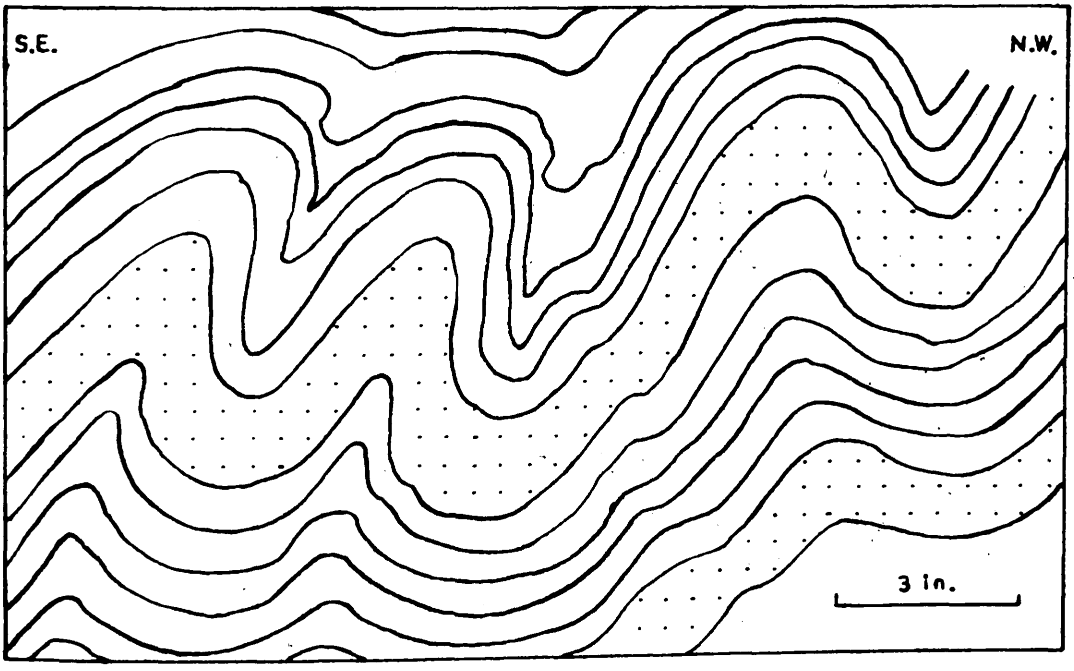


FIG. 38. Late Caledonoid folds in Ben Lawers Schist.
Cnoc na Cuineag.

at the apices of the folds is parallel or sub-parallel to the regional schistosity. Fig. 38 shows the simple undulatory nature of the late Caledonoid folds in the same outcrops.

In the Ben a' Cruachain outcrop of Cairnwell Quartzite the cross folding is of both isoclinal and open types. The surrounding Ben Lawers Schist contains recumbent Caledonoid folds picked out by limestone bands, which are common in the western part of the Ben Lawers outcrop. In the pelitic layers the axial plane schistosity of the recumbent folds forms the regional schistosity. The latter is refolded by isoclinal cross folds and gentle open Caledonoid folds.

d) The Glen Fearnach Synform

In this region the dominant minor structures, as would be expected from the trend of the formations, are the late cross folds and the associated lineation. Early Caledonoid folds, however, are picked out by limestone bands within the Ben Lawers Schist, and their axial plane schistosity is that of the region. At the head of Glen Fearnach towards the apex of the synform the cross folds are even more numerous and obliterate nearly all other structures. Fig. 39 illustrates an isoclinal synform in the Ben Lawers Schist near the slide. It is similar in style to the Glen Fearnach Synform. The "b" lineation of the cross folds consists of mineral elongation and strong crumples on the planes of the regional schistosity. Fig. 40 is typical of the gentle undulations which are the late folds on N.E.-S.W. axis in this region.

Age and Relations of the Folds

The early folds are Caledonoid in trend. Subsequent folding has caused the strike of their axial plunge to vary somewhat but it is

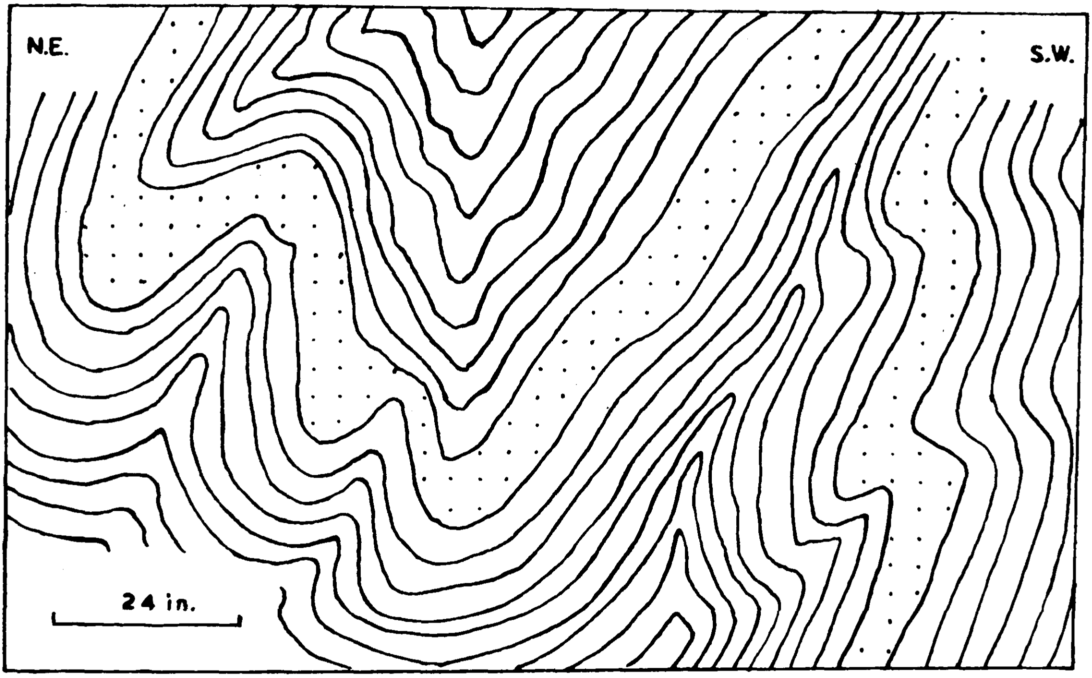


FIG. 39. Cross folds in Ben Lawers Schist.
Glen Fearnach,

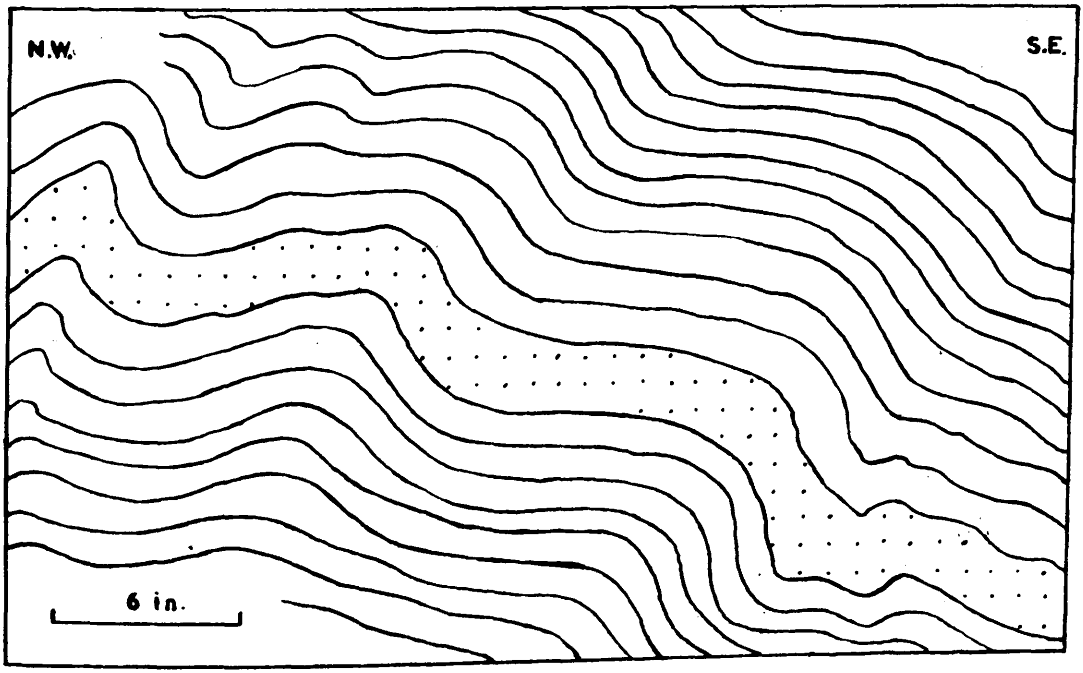


FIG. 40. Late Caledonoid folds in Ben Lawers Schist.
South — west side Carn an t-Sionnach.

usually between N.45°E. and N.60°E. Their axial plane schistosity which forms the regional schistosity has been refolded by the later Caledonoid and cross folds. The former trend N.N.E.-S.S.W. in the north-eastern part of the area but towards the south-west they swing to N.E.-S.W. Similarly the cross folds swing from W.N.W.-E.S.E. in the north-east to N.W.-S.E. in the south-west. When axial plane schistosity associated with the later folds has developed, it is usually parallel to the regional schistosity because the folds are isoclinal. Locally, however, the later folds are more open in character and then the new schistosity is oblique to the older. Thus in parts of the south-western region, where the early schistosity dips to the north-east, the later schistosity also dips to the north-east, but is steeper than the earlier. The angle between the two is usually between 10° and 15°.

The early folds may be correlated with the Caledonoid recumbent folds. Earlier folds on both Caledonoid and cross fold axes are, however, found in the Flat Belt to the south. On the major scale King and Rast have postulated that the cross folds are accommodation structures which resulted from the confinement of the orogenic belt in the direction of the major b-axis. The minor cross folds in this area are later than the Caledonoid recumbent folds but earlier than the later Caledonoid folds. The latter, however, cannot be unfolded without partly unfolding the cross folds. Therefore the two later fold systems were in part contemporaneous. The cross folds must have originated somewhat earlier than the later Caledonoid since they have been refolded by the latter in some places.

VI FAULTS

There are two major faults which are found towards the south-west of the area in Glen Fearnach.

On the south-western side of the more important fault, the Glen Fearnach Fault, a structurally ascending succession is seen from south-east to north-west, but is in fact descending stratigraphically. The lowest group on this side is the Pitlochry Schist, followed by the full succession up to the Killiecrankie Schist except that the Ben Eagach Schist has been eliminated by sliding. On the north-eastern side the succession ranges from the Ben Lui Schist to the Killiecrankie Schist; the Loch Tay Limestone has been cut out by a N.E.-S.W. fault to the south of the present area.

