The Structure and Metamorphism of the Area between Clunie Lodge and the Cairnwell, Aberdeenshire.

Thesis submitted for the degree of
Doctor of Philosophy in the University of London

by

Frank C. Cox

July 1966

Contents

List of Plates

Following Page

List of Figures & Tables

List of Maps

Abstract

The results of detailed mapping confirm the Dalradian Succession suggested by E.B. Bailey, but his structural interpretation of the area proves to be incorrect. Mapping of the Baddoch Burn area indicates that the suggestion by Bailey of a complex system of slides contemporaneous with the original folding occurring in this region is also erroneous. It is shown from further field evidence that the region is affected by two major thrusts which, in this area of study, are developed on either side of the Blair Atholl Series. These thrusts divide the schists into three structural levels. The highest of these, the Morrone Nappe, is a primary structure in which the Ben Eagach Schist is overlain by the older Perthshire Quartzite. The thrust at the base of the Morrone Nappe is gently folded. The thrust-bounded Blair Atholl Series are squeezed out in the Clunie Lodge region, where the upper and lower thrusts merge, and bring the Morrone Nappe in contact with a lower nappe. In this locality the Ben Eagach Schist and the Perthshire Quartzite are exposed at a lower structural level.

Three episodes of folding preceded the thrusting, and the main metamorphism was synchronous with, and overlapped the second folding. Garnet growth occurred during this F_2 period,

and was accompanied by kyanite and staurolite when these movements ceased. Contemporaneous with the third folding, many of the earlier formed minerals were replaced by chlorite. Biotite was also formed during this period and both minerals continued growing after this deformation. The thrust movements were followed by a sinistral folding about a near vertical axis, cauring a marked change of strike in the vicinity of the Cairnwell. Finally normal faulting and brecciation of the country rock was associated with the intrusion of a suite of acid and intermediate dyke rocks.

INTRODUCTION

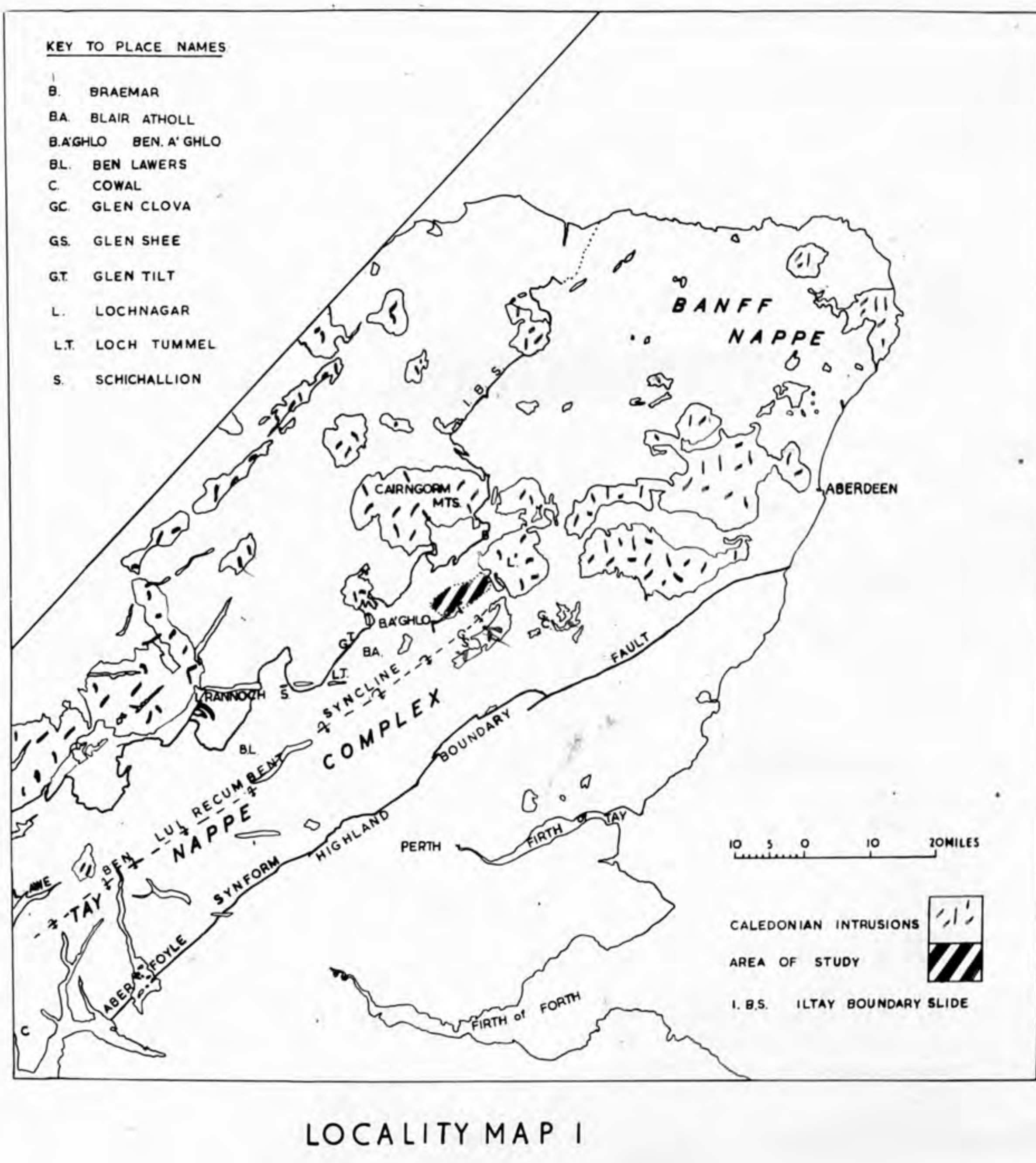
1. Locality

The area of study is situated astride the watershed which forms part of the county boundaries of Perthshire, Forfarshire and Aberdeenshire. It is a part of the Grampian Highlands Plateau, and most of it is dissected by the River Clunie and its tributaries (Locality Map I).

A line trending east from Glen Clunie Lodge to the head of Loch Callater marks the northern margin. In the west the boundary follows the crest of Sgor Mor and An Socach to Loch nan Eun, then swings south-east down Glen Taitneach. Lochs Callater and Kander lie on the eastern side and from Loch Kander a bounding line can be drawn south-westwards through the Cairn of Claise and Glas Maol to Creag na Eun. From this point, a line westwards to the confluence of Alt Anlich with the River Taitneach forms the southern boundary (Locality Map 2).

The rocks of the region are Dalradian Meta-sediments and Meta-igneous rocks which are cut by Caledonian Granites and a suite of acid and intermediate dykes. The Meta-sediments consist of three major groups: a series of schists, thin quartzites and thick limestones; a thick quartzite series; and a dark graphitic schist with striped quartzite and schists.

The Lochnagar Granite is on the eastern margin of the map but within the area mapped there are many granite porphyries and minor felsite dykes. Small diorite intrusions are also fairly common.



LOCALITY MAP I

Lastly small lamprophyric dykes occur throughout the area.

2. Geomorphology

The Grampian Highlands form a dissected plateau which has been undergoing isostatic recovery since the Pleistocene. During the Pleistocene Glaciation the Grampians were covered by a permanent ice cap, which played a major part in the development of the present-day topography. The Clunie, the Baddock Burn and the Callater Burn all flow in glacially deepened valleys. Overdeepening took place in Callater Burn causing the development of Loch Callater. Loch Kander, at the source of the burn, is a perfect corrie lake whilst Loch nan Eun and Loch Vrotachan are formed by a combination of moraine damming and the presence of resistant quartzite. At the spillway of Loch Vrotachan the Perthshire Quartzite occurs in a small outlier resting on grey schist of the Blair Atholl Series. The Blair Atholl Schists have been readily eroded and are now largely covered by drift. The Perthshire Quartzite, however, stands up as a natural dam. Loch nan Eun has a similar position in Grey Schists but in this case a thick lamprophyre dyke blocks the spillway.

The quartzite masses tend to form the higher ground and this led Cunningham-Craig to believe that the quartzite rested unconformably on the schists and limestones. An Socach, a long quartzite ridge, reaches a height of 3059 ft., and the range of hills forming the Perthshire-Aberdeenshire border vary in altitude from 3467 ft., at the Cairn of Claise, to 3502 ft. at Glas Maol. Although Glas Maol is composed of rocks of the Ben Eagach Group these are not the typical

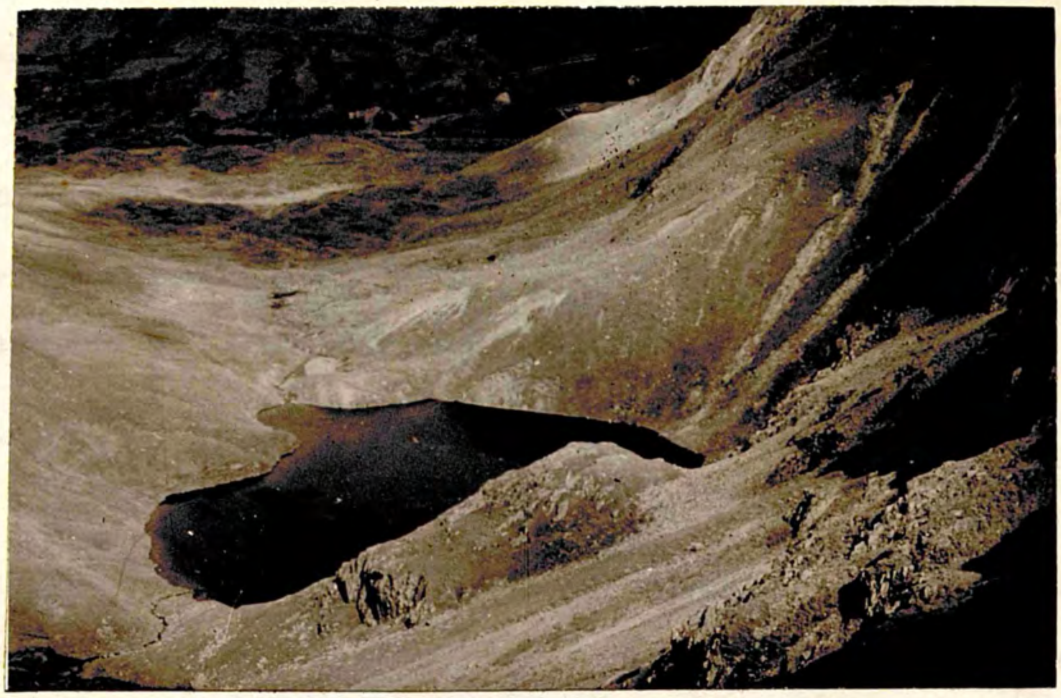


Plate 1a. Loch Kander looking north-east. This corrie lake is situated at the head of the Callater Burn. The foreground is composed of striped schists of the Ben Eagach Transition Series.

Plate 1b. Loch Vrotachan looking north-west from the Carn Mor Porphyry. The western end of the loch is dammed by a thrust klippe of Perthshire Quartzite. The foreground is in the Blair Atholl Series. In the distance the long quartzite ridge of An Socach is visible.

schists but are striped quartzites and schists.

Although many of the minor streams are directly controlled by the local grology, the main regional pattern of drainage does not appear to be related to the structure of the area. It is a dendritic pattern which drains northwards to the Dee and southwards to the Tay.

3. Superficial Deposits

Peat commonly covers large areas of the valleys in this region and is often developed in association with badly drained areas of glacial drift. The dissected moraines associated with glaciated valleys are particularly well developed in the upper region of the Baddock Burn. As the southern watershed is approached, mapping becomes increasinly difficult owing to the development of peat hags. This is particularly true of the southwestern portion of the map which is the source area of the Ey, the Baddock and the Taitneach. Hilltops by contrast are often free from glacial debris and short heather grows on locally derived scree. The quartzites are conspicuous by the development of blocky screes and this is also true of the minor intrusions which show as rusty scars on the hillsides.

4. History of Research

The solution of structural problems by detailed mapping of the minor structures was first used in the Scottish Dalradians by Clough (1887). Bailey, in contrast, used classical lithological techniques, together with the concept of regional pitch and plunge. In a re-application of Clough's ideas, MacIntyre 1951, Weiss and MacIntyre 1955, King and Rast 1956, stimulated the reinvestigation of previously mapped areas of Dalradian and Moine rocks. Many workers were able to show that deformation was polyphase. The swings in strike of the main Dalradian outcrop were thus related to a crossfold episode of deformation in which folds developed at an angle to the strike of the early caledonoid folds.

E.B. Bailey's contribution to the understanding of the structure of the Dalradian rocks in Scotland cannot be minimised. He established the succession for Central Perthshire and was able to apply this to areas mapped by his contemporaries, which due to lack of a detailed stratigraphy were scarcely understood. The area mapped in this study was first published by the Geological Survey on sheet 65 in 1904. It was mapped jointly by G. Barrow and E.H. Cunningham-Craig who were hampered by their disagreement over the stratigraphic succession. For comparison both stratigraphies are shown alongside Bailey's sequence in table 1. Their stratigraphy was to a large extent influenced by their differing views on the structural interpretation of the area, and vice versa. Barrow believed that the original beds were thickened tectonically and this resulted in the production of his "Concertina Structure". Cunningham-Craig thought that the Quartzite rested unconformably on the underlying schists and was now exposed in simple synclines. Bailey visited the region in 1926 and during a few days reconnaissance mapping, with the aid of sheet 65, reinterpreted the ground in the light of his work in Perthshire. His guiding principle was the concept of major recumbent folds often with associated slides. He related the Dalradian structures to a fundamental fold - the Iltay Nappe.

For later reference it is convenient at this stage to describe the form of the Iltay Nappe as shown in a series of papers by Bailey, and expanded in detail by Shackleton, 1958. The root zone of the nappe is thought to lie in the region just south of the Moine-Dalradian boundary. Sturt, in his account of the structure of the Loch Tummel area (1961), is more specific and places it on the axis of the Stron Mor Synform. From this line he shows folds facing north and south. The hinge of the Iltay Nappe is thought by Shackleton to be the Aberfoyle Synform (op.cit.). This together with the Ben Lui Recumbent Syncline is a primary fold. Secondary major folds have been described in many papers on the Dalradian structure. Clough (op.cit.) describes the Cowal Antiform as being a secondary fold on the inverted limb of the Iltay Nappe, and this inverted limb is described in the literature as the Flat Belt. Bailey has given evidence of refolding of the Iltay Nappe in many of his papers. The Cairnwell Synform is one such fold, which is said to cover a large portion of the area mapped (1928). The evidence for the existence of this structure is discussed at length below and in the chapter on structural synthesis. Various folds have been described facing north-west (Sturt, 1961; Rast, 1958), but these are of minor significance compared to the main Iltay Nappe.

In a paper entitled 'Schist Geology; Braemar, Glen Clunie, and Glen Shee', Bailey published the map following p. 28 in which he reinterprets sheet 65 and part of sheet 56, resolving the differences of Barrow and Cunningham-Craig by the application of his Perthshire

Succession. The key structure on the map is the Cairnwell Synform which he develops by linking two of the three quartzite belts in the region. Despite lack of exposure and in some localities contradictory evidence, he shows the major quartzite masses of Barrow's maps joined by thin lines of quartzite justifying this by his recognition of the two-sided nature of the quartzite. On the Cairn of Claise - Glas Maol side are the Ben Eagach group of rocks, whereas the opposite margin is against the Blair Atholl Schists. The axis of the synform runs from Loch Callater to Glen Taitneach. The Baddoch Burn was thought by Bailey to follow the axis of the complementary antiform which has a slide developed on its lower limb. A critical area for Bailey's thesis is the Glen Taitneach section where he shows the closure of the Cairnwell Synform. Barrow, on sheet 65, does not join the quartzites of Creag Easgaidh and Carn Bhinnein, but shows them separated by a belt of Blair Atholl rocks. The merits of these two interpretations are discussed length on p. . F. Matheson (unpublished thesis, 1959) also mapped a part of this area and he confirms the interpretation proposed by Bailey.

5. <u>The Problem</u>

B.C. King (unpublished) has for some years been working in the Braemar area, mapping a region close to the Moine-Dalradian boundary, south-west of Braemar. His work in this region has shown the presence of several thrusts later than the main folding. These thrusts separate the structure into a series of nappes, and as work proceeded it became apparent that the uppermost of these, the Morrone Nappe, is a major unit which extends southwards towards the Aberdeenshire border. It was therefore necessary to relate the Morrone Nappe to the Carnwell Synform of Bailey.

Although there has been much work in recent years on the metamorphism in the Dalradians (Rast, 1958; Sturt and Harris, 1961; Chinner, 1962), there is no published work on the area of south-western Aberdeenshire which is astride Barrow's garnet and kyanite zones. It was proposed to carry out a detailed petrographical study and compare this with data for neighbouring regions.

6. Methods

The area was mapped with the aid of air photographs, and all field data were recorded and transferred to a six-inch base map. Structural data were summarised stereographically on equal area projections and orientated specimens were collected for laboratory examination.

PART ONE

Stratigraphy and Sedimentation

The table following p. 9 compares the stratigraphical interpretations of Barrow, Cunningham-Craig and Bailey. The considerable differences between these authors are largely a result of conflicting views as to the nature of the fundamental structure, but the fact that Barrow and Cunningham-Craig had little experience of what is now the type area of Central Perthshire hindered them greatly, since theirs was an area of greater structural complexity. Bailey had the advantage of having started his Central Highlands work in the Schichallion region (1922), where there was a largely concordant sequence, which he was able to trace along the strike into the structurally discordant areas of S.W. Aberdeenshire (1925, 1928). Bailey's Central Perthshire Succession is as follows:-

Ben Lui Garnetiferous Mica-Schist.
Ben Lawers Calc-Mica-Schist.
Ben Eagach Black (or Dark) Schist including transition beds bordering ...
Perthshire Quartzite Series.
Blair Atholl Series.

The area mapped did not include the Ben Lui or the Ben Lawers Schists, but traverses were made on to the Ben Lawers Schist of Glen Lochsie. Within the area of study it is not possible to confirm or disprove this sequence, since everywhere it can be examined the junction between the Perthshire Quartzite Series and the Blair Atholl Series is a tectonic one. This was clearly Cunningham-Craig's justification for placing the Quartzite at the top of the succession, resting unconformably on the Schists and limestones. However, it is possible to find good exposures of passage beds from the Ben Eagach Schist into the Perthshire Quartzite. Such transitions are developed throughout the region, and a traverse due south from the epidiorite south of Clunie Lodge furnishes numerous exposures of black schist, followed by black schist with flaggy quartzite, followed by flaggy quartzite and finally by massive quartzite. This type of hill traverse with a summit composed of quartzite also supports Cunningham-Craig's order of succession, but the presence of a transition series rules out the suggestion of an unconformity. Bailey, in his 1928 paper, bemoans the lack of evidence in the Braemar district as to the true order of deposition and applies the succession that he was able to prove in Perthshire and Islay. This succession has since been confirmed by many workers in the Scottish Highlands (Sturt, Rast, Shackleton, etc.). It is not possible in the present researches to find any truly satisfactory evidence of younging directions, but the fact that Bailey was able to trace his concordant Perthshire Succession eastwards into this area, and the entirely similar nature of the lithologies observed here, are considered sufficient grounds for applying his succession. However, the direction of closure of the major primary structures is, for this reason, conjectural.

INTERPRETATIONS OF THE STRATIGRAPHICAL SUCCESSION IN S.W. ABERDEENSHIRE.

after Cunningham-Craig 1912

b. Quartzite lying in synclinal folds.

~~~ unconformity ~~~

a+c. Boulder Bed.
Main Limestone Group.
Black Schist with Feldspar Rock. Twinned Chlorite Rock and Tremolite Limestone.

after Barrow 1912

c. Calc flintas.
Boulder Bed and Main Limestone Group.
Black Schist with Feldspar Rock, Twinned Chlorite Rock. and Tremolite Limestone.
Banded Group.

b. Quartzite with rusty weathering at contact with...

a. Lower Black Schist Group

after Bailey 1928

a. Ben Eagach Graphitic Schist.

b. Perthshire Quartzite Series.

c. Blair Atholl Series: comprising an upper Pale Group and a lower Dark Group. The Schichallion Boulder Bed occurs locally near the top of the series.

Equivalent groups are shown by small letters.
~~~

1. Description of sediments

A. "The Blair Atholl Series"

Bailey subdivides the Blair Atholl Series into an upper Pale Group and a lower Dark Group. Although representatives of both groups were recorded, the Pale Group has the greatest areal extent, covering approximately a third of the total area mapped. The Dark Group, however, is only found on the southern margin of the map just east of the Devil's Elbow. The Blair Atholl Series played an important part in the structural growth of the region acting as an incompetent mobile horizon between two major thrust planes. For this reason it is not possible to trace the Series into the higher members of the succession.

(i) "The Dark Group"

At the Devil's Elbow black graphitic schists are seen interbedded with grey mica schists. These black schists are highly micaceous comprising large plates of muscovite with subsidiary biotite and interstitial quartz grains. Garnet is developed as small porphyroblasts ranging in size from about half an inch diameter to the size of a pinhead. They contain many inclusions which were used in determining the relationship of mineral growth to the deformations. The dark nature of the rock is due to the presence of finely disseminated graphite. Pyrite, magnetite and ilmenite are common accessories, and it is the oxidation of these ores that gives the weathered rock a typical rusty

Plate 2a. Tight F_3 folds in flaggy quartzite. Meal Odhar.

Plate 2b. Photomicrograph showing the banding in the Ben Eagach Transition Series. It can be clearly seen that the quartz-rich band is folded over on itself (F_1) and that there is a strain slip schistosity developed in the more micaceous layers (F_3). x 10. Slide 20c.

appearance. Successive deformations have destroyed all trace of the original bedding. The only indication of original sedimentation is seen where the black schist is interbedded with grey schist and limestone. The Ben Eagach Schist is finer grained and contains less quartz than the Dark Schist but in all other aspects it is entirely similar.

The grey schists of this locality are fine grained quartz-mica schists with a somewhat granoblastic texture. In contrast to the strongly lepidoblastic dark schists they rarely contain garnet. Their position in the sequence cannot be exactly defined as repeated folding and flowage particularly in the limestone make the establishment of a more detailed stratigraphy impossible.

The thick grey limestone associated with these schists is a fairly pure marble with occasional schistose bands, which weather out, showing the complex minor folding in sharp relief. A close examination of the banding will show that it too is by no means primary, as it is seen to contain fold closures with long attenuated limbs. The very regular banding sometimes developed is indicative of a highly tectonised condition, where folds have become so flattened and sheared that the original closures are destroyed. Such regular banding is typical of the Moines which are seen to be strongly deformed, north of Braemar. In thin section, the schistose bands consist of a granular mosaic of calcite and quartz, with pale biotite, muscovite, and occasional green hornblende.

Plate 3a. Open crumples in Ben Eagach Black Schist.
Coire Fhearneasg.

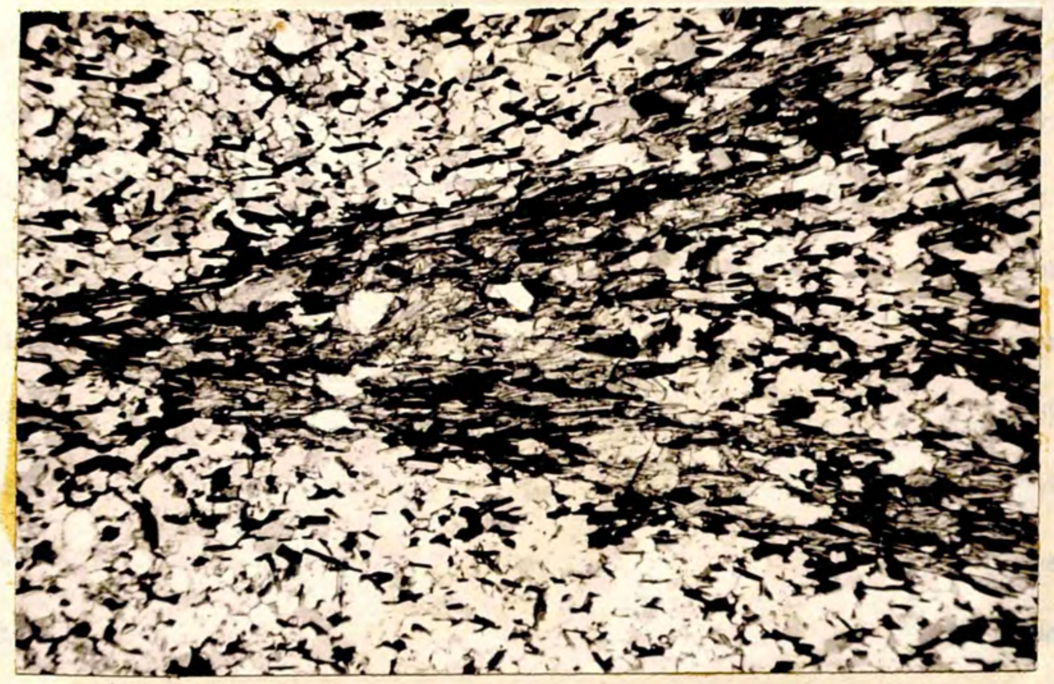


Plate 3b. Photomicrograph of F_2 microfold in a specimen from the Ben Eagach Transition series. x 10.
Slide 9c.

(ii) "The Pale Group"

This comprises a great variety of types which include calcareous schists, schistose limestone, quartz-mica schists, grey lustrous and banded schists, grey quartzites, and white and grey limestones. The Banded Group of Bailey, or Honestone Group of Barrow, does not occur in the area mapped, but is found in the Glen Ey section (B.C. King, unpublished). These are banded quartz granulites and were thought by Barrow to occur close to the quartzite. This can be confirmed in Glen Ey.

The most common member of the Pale Group occurring in the area is a grey lustrous schist, which grades into a grey banded schist in the Upper Baddoch Burn. This grey lustrous schist is well exposed on the small hill just south of Clunie Lodge. It is a grey mica schist dominantly composed of muscovite flakes and numerous knots of quartz, elongated parallel to the 'b' direction of the minor folds. In this locality it is rich in zoisite, and contains a greenish biotite. The former indicates the calcareous nature of the original sediment. This particular group of outcrops has been affected by east-west faulting, and contains a large inclusion of Perthshire Quartzite. Strongly deformed schistose limestones are present as tectonic lenses, a common feature of the lustrous schist, which extends south-westwards along the entire length of the Baddoch Burn. In the upper reaches of this stream, south of the tributary Alte Sron nam Fiadh, and on Sron nam Fiadh itself, the quartz content of the schist increases such that it separates into thin white bands, which alternate

Plate 4a. Steep F_3 folds in massive quartzite. Glen Taitneach.

Plate 4b. F_2 fold in massive quartzite plunges towards 130°. Glen Taitneach.

with grey schist. The mineralogy of these rocks is identical to that of the grey lustrous schist, and as a continuous section is exposed the increase in quartz content is seen to be a gradual change related to the original sedimentation. Thin limestones are developed at several points along this traverse. Some of these are merely a few inches thick so that they could not be recorded on the map. Sedimentary amphibolites are also associated with the grey schist and occur as continuous beds, lenses, and isolated knots. The last mentioned are thin calcareous horizons which have been 'balled up' by deformation, similar to the formation of quartz-rods. Large prisms of green hornblende, together with some xenoblastic biotite, form a decussate texture in an equigranular quartz mosaic. Biotite sometimes replaces the amphibole, but both minerals usually show some alteration to chlorite. In a few specimens actinolite was recorded as the dominant mineral, although a pale green hornblende is more usual. Clinozoisite may sometimes be present but is only of accessory status, together with rutile, apatite and tourmaline. The felspar content of these rocks is quite small. Crystals are rarely twinned but twinned examples give values in the andesine range.

Lustrous grey schists and schistose limestones are also found in the head water region of the Clunie on either side of the Devil's Elbow road, and in a "window" east of Carn Chrianaidh. The latter area is highly tectonised by the thrusting, and contains thin quartzites and grey quartz pelites as well as the more typical grey schist with quartz-rods. To the east of this window on Carn Dubh and Moine

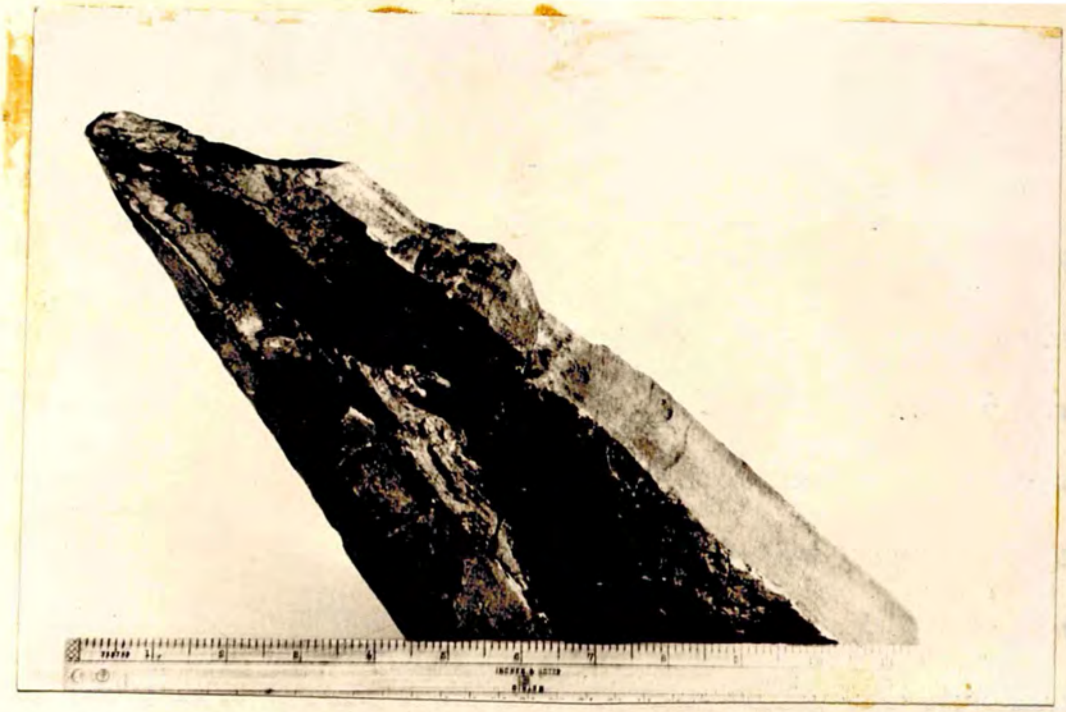


Plate 5a. Small F_3 fold in flaggy quartzite collected from Meal Odhar.

Plate 5b. F3 folds with curved axial planes in flaggy quartzite, Meal Odhar. These folds now plunge south due to the sinistral movement that occurred after the main folding episodes.

Bhealaich Bhuidhe a large area is shown on the map as grey schist. Much of this is covered by drift but where there are outcrops or scree developed on thin soil cover the grey lustrous schist is seen to be present. As the Lochnagar Granite is approached hornfelsing destroys the regional metamorphic effects, and the rock becomes more compact. Garnets are altered to a chloritic aggregate, which converts to biotite as one passes deeper into the aureole and redistribution of the quartz destroys the rods formed during the deformation. The products of these changes are purple and grey hornfelses.

There are two important sections in the Pale Group yet to be considered: (a) Coire Fhedrnesg, a tributary of the Baddoch Burn and (b) Glen Taitneach. They both merit careful study and they are dealt with at length in the discussion of Bailey's structural interpretation. At this point it is sufficient to record the differences seen in the Pale Group of these localities.

Coire Fhedrnesg cuts through grey lustrous schists which grade westwards across the strike into a thick grey limestone followed by quartz-granulites. These are in turn succeeded by a white limestone which is faulted against the Ben Eagach Transition Group. The grey limestone is a ribbed limestone which contains many thin schist bands, which is in contrast to the white limestone, since this is a pure white marble. Thickening south-westwards along the strike, the quartz-granulites form a marked feature. These are the closest approach to the honestones in the area. They are granoblastic rocks, which are sometimes banded, and vary from white to dark grey. They contain thin

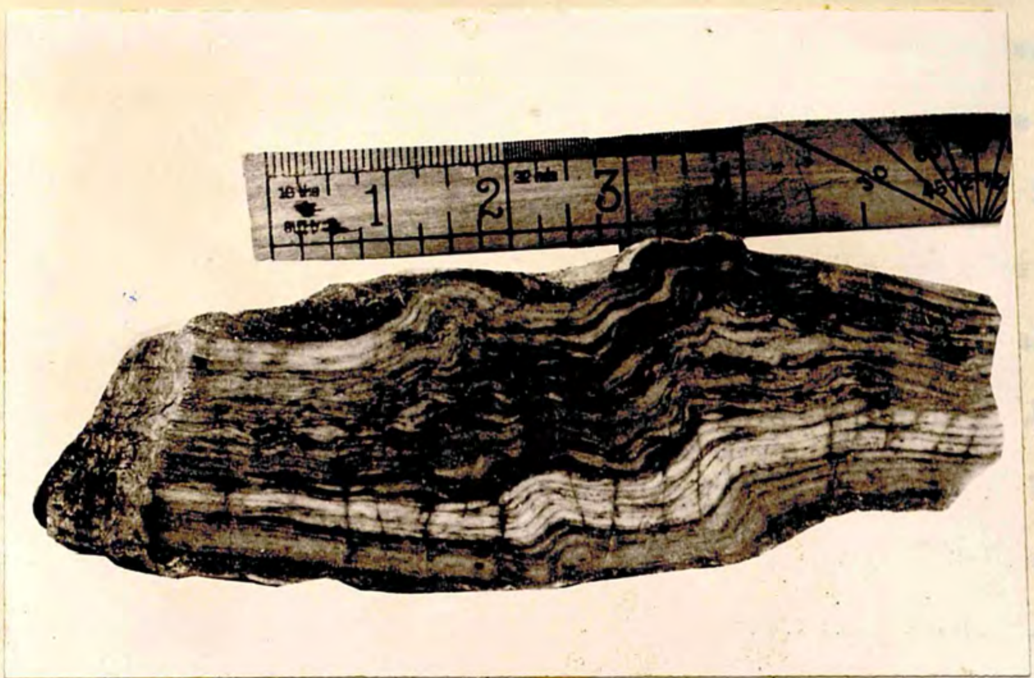


Plate 6a. Polished section of flaggy quartzite close to the Ben Eagach schist transition group. The more schistose levels have formed accommodation structures between the competent quartzite bands. The specimen was collected from Meal Odhar.

Plate 6b. Boudin formed in massive quartzite band. An F_2 fold closure is seen close to the hammer.

limestone bands as well as quartzose horizons. As can be seen from the map both limestones are quite thick and extend for some distance along the strike. A similar limestone-schist relationship is seen in Glen Taitneach where the white marble in this section is also involved in faulting. A pink quartz-porphyry is intruded along its contact with the Perthshire Quartzite. To the north-west the white marble is exposed in a thrust contact with the quartzite. When this structural position is considered together with its completely pure recrystallized character it seems possible that this limestone may itself be tectonic in origin. Unlike the Coire Fhedrnesg section there are no quartz-granulites exposed here. Barrow and Cunningham-Craig both mention the occurrence of a boulder-bed though it is not shown on sheet 65. Bailey goes further and shows two localities on his 1928 map where the boulder-bed is said to occur. Both these localities were visited but the bed was not found.

A traverse across the strike of the Blair Atholl Series, from south-east to north-west, gives a broad approximation of the original sedimentary succession which compares very closely to that given by Bailey for Loch Loch which is to the west on sheet 64:-

Plate 7a. Rodding in massive quartzite plunges to 130°, Glen Taitneach. This rodding occurs just above the thrust at the base of the Morrone Nappe.

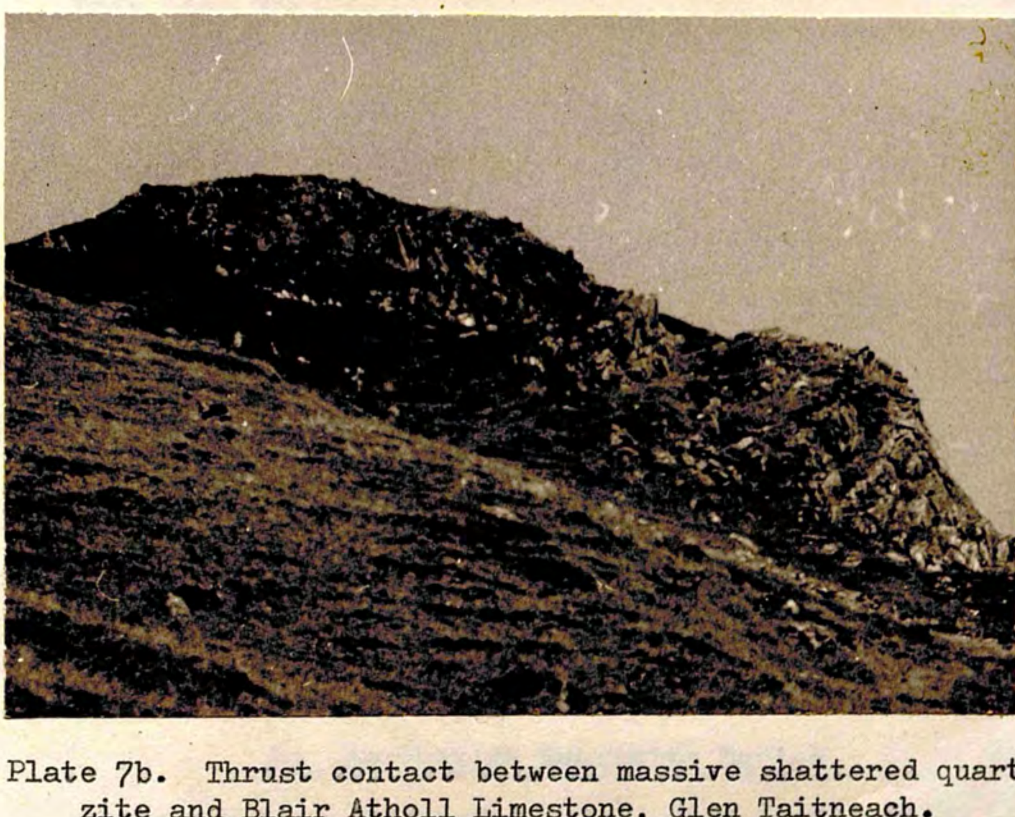


Plate 7b. Thrust contact between massive shattered quartzite and Blair Atholl Limestone, Glen Taitneach.

South-west Aberdeenshire	Loch Loch
White Marble	Cream-White Limestone
Quartz Granulites	Grey Compact Mica Schist or Granulite
Grey Schistose Limestone	Thin-banded Tiger Rock Limestone
Lustrous Grey Schist with Thin Limestones	Grey Banded Quartz-Biotite Granulites (Honestones)
Grey Lustrous Schist with Thin Quartzites and Purple Schists	Ribbed Limestones.
	Flaggy Grey Mica Schists with Thin Limestones
PALE GROUP	
DARK GROUP	
Dark Graphitic Schist with Thin Grey Schists.	Flaggy Grey Limestone.
Grey Ribbed Limestone.	

Although there is no black schist shown in the dark group of this succession, Bailey notes that "Black Schist reappears in the Dark Group exposures of the same line of outcrop half a dozen miles farther east". The marked similarity of these two successions shows that there is almost a complete section of the Blair Atholl Series in S.W. Aberdeenshire.

B. Perthshire Quartzite Series

In Perthshire Bailey recognises three divisions of the Perthshire Quartzite Series. These are the Carn Mairg Quartzite, the Killicrankie Schist, and the Schichallion Quartzite. It is not

Plate 8a. Refolded folds in flaggy banded quartzite. The black bands are graphitic schist. The specimen was collected from Meal Odhar.

Plate 8b. F_2 folds in quartz-rich Blair Atholl schist outcropping in a small stream north-west of Carn Bhinnein.

possible similarly to divide the quartzite of south-west Aberdeenshire, since the massive quartzite makes up the bulk of the succession and there is no major schist horizon comparable to the Killicrankie Schist. This Schist is developed to the west of Glen Taitneach outside the area of study, where for reasons given in the section on structure, it is thought to occupy a higher structural level than the quartzites of the Cairnwell and Socach belts.

At its contact with the Ben Eagach Schist Series, the quartzite is flaggy in character with fine schist bands, and exhibits interesting fold patterns since the thin graphite schist horizons act as a lubricant to the competent quartzite. This flaggy facies contains disseminated iron ores which oxidise and stain the bedding-planes. Below this the massive quartzite is a thick current-bedded series which weathers more rapidly close to the flaggy quartzite, such that it often forms a step in the topography as is seen on An Socach. The current bedding is often sheared and indeterminate, but examples were seen on the Cairnwell and An Socach, where it appeared to face downwards. The bedding shows as dark brown lines within the white quartzite and in thin section is seen to be composed of iron oxides and heavy minerals. Less ambiguous to interpret is the graded bedding that occurs in the more feldspathic horizons. This is seen on Creag a Choire Dhrich, a ridge topped by a granite porphyry north-west of the Cairnwell, and by the foot-bridge across the Baddoch Burn south-west of Clunie Lodge. In both examples the beds are overturned but their relationship to the minor folds cannot be determined. These

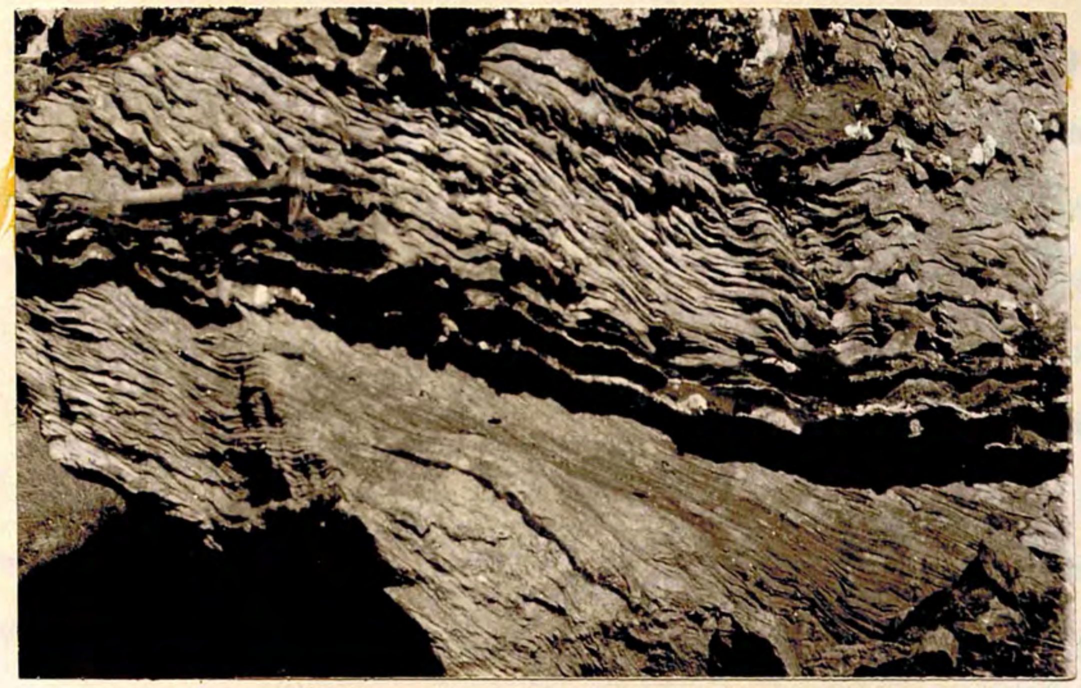


Plate 9a. F_2 folds in grey limestone. Photograph taken near Plate 8b. The folds become progressively overturned and, in the lower half of the exposure, the fold closures are destroyed and a new tectonic banding has been formed.

Plate 9b. F_2 lineation in flaggy quartzite refolded by F_3 movements. Meal Odhar.

quartzites are very feldspathic with the bulk of the mineral occurring in the coarser bands. Feldspar is the most important constituent after quartz in the members of the quartzite series and microcline, orthoclase, andesine, perthitic intergrowths, and graphic intergrowths with quartz were all recorded. It may form xenoblastic porphyroblasts or be present as a constituent of the groundmass. Rounded grains of rutile and zircon are common particularly in heavy mineral concentrations associated with current bedding. Sometimes these concentrations are quite thick and examples of deformed heavy mineral bands were seen. Although these structures are modified by folding, their disharmonic character is indicative of penecontemporaneous non-diastrophic deformation associated with compaction of the original sediment. Similar structures have been described from the Torridonian Sandstone (see Selley et al., 1963).

C. The Ben Eagach Schist

In this locality the quartzite series undergoes a marked facies change from that of central Perthshire. This is due to an increase in the sedimentation rate, resulting in continuous arenaceous deposition. Similarly the Ben Eagach Schist shows an increase in the thickness of its transition group against the quartzite. This group of passage beds becomes increasingly important eastwards where it may represent a part of the quartzite series as well as a major part of the black schist. A thick belt of these striped rocks stretches from Loch Callater to Glas Maol. In detail they contain beds of

Plate 10a. Ptygmatic folding of a calcite vein in grey limestone. North of the Cairnwell in Glen Clunie.

Plate 10b. Refolded folds in grey limestone. Specimen collected in Glen Taitneach. The folds appear to be disharmonic but the pattern is due to the intersection of F_3 and F_2 folds.

flaggy white and grey quartzites, and striped black schist. The latter is made up of an unusually regular alternation of fine quartzite with dark graphitic schist. These alternations are even present at microscopic thicknesses. The schist horizons rarely contain garnet and consist of muscovite and biotite growing lepidoblastically in at least two schistosities and associated with a fine sutured intergrowth of quartz. Although the banding is related to the original sedimentation, very early fold closures were observed in thin section, contained in the quartzose bands. This suggests that the banding has been emphasised by the primary folding. Subsequent deformation has produced micro-boudinage of these bands. In hand-specimen the schist layers are identical to the true black schist, but petrographic investigation shows that they are extremely fine-grained. They contain very little quartz but much graphite dust and disseminated ore. Chlorite is also common, developed as large porphyroblasts or as an alteration product to the biotites. The Ben Eagach schist that eventually dominates the succession is a coarser rock with an identical mineralogy to the dark schist of the Blair Atholl Series. It is a rusty weathering graphitic mica schist, often containing strongly helicitic garnets together with tourmaline rutile, and iron ores as accessories. The little Tremolite limestone and the Feldspar rock of Barrow and Cunningham-Craig were not seen in the area mapped, but occur northwards (B.C. King, personal communication). Staurolite has been recorded from some black schist specimens indicating a fairly high iron content to these rocks.

