METAMORPHIC STRUCTURES OF DALRADIAN ROCKS
IN NORTH EAST SCOTLAND

by

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CHAPTER 1.

1.1 Topography and Location

The north-east of Scotland, bounded to the south by the River Dee and to the west by the Rivers Spey and Avon, contains the greater parts of the counties of Aberdeenshire and Banffshire. Consisting mostly of flat agricultural country it is geographically isolated by the granite hills of the Dee valley to the south, and the Cromdale hills to the west. This isolation is strongly reflected in the native dialects of Aberdeenshire and Banffshire which are less 'anglicised' than those of the rest of Scotland and contain many words peculiar to the area.

Topographically the area can be split into three. The rocky coastline supports many small fishing villages and towns. Inland the weak relief of the Buchan plateau is broken only by occasional small granite hills and quartzite ridges, seldom exceeding 600 feet; it is extensively farmed and is in consequence well served by a network of small roads. As the hills are approached towards the south and west, the landscape changes, cultivation becomes confined to the valleys and straths, good roads become scarce and access to many localities can only be gained by forestry roads and rough tracks. The peaks of Bennachie (1,733 feet), Tap o' Noth (1,851 feet), and The Buck (2,368 feet) are all remnants of an old 1,700 feet plateau, which has been greatly modified by glacial activity; broad straths and glens such as the Howe o' Alford and Strathbogie interdigitate with the high ridges. Southward and westward the straths die out and the hills predominate, gradually rising to the massive Cairngorm
plateau which reaches over 4,000 feet in places.

On the Buchan plateau the vast deposits of glacial drift virtually mask all outcrop, exposure being confined to occasional river gorges and small roadside quarries. Outcrops are little better on hills which are covered in a thick layer of peat; small stream sections are practically the only source of outcrop. In contrast, however, the coast provides magnificent exposure, rocky cliffs extending almost continuously from the mouth of the Spey to the Ythan estuary.

Two areas were chosen for detailed study because they provide evidence relating to many of the problems of North-East geology; fortunately these areas have higher than average outcrop.

The first area is the Golliaston coast section (Geological Survey maps 77 and 87) extending from the Ythan estuary (G.R. NK 010250) northward to the southern edge of the Peterhead granite at Whinnyfold (G.R. NK 082333). The section, running sub-parallel to the regional strike, is about six miles long. It consists of a series of rocky headlands and bays, the cliffs varying from 10 feet to 130 feet.

The second area contains about 100 square miles of country (Geological Survey maps 75, 76, 85 and 86) centred around the Cabrach, about 10 miles S.W. of Huntly. The area consisting of country rock girdling the western end of the Inach Younger Basic mass, is 'horse-shoe' shaped, bounded approximately by Colpy (G.R. NJ 643324), Lower Cabrach (G.R. NJ 378313), Glenkindie (G.R. NJ 435138) and Alford (G.R. NJ 576159). The country is hilly, rising in places to over 2,000 feet, and the flat lying plains of the Inach Younger Basic mass and Old Red Sandstone outliers stand in marked contrast to the hornfels hills of the aureole. Exposure is usually limited to stream sections
although the slate quarries within the aureole provide good outcrop.

In addition to these main areas preliminary investigations were carried out on the Fraserburgh coast section, and in the area around Fyvie.

1.2 General Geology

Despite the paucity of exposure the Dalradian rocks of N.E. Scotland have long formed a classical area in the development of the study of rock metamorphism. The Upper Dalradian, the outcrop of which is approximately bounded by the Rivers Don and Deveron, differs in lithological and metamorphic characteristics from the Lower Dalradian in the adjacent areas. Whereas the Lower Dalradian contains many bands of limestone, quartzite and black schist, the Upper Dalradian consists almost wholly of grit and greywackes. The andalusite-cordierite assemblages of the Upper Dalradian (unlike the classic assemblages of Barrovian metamorphism in the surrounding regions) provide the primary example of Buchan metamorphism.

Read's memoir (1923) of the country around Banff, Huntly and Turriff is the foundation of the modern interpretation of North-East geology. In this memoir Read divides the rocks of Aberdeenshire and Banffshire into two main stratigraphical divisions - the Keith Series and the Banff Series.

The Keith Series which is the more westerly division, outcrops on the coast between Cullen and Boyne Bay and consists of black schists, limestones and quartzites of the orthoquartzitic facies. The lithological sequence was correlated (op.cit., p.71) with that found in the Lower Dalradian succession in Perthshire. Read (1952) extended
his Keith Series (so far restricted to the area of his 1923 memoir) to include the Deeside, Ellon and Inzie head gneisses.

The Banff Series occupying the greater part of the 'knuckle' of N.E. Scotland, consists of sediments belonging to the greywacke facies. Read was unable to correlate the Banff Series with any members of the Central Highland Succession (1923, p.71) although Horne (op.cit., p.72) suggested it was equivalent to the Upper Dalradian. Read postulated that the Banff Series was a 'foreign cake' thrust on to the Keith Series and separated from it by a movement plane, 'The Boyne Line', (op.cit., p.68).

In 1955, Read put forward the case for the Banff Nappe, which he has since regarded as the fundamental structural unit of N.E. Scotland. The evidence for this nappe is largely stratigraphical. Read accepted the earlier views of Horne and Elles (1931) that the Banff Series is equivalent to the Upper Dalradian of the Central Highland Succession, thus the Boyne limestone was correlated with the Deeside limestone and the Loch Tay limestone. Read then states (op.cit., p.22) that as a 'Banffshire geologist' passes westwards from the centre of the Banff Series "he encounters the lower part of the Perthshire Succession in descending stratigraphical order. As he passes southwards from the same position he encounters the upper part of the Perthshire Succession in inverted stratigraphical order". This he explains by the presence of a huge recumbent anticline ("Banff Nappe") closing to the east and plunging gently north. The nappe core is largely composed of gneiss and the upper limb broken by the Boyne dislocation (op.cit., fig. 3, p.19). The nappe is modified by two secondary folds, the Buchan Anticline in the east, first identified by Wilson (1886) and the Turriff Syncline to the...
west, first identified by Read (1923). Later, Sutton and Watson (1955) substituted the term 'Boyndie synform' for the Turriff Syncline and, from their work on the minor structures of the Banffshire coast, characterised the syncline as a huge monocline with its westerly, steep, limb outcropping over the distance between Portknockie and Boyndie Bay.

Read and Farquhar (1956) investigated the nature of the Buchan antiform. They suggested it was caused by an eastward and upward movement of the core of the Banff Nappe (op.cit., fig. 5, p.152). During the updoming there was a gravity-controlled collapse of sediments on the limbs of the Buchan antiform. The easterly directed gravity sliding on the eastern limb resulted in the "piling-up" of the Collieston Beds in a series of recumbent folds. On the gentler western limb westerly directed sliding is indicated by the fold shapes.

Johnson and Stewart (1960) suggested the structures of N.E. Scotland are more complex than had been suggested by either Read (1955, 1956) or Sutton and Watson (1955).

Johnson (1962) working on minor structures and metamorphic textures worked out the detailed structural history, consisting of at least four periods of deformation, viz:–

\[ F_1 \] - nappe formation

\[ F_2 \] - minor structures of Lower Dalradian

\[ F_3 \] - large monoclines (Turriff synform etc.)

\[ F_4 \] - late stage brittle movements

In 1965 Johnson followed the views proposed by Cummins and Shackleton (1955) in relation to the Tay Nappe in suggesting that the Banff Nappe may be in part at least due to gravity slide.

Read (1923) showed that the garnet-sillimanite-kyanite assemblages of the Keith Series differed markedly from the andalusite-
staurolite-cordierite assemblages of the Banff Series. The higher metamorphic grade of the Keith Series led him to propose that it was structurally and stratigraphically lower than the Banff Series and that a considerable metamorphic hiatus existed at the contact between the two Series. Read described the rocks of the Banff Series immediately east of the Boyne Line as 'phyllites' and those of the Keith Series to the west of the Boyne Line as sillimanite gneiss. Elles (1951, p. 27) claimed that the term 'phyllite' implied a low grade rock and in consequence that the metamorphic hiatus across the Boyne Line was very marked, however, from the presence of garnets in the 'phyllite' she suggested that the hiatus was not as great as had been previously supposed. Also, Elles demonstrated that the metamorphic grade increased from Macduff to Old Hythe in the Banff Series and decreased from Old Hythe to Cullen in the Keith Series and suggested that the cause of the metamorphism was centred at Old Hythe.

Read (1952) working on the section along the Ythan valley found that the Buchan metamorphism increased from West to East and from above downwards in the structural sequence; slates grading into andalusite schist and sillimanite-cordierite gneiss. He regarded this as a form of "regional thermal metamorphism culminating in migmatisation" (op. cit., p. 278). Although he showed that the Arnage migmatites swamped the Boyne Line he was unable to date the migmatisation relative to the Buchan antiform.

In their paper on the Buchan Anticline (1956) Read and Farquhar supported the view that the metamorphism was post-tectonic. They suggested that, after orogenic deformation, there was conduction of heat from the migmatite core, causing 'regional thermal' Buchan metamorphism in the enveloping sediments.
Johnson’s (1962, 1963) time-scale, placed the climax of the Buchan and Barrovian metamorphism (which he regards as roughly synchronous) between the nappe formation ($F_1$) and the formation of his $F_2$ folds (Buchan antiform etc.). Although Johnson thought the regional metamorphism to be a ‘static’ crystallisation he differed from Read in placing the climax of the metamorphism before the end of the deformational movements. Whereas Read regarded the Buchan metamorphism as a completely separate event from the Barrovian metamorphism, Johnson considered that their coincidence in time suggested a common cause and went on (1962, p.57) ‘... the special cause (rise of a local migmatite ‘dome’) for the Buchan metamorphism invoked by Read and Farquhar (1956) may be untenable’.

Chinner (1962, 1966) has worked on the zonal distribution of the alumina-silicate polymorphs in N.E. Scotland. He suggests (1962) that the sillimanite gneisses have been superimposed as local heat ‘nodes’, upon an earlier depth controlled metamorphic pattern, characterised by andalusite at high and kyanite at low structural levels. In 1966, using the $\text{Al}_2\text{Si}_3\text{O}_9$ phase diagram and the present distribution of the polymorphs he deduced a distribution pattern of isotherms and isobars over N.E. Scotland at the time of andalusite and kyanite crystallisation. He assumed that the crystallisation was depth controlled and that the isobars and isotherms must have been parallel originally. Their present divergence from parallelism is explained as due to complex syn-metamorphic folding; using this fact and various theoretical arguments Chinner deduces that the regional $F_1$ and $F_2$ movements were contemporaneous.

There are seven separate basic, mainly gabbroic, masses in N.E. Scotland — Huntly, Insch, Bogancloch, Haddo, Arnage, Maud and
Belhelvie — they form part of a large sheet intruded into the Dalradian metasediments after the cessation of the orogenic movements. Read (1923) termed these the 'Younger Gabbros' to differentiate them from the 'Older Gabbros', which ante-date most, if not all, of the orogenic deformation and metamorphism. A further basic mass, the Morven-Gabrach, was regarded by Read as an 'Older Gabbro' but Henry (1938) showed that it was, at least in part, a 'Younger Gabbro'. It's relationship to the other masses is still obscure.

Stewart (1946) described steeply inclined gravity layering in the Belhelvie gabbro, and he concluded the gabbro had suffered post-consolidation folding or tilting. From 'graded' layering at Huntly Shackleton (1948) found the gabbro had its base to the west and that the rocks had been overturned so that the layering dips in inverted order to the west. Shackleton (discussion in Read and Farquhar, 1956) suggested that the evidence indicated that the basic sheet formed by the 'Younger Gabbros' had been folded by the Turriff Syncline and the Buchan Anticline (op.cit., fig. 1, p.155). Read in reply, stated that he could not accept that the layering was ever horizontal nor could he imagine the formation of the Turriff Syncline and Buchan Anticline being separated from the formation of the nappe by a sufficient interval to allow the intrusion and consolidation of the gabbro masses.

This controversy was continued in 1958 by Blundell and Read in a paper that set out palaeomagnetic evidence which purported to show that the magnetic direction in the 'Younger Gabbros' remained constant regardless of the attitude of the banding. From this Blundell and Read concluded that the gabbroic sheet could not have been folded after it consolidated.

Stewart and Johnson (1960) re-examined the evidence bearing on
the structural problem of the 'Younger Gabbros' and concluded that the masses had been folded. They refuted the three arguments put forward by Read in favour of post-deformation intrusion. Firstly, Read (1923, p.156) argued that the cleavage in the Macduff Slates were destroyed in the aureole of the Inesch gabbro. Stewart and Johnson point out that the lack of cleavage in the hornfels is inconclusive evidence because the cleavage may not have developed in the hornfels during the folding of the adjacent gabbro and metasediments. Also, even if it were conclusively shown that the cleavage was destroyed in the aureole it is possible that the cleavage is related to the pre-gabbro Banff Nappe, in which case the evidence is irrelevant to the problem. Secondly, Read (1955, p.156; 1958, p.187) suggested that delicate textures in the gabbros would have been destroyed if the gabbros had suffered deformation. Stewart and Johnson criticised this on the grounds that comparable delicate textures can be observed in the metasediments (e.g. Macduff and Whitehills greywackes) which are strongly folded. Thirdly, Stewart and Johnson disputed the palaeomagnetic work. Blundell and Read's sampling was inadequate. The spread of plotted points on their stereograms was considerable, in the case of Belhelvie over 50°; and even if the plots were realistic it is possible that the already differentiated gabbros had been folded in a semi-consolidated state at a temperature above the Curie-points of the ferromagnetic minerals. Above this point, circa 560°C in gabbros, the magnetic susceptibility of the rock is zero, thus any palaeomagnetic direction exhibited by the rock, must have been acquired when the rock cooled below the Curie-point.

Gribble (1965) working on the Haddo and Arnage 'Younger Gabbros' computed their depth of burial at the time of their intrusion. From the presence of cordierite-andalusite assemblages in the metasediments
surrounding the Haddo gabbro he suggested that during metamorphism the rocks had been at 500-600°C, then taking a probable geothermal gradient he deduced their depth of burial, and in consequence that of the gabbro to be c. 10 km. In support of the figure of 10 km he showed that orthopyroxenes in the gabbro had high alumina percentages indicative of crystallisation under high pressures. Gribble proposed that a depth of burial of 10 km would allow the gabbros to remain above the Curie-point for some considerable time after their intrusion and partial consolidation. Gribble was assuming that the climax of metamorphism and the gabbro intrusion were roughly synchronous events. This assumption was based on figures produced by Bell (1965). Bell carried out a series of Rb/Sr age dates on rocks from N.E. Scotland and was unable to separate within experimental error the metamorphism and the 'Younger Gabbro' intrusion.

Brown et al. (1965) derived a date of c. 440 million years for the F₂ movements in Banffshire using potassium/argon methods similar to Bell's date of 440 million years for the intrusion of the Inach complex.

1.3 Nomenclature

Since the symbols \( F_1, F_2, F_3 \) are widely used in literature to denote successive fold generations on a regional scale, they will be reserved for regional discussions and the symbols \( B_1, B_2, B_3 \) will be used to indicate successive fold episodes in specific areas. The symbols \( S_0, S_1, S_2 \) to denote bedding, first axial plane cleavage and second axial plane cleavage do not have the same regional significance and will be used to discuss both regional and local structural elements. The terms \( L_1, L_2, L_3 \) denoting successive generations of linear elements
will also be used in regional and local discussions. The term S-plane is used to denote any penetrative planar element.

In describing folds the terminology proposed by Fleuty (1964) is used unless otherwise stated. The terms microscopic, mesoscopic and macroscopic are used as defined in Turner and Weiss (1964, pp. 15-16).

Orthogonal axes have been widely used in geological literature to define the structural directions of folds. It is felt, however, that since many workers have proposed different systems their use may lead to ambiguity and confusion. Therefore, they have been largely dispensed with in this thesis and only where it is felt that considerable simplification would be gained by their use have they been employed.

The system adopted is a simplification of that proposed by Sander (1930); the b axis is parallel to the regionally developed fold axis, a is normal to b in the movement plane; c is normal to the ab plane. The ab plane is the movement plane and will normally coincide with the regionally developed schistosity or cleavage.

1.4 Aims

The main aims of the thesis may be summarised thus:

1. (a) To investigate the nature of the Collieston folds; to deduce their relationship to the Buchan antiform and thus decide if their style is more consistent with formation by gravity collapse as proposed by Read (1956) or to some alternative hypothesis.

(b) To investigate the growth of metamorphic porphyroblasts in relation to the sequence of minor structures in the Collieston section.
2. To deduce the structural and metamorphic history of the Cabrach region and in particular:

(a) To determine the nature of the first generation macroscopic folds from an examination of cleavage and bedding intersections.