There is a rapid change in strike from one side of the fault to the other; the dip on the south-western side being from 30° - 60° to the north-west, and on the north-eastern 20° - 30° to the north-east. On the north-eastern side, however, there are some variations in dip; where the Ben Lawers Schist swings to meet the fault near its centre, while at the north-western end the dip has swung from north-east to east.

That the fault is not primarily a tear fault, like so many of the large faults which trend N.E.-S.W. in the Southern Highlands, is shown by the fact that the boundaries of the various formations do not match if any one of them is placed alongside its fellow on the opposite side of the fault. There may, however, be some strike-slip. The north-western boundary of the Ben Lawers Schist, marked by the Southern Slide, shows a displacement of two-fifths of a mile while the southern boundary of the same formation is displaced by nearly two miles. The Loch Tay Limestone is not seen on the north-eastern side of the fault but reappears farther south on the south-western side. Here it dips to the east-south-east at 25° so that the Pitlochry Schist between it and the main outcrop of the Loch Tay Limestone is part of the Flat Belt structure. At its north-western end the fault finally dies out in the Killiecrankie Schist outcrop in Glen Loch.

The structure is that of a normal fault with a moderate downthrow to the north-east to bring structurally higher rocks down against lower but younger ones. The amount of throw is difficult to estimate since the formations on either side of the fault dip in different directions. The downthrow must however be more than the apparent thickness of the Ben Lui Schist and Loch Tay Limestone since Ben Lawers Schist is downthrown to outcrop alongside Pitlochry Schist. The amount of throw may also be exaggerated by the north-easterly dip on the north-east side of the fault since the Loch Tay Limestone may be present just below the surface on a N.W.-S.E. trend. The uncertainty is caused by the cross folding along Glen Fearnach; the fault itself may represent the last resolution of stresses along the N.W.-S.E. axis which was probably in existence along the glen from the beginning of the orogeny.

Using the outcrop displacement of the south-eastern boundary of the Killiecrankie Schist on either side of the fault a maximum downthrow of 1,500 feet to the north-east is estimated but this may be exaggerated by the difference between the strikes on either side. The throw may be considerably less in other parts of the fault. The Glen Fearnach Fault is partly responsible for the preservation of the Cairnwell Synform to the north-east whereas the latter has been removed by erosion from other areas. The fault itself is not well exposed usually occupying the river bed or hollows in the hillside but its outcrop can be traced both by these features and the surrounding rocks. As the fault plane itself is seldom seen slickensides are rare but sometimes occur on neighbouring rocks. Those that do occur are predominantly vertical although some are oblique showing that a little horizontal movement has taken place.

Another minor fault branches off from the Glen Fearnach Fault to run north-east through Ben a' Cruachain; it curves gently along its length to run almost due north so it may have formed as a result of the stresses imposed by the Glen Fearnach Fault. It is also a normal fault downthrown to the west but the throw is of small amount and only slightly displaces the formations. The outcrop displacement is greater at the southern end of the fault and so the throw appears to be greater but this is partly because the Ben Lawers Schist there dips to the north-north-east at 25° whereas the Cairnwell Quartzite on Ben a' Cruachain dips at 60° to the north-east. In fact the throw decreases from 150 feet to the west at the southern end to 50 feet at the Cairnwell Quartzite outcrop on Ben a' Cruachain. Slickensides are vertical showing that the movement is that of a normal fault produced by tension after the compression, which was responsible for the folding, had ceased.

VII. HISTORY OF MINERAL DEVELOPMENT

In the field the minor structures display early folds on the N.E.-S.W. axis, which developed a strong axial plane schistosity. This in turn was refolded, not only along the N.E.-S.W. axis but also on the N.W.-S.E. axis. New local schistosities were also developed by the later folds. All these structures can be recognised under the microscope.

The tectonic events are denoted as follows:-

S_1 Flow cleavage

S_2 Axial plane schistosity, produced by folds which refold S_1

S_3 Strain slip schistosity, oblique to S_2

S_1 is taken as a cleavage rather than as bedding since fine micas have grown along it. Although bedding is usually taken as S_1, the flow cleavage is the earliest planar structure found in the schists of the present area. The folds which may have produced S_1 cannot be found since they have been obscured by the complexity of the later structures. That earlier folds existed is evident from the Flat Belt, where the sequence of early folds has been preserved.

S_1 is folded isoclinally; the folds developed a strong axial plane schistosity, S_2, which, in the field, is seen to be the regional schistosity. It, in turn, is refolded by the crumples associated with S_3, which are found on both N.E.-S.W. and N.W.-S.E. axes, in agreement with the later folds on these trends. Either direction may be dominant according to whether the area affected has been chiefly deformed by the late Caledonoid or by the cross folds. The development of minerals has been similar in each case. Therefore the latest strainslips have been termed S_3 although they lie on both Caledonoid and cross fold directions.

Barrow (1893) classified the metamorphic rocks of the South-East Highlands by the incoming of successive minerals in the pelitic schists with rising temperature and pressure. He placed the whole of the area in the Garnet Zone.

The Blair Atholl Series

a) Schists

In the Dark Schist the flow cleavage, which represents S_1, is characterised by the growth of fine muscovite. This mineral was also formed during S_2 but is coarser than that of S_1. S_2 also causes rotation of garnets between the planes of schistosity; the inclusions, which show the rotation, are more frequent in the rims than in the centres of the crystals. In the Ben-y-Gloe Syncline S_3, the late strain slips, cause the muscovite to recrystallise. This process continues after S_3 and there is also late recrystallisation of quartz and albite. In the Cairnwell Synform, however, S_3 is very strong, with crumples which fold several layers, and which are not only restricted to the micaceous ones. Muscovite formed before, during, and after S_3 as well as during S_2. The muscovite flakes formed during S_2 are cut by those formed during S_3. Micas developed between the periods of movement cut the earlier micas haphazardly, but are themselves cut by the micas of the later schistosity. Clinochlore is later than S_3 and quartz recrystallised after S_3, since

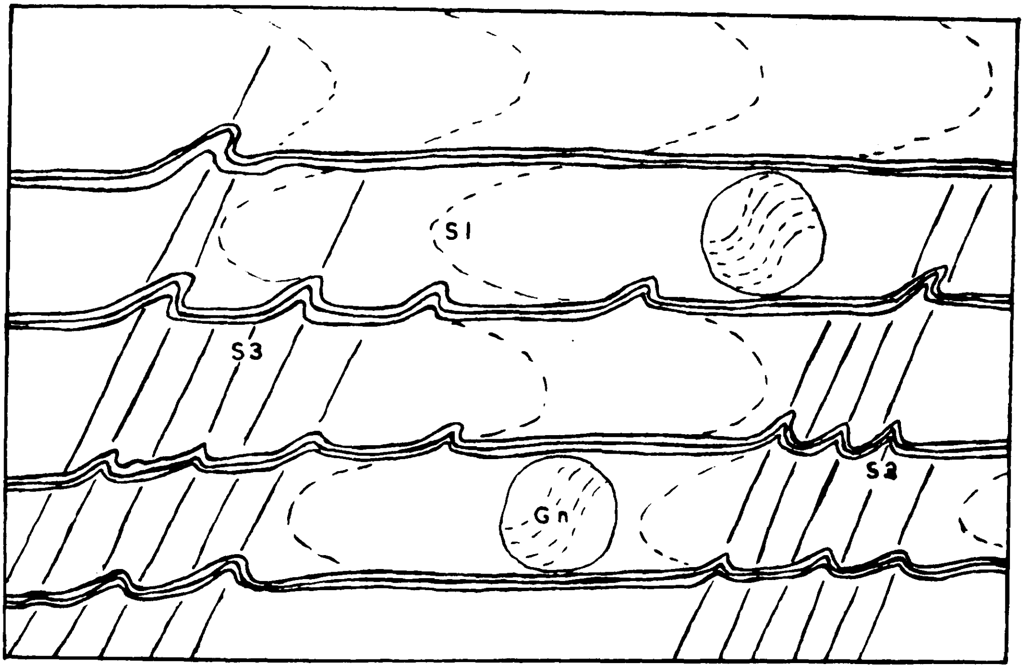


FIG. 41. Sketch of micro-structure showing S1, S2, and S3, and rotated garnets in Blair Atholl Banded Group. Glen Beag.

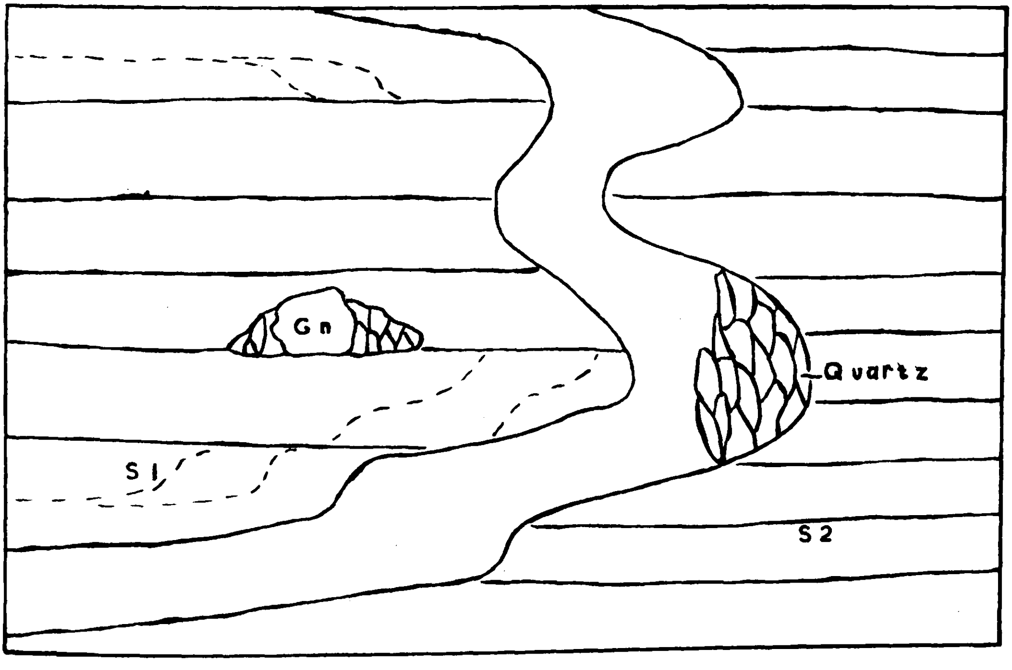


FIG. 42. S3 expressed by quartz orientation. Quartz shadow round unrotated garnet in Killiecrankie Schist. Creag a' Chaise.

the outlines of the quartz blur the minerals orientated by S_3. The strain slips of S_3 often contain iron ore. In the Ben-y-Gloe Syncline biotite appears as a late mineral and is partly mimetic after muscovite. It also replaces the outer portions of some of the garnet porphyroblasts, whereas in the Cairnwell Synform biotite did not form at any stage. Magnetite is a late accessory throughout the outcrop.