Modal analyses of typical lithologies

F1	Grey pelitic schist: Blair Atholl Series
F6	Grey lustrous schist: Blair Atholl Series
F15	Quartzose black schist: Ben Eagach Series
F19	Black schist: Ben Eagach Series
F20	Grey schist with quartz rods: Blair Atholl Series
F50	Lustrous grey garnet schist: Blair Atholl Series
134c	Biotite-chlorite schist: Blair Atholl Series
137c	Purple and green fine grained schist: Blair Atholl Series
96c	Lustrous grey schist with quartz rods: Blair Atholl Series
343c	Grey garnet schist: Blair Atholl Series

Minerals	F1	F6	F15	F19	F20	F50	134c	137c	96c	343c
Quartz	34.2	14.6	33.6	51.6	18.0	30.5	0.9	18.0	39.6	32.4
Biotite	17.7	9.3	6.0	11.9	12.8	19.0	62.0	10.5	-	46.6
Muscovite	36.5	59.8	30.8	12.3	31.1	39.0	0.7	26.5	40.6	
Plagioclase	2.5	15.8	23.2	23.6	35.9	8.1	11.9	13.5	✓	
Chlorite	✓			✓	0.7	2.1	9.7	7.5	5.4	6.8
Epidote	8.8						13.7	-		
Garnet						✓		-	14.4	
Kyanite								22.0		
Staurolite								-		
Rutile	0.03		✓		✓		0.7	✓	✓	
Ores		✓		0.1	1.4	1.1	✓	1.0	✓	.5
Tourmaline		0.05	✓	✓	✓			✓	✓	
Limonite			5.8	✓				-	✓	
Zircon			✓	✓				-		
Hornblende										13.7
Essential components	5	4	5	4	5	6	4	6	4	5
No. of components	7	6	8	9	8	7	8	9	10	5
Points counted	2154	1062	1155	1003	1330	1299	1500	1640	1229	1027

Plate 11a. F_3 folds in rusty quartzite with thin schist bands. Glen Taitneach.

Plate 11b. Steep F_3 folds in massive quartzite looking south-west from Clunie Lodge.

Modal analyses were made of representative schists in the succession and the results are shown on the table following p. .

2. Summary of depositional history in the area

The Blair Atholl Series comprises the Lower Dalradian of Knill, and Rast (1963). It was said by Knill to represent a period of deposition in isolated basins. The marked similarity between the Blair Atholl of south-western Aberdeenshire with that of Perthshire shows that this was not the case over a large area of the Central Highlands. The type of sedimentation suggests a shelf environment, which becomes rather unstable to the south-west where slumps are a common depositional feature (Sturt, 1961). A close examination of the Blair Atholl Series shows it to represent a period of rhythmic deposition, alternating between limestone and schist.

The Dark Group represents quiet deposition of black mud. The abundant iron ore is indicative of an anaerobic environment, with the sulphur being lost during the regional metamorphism. This alternated with a clear water environment and limestone deposition. This was followed by an increase in the depositional rate to silt grade which also alternated with periods of quiescence during Pale Group times. The incoming of the quartzite series is shown by the development of thin quartzites which alternate with thin limestones and schists. This transition group is not seen exposed in the area mapped, for reasons that have been given above, but is seen just south-east of Braemar. The continuous deposition of quartzite in this region, together with the evidence of current action, indicates

Plate 12a. Drag folds in flaggy quartzite on the reverse limb of a major F_3 fold in Glen Taitneach.

Plate 12b. F_3 folds in schistose limestone. In a small stream just west of Carn Bhinnein.

a shelf type environment. This is somewhat different to the conditions in Perthshire where a less uniform series, and the presence of graded bedding and slumping, suggest a deeper water environment. The long transition through alternating schist and quartzite which precedes the Ben Eagach Schist, similarly supports the notion of a shoreline to the north-east. The striped rocks of the Ben Eagach Transition may represent a seasonal climatic change, which caused a variation in the depositional rate, eventually ending with a return to quiet deposition of the black mud of the Ben Eagach Facies.

This summary shows no indication of geosynclinal growth during the lower half of the Dalradian succession in this area, and higher groups, seen in adjacent areas, show that this shelf deposition continued at least to the Ben Lui schist.

The rhythmic nature of deposition is shown by an objective description of the succession in sedimentary terms:

The Ben Eagach Schist.	Black mudstone.
Transition Group.	Alternating mudstone with quartzite.
Perthshire Quartzite Series.	Quartzite.
White Marble	Limestone.
Quartz granulites	Siltstone.
Grey schist with thin quartzites and purple schists.	Silty mudstones with thin quartzites and calc. mudstones.
Dark graphitic schists.	Black mudstones.
Thin grey schists.	Siltstones.
Grey ribbed limestone.	Impure limestone.

Plate 13a. F_2 fold in massive grey limestone in a stream section west of Carn Bhinnein.

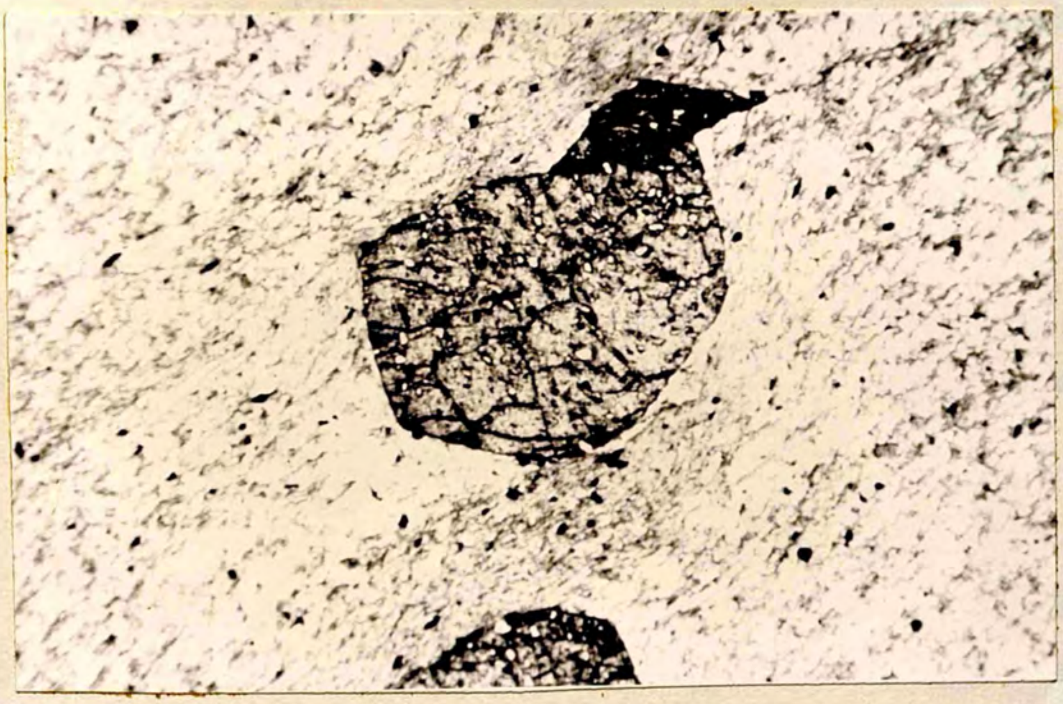


Plate 13b. Photomicrograph of garnet sheared by late faulting movements. P.P.L. x 40. Slide 31c.

PART TWO

Structural History

The structural history of this region is long and complex; it is therefore convenient at this stage to present an outline account which will be elaborated in subsequent sections.

1. Summary of Events

The successive structural episodes can be shown on the evidence of the minor structures to fall into six groups:

(1) Recumbent folds with axial planar schistosity (F_1)

(2) 'Crossfolds' with associated linear structures and schistosity (F_2)

(3) N.E.-S.W. trending folds and linear structures with associated strain-slip (F_3)

(4) Rodding in quartzite, plunging to 130°, close to thrust planes

(5) Open folds

(6) Faults and associated breccias.

Between (4) and (6), there occurs a period of sinistral rotation about a single axis dipping steeply to the S.W. The relationship of the late open folds (5) to this episode is uncertain.

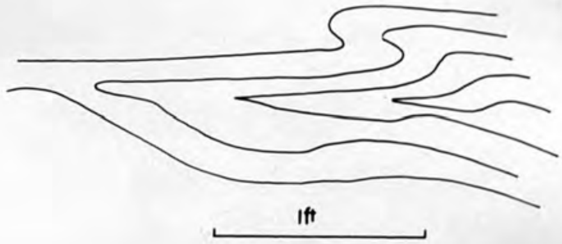
The first major structural event in this area was the growth of the primary nappes on N.E.-S.W. axes with the resultant inversion of the rocks forming the 'Morrone Nappe', a recumbent syncline closing northwards in the hill Morrone, which lies just south of Braemar. The inverted limb of this fold is seen exposed in the An Socach and Cairnwell belts of the Perthshire Quartzite, which overlie the Ben Eagach Schist.

<u>MINOR FOLD STYLES</u>

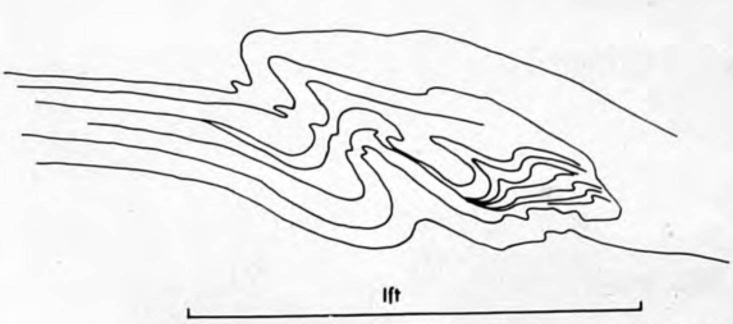
F3 FOLDS – LIMESTONE IN LUSTROUS GREY SCHIST.

THIN BANDS OF QUARTZITE FORM FOLD-CLOSURES IN CALCAREOUS BANDED SCHIST

F3 FOLD IN GREY SCHISTOSE LIMESTONE



F2 FOLD IN LUSTROUS GREY SCHIST



INTERFERENCE PATTERN PRODUCED BY THE INTERSECTION OF THE F3 STRAIN SLIP WITH AN F2 FOLD IN GREY LIMESTONE

The Carn an Tuire belt of quartzite may represent the lower limb of this structure. The evidence for and against this conclusion is discussed in the latter part of this chapter.

'Crossfolding' has produced two major folds in the primary nappe of this region as well as abundant minor folds. These folds have approximately N.W.-S.E. trending axes. The third phase of folding produced several major folds with N.E.-S.W. axes and the ubiquitous development of corresponding minor folds. It was this period that exercised the greatest control in the present outcrop pattern. The culmination of this period of deformation was a squeezing forward of the 'Morrone Nappe' in a thrust movement to the north-west over the incompetent Blair Atholl which formed the envelope to this nappe. During this period open folds were generated in the plane of the thrust. After thrusting, transcurrent faulting produced torsional movements about an axis which plunges steeply to the south-west in the region of the Devil's Elbow. This caused a rotation of the minor structures, refolding of the thrust plane and a marked swing of strike in the Devil's Elbow region. Normal faulting and dyke emplacement was the final structural event to occur in the region. The faulting produced many breccias which have been cemented by later igneous material.

2. Minor Structures

A. Primary Folds

There are examples of refolded folds in all parts of the area, but although several recumbent structures are described, it is doubtful if these are first phase folds. They are more probably recumbent crossfolds. Even sheared fold closures seen within the banding of the

Plate 14a. Late open fold in grey Blair Atholl schist. Glen Taitneach.

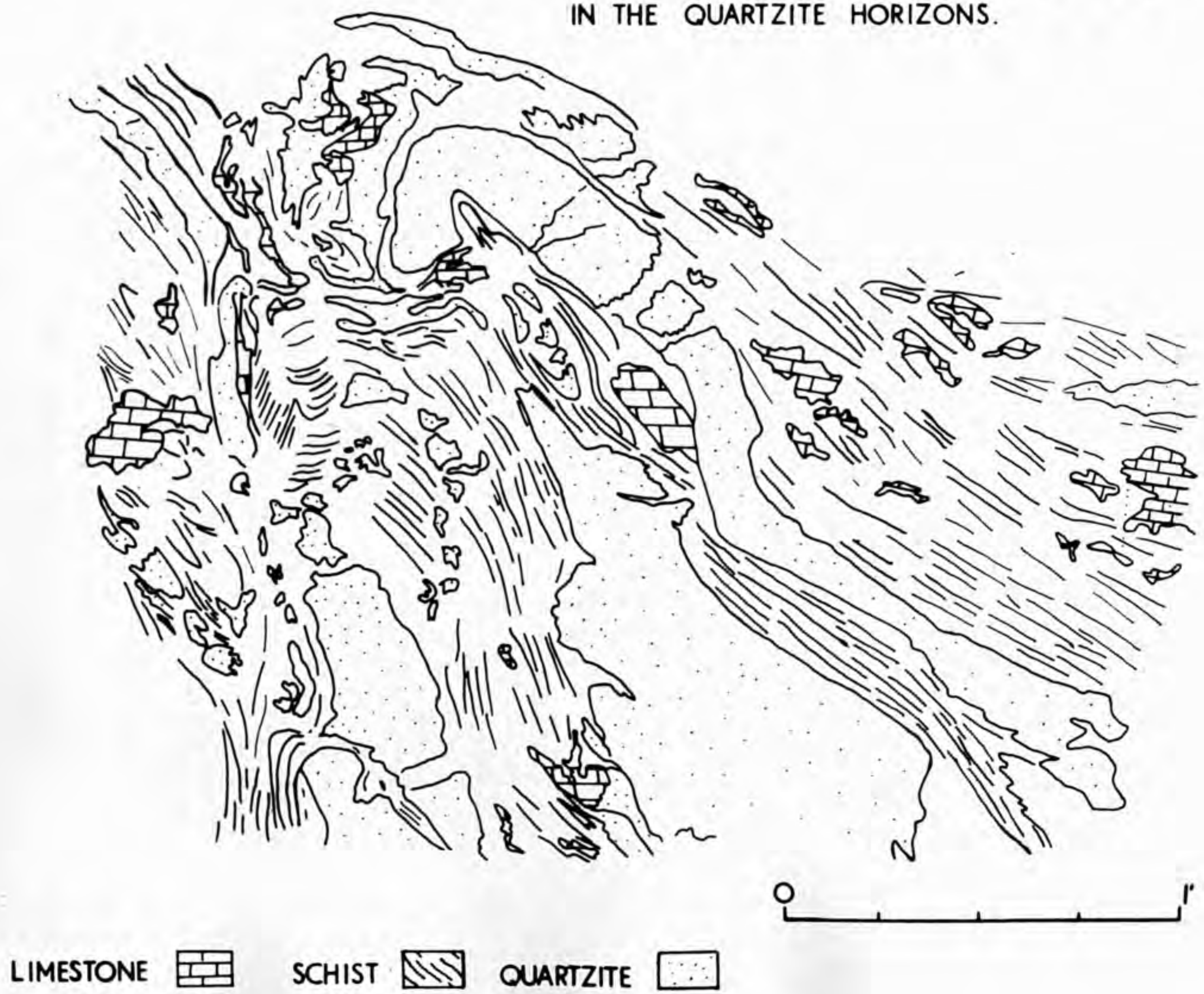
Plate 14b. Steeply plunging F_3 fold in flaggy quartzite. Meal Odhar.

limestone group cannot be accepted as primary, since they are enclosed in a banding which developed during the third phase of movement. However, petrographic examination of the striped transition group of the Ben Eagach Schist shows that the thin quartzite horizons, representing the original bedding, are folded into recumbent isoclines, which have an axial planar schistosity. These are cut obliquely by the F_3 strain slip. It is quite impossible to determine the original axial direction of these folds since this is now obscured by the effects of later deformations. Since the primary nappes appear to trend parallel to the main fold belt it is probable that these minor folds had a similar N.E.-S.W. axial strike.

B. 'Crossfolds'

This term is used by Rast & Platt and King & Rast in papers describing minor folds in the Dalradian Series. These authors use the term genetically to describe folds developed simultaneously at right angles to the primary Caledonian folds. In this account the term is used in a strictly descriptive sense to denote folds which are developed in a secondary deformational episode governed by pressures at an angle to those that produced the primary folds. These folds are ubiquitous and range from somewhat open to tightly isoclinal. The latter are often recumbent. The axial direction of these folds shows a considerable variation, owing to later deformation. This is seen on the equal area plots which show an almost random distribution although, as demonstrated by Ramsay (1960), there is a tendency for them to form two maxima. The style of these folds changes considerably, chiefly as a result of

DETAIL OF AN OUTCROP OF BLAIR ATHOLL ROCKS, OCCUPYING A SMALL WINDOW ONE MILE SOUTH OF CLUNIE LODGE. THE SCHISTOSITY IS OF CROSSFOLD AGE AND FOLDS EARLIER STRUCTURES, WHICH ARE PRESERVED IN THE QUARTZITE HORIZONS.



variation in rock type. This variation is related to the parts played by the three main mechanisms of deformation. The quartzites produce folds which are dominantly concentric, although some shearing usually occurs. The schists deform by 'similar' folding and the limestones form both 'similar' and flowage folds. Within the limestones slides are common and fold style varies with the carbonate content, such that thin bands of pure carbonate may deform by flowage, independent of the enclosing less pure bands. In the transition group where a mixed lithology is present, the schist is seen to flow into fold closures formed by more quartzitic bands.

Within the quartzite, the 'crossfold' episode is often represented by a rodded structure. This is parallel to the 'b' direction of these folds. At its more flaggy margins, the quartzite is folded into tight isoclines. In the schists crossfold closures become squeezed out and detached from their original limbs during the third movement phase. Fold mullions formed in the F_2 movements were seen to be refolded at a number of localities. Dykes emplaced after the F_1 deformation were converted to hornblende schists and epidiorites during the crossfold period. This is shown by a mineral lineation. In the quartzites, feldspars are aligned within the schistosity associated with the F_2 folds. This schistosity is a well-developed planar structure. In the schists, it is reinforced by the lepidoblastic growth of muscovite and biotite, together with elongated quartz needles. In the epidiorite, the original feldspar phenocrysts also show a rudimentary orientation which is parallel to the lineated amphibole. In this case the lineation

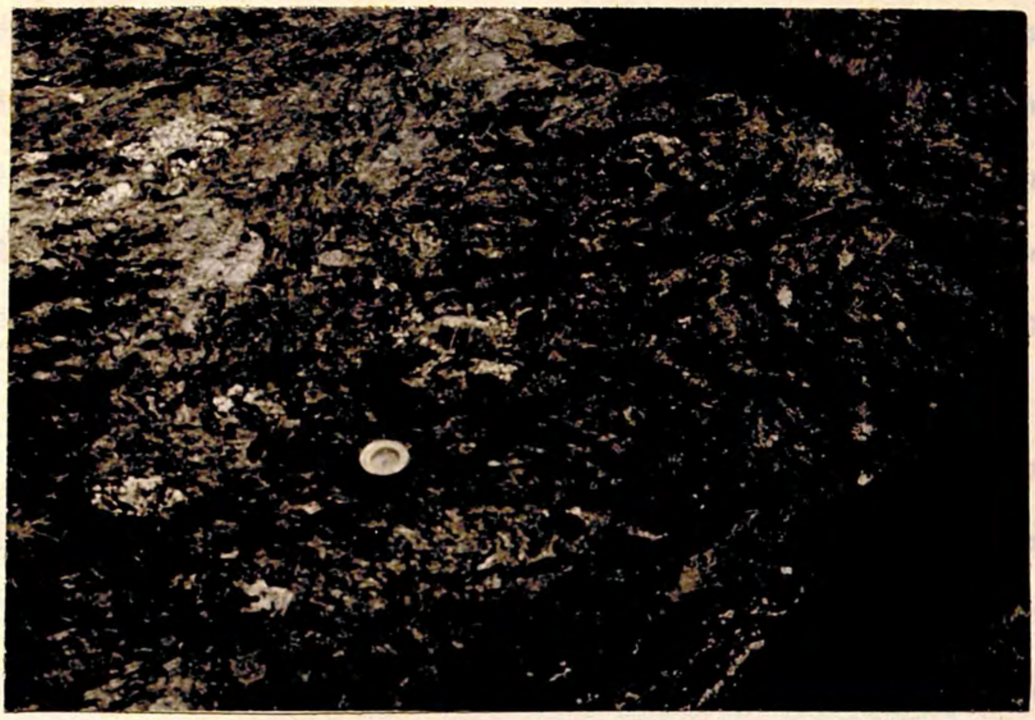


Plate 15a. Phylitic lineation in grey schist, produced by the intersection of the F_3 strain slip cleavage with the F_2 schistosity. Glen Taitneach.

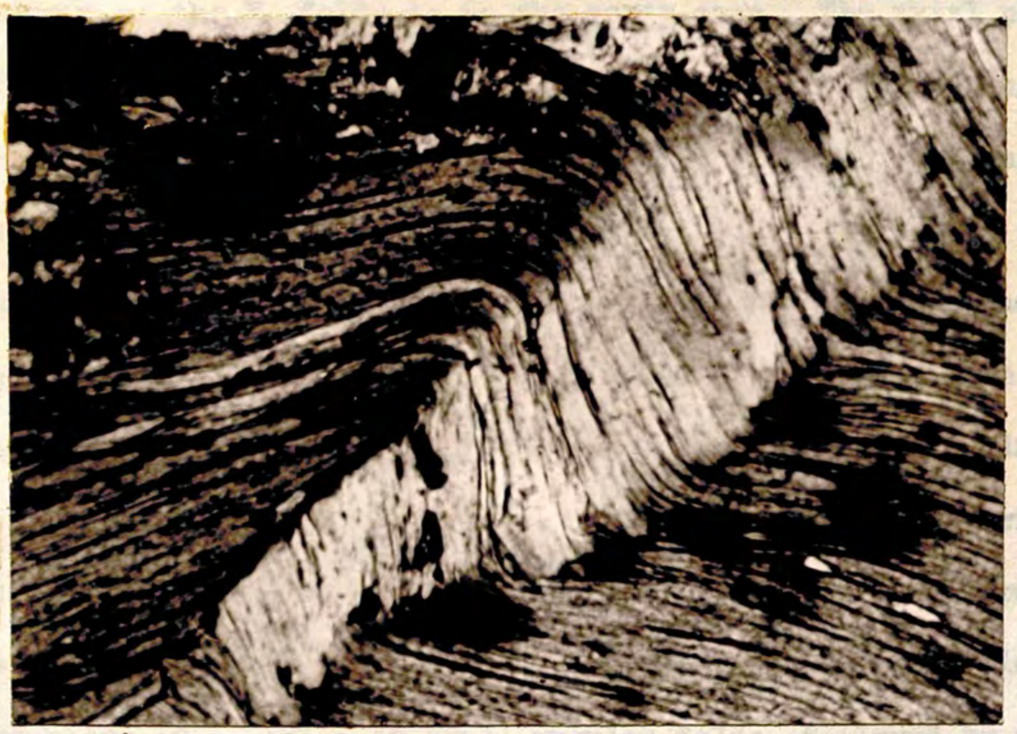


Plate 15b. Photomicrograph of kink band in grey mica schist. P.P.L. x 40. Slide F 63.

is produced by a mechanical rotation of the original phenocrysts. These are now composed of aggregates of clinozoisite and andesine. Quartz rods are common in the Blair Atholl Schists. Although many of these are parallel to the axes of third phase folds, they are also seen to have developed during the second phase of deformation.

C. N.E.-S.W. trending folds

This generation of structures developed during a period of strong N.W.-S.E. compression. They are seen on all scales and are usually associated with a strain-slip cleavage which is parallel to the axial planes of the folds. In the limestones, this deformation is sometimes so intense as to destroy all earlier structures, producing a tectonic banding which contains disorientated fold closures. The regional plunge of the F_3 folds is to the north-east. The axial planes of the folds tend to be overturned towards the north-west. Plunges are fairly high, with the majority between 50 and 60 degrees, but there is great variation throughout the area (see Map 6). Certain fold styles are developed during this phase, which are particularly characteristic. In general these are cleavage folds of the chevron type with movement along a strongly penetrative strain-slip. Commonly developed in the limestones, they are sharp peaked folds which show a considerable variation in the amount of translation along each cleavage plane. This translation, in some cases, shows a periodicity (see fig. 2). One example described consists of a series of small angular folds, followed by a major translation and then another series of small folds. This rhythm is then repeated across the strike of the cleavage. In parts of the quartzite

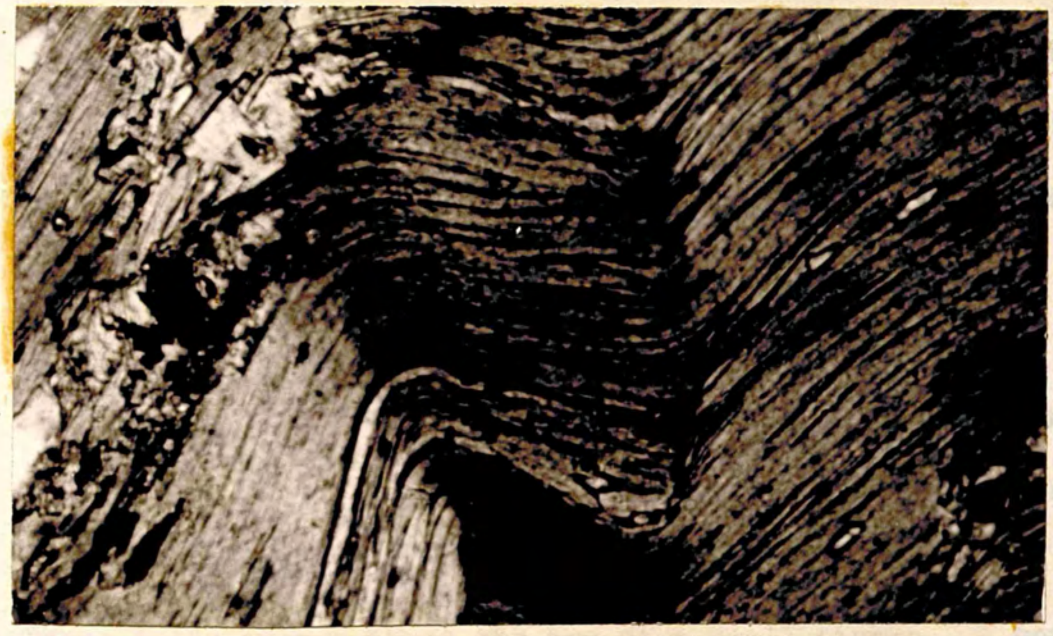
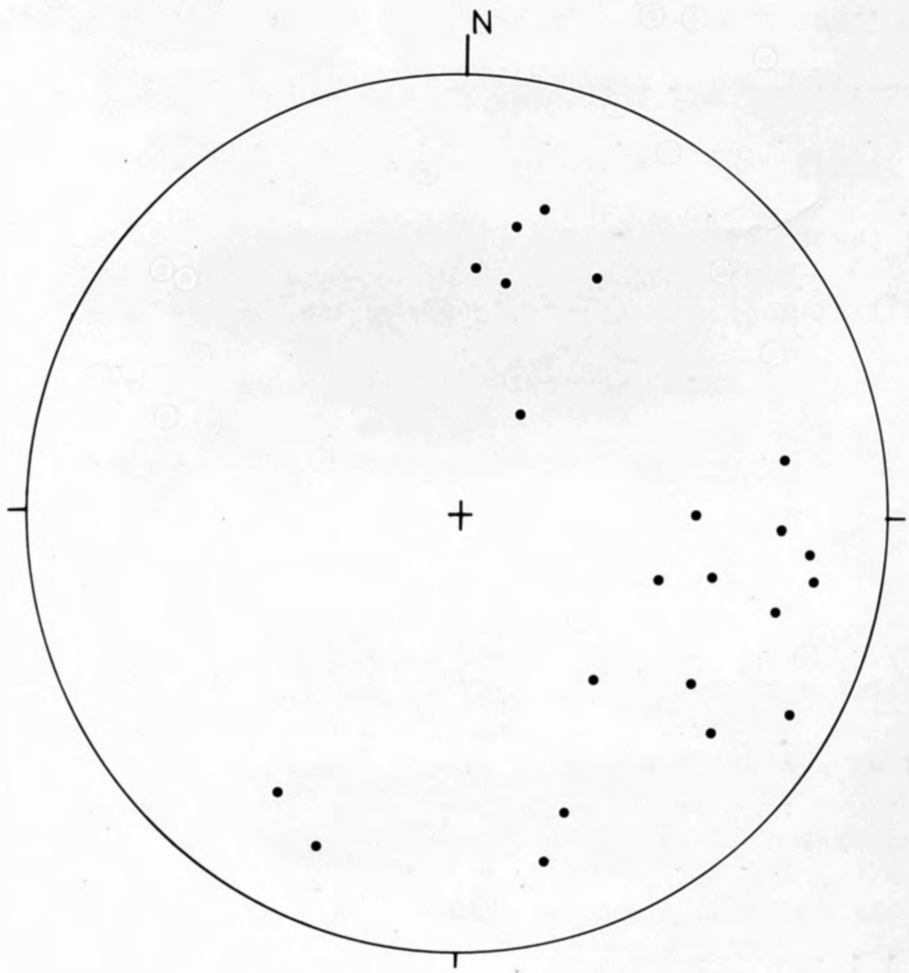


Plate 16. Photomicrograph of kink bands in grey mica schist. P.P.L. x 40. Slide F 63.

outcrop, the flaggy quartzite is seen to form fairly open folds of F_3 age, but in Glen Taitneach the F_3 folds are almost recumbent. Apart from the general exceptions mentioned above, many of the folds produced in this period were identical in style to those produced in the second deformational phase. The F_3 strain-slip is dominantly a mechanical structure but chlorite, epidote and biotite are all found growing in this plane. F_3 linear structures are common. The strain-slip schistosity forms a phylitic lineation at its intersection with the schistosity formed during the crossfold period. This is seen in all schist specimens collected from the area. Quartz and calcite are commonly crystallised in rods parallel to the F_3 folds.

D. Sinistral Movements

A sinistral rotation of the F_3 fold axes can be demonstrated when the caledonian folds for selected areas are plotted on Schmidt nets. From north to south across the area mapped, the direction of plunge of these folds swings about the arc of a small circle. A corresponding swing of strike is seen in the outcrop pattern of the rocks on either side of the thrust plane. This sinistral twist has its axis just east of the Cairnwell, where the beds are seen trending N.N.W.-S.S.E. This axis appears to be plunging steeply to the south-west. It is suggested that this movement could be a result of transcurrent faulting with a displacement of the order of 1 - 1½ miles, or alternatively a localised late crustal warping. The style of the fold indicates sinistral movement about an almost vertical axis which would account for both the swing in strike and the rotation of the F_3 fold axes. Movements favouring



LATE OPEN FOLDS — EQUAL AREA PROJECTION

the former hypothesis have been described in neighbouring regions (e.g. the Loch Tay Fault).

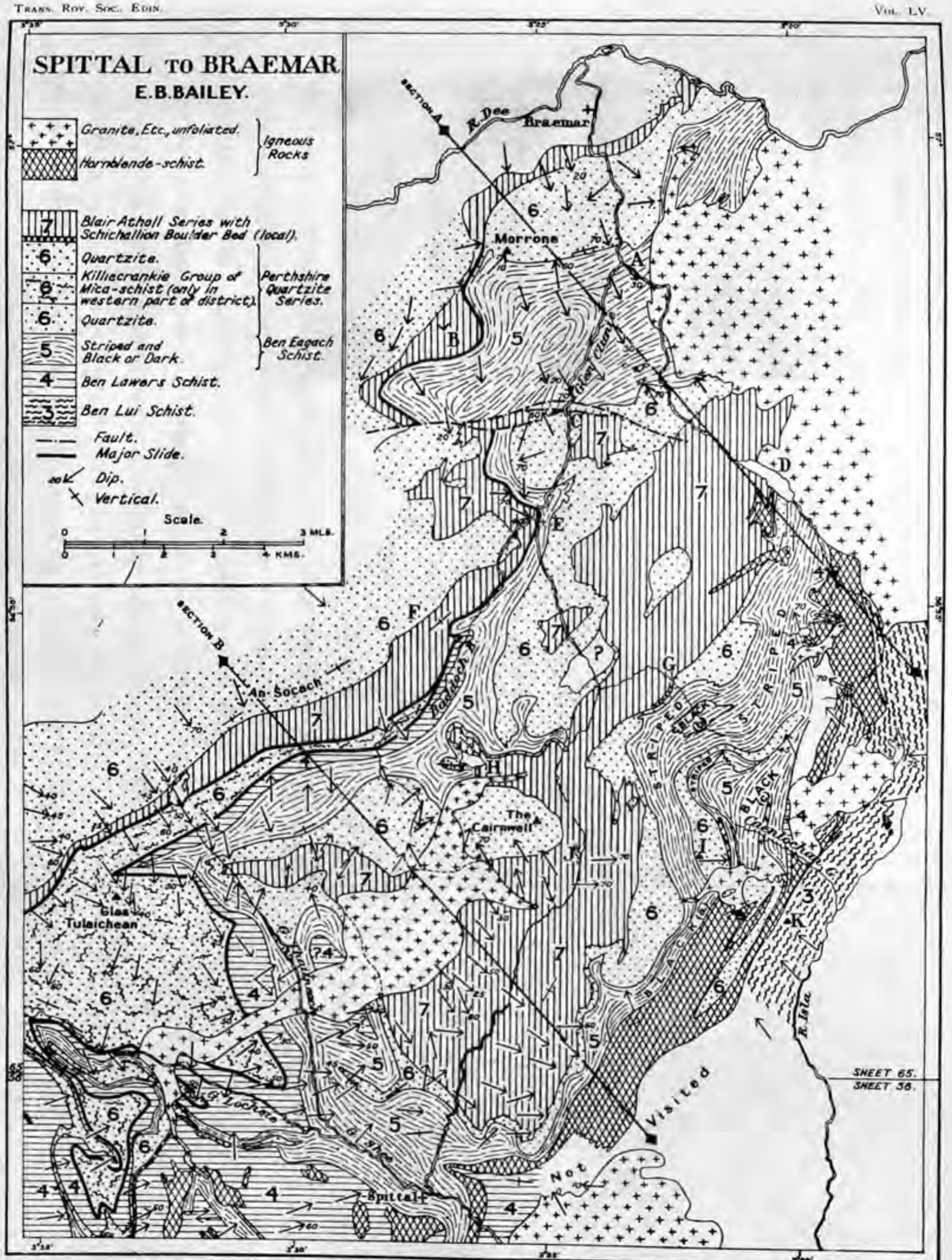
E. Open Folds

These late structures occur throughout the area mapped and are shown plotted on the equal area projection, fig. 4. They show a considerable scatter, which suggests that they are related to extremely local stress conditions (possibly the transcurrent movement described above). Although they are all open folds, they vary in style and pitch. Some are small isolated monoclines, produced by movement on local shear planes. Others are open antiforms and synforms of orthorhombic type, with vertical axial planes and gently plunging axes.

3. Major Structures

A. Bailey's Thesis

Bailey's interpretation of this area, mentioned briefly at the beginning of this account, is here expanded in detail so that it may be compared with the results of the present researches. His structural conclusions rest chiefly on his reading of the stratigraphy at several critical sections. The map summarising his work, which appeared in his 1928 paper, is shown as Map 3 of this account. The area is said to be involved in two major folds, which are developed in a previously inverted sequence. These are the Cairnwell Synform and the complementary An Socach Antiform. These folds are overturned to the north-west with N.E.-S.W. trending axes. The lower limb of the An Socach fold is replaced by a slide which follows the Baddoch



A. Auchallater. B. Coire nam Freumh. C. Newbigging. D. Loch Callater. E. Glen Clunie Lodge. F. Coire Fhearneasg. G. Allt a' Gharbh-choire. H. Loch Vrotachan. I. Glas Maol. J. Devil's Elbow. K. Monega Hill.

Burn and Glen Clunie to Braemar. This slide cuts out the Killicrankie Schist, which is said by Bailey to extend from Glas Tulaichean down the Baddoch Burn to the confluence with the tributary from Loch Vrotachan, whence the Ben Lawers Calc Schist continues along the slide contact with the Blair Atholl Schists and Limestones. Eventually the Ben Lawers is also cut out where the stream Coire Fhearneasg enters the Baddoch Burn. From this point the Ben Eagach Schist is shown by Bailey against the Blair Atholl. The Killicrankie Schist is shown to be stratigraphically equivalent to the Cairnwell Quartzite, into which it passes by facies change across the An Socach Antiform. This fold plunges towards the north-east. The closure of the Cairnwell Synform is shown outcropping in the upper reaches of Glen Taitneach. Here, Bailey links the Cairnwell Quartzite with the quartzite of Carn Bhinnein and maps the successive beds above the quartzite in an acute swing of strike. This is contrary to the interpretation of Barrow, who on sheet 65 shows the Blair Atholl rocks continuing westwards beyond the quartzite outcrops. Bailey maintains that the quartzite forming the Cairnwell Synform shows both its sides throughout its outcrop. On his map tenuous outcrops of quartzite keep this relationship over poorly exposed ground. This subjective approach is seen particularly in the region of Loch Vrotachan where the Cairnwell Mass is linked to Carn Aosda by a thin winding strip of quartzite. On the eastern side of the Clunie, a fold is shown which has a core of unidentified rocks in contact with the Blair Atholl Series within the Cairnwell Synform. Bailey suggests that these rocks are a part of the Killicrankie Schist.

The Cairnwell Synform is regarded by Bailey as a fold on the lower limb of the Iltay Nappe and An Socach lies close to the hinge of the Ben Lui Fold which lies below this nappe.

B. Results of Detailed Mapping

(i) The Baddoch Burn and Coire Fhearneasg

This section is particularly important to Bailey's interpretation, since it is here that he traces the complex westward facing limb of the An Socach Antiform. The field results shown on Map 7 accompanying this account vary considerably from Bailey's 1928 map (Map 3).

The Baddoch Burn rises north-west of Carn nan Sac and drains N.N.E. to its confluence with the Clunie at Clunie Lodge. This is oblique to the regional strike which is N.E.-S.W. It rises in an area covered by peat deposits, but there can be no doubt that its source lies in the Perthshire Quartzite, which shows through the peat cover in blocky screes. At the foot of this westerly trending ridge of quartzite the stream cuts through peat to reveal exposures of black graphitic schist. This relationship is further confirmed across the watershed in Perthshire, where two tributaries of the Taitneach cut through the quartzite ridge, revealing a continuous section through massive quartzite to rusty flaggy quartzite, rusty black schist and quartzite, and finally black schist. These sections show a swing of strike from east-west in the Taitneach tributaries to northeast-southwest in the Baddoch Burn.

Continuing downstream, a series of grey schists with quartz bands and rods and thin limestones strike N.E.-S.W., with a dominantly easterly dip. Dips are high and vary between 50° and vertical as a result of the F_3 folding. So far the section appears to agree with that shown on Bailey's map, which shows that we have crossed from Perthshire Quartzite, through the Ben Eagach Schist to the Ben Lawers Calc-Schist, but at this point the Ben Lawers Schist is said to be in slide-contact with the Killicrankie Schist. This contact was not located and the grey calc schist with limestones continues downstream. Further downstream two eastern tributaries join the Burn. The first of these drains from the westward trending quartzite ridge referred to above. Bailey shows his successive contacts crossing these tributaries. In the first stream the quartzite is in contact with the grey lustrous schist, and the Ben Eagach Schist shown by Bailey is not seen. The next tributary draining from Loch Vrotachan cuts through a small outlier of quartzite. The contact with the schists is not exposed, although further downstream a series of grey schists with quartz rods is encountered. At the confluence of this stream with the Baddoch Burn, Bailey joins two slides and ends the outcrop of his Killicrankie Schist. The present survey could find no evidence to substantiate either the slides or the presence of the Killicrankie Schist. The continuous exposure in the Baddoch Burn revealed a series of grey schists with thin limestones. Continuing the section downstream, Bailey refers the rocks there exposed to the Ben Lawers; in fact the lithologies seen are entirely similar to those seen upstream. At Coire Fhearneasg, Bailey's slide is shown bringing

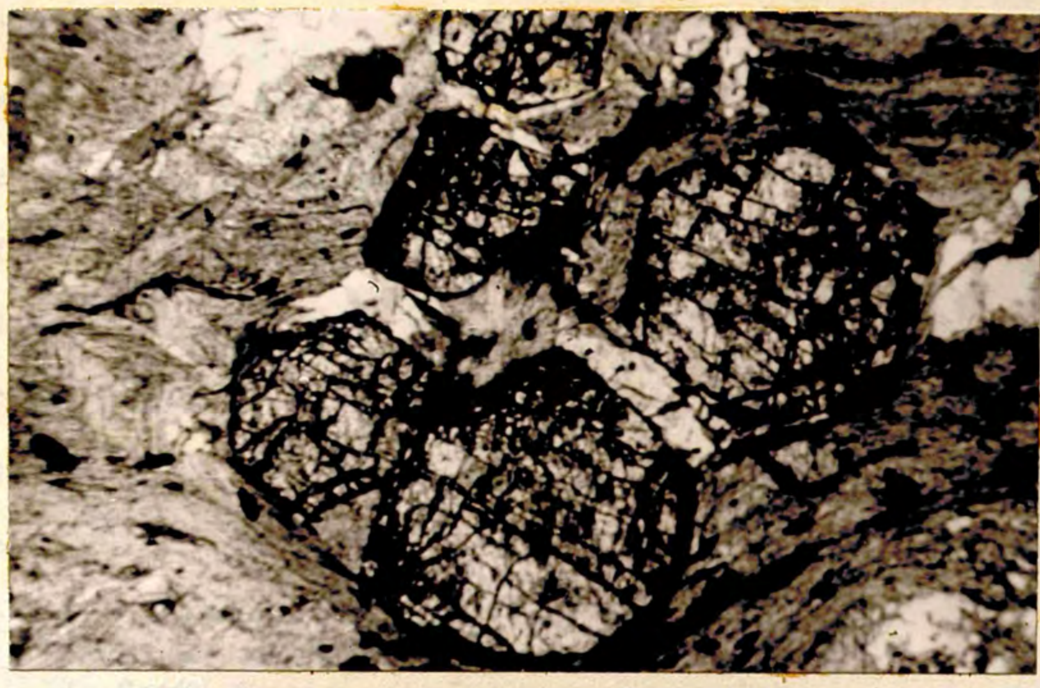


Plate 17a. Photomicrograph of idioblastic crystals of garnet in a matrix of muscovite. P.P.L. x 40. Slide 219c.

Plate 17b. Photomicrograph of linear garnet crystal overgrowing a band of biotite. P.P.L. x 10. Slide 330c.

the Ben Eagach Schist against the Blair Atholl Series and cutting out the Ben Lawers. The graphitic schist is developed at this point, but it is followed downstream by more grey schist. The boundaries of the graphitic schist are marked by dyke rocks. On the southern margin is a granite porphyry and at the northern contact, seen in Coire Fhearneasg, a grey lamprophyre is exposed. In the Baddoch Burn exposure ceases until a small bridge, southwest of Clunie Lodge. Here the feldspathic quartzite is seen overturned. This is indicated by graded bedding.

In Coire Fhearneasg, lustrous grey schist succeeds the graphitic schist and a thick band of grey limestone is developed. Further upstream, more graphitic schist is exposed and again the northern margin is occupied by a grey lamprophyre. This is followed in turn by grey schist with thin quartz granulites. Dips are mostly vertical. Two massive limestones are developed within the schist. The more northerly of these is a pure white marble, whereas the other is grey and schistose. The white limestone has a sharp contact with rusty weathering, flaggy quartzites which contain thin bands of graphitic schist.

The two bands of graphitic schist described above are shown by Bailey to be bounded by a refolded slide. However, mapping on Socach Mor revealed the presence of black schist considerably south of that shown on Bailey's map. This area of schist is bounded by thick granite porphyries, and represents a continuation of the black schist seen in

Plate 18a. Photomicrograph of elongated garnet crystal that has been rotated by the F_3 movements. The quartz inclusions in the garnet are continuous with the schistosity. Calcite has crystallised in the "pressure shadows" which were produced by the rotation. P.P.L. x 10. Slide 203c.

Plate 18b. Photomicrograph of vein of garnet in a quartz schist. The garnet is thought to have replaced an original micaceous band similar to that seen in plate 17b. P.P.L. x 10. Slide 74c.

Coire Fhearneasg. It is therefore suggested that the dyke rocks on either side of the outcrops of black schist have been intruded along normal faults and that the black schist is present as an inlier, faulted into the Blair Atholl Series.

In summary, the Baddoch Burn section is for a major part developed in a series of calc schists and limestones. At its head-waters the quartzite is seen to grade into the Ben Eagach Schist through a series of passage beds. This schist does not continue downstream but two fault bounded outcrops are developed on Socach Mor. No evidence for the existence of the Killicrankie Schist was found in this region. Moreover, the formations ascribed to the 'Ben Lawers' differ in no way from those which Bailey places in the Blair Atholl Series in the vicinity of Clunie Lodge.

(ii) Glen Taitneach

This Glen has been traversed from Loch nan Eun to Alltaulich and is particularly well exposed in its upper half, which crosses the closure of the Cairnwell Synform. The quartzite of Carn Bhinnein is in contact with the Blair Atholl Series on its northern margin. This junction is seen to swing in an arc and is exposed in a tributary to the Taitneach and in the river itself. In both cases the change from quartzite to schist is abrupt. These schists contain two thin schistose limestones, which in turn are followed by further calc schists and a thick white marble. This marble is in contact with massive quartzite to the west, but in the stream calc schist is developed at the quartzite contact. Strikes in this region are

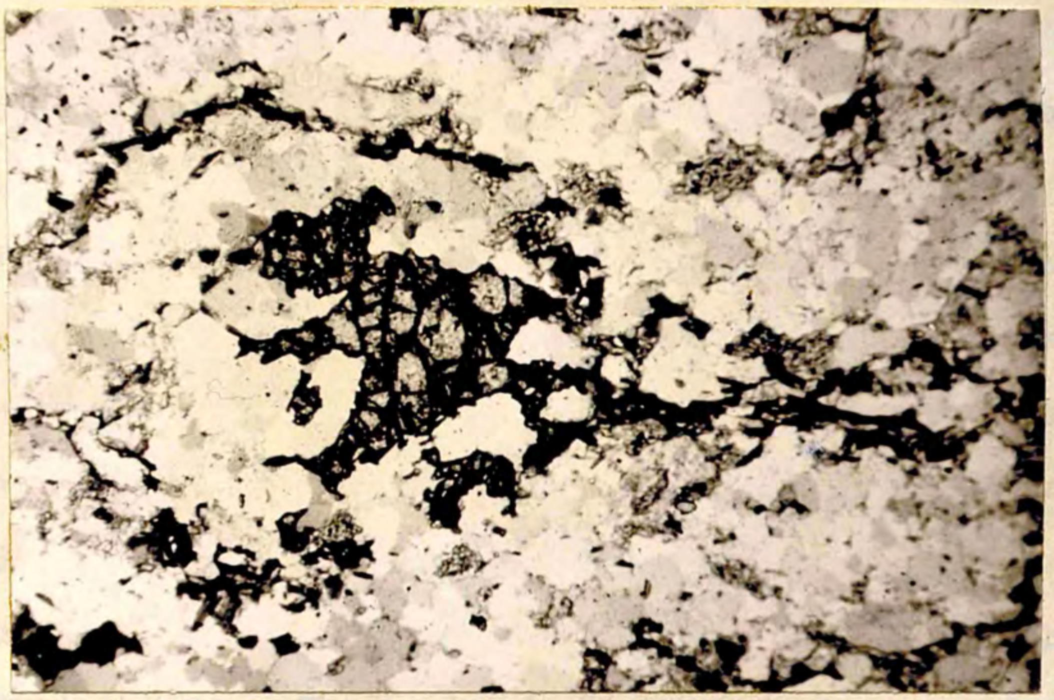


Plate 19a. Photomicrograph of xenoblastic garnet crystal in a quartz schist. The garnet grows out along the boundaries of the quartz crystals and eventually encloses them completely. P.P.L. x 10. Slide 119c.