(b) To examine the swing in trend of the first generation schistosity and in particular the swing round the western end of the Bogancloch basic mass as shown by Johnson and Stewart (fig. 1, 1960) and determine if it is attributable to later folding, distortion during the igneous intrusion or to some other cause.

(c) To investigate the cleavage in the Macduff slates and to relate it to the structural history.

(d) To examine the growth of the metamorphic prophyroblasts and relate them to the structural history.

3. (a) To deduce the age of intrusion of the 'Younger Gabbros' by studying the relationships of the aureole minerals to the structures.

(b) To deduce the probable metamorphic conditions of the country rock at the time of the gabbro intrusion.

4. (a) To re-interpret the regional structures, in particular the nature and mode of formation of the Banff Nappe and the validity of the Boyne Line and other tectonic slides.

(b) To reconsider the relationship of the Buchan and Barrovian zones of metamorphism and to examine their causal mechanism.
CHAPTER 2.

COLLIESTON

2.1 Introduction

Because the Collieston coast section runs 10° or 15° oblique to the regional strike, the rocks dipping about 10° to the east, the succession is ascended structurally and stratigraphically from south to north. Read recognised three main rock groups in the section. The lowest group is the Ellon Gneiss considered by Read (1955) to be Lower Dalradian. This group contains contorted micaceous gneisses and compact grits with occasional dykes of metadolerite. Although almost completely masked on the coastal section by the sands of the Ythan estuary, Ellon Gneiss is exposed inland, mainly in the Ythan valley and in small knolls around Meikle Tarty. Above the Ellon Gneiss and according to Read (1955) separated from them by the Boyne Line are the basal beds of the Upper Dalradian. These beds forming the middle group of the succession, consist mainly of quartzite, pelites and calcareous bands and were correlated by Read and Farquhar (1956) with the Mormond Hill Quartzite. These beds grade upwards into the highest group of the succession which is composed of a series of grits, greywackes, siltstones, calcareous grits and andalusite-cordierite pelites which in accordance with Read and Farquhar (op.cit. p.134) will be collectively termed the Collieston Beds. The present writer believes that Read's correlations are incorrect but since the arguments against them are based on regional considerations the discussion will be deferred to Chapter 4.
2.2 Lithology

Lithological descriptions of the Collieston Beds and the Mormon Hill Quartzite are given by Read and Farquhar (1956) and it is not felt necessary to amplify these here. The Ellon Gneiss has also been described (Read, 1935; 1952; Read and Farquhar, 1956), the present author however disagrees with the use of the term 'gneiss' as applied to many of the rocks mapped as such by Read in N.E. Scotland. A full discussion on this will be deferred until the petrography of the gneisses elsewhere can be considered but it is felt appropriate to include here a brief description of the 'gneisses' around Meikle Tarty and the Ythan Estuary.

They consist dominantly of quartz, plagioclase (approximately An_{30}), cordierite and biotite, with subordinate garnet, andalusite, sillimanite and orthoclase. The texture is schistose. A bedding schistosity being defined by the parallel arrangement of flattened quartz grains and biotites. The quartz grains frequently show complex strain shadows. The cordierites occur both fresh and pinitised, they are large (up to 5 mm) often elongated in the planes of schistosity and contain randomly orientated quartz and biotite inclusions. The sillimanite is usually associated with biotite. In one specimen from the bank of the Ythan (about 3 km above its mouth) a second schistosity is developed; it is marked by small lines of crush with biotite and granulated quartz indicating movement after the main metamorphism.

2.3 Structural Analysis

At least two generations of folding exist at Collieston - \( B_1 \) and \( B_2 \). The elucidation of the structural history is complicated by two factors. Firstly, the trend of the fold axes \( B_1 \) and \( B_2 \) are
FIGURE 2.

Major Structures.

(a) Recumbent folds. Brow of Harroid.

(b) Recumbent anticline with parasitic folds.
   Green Craig.

(c) Recumbent folds. Cock Craig.

Bar in each case represents 75 feet. (23 m)
Dot-dash lines represent the axial plane.
coincident; also the orientation of the axial plane cleavages of the
two generations differ by only 10° to 15°. Secondly, small B₁
parasitic folds present on both limbs of the large B₁ folds are identical
in style and trend with the B₂ folds. Only folds seen to fold the
first generation axial plane cleavage are definitely assigned to second
generation folding. When B₁ and B₂ are coincident the allocation of
many of the linear elements such as quartz rods or axes of boudinage to
one specific generation of folding is impossible. At several localities
along the section B₁ and B₂ are not coincident and the direction of the
first generation linear elements (L₁) often forms angles of 30° to 40°
to the direction of the second generation linear elements (L₂), thus
allowing the styles of the two generations to be more fully examined.

Due to the small angle between S₁ and S₂, second generation
movements often caused a renewed slip along S₁ planes; where this
renewed movement is shown by disruption of minor B₁ structures or by
the recrystallisation of minerals originally defining S₁, these planes
are referred to as S₂ planes, although they may be parallel to the
regionally developed S₁ planes and oblique to the regionally developed
S₂ planes.

To aid description the folds in the following analysis are
divided loosely into major and minor types. Major folds are those
with amplitudes of two metres or more. Minor folds are those with
amplitudes of less than two metres belonging to the same generation of
folding as the major types and generally occurring on the major fold
limbs.

**First Generation Movements** (B₁)

First generation movements consist of three main phases.
Initially flexure-slip folding or buckling (Turner and Weiss, 1964;
p. 473) took place, secondly plastic flattening occurred (Ramsay, 1962;
FIGURE 3.

E. Minor Structures.

(a) Fold in grit band. Pottis Murlan.
(b) Congruous dependent parasitic folds. Green Craig.
(c) Incongruous dependent parasitic folds. Brow of Harrold.
(d) Development of $S_1$ in tight fold. Rockend.
(e) Folded grit band in pelite; broken at hinges. Needle's Eye.
(f) Calcareous pod forming rootless intrafolial fold. Forvie Ness.
(g) Stronger development of $S_1$ in pelitic band than in grit (stippled). Hill of Cransdale.
(h) Boudinage of grit bands (stippled) in pelite. Aver Hill and Collieston.

Bar in (a), (b) and (d) represents 6 feet;
in (c) and (e), 2 feet; in (f), (g) and (h) 1 foot.

Dot-dash lines represent the axial plane.

In (a), (b) and (d) - 1.8 m; in (c) and (e) - 0.6 m; in (f), (g) and (h) - 0.3 m.
(p.313) and finally increased flattening leading to shear folding (Turner and Weiss, 1964; p. 480) during which time a strong axial plane cleavage was induced.

B₁ folds are excellently developed throughout the section, forming a pile of tight recumbent folds, which is ascended from south to north. In the southern half of the section the major mesoscopic folds rarely attain amplitudes of more than one or two metres, however as the pile is ascended the amplitude gradually increases and from Slains Castle northwards folds with amplitudes of 20 to 30 metres are fairly abundant. Sedimentary structures in grit bands around Cock Craig suggest that folds of even greater amplitude may exist on a macroscopic scale. The most perfectly exposed and preserved major B₁ folds are in the areas around Devil's Study and Pottie Murlan. They are all 2-folds, the sense of vergence being to the east. Excellent graded bedding in the grit bands allowed Read and Farquhar (1956) to demonstrate quite conclusively that throughout the section the synclines closed to the west and the anticlines to the east. The fold axes of the major folds plunge N to NNE at about 10°; the axial planes dip gently east at about 15°-20°, in the nose region, however, the dip frequently increases to 40°-50°, the whole nose region tending to droop. Excellent examples of 'drooping' folds can be seen around Pottie Murlan and Green Craig.

An analysis of fold styles was made using some of the principles put forward by Ramsay (1962). Ramsay showed that the value of T (the thickness of a bed everywhere measured parallel to the axial plane) was always minimal at the fold hinges, even when ideal concentric folds have been subjected to plastic flattening (op.cit., p.311, fig.2; p.312, fig. 3). He also showed that in similar type folds T, which in ideal
FIGURE 4.

Graphs showing variations in the thickness (T) of the folded unit measured along lines parallel to the axial plane of the fold (A) (after Ramsay, 1962). Drawings of folds taken from photographs.

(a) Green Craig
(b) Iron Man
(c) Hummel Craig
(d) Fottie Murlan
FIGURE 5.

Calculations of percentage flattening ($X$) in modified flexure folds (after Ramsay, 1962, p. 315, fig. 7).

During flattening $\alpha$ is increased to $\alpha'$ and $t$ modified to $t'$. $t''$ = measurement of $t'$ where bedding dips at $\alpha'/$, measurement of $t'$ at fold hinge.

Graphs: 1. Green Craig
2. Hummel Craig
3. Iron Man
similar folds is constant, was always maximal at the fold hinges and generally had a pattern (op. cit., p. 318, fig. 9; p. 319, fig. 11) entirely different from that derived for modified flexure folds. Measurements were made of variations in T in a section from The Gutter to Green Craig (fig. 4). Most of the folds were the modified flexure type but many of the major folds, with strong S₁, developed approached more closely to similar geometry, some having almost ideal similar geometry. Using the methods proposed by Ramsay (op. cit., p. 314) the percentage flattening in the modified concentric folds was calculated for several folds at Green Craig, Pissing Yad, Devil’s Study and Pottie Murlan, values varied from 25% to 45% but no consistent pattern could be determined. Examples of these calculations are shown in fig. 5. The graph is taken from Ramsay (op. cit., p. 315, fig. 7), the value t'' (measurement of t' where bedding dips at 〈/measurement of t' at fold hinge) was plotted against 〈. For fold 2 the curve follows the ideal graphs of Ramsay fairly closely, but for folds 1 and 3, a wide divergence occurs at values of 〈 greater than 60°, this is presumably due to some element of shear or slip folding attenuating the limbs by extension in 〈.

Parasitic folds are extensively developed on the limbs of the major folds: in style they are similar to the main folds. In many areas around Green Craig and Brow of Harrold incongruous dependent parasitic folds are found (fig. 3c). Many of the parasitic folds are disharmonic and form crenulate folds in the noses of the major folds. Some calcareous bands have been completely disrupted and now form 'rootless intrafolial folds' (Turner and Weiss, 1964, p. 117) with the axial plane lying parallel to S₁ (fig. 3f). Small folds of sandstone in grits and pelites occur with the same style. Although the majority may be due to penecontemporaneous deformation of partially consolidated sediments, the
tightness of folding in some and their relationship to $S_1$ suggest that they are tectonic. The psammitic layers in the limbs of the large folds have often been stretched and boudined, the boudins lying with their long axis parallel to the regional $B_1$ fold axis. In rare cases, mainly in the north of the section, the layers have been boudined due to stretching parallel to the $a$ and $b$ directions of the $B_1$ folds, and form 'chocolate-tablet structures' (Read and Farquhar, 1956, p. 144). The best examples of these structures are exposed at low tide between Slains Castle and Cock Craig.

The axial plane cleavage ($S_1$) is well developed throughout the section, in all rock types. Generally it is parallel or sub-parallel to $S_o$ and the axial planes of the major $B_1$ folds.

In the major folds where the axial planes 'droop' at the fold nose, $S_1$ still remains planar, suggesting that the 'drooping noses' date from an earlier phase of the $B_1$ movements than the flattening phase which induced the $S_1$ schistosity. Although the dip of $S_1$ varies from $0^\circ$ to $40^\circ$ to the east the commonest dip is approximately $20^\circ$ to the east (fig. 6a). In microscope sections taken from the nose of $B_1$ folds the relationship of $S_o$ and $S_1$ can be examined. The bedding shows all degrees of transposition to $S_1$, $S_1$ often becoming dominant and all traces of bedding destroyed. Small parasitic folds formed during the buckling phase of $B_1$ whose axial planes are at high angles to the axial planes of the major folds are occasionally disrupted by movement on the $S_1$ planes during the flattening phase. $S_1$ is generally marked by the parallel arrangement of micas and flattened quartz grains.

First generation linear elements ($L_1$) are extensively developed. Quartz lenses and pods present in the rock before the $B_1$ movements have been disrupted and rolled to form spindle-shaped or more commonly lensoid-shaped rods. The latter have been flattened in $S_1$, with their longest
FIGURE 6.

(a) Poles to $S_1$. 120 points. Contours at 30%, 20%, 10%, 3%, 1% per 1% area.

(b) Poles to $S_2$. 100 points. Contours at 20%, 15%, 10%, 5%, 1% per 1% area.

(c) Poles to axial planes of pegmatite folds. 100 points. Contours at 20%, 10%, 5%, 3%, 1% per 1% area.
FIGURE 7.

(a) Stereo-plot of $B_1$ fold axes. Large dots represent major folds and small dots the minor folds. Open circles represent poles to bedding ($S_o$) measured around the noses of several major folds.

(b) Stereo-plot of $B_2$ fold axes.

(c) Stereo-plot of pegmatite fold axes. Contours at 10%, 5%, 3%, 1% per 1% area.
FIGURE 8.

Stereoplots of \( L_1 \).

(a) Pebble elongation. 100 points. Contours at 20\%,
10\%, 5\%, 3\%, 2\% per 1\% area.

(b) \( s/s_1 \) intersections. 200 points. Contours at 20\%.
15\%, 10\%, 5\%, 1\% per 1\% area.

(c) Quartz rods etc. 150 points. Contours at 15\%.
10\%, 5\%, 3\%, 2\%, per 1\% area.
axis parallel to the $B_1$ fold axis. Cleavage bedding intersections are
commonly seen in the field and lie parallel to the $B_1$ fold axis. One
of the most interesting of the linear elements are the deformed quartz
and K-feldspar pebbles found in the grit bands, the discussion of these
will be deferred to the end of the section.

The trace of first generation linear elements (map 1) along the
section is curvilinear, although generally trending NNE to NE it swings
round to NNW and NW at Perthudden and on the north side of Hackley Bay.
Also, the linear elements can occasionally be shown to have different
orientations in successive ab planes varying by up to $10^\circ-15^\circ$ over a
distance of 3 metres. This suggests that some form of differential
slip took place on the ab planes during the shear folding phase of $B_1$.

Quartzo-feldspathic pebbles.

Bands with sizeable quartzo-feldspathic pebbles, ranging in size
from 2 or 3 mms to 5 or 6 cms, are found intermittently from Hackley Bay
northwards. Although the pebbles are generally strongly orientated rods
parallel to the $B_1$ fold axis, they are occasionally disc-shaped with the
short axis normal to $S_1$. In size the component grains of the quartz
pebbles range from 0.5 to 1.0 mm, considerably coarser than the quartz
grains of the surrounding matrix (rarely greater than 0.1 mm). The
grains are generally equidimensional (fig. 9). Bands and patches of
smaller grains (approximately 0.2 to 0.3 mm) are often found at the
margins of the pebbles (see fig. 9c). Petrofabric diagrams (see fig.
10 and explanation) show a strong maxima of $c$ optical axes parallel to
the regional fold axis. In fig. 10a and b, there is also a partial
girdle in ab (ab is here coincident with $S_1$). The matrix consists of
roughly equal amounts of flattened quartz grains and micas defining a
schistosity. In some rocks there is a veneer of green mica around the
pebbles.
It is considered worthwhile at this stage to examine the processes operative during metal deformation and subsequent annealing and to relate these to the deformation of the quartz pebbles. Harris and East (1960) summarise five distinct stages in the annealing of metals after cold working and suggest a parallel sequence of events in deformed quartz aggregates. The five stages as recognised by Cahn (1950) and Burke and Turnbull (1952) are:

1. **Recovery**: This is the ability of the metal to absorb applied stress without alteration to the fabric or the component grains.

2. **Polygonisation** and (3) **Primary Recrystallisation**: This covers the break-up of the original fabric due to applied stress, the formation nuclei or sub-grains and their subsequent development into grains with an orientation generally different from the parent grains.

3. **Grain Growth**: The growth of grains tending to dissipate remnant strain.

4. **Secondary Recrystallisation**: Further change in grain size due possibly to renewed straining of the fabric.

When a metal has been cold worked or subjected to stress, it contains a large number of dislocations, many of these combine and disappear (extra atoms migrating into vacancies etc.) (McLean, 1965, p.110). The residual dislocations are dissipated in two ways. Firstly, by polygonisation, the metal breaks down into polygons, the dislocations migrate to the polygon boundaries and there coalesce along slip or glide planes to form stable arrays; polygonisation does not imply a reorientation of the lattice and does not in itself create a state suitable for grain growth. Secondly, by recrystallisation, small
sub-grains appear each with a near perfect lattice clear of dislocations, but with the lattice disoriented relative to the lattices of neighbouring grains. Although both polygonisation and recrystallisation usually occur, Hardwick and Teggart (1962) working on the deformation of copper and aluminium showed that metals with high stacking fault energies will polygonise so quickly to reduce strain that all the stress is dissipated before recrystallisation may occur, whereas metals with low stacking fault energies, are so slow to polygonise that recrystallisation alone occurs and dissipates the stress. The sub-grain boundary energy is equal to the stress remnant in the metal after polygonisation (Beck, 1951). Some workers consider that sub-grain growth is dependent both on the sub-boundary energy and the laws of surface tension (i.e. similar to grain growth) (Smith, 1951). However Beck (1951) and Voll (1960) regard sub-boundary energy alone as being the motivating force for growth, sub-boundaries moving away from the centre of the sub-grain whether they are convex or concave.