The Banded Group in the area is almost always a micaceous quartz schist consisting of alternating quartzose and micaceous layers. In the quartzose layers a folded flow cleavage, along which fine muscovite has grown, represents S_1. S_2 is the axial plane schistosity which forms the layering, and rotated the garnets, when these are present. Muscovite grew along it, but also formed after S_2, and during and after S_3. Biotite and clinochlore grew after S_2 and S_3, and the garnet was partly chloritised after S_3. Magnetite is a late mineral, as is albite when present. Late minerals are idiomorphic against those formed earlier and magnetite forms cubic crystals rather than the laths developed during the formation of a schistosity. Both the albite and the quartz recrystallised after S_3. In some localities spots with post-tectonic sphaerocrysts of chlorite are found. Veins with prochlorite, which are sometimes present, are much later in origin. Pyrite was probably an original constituent of the rock, but may have been introduced from the later lamprophyre dykes.

A rock thought to be the matrix of the Schichallion Boulder Bed outcrops on Creag Leacach. It is dark grey in hard specimen with sheared out quartz lenticles. The schistosity, along which biotite has grown, can be correlated with S_2 in the field. Hornblende, ilmenite, and zoisite are later than S_2, since they cut the mica of S_2. The hornblende has been partly replaced by chlorite, which also appears as a late mineral. Late calcite xenoblasts show development of twinning, but afterwards recrystallised.

Intermediate between the schists and limestones of the Blair Atholl Series are some schistose limestones in the Banded Group. Muscovite and biotite formed during both S_2 and S_3. Quartz and calcite recrystallised post-tectonically, and the calcite does not show twin lamellae.

b) Limestones

The Dark Limestone consists of an equigranular mosaic of calcite which shows shape orientation with twin lamellae in the grains which have not been recrystallised. The orientation is parallel to the banding which probably corresponds with S_2 in the schists. The c-axis of the crystals, as shown by the use of a mica plate, is also parallel to the banding. Quartz and zoisite are interstitial to the calcite, and magnetite is a late accessory, forming cubic crystals. S_3 is not present as a strain slip schistosity, but the crumples which form it appear as gentle flexures. In the Ben-y-Gloe Syncline biotite grew during the formation of the banding, and there is little or no late recrystallisation. In the Glen Loch region, however, where the rocks were affected by the formation of the Glen Fearnach Synform, a different sequence of events can be recognised. There was late post-tectonic recrystallisation of the calcite, which partly replaced the zoisite, while the fine graphite contained in the zoisite recrystallised. Biotite is post-tectonic since it is idiomorphic against the other minerals. In the southerly outcrops of the Cairnwell Synform there is little or no post-tectonic recrystallisation, but in the north recrystallisation has caused the obliteration of twinning in the calcite and disintegration of the muscovite formed during S_2.

The White Limestone is essentially similar to the Dark in its composition and metamorphic hostiry, and differs from it only in its lack of graphite. The striped variety, named "Tiger Rock" by Barrow (1905), is due to varying proportions of the minerals in different bands, which correspond with S_2 in the schists. The darker bands consist of calcite with a little interstitial quartz, whereas the lighter are almost entirely composed of quartz. The calcite shows shape orientation, and muscovite flakes formed along the banding. Crumples represent the folds associated with S_3, and both the quartz and calcite show late recrystallisation.

The Perthshire Quartzite Series

a) Quartzites

The Ben-y-Gloe Quartzite is a massive rock which is often felspathic and finely pebbly. Under the microscope it shows well orientated quartz and muscovite. The orientation of the quartz is given by its shape and the position of the "c" axis of the crystals as determined by the use of a mica plate. Albite and accessory magnetite are late minerals, since they form granoblastic crystals which do not follow any of the planar structures. The quartz has undergone syntectonic recrystallisation.

The Cairnwell Quartzite is sometimes a fine-grained, sometimes a pebbly quartzite. In the Cairnwell Synform the former type contains no relict sedimentary grains but farther south-west 5% - 30% of the grains are sedimentary in origin. The rest of the grains are usually fairly well orientated by shape and muscovite flakes grew parallel to S_2 in the schists from field observations. The amount of recrystallisation from north-east to south-west, and where it is strong, it has disorientated the quartz grains.

b) Killiecrankie Schist

The Killiecrankie Schist is a remarkably uniform garnetiferous quartz mica schist, except in the western part of the area where it is more quartzose. There quartz bands are common in the nose of the Glen Fearnach Synform, while the Allt Glen Loch section is entirely quartzitic and was mapped as quartzite by the Geological Survey. Otherwise there is only one mappable quartzite band, which is found on the eastern spur of Glas Tulaichean.

The schist is characterised by a strong schistosity, which is S_2. This has obliterated nearly all traces of S_1, which is followed by fine muscovite. Coarser muscovite grew during the formation of S_2, and garnet porphyroblasts were rotated between the planes of S_2. The cores of these garnets are rich in inclusions, while the rims lack them. Magnetite formed during S_2, since laths of it have grown along the micas which follow S_2. Biotite sometimes grew during S_2, forming an intergrowth with the muscovite, but is more common during and after S_3, when new muscovite and epidote are associated with it; they cut the earlier micas. Unrotated garnets developed during S_3 but were often chloritised post-tectonically, when clinochlore also grew after the late biotite. Hornblende is an occasional late mineral, and late albite, which is found in the part of the outcrop following the Caledonoid trend, is zoned. Quartz, muscovite, and biotite show some post-tectonic recrystallisation, in which the crystals grew to blur the shapes of the grains formed during S_2 and S_3.

Near the boundary slides the schistosity in the Killiecrankie Schist is sharper, while the micas are coarser and show a lamellar intergrowth of muscovite and biotite. There are late strain bands, oblique to the schistosity, which contain calcite. The quartzite found near the slide at the head of Glen Fearnach shows strong syntectonic recrystallisation so that no sedimentary grains are left.

The Ben Eagach Schist

Between the Cairnwell Quartzite and the Ben Eagach Schist on Ben Gulabin there is wide outcrop of transition rocks, which consist of alternating bands of quartz and mica. These bands were formed by a sharp schistosity, probably S_2, during the formation of which muscovite and magnetite grew. Muscovite was also produced during S_3; all the muscovite recrystallised post-tectonically. Biotite and chlorite both formed during the post tectonic period but the chlorite was somewhat later than the biotite, since chlorite sometimes replaces biotite.

The Ben Eagach Schist near the Spittal of Glenshee is a soft, black, finely crystalline, mica-schist, which weathers rusty, owing to its content of pyrites. At this locality it is straight-cleaved and garnet-free. When, however, it is traced to the north-east, round the Cairnwell Quartzite, it becomes somewhat lighter because it contains a smaller proportion of graphite, while the planes of schistosity are puckered and small garnets are common.

In thin section the black variety from Glenshee reveals S_1, S_2, S_3 and S_3^1. S_3^1 is a strainslip similar to S_3 but with a different inclination relative to S_2. The plunge of its crumples, however, remains coaxial with that of the crumples of S_3. S_1 is represented by a flow cleavage along which muscovite has grown and which has been cut through by the schistosity, S_2. Muscovite has developed along S_2, and also along S_3 and S_3^1. Both muscovite and quartz have been slightly recrystallised but recrystallisation may have been somewhat inhibited by the high proportion of graphite present. Late magnetite is accessory.

The dark schist found on the flanks of the Cairnwell Synform shows a well developed schistosity which is S_2. Both muscovite and biotite, with accessory epidote, grew during its formation and also during S_3. Idiomorphic garnets have been rotated between the planes of S_2. Quartz, muscovite, and biotite have all recrystallised post-tectonically. Late magnetite is accessory.

The Ben Eagach Schist of the south-western part of the area is essentially similar to that of the Cairnwell Synform but does not contain so much graphite as at the Glen Shee exposures. Although some rotated garnets are present other garnets are a later growth associated with S_3

but have suffered post-tectonic chloritisation. Biotite is not found in the north-eastern part of the area but towards Glen Fearnach it has developed along S_3 and has suffered post-tectonic recrystallisation along with the muscovite. Near the Ben Lawers Schist in Glen Fearnach post-tectonic hornblende is found in the Ben Eagach Schist. It in turn is replaced by chlorite.

Another peculiar rock is found along some parts of the junction of the Ben Lawers and Ben Eagach Schists in Glen Thaitneich. This is characterised by very large garnets which are associated with S_3, and has been termed the "Big Garnet Rock" (see p. 16). The garnets have a higher proportion of inclusions, mostly quartz, than is usual but the matrix differs little from the normal black schist. The mica, however, has been entirely replaced by a greenish chlorite with the separation of much late magnetite.

The Ben Lawers Schist

The Ben Lawers Schist near the Cairnwell Synform shows S_1 as a flow cleavage with muscovite and chlorite. These minerals also develop along S_2 and S_3. Calcite is orientated along S_2 by shape but disintegration during S_3 has destroyed twinning. Chlorite has recrystallised post-tectonically to form fan shaped crystals intergrown with muscovite. Quartz and calcite also show strong post-tectonic recrystallisation. Late biotite is sometimes mimetic along the schistosity. Ilmenite has developed as an accessory along S_2 while magnetite, sphene and epidote are late.

A little farther south-west the essential picture remains the same but biotite is more common and has sometimes developed along S_2 and S_3. Late hornblende xenoblasts are post-tectonic. Ilmenite has grown during S_2 while epidote is late and is associated with orthite in Glen Lochsie.

In Glen Fearnach the earlier events are similar to those described above, but are partly obscured by strong post-tectonic recrystallisation. This affects muscovite and biotite while calcite takes the form of xenoblasts without twinning. Hornblende and plagioclase are both post-tectonic. The latter shows zoning in dependence on muscovite inclusions; beside the latter there is a thin zone of albite while the main part of the crystal consists of andesine. At the head of Glen Fearnach, however, the plagioclase has suffered extensive sericitisation.

The actinolitic facies of the Ben Lawers Schist is well developed only on Creag Lamhaich. Here S_2 contains chlorite which has been post-tectonically recrystallised. The schistosity, however, has been largely obliterated by the late growth of actinolite poikilitic xenoblasts and garnet which has formed in the interstices between the actinolite. These garnets are riddled with quartz and magnetite inclusions which, however, are not rotated. Magnetite is also a common late accessory in other parts of the rock. A little calcite is also of later growth.