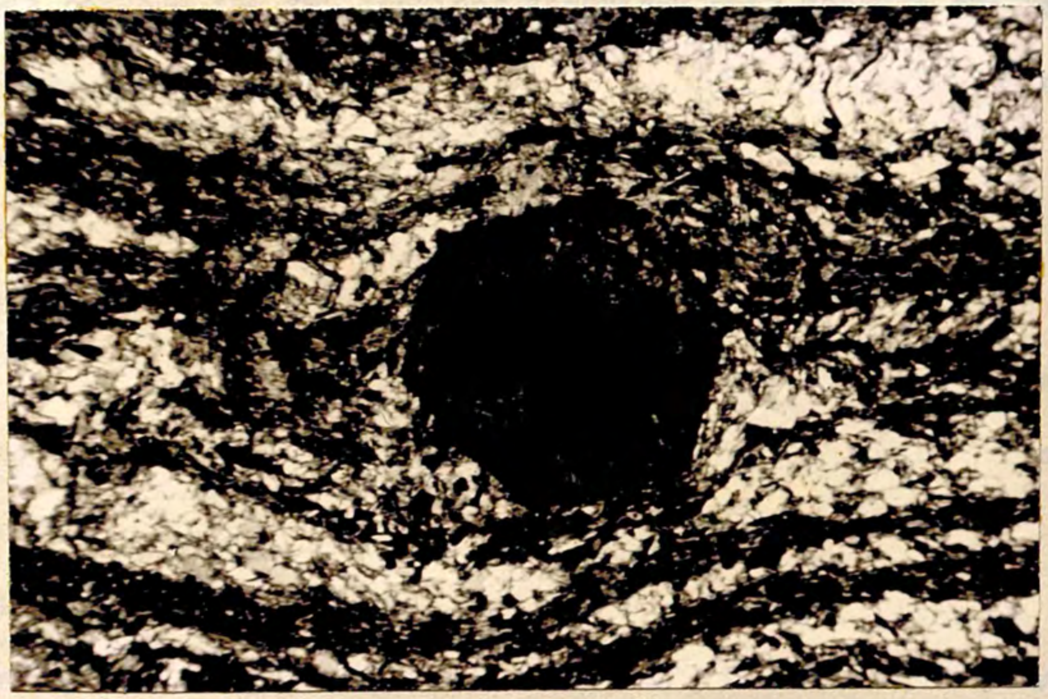


Plate 19b. Photomicrograph of an idioblastic garnet completely replaced by chlorite. The crystal here is growing in a fine grained micaceous matrix. P.P.L. x 10. Slide 104c.

east-west and dips are mostly vertical. The quartzite is highly shattered, but passes northwards into black schist as described above. In Glen Taitneach, the Carn Bhinnein Quartzite is followed by grey lustrous schist and then by massive white limestone, which is separated from the quartzite by a felsite dyke. Both these sections cut across the core of the Cairnwell Synform, but there is no evidence for a repetition of beds across this fold closure. Both margins of the quartzite are entirely different in character, but according to Bailey's interpretation, they are separated structurally by a very short distance. Three separate limestone horizons are developed but are not repeated by the fold closure. It may be argued that the northern limb has been affected by faulting (see evidence of dyke intrusion and shattering), but the section seen in a tributary half-way between the two sections described cuts through the unfaulted contact. Here flaggy quartzite is developed at the contact with the grey schist. This is a rusty weathered rock, similar to that seen at the Quartzite/Ben Eagach margin. In this section the white limestone is missing.

The closure shown by Bailey to occur in the quartzite, on the western side of Glen Taitneach, could not be verified, since this ground is covered by thick peat. Continuing the traverse up the Glen, the Cairnwell belt of quartzite passes into a group of rusty quartzites with thin dark schist bands, which end abruptly against grey schists of the Blair Atholl type. These continue until a grey lamprophyre, which precedes the development of black graphitic schist,

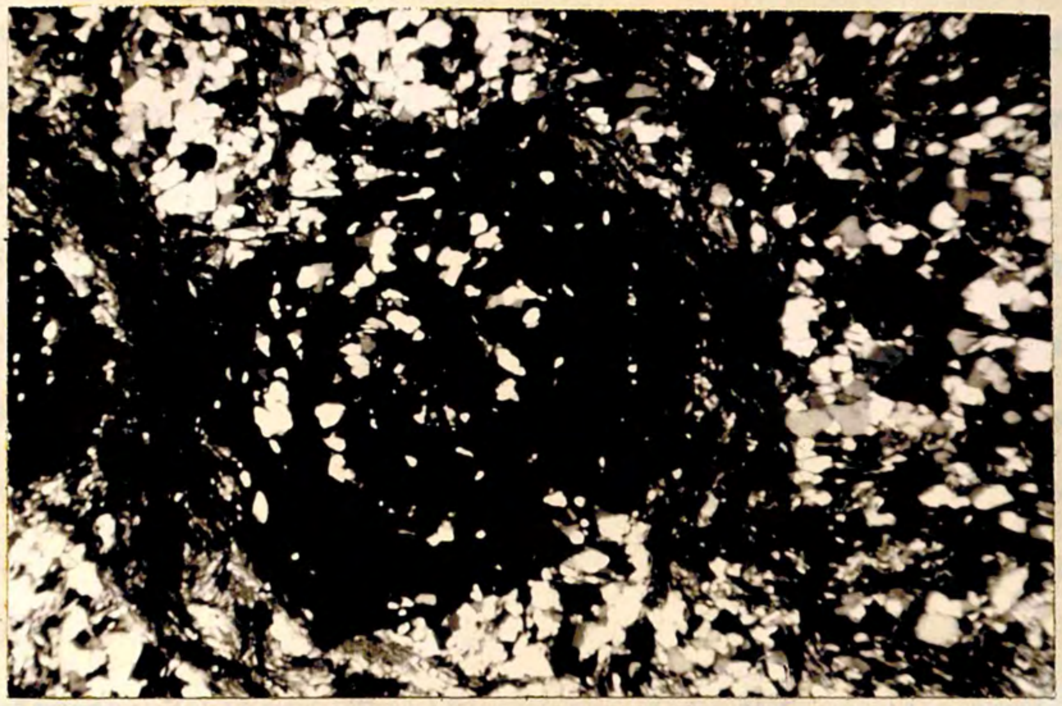


Plate 20a. Photomicrograph of snowball garnet. The inclusion fabric shows that this garnet has rotated well over 90^{o} and the form of the spiral suggests that it formed during deformation and rotated at a constant rate. Nicols crossed. x 10. Slide 216c.

Plate 20b. Photomicrograph of snowball garnet. This crystal has a perfect spiral arrangement inclusion fabric similar to plate 20a above. P.P.L. x 40. Slide 224d.

which is in turn followed by a further grey calc schist. The latter extends upstream to Loch nan Eun. The grey schists contain some very calcareous rocks, rich in tremolite. Quartz schists, of the 'honestone' type, are also present but the Killicrankie Schist was not seen. During the mapping of this region, traverses were made on to the Killicrankie Schist of Glas Tulaichean. This was found to be a quartz schist of a distinctive lithology. It contained large laths of porphyroblastic biotite and evenly distributed almandine garnets. No rocks of this type were seen in the Glen Taitneach Section. The dips measured in this section were all high and although dips in both directions were recorded, they were dominantly to the south-east. There were many examples of third phase folds and these plunged at low angles to the east and east-north-east. Many were overturned almost to recumbency.

If the above description is compared with Bailey's map, several important points emerge:

a) There is no evidence of the closure of the Cairnwell Syncline.

b) The swing of beds about this closure was not seen to occur. The northern margin of the Cairnwell Quartzite is not against the Ben Eagach Schist, but a grey mica schist of the Blair Atholl type.

c) The black schist does occur north of the quartzite, but it is not continuous to the north-east, and its relationship with a grey lamprophyric dyke suggests that in this locality it is a faulted outlier similar to that seen in Coire Fhearneasg.

d) The presence of the Killicrankie Schist and the Ben Lawers Schist could not be confirmed in this locality.

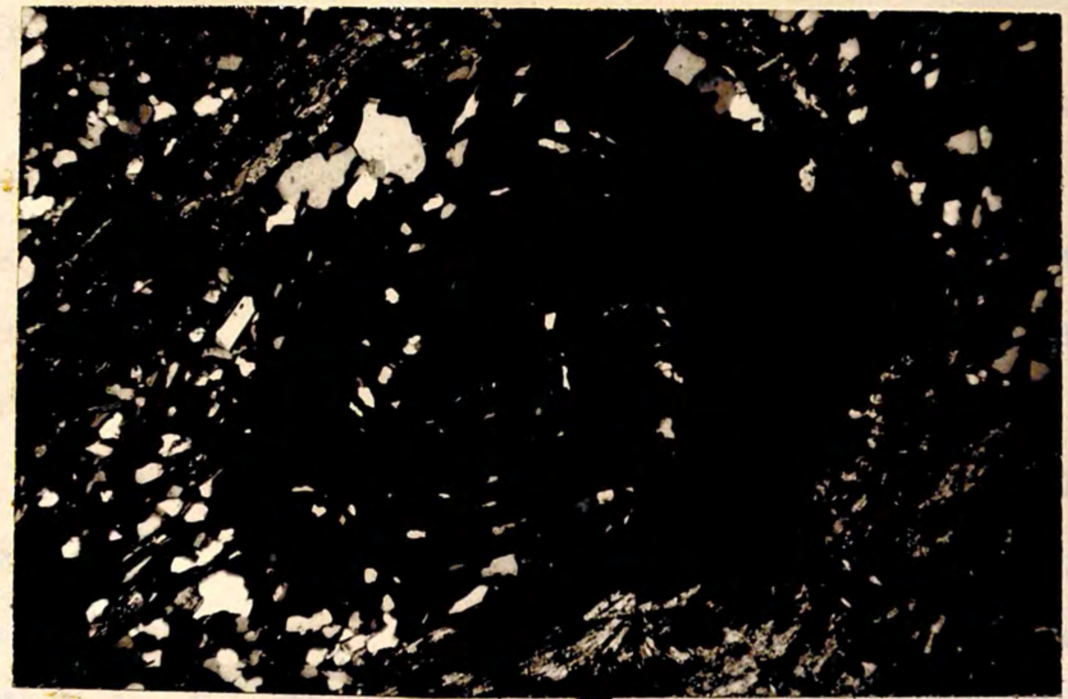


Plate 21a. Photomicrograph of 'S' garnet. The inclusion pattern conforms closely to that seen in fig. 8a and the spiral shows a slight acceleration after the initial formation of the garnet. Nicols crossed. x 40. Slide 212c.

Plate 21b. As above. P.P.L. x 40. Slide 212c.

(iii) The two-sided quartzite hypothesis

The evidence given so far does in fact confirm Bailey's original statement, that the quartzite shows two different contacts in this area. However, the relationship of the quartzite to the various schist horizons is not as would be expected if Bailey's structural interpretation was correct.

In the region of Loch Vrotachan, he links the Cairnwell Quartzite to that of Carn Aosda by a thin winding band of quartzite, which passes through a small outlier at the western end of the Loch. No evidence could be found to support the existence of this thin band. The evidence of topography and leached scree on the top of the ridge, between these two hills, supports a direct linkage. This places numerous exposures of grey schist and blue-grey schist with quartz rods, which are developed on the north shore of Loch Vrotachan, on the Ben Eagach side of BaileyIs structure. These schists are undoubted members of the Blair Atholl Series.

A belt of striped schists with thin quartzites strikes east-west across the ridge of quartzite which links Carn Aosda with the Cairnwell. Dips within this belt are to the south, between 45° and 60°. 'The Cairnwell Synform', at this locality, strikes north-south. The lithological strike is, however, at right angles to this, and the Ben Eagach Transition, i.e. the striped rocks described above, outcrops on the 'Blair Atholl side' of the quartzite. Similar examples can be quoted from several localities.

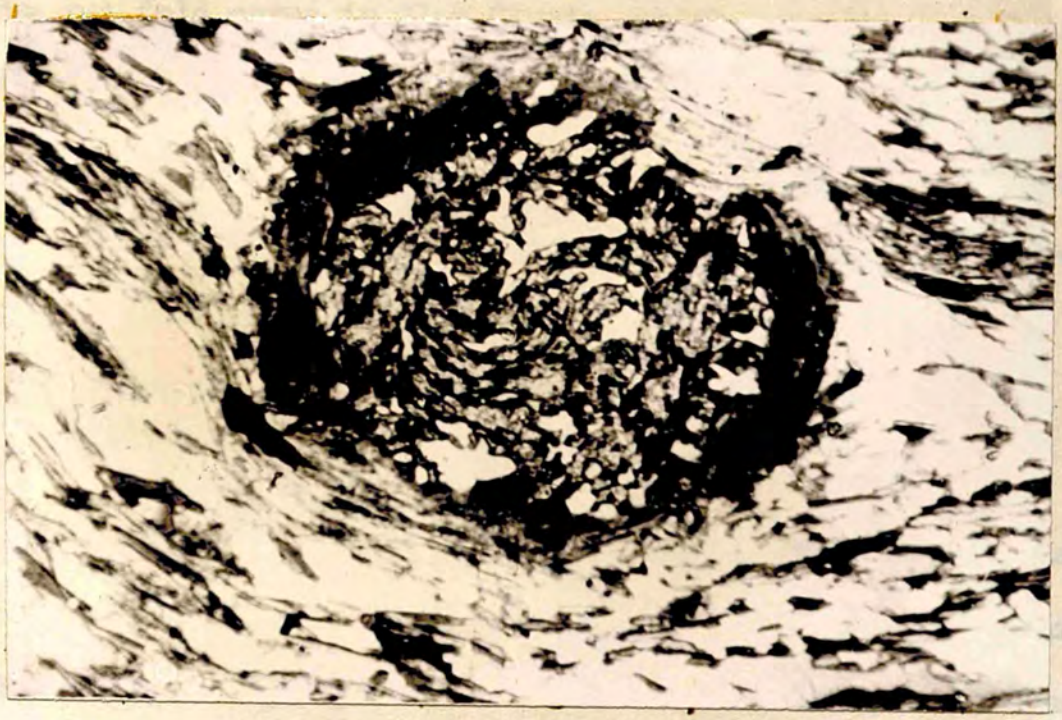


Plate 22a. Photomicrograph of 'S' garnet. P.P.L. x 40.
Slide 57c.

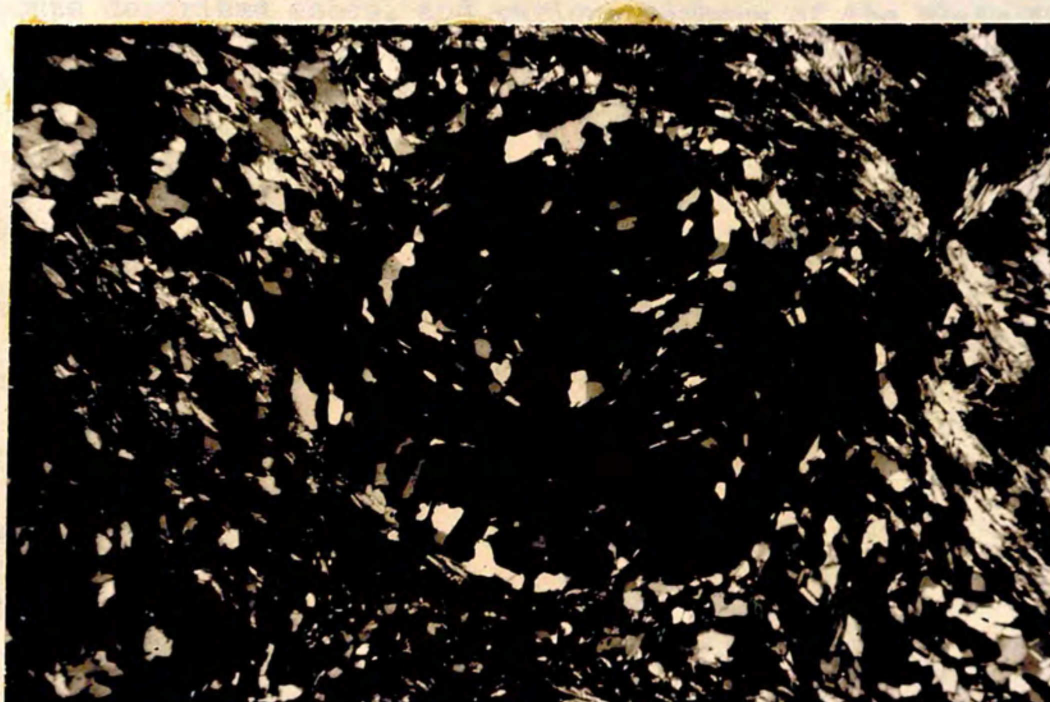


Plate 22b. Photomicrograph of 'D' garnet. The central zone in this example is slightly curved unlike the hypothetical case seen in fig. 9, but the two sets of curves in opposing directions are quite clear. Nicols crossed. x 40.
Slide 52x.

The two fold cores in Glen Clunie, which were shown on Bailey's map by a question mark, were found to consist of striped rusty dark schists and flaggy quartzites. This lithology is again characteristic of the Ben Eagach Transition group, and here too they are in contact with the grey Blair Atholl Schist.

There are two quartzite margins seen to be present in the area:

a) A transition through massive quartzite, flaggy quartzite, striped quartzite with thin schists to black graphitic schists. These marginal groups show a characteristic rusty weathering due to the oxidation of iron ores.

b) An abrupt contact between massive quartzite or the marginal groups described above, and various members of the Blair Atholl Series.

Bailey's statement regarding the Cairnwell Synform, that 'Everywhere where exposures exist, the quartzite on one side grades into black or dark schist with insignificant limestone intercalations (Ben Eagach Schist), while on the other side it is quickly followed by important limestones (Blair Atholl Series)' is a generalisation and cannot be supported. Similarly the continuous nature of the quartzite outcrop forming the Cairnwell Synform was not confirmed, since breaks shown in this outcrop on Barrow's map were found to be substantially correct. The most important of these, the closure of the Cairnwell Synform, has already been discussed, but breaks occur at several points. These are listed below.

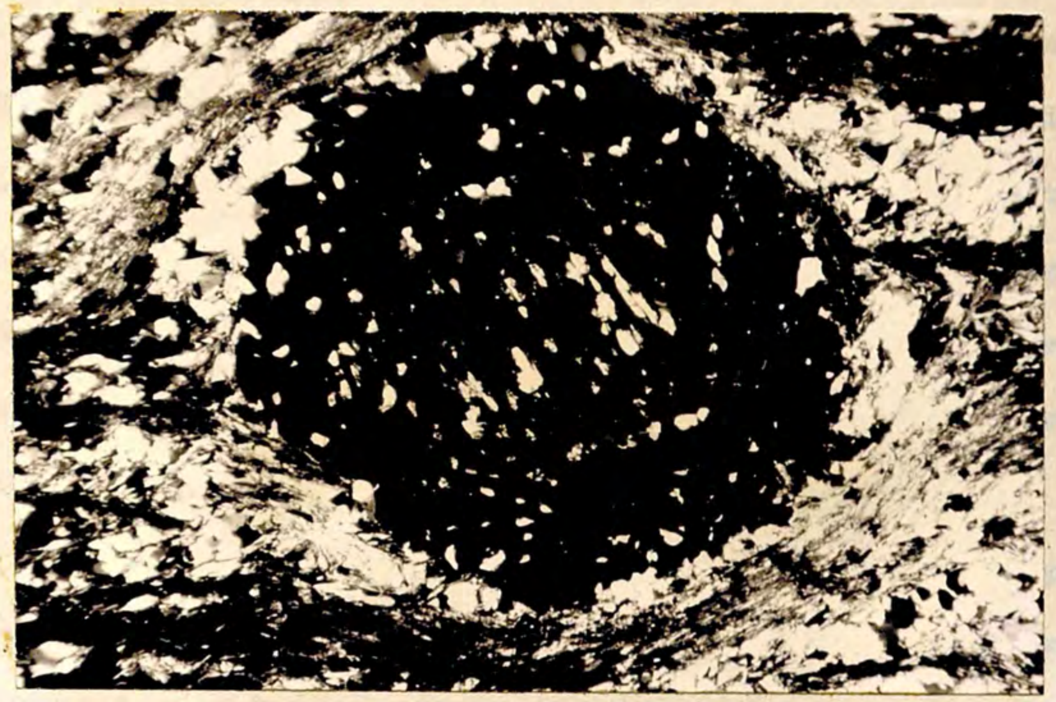


Plate 23a. Photomicrograph of 'D' garnet. This example shows a garnet which has been affected by only a small rotation. Nicols crossed. x 40. Slide 51b.

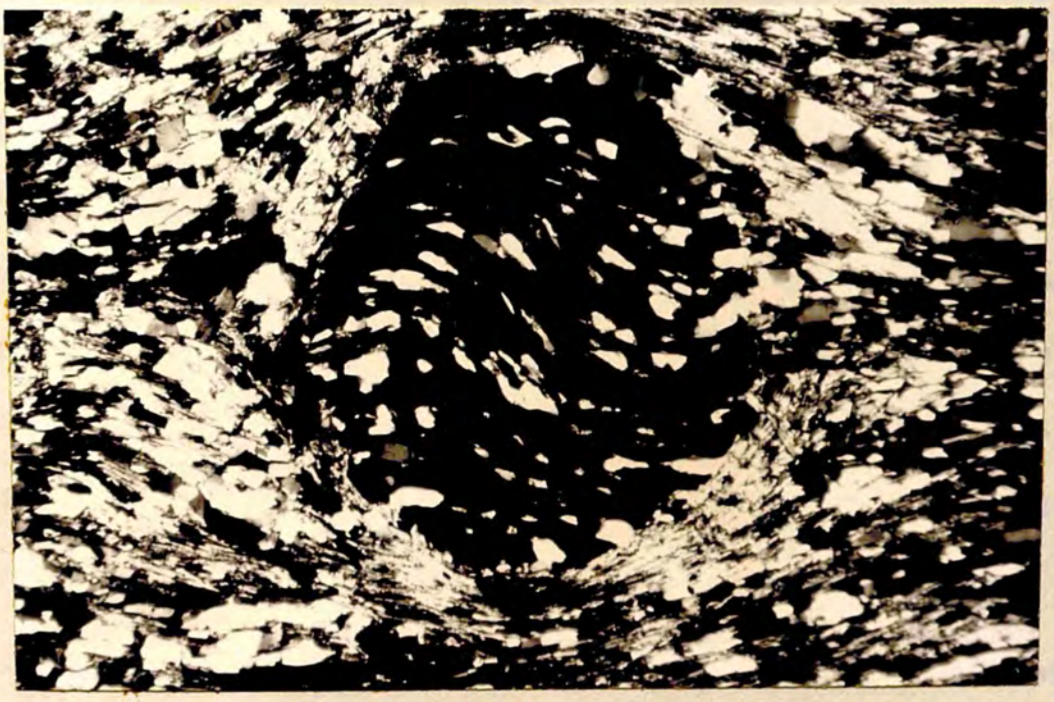


Plate 23b. Photomicrograph of 'S' garnet cut parallel to the vertical edge of plate 23a; this section of a porphyroblast shows that the orientation of the inclusions in the whole crystal is of the type that would be produced by rotation during growth. Nicols crossed. x 40. Slide 51a.

(a) Allt Aulich. Here the quartzite of Carn Bhinnein is shown by Bailey to swing southwards into the Carn Porphyry. This outcrop is drawn through badly exposed ground, but the stream section reveals the presence of the Ben Eagach Transition, although the massive quartzite is not shown. The swing in strike is readily mapped, and substantiates both Barrow's and Bailey's interpretation of a fold closing to the north-west in this locality.

(b) Meall Odhar. Again a break shown by Barrow is ignored by Bailey, in spite of good exposure of the Ben Eagach strike transition, which extends through the gap in the quartzite shown on Barrow's map. This is yet another example of the Ben Eagach rocks occurring within the 'core' of the 'Cairnwell Synform'.

(c) The Carn An Tuirc belt of quartzite. This extends south-west from Loch Callater. In his 1928 paper, Bailey admits that the gaps in the quartzite, shown by Barrow, are through unexposed ground, but he maintains that the two-sided nature of the quartzite in other parts of the region is sufficient justification for joining these outcrops. On the ground no evidence could be found to support this view. Weathering has revealed a scree of striped graphitic schist and thin quartzite, but no massive quartzite was seen.

C. Summary

The points of evidence against the existence of the structures proposed by Bailey are as follows:

a) The closure of the 'Cairnwell Synform', described in Glen Taitneach, cannot be upheld.

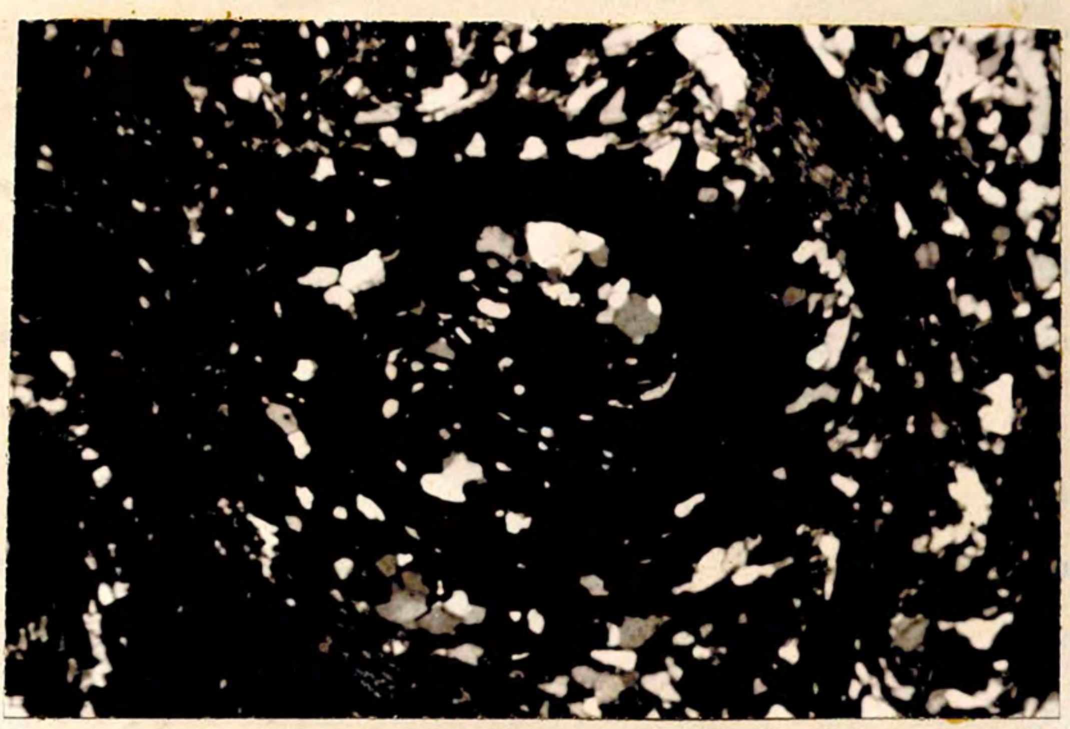


Plate 24a. Photomicrograph of 'D' garnet. This crystal closely follows the pattern predicted by the section in fig. 9. Nicols crossed. x 40. Slide 52c.

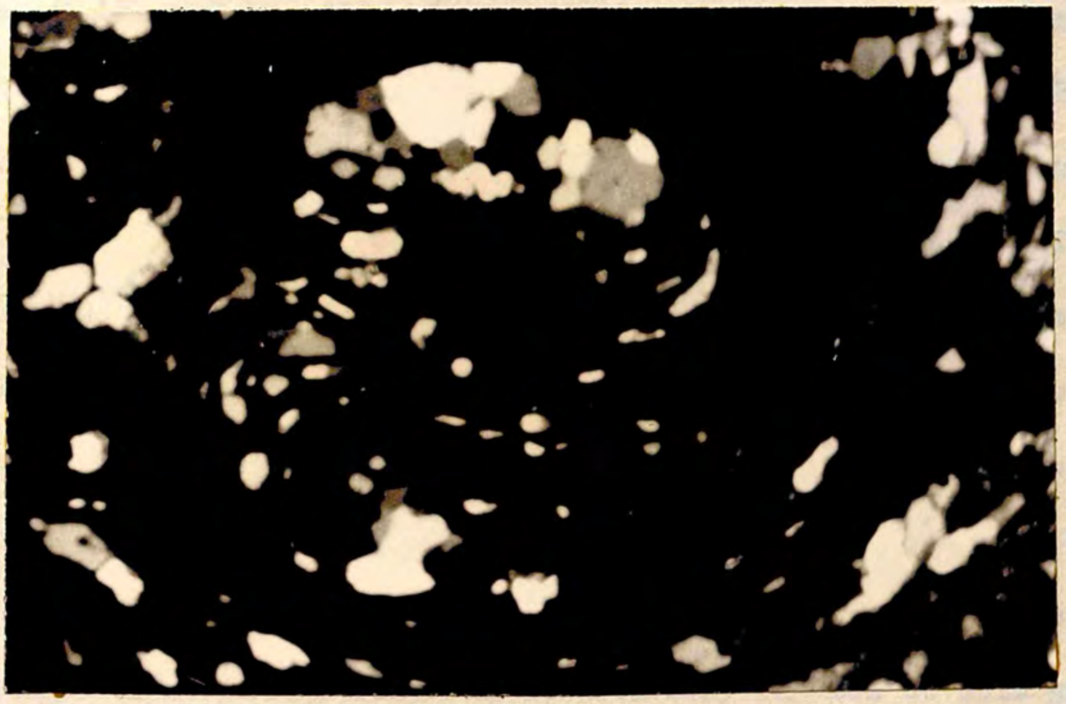


Plate 24b. Photomicrograph of close-up of the 'D' structure shown in plate 24a. Nicols crossed. x 70. Slide 52c.

b) The succession described for the Baddoch Burn was found to be present, only in part. Therefore the slides drawn in this region have no significance.

c) The quartzite forming the limbs of the 'Cairnwell Synform' is discontinuous and Ben Eagach rocks occur on both sides of its outcrop.

d) The margin of the quartzite against the Blair Atholl Series cannot be truly stratigraphical since different members of this series are brought into contact with the quartzite throughout the 'synform'.

D. Alternative Structural Interpretation

As already illustrated the contact between the Perthshire Quartzite and the Blair Atholl Series appears to be transgressive. This could be explained by movements occurring within the Blair Atholl Series which were due to their incompetent nature, such that the quartzite, which is a competent rock, responds differently to deformation and its contact with the Blair Atholl Series is therefore no longer truly stratigraphic. This process does occur, but would not account for major structural differences between the two groups. For the same reason, slide development cannot be evoked to explain the many structural breaks, since a slide by its very nature of formation would be structurally related to both groups. Contacts described above are, on the whole, concordant, but there are many clear examples of strong structural discordances.

Plate 25a. Photomicrograph of 'D' garnet. P.P.L. x 40. Slide 52c.

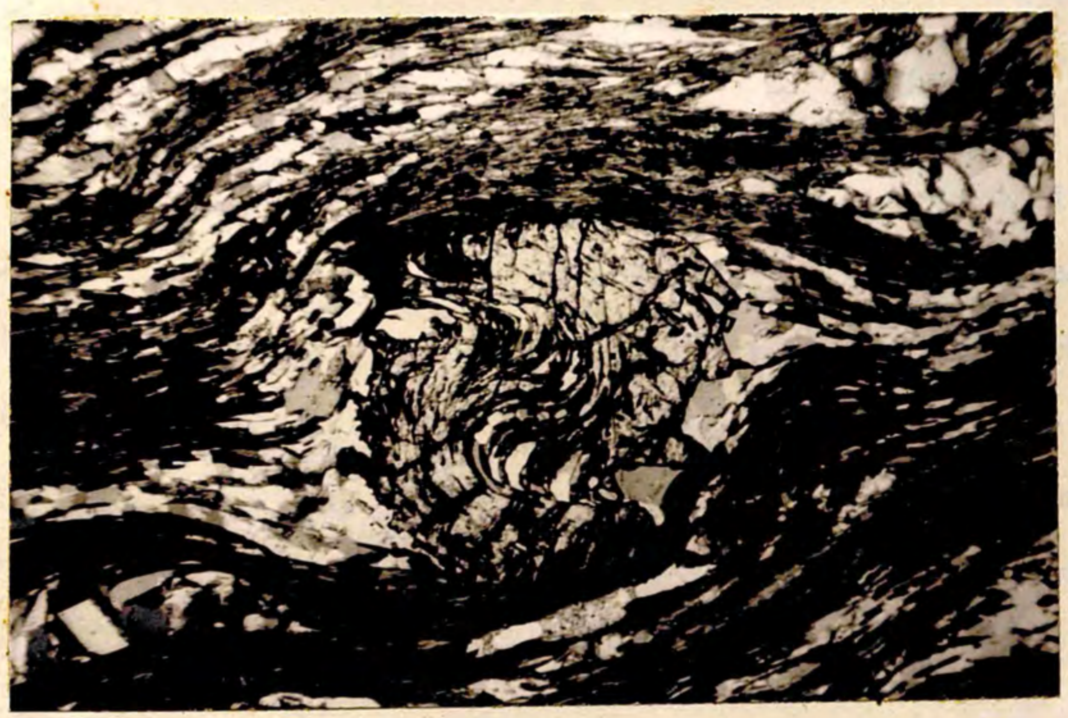


Plate 25b. Photomicrograph of 'S' garnet. This section is cut parallel to the vertical edge of Plate 25a. P.P.L. x 40. Slide 52y.

(i) Carn Bhinnein

This hill is capped by massive quartzite which dips to the south-east. On its lower slopes two massive schistose limestones are exposed. They are striking east-west, with high dips to the north and south, and are involved in folds with vertical axial planes. These rocks strike into the quartzite on its western side to emerge on the eastern side of the hill. The margin of the quartzite strikes across the limestones at right angles.

(ii) An Socach

At the north-eastern end of this quartzite ridge the strike is almost north-south. At a lower topographical level thick limestones and quartz granulites trend directly south-west into the quartzite.

(iii) Alt a Choire Dhoir

In this section thick limestones are seen interbedded with lustrous grey schist, and again the limestones disappear below the quartzite on the northern banks of this Glen. The striking feature of this Quartzite/Blair Atholl junction is that in spite of the high dips shown in both groups, the junction is almost horizontal and is seen to 'V' upstream showing that it is dipping slightly to the north-west.

These examples are the more obvious ones seen on the map, but the discordant nature of the quartzite junction with the Blair Atholl Series can be demonstrated in many more localities

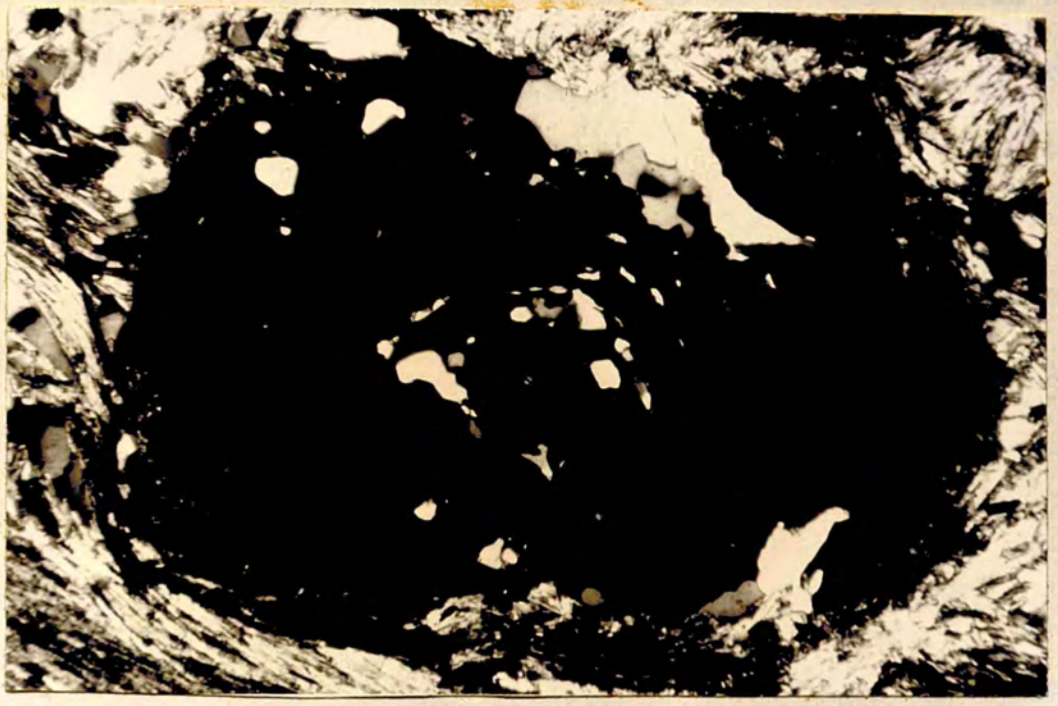


Plate 26a. Photomicrograph of garnet showing a partial 'D' arrangement of inclusions. The section in this example has only passed through one of the two 'folds' contained within the garnet. Nicols crossed. x 40. Slide 90c.

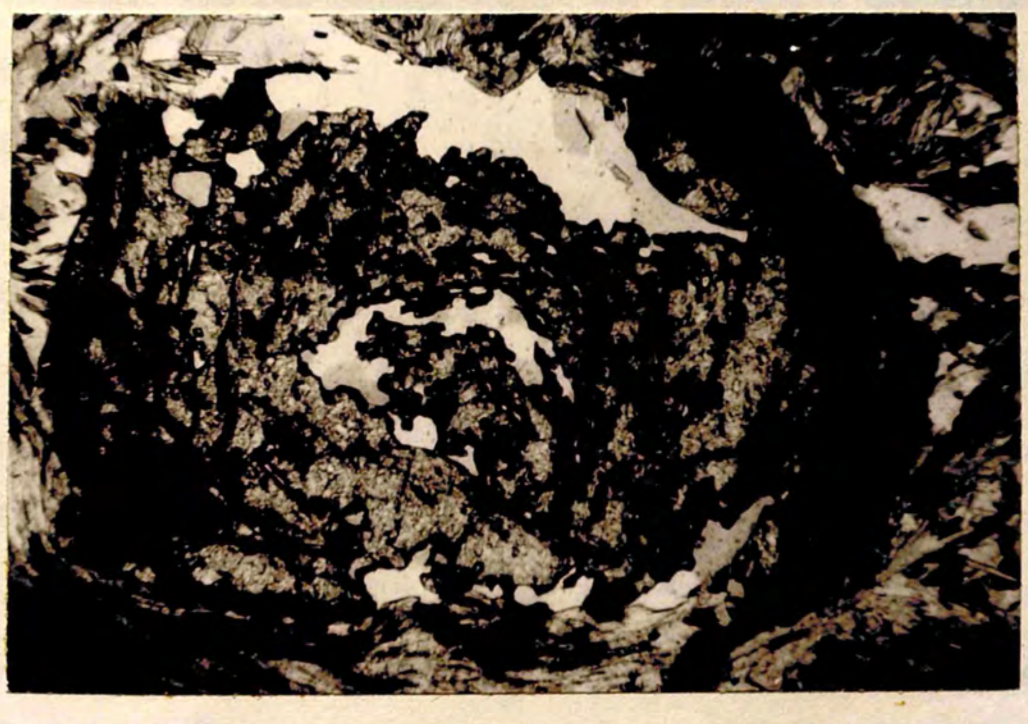


Plate 26b. As above. P.P.L. x 40. Slide 90c.

on the ground. The examples described above were chosen because they are clearly unfaulted contacts and it can be demonstrated that the quartzite boundary is not only discordant with the rocks below it, but has a low angle of dip. This is consistent with the relationships that would be expected if the area was affected by low angle thrusts, and on these grounds it is suggested that the quartzites and associated Ben Eagach Series are separated from the Blair Atholl rocks by a major thrust.

E. The Age of the Thrusting

It can be seen in the field that the thrust is almost horizontal, and has not been affected by any of the three main folding episodes. In fact no third phase structures can be traced across the thrust. Therefore the thrusting occurred after the main folding. The Ben Eagach Schist and Perthshire Quartzite are not involved in tight folds with the Blair Atholl Series and such folds terminate at the thrust boundary. At the Devil's Elbow, the swing of strike, which has been attributed to sinistral movements associated with transcurrent faulting, affects the rocks on either side of the thrust. Thus thrusting occurred pre the sinistral movement. In Glen Taitneach the thrust boundary is clearly exposed. The Blair Atholl Quartzite contact is gently folded and the quartzite above the contact is affected by a strongly penetrative rodding that destroys all trace of earlier structures. This lineation dips towards 130° and is a lineation in 'a', similar to that seen in the Moine Rocks above the Moine Thrust of north-west Scotland. This

Plate 27a. Photomicrograph of 'D' & 'S' section. It is thought that this garnet shows a transition from the 'S' to the 'D' section. The 'D' seems to be developed in the upper half of the crystal. P.P.L. x 40. Slide 212d.

Plate 27b. Photomicrograph of static garnet overgrowing microfolds. Nicols crossed. x 40. Slide 224d.

indicates tectonic transport from the south-east, which is the same as that recorded for the F_3 folds. It is therefore probable that the two periods were produced by the same stresses and that thrusting followed close on F_3.

F. The Form of the Thrust Plane

During the field mapping it became apparent that although the thrust was post the third major folding episode, it has itself a folded form. An attempt was made to determine the style and orientation of these folds by plotting the thrust contact on to a 2½ inch contoured map and constructing approximate strike lines. The results of this line of research are shown on Map 5. Although the folding is relatively simple, it was not possible to complete the form of the thrust for the whole area, but enough strike lines could be drawn to indicate that there is little regularity in the orientation of the fold axes. Many of the contacts of the Quartzite with the Blair Atholl Series are affected by normal faults, but in unfulted contacts complete folds could be determined. The Cairnwell Belt of quartzite and associated Ben Eagach rocks strike east-west. This is related to a series of east-west trending folds at the base of the thrust. These folds are extremely open, with no evidence of overturning. Dips on the limbs are in the order of 15° to 20°. The thrust contours at the base of the Cairnwell throw further light on the effects of the sinistral movements which occurred after the thrusting. On the northern side of this hill the thrust dips approximately south-east, and the strike lines

Plate 28a. Photomicrograph of static garnet overgrowing microfolds. Nicols crossed. x 40. Slide 20c.

Plate 28b. Photomicrograph of garnet overgrowing microfolds. P.P.L. x 25. Slide 218c.

range from 2400' up to 2700', whereas on the southern side of the Cairnwell the true dip is to the north-west and the strike lines range from 2250' down to 2000'. This apparent anomaly can be explained by the refolding of a previously east-west trending syncline about an axis that plunges steeply to the south-west. Such an axis was described under the evidence for sinistral movements. The effect of the refolding is to tilt the limbs of the original open syncline in opposite directions. The high plunge of this secondary fold axis explains the difference in the numerical values of the strike lines either side of the Cairnwell. This is further evidence confirming the pre-transcurrent faulting age of the thrust. North of the Cairnwell Belt, the picture is greatly complicated by faulting, but the strike lines drawn on Carn Chrionaidh are still east-west. On Carn Dubh, a fold can be determined that has no definite axis of elongation. This dome indicates that the folds may not be strictly diastrophic and it is probable that they are to some extent controlled by the rocks beneath the thrust, as well as the pressures that were generating it. In the Glen Clunie Lodge region Blair Atholl Schists and Perthshire Quartzite are exposed in a window below the thrust Blair Atholl rocks. The boundaries of this window are to some extent modified by later faulting, but the northern and southern margins show the Morrone Nappe Quartzite thrust across the Blair Atholl rocks on to the quartzite of a lower nappe. This quartzite has acted as a resistant ridge causing the development of a major anticline trending north-south in the thrust plane. This fold has later been eroded to

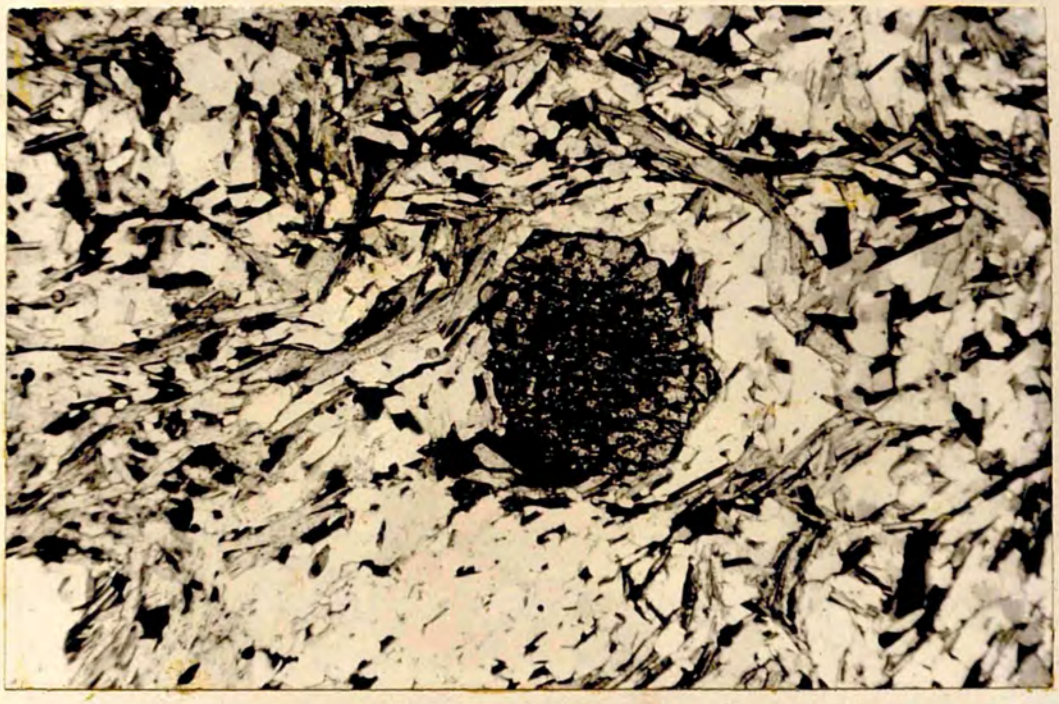


Plate 29a. Photomicrograph of garnet with fine grained inclusion fabric. P.P.L. x 25. Slide 184c.