There is some doubt amongst metallurgists as to whether an oriented fabric is induced during primary recrystallisation or during subsequent growth. Beck (1953) considered two possibilities. Firstly, that nuclei (sub-grains) were created in random orientations and that certain nuclei grew preferentially over their neighbours due to high grain boundary mobility, i.e. oriented grain growth from unoriented nuclei. Secondly, that oriented nuclei existed and gave rise to oriented grain growth. Beck states that oriented growth from unoriented nuclei had been criticised on the grounds that preferential growth along the direction of easiest grain boundary migration (i.e. development of grains with high boundary energies) would give a spread in crystal directions of $30^\circ$, however, if volume growth is considered, i.e. grain boundary mobility cubed, the angle of spread will be greatly reduced. Beck also suggested that
grains lying nearest the axis of the cone of possible growth directions will grow quicker and would, therefore, tend to cut across the smaller neighbouring grains growing oblique to the axis of the cone, i.e. an apparent preferential development of the large grains. Burgers and Tiedema (1953) in a reply to Beck, do not accept his conclusions. They disbelieve that the concept of volume growth will make any substantial difference to the spread of possible growth directions. Burgers and Tiedema regard the growth of the sub-grains as being controlled by two factors. Firstly, sub-grains with high lattice orientations to their neighbours will have high boundary energy and will tend to grow. Secondly, boundaries will preferentially move to their centre of curvature; this will tend to favour large grains since they are more likely to have concave than convex boundaries. Since this latter controlling factor is dependent on surface tension and is independent of lattice orientations it may work in favour of or against the former. Thus, Burgers and Tiedema regard sub-grains large relative to their neighbours and with high angle boundary misfits as privileged for growth. If these sub-grains are present in sufficient number the orientation of the resultant fabric will be fixed by the orientation of these sub-grains. The orientation and frequency of these sub-grains being determined by the direction and amount of stress. That is, for low amounts of cold working most of the fabric will approximate to the orientation of the parent and only occasional sub-grains will exist with high misfit angles (those privileged for growth) and will not in subsequent growth greatly alter the parent orientation (Flinn, 1965, p.63). In greater degrees of cold work many sub-grains will exist at high angles of misfit, sufficient during subsequent growth to impose their orientation on the fabric. Dunn (1953) also believes that oriented nuclei are essential to produce a preferred orientation in the final fabric. Harris and Rast (1960) consider that the sub-grains
or nuclei most privileged for growth are sited in the glide planes produced by polygonisation and that their direction of growth is related to the orientation of these glide planes (presumably sub-grains near the glide planes would be more liable to have high angle misfit to the parent fabric and will thus grow more readily than those some distance from the glide planes). Voll (1960, p.518) states, "that recrystallising grains, which replace parent grains, having a c-maximum, spare both this maximum and possible twin positions. Broad small circle and great circle girdles could develop in the annealed fabric. In metals it has been found that not all the possible positions for grains recrystallising in this way are occupied. Only a few are selected and form the new preferred orientation (Beck, 1951). This is ascribed to the symmetry of strain and its interference with the crystallographic symmetry which determines the possible position of recrystallising grains." Also (op.cit, p.520), "... it seems likely that stress during recrystallisation forces the new grains to fit into the strain-symmetry (with its glide planes and glide directions), if necessary under these unfavourable conditions of parallelism with the parent grains". Elkins (1965a, p.61) states that preferred lattice orientations conform to the symmetry of the deformational ellipsoid.

When primary recrystallisation is complete, i.e., the parent fabric has been transposed to a new grain fabric, residual energy at the grain boundaries will initiate grain growth (Fullman, 1951). Interfacial (surface) tensions are operative during grain growth tending to pull them into equilibrium, i.e. with straight sides and equilibrium angles. Kretz (1966) states that the equilibrium shape is not necessarily attained during grain growth and may result from subsequent diffusion, although Herring (1953) suggested that because of this only very small grains could
achieve equilibrium shapes, Kretz (op. cit.) argues that in the relatively long period of metamorphic crystallisation grains of 1 mm or more could achieve equilibrium. He (Kretz) working on Grenville gneisses and marbles found that interfacial tension was effective in quartz (and other crystallographically isotropic and sub-isotropic assemblages), producing equilibrium fabrics with interfacial angles, at triple grain junctions, approximating to 120°. The energy of a grain is higher at the boundary of a grain than in the core due to lattice distortions between neighbouring grains. Dunn (1953) states that this energy promotes grain boundary migration but it is also largely influenced by simple surface tension laws, viz. a polygon of 6, 12 or 18 sides has equilibrium angles of 120°, 150° or 160° respectively; i.e. generally

$$\theta = 180 \left(1 - \frac{2}{n}\right)$$

(where $\theta$ is the interfacial angle and $n$ is the number of sides of the polygon).

If it has fewer than the equilibrium number of sides it will tend to grow smaller, if it has more than the equilibrium number of sides it will tend to grow larger. Also, grains with more sides than their neighbours will tend to have concave sides and will thus grow whereas grains with less sides than their neighbours will tend to be consumed (Voll, 1960). Smith (1951) states that in the filling of an irregular space by polygons a simple relationship exists, viz.

$$P - E + C = 1$$

(where $P$ = number of polygons, $E$ = number of edges, $C$ = number of corners). Thus the sides of a grain will be curved to a greater or lesser degree in order to reconcile surface tension requirements with the topological requirements (i.e. the necessity to fill space). Voll (1960, p.526 and fig. 8a) quotes the triangle of forces to determine the interfacial
angles at a triple junction,

\[
\frac{\gamma_1}{\sin \alpha_1} = \frac{\gamma_2}{\sin \alpha_2} - \frac{\gamma_3}{\sin \alpha_3}
\]

(where \(\gamma_1, \gamma_2, \gamma_3\) are the interfacial (surface) tensions and \(\alpha_1, \alpha_2, \alpha_3\) are the interfacial angles).

The formula becomes more complicated if the grains are of different phases or where the interfacial tension is controlled by the relative grain orientations, Voll (1960). Kretz (1966) states that for crystallographically isotropic or sub-isotropic materials the effects of relative grain orientation are negligible (where the angle of misorientation is greater than 15°) and will not effect the grain boundary angles, although they may cause the interfacial angles to vary by a few degrees from the equilibrium value.

Voll (1960) states that grains will first achieve equilibrium angles and that the edges adapt by curvature. This curvature induces growth (Smith, 1951; Voll, 1960). The ultimate aim of grain growth is to achieve straight sides but growth may cease as the boundary curvature approaches a straight line (due to various locking mechanisms, Voll, 1960).

Secondary recrystallisation leads to the selective growth of large crystals due often to elevation of temperature (Harris and Rast, 1960). The growth of grains, with relatively low strain energy, at the expense of their more highly strained neighbours, sometimes called ‘strain induced boundary migration’ may be considered as a form of recrystallisation without the nucleation of new grains (Pullman, 1951; Smith, 1951). Strain induced boundary migration has been described by Beck and Sperry (1950), Burgers and Tiedma (1953) and Voll (1960). A boundary will tend to move towards the side of highest strain, but since strain is inhomogeneous along the boundary the outline becomes ragged (Voll, 1960, fig. 6). Voll
believes the ragged boundary may also be influenced by some crystallographic control. Fullman (1951) states that ragged boundaries may in part at least be due to the absorption by large grains of small grains at their margins. Voll (1960) regarded syn-tectonic strain induced boundary migration as the most common in quartz fabrics. Beck (1951) states that generally when a boundary moves under the influence of strain the new crystal has the same orientation as the parent.

The processes of annealing may now be summarised. When a piece of metal is cold-worked, polygonisation occurs initially to relieve strain, with the appearance of glide and slip planes. Residual stress is then dissipated by primary recrystallisation with the appearance of dislocation free sub-grains; sub-grains with high misfit angles to the original grains are privileged for growth. If the amount of stress was high enough, sufficient sub-grains with high misfits will develop to impose their orientation on the fabric. The orientation is conditioned by the symmetry of the applied stress field. Remnant stress of the grain boundaries will then facilitate grain growth, resulting in a general coarsening of the fabric. If the original cold working was too weak to induce sub-grain formation, strain induced boundary migration may occur.

Flinn (1965b) states that the c-axis of quartz "must tend to be aligned to the greatest compressive stress". He (Flinn, 1956) quotes examples of the deformed quartzitic pebbles in the Funzie Conglomerate of Fetlar in Shetland, where the c-axes of the component quartz grains form girdles and partial girdles, the axes of which lie parallel to the direction of elongation of the pebbles. Similar results are reported by Strand (1944) on the deformed Bygdin conglomerates in Norway. Flinn, however, is unable to describe how these girdles could form relative to
the stress field. Whitten (1966, p. 291) describes the Errigal Quartzite of N.W. Ireland, which has suffered deformation and recrystallisation, the component grains show a strong dimensional lineation parallel to the regional fold axis; a petrofabric analysis of the quartz (op. cit., fig. 244) shows a girdle whose axis lies parallel to the fold axis. Flinn (1965a, pp. 65-67) discusses the relation of crystallographic directions in thermodynamically stable preferred orientations to the stress field. He states (op. cit., p. 66) that the general conclusion of metallurgists is that the preferred orientation for a given mineral is with the direction of maximum compressibility parallel to the direction of maximum compressive stress. Doubt, however, exists as to whether the direction of maximum compressibility is the direction of maximum compliance or the direction of maximum linear compressibility. Flinn argues that for maximum stability in quartz the directions of maximum compliance must be approximately parallel to the direction of maximum compressive stress, i.e. the c-axis of quartz grains will be normal to the maximum compressive stress. Flinn then argues (op. cit., p. 67) that in quartz the directions of maximum compliance are at an angle of over 45° to the c-axis, which is, therefore, the direction of minimum linear compressibility. Therefore, when \( K' = \infty \) the quartz c-axes will be parallel to the long axis of the deformational ellipsoid and for \( K' = 0 \), the c-axes will form a girdle whose axis will be parallel to the shortest axis of the deformational ellipsoid. In the quartz pebbles at Collieston the long axis of the deformational ellipsoid may be parallel to the long axis of the rods, or it may be, as suggested by Ramsay (1967, p. 220) at some considerable angle to the long axis of the rods. The value of \( K' \) calculated for the pebbles from which the petrofabric diagrams were constructed (fig. 10) was 0.5. If the long axis of the deformational ellipsoid was parallel to the long axis of the rods, and thus parallel to \( b \), the short axis of the discs
being likewise parallel to \( c \). Then Flinn's theory, as outlined above, would predict a partial girdle in \( ab \) and a maximum parallel to \( b \). This agrees with the results shown on the petrofabric diagrams. If the long axis of the deformational ellipsoid was at a high angle to the long axis of the rods then the theoretical evidence would be irreconcilable with the petrofabric data. It is therefore fairly safe to assume that the long axis of the deformational ellipsoid was parallel to the long axis of the rods.

Harris and Rast (1960) point out that the essential difference between the cold-working of metals and the deformation of a quartz fabric is that when the pressure used in cold-working is released the only stress remaining is that within the crystals whereas in regionally metamorphosed and deformed rocks the pressure is unlikely to dissipate quickly and a directive stress is probably present during recrystallisation and grain growth. Such a directive stress might be expected to induce the grain shape (like the pebble shape) into parallelism with the strain ellipsoid. Flinn (1956) however found in the Funzie Conglomerate that the grain shapes were more nearly equidimensional than the conglomerate pebbles which he attributes to an original deviation of the pebbles from a spherical shape. Where the grains do show slight elongation it is in the same direction as the pebbles, i.e. the longest axis of the quartz grains are aligned parallel to the longest axis of the deformational ellipsoid (Fairbairn, 1950).

The relationship of deformed pebbles to fold geometry has been widely discussed in geological literature (summaries in Whitten, 1966, pp. 268-293; Ramsay, 1967, pp.187-221). Pebbles have been described flattened in the axial plane and with a preferred direction of elongation parallel or normal to the fold axis. Whitten (op.cit., fig.220 and fig. 221) shows pebbles elongated parallel to \( b \). He states (op.cit., p.270),
"Characteristically, the longest axes of such pebbles define a strong lineation parallel to the B-geometric fold axis." Agron (1963) describes pebbles elongated parallel to b, due to compression normal to b, the pebbles have been boudined ("pebbles terminate in beards of cataclasticised material") due to this compression. Anderson (1948) deduced from symmetry concepts that the direction of elongation of deformed pebbles would be parallel to the direction of shearing. Cloos (1947) found in deformed oolites from South Maryland that the direction of elongation was normal to the b axes within the ab plane. Flinn (1956) found that the preferred direction of elongation of pebbles in the Junzie Conglomerate was unrelated to the local fold geometry, and attributed the deformation to an orthorhombic stress field, i.e. compression in the plane normal to the direction of elongation of the pebbles (Einengung of Sander, 1948, p.70). Flinn regarded plastic flow of the matrix as being partly responsible for the preferred orientation of the elongated pebbles. Kvale (1953) states that in the deformed conglomerate of Bygdin, Norway, the pebbles are elongated in the direction of transport but he also mentions the presence of small folds whose axis parallel the direction of elongation. At Collieston the deformation, elongation and lineation of the pebbles parallel to b is most easily attributable to the flexural phase of folding. However it is possible extension may have occurred during the flattening phase, the pebbles being 'rolled out' between the s-planes. Cloos (1947) attributes extension parallel to b as caused by arcuation of the regional fold hinge line. That such arcuation took place at Collieston is suggested by the curvilinear trace of L1; it is possible therefore that arcuation on a local or regional scale may be the causal mechanism; at least in part, of the b lineated pebbles. Ideally, this could be proved, by a detailed study of 'K'
FIGURE 9.

Drawings of deformed pebbles from Aver Hill, made from sections under plane polarised light. In 'b' and 'c' the pebbles are flattened parallel to $S_1$ (shown by orientation of micas); in 'a' $S_1$ is oblique. The regional fold axis is normal to the plane of the drawings. The stippled grains are quartz and the clear grains (f) are K-feldspar. The bar represents 1 mm, in all cases.
FIGURE 9a.

(a), (b), (c): The quartzose pebbles shown in fig. 9, with the sutured boundaries (due to late stage deformation) removed to illustrate equilibrium fabric. The dotted angles approximate to the equilibrium value of 120°. Scale as in fig. 9.

(d): Histogram showing distribution of 100 interfacial angles of grains in the quartz pebbles.
FIGURE 10.

Petrofabric diagrams of quartz c-axes in deformed pebbles from Aver Hill. Axes refer to the geometrical fold axes as defined on p. 11.

(a) 350 points. Contours at 7%, 6%, 5%, 4%, 2% per 1% area.

(b) 300 points. Contours at 8%, 5%, 3%, 2%, 1% per 1% area.

(c) 300 points. Contours at 7%, 5%, 4%, 3%, 1% per 1% area.
values along the section using the methods proposed by Flinn (1962),
this however is impractical since bands with sizeable pebbles are scarce
throughout the section, and the smaller grit particles although indicating
the general sense of deformation were almost certainly inequivalent in their
undeformed state thus precluding analyses.

A third possible cause of elongated pebbles parallel to the fold
hinges is described by Ramsay (1967, p.220), where the special coincidence
of original fabric and a strain ellipsoid, the longest axis of which is
normal to the fold, deforms pebbles such that their longest axis parallels
the fold hinge. The petrofabric evidence, however, discussed above
suggests that the long axis of the strain ellipsoid was parallel to the
fold hinge, and that this third possibility is not applicable.

From the above evidence the probable history of the pebbles may be
deduced. Firstly, deformation rotation and elongation of the pebbles
parallel to \( b \), recrystallisation of the component grains and the imposition
of a preferred optical orientation parallel to \( b \); possibly a faint
dimensional elongation of the grains parallel to \( b \). Secondly, a probable
rise in temperature causing secondary recrystallisation and grain growth
in static conditions destroying any dimensional orientations of the grains
and forming an equilibrium assemblage (see fig. 9a and explanation) as
evidenced by interfacial angles. Thirdly, weak deformation, causing
strain induced boundary migration; evidenced by the formation of sutured
boundaries, without destruction of the optical orientation. The presence
of patches of granulated quartzes at the margins of the pebbles, the
resemblance of the pebble in fig. 9b to a 'necked' boudin and the
veener of mica all suggest some late stage brittle deformation of movement
at temperatures too low to allow annealing. It is probable the strain
induced boundary migration is linked to this period of deformation; the
grains in the centre of the pebble being strained whilst those at the margins were broken. The large size of the pebble grains relative to those of the matrix is probably due to two factors. Firstly, during recrystallisation and growth, of the pebble grains, the matrix quartzes would be unable to coalesce due to intervening micas and thus growth would be greatly inhibited. Secondly, isolated large grains in the matrix would be more likely to break down during the later movements than the internal grains of the pebbles since deformation apparently only penetrated the margins.