The limestones in the Ben Lawers Group are essentially similar to those of the Blair Atholl Series. They are most common along Glen Fearnach and their metamorphism corresponds to that of the schists in this area. S_2 is shown by coarse calcite with good shape and lattice orientation, the latter being revealed by strong twinning. Muscovite included in the calcite is also parallel to the schistosity. It contains graphite, as does late albite. Interstitial quartz, magnetite, and tabular epidote are late accessories. Near the head of the glen the calcite grains vary greatly in size in the different planes of schistosity and large idiomorphic garnets without inclusions are of late growth.

The Epidiorites

The epidiorites in this area, when they have not suffered retrogressive metamorphism, can be placed in two main categories according to the presence or absence of garnet. According to Wiseman (1934) both types can be equated with the garnet zone of the semi-pelites. Both types are chiefly composed of hornblende and plagioclase and can be further subdivided by the presence of biotite, epidote, or both these minerals.

The epidiorites may conveniently be considered, not on their mineral content, but on their structural position.

Epidiorites in the Ben Lawers Schist

The epidiorites in the Ben Lawers Schist usually lack garnet. A specimen from the centre of a thick sill serves to illustrate the least metamorphosed epidiorites found in the area. It has been so little affected by later movements that it is more igneous than metamorphic in character. In hard specimen it shows no sign of the schistosity usually found to at least some degree in an epidiorite. A thin section reveals that it consists of an aphanitic groundmass of hornblende and plagioclase crystals with a doleritic texture in which are set pseudomorphs of chlorite after phenocrysts of augite. Epidote, magnetite and granular sphene are accessories while calcite is secondary.

The texture serves to show that the rock has been preserved from most of the effects of regional metamorphism by its presence in the centre of a thick sill.

The usual type of epidiorite reveals good grain orientation which may be equivalent to S_2 in the schists. This orientation is formed by the growth of large hornblende crystals and accessory epidote. Magnetite sometimes formed along the grain boundaries of the hornblende. Gentle crumples may represent the crumples associated with S_3 in the schists. Smaller hornblendes have grown along S_3. Late magnetite is a common accessory and plagioclase has undergone post-tectonic recrystallisation. The plagioclase ranges from albite to andesine. When garnets are present they are usually chloritised.

Hornblende schists found at the margins of the sills usually consist of streaks and lenticles of the epidiorite within the country rock. They contain the same structures as the surrounding schists. Farther out from the intrusions, the country rock contains hornblende crystals which have been introduced from the epidiorites during metamorphism.

Epidiorites in the Killiecrankie Schist

The epidiorites in the Killiecrankie Schist follow the planes of the regional schistosity (S_2), and have been refolded by the folds associated with S_3. They are usually finer grained than those in the Ben Lawers Schist and garnetiferous types are common. They show strong orientation of the hornblende crystals and sometimes biotite and epidote are similarly aligned. This orientation may represent S_3 in the schists. Garnets, both with and without inclusions, are present but have not been rotated. The plagioclase has recrystallised post-tectonically and is usually of the composition of andesine. Late magnetite and sphene are accessories.

Retrogressive Metamorphism

A characteristic feature of those epidiorites in the garnet zone which have not suffered retrogressive metamorphism is the absence of muscovite. In retrogressive metamorphism, which is caused by late shearing, the hornblende, biotite, and garnet are converted into chlorite and calcite. At a later stage in the process white mica is also formed. There is an increase in the proportion of the albite molecule in the plagioclase but this alteration does not occur so readily as those in the ferromagnesian minerals.

Summary of Mineral Development

In the schists S_1 is characterised by the growth of fine muscovite. S_2 rotates garnets when these are present, and muscovite and sometimes biotite and chlorite have formed along it. Ilmenite and magnetite may be accessories associated with S_2. Muscovite, biotite, and chlorite are also found along S_3. Biotite and chlorite have often developed after S_3; the chlorite is usually later than the biotite. In the Ben Lawers Schist calcite was orientated by S_2 but recrystallised during S_3. Plagioclase porphyroblasts and hornblende are late minerals. Quartz, mica, and albite have usually suffered post-tectonic recrystallisation.

The limestones show good orientation of calcite during the formation of a banding which may be correlated with S_2. Later crumpling, however, has often caused recrystallisation.

Sedimentary grains are best preserved in the south-western outcrops of the Cairnwell Quartzite, where they may make up 25% of the rock. The remainder of the grains are usually fairly well orientated. Post tectonic recrystallisation is usually slight. The Cairnwell Quartzite of the type area and the Ben-y-Gloe Quartzite show good orientation with syntectonic recrystallisation. This orientation may correspond with S_2.

Syntectonic recrystallisation in all rock types is strongest along Glen Fearnach. Unrotated garnets are chiefly found in Glen Fearnach.

The epidiorites in the Ben Lawers Schist are characterised by the growth of hornblende along the schistosity, which probably corresponds with S_2, and plagioclase has recrystallised post-tectonically. Those in the Killiecrankie Schist have been intruded along S_2 and their minerals show orientation corresponding to S_3. Garnetiferous types are more common in the Killiecrankie Schist.

VIII MAJOR INTRUSIONS

Two major intrusions are present in the area, the Carn Mor Granite or Porphyry and the Glen Shee Diorite. They are dissimilar in form as well as in composition although both probably belong to the same period of intrusion, that of the Younger Granites of Caledonian age. These are post-tectonic masses in which the mode of emplacement was intrusion rather than replacement as in the Older Granites which often take the form of gneisses.

1. The Carn Mor Porphyry

This rock is variable in texture in different parts of its outcrop. On Carn Mor itself it is a fine granite and has been coloured as such on Sheet 65 of the Geological Survey one-inch map of Scotland. A peculiarity of its outcrop, however, is the number of apophyses which extend from the main mass and these grade down in grain size to that of a quartz porphyry. The chief of these runs south-west across Glen Lochsie and then turns through a right angle to the south-east to form the crest of the ridge between Glen Lochsie and Glen Fearnach. Its outcrop becomes narrower and its texture finer along this outcrop until it dies away on Lairig Charnach. The form of this apophysis is that of a dyke cutting the metasediments as is that of the tongue which is well exposed on Carn nan Sac and extends to the Allt a' Ghlinne Bhig and also of that on Creag a' Choire Dhirich.

The margins of the main outcrop, however, are not well enough exposed to reveal the nature of the contacts since the intrusion stands above the country rock like a wall on the higher parts of the hills and scree obscures the junctions. This attitude would seem to indicate that the intrusion takes the form of a sill of which the south-western tongue is the feeder dyke. Alternatively the tongue may have been fed from the sill the feeder of which is not exposed since it occurs below the sill. Another argument in favour of the intrusion being a sill is that there is no displacement of the host rocks which would be expected if an intrusion of this size emplaced from below. The main body of the intrusion is everywhere in contact with the Blair Atholl Series while the tongues cut through the underlying rocks to reach the Ben Lawers Schist in one place. A striking feature of this large intrusion is the slight thermal effects it has produced on the surrounding schists which are only baked or indurated for a few feet. This supports the conclusion that the form of the intrusion is that of a sill.

Petrographically the porphyry on Carn Mor is composed of quartz, orthoclase and plagioclase with chloritised mica and magnetite as accessories. The quartz is cleared and unaltered but is lobate in form indicating that it has been corroded by the felspar. The latter, on the other hand, has been largely altered; the orthoclase in particular has been affected. This alteration chiefly consists of sericitisation. The felspar which is more abundant than the quartz, occurs in large crystals, the orthoclase being euhedral and the subordinate plagioclase, some of which is well zoned, subhedral. The plagioclase is of the composition of oligoclase.

The tongue reaching down to Glen Beag is similar in composition but different in texture. The rock found here is a porphyry formed of phenocrysts of altered felspar together with a few quartz grains set in a matrix of smaller crystals of the same minerals, the felspar being similarly altered and the quartz even less evident than in the phenocrysts. The felspar of the phenocrysts is chiefly plagioclase about oligoclase. Occasional phenocrysts of chloritised biotite with granular sphene and secondary calcite appear while magnetite is accessory.

A marginal variety from the Clais Mor is more acidic in composition. Rounded phenocrysts of quartz are rare and most of the rock is composed of altered felspar laths which are chiefly orthoclase but there is some oligoclase. Chlorite forms after biotite and sericite is the commonest alteration product of the felspar. Magnetite is accessory and calcite secondary.

The dyke like part of the intrusion crossing the Lochsie Burn shows the same type of quartz and felspar phenocrysts as those found in Glen Beag. The felspars in both the phenocrysts and the groundmass are so heavily sericitised that they are difficult to determine but both orthoclase and some plagioclase are present. Some large chlorites appear to be replacing biotite, and ilmenite is accessory.

2. The Glen Shee Diorite

This intrusion occupies low ground to the east of Glen Shee which mainly lies outside the area of this thesis so that only its northern and eastern margins have been mapped, where it cuts the Ben Lawers Schist and the Duchray Hill Gneiss. To the north the diorite appears to pass under the country rocks forming the high ground of the Creag of Rinnavey but its eastern margin is probably vertical.

It has been described in detail by Williamson (1935) and the following is confirmatory of his findings. The diorite is poorly exposed over most of its area although its presence can be ascertained by the frequent occurrence of boulders. The two main areas of exposure to be described are near Dalhenzean and along the base of the Creag of Rinnavey. There are other marginal exposures further east but these have not been mapped.

The great mass of the rock is made up of what Williamson has termed the "Main Granodiorite". It is medium grained and pinkish in colour because of weathered felspar which together with grey quartz is the chief constituent of the rock. There are small patches of mafic minerals. In this section the felspar can be seen to be dominantly plagioclase which forms well zoned euhedral to subhedral crystals. It varies from oligoclase to acid andesine in composition and shows frequent sericitisation. Quartz and a little orthoclase are moulded on the plagioclase. Biotite is fairly abundant and is strongly pleochroic from yellow to dark brown. It also shows lamellar twinning and is sometimes altered to chlorite. Hornblende is a pale green variety and shows twinning. It is optically negative with an extinction angle of 22°. Sphene, magnetite and pyrite are accessory and small euhedral crystals of apatite appear in places.

A more acid variety is found on Craigenloch Hill which is white in colour because of less altered plagioclase. It contains a smaller proportion of the ferromagnesium minerals and is slightly finer in grain probably because it is marginal.