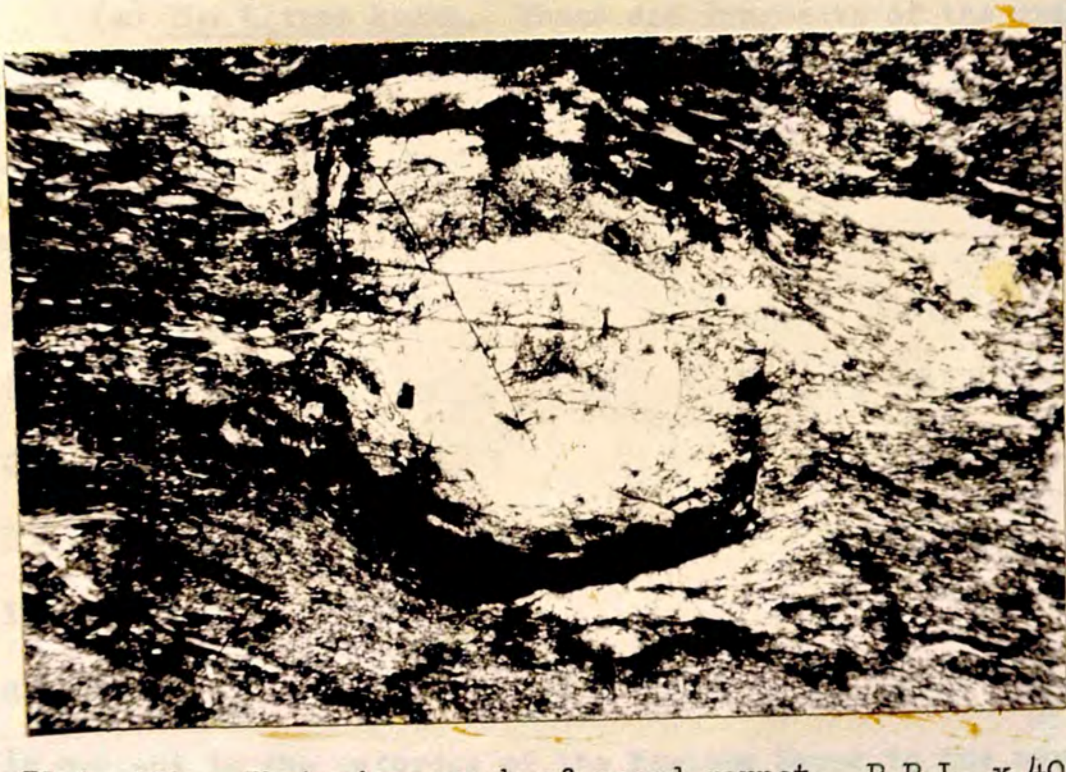


Plate 29b. Photomicrograph of zoned garnet. P.P.L. x 40. Slide 110c.

expose the Lower Nappe.

G. The Major Structural Units

The effect of the thrusting episode has been to divide the area into three structural levels:

(i) The Morrone Nappe

(ii) The Blair Atholl Thrust Zone

(iii) The Lower Nappe

(i) The Morrone Nappe

The Morrone Nappe comprises all the rocks, which in this region lie structurally above the Blair Atholl Series. They are here described in two groups to facilitate the understanding of their overall structural relationships.

(a) The Klippe Rocks. These are fragments of the original nappe, which are now separated from the main structure by erosion. They all occur north and west of the Ben Eagach Transition outcrop, which strikes south-west from Loch Callater. Carn Bhinnein is not included as it is linked directly to the Ben Eagach Transition of the Loch Callater region. In each of the klippe the Perthshire Quartzite outcrops on the summits of the hills and grades into the Ben Eagach Schist below. This schist dips beneath the quartzite in the Tay order of succession, which according to Bailey's stratigraphy is an inversion. This inversion is of regional extent and is present in the outcrops of the Morrone Nappe to the north and north-west of the area mapped (B.C. King, personal communication). This inverted succession has been folded by the crossfold and the

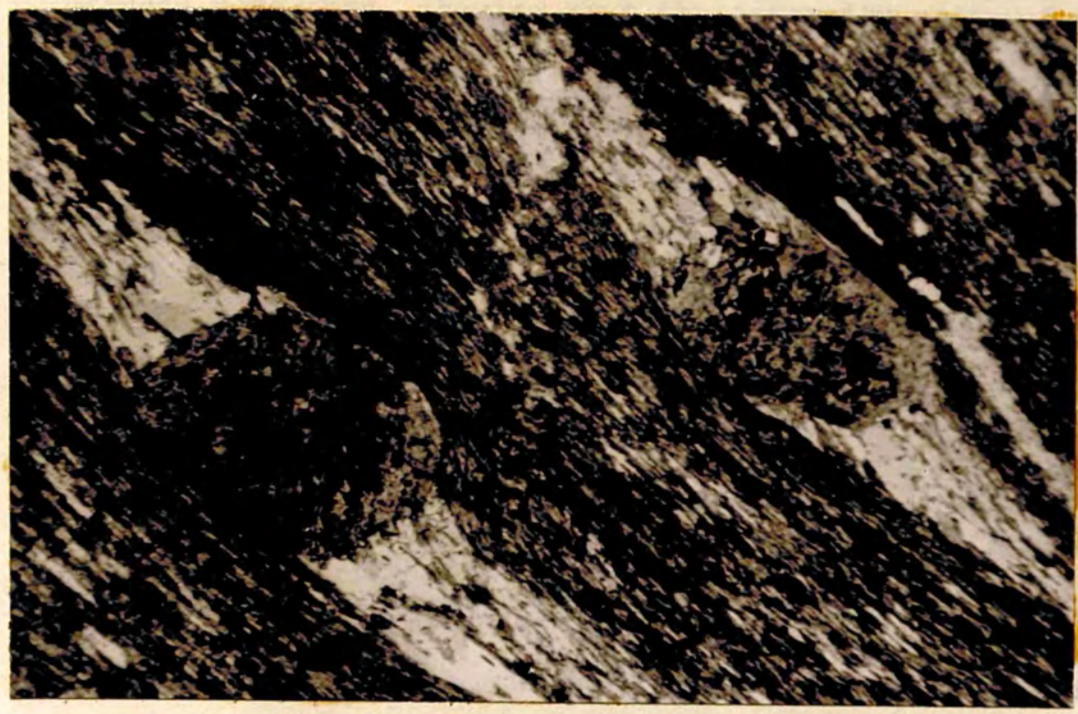


Plate 30a. Photomicrograph of rotated garnets. Quartz has crystallised in the 'pressure shadows'. The garnet is largely replaced by chlorite. P.P.L. x 10. Slide 24c.

Plate 30b. Photomicrograph of rotated linear garnet. The inclusion fabric is continuous with the schistosity and fresh quartz has crystallised in the pressure shadows. Compare with plate 17b. P.P.L. x 10. Slide 330c.

caledonoid movements, showing that the inversion occurred during the primary folding. The klippe rocks form a part of the upper inverted limb of a primary syncline. The closure of this fold and its axial trace cannot be determined in this area but the thickening of the quartzite in the hill Morrone, just south of Braemar, could represent the hinge. North-east of this hill, the quartzite is seen to pass conformably downwards through a transition group to the Blair Atholl Series. This uninverted sequence is the lower limb of the fold which can be traced into the quartzite of Morrone, where it is terminated against the thrust. The southern margin of the Morrone Quartzite swings in an apparent closure at its boundary with the black schist. This closure appears to plunge towards the north-east (B.C. King, personal communication).

Within the klippe, secondary folds have preserved the Ben Eagach Transition and the Ben Eagach Schist. In Glen Clunie two antiforms, with caledonoid axes, are developed wouth-west of Carn Dubh. These folds plunge steeply to the south-west and have steep dips on both limbs. Their axial planes appear to be vertical. On Creag a Choire Dhirich, a long ridge topped by granite porphyry, a fold core of Ben Eagach Transition is seen striking east-west. This is approximately half way along the ridge. At its northern end a similar structure is terminated by a normal fault. Again the fold core is within the striped transition. This is probably a continuation of the fold seen to the south-west. Both structures are fairly open. Dips on either limb vary between 45° and 50°.

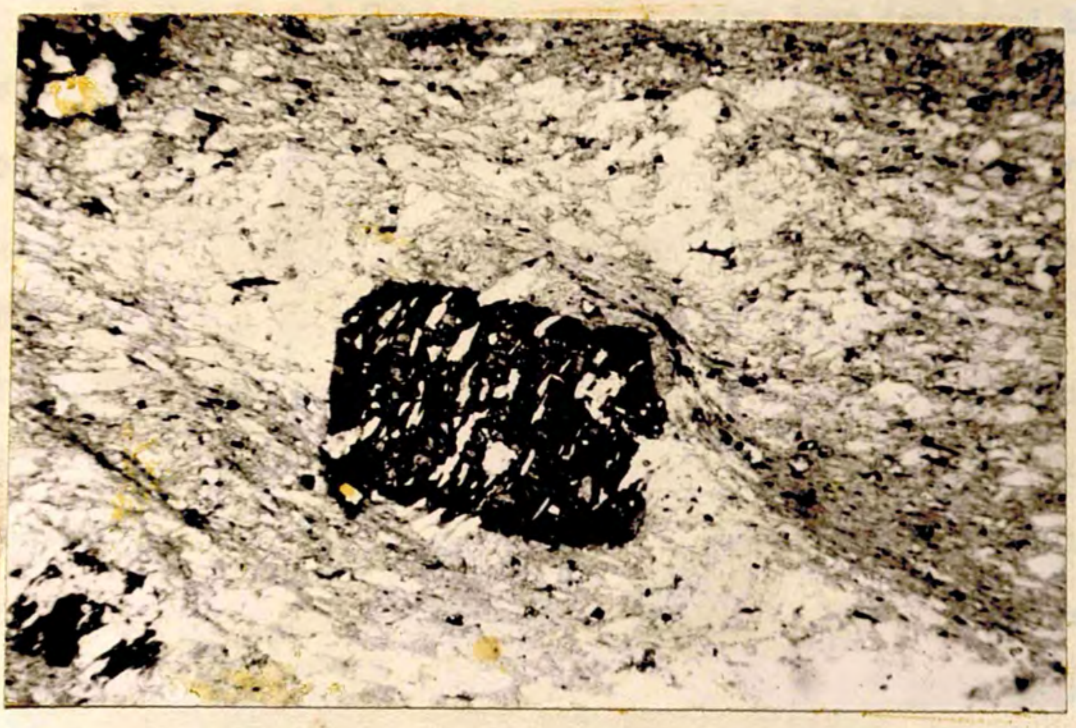


Plate 31a. Photomicrograph of garnet rotated by strain-slip cleavage. P.P.L. x 10. Slide 121c.

Plate 31b. Photomicrograph of rolled garnets. The garnets in this schist are all nearly spherical and show the development of quartz in the 'pressure shadows'. P.P.L. x 10. Slide 342c.

The Ben Eagach Schist appears to have been developed in a N.E.-S.W. trending zone, which occurs above the thrust along the Baddoch Burn. The area just south of Glen Clunie shows a fragment of this belt swinging in an arc at its contact with the quartzite. This indicates a low dip to the south-east and is possibly related to the dip of the primary structure. Further up the Baddoch, blocks of black schist are downfaulted into the Blair Atholl Series, but on the western banks of the Glen further faulting hides the original schist quartzite contact. At the headwaters of the Baddoch Burn the curve of the Ben Eagach Schist/Quartzite contact again indicates a southerly dip. This suggests that the whole of the upper limb of the Morrone Nappe is dipping to the south-east, although in places it has been modified by later folding.

(b) The Carn an Tuirc Belt. This area forms a continuous outcrop stretching from Loch Callater south-westwards to Meall Odhar, via Glen Shee north-westwards to Carn Bhinnein. The southern part of this belt occurs outside the area mapped.

The Striped Transition Series here shows its greatest development, replacing much of the normal black schist. The black schist does occur in isolated pockets which may represent fold closures, but this interpretation cannot be proved, because of poor exposure coupled with the rapid changes in lithology seen in this series. Dips are generally high and to the south-west. The discontinuous nature of the Perthshire Quartzite was noted by Bailey, who explained it as being a result of poor exposure. It is more probable that this straight junction is a result of normal

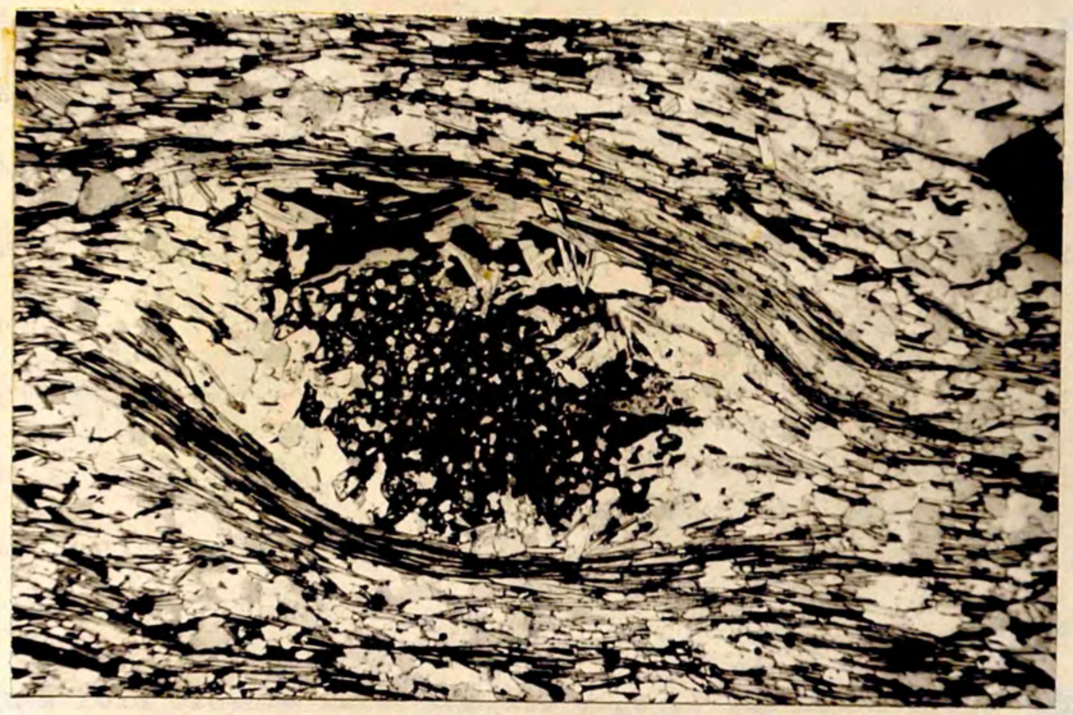


Plate 32a. Photomicrograph of garnet with fine grained inclusion fabric. This crystal is being replaced by biotite and muscovite. P.P.L. x 40. Slide 344c.

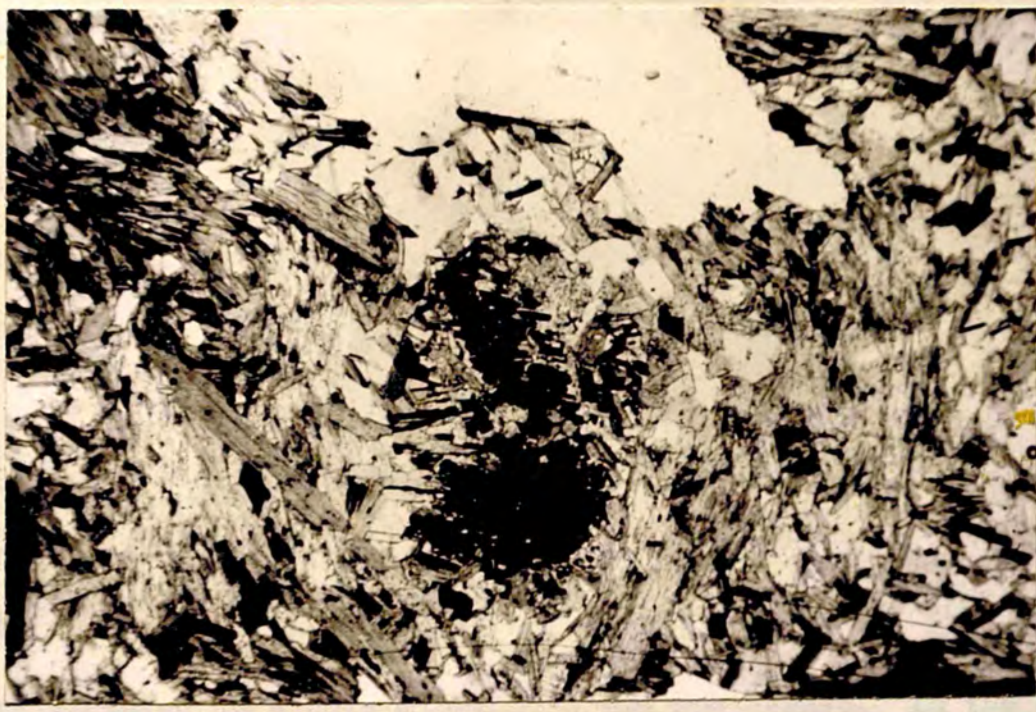


Plate 32b. Photomicrograph of garnet largely replaced by biotite and muscovite. P.P.L. x 40. Slide 193c.

faulting, since it is parallel to the many caledonoid trending faults seen in this region. The change of strike from Carn an Tuirc (N.E.-S.W.) to Meall Odhar (N.-S.), must be related to a major synclinal warp. Bailey continues this swing of strike southwards on to sheet 56, and eventually rejoins sheet 65 in the present area of study at Carn Bhinnein. The results of the present research show that the quartzite of Carn Bhinnein does not extend southwards as shown by Bailey, but the swing of strike is seen to be present in the Ben Eagach rocks. The strikes swing in a fold closure which has its core to the south-east. This appears to be a parasitic fold on the limb of a major cross flexure. It is significant that the closure of this major fold, shown by Bailey to occur in Glen Shee, is not truncated by the thrust movements. This could indicate that the thrust leaves the Quartzite/Blair Atholl junction to the south of the region mapped, and that the Quartzite/Blair Atholl contact in Glen Shee may not be thrust. This closure is complementary to that described in the Carn an Tuirc region.

(c) The relationship of the Klippe Rocks to the Carn an Tuirc Belt. The problem of correlation between these two groups arises because they are never in contact. The dips in both groups are fairly high, but the disposition of the outcrop suggests that the sediments are arranged in sheets dipping to the south-east. In the klippe rocks the sheets have a low dip, in contrast with the Carn an Tuirc Belt where the dips are high. There is no doubt as to the inversion

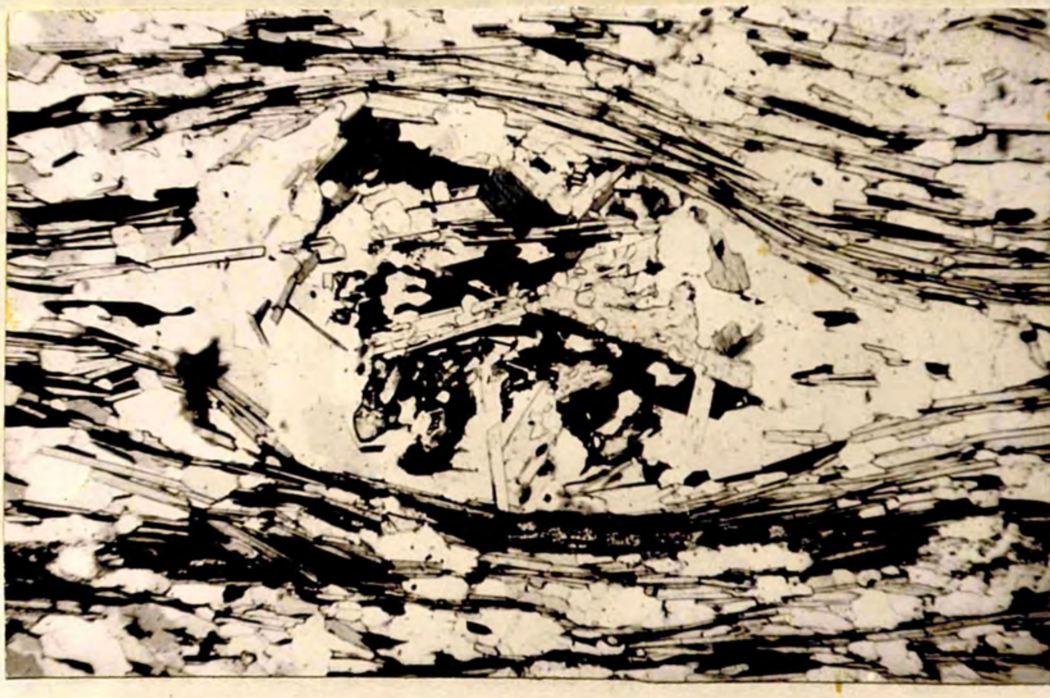


Plate 33a. Garnet completely replaced by biotite and muscovite. The original fabric of quartz inclusions is still present in the micas. P.P.L. x 40. Slide 344c.

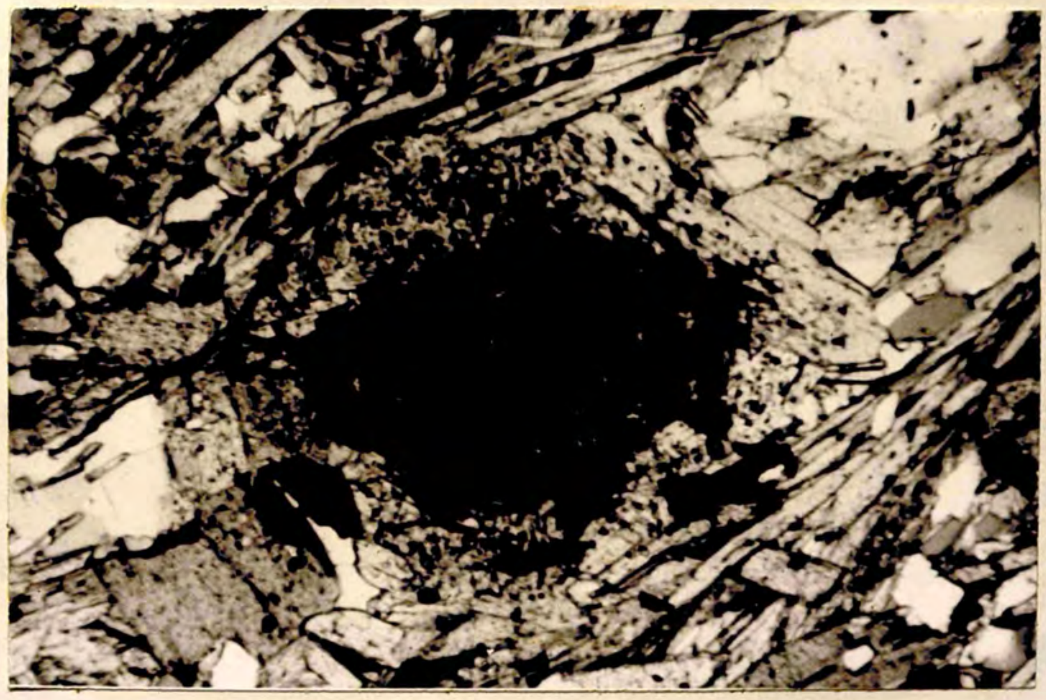


Plate 33b. Photomicrograph of garnet with fine grained inclusion fabric. The margins of this crystal have been replaced by muscovite but the small quartz inclusions remain preserved. P.P.L. x 53. Slide 195c.

of the klippe rocks, but in the Carn an Tuirc Belt the position is not so clear. From the highland border, dips become flatter in a regional inversion, which steepens as the lower Dalradian Series is approached, This has been recognised by several workers (Bailey, Shackleton etc.) as part of the inverted limb of a recumbent syncline, 'The Ben Lui Fold'. The closure of this fold does occur at the surface in the south-west highlands. Rast shows it below the rocks of the Schichallion area (1963), and suggests that it extends north-eastwards beneath Glen Shee. It may in fact occur at the surface in the Braemar region, in the hill Morrone. It is possible that the Morrone Nappe represents part of the closure of the Ben Lui Fold. A difficulty is encountered when the relationship of the Carn an Tuirc rocks to this structure is considered. These rocks could be directly correlated with the klippe rocks, therefore forming a part of the upper limb of the Ben Lui Fold, or they could represent part of the lower limb of this structure. The hinge of Morrone in this case would then constitute a fragment of the main closure which was developed in the broad expanse of Ben Eagach and Ben Lawers Schists, occurring south of the area mapped. These two alternatives are shown diagrammatically in figure 5. Both these hypotheses require certain conditions:

I. <u>The rocks of Carn an Tuirc equal the klippe rocks which are equal to the upper limb of the Ben Lui Fold.</u>

(i) There is one thrust separating the core rocks and the upper limb from an envelope of Blair Atholl.

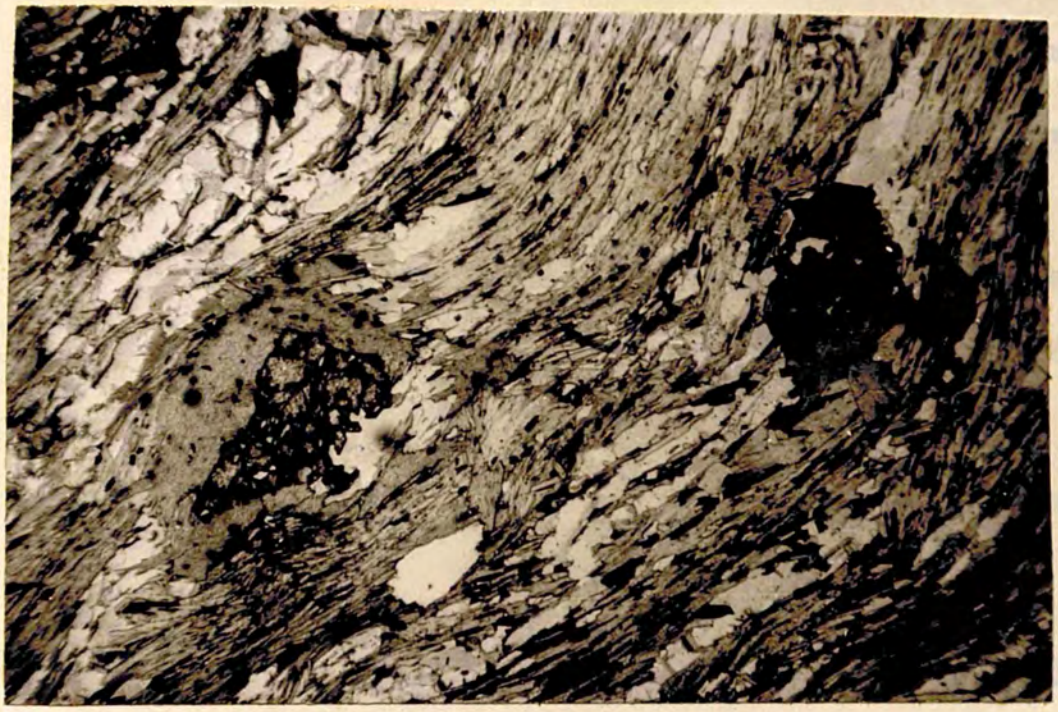


Plate 34a. Photomicrograph of garnets replaced by chlorite.
P.P.L. x 10. Slide 232c.

Plate 34b. Photomicrograph of 'S' garnet replaced by chlorite.
Although the garnet is completely replaced the inclusion fabric is preserved. P.P.L. x 40. Slide 337.

(ii) The lower limb is never seen and a thrust movement of several miles causes it to be hidden beneath the region, south of Glen Shee.

(iii) A rapid change in dip must occur from the klippe rocks to the Carn an Tuirc rocks, allowing the preservation of the striped Ben Eagach Transition.

(iv) The break between the klippe rocks and the Carn an Tuirc is of no major structural significance.

II. <u>The klippe rocks equal the upper limb of the Ben Lui Fold and Carn an Tuirc is a part of the lower limb.</u>

(i) There is a thrust developed at the base of each group.

(ii) The hinge of the Ben Lui Fold occurs in the Glas Maol region.

(iii) The Morrone Nappe core originates from this hinge region.

(iv) The break between the klippe rocks and the Morrone Nappe sediments to the south is due to the intersection of two thrust planes and is of major structural significance.

I (i) The presence of a thrust at the base of all the rocks forming the Morrone Nappe has already been demonstrated. The strong discordancy seen at Carn Bhinnein leaves no doubt that these rocks have a thrust relationship with the Blair Atholl, similar to that of the klippe rocks.

(ii) A movement of these dimensions is quite possible. The Moine Thrust has moved an even greater distance.

Plate 35a. Photomicrograph of fractured garnet. Chlorite has grown along the fracture. P.P.L. x 40. Slide 51d.

Plate 35b. Photomicrograph of fractured garnet partially replaced by chlorite. P.P.L. x 40. Slide 204c.

(iii) The change in dip is needed if the quartzite of Carn an Tuirc is to pass over the striped transition rocks. This dip change does in fact occur, as ss shown by the presence of the two cross-folds described above. The Ben Eagach Transition is developed in the core of one of these folds.

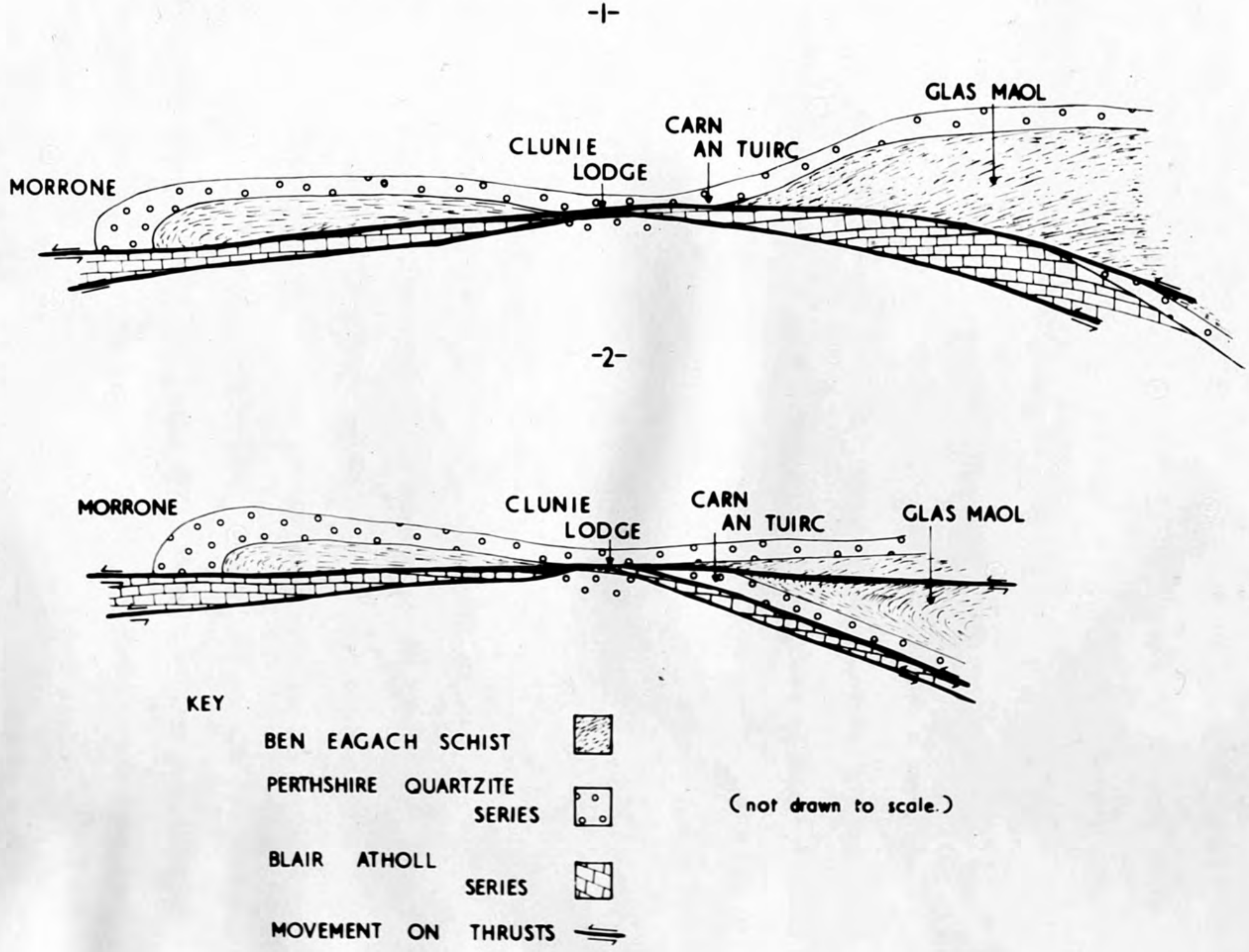
(iv) The break between the klippe rocks and Carn Bhinnein is fairly straight. Part of this is due to normal faulting on the southern side of Creag Easgaidh. The Loch Callater - Meall Odhar line is also fault controlled.

II (i) The presence of a thrust at the base of each group has been considered, but in this case the thrust at the base of the klippe would pass above the Carn an Tuirc Belt, and the thrust at the base of this belt would then be generated by the klippe thrust. There is no evidence of a higher level of thrust rocks occurring south of the Carn an Tuirc Belt.

(ii) If the hinge of the primary fold is within the Ben Eagach Transition Group of Glas Maol, then it would be expected that the hinge thrust forward to Morrone would contain similar lithologies. This is not the case. The gradual decrease of the Transition Group in favour of the black schist, northwards, is in keeping with a facies variation along a continuous horizon, and therefore favours interpretation 'I'. The great development of Ben Eagach and Ben Lawers rocks to the south-west could be explained by either primary or crossfolding.

(iii) The dips at Morrone are low and to the south-east but in

THE MORRONE NAPPE — ALTERNATIVE STRUCTURAL INTERPRETATIONS.



the Glas Maol region they approach the vertical, suggesting that these two regions have quite different structural histories.
(iv) The break between the two groups is affected by normal faulting but this does not invalidate the second thesis, since faulting would be likely to occur at a line of weakness, such as a thrust intersection.

The argument for the first interpretation is felt to be the stronger and the Morrone Nappe therefore represents a probable continuation of the Ben Lui Fold, seen in the flat belt, which has been thrust to the north-east over an envelope of Blair Atholl. The lower limb of this fold is lost beneath the overthrust rocks and probably occurs in the Glen Shee region, thus making a minimum movement of fifteen miles.

(ii) The Blair Atholl Thrust Zone

This zone of incompetent rocks comprises the envelope of the primary recumbent syncline. These rocks, due to their high lime content, acted as a lubricant to the main thrust slice. As a group, the Blair Atholl Series was deformed only at its margins, as all earlier structures are readily recognised within the series. The thick limestone horizons show the greatest deformation. Sometimes this is a simple banding, produced by the F_3 movements. The structural continuity in large areas of the Blair Atholl Series shows that they have moved en masse in a block bounded by thrust planes. The one exception to this model is the small window

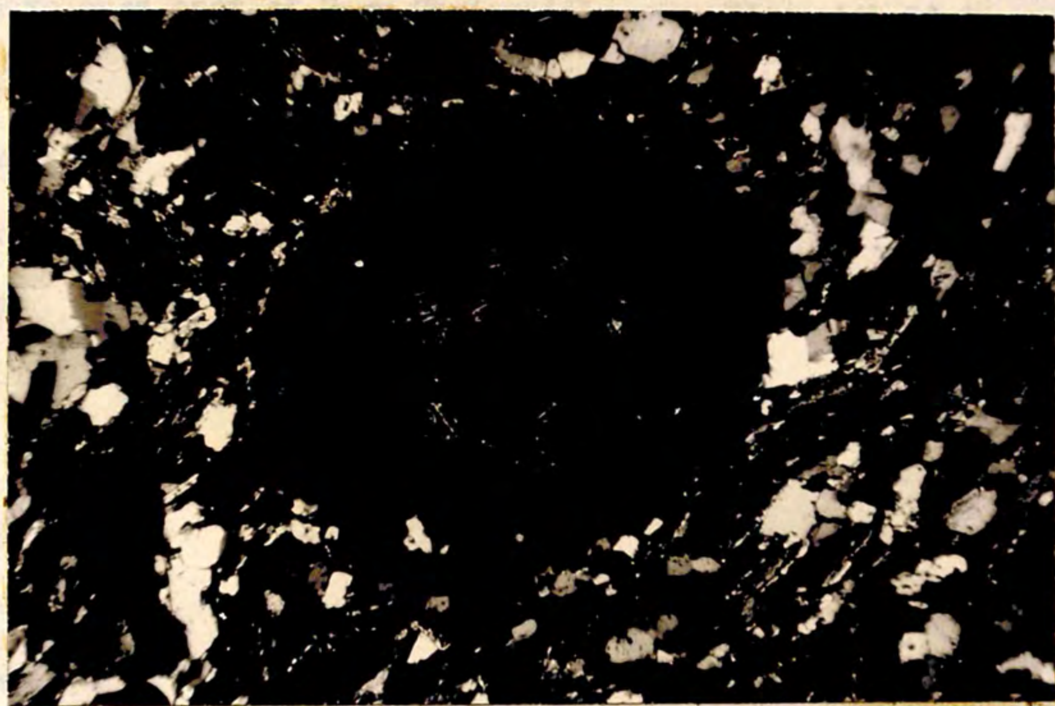


Plate 36a. Photomicrograph of zoned replacement of garnet. The garnet has been nearly completely replaced by fine chlorite crystals except for the ring of sericite near the centre. Nicols crossed. x 40. Slide 154c.

Plate 36b. Photomicrograph of garnet replaced by sericite veins. The fold on the right was originally composed of micas but is now replaced by feldspar which preserves the original structure. Nicols crossed. x 60. Slide 348c.

developed east of Carn Chrionaidh. The Blair Atholl is greatly disturbed and there was no consistency in the fold axes. At this locality the thrusts on either side of the Blair Atholl block are seen close together, until at Carn na Greine, they meet and the Blair Atholl is squeezed out. The effect of this is greatly to tectonise the thin slice of Blair Atholl.

The quartzite of Sgor Mor and that of Creag Easgaidh have at their southern contacts a white crystalline marble which appears to be quite structureless. In both examples it occupies the thrust contact between the Quartzite and the Blair Atholl Series, and it may have recrystallised during the thrust movements.

(iii) The Lower Nappe

The black schist and quartzite which occur to the east of Clunie Lodge are structurally below and discordant with the Blair Atholl Grey Schist. The northern half of this window has been mapped by B.C. King and comprises steeply dipping quartzite and black schist. Unlike the junction between these rocks in the Morrone Nappe, there is no development of a transition group (personal communication). In the area mapped for this thesis, the dips and strikes show the development of a major syncline and it is evident that these beds are not inverted. In Glen Ey, quartzite is associated stratigraphically with Blair Atholl Series below the thrusting (B.C. King, personal communication), showing that lower members of the succession appear south-westwards in the lower nappe.

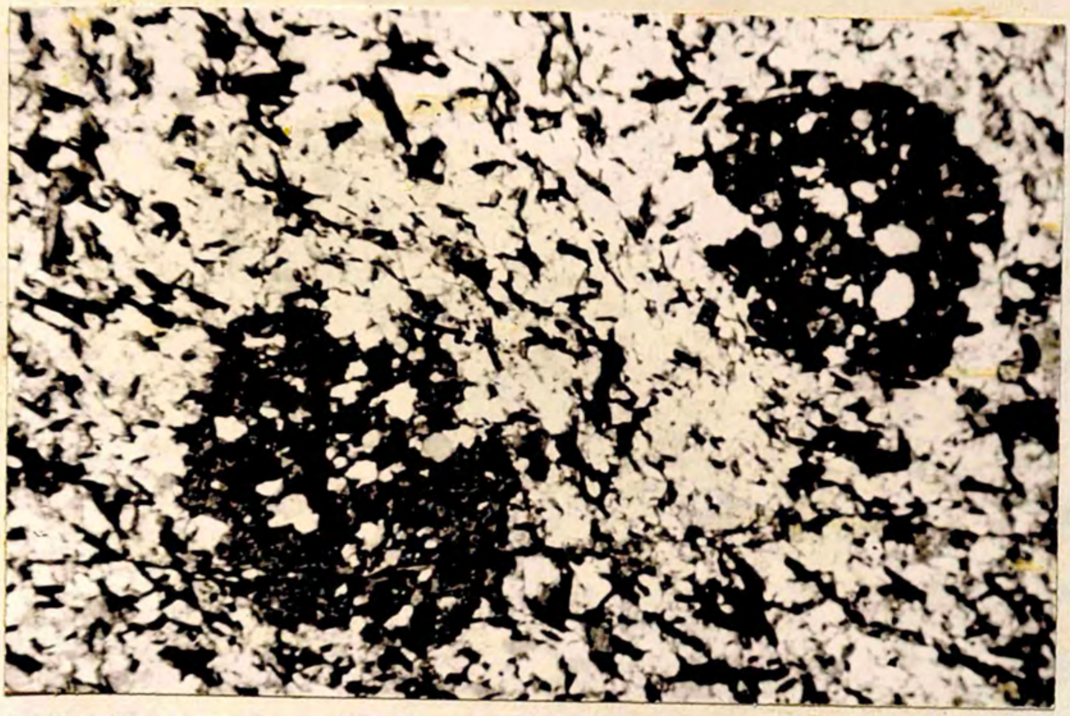


Plate 37a. Photomicrograph of garnet affected by hydrothermal action. The garnet on the left is cut by a fracture in the schist and replaced by fine chlorite crystals whereas the garnet on the right is unaltered. P.P.L. x 10. Slide 80c.

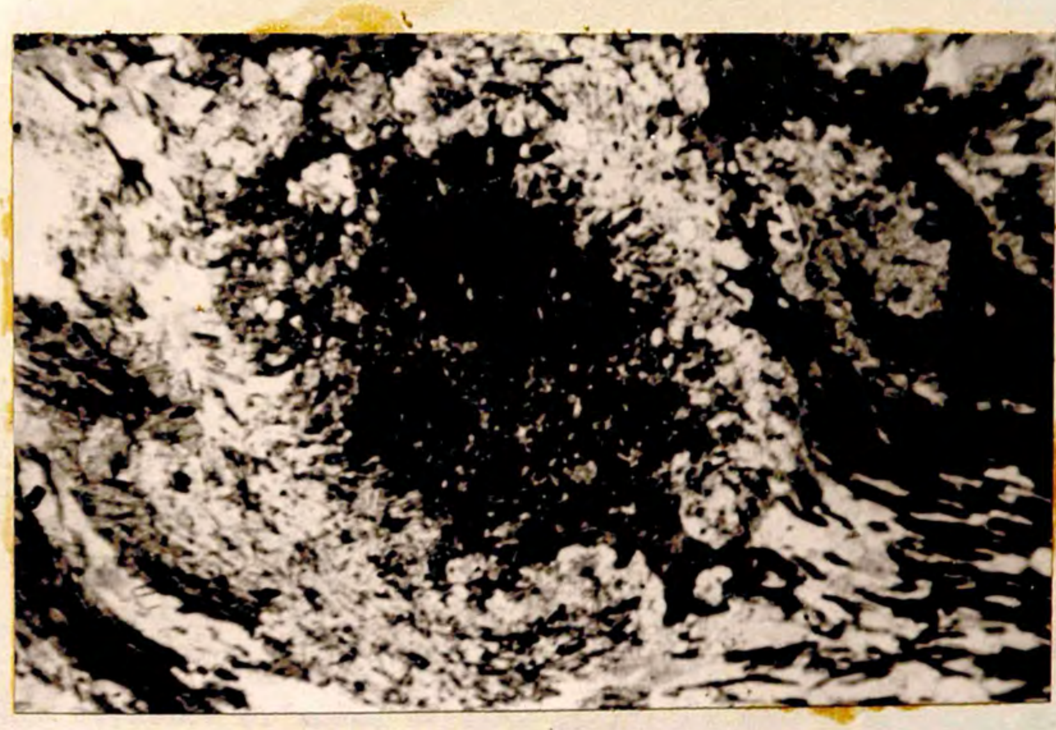
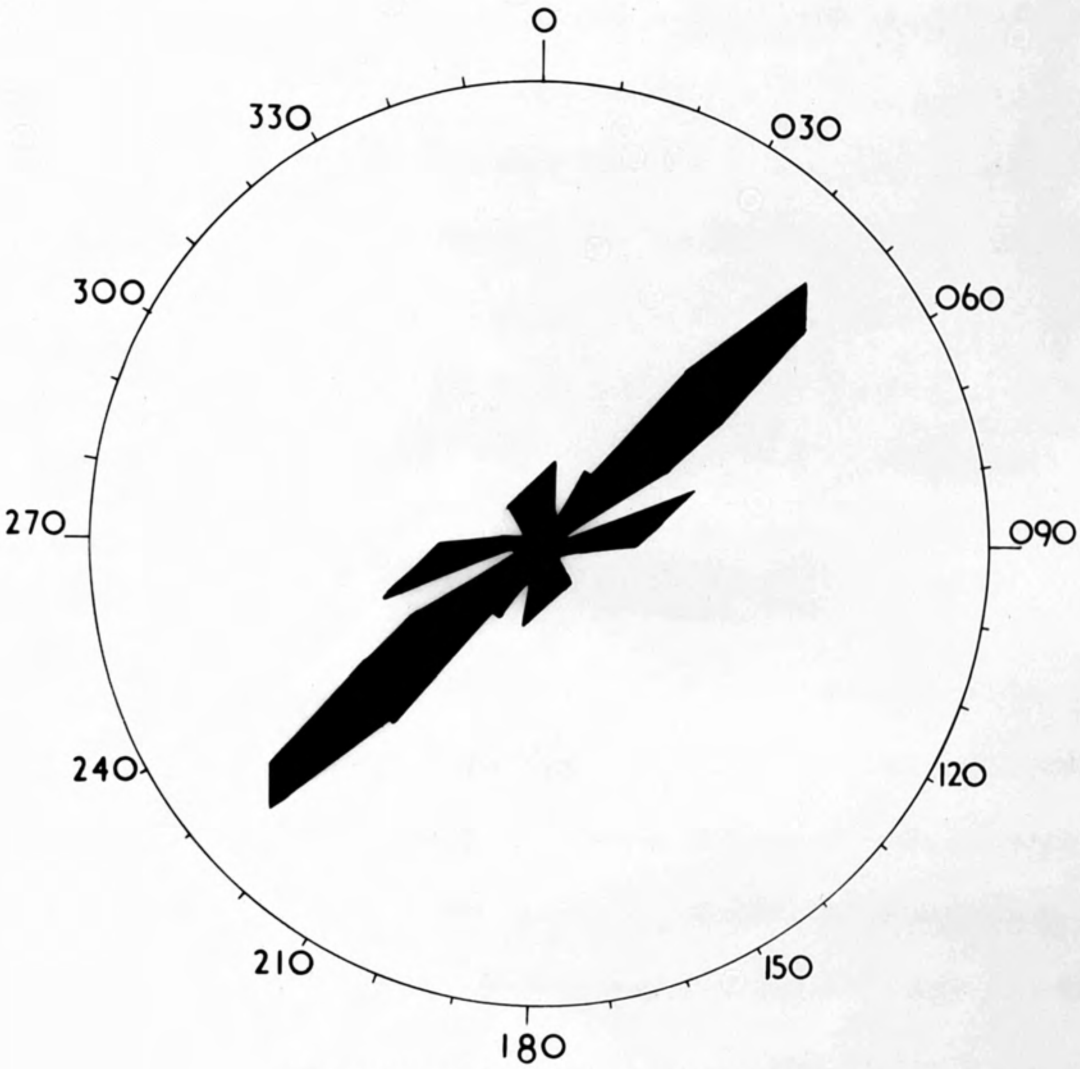


Plate 37b. Photomicrograph of garnet replaced by sericite and feldspar. The original inclusion fabric of the garnet is preserved but it has been completely converted to an aggregate of sericite, quartz and ore which is in turn being replaced by feldspar at its margins. P.P.L. x 40. Slide 146c.