The significance of the pebble history to the regional structural history will be discussed later (p. 39).

Second Generation Movements (B₂)

Between the first and second movements the metamorphism of the area reached a climax (2.5) marked by the growth of andalusite and cordierite porphyroblasts. Since B₂ fold movements have disrupted the metamorphic fabric the B₂ structures are readily distinguished in thin section from B₁ structures.

In style B₂ folds are similar to those of B₁ except that they are of much smaller amplitude and are seldom more than two metres across. Generally they are less flattened than the B₁ folds tending more towards a concentric style. When developed on the limbs of the major B₁ folds they often resemble in style and trend the parasitic B₁ folds. In these circumstances B₁ and B₂ can only be satisfactorily distinguished by showing that B₂ folds S₀, S₁ and the metamorphic fabric.

Measurements of flattening in B₂ folds reached maximum values of 35% to 40%. Most however were 10% to 20% less and thus considerably less than the flattening calculated for the B₁ folds. Like the B₁ parasitic folds many B₂ folds are disharmonic and show crumpling in the
nose region. The axial plane orientation, although variable, is generally
sub-horizontal dipping at about 10° to the east (fig. 6b). Curvature of
the axial plane due to 'drooping' in the nose is much less common than
in the B_1 folds. Like B_1 they are Z-folds with a sense of vergence to
the east.

The axial plane cleavage (S_2) is less extensively developed than
S_1, being confined largely to the incompetent pelitic bands. An incipient
cleavage is occasionally developed in the competent bands. A 'strain-slip'
relation of S_1 and S_2 can be clearly seen at low tide on Perthudden shore
south of Collieston harbour. An interesting example of refracted cleavage
occurs near Pottie Murlan (fig. 12d). A B_1 fold, defined by a quartzose
band in pelite, has been sheared along an S_2 plane. The cleavage in the
pelite is parallel to S_2; in the quartzose band it is oblique to S_2. This
may be due to the failure of S_2 to develop in the band, the cleavage there
being original S_1. S_1 in the pelite having been transposed to S_2.

During the B_2 movements S_1 planes were reactivated and slip occurred
along them resulting in the disruption of the metamorphic fabric. Thus
the planes become, by the definition proposed on p.15, S_2 planes. In
one or two localities the S_1 planes have been deformed into asymmetrical
'drag folds'. According to Ranberg (1959) and Ghosh (1966), who carried
out tests on the experimental deformation of putty and plasticine models,
simple shear parallel to S_1 could not form these 'drag folds'. Before
folds of this nature could be produced S_1 would have to be oblique to the
shearing couple. This is a realistic proposition since the strain
ellipse of the B_2 deformational movements was oblique to that of the B_1
deformational movements as shown by the angle between the B_1 and B_2 axial
planes. Ghosh showed (op. cit., p.173) that initially the axial planes of
the 'drag folds' would be oblique to the long axis of the strain ellipse,
especially since the angle between the direction of shear and the S_1 planes
FIGURE 11.

B2 Minor Structures.

(a) Folded grit band (stippled) and S1. S2 is only developed in the pelite. Hackley Bay.

(b) Folded S1 with incipient S2 developed. Shayne.

(c) Folded grit band (stippled) and S1. S2 is only developed in the pelite. Devil's Study.

(d) As (b). Smithy.

(e) B1 fold shown by grit band (stippled) with S1 and S2. Shayne.

(f) L2 crinkle folding L1 (S/S1 intersection).

Whinnyfold.

Bar in (a) and (c) represents 3 feet; in (b) and (d), 6 inches; in (e) and (f), 1 inch.

In (a) and (c) - 91 cm; in (b) and (d) - 15.3 cm; in (e) and (f) - 2.54 cm.
Examples of $B_2$ movements.

(a) Grit band (stippled) defined a $B_1$ fold disrupted by slip on $S_2$ planes, near Collieston. Bar represents 2 feet. (61 cm.)

(b) Quartz vein, the lower half disrupted by slip on $S_2$ planes. Cock Craig. Bar represents 10 feet. (3 m)

(c) $B_1$ fold defined by grit band stippled disrupted by slip on an $S_2$ plane (in this case a reactivated $S_1$ plane), near Green Craig. Bar represents 40 feet. (12.2 m)

(d) Similar to above. 'Refraction' of $S_1$ cleavage; see text for possible explanations. Pottie Murlan. Bar represents 60 feet. (18.3 m)

(e) $S_1$ cleavage partly transposed to $S_2$ on a 'strain-slip' pattern. Perthudden. Bar represents 1 inch. (2.5 cm)

(f) Preferential development of $S_2$. In pelitic bands $S_1$ has been completely transposed to $S_2$, in grit bands (stippled) relic $S_1$ planes can be seen. Bar represents 1 inch. (2.5 cm)
FIGURE 13.

Stereo-plots of $L_2$.
(a) Boudin axis, mainly pegmatites.
(b) Plots of $L_2$.
(c) Plot of $L_2$ micro-crinkles.
FIGURE 14.

Linear Trends ($L_2$) of metamorphic porphyroblasts.

(a) Stereo-plot of main directions.
(b), (c), (d) - Examples of Rose diagrams used to deduce porphyroblast alignment.

(b) Slains Castle,
(c) Whinnyfold,
(d) Perthudden.
is small (circa 15°), as deformation proceeded they would however tend towards parallelism. Reactivation of the $S_1$ planes is shown clearly in a locality south of Cock Craig. At the top of a vertical section a quartz vein can clearly be seen cutting $S_1$; thin section examination shows no sign of strain or distortion of the quartz grains, but when traced down it becomes disrupted and broken by movement on $S_1$ planes (fig. 12b). At a locality just north of Collieston harbour on Hill of Cransdale a $B_1$ fold has been disrupted by movement along $S_1$ planes (fig. 12a).

$L_2$ is not as extensively developed as $L_1$. In several areas to the south of Whinnyfold small crenulations defining $L_2$ can be seen to fold $L_1$ (fig. 11f). Also, $S_2/S_0$ intersections distort $S_1/S_0$ intersections. The less intense nature of the second movements is evidenced by the fact that the cordisite and andalusite porphyroblasts have not attained any obvious preferred orientation during $B_2$. This contrasts with the development of strongly orientated pebbles during $B_1$. Where alignment of porphyroblasts can be seen or deduced from rose diagrams (fig. 14) it is parallel to the regional fold axis. This faint lineation parallel to the $B_2$ fold axis and the presence of rotated porphyroblasts on the limbs of many $B_2$ folds (fig. 18a; 24) are indicative of an initial buckling or flexural-slip phase of $B_2$. During the second, flattening or slip-folding phase, inducing $S_2$, slight differential movement occurred on the $S_2$ planes similar to that seen in the corresponding phase of the $B_1$ movements, but nowhere was it particularly intense and the trace of $L_2$ along the section is virtually rectilinear.

**Pegmatites**

Pegmatite veins are found throughout the Collieston section, but are particularly abundant between Hackley Bay and Aver Hill. They
consist of quartz and feldspar with occasional patches of accessory biotite. The veins range from 1 cm to 20 cms in thickness and are usually folded or boudined. The pegmatite fold axes are generally parallel to the regional $B_1$ and $B_2$ fold axes (fig. 7c) but a small number show widely varying directions. The folds vary greatly in style, from almost perfect concentric or pytymatic types to folds of a more similar style. The veins are often broken at fold hinges or sheared out along $S_2$ planes. Intrafolial and rootless intrafolial folds are found. Axial planes are generally parallel to the regional $S_2$ planes (fig. 6c); although occasional examples are found with axial planes strongly oblique to the regional $S_2$. Axial plane cleavage is seldom developed in the competent pegmatites, although thin veins are occasionally disrupted by movement on the $S_2$ planes. Boudinage is rare but where found is usually parallel to the regional $B_2$ fold axis. In two areas to the north of Collieston pegmatite boudins with the long axis parallel to the $a$ axis of the second generation movements were found. Boudinage presumably formed during the flattening phase of $B_2$. The boudin axes are usually parallel to $L_2$ and do not follow the curvilinear trace of $L_1$.

Ramberg (1959, p.126) showed that pegmatite sheets lying oblique to the foliation of the host rock subjected to the same homogeneous strain as the host rock and deforming simultaneously with the host rock will deform into folds whose axes are oblique to the axes of the folds of the host-rock foliation. It is therefore probable that the pegmatite fold axes which now lie at high angles to the regional fold axis were formed in pegmatite sheets which were originally lying oblique to the regional foliation. Contact strain phenomena in such cases produces a distortion of the host rock foliation. In figs. 15b and 15c distortion is shown by the $S_2$ planes (reactivated $S_1$ planes), this distortion is confined to a zone equal to the wavelength of the folds (Ramberg, 1959, p.127).
fig. 15(d, S1 cleavage has been preserved between two folded pegmatite sheets whilst the rest of the rock shows well developed S2 cleavage axial planar to the pegmatite folds. Mukhopadhyay (1965) suggested from field and experimental evidence that in modified flexure folds axial plane cleavage, defined by the parallelism of biotite flakes forms preferentially in incompetent bands on the concave side of competent bands and that biotite flakes would tend to lie parallel to the bedding surfaces on the convex side (op.cit., fig. 1, p.416). He reasoned that compression on the concave side would align the long axes of deformational ellipses parallel to the axial plane of the fold, but strain on the convex side would align them parallel to the bedding surfaces. He assumed that biotite flakes would crystallise parallel to the long axes of the ellipses. This seems to be in direct contradiction with the pattern of schistosity shown in fig. 15(d). However, if two competent bands with an interbedded incompetent layer are subjected to pure concentric or weakly modified concentric folding, T (the thickness of the incompetent unit measured everywhere normal to the bedding surfaces) will remain constant, there can, therefore, be no compression in the axial zone and consequent development of an axial plane cleavage. Consequent flattening and modification of the concentric folds will however deform the incompetent band such that T will become maximal in the axial zone, with consequent elongation of the strain ellipse parallel to the axial plane and the transposition of the bedding foliation to an axial plane cleavage. In fig. 15(d), it appears this latter stage was never achieved the rigid pegmatites protected the interbanded material from the strong flattening which produced the external S2 planes; flattening in the interbanded layer being insufficient to recrystallise the micas. The whole could be regarded as a rigid passive block within the kinematically active S2 planes.
FIGURE 15.

Fold styles in pegmatites.

(a) $B_2$ fold with $S_2$ schistosity. Bennet's Love.

(b) and (c) $B_2$ folds with distorted $S_2$ cleavage

(cf. Ramberg, 1959, fig. 13, p. 127). In (b)
the pegmatite has broken at the hinges, Bennet's Love.

(d) Two veins folded with $S_1$ by $B_2$, $S_2$ developed.

Shevrock.

(e) Small pegmatite vein broken and distorted by $S_2$ cleavage. Rockend.

(f) Examples of pegmatite veins broken by $S_2$ cleavage.

Collieston.

In (a), (b), (c), (d) and (e) the bar represents
6 inches; in (f) 1 inch.

In (a), (b), (c), (d) and (e) $- 15.3$ cm;
in (f) $- 2.54$ cm.
The following facts are pertinent in determining the age of intrusion of the pegmatites.

1. The fold crests are often thickened relative to the limbs
2. The veins are sheared by $S_2$ planes
3. Rootless intrafolial folds are found
4. The veins are not sheared by $S_1$ planes
5. The axial plane of the folded pegmatites are generally parallel to $S_2$

Following the arguments of Dalziel and Johnson (1963) it appears from (1) that the veins predate the flattening phase of $B_2$ and the formation of $S_2$. This is supported by (2) and (3). From (4) and (5) it is almost certain that the veins post date the flattening phase of $B_1$ and the formation of $S_1$. The most likely age for the pegmatite intrusion is therefore between $B_1$ and $B_2$ although they may be synchronous with the early buckling stage of $B_2$.

**Structure of Igneous Rocks**

Metadolerites are found at several localities throughout the section. The best examples can be seen on the cliff face to the south of Hall's Hole. The metadolerite, originally a sill, has been folded by a major $B_1$ fold and cut by $S_1$. Most of the original minerals have been destroyed and a schistose texture induced.

Quartz dolerite dykes are found at Shevrock in Peterhead Bay and at several localities along the coast. They are later than the orogenic structures and cut across them in a random orientation.

In the north of the section the Collieston Beds are in contact with the Peterhead granite. The junction is relatively sharp. Xenoliths of country rock appear in the granite and are not substantially disorientated or altered. Although in the immediate vicinity of the
granite the country rocks have been disrupted by granite veining there is no large scale distortion of structural elements, the strike and $B_1$ and $B_2$ structural elements having constant direction.

2.4 Structural Interpretation

Read and Farquhar (1956) postulated that the Collieinston folds were due to gravity slumping of sediments on the limb of the uprising Buchan Anticline. Their evidence rests mainly on the eastward sense of movement of all the folds they investigated at Collieinston allied to the slope of the basement, which they regarded as the Ellon Gneiss.

The present author believes this theory is supported by strong circumstantial evidence from the structural analysis.

The style of the major folds, with thickened noses, attenuated limbs, dropping axial planes and a generally chaotic structure (fig. 2) is consistent with gravity slumping (De Sitter, 1956, p. 289). The presence of incongruous dependent parasitic folds on the limbs of the major $B_1$ folds is difficult to reconcile with any form of lateral compression; a much more reasonable explanation being one of slumping in a direction normal to the regional fold axis. The increase in amplitude of the major $B_1$ folds without increase in the degree of deformation as the pile is structurally ascended seems to strongly favour some form of gravity collapse.

Such a mode of formation could account for the initial flexure folding phase of $B_1$. As the sediments piled up flexure folds in the lower beds would be tightened and flattened and an $S_1$ cleavage imprinted. As mentioned on p. 17 many of the large folds approach similar geometry (fig. 4b). According to Ramsay (1962) such folds could never have undergone flexural deformation because beds in a flexural fold, even when
modified by flattening are always thicker on the limbs than in the crest (measured parallel to the axial plane). However, this is only true if the flexure fold is modified by homogeneous flattening. If flattening is stronger at the crest than on the limbs similar geometry could be imprinted. If the concept of gravity collapse as the causal mechanism of the $B_1$ folds at Collieston is correct, the stress fields operative would be complex (De Sitter, 1956, pp.289-290), in which case inhomogeneous flattening would be a practical possibility. Also, in a plastically slumping pile of sediments folding would be partly analogous to flow folding (Wynne-Edwards, 1963) and the folds capable of developing a variety of geometries. It is during the $B_1$ movements that the deformation, recrystallisation and elongation of the quartzo-feldspathic pebbles occurred. The cake like pebbles may have formed in the crest of local arcs during arcuation of the regional hinge line (p.29) or due to differential flattening.

Evidence indicates that at the beginning of the $B_2$ movements renewed slip took place along the $S_1$ planes, causing disruption of the $B_1$ folds. The $B_2$ folds show the same history of buckling, modification by flattening and imprinting of axial plane cleavage as do the $B_1$ folds. The $S_2$ planes are nearer horizontal than the $S_1$ planes. To the present author this is also consistent with a possible regeneration of gravity flow. From regional considerations (q.v.) it is reasonable to assume that the slope of the limbs of the Buchan Anticline increased before or during the $B_2$ movements. Thus a picture emerges of the eastern limb of the Buchan Anticline gradually steepening; the $B_1$ folds beginning to slide and shear out along the $S_1$ planes, and as movement increases $B_1$ folds refolding and tightening; $S_1$ becoming deformed into asymmetric 'drag-folds', until the sedimentary pile finds a new 'angle of repose'
on the steeper slope of the Buchan Anticline. Flattening occurs and the imprinting of $S_2$. It was during the $B_2$ movements that the pebbles (having undergone secondary recrystallisation during the metamorphism between $B_1$ and $B_2$) suffered the late stage deformational effects. Flattening and movement of the $S_1$ and $S_2$ planes boudinising the pebbles and veneering them with mica.

The concept of gravity collapse is also consistent with the regional pattern as will be discussed in Chapter 4.