At Dalhenzean the marginal phase of the intrusion is somewhat more basic than the main body probably because it represents one of the early phases of intrusion. Its mineralogy is similar to that of the main granodiorite but the plagioclase is slightly more basic and the mafic minerals are more abundant.

Below the Craig of Rinnavey a porphyrytic variety of the diorite forms the margin. This is formed of large euhedral and subhedral felspar phenocrysts together with some smaller phenocrysts of quartz, biotite and scarce green hornblende. Plagioclase is dominant over orthoclase in the phenocrysts and consists of zoned andesine while the biotite and hornblende are chloritised. The phenocrysts are set in a groundmass of granular plagioclase, quartz and orthoclase. Epidote, zircon, ilmenite, magnetite and pyrite are accessories. Sphene and rutile are associated with the chlorite.

<u>Thermal Metamorphism caused by the Diorite</u>

a) <u>Contact with the Ben Lawers Schist</u>

The two crags on either side of Glen Shee, the Craig of Rinnavey on the east and Creag Bhinnein on the west which lie to the north of the diorite stand up like a wall above the low-lying intrusion. This is due to hardening by the alteration of the Ben Lawers Schist so that the crags have resisted erosion more than is usual for this formation. The Ben Lawers Schist is a variable group which is reflected in the variety of its hornfelses although individual beds cannot be followed into the aureole of the diorite. The hornfels can be divided into broad groups a) pelitic and b) siliceous. The pelitic variety is a fine grained mixture of diopside and andesine. From its habit sericite replaces both cordierite and silliemanite while andalusite is also found. Interspersed among the amphibole and plagioclase crystals are quartz, magnetite, biotite and apatite. A vein cutting this hornfels now almost entirely consists of chlorite but also contains small plagioclase and biotite crystals so probably once was dominantly micaceous. Magnetite is accessory in the vein.

The siliceous type consists of quartz and biotite together with some plagioclase. Strongly biotite rich layers in which the biotite is a strong reddish brown and iron rich as is common in thermal metamorphism are present. Patches of chloritised biotite are found alongside fresh dark crystals of the mineral so the latter appears a second post-chloritisation generation. Patches of pelitic material are found in the psammitic and vice versa.

On Creag Bhinnean the dominant rock type is a fine grained type which is poorly laminated. It is made up of porphyroblasts of bright green hornblende set in a quartzo-felspathic matrix which has been somewhat altered. Sericite is also a constituent. Magnetite is a frequent accessory usually associated with the hornblende and chlorite replaces small garnets. A vague isoclinal folding has affected the hornblende crystals and the strain slip direction is followed by quartz veins. The greater width of the aureole here supports the view that the diorite underlies this crag and the Craig of Rinnavey.

The epidiorites within the Ben Lawers Schist have also undergone thermal metamorphism by the Glen Shee Diorite. They are essentially composed of green hornblende and plagioclase and a little biotite, mostly altered to chlorite, which is a typical composition for an epidiorite. The hornblende, however, has been broken down into smaller crystals by the thermal metamorphism. Magnetite is abundant and sometimes appears as granular aggregates within the hornblende which is strongly pleochroic. The plagioclase which is of the composition of andesine ranges in size from large crystals to small needles. It is cloudly with alteration but shows zoning. Masses of chlorite and iron ore appear to be secondary after garnets. Quartz and sphene are infrequent while small diopsidic pyroxenes appear in some specimens. Small flecks of pyrite which is a characteristic accessory mineral of the diorite are present.

b) Contact with the Duchray Hill Gneiss

Slivers of Duchray Hill Gneiss which have been thermally metamorphosed by the Glen Shee Diorite are caught up between it and the large patch of felsite to the north of the main intrusion. This outcrop was mapped as granite by the Survey but recognised by Williamson as felsite which is often altered. The largest of these slivers is found at the eastern end of the Craig of Rinnavey.

Petrographically the unaltered Duchray Hill Gneiss is an oligoclase muscovite biotite gneiss consisting of well banded quartz felspar layers alternating with micaceous ones. Plagioclase is the dominant constituent in the quartzo-felspathic layers and forms large crystals of subhedral or elongate shape. Its composition is that of oligoclase while orthoclase is rare. The quartz is nearly as frequent as the oligoclase but forms smaller grains, the larger of which often show extinction. The quartz crystals have interlocking margins to both the felspar and other quartz while the quartz and felspar boundaries are often followed by a yellowish brown limonitic film. Small flakes of biotite and sericite are enclosed by the quartz and felspar.

The micaceous layers are formed of biotite and six-sided muscovites which the Survey thought proved that the rock was igneous in origin. Numerous garnets are present in forms ranging from euhedral to shimmer aggregates. Plates of tourmaline sometimes replace the micas. Epidote, apatite and ilmenite are accessory.

The micaceous layers represent the Ben Lui Schist host rock while the quartzo-felspathic layers are the later invasive portion. The latter follows both the bedding and the axial plane schistosity and is therefore later than the recumbent folding.

Boundaries cannot be definitely drawn between the Gneiss and the Ben Lui Schist since the proportion of granitic material varies over the area but generally is greatest in the centre of the outcrop and decreases outwards. Quartzitic intercalations are found in the gneiss but these contain a high proportion of oligoclase and have been affected by the formation of the gneiss.

In gneiss thermally metamorphosed by the Glen Shee Diorite the alteration produced is more apparent in the micaceous layers. In them the biotite crystals break down into a decussate network and assume a reddish brown tinge commonly found in the biotite of a hornfels. Muscovite appears to be subordinate to the biotite in these layers. Yellowish chlorite is associated with the biotite and also replaces the shimmer aggregates around garnets. Ilmenite and clinozoisite are accessory.

The quartzo-felspathic layers sometimes show recrystallisation into a finer grained mosaic. Pyrite is often introduced from the diorite of which it is a characteristic accessory mineral.

IX MINOR INTRUSIONS

There are two chief groups of minor intrusions in the area, both of which are found in all regions. The more acid mainly includes granitoid porphyry and felsite sheets which follow the schistosity and so help to illustrate the regional structure. The thicker and coarser members of this group are porphyries while the thinner are felsites as are some dykes which cut the dykes of the lamprophyre group which is earlier and more basic. The latter dykes were termed lamprophyres by the Survey although it was recognised that they are very variable in composition. Barrow (1912) states that "In mode of occurrence and also to a great extent in composition they resemble the rocks for which Gumbel proposed the term lamprophyre, and seeing that they must be grouped together for mapping purposes that seems the best name to apply to them". Although in fact some true lamprophyres are present, diorites, dolerites and porphyrites are more common. This wide range in composition caused the Survey to map some of the quartz porphyries as lamprophyres even when they are not typical lamprophyres and are sheet-like in form.

Porphyries

The group term porphyry includes porphyries in which felspar is the chief mineral but also quartz porphyries in which there is an appreciable proportion of quartz in both phenocrysts and groundmass and felsites which are the finer grained equivalents of both types.

Quartz porphyries and porphyries are chiefly found in the northern part of the area while felsites predominate in the southern.

The true porphyries consist of large felspar phenocrysts together with some smaller ones of quartz set in a groundmass of quartz and felspar. The felspar is more abundant than the quartz and varies in composition in different specimens from equal orthoclase and plagioclase to dominant plagioclase which ranges from oligoclase to labradorite; it is usually altered. The quartz phenocrysts are often corroded by the groundmass. There are some small chlorite phenocrysts which are usually after hornblende but sometimes after biotite. Chlorite is also present in the matrix and sphene, epidote, magnetite and apatite may be accessory while calcite is a common secondary mineral.

The quartz porphyries are similar in type but contain a higher proportion of quartz and orthoclase relative to the plagioclase. The latter ranges from albite to oligoclase and phenocrysts of perthite are also found.

The felsites are finer grained than the porphyries and are usually composed of a very fine grained matrix of quartz and felspar in which are set phenocrysts of quartz and felspar, together with some smaller ones of biotite, often being replaced by chlorite. Although the felspar in both phenocrysts and matrix is altered it can be recognised as chiefly orthoclase but dome albite or oligoclase is sometimes present. Magnetite sometimes forms small phenocrysts as well as being a common accessory, as are sphene and apatite.

Contact Metamorphism caused by the Porphyries

The thermal effects of these intrusions on their host rocks is generally slight, being confined to baking a few inches from the contact. In the Allt Aulich, however, there is a porphyritic diorite in the form of a dyke which has produced considerable effects on the country rock.

It cuts through Ben Eagach Schist and Cairnwell Quartzite; the latter, however, has suffered little. The quartz in the schist likewise has been unaffected but the plagioclase and perthite associated with it show extensive sericitisation and recrystallisation. The mica bands, however, are now completely broken down into sericite and the latter has been replaced by chlorite in parts. Magnetite and graphite as accessories are little affected.

Lamprophyres

They occur only as dykes but resemble the Glen Shee Diorite in composition and since they are earlier than the porphyries which cut them. If they are associated with the diorite while the porphyries are linked with granites like the Carn Mor Porphyry then the latter must be younger than the Glen Shee Diorite. The diorite and the lamprophyres then probably represent an early intermediate phase of the Younger Granite intrusive period.

The dykes nearly always trend between N.E.-S.W. and N.N.E.-S.S.W. which indicates that there was tension acting at right angles to this direction after the stresses which had caused the folding had ceased.

The lamprophyre dykes range in texture from moderately coarse grained to fine grained and from granular to porphyritic. Their width is seldom more than a few feet while hardly ever less than one foot. In hand specimen they are usually reddish in colour because of the presence of ferric oxide formed during weathering but are bluish-grey when fresh.

In the true lamprophyres both hornblendic and biotitic types are common with these minerals forming small round patches on the surface of the rocks. Petrographically the hornblendic variety consists of phenocrysts of green hornblende which may vary from large crystals to some which are little bigger than those of the matrix. They are set in a quartz felspar matrix in which plagioclase near andesine is dominant but there is a little orthoclase. The phenocrysts show considerable corrosion by this matrix and large patches of chlorite and calsite may represent former hornblende crystals. Magnetite, granular sphene and epidote usually in the form of needles are accessories.

The biotitic lamprophyres are essentially similar to the hornblendic ones except that biotite, which is often chloritised, takes the place of hornblende. At the same time the groundmass is more acidic and orthoclase is more common than plagioclase which remains of andesine composition. Quartz is also more common than plagioclase but is subordinate to the latter in hornblendic lamprophyres. The strongly corroded and highly altered phenocrysts show that reaction with the matrix has occurred. Magnetite is a common accessory while epidote is less frequent. Calcite and chlorite are secondary. The presence of mafic phenocrysts, which are not in equilibrium with the groundmass and so have reacted with it, is an essential feature of the lamprophyres as classified by Rosenbusch after Gumbel.