H. Faulting

A summary of faulting within the area (fig. 7) shows a fault pattern which is dominantly caledonoid in trend with two sets complementary to this at 170° and 80° respectively. It is suggested that this arranagment is due to the strong development of the F_3 folds and their associated strain-slip schistosity. Later faults and dyke intrusions tend to follow these earlier structures.

Much of the quartzite outcrop is faulted and it was found in some cases that the boundary of the Morrone Nappe with the Blair Atholl Series beneath is a straight vertical contact, often associated with dyke intrusion and the brecciation of the quartzite. There are several strongly faulted belts crossing the area of study. Immediately south of Clunie Lodge the quartzites of the Lower Nappe in Glen Clunie and the Upper Nappe quartzite in the Baddoch Burn region are highly shattered and the intervening Blair Atholl Schists are cut by quartz veins. At two localities within the Blair Atholl Series there are large faulted blocks of shattered quartzite. The trend of this zone is approximately 55°. A similar belt is seen to cross Glen Clunie just north-west of Glas Maol. The quartzite is brecciated and intruded by felsite and porphyrite dykes. Tectonised Blair Atholl Schist is enclosed in faulted windows within the Morrone Nappe. The presence of these schists indicates that a vertical displacement has occurred although since these exposures are close to the thrust boundary of the Nappe the displacement is not likely to be great.



SUMMARY OF FAULTS — ROSE DIAGRAM

(to nearest 5°)

PART THREE

Regional Metamorphism

1. Introduction

W.Q. Kennedy (1948) published a map which showed the displacement of the metamorphic zones in the Scottish Highlands by the Great Glen Fault. The metamorphic zones form a large thermal anticline which closes towards the south-west. The area mapped lies in an embayment of this major structure. This embayment is bounded to the west by the Tay Fault and in the east a digitation in the Kyanite Zone forms the boundary. The Garnet Zone is brought northwards as a partial result of the Loch Tay tear faulting and the presence of a thermal syncline which closes northwards. The area of study is astride the axis of this latter structure and is almost surrounded by the Kyanite Zone. The Staurolite Zone is omitted by Kennedy since it is discontinuous. Both kyanite and staurolite occur within the area mapped but these are localised 'hot spots', consistent with Kennedy's model in which the Kyanite Zone dips gently beneath the area towards the south-west.

Several authors have published papers in which they attempt to interpret the textural relationships of the mineral phases and relate these to the deformational history of the rock (Krige 1916, De May 1942, Cloos and Heitanen 1941, Rast 1958, Sturt and Harris 1961, Johnson 1963). Johnson in his 1963 paper correlates the metamorphic history of the 'Barrovian' Region with that of the 'Buchan' Region. The evidence he uses for the former is taken chiefly from the work of Rast, Sturt and Harris in Perthshire and

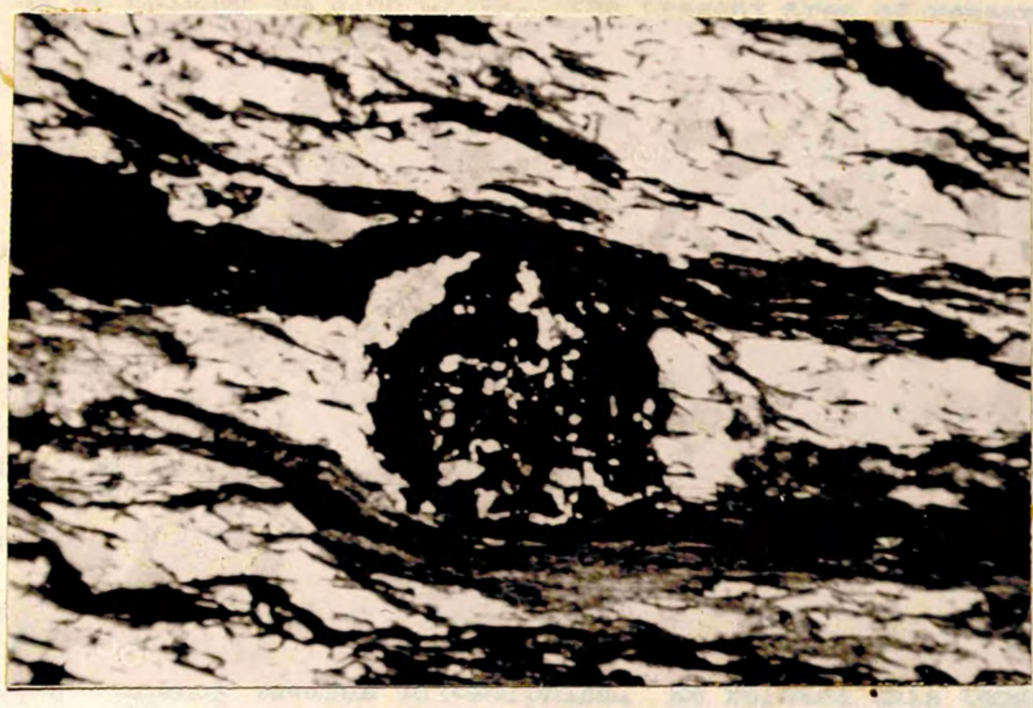


Plate 38a. Photomicrograph of garnet replaced by ore.
P.P.L. x 10. Slide 144c.

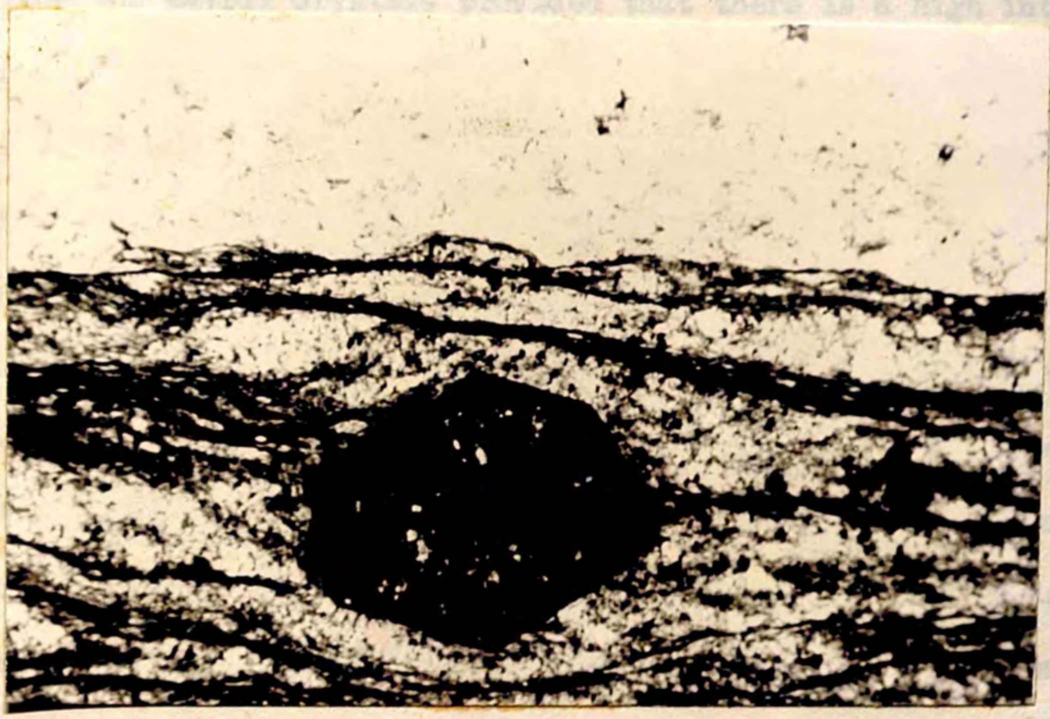


Plate 38b. Photomicrograph of garnet replaced by ore.
P.P.L. x 10. Slide 242c.

that of Chinner in Glen Clova. The present area of research fills an important gap in this regional study and the results of the textural work are given below.

2. Garnet

A. Morphology

Numerous processes have been suggested in order to explain the variation in morphology seen in garnets of regionally metamorphosed rocks. Beke (1904) published the crystalloblastic series in which he lists the metamorphic minerals in order of their tendency towards idiomorphism. He relates this tendency to the differences in their forces of crystallisation. Ramberg (1952) states that this is one of the several factors controlling crystal form. He suggests that a porphyroblast may only push aside the matrix crystals provided that there is a high interfacial energy. He says that it is for this reason that garnet will enclose quartz but will push aside mica. In fact the garnet-bearing schists of this area are seen to grow across the micas and absorb them, utilising them in the formation of fresh garnet and some of the examples seen in the quartz-rich rocks are quite free from quartz inclusions. Rast (1965) says that the speed of growth and dissolution are the most important factors affecting idiomorphism and the presence of inclusions. In most of the garnet schists the abundance or lack of quartz inclusions was seen to vary from crystal to crystal and since the growth rate and dissolution are likely to be constant for the area covered by one thin section, the above

Plate 39a. Photomicrograph of knee-shaped crystal of staurolite.
P.P.L. x 40. Slide F 43.

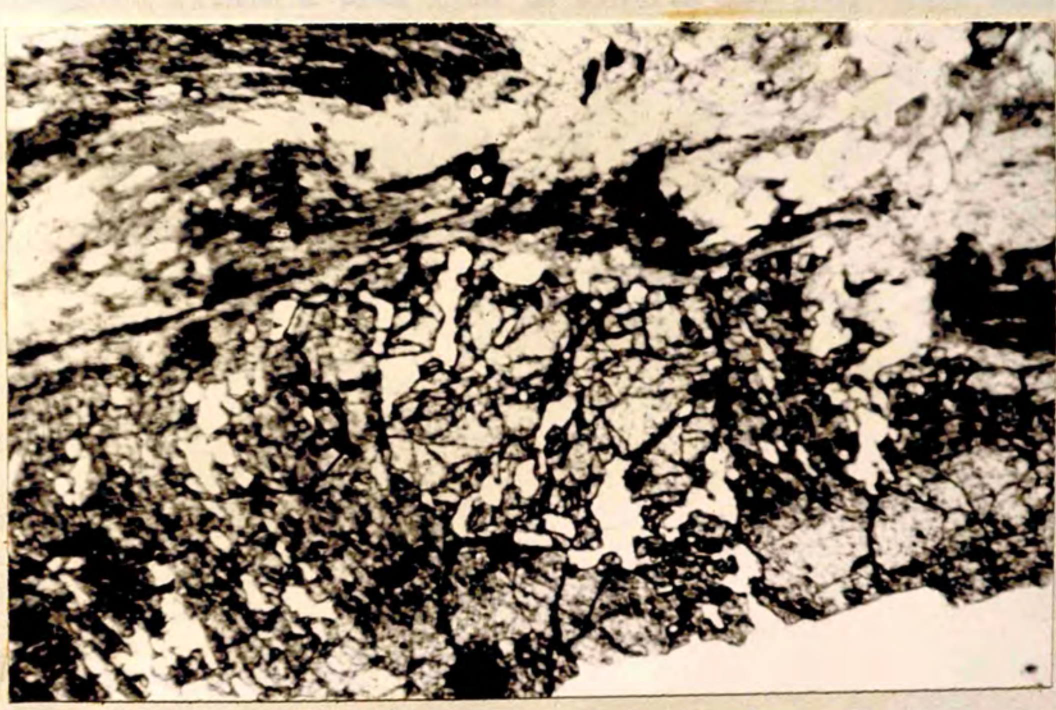


Plate 39b. Photomicrograph of garnet enclosed in staurolite.
P.P.L. x 40. Slide 342c.

explanation is not satisfactory.

Garnet occurs throughout the area mapped, and the majority of crystals described were subidioblastic, often containing inclusions of ore, quartz, calcite and less commonly epidote. Some crystals were seen to be strongly xenoblastic and grew as veins parallel to the dominant schistosity (Plate 18b). In such cases the prime factors controlling growth were partially chemical and partially structural. Mineral growth would occur along a band of pelitic material, rich in biotite, which is easily assimilated in the growth of fresh garnet. Plate 18a shows a rotated garnet which has been affected by post cross-fold movements. The orientation of the inclusions within this example gives a clear indication of its original relationship to the schistosity and therefore the reason for its tabular form. Prior to rotation the garnet was elongated within a band rich in biotite and ore. This band occurs within a quartz/calcite mosaic which acted as a chemical barrier to growth outside the band. Plate 18b shows the end product of this process where most of the original pelitic band has been replaced by garnet.

In general idiomorphic crystals occur in micaceous and fine grained rocks, whereas skeletal crystals are found to occur in schists which have granoblastic fabrics. Photomicrographs are shown in the following pages illustrating this point. It appears that if it is assumed that the growth of the mineral is by ion migration along grain boundaries, then the garnet growing in a coarse grained rock would receive the elements necessary for growth

Plate 40a. Photomicrograph of kyanite being replaced by sericite.
P.P.L. x 40. Slide 349c.

Plate 40b. Photomicrograph of kyanite being replaced by sericite.
P.P.L. x 25. Slide 350c.

at a series of points on its growing surface, whereas in fine grained rocks ion migration is more homogenous and crystal growth is therefore more even.

B. Sequence of Crystallisation

(i) Syntectonic growth

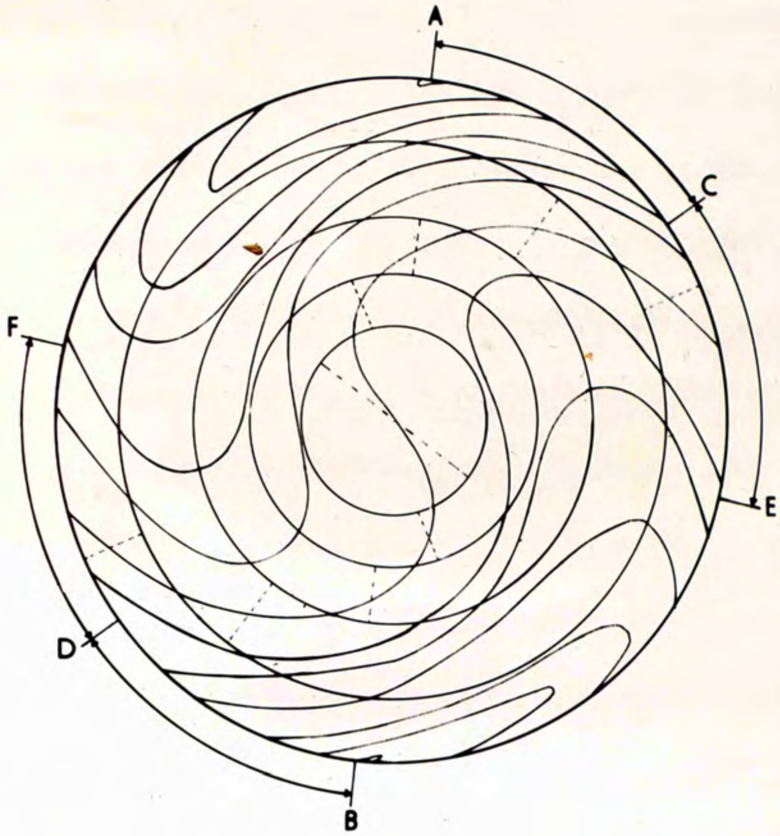
The interpretations of metamorphic textures found in the literature are in many cases subjective. This is particularly true of the descriptions of garnets which are said to have grown during deformation. Admittedly it would be difficult to construct an experiment in which syn-tectonic garnets were formed, but it is possible by observation to test out the validity of the hypotheses regarding the syn-tectonic rotation of porphyroblasts. Many of the examples described in the literature could equally well be produced by static growth of the porphyroblast over a pre-existing microfold.

Spry (1963) attempts an explanation of 'S' garnets in terms of a sphere rotating about a single axis between two planes (fig. 10). In this paper he states "the Si consist of parallel doubly curved cylindroidal surfaces so that a thin section cut parallel to the rotational axis shows straight Si." He later mentions that the inclusions in the garnets he sectioned did not show this straight line arrangement. This he says indicates that the rotation is not cylindroidal.

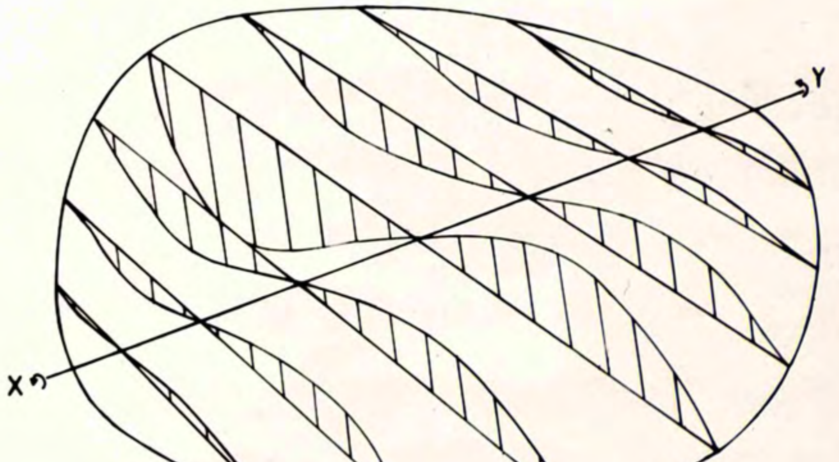
When examples of garnets with curved inclusion trails were examined in schists from the area of study, it was seen that all

INCLUSIONS IN GARNET I

a



b

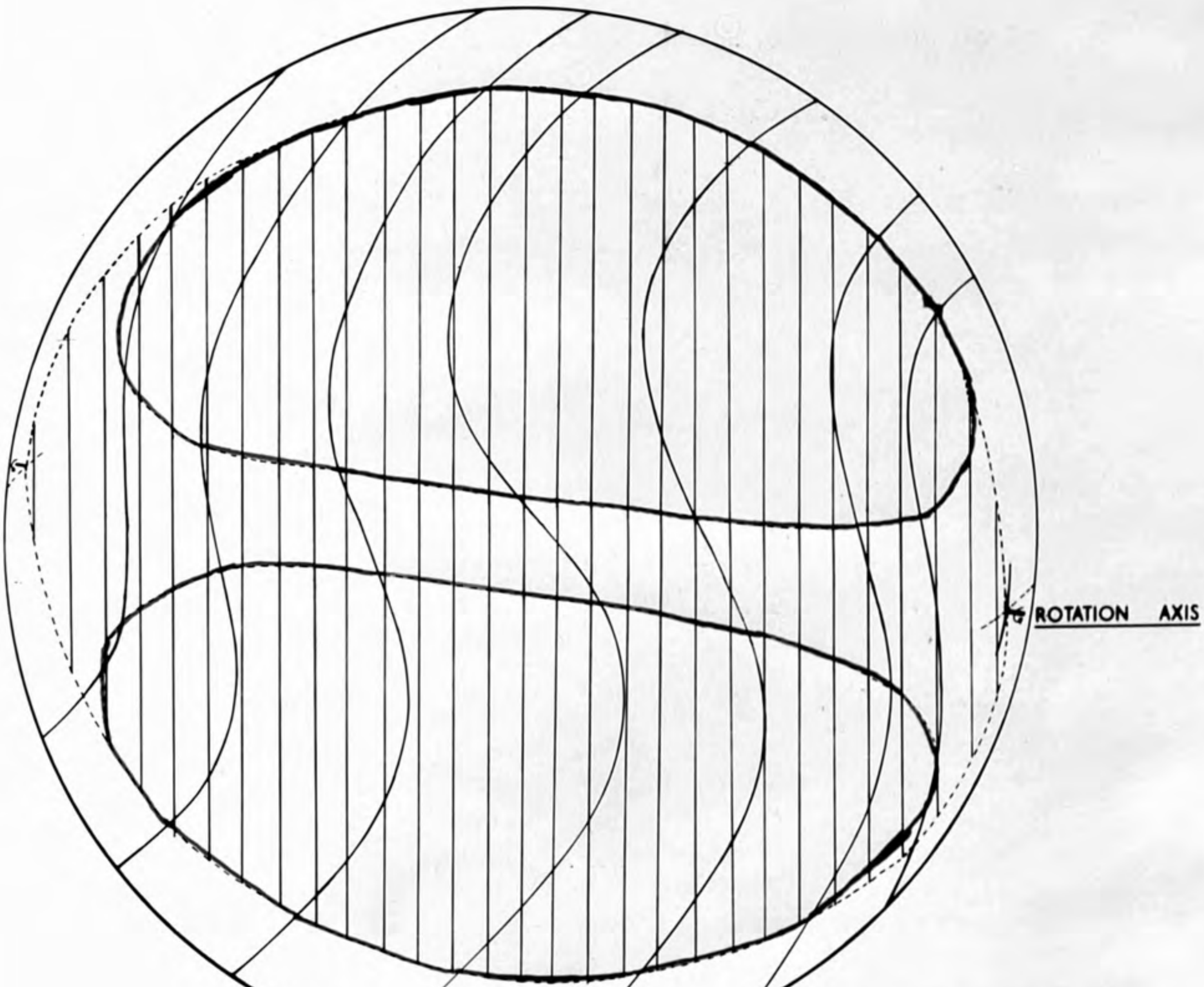


sections gave curved trails. It was therefore decided to construct a three dimensional model, assuming the rotation of a growing sphere about a single axis and to determine the inclusion patterns obtained in different sections. This would show if Spry was in fact correct in his assumption of a straight Si in the section parallel to the rotation axis. It was also hoped that this would produce some criteria by which a syn-kinematic garnet could be distinguished from one overgrowing a microfold. The results of this study are shown diagrammatically in figures 8 and 9.

There are in fact two sections which are quite distinctive of syn-tectonic garnets. These give patterns which could not be developed as a result of overgrowing normal microfolding.

(a) The section normal to the rotation axis which passes close to the centre of the crystal. This section is shown diagrammatically in figure 8a and can be compared with actual examples in plates 20a, 21a, 21b, 22a, 23b and 25b. The diagrammatic section (fig. 8a) shows the pattern produced by a rotation greater than 90° and examples where there is less than 90° of rotation can be confused with microfolding unless further evidence is available from other sections. The majority of the examples shown in the literature are of rotations less than 90° and on their own merits are not conclusive (see Spry 1963, Sturt and Harris 1961, and Rast 1958). This is not to say that rotation has not occurred in these examples, but that as similar patterns could be produced by static growth of garnet and later destruction

INCLUSIONS IN GARNET 2



of the Se fabric during further deformation and crystallisation these interpretations are subjective.

The internal spiral shown in figure 8a was drawn with the following assumptions:

(i) The crystal is spherical.

(ii) It grows at a constant linear rate (kI).

(iii) The speed of rotation is constant (k2).

Thus the radius of curvature of the inclusion plane decreases from the centre of the crystal. Figure 8a does allow for a short period of acceleration in k2 after the nucleation of the crystal, so that the maximum curvature occurs either side of the central zone. This is consistent with most natural examples (plates 21a, 21b, 22a, 24a). However plates 20a and 20b do fit the above assumptions exactly. It is seen that any change in the ratio kI : k2 will affect the form of the spiral. W. Schmidt and F. Beke (see Fairbairn 1949, p.144) investigated examples where k2 varied whilst kI remained constant and they obtained values ranging from 3 - 5.6 for the ratio kI : k2 (see also D.P. Grigor'ev 1965, p.102). Plates 20a and 20b show garnets that must have nucleated during deformation, so that the displacement of the schistosity was already at a constant rate (assuming that kI was constant). The other examples described above will have grown earlier, since if kI was constant as seems likely, their inclusion fabrics show a period of acceleration of k2. Similarly where spirals are seen to show a long open curve towards the periphery, then deceleration would have occurred. In fact no examples were found where this was the case and it is possible that deformation ended abruptly. If kI is not constant then an increase in this value will result in a decrease of the radius of curvature and conversely an increase corresponding to a decrease of kI.

If figure 8b is considered, it is seen that successive sections cut normal to the rotation axis have the effect of producing less pronounced spirals, such that sections cut furthest from the centre of the crystal contain inclusion patterns that are almost straight. It is therefore desirable that sections used in this type of study should be made to contain the largest diameter of garnet possible so that the maximum spiral is seen.

(b) Sections cut in a narrow zone* parallel to the axis of rotation (* see fig. 8a). If a model is constructed in which the successive profiles shown in figure 8b are drawn accurately and linked by tie lines it will be seen that the successive layers of inclusions form a surface which can be compared to two folds with curved axial planes. Figure 9 shows this surface within a sphere and its intersection with a plane passing through the sphere parallel to the axis of rotation (shown in red). This intersection takes the form of two 'D's which have their straight edges parallel to the rotation axis. In this diagram only the surface which shows the greatest amount of rotation is shown. Section figure 8a shows that there are a family of curves which form a series of surfaces within the crystal, and the section shown

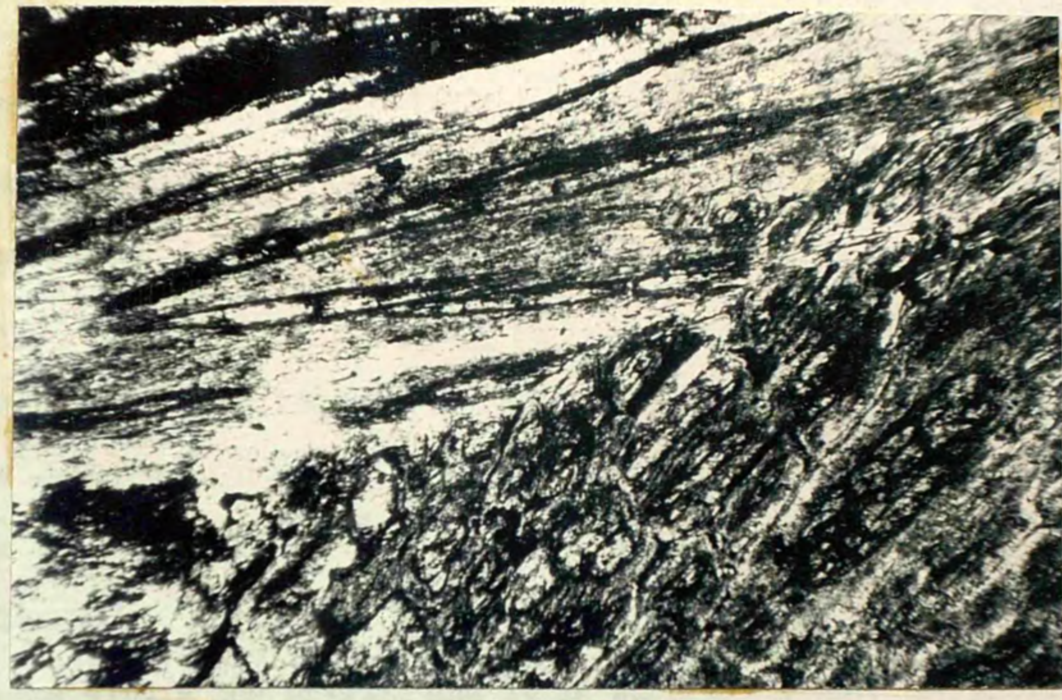


Plate 41a. Photomicrograph of acicular crystals of kyanite. P.P.L. x 60. Slide 347c.

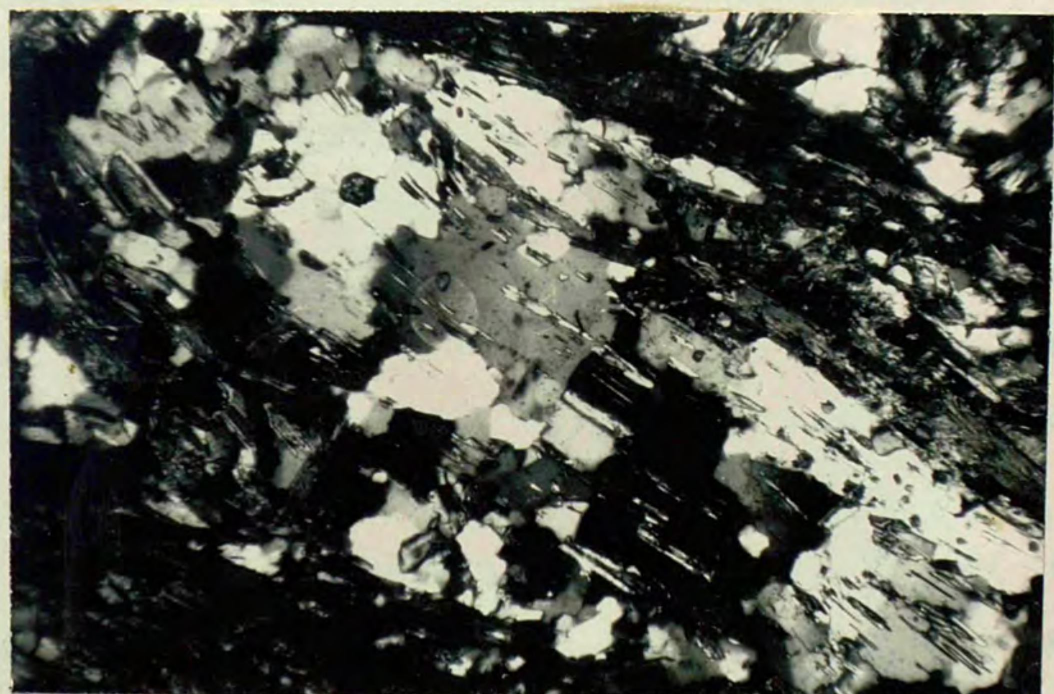


Plate 41b. Photomicrograph of inclusions of muscovite and biotite in quartz. These micas are parallel to the schistosity developed during the F_2 movements. Nicols crossed. x 60. Slide 167c.

in figure 9 should pass through a number of these surfaces with the resultant effect of producing a series of 'D"s of diminishing size. Since 'S' garnet is the term used to describe garnets with spiral inclusion trails which have suffered rotation (section (a) above) then this section (b) should be referred to as a 'D' garnet section. All sections drawn parallel to the rotation axis will not produce 'D' sections. In figure 8a the section C-D will show the maximum number of 'D's but sections cut within the arc E-F to A-B will also give 'D' sections. This is quite a large area within the crystal and it is surprising that 'D' sections are not more common. The explanation is that the majority of 'S' garnets described in the literature show rotations less than 90^{o} and not of the type shown in figure 8a or in plates 20a, 21a, 21b, 22a and 24a. The arc in which the 'D' section can be cut diminishes rapidly with the amount of rotation so that the section in figure 9 is a special case and when this is realised in the light of Spry's statement (op.cit.) it is probable that such sections have been simply overlooked. Plate 25a shows a garnet cut along the plane C-D of figure 8a. Accompanying it is the 'S' section obtained from a slice cut normal to the plane of this photograph and parallel with its vertical edge.

If the inclusions are considered as planar elements it is a further feature of the surface they lie on that they will appear elongated near the centre of the crystal since in this region the inclusion surface is normal to the plane of section. Towards

Plate 42a. Photomicrograph of biotite glimmerite. This rock is composed almost entirely of biotite with some minor quartz and epidote. P.P.L. x 10. Slide 197c.

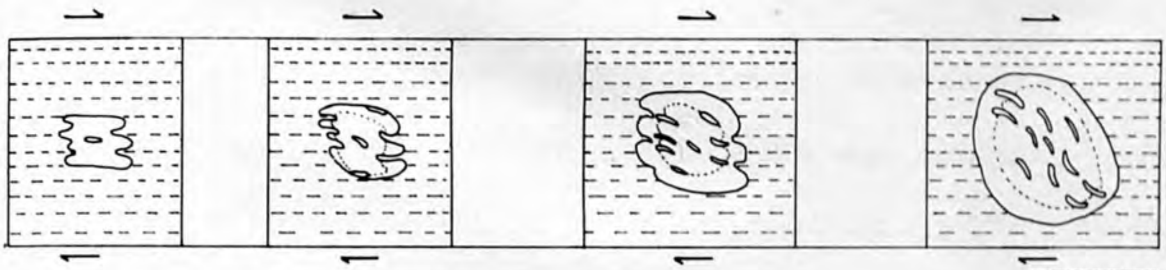
Plate 42b. Photomicrograph of biotite growth associated with the development of F_3 strain-slip cleavage. P.P.L. x 10. Slide 123c.

the margins of the garnet the angle between the inclusion plane and the section changes so that the elongation of the inclusion becomes less apparent. This effect is particularly well seen in plate 23a; the 'D' becomes lost towards the margins as the orientation of the inclusions becomes less obvious. This is also facilitated by a much smaller rotation as is shown by the accompanying 'S' section of the same rock. The 'D' section of this example is by itself open to error of interpretation as it could be suggested that the crystal grew during the static period following deformation and that the central zone preserves the original orientation of the quartz fabric. This is destroyed, as post-tectonic recrystallisation proceeds, but from the 'S' section cut normal to this section the true three dimensional orientation of the inclusions may be inferred.

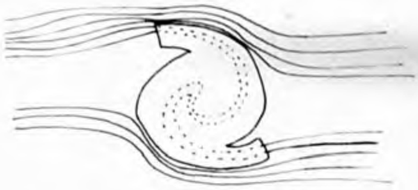
Plates 26a & b show an unusual section in which only one of the two 'D's is seen. It is easy to see the relationship of this section to the whole structure by referring to figure 8a. Plates 22b and 34b also show 'D's and the halfway stage between the 'S' and 'D' sections is seen in plate 27a. This latter section shows the danger of confusion between syn-tectonic garnets and static garnets overgrowing microfolds. It cannot therefore be used on its own merit but only in conjunction with types (a) or (b) of this account. It was found that all sections cut outside the particular zones described above are likely to be confused with examples showing static growth.

The assumption in this study that syn-tectonic garnets can be

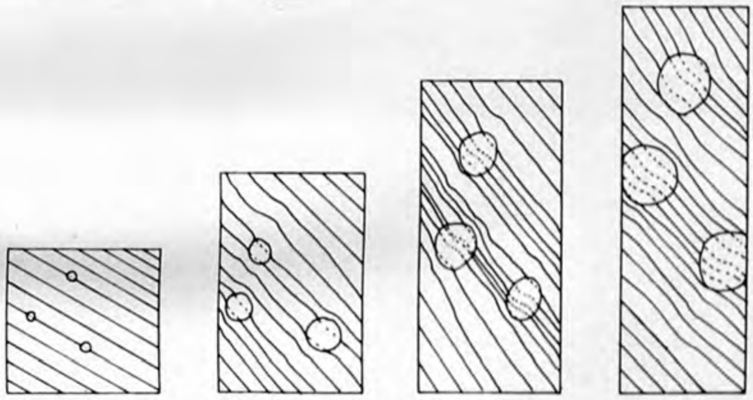
HYPOTHESES FOR THE ORIGIN OF ROTATIONAL STRUCTURE IN GARNET



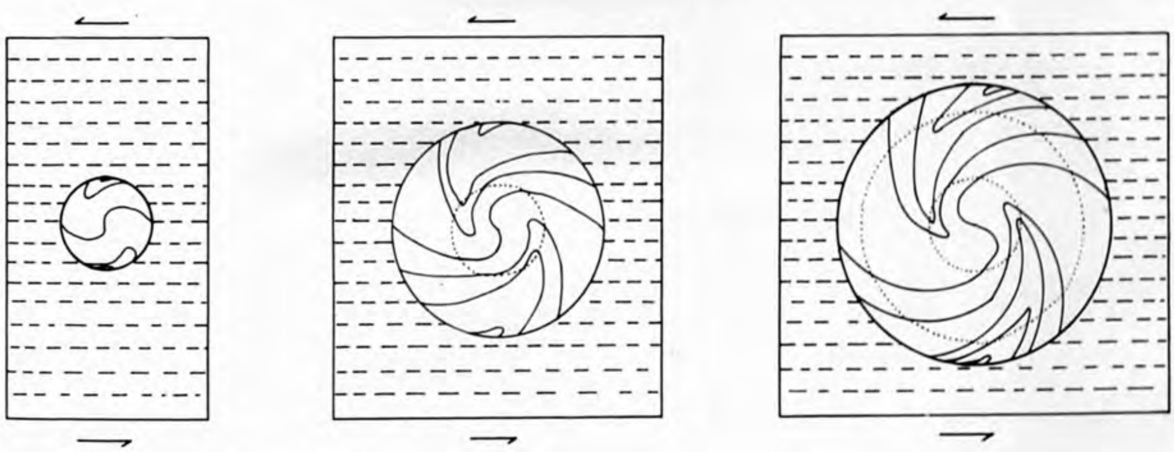
AFTER SPRY 1963.



AFTER ZWART 1962.



AFTER RAMSAY 1962.



HYPOTHESIS CONTAINED IN THE PRESENT ACCOUNT.

regarded as rotating about a single axis is not accepted by J. Ramsey (1962). He suggests that syn-tectonic garnets do not rotate but that they grow over a steepening schistosity which is itself rotating as a result of progressive deformation. Such a mechanism will only account for up to 90° of rotation. The examples figured in the photomicrographs accompanying this section nearly all show rotations of over 90°. Plate 20a shows over 360° of rotation and the suggestion that the rotation of porphyroblasts does not occur is invalid. The flattening process was not considered when the form of the spiral was discussed above and it may be a further factor affecting the spiral form.

(ii) Static growth

Some examples of garnet were seen to have grown during the deformation period and to have continued when it had ceased. Rotated cores were seen to grade into static margins which overgrew the schistosity but the majority of garnets described grew during the static period which followed the crossfold deformation. This agrees with the results published by most other workers in the Caledonian fold belt (see M.R.W. Johnson, 1963). Many of the examples were seen to overgrow F_2 microfolds associated with F_2 lineations.

Evidence for a pre-cross-fold phase of growth is not as clear. Pre-deformational garnets have been described by Rast, Sturt and Harris, and Johnson but similar examples were not found in the rocks of the present area of study. One group of garnets

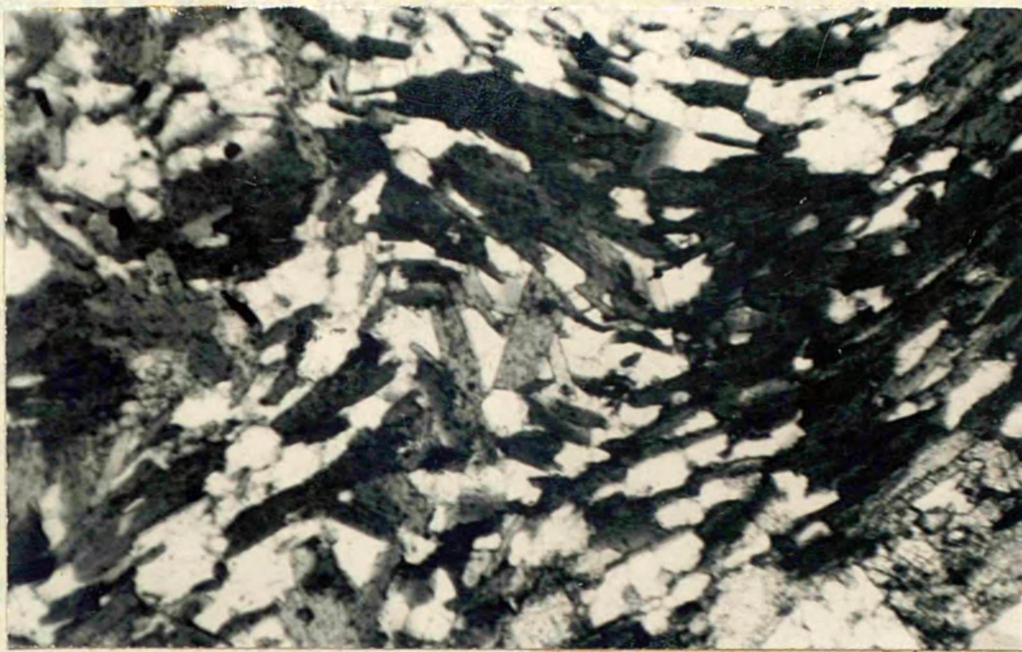


Plate 43a. Photomicrograph of biotite forming F_2 microfolds. P.P.L. x 10. Slide 66c.

Plate 43b. Photomicrograph of post F_3 biotite. P.P.L. x 10. Slide 347c.

show fine grained inclusion fabrics. These fabrics are considerably finer than those of the matrix in which the garnet occurs and probably represent an earlier stage of crystallisation. Plate shows a garnet of this type overgrowing an F_2 microfold. Chinner (1961) describes garnets occurring in schists with high oxidation ratios. These schists are of local occurrence in Glen Clova and characterised by the presence of green biotite and accessory haematite. The garnets in these rocks have fine grained inclusion fabrics and Chinner suggests that the size of the inclusions may be related to the chemical composition of the garnet. The garnets from the Cairnwell area have a similar local occurrence to those of Glen Clova and are found in the grey schist of the upper Baddoch Burn. They also are characterised by green biotite but haematite is absent. Time was not available to compare these schists directly with those described in Chinner's paper, by chemical analysis, but it seems unlikely that these garnets do contain pre F_2 fabrics.

In summary garnet growth commenced during the cross-fold period and reached its acme during the static period that followed these movements.

(iii) The effects of the late Caledonoid movements

Garnets showing evidence of rotation after growth are quite common. The effect of the F_3 deformation was to reactivate the schistosities formed during cross-folding by the development of

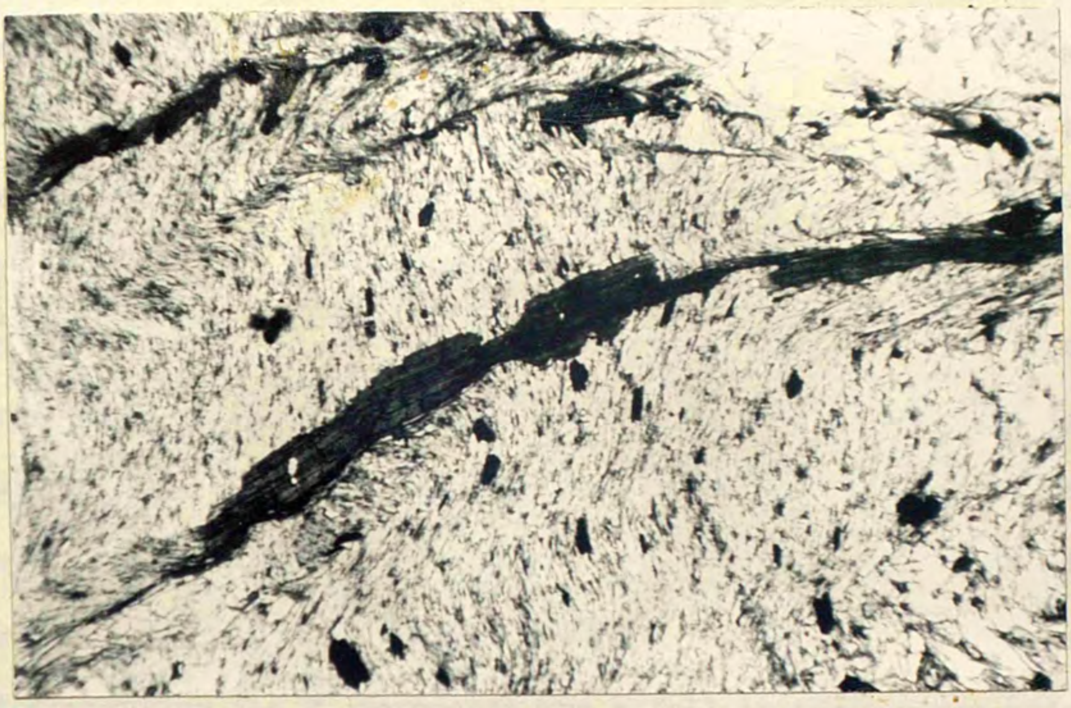


Plate 44a. Photomicrograph of biotite overgrowing F_3 strain-slip cleavage. P.P.L. x 10. Slide 122c.

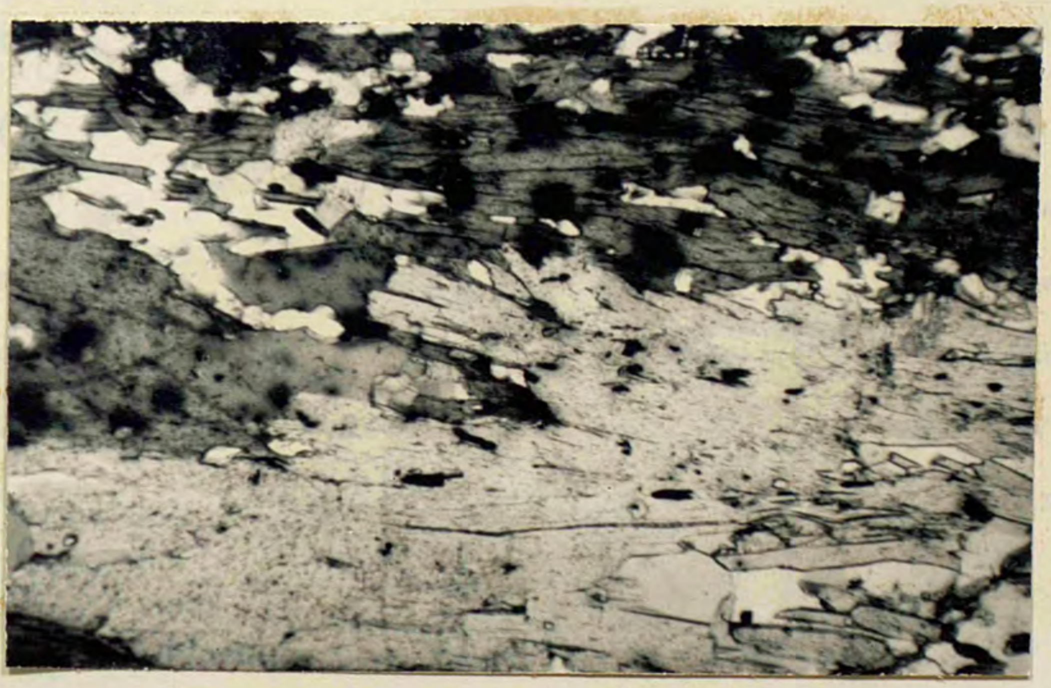


Plate 44b. Photomicrograph of biotite replaced by chlorite. P.P.L. x 40. Slide 54c.

strain-slip. This meant that movements acting within the schistosity planes would cause the garnets to rotate and 'open' the schistosity on either side of the crystal, producing a release of pressure in these two areas. Plates 30a and 30b show quartz growing in the pressure shadows and in plate 18a calcite occupies a similar position. Ramsey (op.cit.) shows that a similar pattern would be produced by flattening but since, in the consideration of syn-tectonic garnets, it was shown that crystals do rotate it seems reasonable that these structures were produced by the same mechanism. Accompanying the F_3 movements was a fall in temperature and garnets involved in rotation during this period usually have a selvage of chlorite or are completely replaced by this mineral. Some rounding of the crystal may occur at its margins as a result of rotation. Plate 31b shows two rotated crystals from a section in which all the garnets are almost perfect spheres.