2.5 Metamorphism

Mineralogy

The metamorphic grade at Collieston increased from north to south, that is as the structural pile is descended. In the north the metamorphic porphyroblasts are small 'knots' which are mineral aggregates identical in mineralogy to the surrounding groundmass, but considerably finer in grain size. The rocks are composed of pale green to clear micas, quartz and an abundance of fine ores. Bands of high ore concentration tend to alternate with clear quartz bands defining bedding, these layers vary from 0.07 mm in the 'knots' to 1.00 mm in the coarser grained rocks. This type of mineralogy persists southwards to Slains Castle although, as one traverses this part of the section, the grains of the matrix become gradually coarser, ranging up to 2 or 3 mm, the material in the 'knots' remain very fine. At Portie shore, south of Slains, green micas appear through southwards to Collieston - where they form up to 15% of the mode - they change through greenish brown to deep red brown and brownish black which colour they remain for the rest of the section. It is worth considering at this stage the significance of colour changes in biotites. Most workers (Tilley, 1925; Ambrose, 1936; Engel and Engel, 1960) agree that biotites change colour from
green through greenish brown to brown or reddish brown with increasing metamorphic grade. There appears, however, to be some doubt as to the chemical changes causing the colour changes. Phillips (1930) regarded it simply as an increase in the ratio of ferric to ferrous iron — although the total iron content fell — with increasing grade. Several workers (Barth, 1936; Engel and Engel, 1960; Lambert, 1959) found a similar decrease of the iron content and a corresponding increase in the content of magnesia and titania with increasing grade. Miyashiro (1956) and De Vore (1955) however, found that the iron content increased with grade. Snelling (1957) states that where garnet coexists with biotite it will preferentially absorb iron, and that coexisting cordierite will preferentially absorb magnesia. Engel and Engel (1960) also state that on the appearance of almanditic garnet during metamorphism iron will invariably decrease in the biotites. Deer, Howie and Zussman (1962, Vol. 3, p. 75) suggest, therefore, that decreases or increases of magnesia and iron in biotites during metamorphism are due to the effects of coexisting minerals and are not directly responsible for colour changes. In a study of 56 biotite compositions Hall (1941) arrived at three important conclusions. Firstly, that iron, whether in the ferrous or ferric state, is responsible for the green or greenish blue colour in biotites, titania for the browns and reds and that magnesia tends to dilute or mask the effects of titania. Secondly, that in brown and red brown biotites the percentage of iron and titania is generally, but not invariably high, and that the percentage of magnesia is low. Thirdly, that the colour effect of titania is dominant over that of iron. Thus in a green biotite the colour is due solely to the iron content the colour effect of the titania (if present) being masked by magnesia. If the percentage of titania is increased it will cease to be masked by the
magnesia and the biotite will become brown or reddish brown; a similar
change will obviously take place if magnesia is subtracted from the
biotite (assuming the presence of titania). In the Collieston coast
section there is a marked correlation between the appearance of biotite
and a fall in the modal percentage of iron ore (fig. 16). It, therefore,
seems probable that as the biotites develop during metamorphism they
absorb iron and titania from the ores (e.g., ilmenite). This absorption
of titania could alone account for the change of the biotites, during
development, from green to brown, but it is possible that the developing
cordierites would absorb magnesia from the biotites (Snelling, 1957)
effectively increasing the titania percentage. In the gradational
change of biotites from green to brown along the section local variations
occur. South of Brunt Leugh, almost 1 km north of the first extensive
development of brown biotite, a rock was found with pale brown biotites,
this is presumably due to some variation in the original composition,
either a higher than average titania content or a lower than average
magnesia content. Green biotites in rocks south of Bennet’s Love or
elsewhere within the zone of brown biotites are due to secondary
alteration.

Southwards, the knots become progressively free from inclusions.
At Pottie Murlan many of the knots are recognisable as cordierite despite
the abundant inclusions and at Collieston they are easily recognisable as
cordierite with well developed sector twinning and still retaining trails
of included ore. Southwards from Bennet’s Love the inclusions in the
cordierite cease to have any obvious orientation and the quartz, biotite
and ore grains are spasmodic and not organised into foliae.

Although the growth of cordierites from the ’knots’ may be
clearly demonstrated southwards along the section, the relation of
’knots’ and andalusite crystals is obscure. Crystals of andalusite
Approximate modes of the main metamorphic minerals along the Collieaston Section.
can be recognised in rocks just north of Collieston but from there to Bennet's Love occurrences of andalusite are rare, south of Bennet's Love andalusite becomes fairly abundant constituting up to 20% of the mode. The andalusite crystals often contain fine trails of quartz similar to those found in cordierite crystals.

In the extreme south, that is in the Ellon Gneiss, fibrolite appears apparently replacing biotite, the fibrolite appears at the expense of andalusite which gradually disappears as fibrolite increases in quantity although the two polymorphs are not observed in contact with one another.

In the extreme north clear prismatic andalusite occurs within the Peterhead granite aureole but is a late stage thermal effect unconnected with the main metamorphism of the section.

Texture

Porphyroblasts in rocks collected between Aver Hill and Hackley Bay contain continuous trails of biotite defining a bedding schistosity, the bedding is defined by bands rich in ore. The biotite grains are the same size at the centre and the margin of the porphyroblast. In the northern part of the section the metamorphic grade was too low for the formation of biotite and the schistosity in the matrix is defined by white or green micas and flattened quartzes. The fabric of the 'knots', in the north, is very fine — many grains being less than 0.05 mm — and therefore difficult to examine. However, the micas appear to be lying parallel to the bedding and it is probable that the 'knots' are overgrowing a schistosity. No where are the included trails found to be folded or curved. The knots appear to have grown in a static phase post dating the formation of the earliest schistosity (S₁). Rarely, knots which have grown in the nose of folds show included bedding trails
oblique to the schistosity (fig. 17a). In figure 17c the trails of ore defining the bedding have been partially transposed to the orientation of the schistosity. In figure 17d, small folds in the bedding are cut by micas which define the schistosity. Several knots (figure 17b) contain small tight, almost isoclinal folds with the axial planes parallel or sub-parallel to the bedding and schistosity planes; these may represent tectonic folds but cannot be distinguished from original penecontemporaneous sedimentary structures.

The included trails of many crystals are oblique to the schistosity planes of the external fabric (fig. 18b). Clear evidence for opposite senses of rotation on opposite limbs of a B2 fold are shown in figure 18a. This dates the growth of the porphyroblasts as pre-B2 buckling. They must therefore have grown in a static phase between B1 and B2 movements; the included schistosity is S1. It can be clearly demonstrated in several thin sections showing porphyroblasts that the included S1 fabric is not parallel in different crystals, proving that the 'knots' were rotated between schistosity planes rather than the schistosity planes rotating around passive crystals as suggested by Ramsay (1962). During the B2 flattening movement on the S2 planes (in some cases this is merely reactivated S1 planes) caused recrystallisation of the porphyroblast margins evidenced by a shell around the 'knot' with an included fabric coarser than the included fabric of the core (fig. 19a). The S2 planes defined by folts of white mica curve around the knots and the included coarse fabric of the porphyroblasts often shows trails curved parallel to the crystal margins. Rarely, crystals have developed 'ears' (fig. 19b). The 'ears' extend on opposite sides of a crystal, suggesting that crystallisation or growth was taking place during differential movement, indicated by arrows in the diagrams, of the enveloping S2 planes. Examples of boudined crystals can be seen in a locality to the south of
Micro-Textures 1.

Diagrams illustrating relationship of $S_0$, $S_1$, and $S_2$.

(a) Knot contains $S_0$ and $S_1$. $S_0$ is defined by bands of ore and $S_1$ by mica flakes. In the external fabric $S_2$ is defined by micas along with magnetite and quartz, Slains Castle.

(b) Small tight folds of $S_0$ in knot. $S_0$ is defined by ore bands, $S_1$ by micas which lie parallel or sub-parallel to $S_0$ and the axial planes of the folds. Concentrations of magnetite crystals in the external fabric define relic bedding lying parallel to $S_2$ defined by large mica flakes and flattened quartzes. Old Slains.

(c) $S_1$, cleavage in knot, defined by micas, has disrupted $S_0$ into a 'strain-slip' pattern. As in (b) ore bands define relic bedding in the external fabric and mica flakes $S_2$. Green Craig.

(d) Wavy trails of ore defining $S_0$ cut by $S_1$ micas within knot. The external fabric consists of ore crystals, flattened quartzes and large felts of mica defining $S_2$. Green Craig.

(e) Two knots with $S_0$ and $S_1$ parallel in the internal fabric but lying at right angles to each other. $S_2$ defined by micas and quartz grains, Brunt Heugh.

In all cases the external fabric is coarser than the internal fabric.
Micro-Textures 3.

(a) Evidence of two growth stages in knot. Core contains fine flakes of biotite ($S_1$) at an angle to the trails of coarse biotite in the margins of the knot. These internal trails of coarse biotite ($S_{21}$) are identical to the external fabric where the biotites define $S_2$ ($S_{2e}$). Thus some growth of the knot must have occurred during or after $B_2$. Bennet's Loe.

(b) Similar to (a) but secondary growth area has produced "ears" suggesting that crystallisation took place under differential movement indicated by the arrows. Slains Castle.

(c) Boudinage of knots. Internal trails of $S_2$ (mainly small biotites) converge towards the knot ends. External $S_2$ fabric contains coarser biotites and quartzes. Collieston.

(d) Small folds in bedding ($S_0$) defined by ore trails. Folds have a pronounced axial plane cleavage ($S_2$). Inset knot with included trails of $S$ and $S_1$ showing area of secondary growth. $S_2$ is defined by biotite flakes. $S_1$ has been destroyed in external fabric. Slains Castle.
Collieston (fig. 19c): the internal fabric of the crystal 'pinches out' suggesting that plastic deformation, 'necking', took place before rupture. The long axis of the crystal boudines lie in the schistosity planes. Although it is not possible to be definite as to the causal mechanism it was more probably flattening normal to the schistosity planes than stretching parallel to them during flexure folding since the crystals are not associated with any obvious folds and are almost certainly of too small a scale to be effected by the larger folds. Several cordierite porphyroblasts in the southern half of the section are associated with large crystals of white mica which are either included within the crystal or penetrate it from the groundmass. These micas are much larger than the other grains of the included fabric and bear no relation to any internal trails. They are almost certainly late stage breakdown effects.

Generally the porphyroblasts have a well developed prismatic shape. The long axes usually have a random orientation within the \( S_1 \) and \( S_2 \) planes. South of Collieston harbour the porphyroblasts occur as large disc shaped crystals with their short axis normal to the \( S_1 \) and \( S_2 \) planes. The discs range up to 4 or 5 cms in diameter. Since these crystals are boudined (see above) it is probable that their shape is due to flowage under flattening strain. If recrystallisation had occurred it would almost certainly have completely destroyed the included trails.

**Nucleation and Growth of Porphyroblasts**

The origin of 'knots' in metamorphic rocks and their growth into relatively inclusion free crystals, has been discussed in geological literature (Barker, 1950, pp.50-51). However, no published work is known to the present author on the problems of nucleation of the knot.

The problem may be stated thus - why, in rocks of apparently homogeneous mineralogy are small patches ('the knots') considerably
finer grained than the matrix?

It has been suggested to the author in discussion that the knots represent retrograded rather than embryonic cordierites. This argument appears to be invalid in the Collieston material for two reasons. Firstly, several lines of evidence— the inversion of andalusite to sillimanite in a traverse southwards along the section; the general coarsening of the rock fabric southwards; the change from pale green to dark red biotites southwards,—suggest that the knots are low grade or initial stage minerals. Secondly, the included fabric of the knots is inconsistent with retrogression. The cordierites in the higher grade rocks at Collieston contain a few coarse inclusions of quartz, biotite and occasional magnetite, all lying in random orientation; whereas in the cordierites of the lower grade rocks the inclusions are fine grained and arranged in continuous trails parallel, in unrotated knots, to the bedding directions in the external fabric. Thus, in order to postulate a retrogressive origin for knots it would have to be assumed that the crystals initially exsolved coarse unoriented inclusions which proceeded during retrogression to break up into fine grains and to arrange themselves parallel to the external bedding. This is impossible. Also ruled out is the possibility that the rows or trails are controlled during exsolution by the cordierite structure and lie parallel to the bedding only by coincidence, as proposed for certain preferred orientations of inclusions in garnets (Powell, 1966). This would only be a valid proposition if the cordierite crystallographic directions were everywhere parallel to the bedding, since however, the cordierites nucleated at the earliest during the imprinting of $S_1$ any preferred crystallographic direction would be parallel to $S_1$ (see p. 26) rather than bedding. As already described in the noses of the folds cordierite porphyroblasts show included trails oblique to the included micas defining $S_1$ and
therefore the trails would be oblique to any preferred crystallographic direction. Also, most cordierites show at least a small degree of sector twinning; exsolved inclusions would almost certainly be controlled by this and follow parallel to the twin planes. The density and close proximity of the small included grains to each other prohibits any suggestion that these were original large inclusions which have been reduced in size.

If the hypothesis that the knots are retrograded cordierites is dismissed the acceptance of knots as low grade or embryonic cordierites returns us to the initial problem set out above—how can a patch of groundmass ('the knot') apparently identical mineralogically with the surrounding material resist a coarsening of grain in the host material?

The only reasonable explanation is that the grains are separated from each other by some form of crypto-crystalline cordierite mesh, thus prohibiting their coalescing and a consequent coarsening of grain. The nucleation of such a mesh must be complex. Most workers accept that nucleation of statically growing minerals is due to some form of lattice disarray in the original phase leading to the formation of a more stable lattice and new phase. The lattice disarray may be due to a change of temperature inducing chemical disequilibrium, or to the physically disrupting effects of residual stress from some previous tectonic movement (summary in Rast, 1969, pp. 77-82). The present author feels that the concept of new phases nucleating in pockets of residual stress is rather tenuous; he feels that it is more probable that nucleation or the production of an embryo of the new phase should occur during the actual tectonic deformation although actual crystal growth may not take place until the cessation of movement. Hardy and Heal (1956) working on growth and nucleation in metals recognise a 'transient zone' during growth where the free energy of the nucleus or embryo is greater than that of the
matrix such that there is a tendency for the embryo to dissolve but as atoms are lost so new atoms are absorbed and the embryo exists in dynamic equilibrium with a steady size being maintained. They give no indication of the life span of the 'transient-zone' and whether or not it is likely to be negligible in geological processes, but it is conceivable that nuclei created during the last spasms of movement might persist into the static phase before growing. Therefore it is possible that cordierite nuclei were formed during the latter stages of the B₁ movements or even immediately afterwards as the lattice disarrays caused by the B₁ stress readjusted to equilibrium arrays. The nuclei would also tend to favour areas or bands where magnesium and iron were relatively abundant. If nucleation did occur under stress or in areas of lattice disarrays due to stress it is possible this might control the dimensions of the crystals. It is more probable, however, that the growth of the knot and its dimensions (not its crystallographic or structural orientation) were controlled by areas of appropriate composition and the availability of magnesium and iron ions. The crypto-crystalline mesh is probably some form of skeletal cordierite growth spreading rapidly from the nucleus and enveloping the grains of the surrounding groundmass. Once the mesh has been created it is not difficult to envisage its growth and expansion at the expense of the included material, whilst the external fabric was becoming coarsened. Rapid skeletal or dendritic growth is well known in the formation of chiastolite crosses (summary in Rast, 1965, p.86), it is believed that the rapid dendritic growth occurs in areas of supersaturation and that as this growth lowers the saturation so the crystals grow slowly in the areas between the dendritic branches, growth of this nature would support the hypothesis that the dimensions of the crystal are limited by areas of appropriate composition, the skeletal growth ceasing outwith the areas of supersaturation. Whether or not sector
twinning is inherent in the cordierite crystals from the beginning of grain growth is uncertain, but if not it must develop very quickly since crystals with large numbers of inclusions and thus only partially developed show a patchy extinction equivalent to simple twinning. Most workers (Naidu, 1954; Venkatesh, 1952) agree that simple twinning is indicative of slow growth and that complex twinning of fast growth, a conclusion suggestive that the twinning in the cordierite crystals at Collieston occurred during the relatively slow growth of the area between the skeletal branches rather than during the rapid growth of the dendrites.

In order to test the validity of the concept of a crypto-crystalline mesh within the knots, several knots were powdered and investigated by X-ray diffraction to find if a cordierite lattice structure could be found. The knots were extracted by means of a modified dentist's drill and the method used was similar to that used by Bosma (1964) in an investigation of similar rocks in the Vosges.

At low 2θ values many of the cordierite peaks were masked by peaks of minerals included in the knots (quartz, white mica and iron ore). At high 2θ values the cordierite peaks were not sufficiently sensitive (artificial powders were made up of pure cordierite to test what percentages of cordierite could be determined), also magnetite peaks tended to interfere. Attempts were made to separate off some of the included material, quantities of quartz and white mica were removed, but the percentage of cordierite (if it was present) was still too low to show at high values of 2θ. The difficulty in attempting a mineral separation was largely that it had to be run 'blind', because any cordierite present was not optically recognisable and was, at best, only in very small amounts. This prohibited the use of the magnetic separator. Heavy liquid separation was tried but the specific gravities of cordierite, quartz and white mica are so close that only trial separation at various
densities could be attempted and both the separate and residue tested. It appears the only method of testing the concept of a crypto-crystalline cordierite mesh would be by electron probe work.