Corresponding to these two varieties are rocks which may be termed hornblende and mica porphyrites because they contain a smaller proportion of the ferromagnesian minerals as microphenocrysts. Quartz and felspar are also found as small phenocrysts and occur in the groundmass together with the appropriate mafic constituent. Reaction between the phenocrysts and the matrix is less intense than in the lamprophyres.

There is a further group of these dykes which may best be described as dolerites. They are chiefly composed of small equigranular felspar laths, the greater proportion of which are plagioclase. The composition of this mineral ranges from andesine to labradorite. A little subhedral quartz occurs in the more acidic varieties. Amongst these grains are set some small phenocrysts of orthoclase and plagioclase, the latter appearing to be somewhat more acidic than the smaller laths of the matrix. There may also be present a few crystals of calcite, probably secondary, which contain rounded quartz inclusions. In the groundmass chlorite is common after hornblende and magnetite is a common accessory which occasionally forms large crystals.

Finer grained specimens show small felspar phenocrysts of lath-like shape in a fine matrix of felspar with a little quartz and chloritised mafic minerals. These felspar phenocrysts are approximately the same size as those found in the groundmass of the coarser types.

Andesine is the chief felspar in the phenocrysts while hornblende appears to be the dominant mafic mineral in the groundmass. Magnetite is accessory and calcite secondary.

Contact Metamorphism caused by the Lamprophyres

The thermal effect of these dykes is generally slight but occasionally the country rocks show some degree of hornfelsing.

X CONCLUSIONS

Bailey's stratigraphical sequence is confirmed.

His mapping is modified in detail only in regard to the linking of various outcrops of Cairnwell Quartzite. The most important difference occurs at the head of Glen Fearnach, where the Ben Eagach Schist has been cut out by the Southern Slide, and does not swing round the nose of the Glen Fearnach Synform to join the quartzite outcrop on the north-eastern side of the glen.

The basic structure of the area is thought to be formed by two Caledonoid recumbent folds, the Ben-y-Gloe Syncline and the Ben Lui Syncline. The Ben-y-Gloe Fold outcrops in the north of the area, while the Ben Lui Syncline covers the rest. The latter was refolded by later folds on N.E.-S.W. and N.W.-S.E. axes which complicate the outcrops.

The relations between the various belts of the Perthshire Quartzite are thought to be different from those envisaged by Bailey (1925). The minor folds in Glen Mor suggest that the Ben-y-Gloe Quartzite forms a synform and not an antiform as held by Bailey. The Ben-y-Gloe Quartzite would then pass to the Killiecrankie Schist over the nose of an anticline, whose core is formed by the Blair Atholl Series outcropping between the two members of the Perthshire Quartzite Series. The Killiecrankie Schist and the underlying Blair Atholl Series form the lower limb of the Ben Lui Fold, of which the Ben Lawers Schist forms the core, except in the south of the area where the Ben Lui Schist is found. The Ben Eagach Schist was eliminated by sliding in the lower limb so that the

Ben Lawers Schist of the core lies on the Killiecrankie Schist. A strip of Ben Eagach Schist is preserved in Glen Fearnach.

The Cairnwell Synform is a later downfold on the N.E.-S.W. axis, in which the upper limb of the Ben Lui Fold is preserved. The Cairnwell Quartzite would link with the Ben-y-Gloe Quartzite over the outcrop of the Killiecrankie Schist, so that the Ben-y-Gloe Syncline could be regarded as the extended nose of the Ben Lui Syncline. The axial plane of the Ben-y-Gloe Syncline, however, dips steeply to the south-east, whereas that of the Ben Lui Fold is essentially horizontal but has been modified by later folds.

The Ben Eagach Schist and Perthshire Quartzite outcrops to the south-west of Glen Shee are the cores of downfolds of the Cairnwell Belt on the N.W.-S.E. axis, while the Killiecrankie Schist appears in the cores of antiforms. The Ben Lawers Schist forms the envelopes of the folds. The Glen Fearnach Synform is a similar downfold with south-easterly plunge; the Ben Lawers Schist forms the core and the Killiecrankie the envelope. The axial plane of the Glen Fearnach Synform dips to the north-east.

Evidence for the three fold systems is given by the minor structures. Early Caledonoid folds with a strong axial plane schistosity were refolded on both the N.E.-S.W. and the N.W.-S.E. axes. The later Caledonoid folds are later than the cross folds, since they refold the latter. The late Caledonoid folds, however, cannot be unfolded without partly unfolding the cross folds, so that both systems must be in part contemporaneous. Strain slip schistosities are sometimes associated with the later folds.

In the schists, mica has grown in sequence along the regional schistosity, the later strain slips, and also along planes earlier than, and cut by the regional schistosity. The micas, together with quartz and felspar, have undergone post-tectonic recrystallisation. Some of the garnets have been rotated between the planes of the regional schistosity, but others are later, and have not been rotated. The quartzites and limestones appear to show grain orientation by shape parallel to the regional schistosity.

Two sets of epidiorites are present in the area. Those in the Ben Lawers Schist were intruded before the formation of the regional schistosity, which cuts through them. The epidiorites in the Killiecrankie Schist, however, were emplaced along the schistosity and were refolded with it.

It is suggested that the Carn Mor Porphyry is a sill rather than a stock because of its field relations and petrography. Williamson's work on the Glenshee Diorite and its thermal metamorphism is confirmed.

The lamprophyre suite of dykes contains other rock types as well as true lamprophyres. The quartz porphyry and felsite sills follow the regional schistosity.

Acknowledgements

The writer desires to offer his sincere thanks to many people for their encouragement and advice during this work.

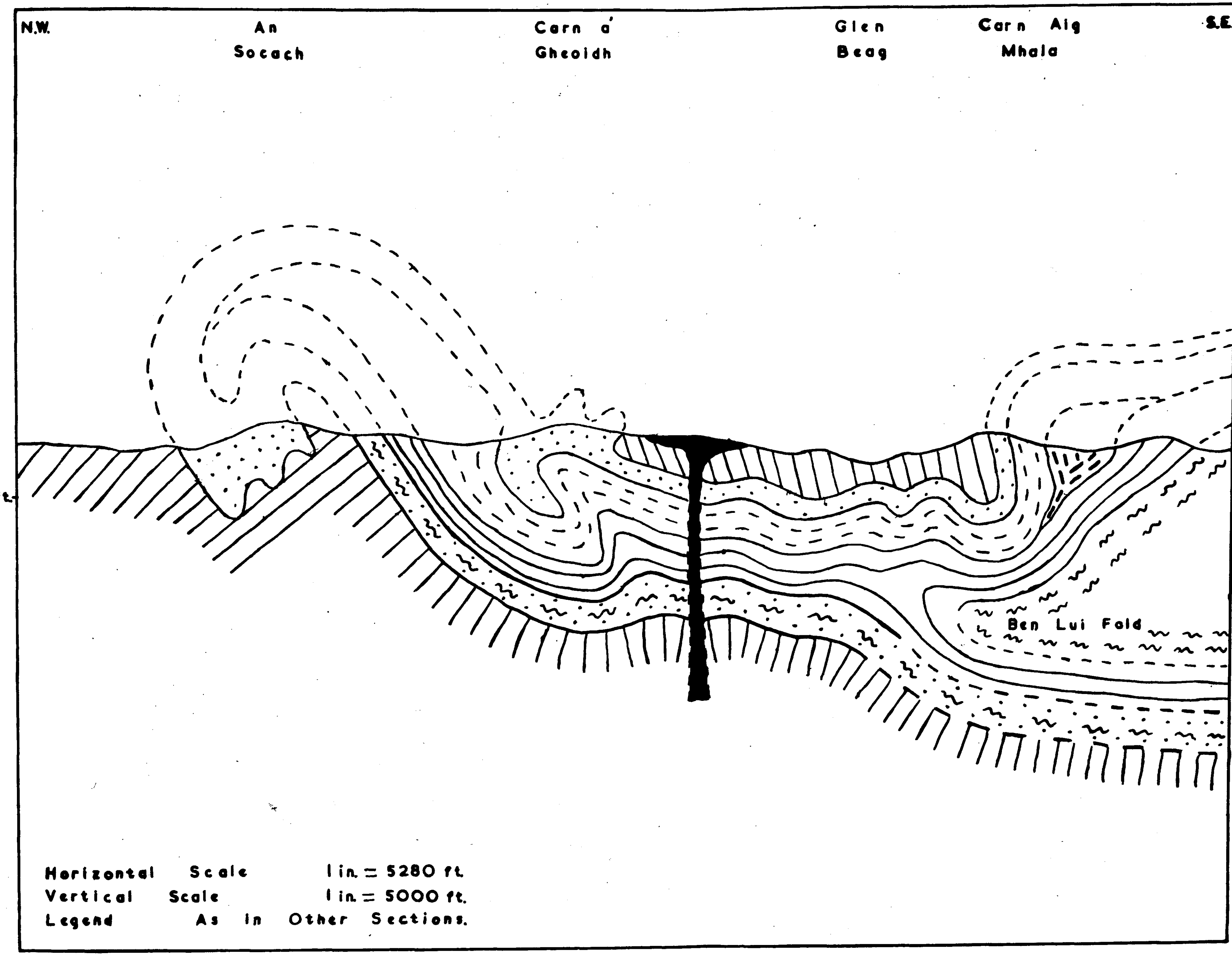
He is especially grateful to Professor B.C. King for originally suggesting the subject and for his help and guidance during the course of research, both in the field and laboratory. His thanks are also due to Professor T.N. George for his encouragement and for reading the manuscript.

Special mention should be made of Dr. G. Voll for his guidance in the microscope work.

The writer also acknowledges his indebtedness to the trustees of Murdo Macaulay's Charitable Fund for providing a maintenance grant for the three years spent on research.

He is grateful to landowners who allowed access to their ground, especially Sir D. Heathcoat Amory of Glenfernate Lodge and Mr. Spearman of Fealar Lodge for the use of their private road.

FIG. 43. N.W.-S.E. SECTION ACROSS THE AREA.



REFERENCES

ANDERSON, E.M. 1923. The geology of the schists of the Schichallion District.
Quart. Journ. Geol. Soc. Lond. 79, p.433.

BAILEY, E.B. 1910. Recumbent Folds in the Schists of the Scottish Highlands.
Quart. Journ. Geol. Soc. Lond. 66, p.586.