(iv) Breakdown of garnet

It has been suggested above that the late Caledonoid movements coincided with widespread diaphoresis and examples have been given of the effects of these movements upon the garnet porphyroblasts. This period was only the beginning of a regional breakdown of all the higher grade minerals which continued long after the late Caledonoid movement ceased.

In the case of garnet several breakdown products were recognised and these differ according to the process that caused the replacement.

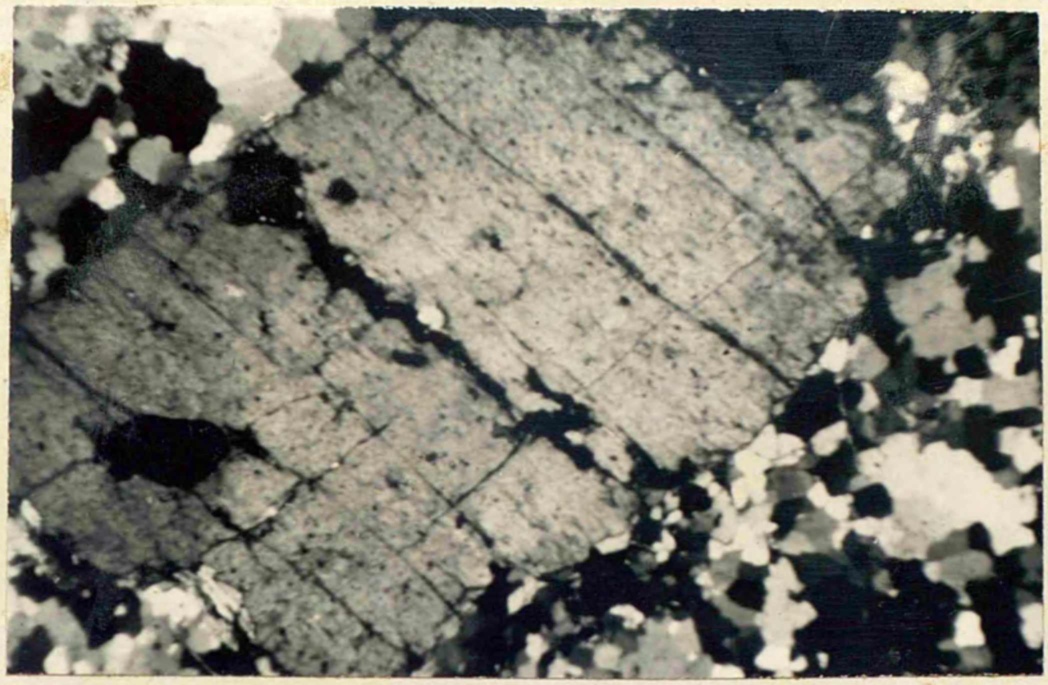


Plate 45a. Photomicrograph of feldspar porphyroblast growing in quartzite. Nicols crossed. x 10. Slide 65c.

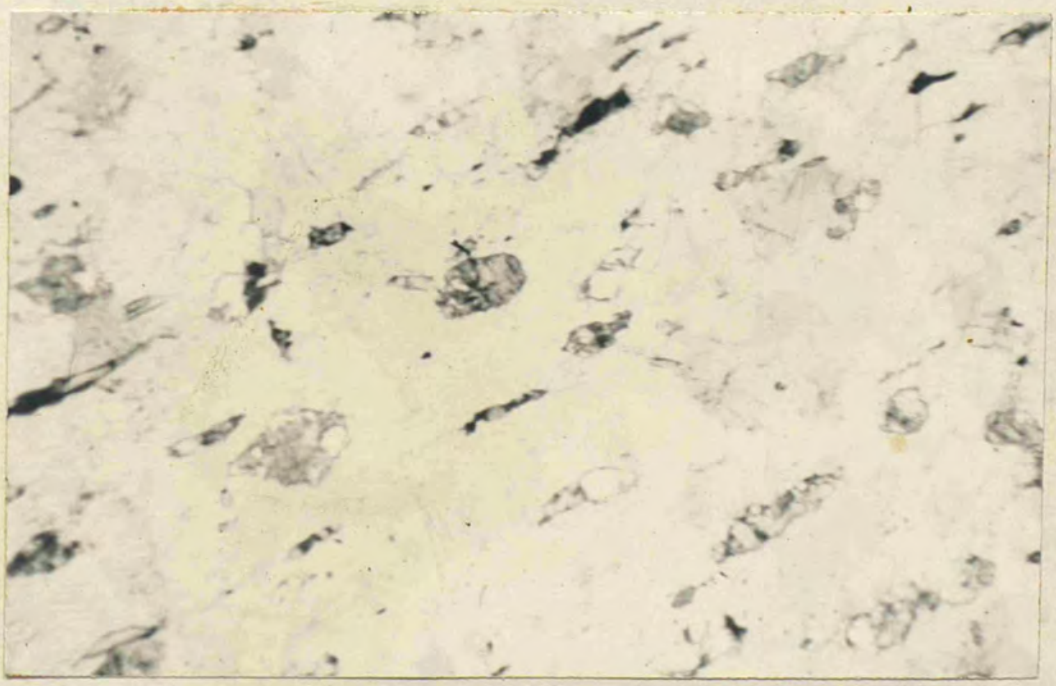


Plate 45b. Photomicrograph of feldspar lineation in quartzite. This is an F_3 lineation. P.P.L. x 10. Slide F 23.

Types of replacement

1. Biotite/muscovite aggregates
2. Chlorite/sericite 'dust'
3. Fresh biotite and chlorite crystals
4. Fresh chlorite and muscovite crystals
5. Fresh muscovite and ore
6. Chiefly ore
7. Feldspar and minor sericitic aggregates.

The earliest evidence of garnet breakdown is found in those schists described above, containing garnets with fine grained inclusion fabrics. Plates 32a, 32b and 33b show clear evidence of garnet being reabsorbed into the surrounding fabric. In plate 33b the margins of the garnet are replaced by fresh muscovite and ore. The old inclusion fabric is retained within the muscovite. In plates 32a and 32b the reabsorption has reached a further stage and fresh biotite, muscovite, quartz and ore have grown on the site of the earlier garnet. These examples indicate that the original garnet has become unstable, but the grade of metamorphism was still high since large fresh biotites were still forming. It is probable that this breakdown took place before the start of the late Caledonoid movements. These movements affected garnets in a number of slides. In some cases garnets are fractures with the resultant growth of fresh chlorite (plate 35a). Such fractured crystals were possibly affected by the slightly more brittle movements that followed F_3. During this post F_3 period chlorite continued to grow

Plate 46a. Photomicrograph of twinned andesine overgrowing muscovite. The twin lamellae cross the earlier schistosity. Nicols crossed. x 10. Slide 246c.

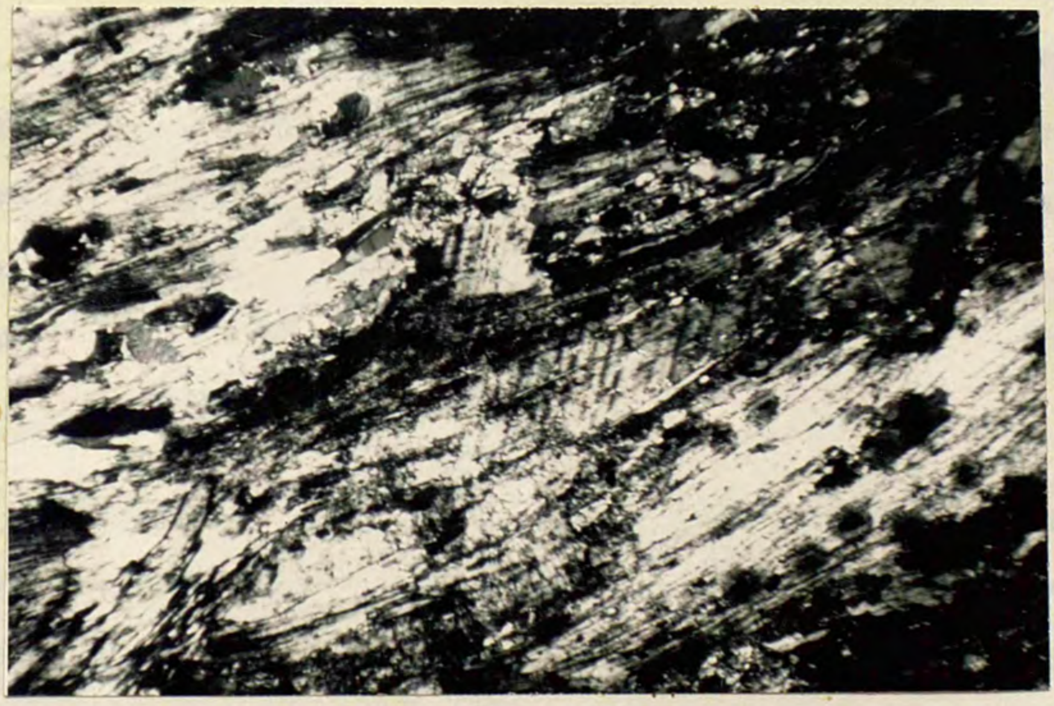


Plate 46b. Photomicrograph of twinned andesine overgrowing muscovite. Nicols crossed. x 10. Slide 246c.

and locally temperatures were still high enough for biotite to develop after garnet. After the thrusting episode came a period of igneous activity and locally garnets are destroyed by hydrothermal activity. In these examples the garnets are often complately replaced by 'dust' aggregates of chlorite and sericite. In plate 37a a garnet is altered to fine chlorite at its contact with a small crack in the rock, whilst in other parts of the slide garnets are unchanged. This suggests the action of emanations passing along the crack. Plate 36b shows the replacement of garnet at its margins by sericite/chlorite 'dust' and complete replacement of the micas by feldspar. This process is seen continued in plate 36b, where the garnet is completely replaced by a sericite/chlorite aggregate and its margins are being replaced again by feldspar.

Some examples are shown where ore seems to replace completely the original garnet. This is probably the end stage of another two stage process wherein ore, formed as a result of the initial breakdown, slowly accumulates on the site of the original porphyroblast.

C. Staurolite and Kyanite

Although this region of study lies largely within the garnet zone both staurolite and kyanite occur locally. Most of these localities are confined to the Lower Nappe, but within the Black Schist of the Upper Nappe, outcropping in the Baddoch Burn, kyanite

Plate 47. Photomicrograph of a typical epidote schist from the Blair Atholl Series. P.P.L. x 10. Slide F 1.

is found at one locality and south of this locality staurolite was recorded.

Kyanite was seen to present a morphology almost as varied as that of garnet. Some crystals described (plate 40b) were short and equant with many inclusions whereas others (plate 41a) were of an acicular nature. In most examples the inclusion fabric is finer than the matrix, a common characteristic of the kyanite in this area. In every example described the kyanite appears to have grown after the F_2 movements. The difference between the fabric of inclusions and the matrix shows that the latter underwent continuous recrystallisation during the growth of kyanite. The breakdown of kyanite parallels that of garnet. In plate 38b the garnet is completely replaced by a chlorite-sericite aggregate while the kyanite is converted to sericite at its margins and along cleavage planes. In some examples the sericite aggregate recrystallises to form crystals of muscovite.

Staurolite sometimes occurs in association with kyanite but is more commonly found without this mineral. It is usually idioblastic and occasionally develops geniculate twins. Inclusions of quartz are common and, like kyanite, staurolite overgrows the F_2 microfolds. In some examples staurolite was seen to enclose post F_2 garnets which shows that the period following the cross-folding was one of slowly rising temperature, locally passing through garnet grade, followed by staurolite grade and probably culminating in the growth of kyanite. Staurolite appears to have been more

Plate 48. Photomicrograph of syn F_2 epidote. P.P.L. x 10. Slide 62c.

stable than kyanite. Most of the crystals described are fresh and unchanged but in a few examples sericite replaces the margins of porphyroblasts. In these cases the excess iron has evidently been eliminated as ore.

D. Biotite

This mineral occurs throughout the area mapped. Its colour varies according to the type of schist in which it occurs. Calcite-bearing schists invariably contain a pale brown biotite, whereas a green biotite is found in association with zoisite or in other examples with garnets containing fine grained inclusion fabrics. Medium brown biotite is however typical of the majority of schists. The pale brown colour of the biotite in the calcareous schists probably reflects a higher content of phlogopite due to the presence of original dolomite. The development of green biotites have been correlated by Chinner (op.cit.) with a high content of ferrous iron.

The morphology of biotite is directly related to the stage of crystallisation. Syntectonic crystals are well formed with their 001 faces parallel to the schistosity. Syn F_3 crystals are the most idioblastic and free from inclusions as little recrystallisation followed the late Caledonoid movements. Recrystallisation following F_2 folding destroyed much of the evidence of the schistosity that was developed during this period.

No biotite can be recognised as having formed before the cross-fold episode owing to the effects of later recrystallisation. Thus biotite may have grown after F_1 folding but there is no suppor-

Plate 49. Photomicrograph of F_2 microfolds in an epidote schist. This rock is almost entirely composed of quartz and epidote. P.P.L. x 10. Slide 307c.

ting evidence. The period following the cross-fold movements marks the greatest development of biotite. After this biotite growth ceased in many parts of the area and during the late Caledonoid movements biotite was generally replaced by chlorite. Some fresh biotite did grow during this period. Small idioblastic crystals of biotite are found, however, within the F_3 strain-slip schistosity. Biotite also grew as a breakdown product after garnet and amphibole. Locally, biotite growth continued after the F_3 movements but this too gave way to chlorite growth. Local hornfelsing has caused the recrystallisation of biotite and in some examples the post F_3 chlorite is converted to green biotite at its margins and along its cleavages.

Biotite enrichment has occurred in some schists with the resultant formation of a biotite glimmerite. These schists also contain small amounts of basic plagioclase and probably represent metamorphic 'fronts'. This enrichment occurred before the F_3 folding since the biotite has been converted to chlorite along strain-slip planes which were developed during this folding.

E. Chlorite

The growth of chlorite commenced with the third phase of movement. Its paragenesis has been largely described above in the consideration of the breakdown of garnet and biotite and large amounts of this mineral were formed by this process. Chlorite was also found to develop in the strain-slip schistosity in a similar manner to the syn F_3 biotite. This may signify that temperature

Plate 50a. Photomicrograph of epidote schist. The texture in this specimen is an exclusive mosaic of epidote. P.P.L. x 10. Slide 315c.

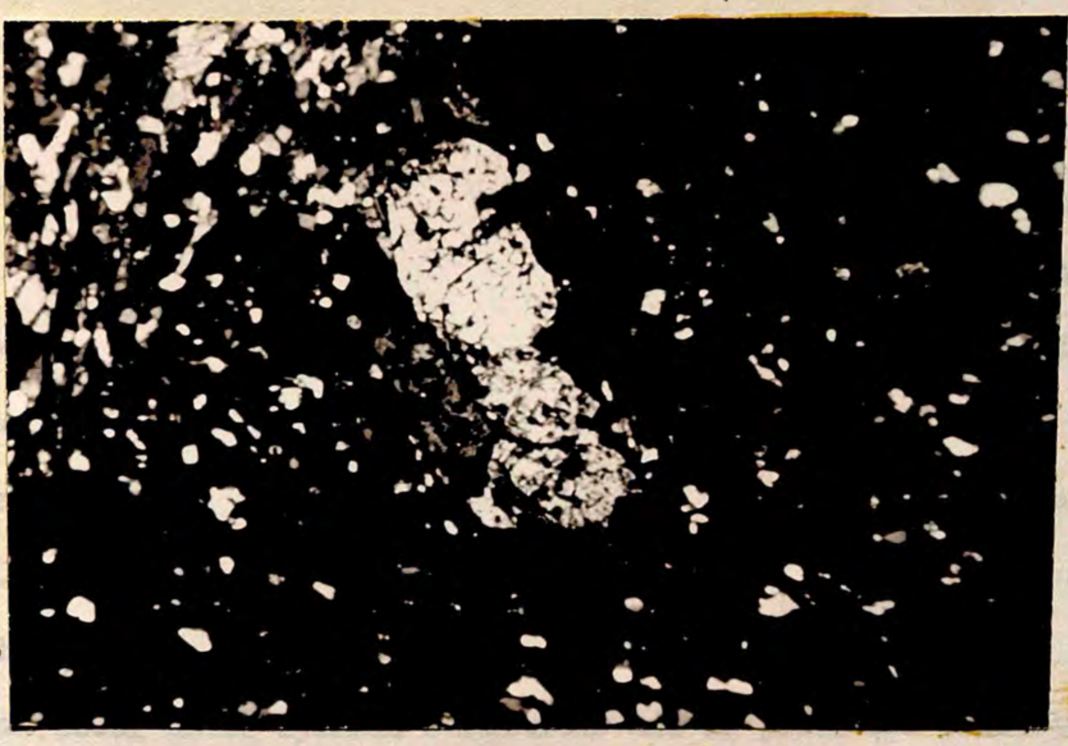


Plate 50b. Photomicrograph of epidote crystal enclosed in garnet. The garnet developed post the F_2 folding. Nicols crossed. x 40. Slide F 2.

gradients were by no means uniform at the beginning of the late Caledonoid movement phase and both these minerals were able to grow at the same time, depending on extremely local conditions of pressure. This lack of uniformity continued after the F_3 movements. Post F_3 shearing movements have caused the development of chlorite along shear planes and this is particularly true of sheared amphibolites, where the original amphibole has been completely converted to chlorite.

As stated above, chlorite also occurs as a breakdown product after garnet, hornblende or biotite in contact aureoles.

F. Feldspar

The original sediments probably contained some feldspar as detrital grains, the preservation of which has recrystallised in situ. Such feldspar is often found associated with graded bedding. It is dominantly orthoclase but some plagioclase may be present. The orthoclase usually shows some sericitisation. The plagioclase is less altered and gives extinction angle values within the andesine range. In some quartzites, large porphyroblasts of orthoclase and perthite have developed within a fine quartz mosaic. This is probably the result of potassium metasomatism for which there is clear evidence in the schists. This metasomatism occurred after the third phase of deformation. Some recrystallisation of feldspar did occur under dynamic conditions and in plate 42a orthoclase has a definite linear orientation. This lineation is associated with

Plate 51. Photomicrograph of chlorite porphyroblast overgrowing an earlier schistosity. P.P.L. x 10. Slide 79c.

the second movement phase and involves a redistribution of the original feldspar. In plate 26 earlier phenocrysts of plagioclase have become mechanically aligned during the cross-fold movements. These former crystals now consist of aggregates of epidote and feldspar.

Feldspar is also present in many of the schists. It is rarely twinned and often shows some alteration. In these cases it is developed as an accessory mineral. These occurrences result from the recrystallisation of detrital grains but sodium and potassium metasomatism cause the growth of fresh feldspar in restricted localities after the F_3 deformation. Andesines are seen to replace muscovite and grow across the microfolds. The structure of the micas is preserved within the feldspar by inclusions of graphite dust. Albite twinning may be present and is often at an angle to the inclusion trails. The extinction angles give values of plagioclase which is of the composition An. 34.

G. Epidote

Epidote minerals are commonly found associated with amphibole in the amphibolites and epidiorites. These occurrences of epidote are dealt with separately under the section devoted to these rocks.

Epidote schists and epidote/biotite/quartz schists are a common feature of the Blair Atholl Series and have developed from a slightly calcareous original sediment, possibly a calcareous mudstone. Plates 47a and 48a show typical epidote-bearing schists. In both these examples the epidote mineral is clinozoisite. Some

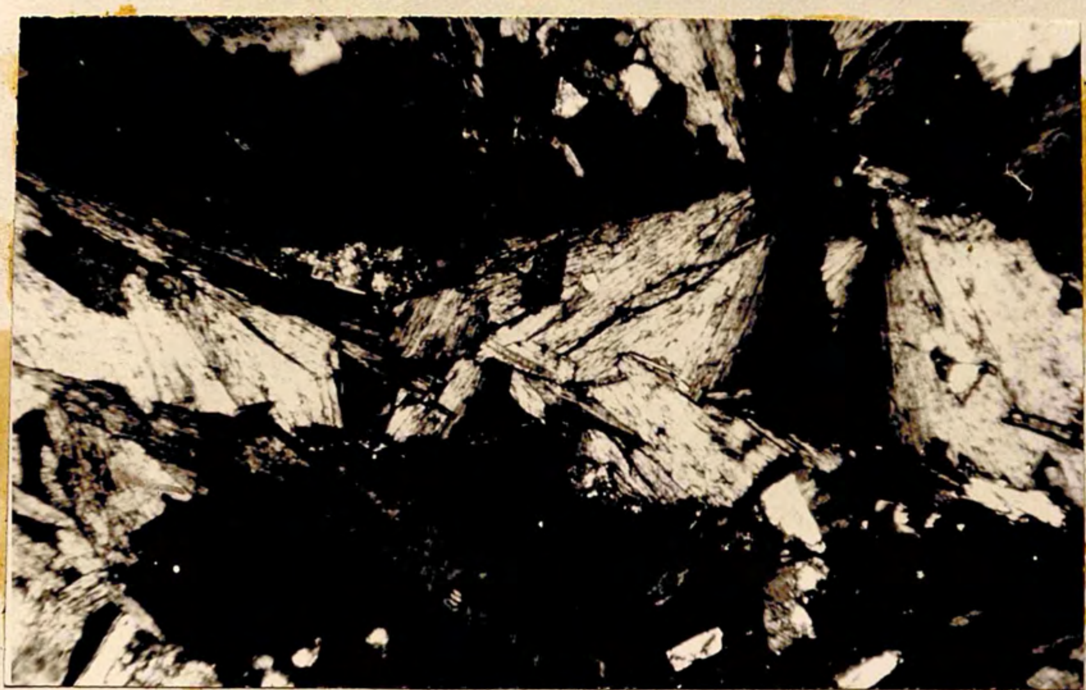


Plate 52. Photomicrograph of chlorite schist. This schist was developed in association with faulting following the F_3 movements. Nicols crossed. x 10. Slide 56c.

epidote schists contain over 75% of clinozoisite with some quartz and small quantities of feldspar and white mica. Schists of the type shown in plates 49a & 50a contain a green biotite similar to that seen in the schists bearing garnets with fine grained inclusions (see above). This suggests that the green coloration of the biotites is related to the chemical composition of the rock. The earliest formed epidote minerals recognised are syn F_2 in age and plate 47b shows a strong lineation of this mineral which is associated with F_2 fold axes. Epidote that grew after this period tends to form xenoblastic grains. Clinozoisite is sometimes seen replacing a larger crystal and also occurs in regular patches. This replacement is after earlier feldspar and is more commonly found in the epidiorites. The rock is enriched in biotite and contains feldspar, biotite, chlorite and clinozoisite. This enrichment probably occurred in association with the increase in metamorphic grade that followed the cross-fold movements.

3. Amphibolites and Epidiorites

In the field it is often difficult to determine the differences between para and ortho amphibolites. The latter are rarely cross-cutting, with only occasional relic igneous textures visible in the hand specimen. Many of these rocks may have been derived from basic sills or lava flows so that in many cases they are structurally indistinguishable from bedded sediments of basic composition. In a number of cases, however, petrographic examination reveals relic

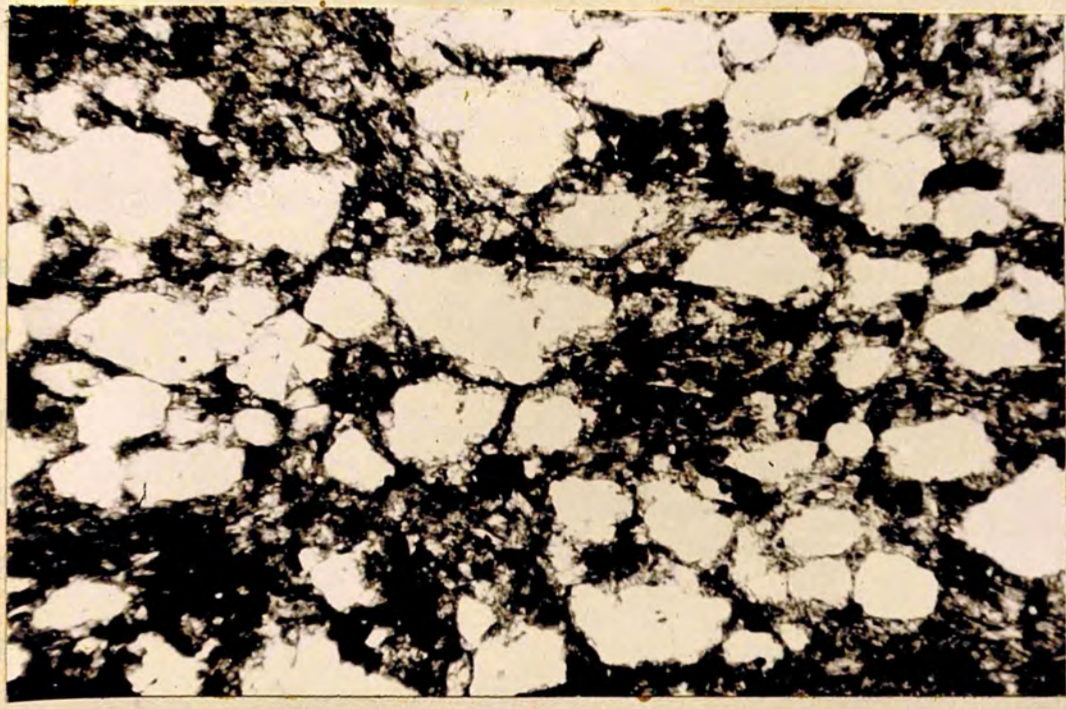


Plate 53a. Photomicrograph of hornfels. The ferro-magnesian minerals now form a fine matrix of chlorite and sericite. The quartz grains have recrystallised. P.P.L. x 10. Slide F 35.

Plate 53b. Photomicrograph of actinolite replaced by fine chloritic aggregate. P.P.L. x 10. Slide 73c.

igneous textures.

A. Para Amphibolites

These rocks are usually interbedded with a calcareous succession and contain calcite and quartz bands in definite regular layers. The amphibole varies in composition from a deep green hornblende to a pale green actinolite or colourless tremolite. In many of these schists the amphibole is accompanied by equal amounts of biotite. Calcite is abundant and variable quantities of epidote are usually present. Epidote may be present as an accessory or as a major constituent of the rock. These rocks contain large amounts of quartz and feldspar sometimes forms xenoblastic porphyroblasts which are full of inclusions. Garnet-bearing para amphibolites were recorded but garnet is more commonly found in the ortho amphibolites. In most examples the amphibole has grown during the cross-fold movement and in many cases a definite lineation has developed parallel to the F_2 fold axes. Continued crystallisation and nucleation of fresh amphibole rarely destroys this linear structure. In some cases the growth of amphibole has been entirely after the second deformation and long acicular crystals are seen to grow in random orientation. The crystals are usually idioblastic with some inclusions of ore, epidote and quartz. The complete breakdown of amphibole to form similar aggregates to those seen developing after garnet in the regional schists is not uncommon. Plate 47a shows an actinolite crystal completely replaced by a biotite/sericite/quartz aggregate. Chlorite and calcite are more

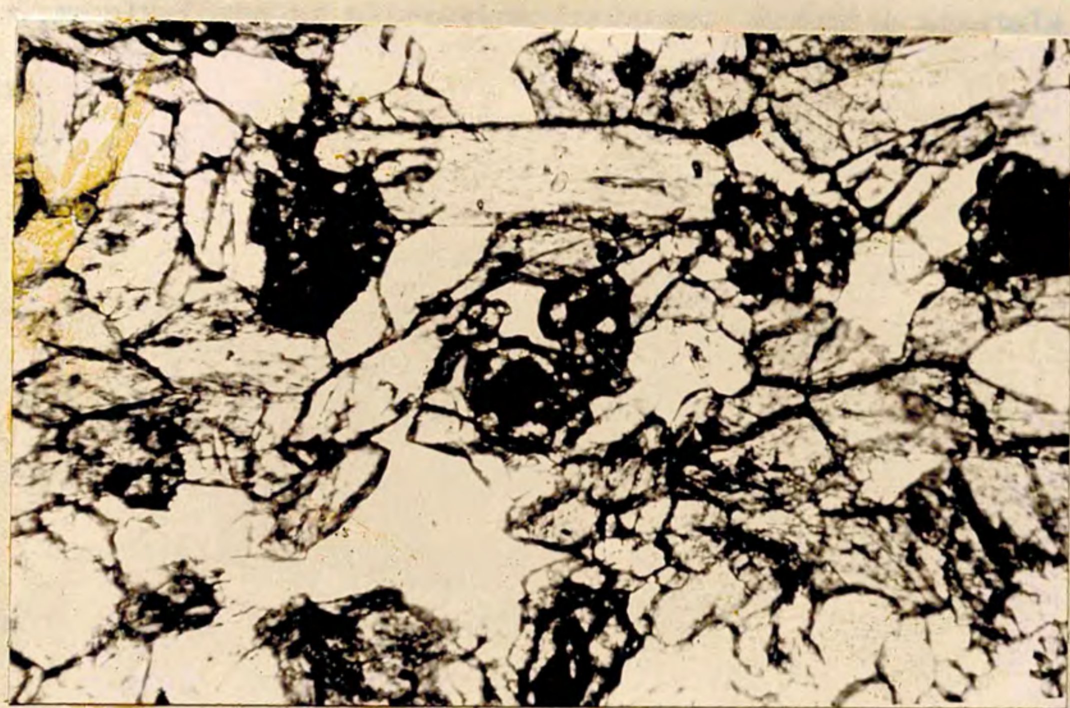


Plate 54a. Photomicrograph of rutile crystals in an epidiorite surrounded by coronas of sphene. P.P.L. x 75. Slide F 14.

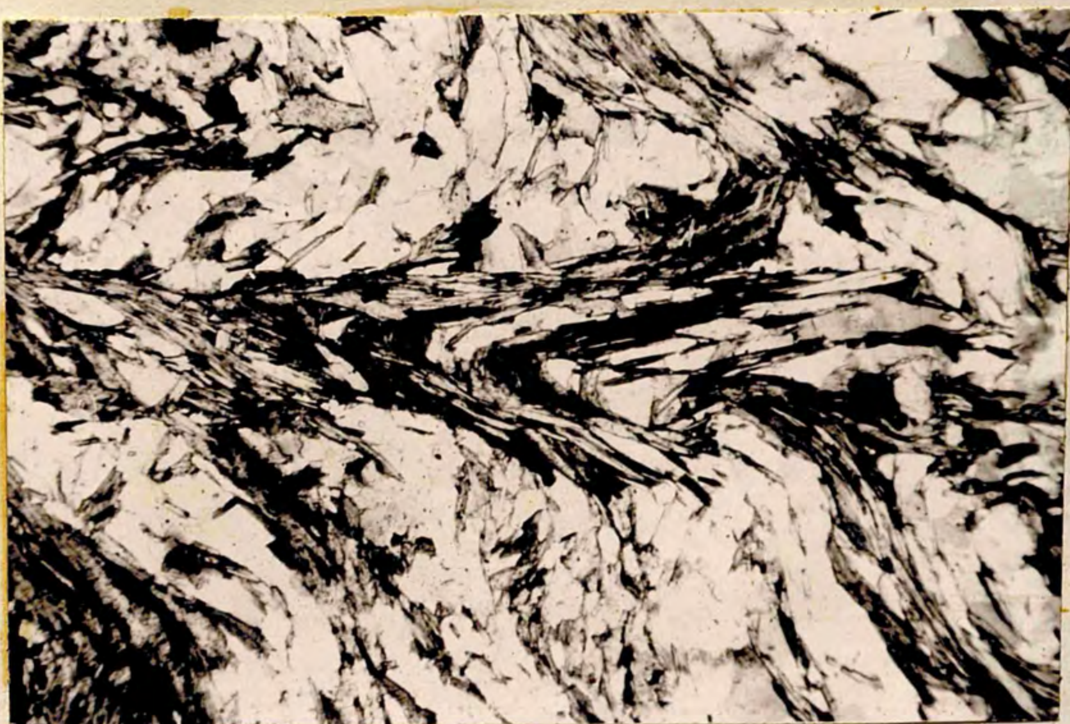


Plate 54b. Photomicrograph of an angular F_2 microfold in a quartz amphibolite. P.P.L. x 10. Slide 140c.

commonly found as alteration products. Chlorite crystals grow along the cleavage planes and when a basal section of amphibole is being replaced, the original intersecting cleavage pattern is preserved by the orientation of the chlorite crystals. These breakdowns occur during and after the third movement phase.

When garnet is present it is generally fresh and idioblastic, containing many inclusions. It is rarely an essential mineral in the para amphibolites and Wiseman (1934), when describing ortho amphibolites, remarks on its uneven distribution. He suggests that garnet formation is probably related to local differences in chemical composition within the original "igneous" rock. This appeared to be equally true of the para amphibolites and is more apparent, as the garnet is often a minor constituent. In all the examples described the growth of garnet was after the second deformation.

An important feature of the truly para amphibolites is the relative absence of rutile compared with its abundance in the more basic amphibolites. Ores are common accessories in both rock types. Both clinozoisite and epidote were recorded in the para amphibolites but these minerals were not always present and varied from accessory to essential.

B. Ortho Amphibolites and Epidiorites

"Epidiorite" was originally used as a field term and after many attempts at a more precise definition Wiseman (1934) recommended that it should be used in its original sense, indicating a

Plate 55a. Photomicrograph of hornblende and biotite forming an F_2 microfold. P.P.L. x 10. Slide 181c.

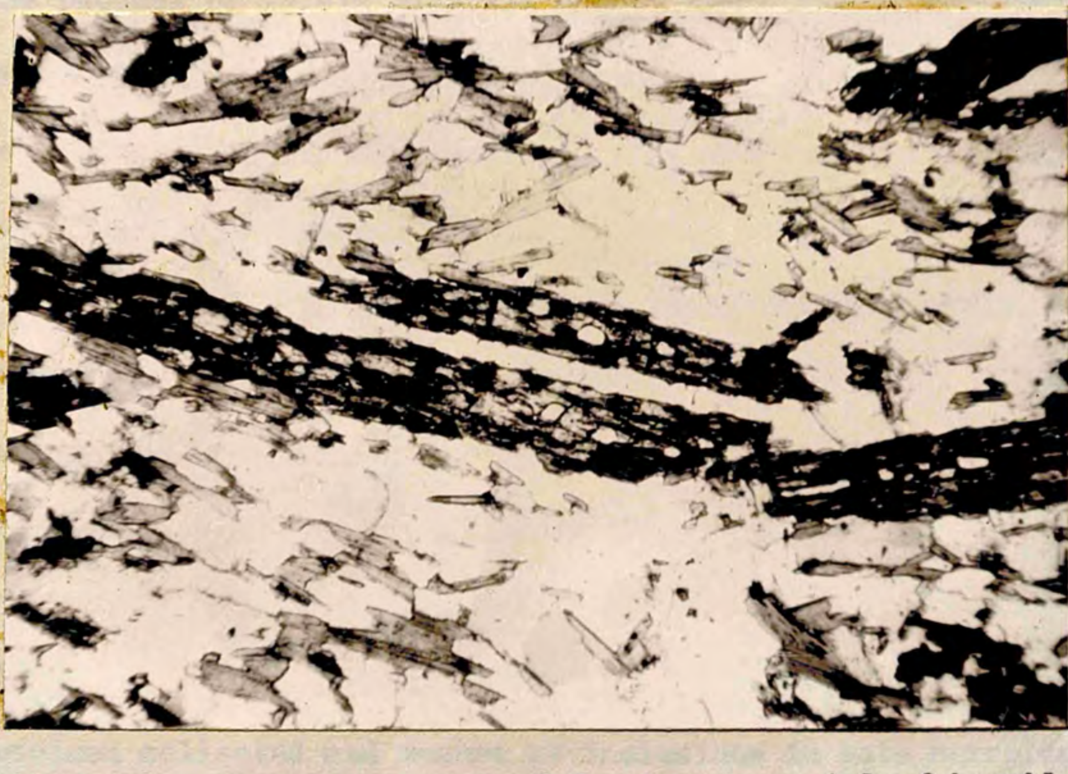


Plate 55b. Photomicrograph of fractured crystal of hornblende in a biotite-quartz schist. P.P.L. x 10. Slide 345c.

metamorphosed igneous rock that contained hornblende. This is the definition used in this account, but with the qualification that schistose hornblende-bearing rocks are not always easily recognised as igneous.

The amphibole of this group is usually a deep green and may have a faint bluish tinge. Some pale actinolitic hornblende was seen in a few examples but no colourless amphibole was found. The crystals are less acicular than those of amphibolites which are clearly sedimentary in origin and they vary from xenoblastic to idioblastic. They are usually full of inclusions which are often arranged in a pattern indicating an earlier ophitic texture; the inclusions consist of aggregates of clinozoisite, zoisite or epidote together with an untwinned feldspar, which has low relief. The patches of felsic minerals occupy the sites of original phenocrysts. In many examples an original porphyritic texture can be recognised, in contrast to the ophitic texture seen in originally coarse grained rocks.

Biotite is generally absent in the ortho amphibolites but may occur, however, in accessory amounts (less than 10%). It replaces amphibole growing along the cleavage planes, whereas in the para amphibolites it often forms independent crystals.

The epidote mineral may be zoisite, clinozoisite or epidote. It grows in granular aggregates throughout the rock in almost every specimen collected and occurs as inclusions in both hornblende and garnet. In some examples small grains overgrown by quartz were

Plate 56a. Photomicrograph of biotite replacing hornblende.
P.P.L. x 60. Slide 198c.

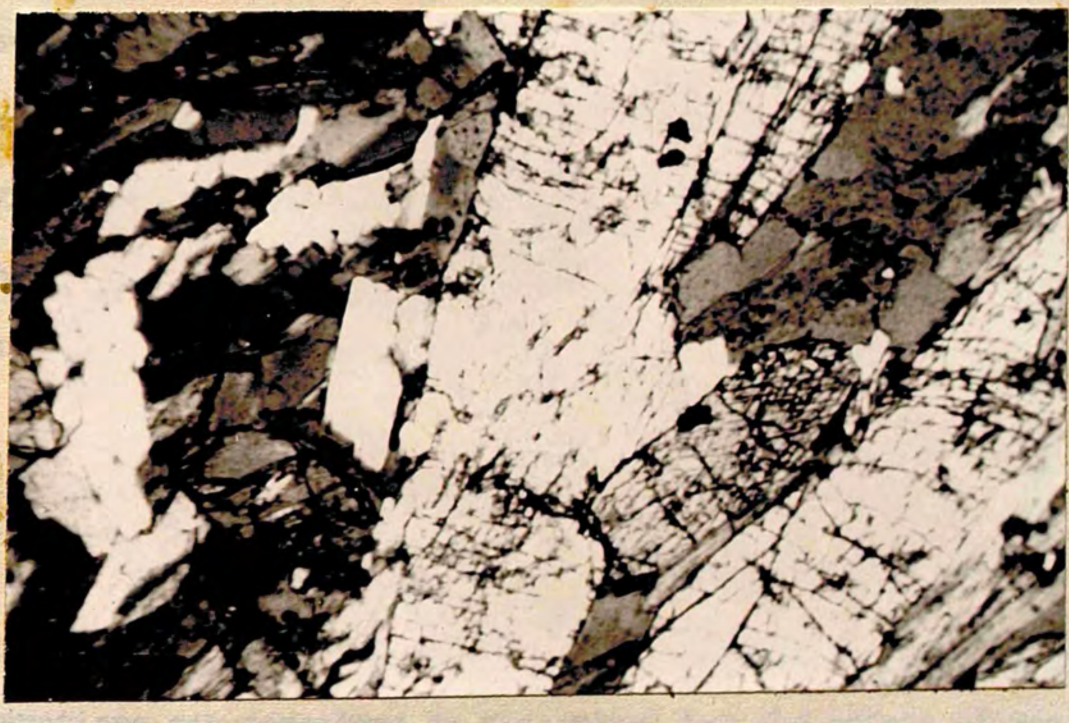


Plate 56b. Photomicrograph of biotite-actinolite schist.
P.P.L. x 40. Slide 217c.

probably among the first metamorphic minerals to form in the rock. Their enclosure by quartz seems to confirm this and indicates the subsequent release of silica, probably in the breakdown of pyroxene, as metamorphism proceeded. The epidote minerals appear to have grown after the F_2 movements and large crystals of epidote occupy the sites of the original feldspar. The inclusion of epidote in garnet shows that it preceded the growth of this mineral. Garnets may be an inch or more in diameter. Their pattern of inclusions showed that they grew under static conditions after the F_2 movements. The inclusions of quartz, calcite, ore and epidote are continuous with the matrix fabric. Rotation of the crystals after growth often deforms the matrix schistosity.

Rutile is invariably present in the epidiorites. It is not the typical red colour, but a yellowish-brown. It is sometimes found overgrowing ore and in such cases probably formed from ilmenite, but it is likely that some titanium would be released from the original pyroxene as a result of the regional metamorphism. Rutile itself may be replaced by sphene and plate 51a shows coronas of this mineral surrounding rutile.

C. Age and Possible Origins of the Ortho Amphibolites and Epidiorites

When the original nature of the former igneous rock is considered the field relationships are rarely conclusive. Discordant junctions can sometimes be recognised but the effect of the later deformation was to destroy the earlier contact relationships. Some

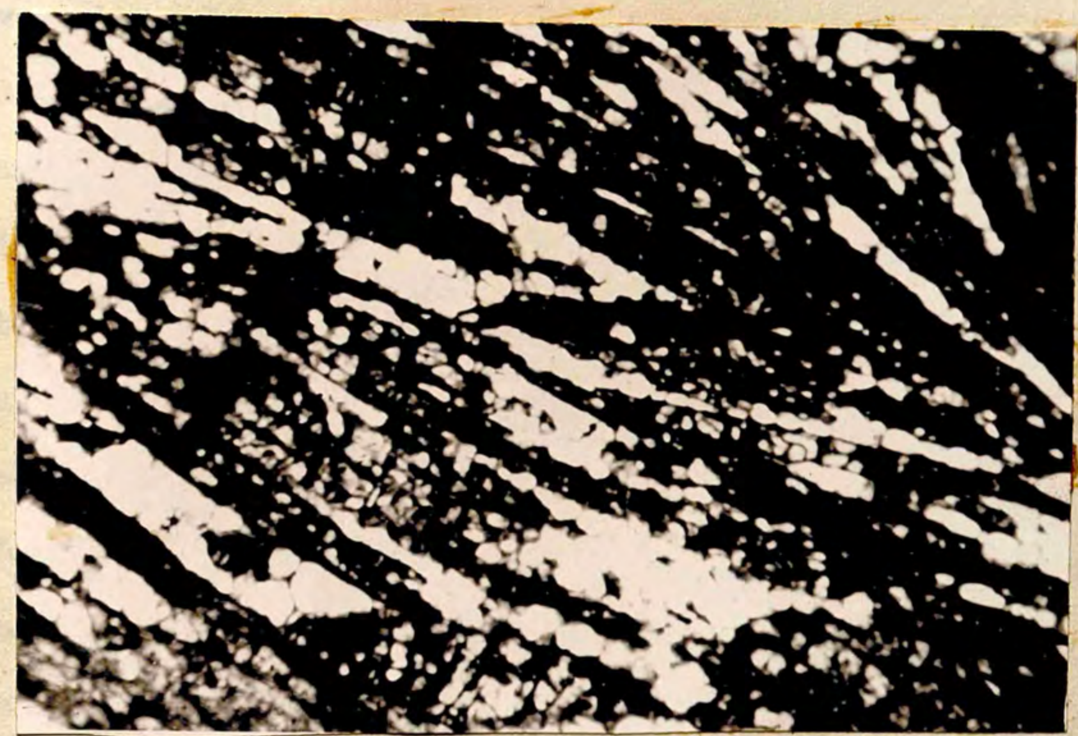


Plate 57a. Photomicrograph of zig-zag microfolds in hornblende amphibolite. P.P.L. x 10. Slide 25c.

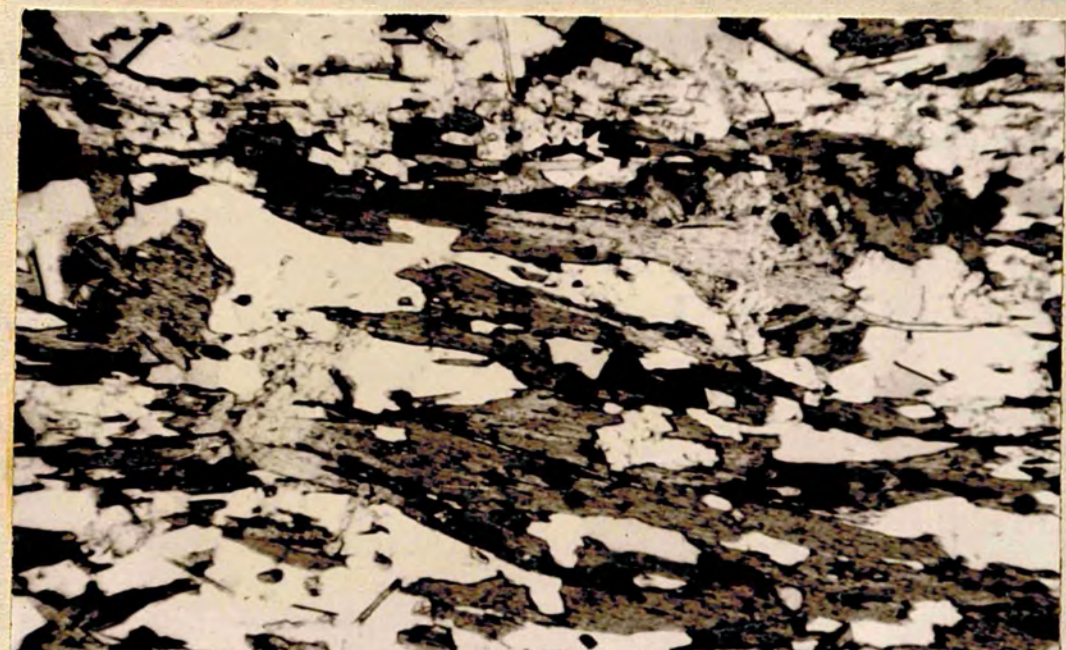


Plate 57b. Photomicrograph of biotite replaced by chlorite. P.P.L. x 40. Slide 338c.

very irregular contacts were seen but these could be the result of deformation rather than intrusion. Recrystallisation has destroyed any evidence of chilled margins but relic textures do show the igneous origins of the rock. In particular relic porphyritic texture and relic ophitic textures give an indication of an igneous origin. The ophitic texture and the preponderance of amphibole show that these were former basic intrusives. This texture has been found in many small concordant epidiorites. These were possibly doleritic dykes. The coarse texture may be the result of a long cooling history as these rocks were almost certainly intruded during the regional metamorphism. Quite large masses of epidiorite occur within the area of study. They are all metamorphosed to hornblende-rich rocks and no relic pyroxene remains.