As mentioned above the relationship between cordierite crystals and the knots is clearly demonstrable at Collieston. However, it is not known whether any of the knots are embryonic andalusites (the powders tested for cordierite were also tested for andalusite but with negative results). From observations in other areas (Fyvie area, aureole of Insch Younger Gabbro) the author is certain that the andalusite did develop from the knots by a similar process to that of cordierite. The lack of intermediate types, that is andalusite with abundant fine grained inclusions, (the andalusites which are found in the Collieston section have only a small number of inclusions usually quartz in random orientations similar to the high grade cordierites) may be due to lack of areas of suitable composition within the belt where the pressure-temperature conditions during the metamorphism would have produced the intermediate types.

The development of sillimanite will be discussed on a regional basis in Chapter 4.
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Pegmatites folded
Intrafolial folds produced
Some crystals broken by movement on S\textsubscript{2} planes; others deform plastically
2.6 Introduction

The Rosehearty - Fraserburgh coast section on the northern coast of Aberdeenshire runs at approximately right angles to the regional strike through rocks forming the western limb of the Buchan Anticline. The rocks, comprising Read and Farquhar's (1956) Kinnaird's Head Group and Rosehearty Beds, are probably equivalent in part at least to the Collieston succession; they are descended structurally from west to east. The lithology of the section described in detail by Read and Farquhar (1956) can be regarded as a series of grits, greywackes and calcareous bands younging westwards. The calcareous bands numerous around Fraserburgh die out westwards where the grits and greywackes become dominant. Andalusite and cordierite porphyroblasts are found throughout the section. Although there is no apparent change in grade along the section nor significant change in grain size, the presence of sillimanite in rocks at Kinnaird's Head and slates to the west of the section suggest that on a regional scale the grade increases from west to east.

Read and Farquhar (1956) regarded the folds on the coast section between Quarryhead and Fraserburgh as resulting from gravity motivated westward sliding of the sedimentary pile off the upraising Buchan Anticline similar, although on a shallower slope, to the eastward movement of the Collieston beds (op. cit., fig. 5); the metamorphism post-dating the movements. Sutton and Watson (1956) discussing the Boyndie Syncline suggested that corrugations on the eastern limb (i.e. the western limb of the Buchan Anticline) were due to the squeezing out of incompetent bands from the core of the major fold. Sutton and Watson felt it unnecessary to invoke the presence of a huge recumbent anticline - the
Banff Nappe - to explain the disposition of the rocks in north-east Scotland, and suggested that the present disposition resulted solely from folding around a north-north-east axis coupled with differential movement of the various lithological members during folding.

Johnson (1962) in a detailed study of the Banffshire coast section erected a structural time scale comprising four fold episodes ($F_1$, $F_2$, $F_3$, and $F_4$). The formation of the Boyndie Syncline and complementary Suchan Anticline he regarded as $F_3$, the folds in the Rosehearty-Fraserburgh section (as described by Read and Farquhar, 1956) he regarded as equivalent to his $F_4$. Loudon (1963) in an extensive study of the sedimentation and structure of the coast section from Boyne Bay to Fraserburgh did not accept Johnson's time scale. Loudon made three points. Firstly, that the geometry and style of folds were intimately dependent on the relative viscosities of the rocks being folded and on the varying lithological assemblages and thicknesses of different bands, such that rocks of different viscosities and different lithological assemblages produced different fold geometries in response to the same stress field, and therefore geometrical criteria were not in themselves sufficient evidence to separate different fold episodes. Secondly, Loudon criticised several apparent examples of refolded folds; by developing arguments proposed by Flinn (1962) and Ramberg (1963), he considered a thin competent layer enclosed in a medium restricted by two thick flat beds, on either side, then initially, in response to stress oblique to the layering the competent layer would buckle into asymmetric overturned folds, whereas the thick layers would deform by uniform shortening; continued stress would buckle the thick layers and fold the included already folded competent layer; the vergence of the minor folds in the competent layer indicating their formation before that of the major fold.
(a), (b), (c). Characteristic fold profiles of the Rosehearty - Fraserburgh section.
Approximately 1,000 ft. (305 m.) in each case.

(d) Large recumbent fold with 'drooping' nose.
Quarryhead. Bar represents 100 ft. (30.5 m.)
Thirdly, Loudon criticised certain examples of curved axial planes as examples of refolding suggesting they were due to differential lateral movement of beds during folding, incompetent layers moving relatively further than competent layers. Loudon proposed various sequences of fold formation in specific areas but was unable to arrange these into any chronological order. He did not attempt to construct any structural time scale. Loudon, however, ignored the effects of deformation on the metamorphic fabric as a guide to chronologically separating different fold episodes. He criticised Read and Farquhar's concept of gravity motivated westward sliding of the sedimentary pile as the causal mechanism of the folds at Rosehearty and Fraserburgh, as a westward extrapolation would imply that the sediments moved up the tectonic slope west of the axis of the Boyndie Syncline.

Since the Rosehearty–Fraserburgh section is at right angles to the Collieston coast section it was felt that an examination of the structure and metamorphism would provide results complementary to those obtained from Collieston and thus assist an interpretation of the regional structure and in particular the nature of the Suchan Anticline. A brief field survey was, therefore, carried out, no attempt was made to elucidate the detailed structural and metamorphic history, the object being simply to reconcile as far as possible the various views expressed by the previous workers.

2.7 Structure

Characteristic fold profiles along the Rosehearty–Fraserburgh section (figs. 20a, b, c; Read and Farquhar, 1956, fig. 4) show a series of gentle rounded vertical or sub-vertical folds which periodically tighten along the section to form a series of tight asymmetric steeply inclined or overturned folds, with axial planes dipping to the east. The
axes trend north to north-east the plunge varying from $0^\circ$ to $20^\circ$. They are all S-folds the sense of vergence being to the west. The asymmetric folds have their steeper limbs on the westward side, and Read and Farquhar put this forward as evidence in support of westerly movement. From observations of graded bedding and cleavage-bedding relationships they found that the anticlines close consistently westwards and the synclines consistently eastwards, this Read and Farquhar consider indicative of westerly movement. This sense of movement is also supported by the presence of a small thrust near Pouk, displacing the upper beds to the west. A similar sense of movement can be seen in other thrusts throughout the section. Examples of boudinede grit bands can be seen in various localities, the boudin axes lying parallel to the fold axes. A particularly good example of boudinage at Sandhaven has been described by Walls (1937). Several of the large folds have curved axial planes, ‘drooping noses’ and a generally chaotic structure (fig. 20d) similar to many of the Collieston folds (c.f. 2.1, fig. 2). At Quarryhead microfolds, associated with the larger folds, fold an early schistosity. The earlier schistosity is disrupted on a strain slip pattern and a new cleavage developed axial planar to the microfolds. In this example the large folds plunge at $24^\circ$ to the north-north-east, the microfolds are parallel in trend, plunging at $18^\circ$ to the north-north-east. The axial planar cleavage dips at $45^\circ$ to the south-east.

Similar examples of microfolds disrupting an earlier schistosity were found at Long Craig, Hungry Hoy, Pittulie and near Kinnaird Head. At Long Craig small shears disrupt the earlier schistosity the sense of shearing being to the west. Two cleavages can be seen, sporadically, in the rocks from Katty's Leap to Creag an Dide, the secondary cleavage being confined to the pelitic bands.
There is no marked lineation of the quartz-feldspathic pebbles in the grit bands as seen in similar rocks along the Colliearton section.

The early schistosity will be termed $S_1$, the major folds and associated microfolds $B_2^*$, and the axial plane cleavage of $B_2$ will be termed $S_2^*$. It should be emphasised that these terms have only a local significance and that in particular $S_1$ does not necessarily imply an equivalence to the regional first schistosity ($S_1$ of Johnson, 1962).

2.8 Metamorphism

The metamorphic textures of andalusite porphyroblasts in the Rosehearty-Fraserburgh section have been amply described by Johnson (1962). He shows conclusively that the andalusite growth pre-dates the local $B_2$ folds. When $S_1$ is the dominant structural element, the andalusites tend to be aligned parallel to it, and the straight trails of inclusions in the andalusite are also parallel. The andalusite porphyroblasts cut across $S_1$. The growth of the andalusite porphyroblasts is, therefore, demonstrably later than $S_1$. Where $B_2$ microfolds are present they can be shown to fold, break and roll the andalusites. In many sections $S_1$ has been completely transposed to $S_2$ in the groundmass and can only be identified as relic trails within the porphyroblasts. The inclusions within the andalusites are generally finer grained than the groundmass grains. Cordierite porphyroblasts show the same relationships to the structures as the andalusites, often containing $S_1$ trails, marked by the alignment of flattened quartzes and biotite flakes, oblique to the external $S_2$ cleavage. The girdling of many of the cordierite porphyroblasts by white mica felts suggests some form of post-crystallisation slip at the margins of the porphyroblasts.

There is, therefore, conclusive proof that the andalusite and
FIGURE 21

(a) Andalusite crystals (A) containing flattened quartzes and micas defining $S_1$, in the matrix $S_1$ has been folded by small $B_2$ microfolds and a second cleavage ($S_2$) induced. The top andalusite crystal is slightly bent due to the effects of $B_2$ folding. Rosehearty.

(b) Cordierite crystal (C) containing flattened quartzes and micas defining $S_1$, oblique to external $S_2$ planes. Possible shattering of cordierite margins due to movement on $S_2$. Rosehearty.

(c) Cordierite crystal (C) surrounded by $S_2$ planes with suggestion of a 'shadow-zone' to the left of the crystal. Rosehearty.

(d) Bedding ($S_0$) defined by quartz rich bands oblique to $S_2$. Cordierite crystal (C) pre-dates $S_2$. Rosehearty.

(e) Relationship between $S_0$ and $S_2$: $S_0$ folded by $B_2$ microcrinkles. Rosehearty.

(f) Andalusite crystals (A) with later $S_2$ cleavage. Rosehearty.
cordierite porphyroblasts grew in a static period before the \( B_2 \) movements and the development of the associated \( S_2 \) cleavage.

2.9 Interpretation

Read and Farquhar's (1956) hypotheses for the formation of the Rosehearty - Fraserburgh folds can therefore no longer be regarded as strictly valid, since they did not consider polyphasic movement nor the existence of movement after metamorphism. From Johnson (1962, table 1) it follows that, since the \( B_2 \) movements at Rosehearty postdate the metamorphism they are almost certainly equivalent to the \( F_3 \) or \( F_4 \) movements of Banffshire. Johnson proposed that they were equivalent to \( F_4 \) and that \( S_2 \) at Rosehearty was equivalent to his \( S_4 \). Johnson's evidence, however, is not conclusive and, since he could not demonstrate that the \( B_2 \) movements folded \( F_3 \) structures, he has based his equations on the similarity of the \( B_2 \) folds in style and orientation to his \( F_4 \) folds, a principle criticised by Loudon (1963). In style however the \( B_2 \) folds are not dissimilar to Johnson's \( F_3 \) folds, only in orientation of the axial planes and the consequent sense of movement do they differ. \( F_3 \) (Banffshire) planes dipping NW, the \( F_4 \) (Banffshire) and \( B_2 \) (Rosehearty) planes dipping ESE.
It is worthwhile to note in equating the $B_2$ and $F_3$ movements that Johnson's $F_4$ folds are confined to a belt within the Lower Dairadian - "$F_4$ folds do not appear in the higher and lower structural levels exposed on the Banffshire coast" (Johnson, 1962) - whereas $F_3$ folds are developed throughout Johnson's Banffshire section. If $B_2$ were equivalent to $F_4$, then $F_4$ structures would occur in two separate belts within the structural pile, the causal mechanism of such a structure is difficult to imagine. If $B_2$ is equivalent to $F_3$, then $F_3$ structures will be present throughout the structural pile although changing their sense of direction across or near the axis of the Boynie Syncline.

The sequence of events on the Rosehearty - Fraserburgh section can, therefore, be summarised as follows. Firstly, the formation of a schistosity ($S_1$) marked by the alignment of biotites and flattened quartz grains. Secondly, the growth of andalusite and cordierite porphyroblasts over the $S_1$ schistosity and a general coarsening of grain. Thirdly, the formation of $B_2$ folds with an associated microcrinkle, folding $S_1$, disrupting the metamorphic fabric, bending and occasionally breaking the porphyroblasts, the formation in some areas and in particular in pelitic bands of an axial plane cleavage ($S_2$) often completely destroying all trace of $S_1$. 
2.10 Introduction

The section along the Ythan valley was described by Read (1952) as the type example of Buchan metamorphism. In the western part of the section Macduff Slates develop small spots or knots of incipient cordierite and andalusite, eastwards these develop into large prismatic crystals to form the characteristic andalusite - cordierite assemblage of the Fyvie schists. This is followed eastwards by the culminating phase of metamorphism, the sillimanite bearing Ellon Gneiss. An eastward traverse of the Ythan section is across the western limb of the Buchan Anticline and thus encounters successively deeper structural zones. Gribble (1966) investigated the lower part of the Ythan valley - from Little Gight to Methlick - largely to determine the possible thermal effects of the Haddo and Arnage basic masses on the regional metamorphic pattern. The present investigation was made to investigate the possible thermal effects of the Insh gabbro on the regional andalusite schists (the Fyvie Schists) and to determine if post-metamorphic deformation could be demonstrated.

2.11 Metamorphism

Specimens were collected from most of the outcrops of the Macduff Slates and the Fyvie Schists to the north of the eastern end of the Insh mass. Although a general rise in grade was established towards the gabbro, owing to the extremely poor exposures, it proved impossible to determine the effects of the basic intrusion on the regional metamorphic pattern. As far as it could be judged no retrogression occurred within the andalusite schists at the probable extremity of the
thermal aureole (as deduced from its appearance in the Macduff Slates). Although this might suggest that the country rocks were hot at the time of intrusion, it is too indefinite to be quoted as evidence, and the problem was left unresolved, in this area (see, however, 5.3).

In general the metamorphic progression eastwards along the Ythan valley is equivalent to the metamorphic progression southwards along the Collieston coast section. In the western half of the Ythan section knotted schists occur bearing a striking resemblance, both texturally and mineralogically, to those of Collieston. Specimens from near Fetterletter and Craig Harrow provide evidence of post metamorphic cleavage. 'Knots' within the rock show an included fabric of biotite, white mica and flattened quartz. Alternating layers of biotite and quartz are interpreted as original bedding; the alignment of biotite and flattened quartz grains is interpreted as a schistosity. The bedding and schistosity are parallel or sub-parallel. In the groundmass the grains are generally coarser than the included material of the knots; biotite and quartz rich layers can be recognised and are regarded as relic bedding, the direction of bedding in the groundmass is oblique to the bedding and schistosity direction of the included fabric. A schistosity is also present in the groundmass, as is evidenced by the partial recrystallisation of biotite flakes. This schistosity is oblique to the groundmass bedding and the included fabric. Since the included fabric shows that bedding is parallel to the included schistosity, the external schistosity oblique to the bedding is interpreted as a later schistosity. The suggested sequence of events is therefore, (1) the imprinting of a schistosity \( S_1 \) on the bedding, (2) the growth of the metamorphic porphyroblasts, (3) the rotation of the porphyroblasts and the imprinting of a second schistosity \( S_2 \). The proposition that \( S_1 \)
is parallel to bedding can be demonstrated in sections from Newbigging. No metamorphic porphyroblasts are present in the rock, bedding is defined by the alternation of mica and quartz rich layers; \( S_1 \) defined by the alignment of micas and quartz grains parallel to the bedding. A specimen from Den of Crichtie shows weak folding of \( S_1 \) with an incipient development of an axial plane cleavage \( (S_2) \). Down stream near Little Gight specimens of andalusite schist were collected and examined. The fabric of the rock is generally coarser than that of the rocks described above and contain abundant andalusite and cordierite crystals. The andalusites contain coarse quartz and occasionally biotite inclusions, these can be seen to define trails oblique to the external schistosity and apparently indicate post metamorphic movement. The textural evidence would, therefore, suggest the following history; (1) imprinting of \( S_1 \), (2) metamorphism, (3) folding, rotation of porphyroblasts and imprinting of \( S_2 \). Although there is local crystallisation of biotite on the \( S_1 \) planes, the general development of biotite would appear to post-date the first appearance of 'knots' and 'spots'.
CHAPTER 3.

CABRACH - RHYNIE AREA

3.1 Introduction

A structural and metamorphic study of this area is of particular interest on three points. Firstly, the area straddles the Boyne Line - Read's (1955) tectonic break between the sillimanite gneisses of the Lower Dalradian and the andalusite - cordierite schists of the Upper Dalradian. Secondly, the thermal aureole of the Boganloch mass lies within the bounds of the area. Thirdly, the westward continuation of the Boyndie Syncline supposedly passes through the Lower Cabrach (Johnson and Stewart, fig.4, 1960). Since these problems are of regional interest, only the data will be presented in this chapter, the interpretation being discussed in the relevant sections of chapters 4 and 5. Apart from the relevant Geological Survey one-inch sheet memoirs (Wilson and Hinxman, 1890; Hinxman, 1896, 1902; Read, 1923) very little work has been published on the area. The only paper which is perhaps applicable to the present investigation was a study of pillow lavas at Ardwell Bridge by McGregor and Roberts (1963).