1922. The Structure of the South-West Highlands of Scotland.
Quart. Journ. Geol. Soc. Lond. 78, p.321.

1925. Perthshire Tectonics: Loch Tummel, Blair Atholl and Glen Shee.
Trans. Roy, Soc. Edinb. 53, p.671.

1928. Schist Geology: Braemar, Glen Cluie and Glen Shee.
Trans. Roy.Soc. Edinb. 55, p.737.

1934. West Highland Tectonics: Loch Leven to Glen Roy.
Quart. Journ. Geol. Soc. Lond. 90, p.462.

and H.B. MAUFE. 1916. The geology of Ben Nevis and Glencoe.
Mem. Geol. Surv. U.K.

and W.J. McCALLIEN. 1937. Perthshire Tectonics: Schichallion to Glen Lyon.
Trans. Roy. Soc. Edinb. 59, p.79.

BALK, R. 1936. Structural and Petrologic Studies in Dutchess County, New York. Part I.
Bull. Geol. Soc. Amer. 47, p.685.

BARROW, G. 1893. On an Intrusion of Muscovite Biotite Gneiss in the South-eastern Highlands of Scotland and its accompanying Metamorphism.
Quart. Journ. Geol. Soc. Lond. 49, p.330.

1904. On the Moine Gneisses of the East-Central Highlands and their Position in the Highland Sequence.
Quart. Journ. Geol. Soc. Lond. 60, p.400.

et. al. 1905. The geology of the country around Blair Atholl, Pitlochry and Aberfeldy.
Mem. Geol. Surv. U.K.

and E.H. CUNNINGHAM CRAIG. 1912. The Geology of the district of Braemar, Ballater and Glen Clova.
Mem. Geol. Surv. U.K.

et. al. 1913. The Geology of Upper Strathspey, Gaick, and the Forest of Atholl.
Mem. Geol. Surv. U.K.

BILLINGS, M.P. 1937. Regional metamorphism of the Littleton - Moosilauke area, New Hampshire.
Bull. Geol. Soc. Amer. 48, p.463.

CLOOS, E. 1946. Lineation, a critical review and annotated bibliography.
Geol. Soc. Amer. Mem. 18.

CUMMINGS, W.A. and R.M. SHACKLETON. 1955. The Ben Lui Recumbent Syncline (S.W. Highlands).
Geol. Mag. 92, p.353.

GILMOUR, P. and D.B. MACINTYRE. 1954. The Geometry of the Ben Lui Fold (Scottish Highlands).
Geol. Mag. 91, p.161.

GUNN, W. et. al. 1897. The Geology of Cowal.
Mem. Geol. Surv. U.K.

HARKER, A. 1932. Metamorphism. and 3rd Edition 1950.

HOLTEDAHL, O. 1952. The structural history of Norway and its relation to Great Britain.
Quart. Journ. Geol. Soc. Lond. 108, p.65.

KING, B.C. 1955. The Tectonic Pattern of the Lewisian around Clashnessie Bay near Steer, Sutherland.
Geol. Mag. 92, p.69.

and N. RAST. 1955. Tectonic Styles in the Dalradians and Moines of parts of the Central Highlands of Scotland.
Proc. Geol. Assoc. 66, p.243.

and N. RAST. 1956. The Small-Scale Structures of South-eastern Cowal, Argyllshire.
Geol. Mag. 93, p.185.

KOLDERUP, C.F. and N.H. 1940. Geology of the Bergen Arc System.
Bergens Mus. Skr. 20.

FAIRBAIRN, W.H. 1942. Structural Petrology.

KVALE, A. 1953. Linear structures and their relation to movements in the Caledonoids of Scandinavia and Scotland. Quart. Journ. Geol. Soc. Lond. 109, p.51.

KNOPF, E.B. and E. INGERSON. 1938. Structural Petrology. Geol. Soc. Amer. Mem. 6.

MACGREGOR, A.G. 1948. Scotland: The Grampian Highlands. British Regional Geology. Geol. Surv. U.K. 2nd edition.

MACINTYRE, D.B. 1951. The tectonics of the area between Grantown and Tomintoul (mid-Strathspey). Quart. Journ. Geol. Soc. Lond. 107, p.1.

1952. The tectonics of the Beinn Dronsig Area, Attadale. Trans. Edinb. Geol. Soc. 15, p.258.

PHILLIPS, F.C. 1930. Some Mineralogical and Chemical Changes Induced by Progressive Metamorphism in the Green Bed Group of the Scottish Dalradians. Mineralogical Mag. 22, p.239.

RAST, N. 1957. Tectonics of the Schichallion Complex. Quart. Journ. Geol. Soc. Lond.

and J. PLANT. 1957. Cross Folds. Geol. Mag. 94, p.159.

READ, H.H. 1955. The Banff nappe: an interpretation of the structure of the Dalradian rocks of North-East Scotland. Proc. Geol. Assoc. 66, p.1.

REYNOLDS, D.L. and A. HOLMES. 1954. The Superposition of Caledonoid Folds on an Older Fold System in the Dalradians of Malin Head, Co. Donegal. Geol. Mag. 91, p.417.

ROGERS, A.F. and P.F. KERR. 1942. Optical Mineralogy.

SUTTON, J. and J. WATSON. 1954. The Structure and Stratigraphical Succession of the Moines of Fannich Forest and Strath Bran, Ross-shire. Quart. Journ. Geol. Soc. Lond. 110, p.21.

TILLEY, C.E. 1925. A Preliminary Survey of Metamorphic Zones in the Southern Highlands of Scotland.
Quart. Journ. Geol. Soc. 81, p.100.

TURNER, F.J. 1938. Progressive regional metamorphism in southern New Zealand.
Geol. Mag. 75, p.160.

1948. Evolution of the Metamorphic Rocks.
Geol. Soc. Amer. Mem. 30.

and J. VERHOOGEN. 1950. Igneous and Metamorphic Petrology.

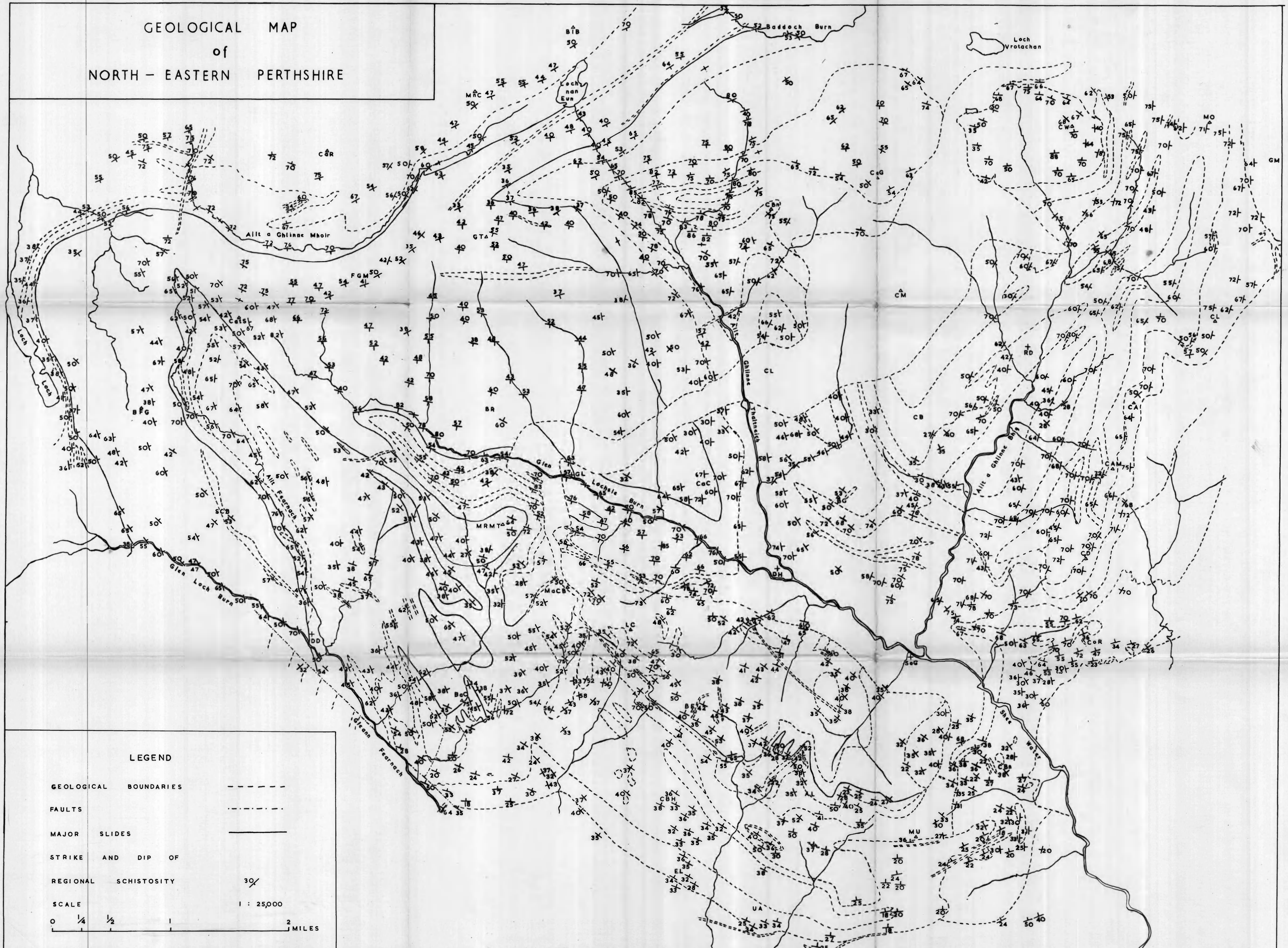
WHITE, W.S. and R.H. JAHNS. 1950. Structure of Central and East-Central Vermont.
Journ. Geol. 58, p.179.

WILLIAMSON, W.O. 1935. The Composite Gneiss and Contaminated Granodiorite of Glen Shee, Perthshire.
Quart. Journ. Geol. Soc. Lond. 91, p.382.