Most of the amphibole post-dates the second movement phase, though in some examples amphibole had grown during F_2. This is shown by a lineation parallel to the F_2 folds. This indicates two periods of intrusion, one prior to the second deformation and another directly following this period.

4. Accessory Minerals

The minerals which only occur in accessory amounts can be divided into two groups on a basis of origin.

1) Those minerals which were probably present in the primary sediment and have recrystallised during metamorphism. These include apatite, tourmaline, zircon, rutile and ore.

2) Those minerals arising from metamorphic reactions. These include rutile, sphene and ores.

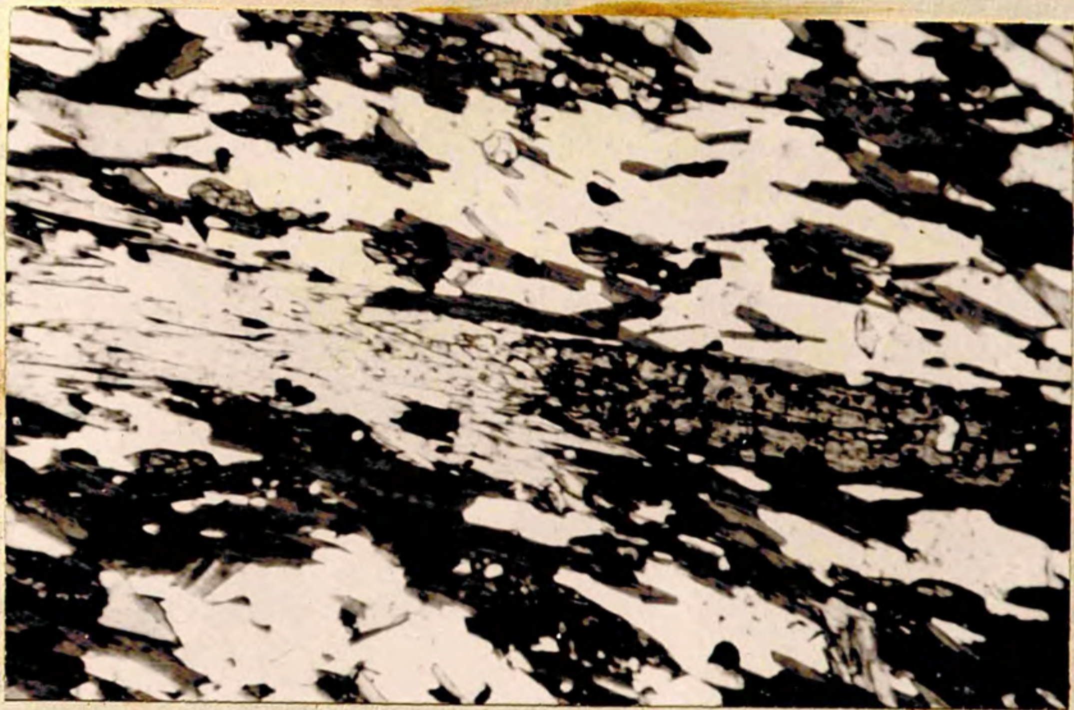


Plate 58a. Photomicrograph of hornblende replaced by chlorite.
P.P.L. x 40. Slide 343c.

Plate 58b. Porphyritic texture in epidiorite. The 'phenocrysts' are now aggregates of epidote and feldspar. They show a general alignment parallel to the hornblendes.

A. Apatite and Tourmaline

These minerals usually develop as a result of metasomatism associated with acid intrusions. They not only occur throughout the area but also on a regional scale throughout the Dalradian metasediments. For this reason they are regarded as having grown by the recrystallisation of primary sedimentary grains. Their presence in the sediments indicates the erosion of a source area intruded by granitic rocks. Tourmaline often shows a rudimentary orientation, but it is not clear if this was associated with any of the major episodes of deformation. It occurs as the deep green pleochroic variety (schorlite), and forms individual short, tabular prisms.

Apatite is less widespread and is only present as a very minor accessory.

Although it is suggested that these minerals were deposited with the original sediments it is possible that locally some tourmaline and apatite may have grown as a result of boron and chlorine metasomatism but there is no evidence of this.

B. Titanium Minerals

Ilmenite and rutile were probably both present as sedimentary grains, and as for tourmaline and apatite this is inferred from the extremely wide occurrence of these minerals. Some rutile was formed by the breakdown of ilmenite and possibly by the breakdown of garnet. In the epidiorites much of the ilmenite will have formed during the crystallisation of the igneous rock, but more

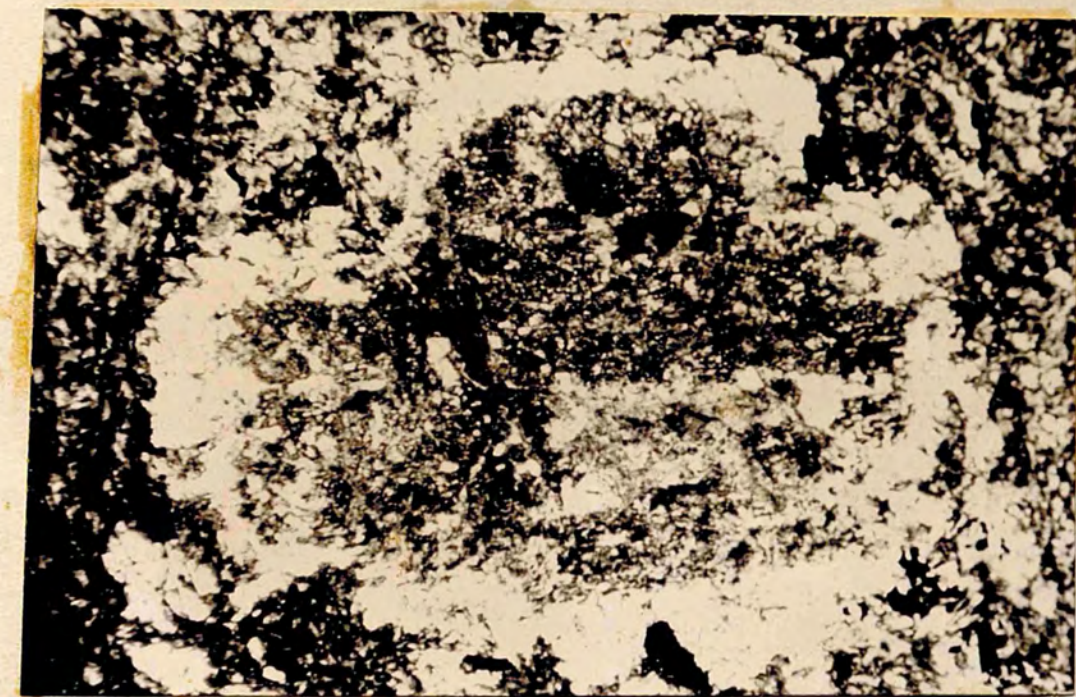


Plate 59. Photomicrograph of altered phenocryst in epidiorite. The alteration product is composed of epidote, sericite and feldspar. P.P.L. x 10. Slide 328c.

titanium will have been released by the conversion of pyroxene to amphibole. Sphene was only seen in the epidiorites where it formed coronas around rutile.

C. Zircon and Iron Ores

Sedimentary zircon is a common accessory in the quartzites where it occurs in association with magnetite, haematite or limonite. These minerals form definite bands which trace out the pattern of the earlier current bedding. The magnetite is often oxidised so that the original current bedding appears as a series of curved brown lines. Heavy mineral sorting of this type is a common feature of sediments deposited by current action. Magnetite is also produced in a number of metamorphic reactions. The most common of these is in the breakdown of garnet. Plate 33b shows a garnet which has been partially replaced by muscovite and the original iron is now distributed throughout the rock in grains of magnetite.

Plate 60a. Spheroidal weathering in quartz porphyry. Glen Taitneach.

Plate 60b. Spheroidal weathering in quartz porphyry. Glen Taitneach.

PART FOUR

Minor Igneous Intrusions

Following the main structural and metamorphic events, a series of dykes and sheets were intruded on a regional scale. They form two main groups, although it is possible to subdivide within these groups on a basis of mineralogical and textural variations.

1. Acid Intrusives

All the dyke rocks described under this heading are porphyritic. They range in size from narrow dykes, of a few inches thickness, to larger boss-like masses, the size of the Carn Mor Porphyry. Dykes of only a few feet across may extend continuously for a mile.

A. Felsites

The finest acid grained intrusives are pink and white felsite dykes. These rocks all show some evidence of devitrification. Spherulitic texture is common and alkali feldspar is seen growing in a radial pattern with quartz. This sometimes makes up the whole of the groundmass. Some examples described are granophyric but an interplay between granophyric and spherulitic texture is common. The groundmass is usually sericitised to a greater or lesser extent. This may have occurred in association with the later movements that have affected these rocks. Phenocrysts of quartz, plagioclase and/or orthoclase are common and smaller phenocrysts of biotite or muscovite may be present. The feldspars are usually zoned and the plagioclase

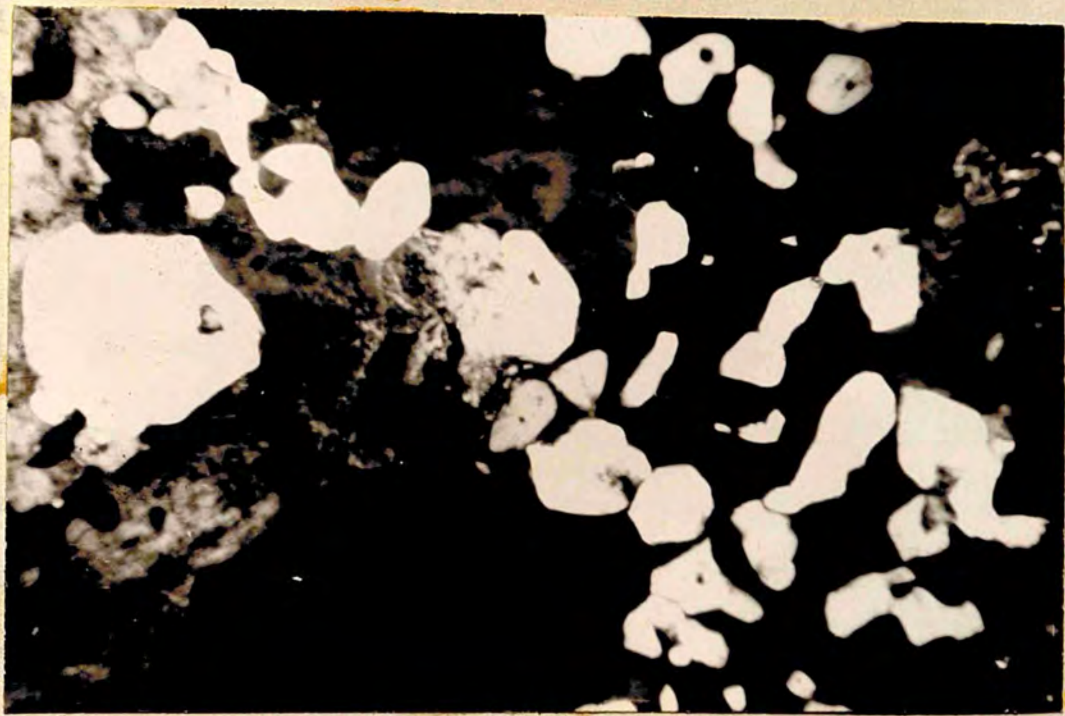


Plate 61a. Photomicrograph of graphic intergrowth between quartz and orthoclase. Quartz porphyry. Nicols crossed. x 60. Slide F 39.

Plate 61b. Photomicrograph of granophyre. Nicols crossed. x 40. Slide 244c.

gives values within the andesine range. Mineralogically these rocks range from rhyodacites to dacites in composition.

B. Quartz and Quartz/Feldspar Porphyries

Some dykes and sheets are completely crystalline porphyries, although their form is identical to that of the felsites described above and they are of the same mineralogical composition. This suggests a slower heat loss had occurred. The largest igneous bodies occurring within the area mapped are all granite porphyries, and even though the Carn Mor Porphyry, the largest of these intrusions, covers several square miles, it remains a porphyritic rock. In its marginal facies it is a pink felsite of rhyodacite composition, showing the relationship of this rock-type to the granite porphyries.

The groundmass of the Carn Mor Porphyry consists of quartz, orthoclase and plagioclase feldspar. Micrographic intergrowths are common and all the crystals are anhedral. Small crystals of chlorite and epidote are present replacing altered phenocrysts and as a part of the groundmass. Both these occurrences show similar textural relationships. The chlorite retains the form of the earlier hornblende which it pseudomorphs. The epidote crystals are enclosed by the chlorite and they too have been formed by the breakdown of the original amphibole. As is seen in the felsites, the whole of the rock is sericitized and minute crystals of colourless mica are scattered indiscriminately through both the groundmass and phenocrysts. The Carn Mor Porphyry is a porphyritic micro-adamellite

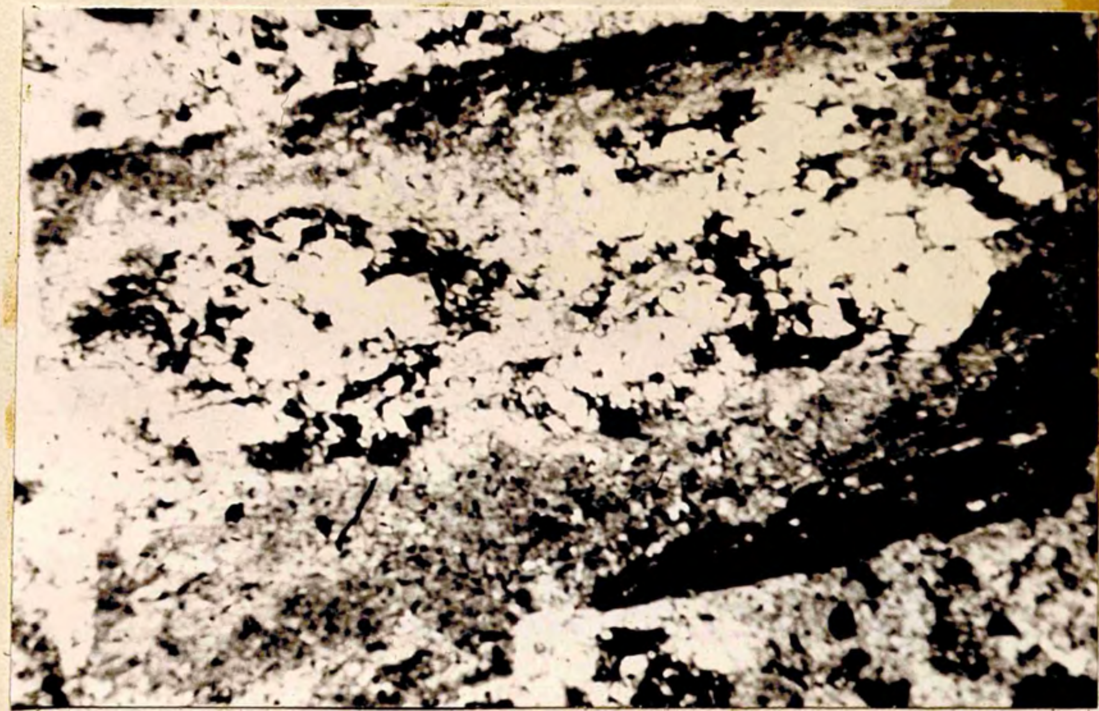


Plate 62. Photomicrograph of altered feldspar phenocryst in quartz/feldspar porphyry. P.P.L. x 40. Slide 187c.

since at least fifty per cent of the feldspar is andesine. Orthoclase and perthite do not commonly form phenocrysts as in many other feldspar porphyries. Altered hornblende, andesine and xenomorphic quartz are the chief phenocrysts. Alteration of the feldspar has resulted in the growth of calcite interstitially within the groundmass. Chlorite phenocrysts are often bent, and because they replace hornblende, and the deformation affects the optics of the chlorite, the deformation occurred after the breakdown of hornblende, and is further evidence of late brittle movements. The petrographic description of the Carn Mor Porphyry equally fits the other quartz and feldspar porphyries found throughout the region. Micrographic texture is not always found but in some examples it becomes so important that the term granophyre can be used. The relative proportions of orthoclase and andesine vary considerably but andesine is always present. All these rocks contain some magnetite and sphene is a common accessory. Biotite may also occur.

C. Igneous Cemented Breccias

Many of the dykes are intruded along fault planes, in fact posthumous movement has affected some dykes. Some faults are accompanied by a large amount of brecciation of the country rock. These breccias are often cemented by felsite. Not all the breccia fragments are country rock; fragments of quartz porphyry

Plate 63a. Grey porphyrite dyke. Glen Clunie.

Plate 63b. Photomicrograph of grey porphyrite. Nicols crossed. x 10. Slide 105c.

and felsite were also recorded. The groundmass cement may be devitrified glass or a fine grained mosaic of quartz and orthoclase. Small crystals of white mica may also be present.

2. Intermediate Intrusives

A. Porphyrites

The fine grained members of this group are not as porphyritic as the acid felsites and porphyries. They fall under the general field term of porphyrite. The fresh rock is grey in colour but weathering on exposed surfaces causes this to change to a dull red, which makes the screes recognisable at some distance in the field. The phenocrysts are extremely sporadic. Andesine is the most common, but quartz and chlorite may be present as well. The latter is readily seen in the hand specimen, forming dark green clots in the light grey matrix. As with the acid rocks chlorite is a pseudomorph after hornblende. The hornblende is not always converted to chlorite and is occasionally present as green-brown phenocrysts. The andesine crystals are usually zoned and show complex twinning. The variation from the core to the margin is not great and remains within the andesine range. The groundmass crystals are over fifty per cent plagioclase and they too are zoned and optical determination is difficult, but similar values to those of the phenocrysts were obtained. A coloured mineral is an important constituent of the groundmass. Biotite, chlorite

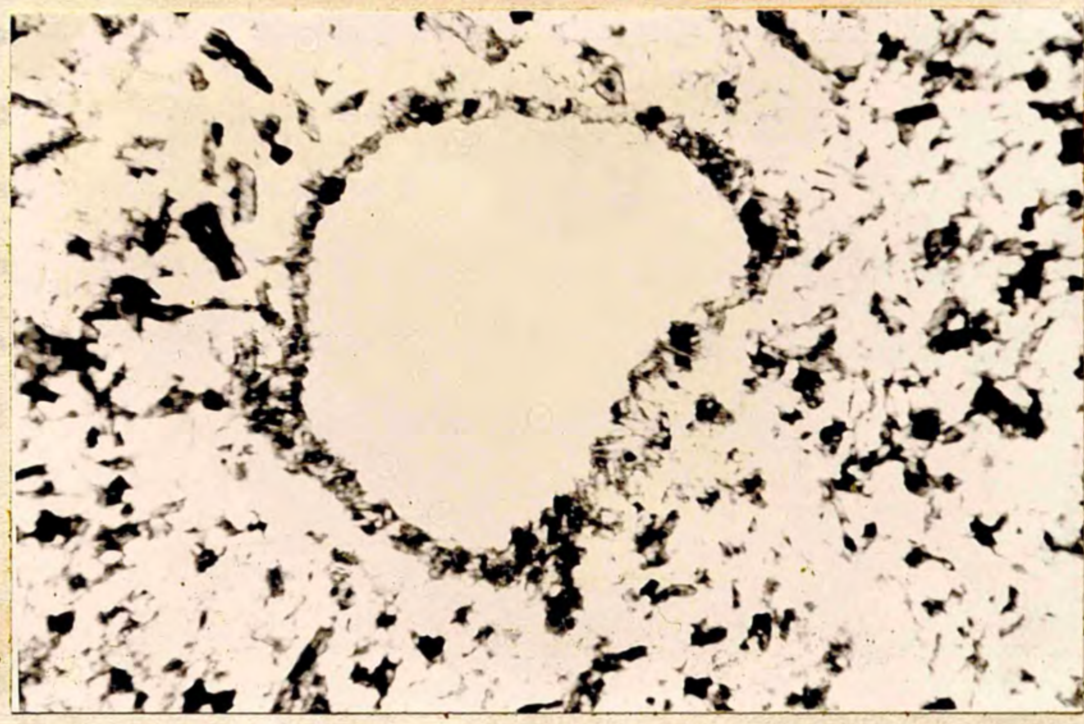


Plate 64a. Photomicrograph of quartz phenocryst in grey porphyrite. The crystal is mantled by small crystals of mica and ore. P.P.L. x 10. Slide 331c.

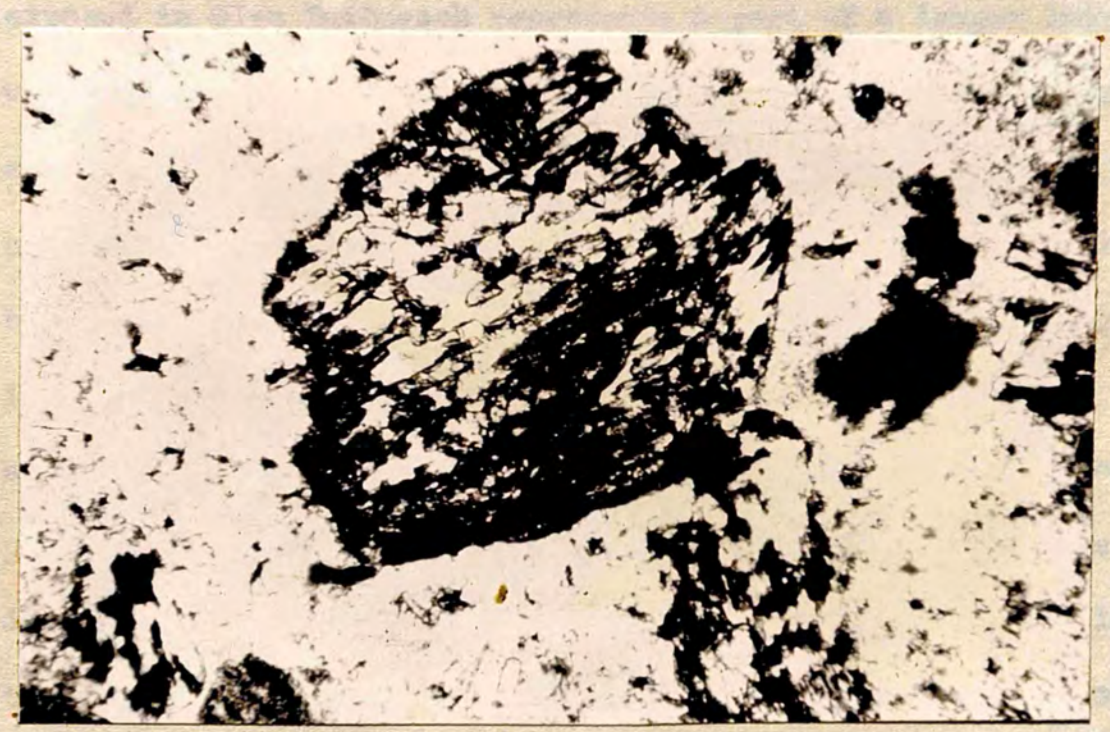


Plate 64b. Photomicrograph of brown hornblende phenocryst. This crystal is altering to chlorite and small epidote crystals. P.P.L. x 10. Slide 187c.

and muscovite constitute the chief minerals. Some idiomorphic pseudomorphs resemble augite. The laths of plagioclase commonly show a rudimentary orientation suggesting that some flowage occurred prior to complete consolidation. These dykes range from a few inches to two or three feet across and can be traced for distances similar to those of the felsites.

B. Diorites

Larger bodies which have a similar mineralogy to the porphyrites are less common in occurrence than the granite porphyries. They are not porphyritic and are of diorite composition. The largest of these intrusions outcrops in Glen Taitneach. This is a medium grained diorite and it is probable that the small dyke exposed in Glen Taitneach represents a part of a larger intrusion which is not yet uncovered. The country rock here is quartzite and it is difficult to detect any evidence of hornfelsing. The essential minerals are hornblende and plagioclase with subsidiary biotite and small amounts of quartz and magnetite. The plagioclase is zoned and altered at the margins and along the cracks to saussurite. The combined carlsbad-albite twinning gave a composition value of An.40, although zoning and alteration make determination difficult. The andesine has an ophitic relationship to a brown hornblende, which is only partly changing to chlorite, unlike the amphibole of the acid rocks which is completely replaced. Biotite crystals are also being converted to chlorite along the

Plate 65a. Photomicrograph of spherulitic texture in felsite. Nicols crossed. x 10. Slide 89c.

Plate 65b. Photomicrograph of quartzite breccia cemented by felsite. Nicols crossed. x 10. Slide 67c.

cleavages. Calcite forms occasional xenomorphic patches and is probably produced in the breakdown of feldspar and hornblende. Some small grains of quartz are present in accessory amounts and occupy interstices between the plagioclase laths. They show undulose extinction. A small intrusion with an identical mineralogy occurs on Carn na Greine. This rock has a chilled margin which is finer grained than the Glen Taitneach intrusion but in its centre the texture is the same. The fine grained marginal facies, however, has the same mineralogy and although it is texturally similar to the porphyrites it still has abundant brown pleochroic hornblende preserved.

In other examples of diorite complete and partial replacement of brown hornblende by a fine aggregate of epidote and chlorite has occurred. In one example the brown hornblende had become green at its margins. In all the specimens examined the plagioclase was zoned and altered. Extinction values were always within the andesine range.

Porphyrites are less common in occurrence than quartz porphyries and felsites. Diorite intrusions are even less widespread and only form small bodies. The alteration of all the minor intrusives may be due to the presence of water either in the country rock or within the magma.

The age relationship between the various types is not completely clear. Porphyrite dykes cut felsite dykes in two localities. In the Baddoch Burn a felsite is apparently cut by a quartz/feldspar porphyry. Just north of the Cairnwell a porphyrite is intruded along a fault which displaces the Carn Mor Porphyry and a felsite to the east of this also cuts the Porphyry. On this small amount of evidence at least three phases of acid intrusion can be recognised, followed by the intrusion of porphyrite, but it is felt that the evidence from this small region is insufficient. It is therefore suggested that there were several phases of dyke intrusion and that the acid intrusives probably preceded the porphyrites.

SUMMARY AND CONCLUSIONS

After the initial deposition of a series of limestones, schists and quartzites the area was thrown into recumbent folds, with the resultant inversion of the succession (F_1). Associated with the major structures were minor isoclinal folds which were to become sheared and largely destroyed by subsequent deformations, although some of the original fold closures are seen preserved in the banded Ben Eagach Transition Group. Following the F_1 folding the regional metamorphism began to take effect and it is probable that dolerite dykes were emplaced (epidiorites). At this stage the metamorphism would only have risen to biotite grade. Further deformation followed and was accompanied by the growth of biotite, hornblende, epidote and garnet (F_2). This period of syn-tectonic metamorphism produced a strong schistosity composed of biotite and muscovite and a linear orientation of the hornblende. Garnets that started to grow during this period of folding continued growing after the deformation had ceased, when the growth of garnet became more widespread and kyanite and staurolite developed locally. The third folding (F_3) was on N.E.-S.W. axes and was accompanied by widespread diaphthoresis. Garnet is replaced by chlorite, biotite, muscovite and ore. Hornblende is replaced by chlorite and biotite and kyanite and staurolite are replaced by sericitic aggregates. Locally, fresh biotite grows within the F_3 strain-slip schistosity and in many parts of the area chlorite occupies the strain-slip. Folds of this period tend to have steep axial planes which dip to the south-east. Both chlorite and biotite continued to grow after the third folding which was followed closely by the development of major thrusts. These thrusts associated with the Blair Atholl Series divide the region into three structural layers, viz.: the Morrone Nappe, a thrust zone composed of Blair Atholl Series and a Lower Nappe. It is suggested that the Morrone Nappe represents a complication in the upper limb of Bailey's Ben Lui fold (compare Bailey 1928). Following the thrusting were torsional movements which refolded the F_3 folds by a sinistral rotation about an almost vertical axis. This movement also affected the thrust in the region of the Cairnwell. The movement is in the same sense as the Loch Tay Fault and the tear fault developed south of Braemar close to the Moine/Dalradian Boundary. The normal faulting that followed was accompanied by brecciation and the intrusion of felsite and granite porphyry. There is more than one phase of acid intrusion. These appear to be followed by the intrusion of diorite and intermediate porphyry.

REFERENCES

Bailey, E.B. 1922. The Structure of the southwest Highlands of Scotland. Quart.J.Geol.Soc.Lond., 78.

__________ 1925. Perthshire Tectonics: Loch Tummel, Blair Atholl and Glen Shee. Trans.Roy.Soc.Edinb., Vol.LIII, 33.

__________ 1928. Schist Geology: Braemar, Glen Clunie and Glen Shee. Trans.Roy.Soc.Edinb., Vol.LV, 28.

__________ 1930. New Light on Sedimentation and Tectonics: Loch Leven to Glen Roy. Geol.Mag., 67.

__________ & McCallien, W.J. 1937. Perthshire Tectonics: Schiehallion to Glen Lyon. Trans.Roy.Soc.Edinb., 59.

Barrow, G. & Cunningham Craig, E.H. 1912. The Geology of the Districts of Braemar, Ballater and Glen Clova. Mem. Geol.Surv., 65.

Beke, F. 1924. Struktur und Kluftung. Fortschr. Min., 9.

Chinner, G.A. 1962. Regional Metamorphic Sequences in the Light of the Al_2SiO_5 Polymorphs. Proc.Geol.Soc.Lond., 1594.

Clough, C.T. in Gunn, W. et al. 1897. The Geology of Cowal. Mem.Geol.Surv.Scotland.

Cloos, E. & Heitanen, A. 1941. Geology of the "Martic Overthrust" and the Glenarm Series in Pennsylvania and Maryland. Spec. Paper Geol.Soc.Am., 35.

Cummins, W.A. & Shackleton, R.M. 1955. The Ben Lui Recumbent Syncline (Southwestern Highlands). Geol.Mag., 92.

Fairbairn, H.W. 1949. The structural petrology of deformed rocks. Cambridge 42 Mass.: Addison-Wesley Press Inc.

Grigor'ev, D.P. 1966. The Ontogeny of Minerals. Israel Program for Scienticic Translations, Jerusalem.

Johnson, M.R.W. 1963. Some time relations of movement and metamorphism in the Scottish Highlands. Geologie en Mijnbouw.

Kennedy, W.Q. 1948. The significance of thermal structure in the Scottish Highlands. Geol.Mag., 85.

King, B.C. & Rast, N. 1955. Tectonic styles in the Dalradians and Moines of parts of the Central Highlands of Scotland. Proc.Geol.Assoc.Lond., 66.

__________ 1956. The small-scale structures of south-eastern Cowal, Argyllshire. Geol.Mag., 93.

Knill, J.L. 1963. A sedimentary history of the Dalradian Series. P.99 in 'The British Caledonides', ed. Johnson & Stewart. Oliver & Boyd.

Krige, L.J. 1916. Petrographische Untersuchungen im Val Piora und Umgebung. Ecl.geol.helv., 14, 519.

Matheson, F. 1959. The Structure and Metamorphism of N.E. Perthshire. Unpublished thesis, University of Glasgow.

McIntyre, D.B. 1952. The tectonics of the area between Grantown and Tomintoul (mid Strathspey). Quart.J.Geol.Soc. Lond., 107.

Ramberg, H. 1952. The Origin of Metamorphic and Metasomatic Rocks. (A treatise on recrystallization and replacement in the earth's crust.) University of Chicago Press.

Ramsey, J.G. 1960. The deformation of early linear structures in areas of repeated folding. J.Geol., 68.

__________ 1962. The geometry and mechanics of formation of 'similar' type folds. J.Geol., 70.

Rast, N. 1958. The metamorphic history of the Schiehallion complex (Perthshire). Trans.Roy.Soc.Edinb., 63.

__________ 1958. The tectonics of the Schiehallion complex. Quart.J.Geol.Soc.Lond., 144.

__________ 1963. Structure and metamorphism and the Dalradian rocks of Scotland. P.123 in 'The British Caledonides', ed. Johnson & Stewart. Oliver & Boyd.

Rast, N. 1965. Nucleation and growth of metamorphic minerals. P.73 in 'Controls of Metamorphism', ed. Pitcher & Flinn. Oliver & Boyd.

_______ & Sturt, B.A. 1957. Crystallographic and geological factors in the growth of garnets from central Perthshire. Nature, 79.

_______ & Platt, J.I. 1957. 'Crossfolds'. Geol.Mag., 94.

_______ & Harris, A.L. 1960. Orientated quartz inclusions in garnets. Nature, 185.

Read, H.H. 1955. The Banff nappe: an interpretation of the structure of the Dalradian rocks of N.E. Scotland. Proc.geol.Assoc.Lond., 66.

Selley, R.C., Shearman, D.J., Sutton, J. & Watson, J. 1963. Some underwater disturbances in the Torridonian of Skye and Raasay. Geol.Mag., 100.

Shackleton, R.M. 1958. Downward-facing structures of the Highland Border. Quart.J.Geol.Soc.Lond., 113.

Spry, A. 1963. The origin and significance of snowball structure in garnet. J.Petrology, 4.

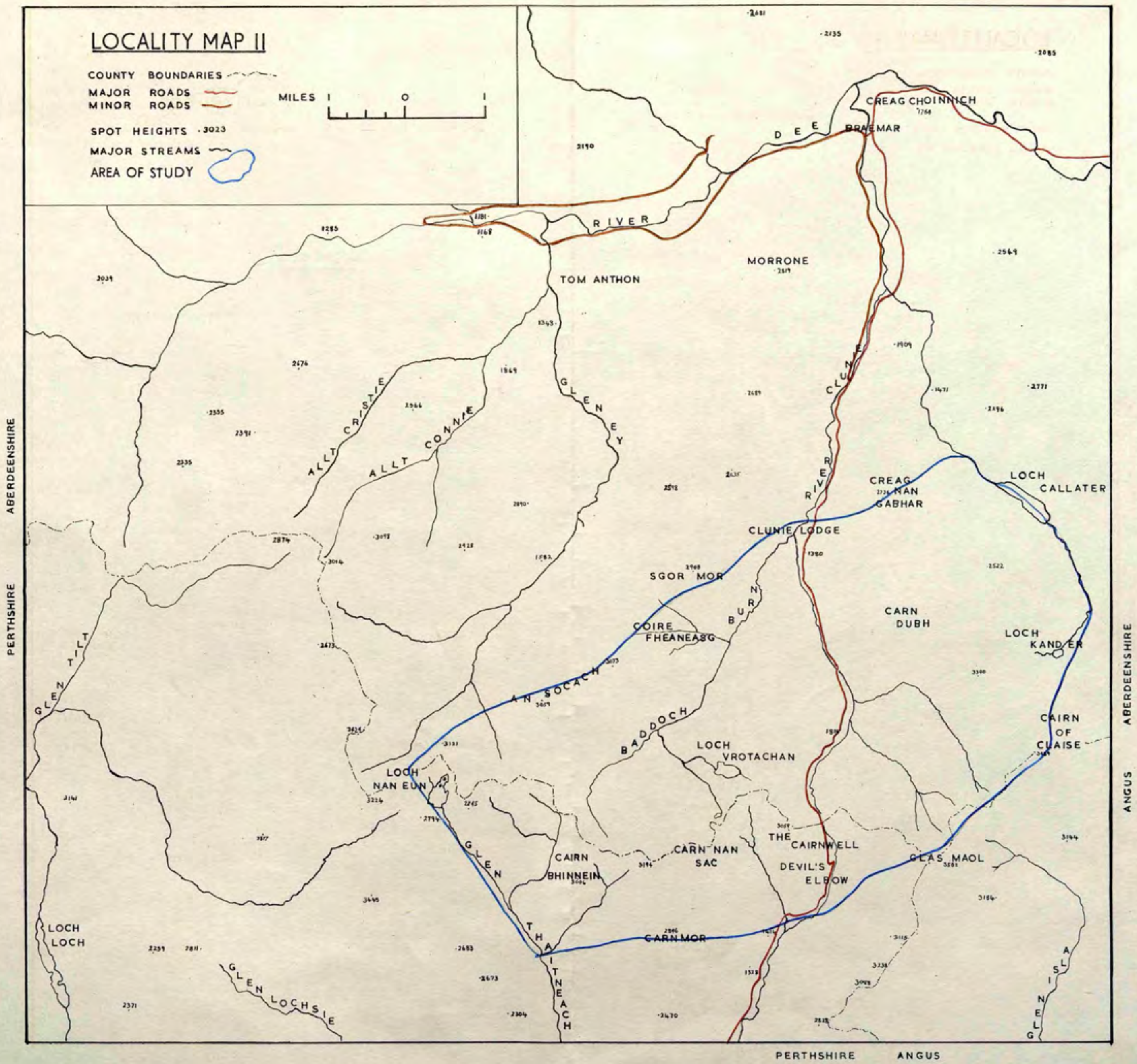
Sturt, B.A. 1961. The geological structure of the area south of Loch Tummel. Quart.J.Geol.Soc.Lond., 117.

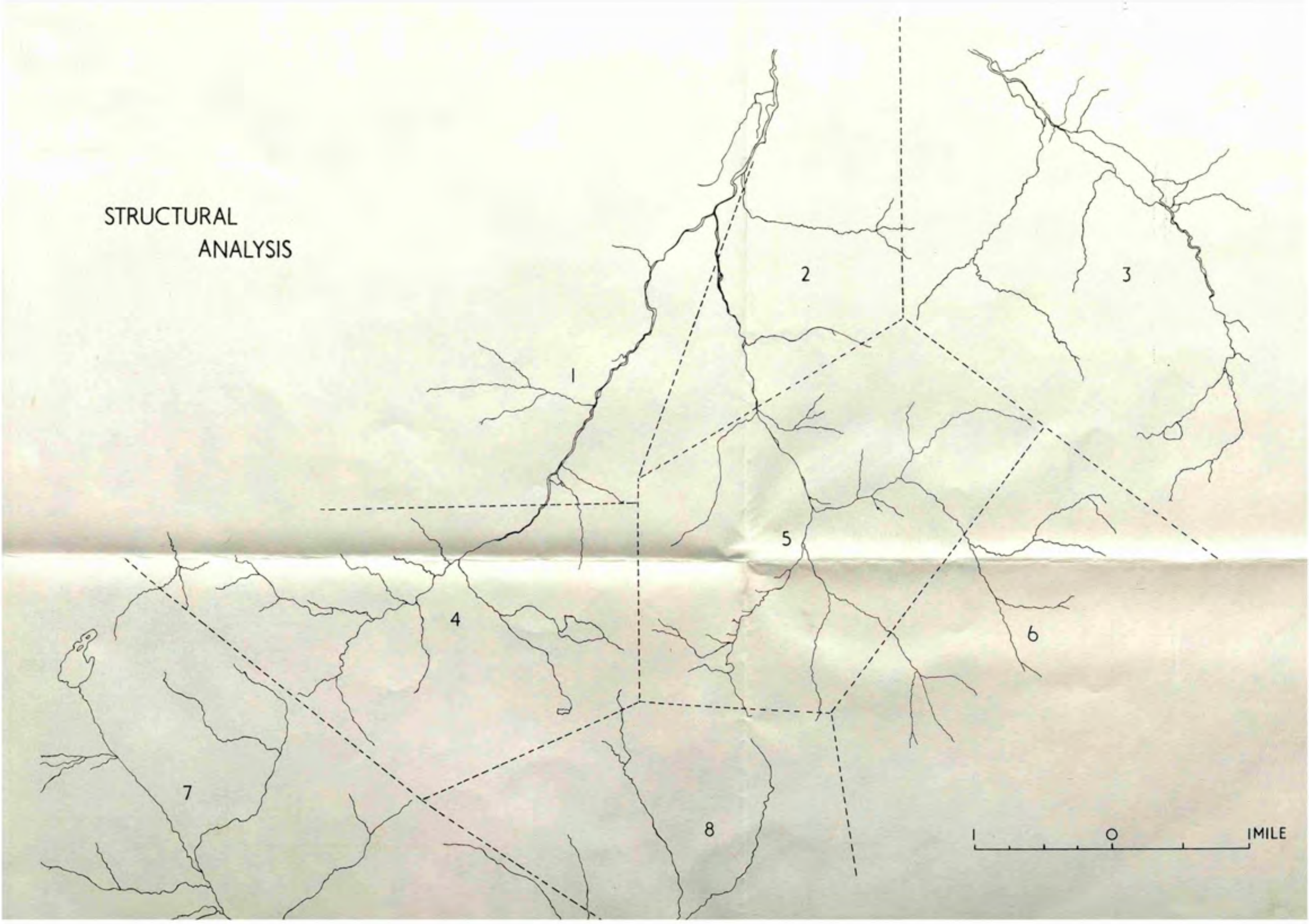
_________ & Harris, 1961. The metamorphic history of the Loch Tummel area, central Perthshire, Scotland. Liv. & Manch.Geol.Journ., 2.

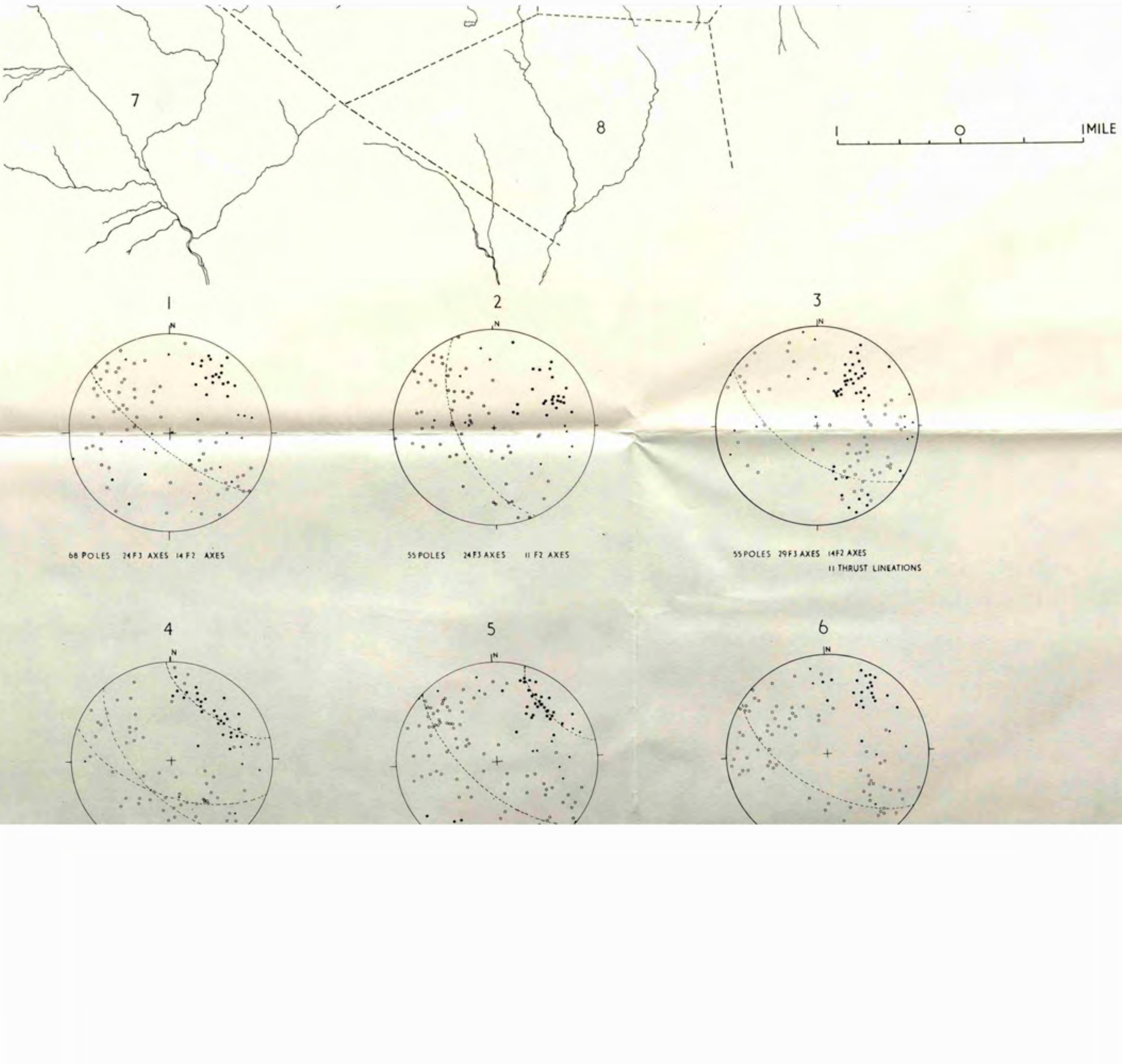
Treagus, J.E. 1964. Notes on the structure of the Ben Lawers synform. Geol.Mag., 101.

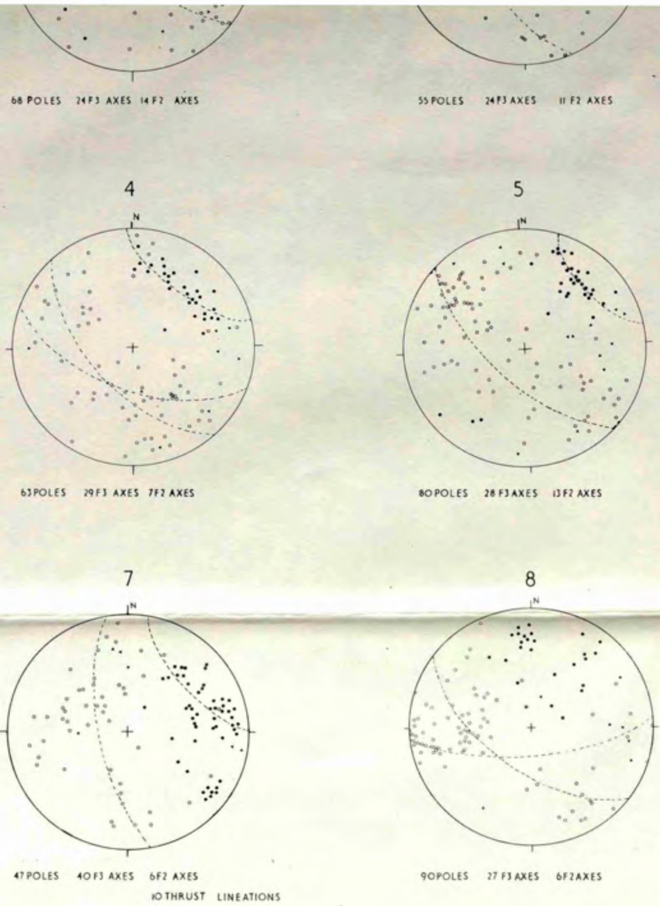
Weiss, L.E.& McIntyre, D.B. 1957. The structural geometry of the Dalradian rocks at Loch Leven, Scottish Highlands. J.Geol.