3.2 Lithology

The accurate mapping of lithological units or the construction of a litho-stratigraphic section, in any but the broadest detail is impossible in this area, for two main reasons. Firstly, the extremely poor exposure does not allow the tracing of quartzitic, psammitic or calcareous units across country nor can the roles of facies change and tectonic cut-out usually be ascertained in the 'disappearance' of
quartzite and other bands. Secondly, the often radical changes in metamorphic grade along the strike make it difficult to recognise a lithological unit in isolated outcrops. For example, along strike a pelitic band may appear as spotted slate, andalusite schist and sillimanite gneiss. In particular, gneissose rocks having suffered partial melting, metamorphic differentiation and possible metasomatism, are not always easy to ascribe to an original lithology.

Around Cabrach and in the area south of the Bogancloch mass the rocks strike approximately NNE - SSW and dip to the east; in the area north of the Bogancloch mass the strike is generally E - W, the rocks dipping to the south, at the eastern end of the Bogancloch mass the strike swings round to a NNE - SSW trend running northwards through Strathbogie, the dip is generally to the east.

In the extreme west of the area the rocks are generally a mixed assemblage of pelites, black schists, quartzose schists and grits with frequent quartzite and epidiorite lenses and bands. These rocks occupy the ground to the west of a line from Dumeath southwards along the Deveron through Ardwell and Aldivalloch to the northern tip of the Morven - Cabrach mass. On the eastern bank of the upper part of the Deveron and in patches between Ardwell and Aldivalloch, a fine grained black slate outcrops (see Map 2). To the east of this and occupying the ground eastwards to the edge of the present area of study (see Map 2) is an assemblage of pelites, grits and occasional quartzites. Eastwards the grit bands become predominant. Within this latter group several quartzite bands can be recognised, the main one occupying the ground from Mount of Haddoch north-westwards to Ardwell and from Daugh of Corinacy south-westwards to Torniechelt. In the area to the south and east of the Bogancloch mass, the rocks are mainly pelitic or semi-pelitic
with occasional quartzite and grit bands. For ease of discussion, these groups will be named as follows (it must be stressed, however, that these groups are only used in a geographical sense and are not meant to have any litho-stratigraphic implications):

1. Meikle Firbrights Group: the extreme western group.

2. The Black Schist: as described above.

3. The Aldivalloch Group: that part of the group, lying to the east of the Black Schist, which lies south of the large quartzite outcrop described above.

4. The Corinacy quartzite: the large quartzite described above.

5. The Pingleenny Group: that part of the group, lying to the east of the Black Schist, not included in (3) and (4) above, and extending to the limit of the area.


Sedimentary structures are rare, although occasional examples of graded bedding can be found. It is, therefore, difficult to decide, within the area, the younging direction of the rocks. However, from correlations northwards (Read, 1923, 1955) it would appear reasonably certain that the rocks young consistently eastwards across the area. Read (1955) considered the Meikle Firbrights and Black Schist Groups as approximately equivalent to the Boyndie Bay Group and the lower part of the Macduff Slates. Read's correlation of the Buck Group with the Banffshire succession is complicated by his use of metamorphic grade as a stratigraphical indicator. On the Banffshire coast Read (1936) regarded the succession as: (a) the Portsoy Group, younging upwards to, (b) the Cowythe Gneiss - a sillimanite - biotite - oligoclase gneiss - this was followed by, according to Read, a major tectonic break - The Boyne Line - above this lay in ascending order, (c) the Boyne Limestone, (d) the andalusite bearing Whitehills and (e) Boyndie Bay Groups,
(f) the Macduff Slates. In the Cabrach region group (4) is andalusite bearing, as also is the western part of (5). In the southern part of (1) is a patch of sillimanite gneiss, the outcrop of which broadens southwards along the western margin of the Morven - Cabrach mass. In the Buck Group (6) the south-western part is predominantly sillimanite gneiss and the north-eastern part mainly andalusite schist. Read equated the areas of andalusite schist to the Boyndie Bay Group and the areas of sillimanite gneiss he equated to the Cowhythe Gneiss. The major tectonic break, according to Read, occurred on the Banffshire coast between the Cowhythe Gneiss and the andalusite bearing Whitehills and Boyndie Bay Groups. In the Cabrach area, andalusite bearing rocks are in juxtaposition with rocks closely resembling the Portsoy Group. Read (1955) therefore suggested that the Cowhythe Gneiss had been cut out at the Boyne Line, in the Cabrach. He further suggested that the break continued southwards separating the sillimanite gneiss and andalusite schist of the Buck Group.

If the present metamorphic effects are removed, the lithological sequence within the area can be regarded as a gradational sequence from orthoquartzitic to turbiditic facies rocks from west to east. The black schists, pelites, epidiorites and quartzite assemblages of the Meikle Firbriggs Group giving way fairly abruptly to grits, pelites and quartzites of the Finglenny and Ardwell Groups, these in turn grading up into a predominantly grit and greywacke group as found in the extreme east of the Finglenny Group. The several quartzites outcropping in the Buck Group and also the Corinacy Quartzite are generally pure white quartzites. The margins, however, are generally diffuse, pure quartzite grading into quartzose schist and psammite, and often interdigitating with pelite. Nowhere in the Buck Group can pure quartzites be seen in
juxtaposition with pelite or semi-pelite, and it is perhaps not unreasonable to suggest that the quartzites represent lenses within the original lithological sequence.

Although the lithological sequence can generally be regarded as gradational, and the presence of 'isolated' quartzite bands reasonably attributed to facies change, certain abrupt changes in the lithology can only reasonably be interpreted as tectonic cut-outs. In a traverse southwards along the Deveron valley from Duneath, the Black Schist is progressively in contact with the Finglenny Group, the Corinacy Quartzite and the Ardwell Group. Also, south of Ardwell, the Ardwell Group is in juxtaposition with the Meikle Firbriggs Group. Black Schist reappearing between them just north of Aldivalloch (Map 2). In the burn behind Hillock of Echt, black schist outcrops about 35 m from pure white quartzite. Black schist, shattered and broken, outcrops at the roadside ca. 460 m east-south-east of Ardwell. Immediately across the road, ca. 40 m from the black schist, andalusite schists of the Ardwell Group are exposed. Similar phenomena can be seen at the head of the Allt Beach. In the burn running westwards from Aldivalloch a wide crush band can be identified. It, therefore, seems reasonable to assume that some major tectonic cut-out has occurred. The shearing may be contained within a wide band which contains several minor shear planes. The disappearance of the sillimanite gneiss northwards from Aldivalloch also suggests that some form of tectonic cut-out has operated.

In summary the evidence can be given as follows. The rocks of the Rhynie - Cabrach area form a generally conformable lithological sequence grading from a quartzite - pelite - epidiorite assemblage in the west to a predominantly grit - greywacke assemblage in the east. A major shear belt follows the Deveron valley northwards from Aldivalloch.
as evidenced by the cut-out of part of the lithological and metamorphic sequence. The shearing is, at least in part, post metamorphic. The significance of the shearing and its relation to Read's (1955) Boyne Line will be discussed fully in chapter 4.

3.3 **Structure**

The area has notoriously poor outcrop, exposure being confined to stream sections. Minor structures are so rare and scattered as to render any structural analysis based on them inexact. The only method of deducing the major structures is by detailed examination of the cleavage bedding relationships. This was done and the results—the attitude and trend of the cleavages and bedding are shown in Maps 2, 3 and 4. Two generations of cleavage were found, one post-dating the other pre-dating the metamorphism. They could only be separated by thin section examination.

Because the significance of the structures is discussed in chapter 4, only brief explanations need be given here.

(a) **Bedding surfaces** ($S_0$)

The recognition of bedding planes ($S_0$) was relatively easy in the rocks to the north of the Bogancloch mass and in those of the Deveron valley. In the high grade gneiss to the south of the Bogancloch mass nearly all trace of bedding has been destroyed and could only be measured at the junction of major lithological units.

(b) **First generation movements** ($B_1$)

The first generation schistosity ($S_1$) is in general parallel in trend to the bedding, although it may deviate by 20 or 30°. Although few first generation fold closures could be identified, the repetition of distinctive lithological bands and the near parallelism of $S_0$ and $S_1$
as seen in sections — in the Deveron valley — running normal to the strike, suggest that the first generation folds were a series of tight, almost isoclinal folds. This conclusion, is supported by the presence of many parallel lenses of epidiorite and quartzite outcropping to the west of the Meikle Firbriggs Group. North of the Bogancloch mass the stream sections generally run parallel to the strike and it is difficult to demonstrate repetition of the lithological units, but what evidence there is suggests the folding is similar to that of the Deveron valley.

In the Deveron valley the strike of $S_1$ is NNE - SSW with dips of 50 - 70° to the east. North of the Bogancloch mass the trend of $S_1$ swings round to ENE - WSW, the dip being generally to the south. South of The Buck the trend of $S_1$ defines two large flexures. Along the eastern margin of the Morven - Cabrach mass the trend of $S_1$ is NNW - SSE the dip being eastwards; the trend swings round near Sand Hill and runs NNE - SSW towards The Buck, dipping to the west; from The Buck the trend swings round through Clayhooter Hill and then southwards to Glova Hill on a NNW - SSE trend with an eastward dip.

First generation linear structures are rare, generally being represented by $S_0/S_1$ intersections.

(c) Second generation movements ($E_2$)

Although second generation minor folds ($E_2$) can be demonstrated, it is the trend of the second cleavage ($S_2$) which is most useful in deducing the nature of the second generation movements.

$S_2$ has an almost uniform NNE - SSW trend over the area. It therefore has a parallel trend to $S_0$ and $S_1$ in the Deveron valley but cross-cuts the trend of $S_0$ and $S_1$ north of the Bogancloch mass. South of the Bogancloch mass it lies roughly parallel to the trend of $S_1$ on the
FIGURE 22.

(a) Section up the Allt Deach, showing the present day disposition of a grit band (stippled).

2,000 ft. (610 m.)

(b) Possible disposition of the grit band, above, with the effects of the B₂ movements removed.

(c) S₀ defined by the pelitic band between quartzitic bands. S₁, defined in the pelitic band by the parallelism of micas, is parallel to S₀. Spasmodic development of S₂, largely confined to the pelitic band. In Deveron ESE of Ardwell.

(d) Similar to (c), but complete transposition of S₁ to S₂ in the pelitic band. In Deveron ESE of Ardwell.

(e) Similar to (c), strong development of an S₂ fracture cleavage. Glen Laff.

(f) B₂ monoclinal flexure. Kindie Burn.

Bar in all cases represents 1 ft. (30.5 cm.)
'limbs' of the flexures - defined by the trend of $S_1$. $S_2$ cross-cuts the trend of $S_1$ at the 'nose' of the flexures and generally lies parallel to the axial plane of the flexures. It is therefore reasonable to ascribe these flexures to the effects of the $B_2$ movements.

The style of the minor $B_2$ folds varies throughout the area. In the andalusite schists of the Deveron valley and around Glova Hill they are generally monoclinal flexures. At Tap o'Noth and elsewhere within the zone of high grade rocks, strongly contorted $B_2$ folds with random orientations occur. This suggests they were formed when the rock was an inhomogeneous, highly plastic medium.

The interference of the second generation movements upon the first generation fold pattern is difficult to determine. In the Deveron valley the $S_0/S_2$ and $S_1/S_2$ intersections suggest that the $B_1$ folds were opened and gently refolded by the $B_2$ folding. This is shown diagrammatically in figure 22, a and b. Figure 22 a illustrates the present attitude of a grit band in a section along the Allt Deach. From the attitude of $S_2$ planes, it is possible to deduce and remove the effects of the $B_2$ movements. The pre-$B_2$ attitude of the $B_1$ folds is thus determined (fig. 22b) as an isoclinal or sub-isoclinal sequence.

The development of $S_2$ is sporadic being generally poorly developed. $S_1$ and $S_2$ intersections with $S_0$ occasionally produces mullion structures in the quartzites. $B_2$ microcrinkles define an $L_2$ lineation as also do $S_0/S_2$ and $S_1/S_2$ intersections.

3.4 Petrography

(a) Sillimanite bearing rocks

Sillimanite in the form of fibrolite is ubiquitous in the gneisses occupying the south-west portion of the present area and also in the
innermost zone of the Bogancloch aureole. It is strongly associated with the apparent dissolution of biotite. Three stages can be recognised: (1) the edges of the biotite crystal become diffuse and appear to be breaking up into a multitude of fibrolite needles; (2) long matted cords of fibrolite surround small relic cores of biotite; (3) mats, felts and cords of fibrolite form bands and stringers in the rock; biotite being absent. Small fibrolite needles are occasionally enclosed in quartz and plagioclase crystals. Iron ore is often, but not invariably, associated with the fibrolite. Cordierite occurs as both fresh, sector twinned porphyroblasts, and also as almost completely altered patches of chlorite, white mica and pinite. Small diffuse inclusions usually of biotite and quartz occur within the cordierite. Andalusite is occasionally found in fibrolite bearing rocks, tending to disappear as the modal percentage of fibrolite increases. The andalusite is invariably strongly sieved with quartz, the quartz generally constituting 50% or over of the porphyroblasts. Plagioclase is common; myrmekite appears occasionally. Potash feldspar occurs in many of the gneisses constituting up to 60% of the mode. Large muscovite plates occur forming up to 40% of the mode. Muscovite and potash feldspar are mutually exclusive. The muscovite flakes are larger than the groundmass micas and cross-cut, often in random fashion, the fabric of the rock. They are undoubtedly late stage. Euhedral garnets up to 2 mm occur in some rocks as accessories.

(b) Andalusite bearing rocks

Andalusite is an abundant mineral in the area bounded by The Buck Clayhooter Hill and Clova Hill, and also in the Deveron valley. Andalusite porphyroblasts are generally large, ranging from 5 mm to 9 cm with an average of around 8 - 9 mm. In some rocks they form upwards to
60 or 70% of the mode. Chiastolites showing well developed crosses are particularly abundant around Ardwell. Andalusite is generally associated with quartz, biotite and accessory amounts of iron ore. Generally the andalusite porphyroblasts contain trails of inclusions composed of small biotite flakes and flattened quartz grains. The included grains (ca. 0.1 mm) are smaller than similar grains of the matrix (ca. 1.0 mm). Cordierite is generally absent from these andalusite-bearing rocks, however this is not invariably true, fresh, sector twinned cordierite occasionally appearing in association.

(c) Slates and Spotted Slates

These are very similar to rocks at the northern end of the Collieston coast section. The lowest grade rocks contain 'knots' apparently identical to the groundmass but slightly finer grained. As the grade increases the knots clear of inclusions to form optically recognisable cordierite and andalusite. The andalusite and cordierite porphyroblasts are generally segregated, occurring in separate patches.

It is not intended to discuss the significance of the mineralogy of the slates as they are virtually identical to the metamorphic assemblages at Collieston and the arguments proposed in the Collieston section (2.5) are relevant to Cabrach slates and knotted schists. The significance of the fibrolite assemblages will be discussed in chapter 4.

3.5 Metamorphism

It can be clearly demonstrated from the evidence of metamorphic textures that post-metamorphic deformation has occurred. Both andalusite and cordierite porphyroblasts are frequently found with inclusions arranged in trails defining both bedding and schistosity. These trails are usually oblique to the external schistosity, indicating a rotation of
the porphyroblasts or the transposition of the external schistosity after the porphyroblast crystallisation. In the lower grade rocks (where cordierite and andalusite crystals contain abundant inclusions) it is possible to recognise relic bedding and schistosity within the porphyroblast. The bedding is defined by the alternation of quartz rich and iron ore rich bands. The schistosity is defined by the parallel arrangement of micas and flattened quartz grains; this schistosity dominates the fabric. The schistosity can be regarded as a slaty or flow cleavage which generally lies parallel to the bedding. In the higher grade rocks the inclusions are fewer and coarser in grain size. In these rocks it is not generally possible to recognise bedding but the general linear arrangement of included micas and quartz grains readily defines the slaty cleavage. This cleavage is the $S_1$ cleavage described above (3.3). In the matrix of the rock the external schistosity is generally defined by the parallel arrangement of biotites. In the lower grade rocks - knotted schist - bedding can be recognised by the alternation of quartz rich and mica rich bands; the slaty cleavage ($S_1$) lies parallel to the bedding dominating the fabric. Oblique to $S_o$ and $S_1$ a secondary schistosity is occasionally evidenced by the recrystallisation of biotite along discrete planes. This second schistosity is sometimes parallel or sub-parallel to the bedding and first schistosity but is generally oblique. This second cleavage is $S_2$ as described above (3.3). In the lower grade rocks the external $S_o$ and $S_1$ are oblique to the included $S_o$ and $S_1$, thus indicating rotation of the porphyroblasts. In the higher grade rocks it is often difficult to define $S_o$ in the matrix, also the general high degree of recrystallisation has tended to destroy $S_1$ and in consequence it is often difficult to distinguish which cleavage is present in the groundmass. In some
cases cordierites and andalusites show curved trails. In a rock from near The Buck (fig. 23) an andalusite crystal was found exhibiting gently curved trails of inclusions, these however were parallel to the margins of the crystal which were also gently curved. It is suggested that this texture represents slight post-growth bending of the crystal, similar to cordierite textures from Collieston. This seems to be confirmed by the convergence of the trails towards the end of the crystal. In the cordierites curved trails of a different type are found. The trails are straight over the greater part of the crystal curving slightly at the margins, in opposing directions on the opposite margins. This would seem to indicate slight rotation of the crystals during the later growth stages. The inclusions forming the curved part of the trail are not noticeably different in size from those forming the straight part of the trail; the significance of this will be discussed later.