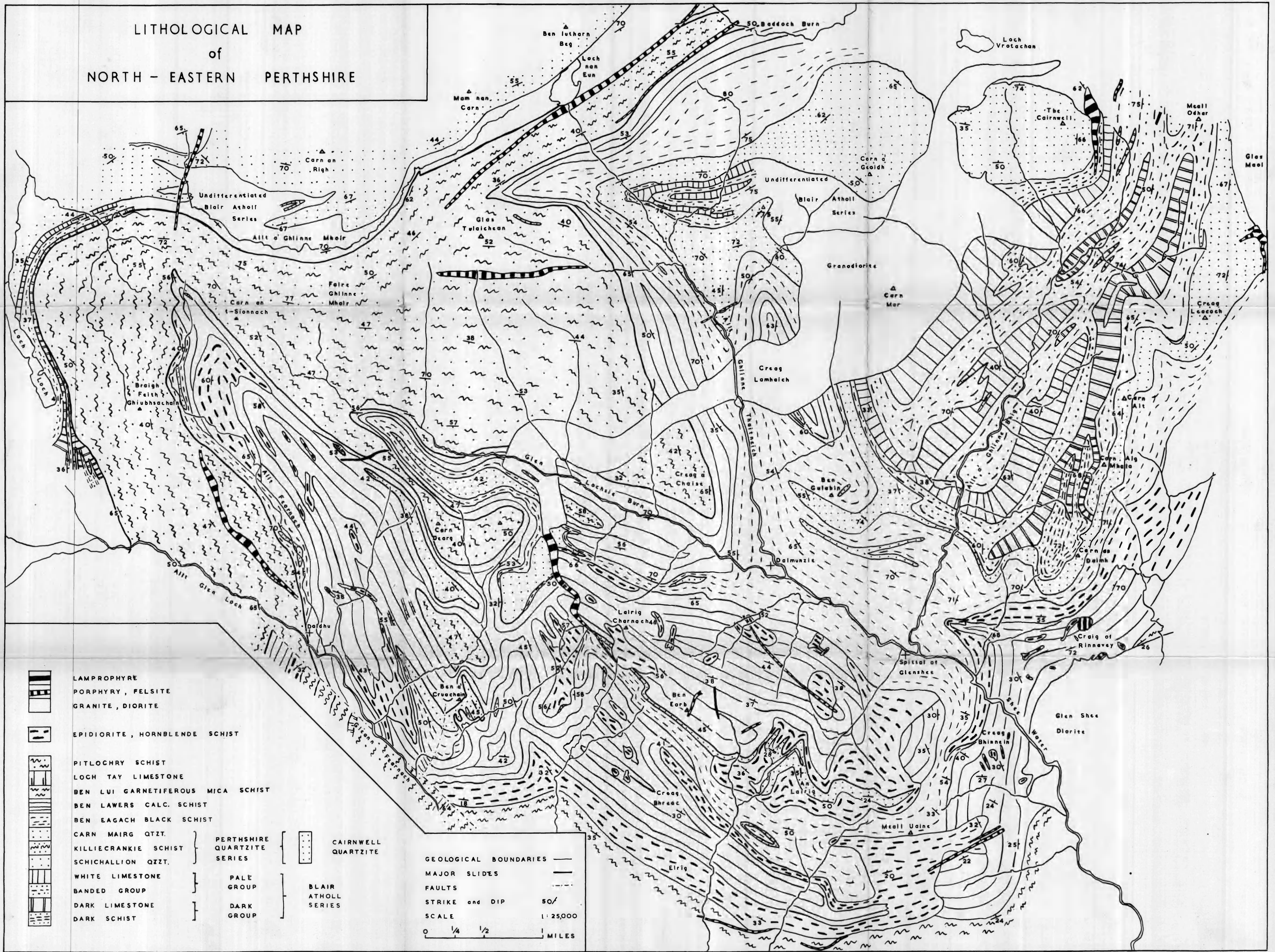
1936. Some Minor Intrusions of Glen Shee, Perthshire.
Geol. Mag. 73, p.145.

WISEMAN, J.D.H. 1934. The Central and South-West Highland Epidiorites: a study in Progressive Metamorphism.
Quart. Journ. Geol. Soc. Lond. 90, p.354.

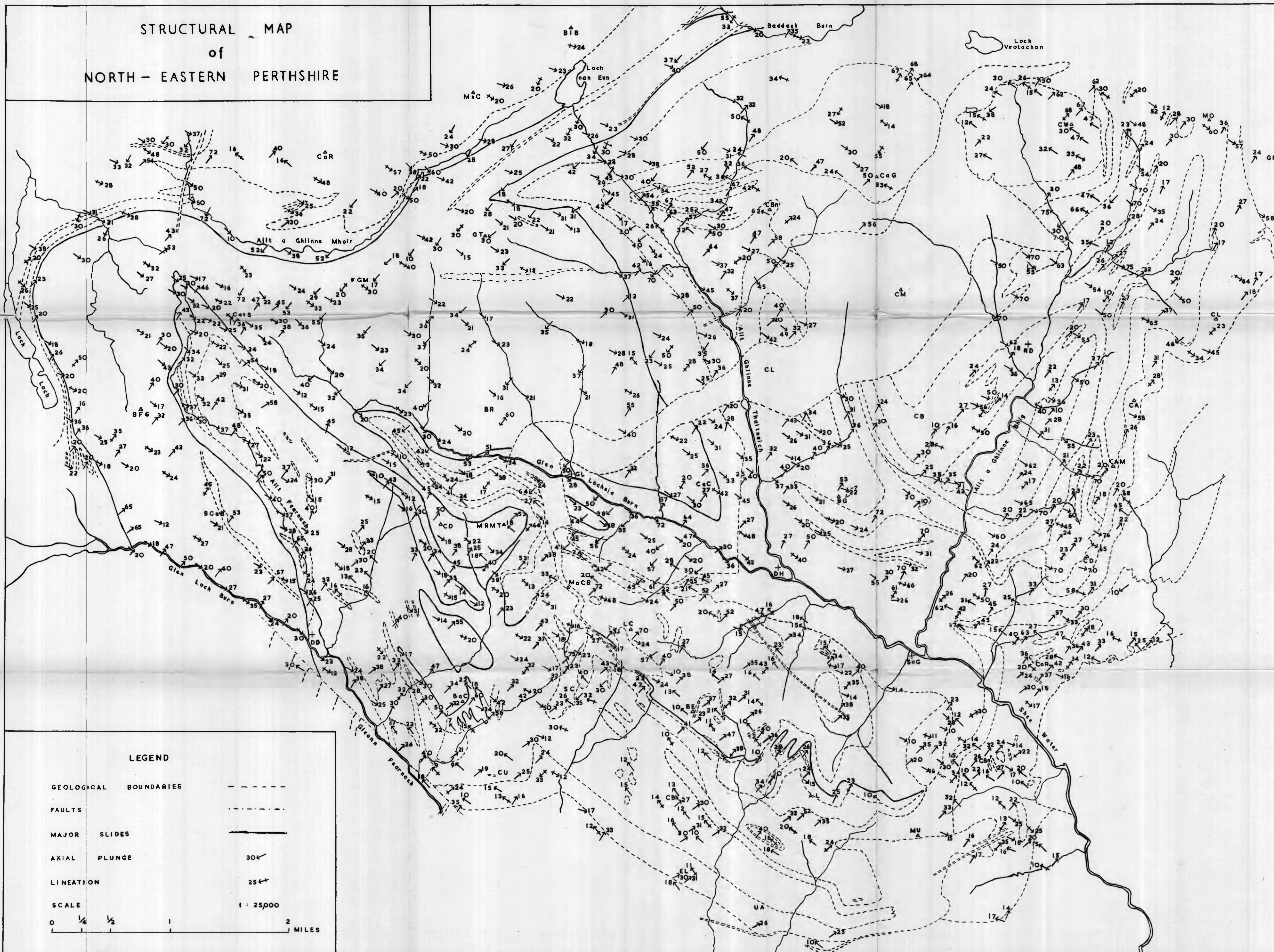
WILSON, G. 1953. Mullion and rodding structures in the Moine Series of Scotland.
Proc. Geol. Assoc. 64, p.118.



GEOLOGICAL MAP
of
NORTH – EASTERN PERTHSHIRE
Baddoch Burn
Loch Vrotachan
Loch nan Eun
Allt a Ghlinne Mhoir
Loch Loch
Glen Lochsie Burn
Glen Loch Burn
Allt Fearnach
Gleann Fearnach
Allt Ghlinne Thaineich
Allt a Ghlinne Bhig
Shee Water
LEGEND
GEOLOGICAL BOUNDARIES
FAULTS
MAJOR SLIDES
STRIKE AND DIP OF
REGIONAL SCHISTOSITY
SCALE
1 : 25,000
0 1/4 1/2 1 2 MILES



LITHOLOGICAL MAP
of
NORTH - EASTERN PERTHSHIRE
LAMPROPHYRE
PORPHYRY, FELSITE
GRANITE, DIORITE
EPIDIORITE, HORNBLENDE SCHIST
PITLOCHRY SCHIST
LOCH TAY LIMESTONE
BEN LUI GARNETIFEROUS MICA SCHIST
BEN LAWERS CALC. SCHIST
BEN EAGACH BLACK SCHIST
CARN MAIRG QTZT.
KILLIECRANKIE SCHIST
SCHICHALLION QTZT.
PERTHSHIRE QUARTZITE SERIES
CAIRNWELL QUARTZITE
WHITE LIMESTONE
BANDED GROUP
PALE GROUP
DARK LIMESTONE
DARK SCHIST
DARK GROUP
BLAIR ATHOLL SERIES
GEOLOGICAL BOUNDARIES
MAJOR SLIDES
FAULTS
STRIKE and DIP 50
SCALE 1:25,000
0 1/4 1/2 1 MILES
Ben Iutharn Beg
Loch nan Eun
Baddoch Burn
Loch Vrotachan
Mam nan Carn
Carn an Righ
Undifferentiated Blair Atholl Series
Allt o' Ghlinne Mhoir
Glas Tulaichean
Faire Ghlinne Mhoir
Carn an t-Sionnach
Carn a' Gheoidh
Granodiorite
The Cairnwell
Meall Odhar
Glas Maol
Carn Mor
Creag Leacach
Creag Lamhaich
Ghlinne Thaitneich
Loch Loch
Braigh Feith Ghiubhsachain
Allt Fearnach
Allt Glen Loch
Glen Lochsie Burn
Creag a' Chaise
Ben Gulabin
Carn Aig Mhala
Carn Alt
Carn Dearg
Carn an Daimh
Dalmunzie
Lairig Charnach
Craig of Rinnavey
Spittal of Glenshee
Daldhu
Ben a' Chroachan
Ben Earb
Creag Bhiannin
Glen Shee Diorite
Shee Water
Creag Bhreac
An Lairig
Meall Uaine
Elrig
Gleann Fearnach


STRUCTURAL MAP
of
NORTH – EASTERN PERTHSHIRE
LEGEND
GEOLOGICAL BOUNDARIES
FAULTS
MAJOR SLIDES
AXIAL PLUNGE
LINEATION
SCALE
1 : 25,000
0 1/4 1/2 1 2 MILES
Loch Vrotachan
Baddoch Burn
Loch nan Eun
Allt a Ghlinne Mhoir
Glen Loch Burn
Glen Lochsie Burn
Allt Ghlinne Thaitneich
Allt a Ghlinne Bhig
Allt Fearnach
Gleann Fearnach
Shee Water
Loch Loch