Zwart, H.J. 1962. On the determination of polymetamorphic mineral associations and its application to the Bosost area (central Pyrenees). Geol.Rundsch., 52.


LOCALITY MAP II
COUNTY BOUNDARIES
MAJOR ROADS
MINOR ROADS
MILES 1 0 1
SPOT HEIGHTS ·3023
MAJOR STREAMS
AREA OF STUDY
CREAG CHOINNICH
DEE
BRAEMAR
RIVER
TOM ANTHON
MORRONE
GLEN EY
ALLT CRISTIE
ALLT CONNIE
RIVER CLUNIE
CREAG NAN GABHAR
LOCH CALLATER
CLUNIE LODGE
SGOR MOR
COIRE FHEANEASG
BURN
CARN DUBH
LOCH KANDER
AN SOCACH
BADDOCH
LOCH VROTACHAN
CAIRN OF CLAISE
LOCH NAN EUN
GLEN TILT
GLEN TAITNEACH
CAIRN BHINNEIN
CARN NAN SAC
THE CAIRNWELL
DEVIL'S ELBOW
GLAS MAOL
CARN MOR
LOCH LOCH
GLEN LOCHSIE
GLEN ISLA
PERTHSHIRE
ABERDEENSHIRE
ANGUS


STRUCTURAL
ANALYSIS
1
2
3
4
5
6
7
8
1 0 1 MILE


7
8
1
0
1 MILE
1
N
68 POLES 24 F3 AXES 14 F2 AXES
2
N
55 POLES 24 F3 AXES 11 F2 AXES
3
N
55 POLES 29 F3 AXES 14 F2 AXES
11 THRUST LINEATIONS
4
N
5
N
6
N



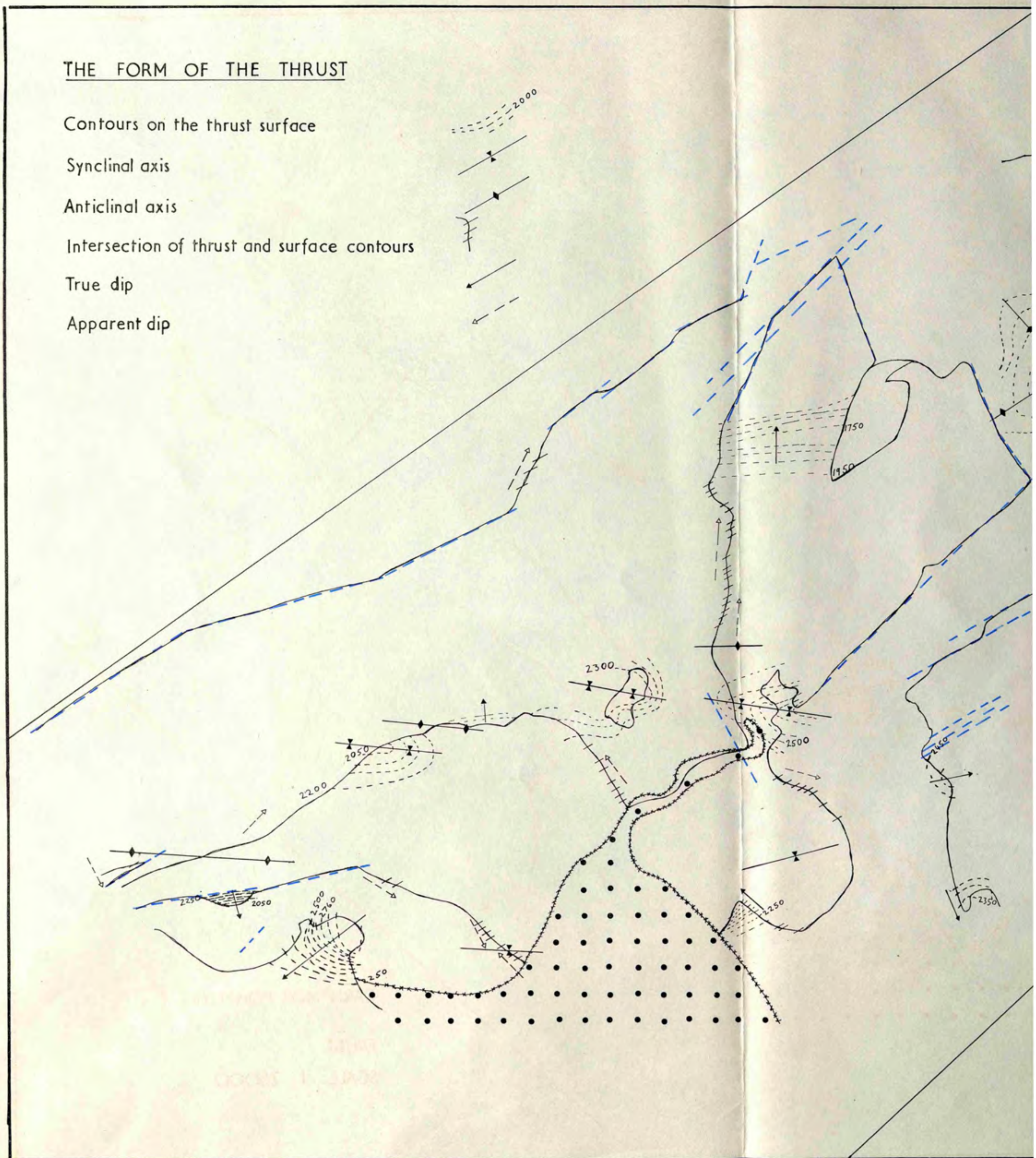
KEY

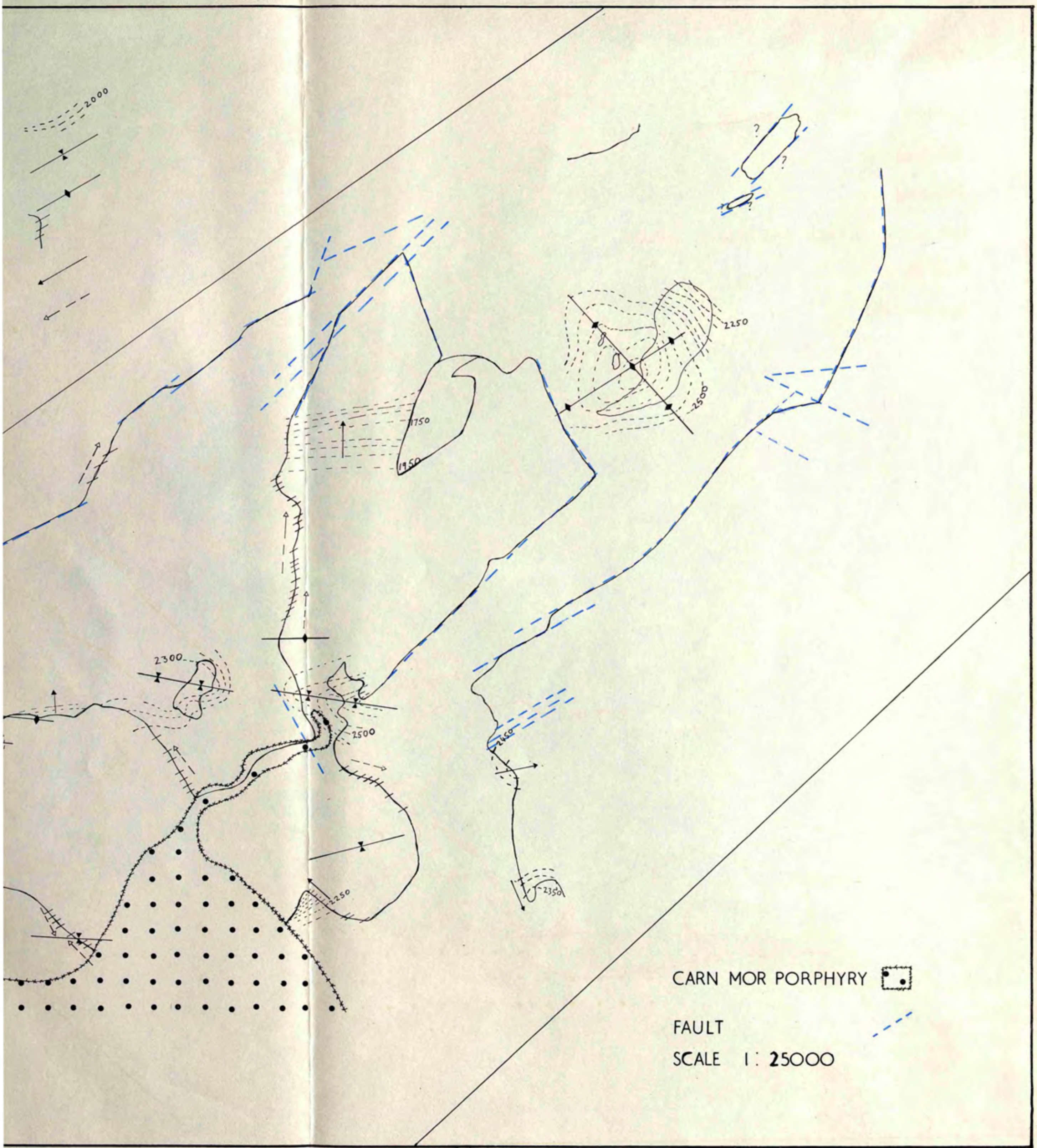
- ◦ POLES TO S PLANES
- • F3 FOLD AXES
- • F2 FOLD AXES
- • LINEATION ASSOCIATED WITH THRUSTING.

GREAT CIRCLES ARE DRAWN AT 90° TO F3 MAXIMA.
PARTIAL SMALL CIRCLES ILLUSTRATE THE EFFECT OF THE TRANSCURRENT MOVEMENT UPON THE F3 FOLDS.

ALL DATA PLOTTED ON EQUAL AREA PROJECTIONS

THE FORM OF THE THRUST

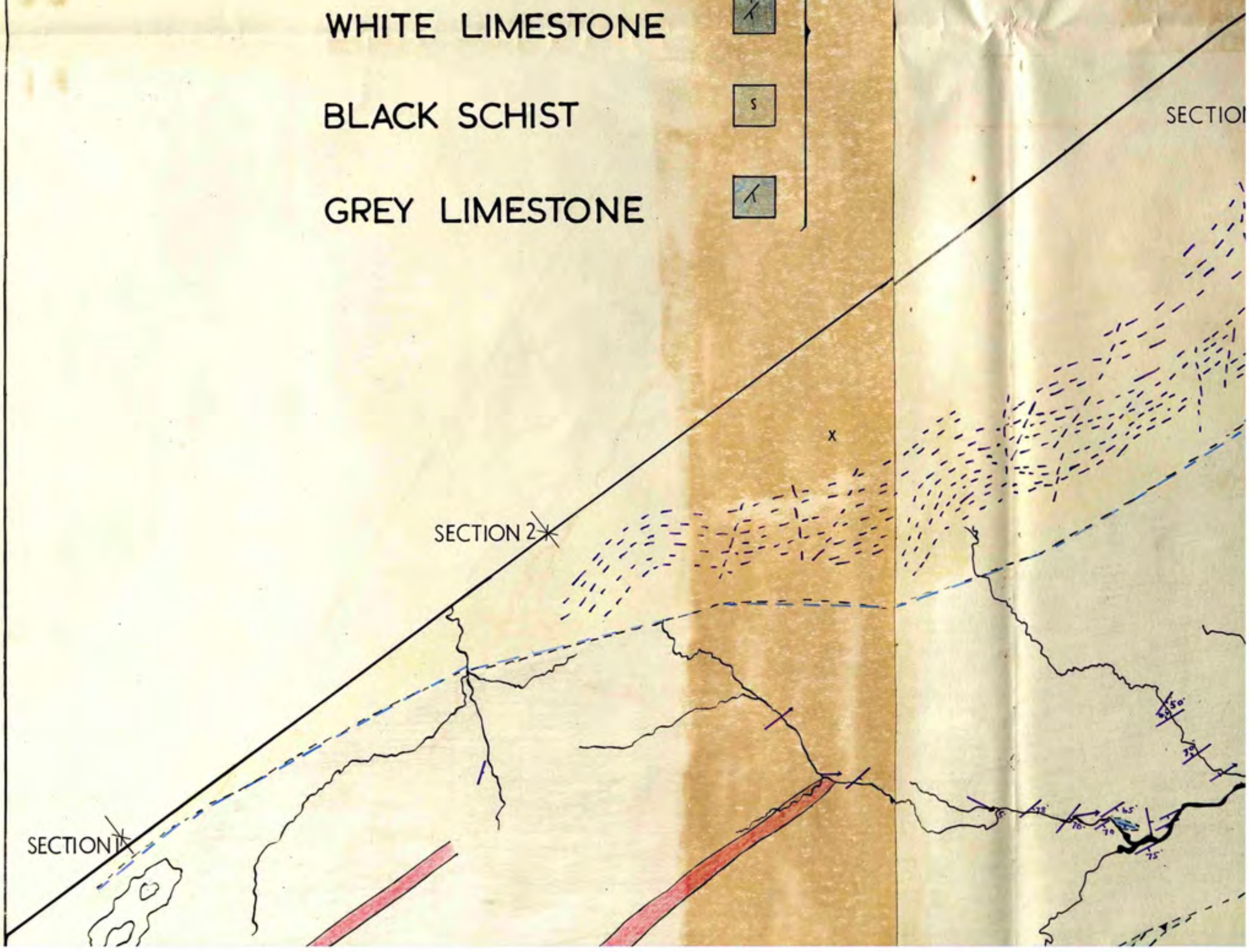


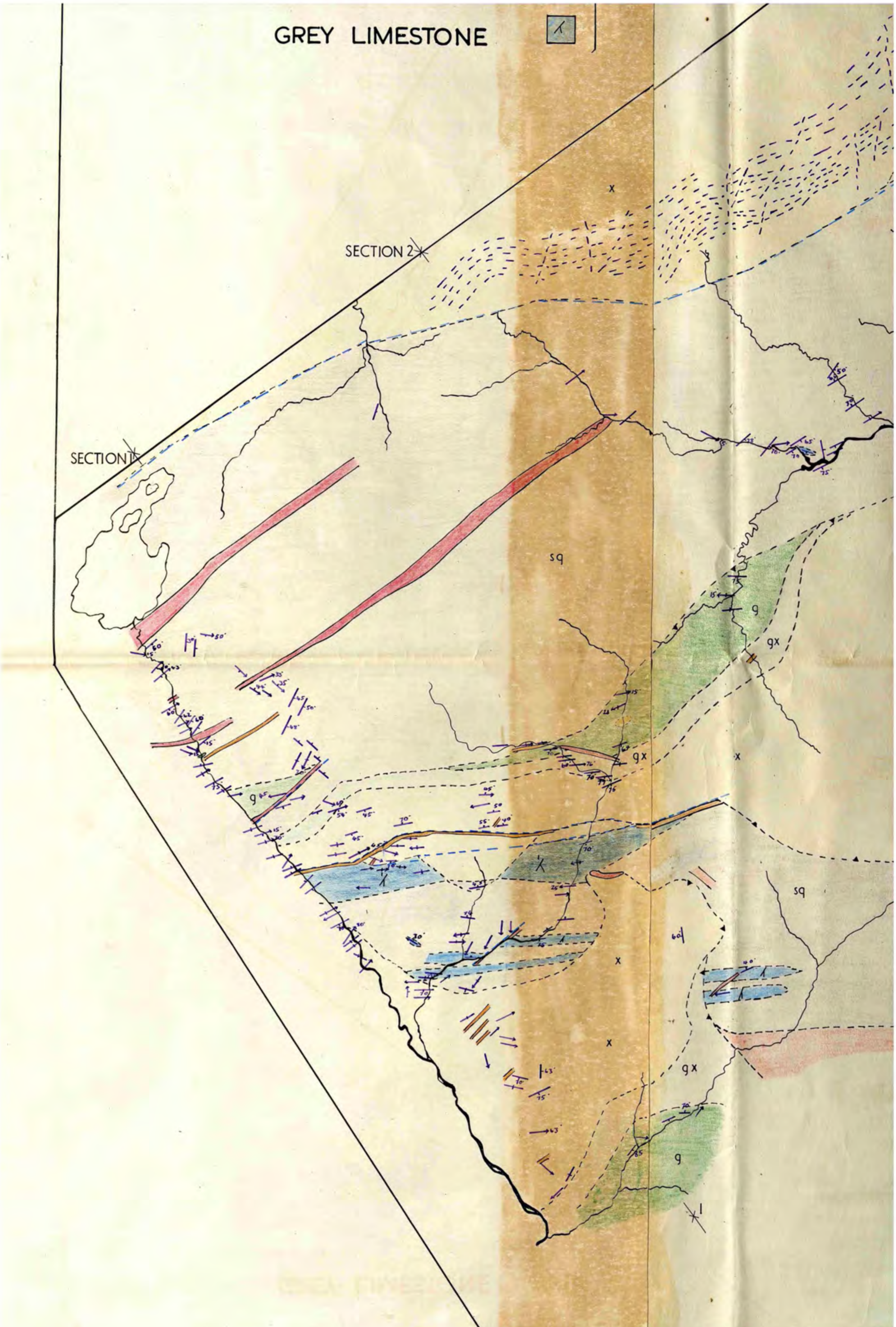


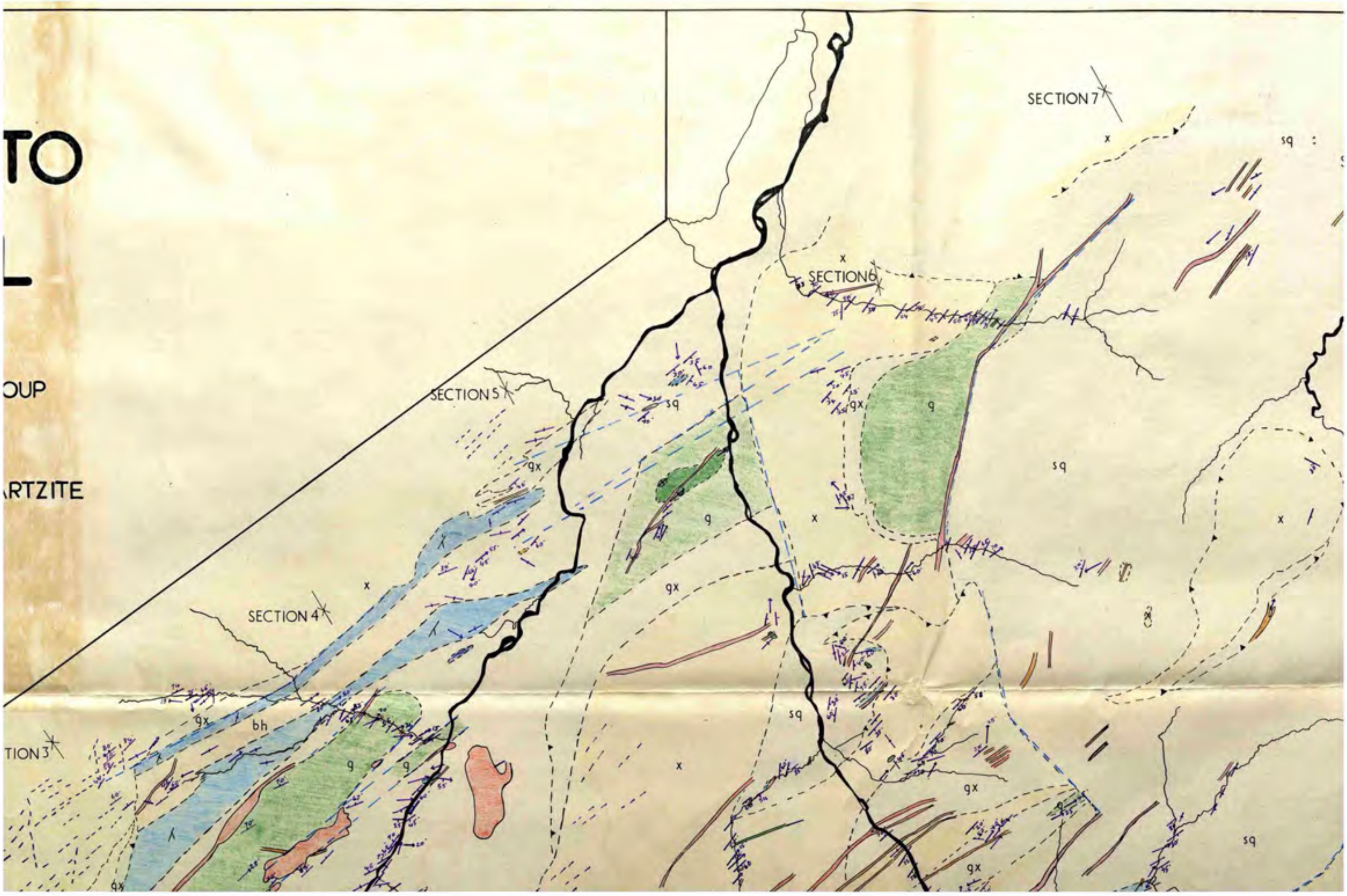
2000
2250
2500
1750
1950
2300
2500
2350
CARN MOR PORPHYRY
FAULT
SCALE 1 : 25000

CLUNIE LODGE T
THE CAIRNWELL

BLACK SCHIST	g	BEN EAGACH GROU
STRIPED SCHIST	gx	
QUARTZITE	x	PERTHSHIRE QUART
GREY QUARTZ GRANULITES	bh	BLAIR ATHOLL SERIES
GREY SCHIST	sq	
WHITE LIMESTONE		
BLACK SCHIST	s	
GREY LIMESTONE		

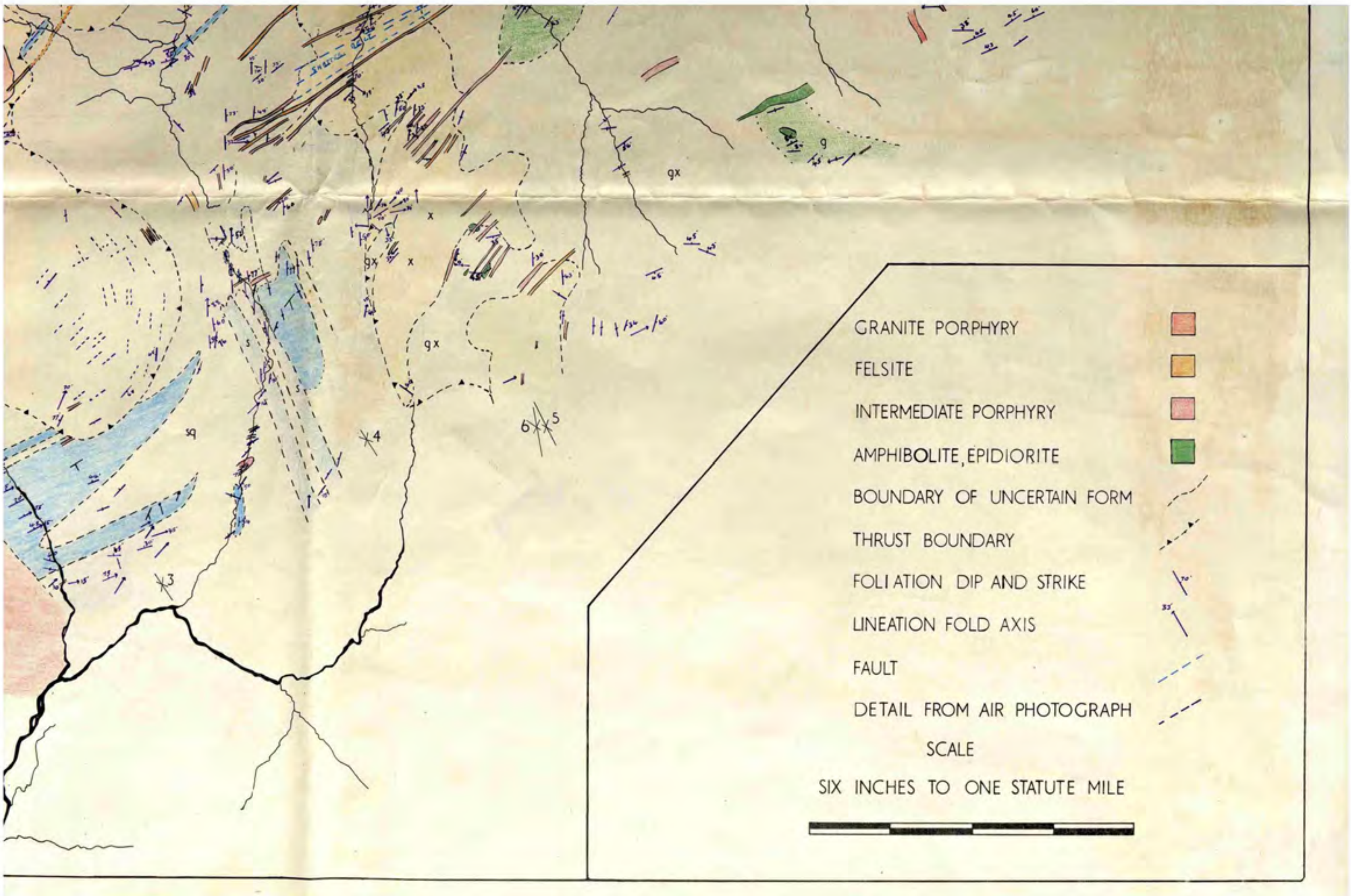



GREY LIMESTONE
SECTION 2
SECTION 1
x
sq
g
gx
g
x
sq
x
x
gx
g


TO
OUP
ARTZITE
SECTION 7
SECTION 6
SECTION 5
SECTION 4
TION 3
sq
gx
g
x
bh


SECTION 3
gx
bh
g
x
sq

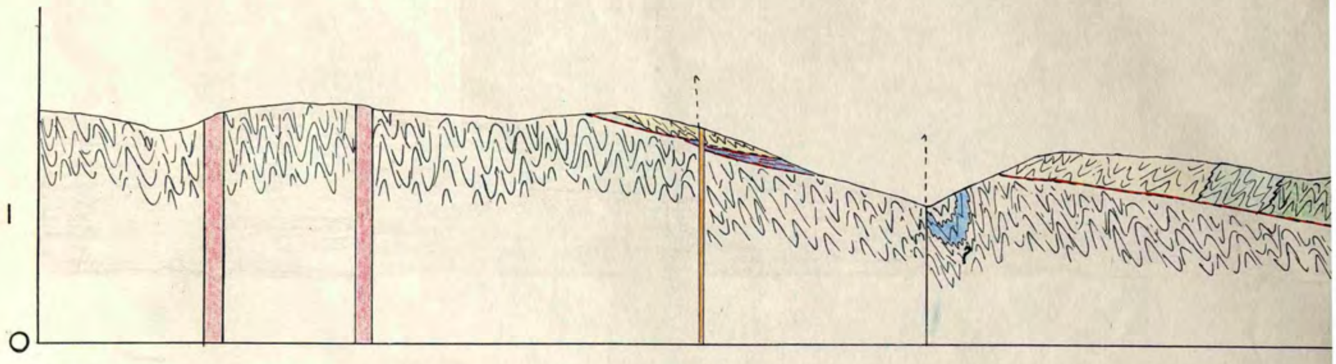
gx
x
sq
T
2
3
4
5
6


GRANITE PORPHYRY
FELSITE
INTERMEDIATE PORPHYRY
AMPHIBOLITE, EPIDIORITE
BOUNDARY OF UNCERTAIN FORM
THRUST BOUNDARY
FOLIATION DIP AND STRIKE
LINEATION FOLD AXIS
FAULT
DETAIL FROM AIR PHOTOGRAPH
SCALE
SIX INCHES TO ONE STATUTE MILE

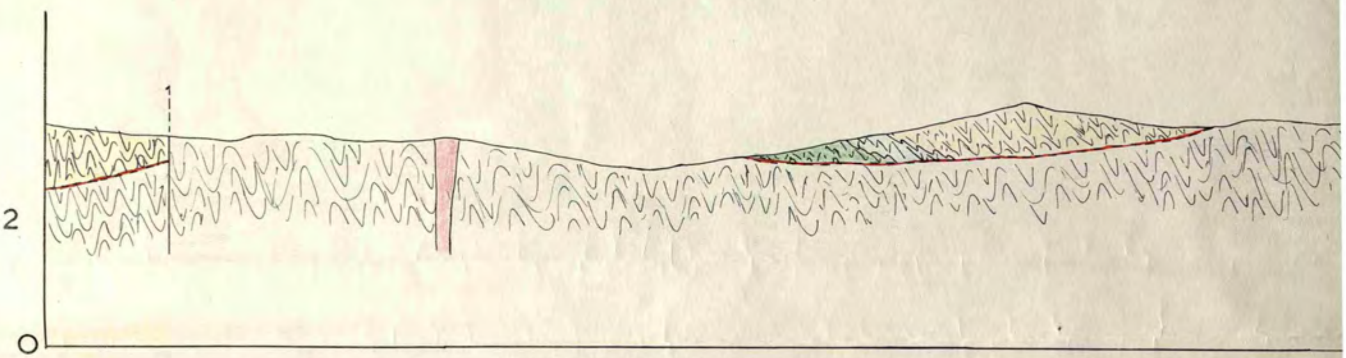
sq
x
gx
8
sq
x
gx
x
gx
g
g
x
gx
g
7
x
g
g
gx
6
5
GRANITE PORPHYRY
FELSITE
INTERMEDIATE PORPHYRY
AMPHIBOLITE, EPIDIORITE
BOUNDARY OF UNCERTAIN FORM

SECTION 7
SECTION 8
SECTION 6
x
sq
g
gx
8

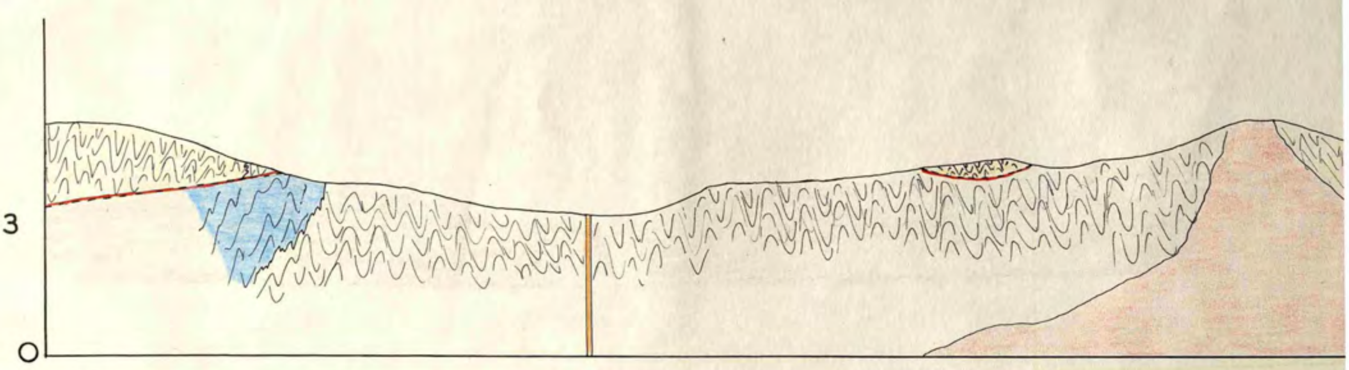
SECTIONS 1-8



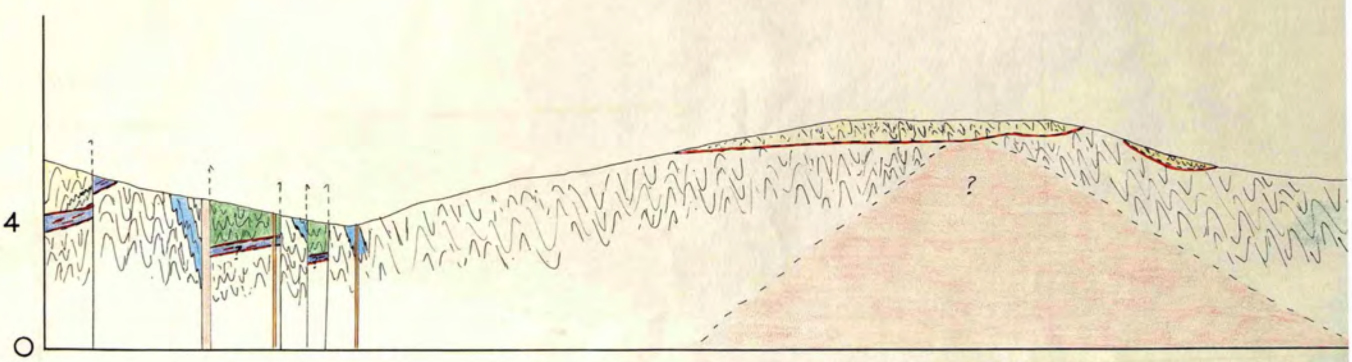
N.W.



N.W.

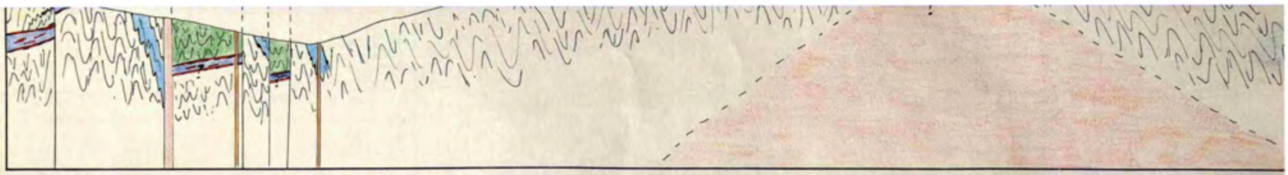


N.W.



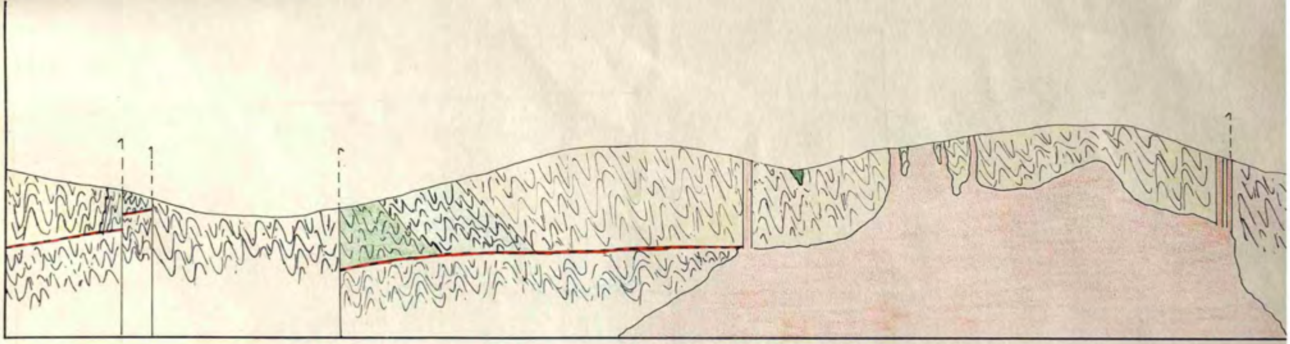
4

O



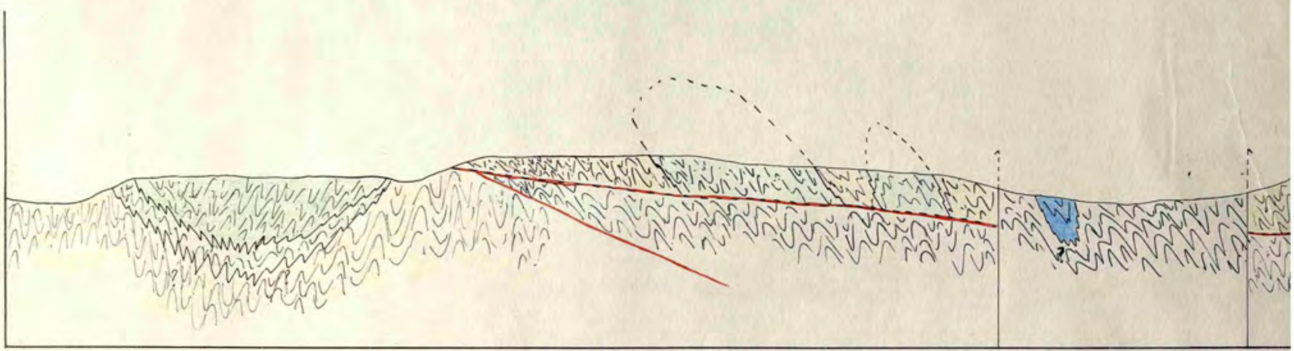
N.W.

5



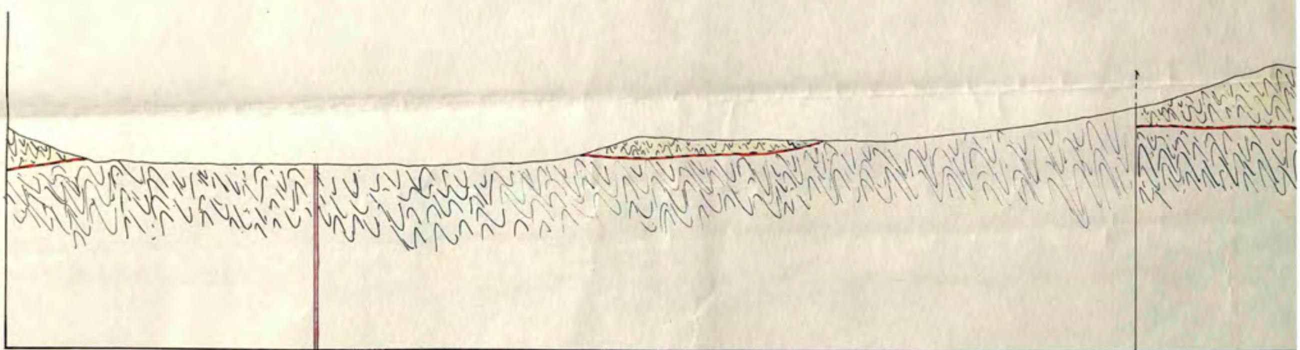
N.W.

6



N.N.W

7

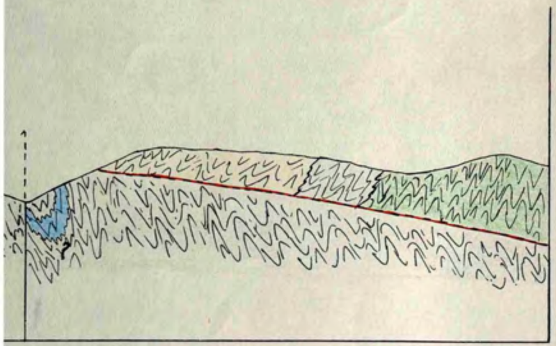


N.W.

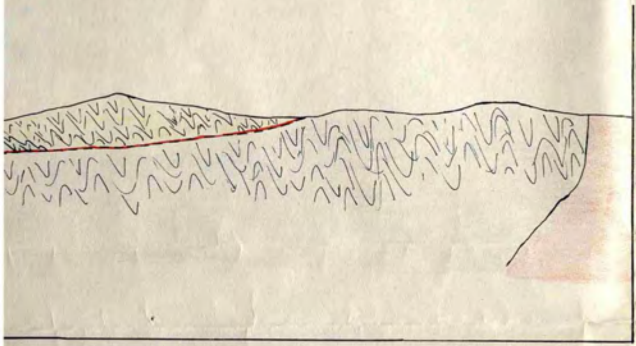
8

N.W.

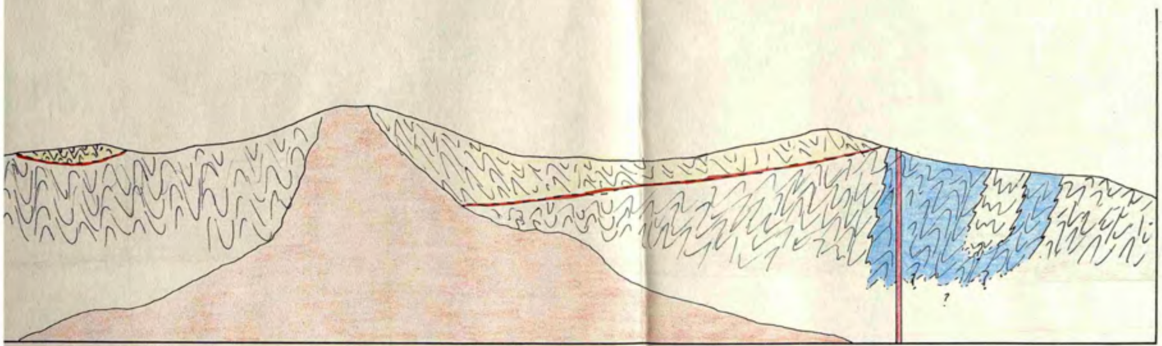
SECTIONS 1-8



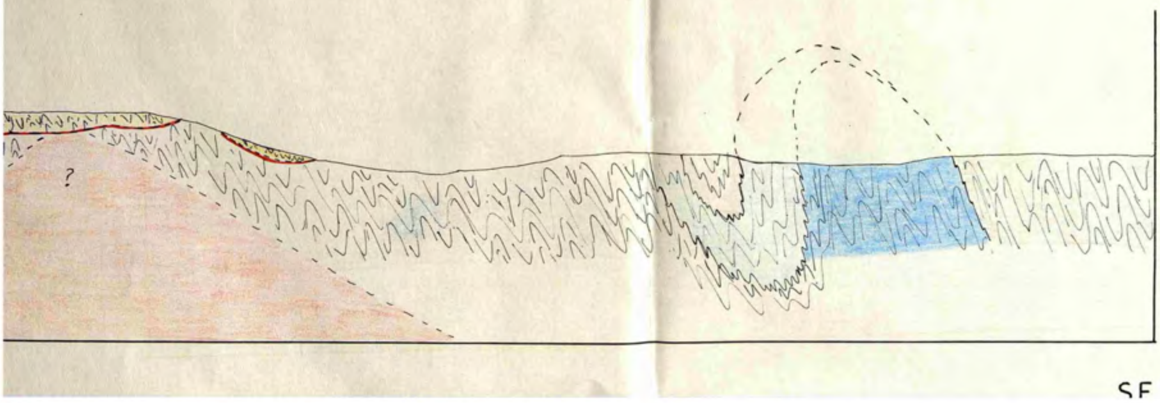
S.E.



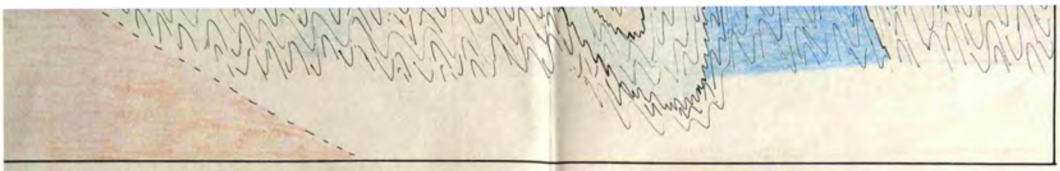
S.E.



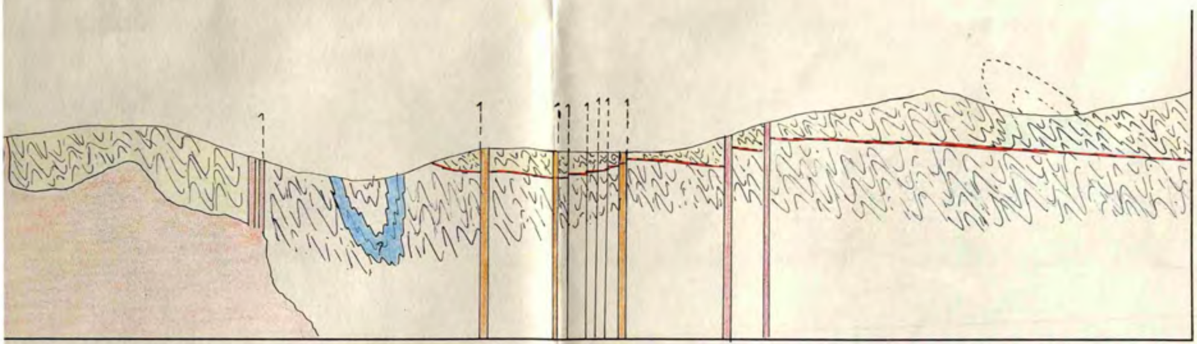
S.E.



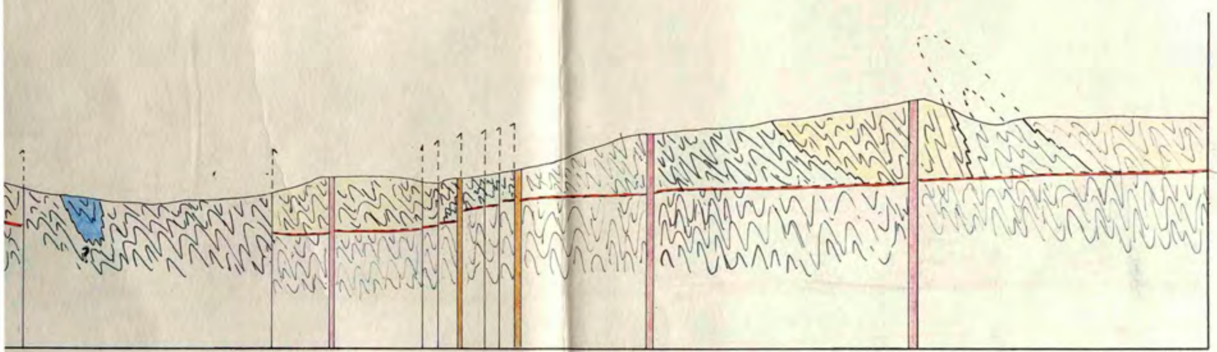
S.E.



S.E.

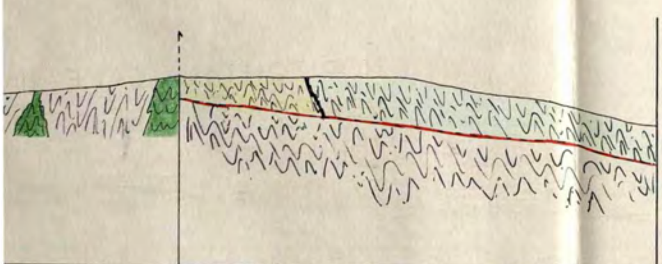


S.E.



S.S.E.

S.E.



S.E.

HORIZONTAL SCALE 1inch : 860ft.
VERTICAL SCALE 1inch : 1000ft.
THRUST
F3 FOLDS SHOWN DIAGRAMMATICALLY