Several rocks from within the northern and southern aureoles of the Bogancloch mass contain porphyroblasts with a zoning of inclusions. Andalusites often show a central zone with abundant dust like inclusions of ore and white mica flakes; the outer zone - forming in total about half the width of the crystal - is completely free of inclusions. The crystals are generally subhedral and the margins of the central zone parallel to the outer edges. The central zone is optically indistinguishable from the andalusite knots found in the spotted slates or knotted schists. Three possible explanations exist to explain this texture. Firstly, the zones may represent two different rates of growth. Drawing analogies to the formation of chiastolite crosses as proposed by Rast (1963, p. 85) the central zone may represent a zone of rapid growth, the marginal zone one of slow growth. Secondly, the
central zone from its similarity to the 'andalusite knots' of the spotted slates may represent formation at lower temperatures or lower pressures than the outer zone. Thirdly, the whole crystal may have originally contained inclusions and a subsequent change in metamorphic conditions cleared the margins. Whichever of these explanations is correct, the andalusite obviously underwent polyphased growth. Also, rocks were found within the aureole which contained cordierites with a zoning of inclusions. The cordierites generally have ragged boundaries and contain patches of fine-grained dust-like inclusions of iron ore and white mica, the remainder of the crystal showing included grains of biotite and quartz, larger than the dust-like inclusions but smaller than the groundmass material. The fine-grained patches are similar to the cordierites of the spotted slates. Occasionally there is only one patch of fine inclusions which in form mimics the outlines of the crystal (fig. 23g). This texture would, as in the andalusites, seem to indicate polyphased growth.

One interesting rock from the southern aureole of the Bogansloch mass, about midway between the Buck and Clayhooter Hill is largely composed of cordierite porphyroblasts. The cordierites contain patches of fine-grained material (fig. 23h) and also andalusites which themselves exhibit polyphased growth textures. The patches within the cordierite would appear to represent original low-grade cordierites; subsequent prograding of the rock having promoted further growth and the coalescing of the small pre-existing cordierites into one large crystal. The history suggested by these rocks is as follows. Metamorphism produced spotted slates with andalusites and cordierites containing abundant fine-grained inclusions. Subsequent to this, after the cessation of crystallisation, a change in the metamorphic conditions promoted further
growth of the andalusites and cordierites, the cordierites including fabric coarsened during the first stage of metamorphism. Growth of the cordierite was more rapid or continued longer than the growth of andalusite, and in consequence the andalusites are enveloped by the cordierite.

It is suggested that this second growth stage or change in the metamorphic conditions was due to the basic intrusion. The significance of the textures will be further discussed in the sections on the basic intrusion (5.3). As is demonstrated in 5.2 the $S_2$ cleavage of the Cabrach region cuts the thermal metamorphic fabric. It is, therefore, suggested that sometime after the imprinting of $S_1$, metamorphic crystallisation reached a climax. Subsequent to this the basic sheet was intruded and 'boosted' the metamorphic grade in the aureole, with the renewed growth, amongst other effects, of andalusite and cordierite. This was followed by the second deformational movements which disrupted the aureole fabric. It is possible that the curved cordierite trails referred to above indicate that cordierite growth overlapped, slightly, in localised patches, the beginning of the second movements.

3.6 Summary

The structural and metamorphic history of the Cabrach can be summarised as follows.

1) $B_1$ movements: Intense, tight, possibly isoclinal folding of bedding ($S_0$) and the imprinting of a slaty cleavage ($S_1$), dominating the fabric of the rock.

2) $M_1$ metamorphism: Climax of regional metamorphism during the static phase following the cessation of $B_1$ movements. Growth of andalusite, cordierite and sillimanite.
(3) Intrusion of basic masses.
(4) \(M_2\) metamorphism: Modification of the metamorphic pattern and secondary growth of regional metamorphic porphyroblasts, due to the thermal effects of the basic sheet.
(5) \(B_2\) movements: Monoclinal folding of \(S_0\) and \(S_1\); intense folding in 'gneissose' rocks. Imprinting of \(S_2\): recrystallisation of the metamorphic fabric. Large scale shearing following the Deveron valley northwards from Aldivalloch, with consequent cut-out of part of the litho-stratigraphic section and the metamorphic zonal pattern.

(5a) \(M_3\) metamorphism: The rocks show no evidence of cataclasis nor mechanical shattering of crystal grains. The quartz grains are free of strain shadows and micas at the crest of the \(B_2\) microcrinkles are bent but not broken. The cordierite porphyroblasts although broken show evidence of recrystallisation. It can, therefore, be reasonably concluded that during the \(B_2\) movements the rocks were still hot and that recrystallisation of the matrix and porphyroblasts occurred in response to the \(B_2\) stresses. The breaking and subsequent annealing of the porphyroblasts is indicative of initial high strain rates in rocks hot enough to allow recrystallisation.
CHAPTER 4.

STRUCTURE and METAMORPHISM of N.E. SCOTLAND

4.1 Introduction

It is intended in this chapter to use the data derived from the study of the minor structures and metamorphism of the Cabrach and Collieston areas to re-examine the structural and metamorphic history of N.E. Scotland.

There will be three principal sections in this chapter, dealing with, firstly, the stratigraphy and its relationship to major structures; secondly, the structural evolution in relation to the various phases of deformation, and thirdly, the metamorphism - its relationship to the structural history; the distribution of isograds with regard to the cause or causes of the metamorphism; the genesis of certain of the minerals.

4.2 Stratigraphy

Many workers in the Highlands, especially E.B. Bailey and his school, have used the distribution of stratigraphical units as the key to major structures. The 'disappearance' of individual limestone and quartzite horizons led them to invoke the presence of 'slides' and 'faulted-folds' in many parts of the Dalradian. Many of these 'disappearances' could, however, be due to rapid facies change, but despite the fact that the concept of lithological facies variations, both parallel and across the strike, has long been recognised, it has received very little investigation until recently. Since Read's (1955, 1956) concept of the major structures of N.E. Scotland -
Banff Nappe, Boyne Line, Buchan Anticline - is based on the disposition of the stratigraphical succession, it would be appropriate to re-consider his evidence, paying attention to facies change. This section will, therefore, be divided into three parts. Firstly, a review of the concept of rapid facies change in the Dalradian; secondly, the lithology of the Upper Dalradian rocks of N.E. Scotland; thirdly, the grouping of these rocks into broad divisions with similar lithological assemblages.

Dalradian stratigraphy contains many names of purely local significance, and this makes correlations difficult and often misleading. Names often refer to the metamorphic grade of the rock such that distinct lithological units may be termed phyllite, schist and gneiss along their length, e.g. the Ben Lawers Schists, Ardinishaig Phyllites and Cowhythe Gneiss all refer to one lithological horizon. In an attempt to simplify the stratigraphy Anderson (1948) proposed the division of the succession into broad groups each with a characteristic lithological assemblage. The names of the groups referring to their dominant lithologies. In Banffshire, Anderson proposed the following grouping:

```
( Upper Psammitic Group  
  ( Upper Pelitic and Calcareous Group  
    ( Lower Psammitic Group  
      ( Lower Pelitic and Calcareous Group, etc. Cowhythe Gneiss

  ( Maccuff Group
    ( Boyndie Bay Group
      ( Whitehills Group
        ( Boyne Limestone
```

Anderson implied that the Lower Psammitic Group (represented by the Ben Lui Schists in the Central Perthshire succession) was cut out of the Banffshire succession by movement on the Boyne Line. Johnstone
<table>
<thead>
<tr>
<th>POSITION</th>
<th>COLLECTION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Legian Group</td>
<td>Base Legian Group</td>
<td>Base Legian Group</td>
</tr>
<tr>
<td>False Bar Gap</td>
<td>False Bar Gap</td>
<td>False Bar Gap</td>
</tr>
<tr>
<td>Collection Base</td>
<td>Collection Base</td>
<td>Collection Base</td>
</tr>
<tr>
<td>Gill Group</td>
<td>Gill Group</td>
<td>Gill Group</td>
</tr>
<tr>
<td>Gulf Trench</td>
<td>Gulf Trench</td>
<td>Gulf Trench</td>
</tr>
<tr>
<td>Pawnee Group</td>
<td>Pawnee Group</td>
<td>Pawnee Group</td>
</tr>
<tr>
<td>Collection Base</td>
<td>Collection Base</td>
<td>Collection Base</td>
</tr>
</tbody>
</table>

These are the positions and descriptions of the layers and groups found in the Upper Middle Field.
(1967) whilst accepting Anderson's grouping in principle changed it in detail, thus:

```
( Upper Psammitic Group )
(     )
(     )
( Upper Calcareous Group )
(     )
Lower ( Lower Psammitic Group )
(     )
( Pelitic and Calcareous Group etc.)
```

Macduff Group
Whitehills Group
Boyne Limestone
Cowhythe Gneiss

Johnstone, therefore, suggested that the top of the Cowhythe Gneiss was equivalent to the Lower Psammitic Group; he does, however, mention the possibility that the Lower Psammitic Group may be cut out at the Boyne Line or disappear due to lateral facies change.

Although Anderson's (1948) broad litho-stratigraphic groups partially overcome the problems of rapid facies change, it was Knill (1960) who first seriously considered the problems of rapid facies change in Dalradian stratigraphy. Knill (1963, p.117) stated, "... it has been recognised that rather more extensive variations in facies occur at individual levels within the Dalradian than is indicated by the normally accepted stratigraphical correlation tables. Local facies changes appear to be particularly characteristic of the upper part of the Middle Dalradian and the sequences in separate areas show noticeable, but minor, differences". Knill found in the south-west Highlands that several well established horizons showed considerable variation in lithology; "The Tayvallich Limestone Group outcrops as a well-defined horizon lying between the Crinan Grits and the Tayvallich Lavas over most of the Loch Awe area. However, in Glen Aray, the group
is discontinuous, being represented by lenticles of limestone and conglomerate. The thickness of the Tayvallich Group varies considerably, ranging from a few feet to over five hundred feet in some areas" (op. cit., p. 111). The group varies from limestones and dark phyllites in the west to limestone breccias, conglomerates and grits in the east. Variations in the thickness of groups is common in the Dalradian, e.g., "The Forthshire Quartzite Series is up to three miles thick in southern Islay and Jura up to one and a half miles thick around Schichallion and probably less than a mile thick in Banffshire" (Rast, 1963, p. 126). To overcome the complications of rapid facies change Knill (1959) proposed the term 'sedimentary associations' for groups with characteristic lithological assemblages. Roberts (1966) suggested that Knill's grouping was too restricted, that the 'sedimentary associations' reflected only the material available for deposition and not the conditions of deposition. Roberts suggested that within a basin of deposition, limestones and carbonate sediments might be forming in one area where little material was being brought into the basin, whereas in another area considerable material could be deposited to form clastic sediments which although differing markedly in lithology from the carbonate sediments should be correlated with them. Roberts proposed the term 'sedimentary affiliations' for broad groups to include all sediments laid down 'in the same general depositional environment'.

The present author feels that the concept of some form of grouping with characteristic lithological assemblages is essential for a proper understanding of Dalradian stratigraphy, both from the point of view of correlation and the subsequent elucidation of structures. Much confusion exists in Dalradian stratigraphy (as pointed out by Anderson, 1948) as to the nature of such 'key horizons' as the Loch Tay Limestone
and its equivalents. It is often unclear as to whether reference is to a limestone unit or the whole assemblage within which the limestones are developed. The implication often exists in correlating such units as the Boyne Limestone, Loch Tay Limestone and Tayvallich Limestone that a single limestone band stretched right across the strike of the Dalradian, when in fact the only inference that can be drawn from such correlations is the existence of a lithological assemblage continuous along the entire strike of the Dalradian within which large limestone bands are characteristically developed. The realisation that limestone and quartzite units exist as lenses or bands within a particular lithological assemblage, but not necessarily as continuous units, nor even with all the lenses lying within the same horizon, is of primary importance in the elucidation of structures by the disposition of stratigraphy. The 'disappearance' of quartzites and limestones is not necessarily an indication of tectonic cut out. The value of this principle has been demonstrated by various workers in the Dalradian. For example, Harte (1966) working on the detailed stratigraphy and structure of Glen Esk believed that many lenticular calcareous bands were deposited in isolated basins, and also that quartzite and limestone horizons might grade into one another along the strike. He, therefore, rejected Bailey's (1928) correlations of individual horizons. He suggested that broad stratigraphical units with distinctive lithological assemblages, could be traced across country. By the use of these broad units shown in Map 5 and table 1, Harte was able to deduce the main structures of his area and, in the process, disperse with many of the small slides suggested by Bailey. Similarly Voll (1964), working in the classic Ballachulish area, suggested that rapid facies change could explain many of the stratigraphical anomalies used by Bailey as
evidence for the nappes and slides of the Ballappel formation.

Before those principles can be applied to the north-east of Scotland it is necessary to consider briefly the lithology of the Upper Dalradian in Banffshire and Aberdeenshire. The Dalradian succession grades upwards from an orthoquartzite facies assemblage to a turbidite facies assemblage. These assemblages are approximately equivalent to the Lower and Upper Dalradian, respectively. Read (1923) originally considered the Keith Series (later correlated with the Lower Dalradian) and the Banff Series (later correlated with the Upper Dalradian) as two entirely different divisions separated by a plane of movement (the Boyne Line), the Banff Series characterised by grits and greywackes, the Keith Series by orthoquartzitic facies assemblages. The base of the Banff Series (and the Upper Dalradian) was taken as the base of the Boyne Limestone. However, Sutton and Watson (1955) pointed out, "The greywackes and grits of the Banff Division are quite unlike any of the rocks of the underlying Keith Division. Nevertheless there is no sudden change in sedimentary facies of the junction of the two divisions, and the Boyne Limestone, the lowest member of the Banff Division would not be out of place among the limestones, quartzites and argillaceous rocks that make up the lower part of the Dalradian sequence. Indeed the Boyne Limestone might be regarded as the last deposit of this type in the north-east Scotland succession." Sutton and Watson suggest at the end of the Boyne Limestone times calcareous muds were being laid down, but a land mass emerging to the north-west provided detritus to form clastic sediments. Initially calcareous grits and flags, grading up into siliceous grits, and these in turn into greywackes. They regard the sinking of the geosyncline giving rise to the deep-water greywackes as complementary to the emergence of the land mass to the north. Knill
(1963) suggested that the incoming detritus in Upper Dalradian times was laid down in a trough trending NE - SW. Knill envisaged greywacke sediments being laid down in the centre of the trough with dark calcareous and argillaceous sediments forming the marginal facies and interdigitating with the greywacke. Sutton and Watson (1955) found that the Boyne Limestone Group was a calcareous assemblage largely devoid of clastic sediments. The lower part of the Whitehills Group was a mixture of carbonate and clastic sediments with calcareous flags and grits; the upper part of the Whitehills Group was predominantly siliceous grits and the Boyndie Bay and Mauduff Groups were mainly greywackes. This gradational sequence in the Upper Dalradian, from a zone of carbonate sediments to one of greywackes is difficult to demonstrate inland, owing to the lack of exposure, however, from the detailed lithological descriptions given in various memoirs of the Geological Survey and from personal observations the author is satisfied of its existence.

An appreciation of the lithological sequence of north-east Scotland is unfortunately complicated by the variation in metamorphic grade of the rocks. Many of the boundaries between the stratigraphical units appear to have been based more on considerations of changes in metamorphic grade than on changes in lithology, e.g. the boundary between the gneisses and andalusite schists. The Cowhythe Gneiss, now mainly composed of oligoclase - biotite - gneiss, contains, especially in the west, limestones (Rosehall Croft Limestone) calcareous bands and quartzitic ribs (more common in the east). The Cowhythe Gneiss therefore forms a perfectly sound litho-stratigraphical unit with the overlying Boyne Limestone and the lower part of the Whitehills Group. In demonstrating the gradational sequence of sedimentation in the Upper Dalradian of Banffshire, Sutton and Watson (1955) regrouped the stratigraphical divisions of Read (1923)
to allow for metamorphic change, "in this grouping, rocks of similar original lithology have been placed together and the effects of subsequent metamorphism have been disregarded. Thus, for example, slates, spotted slates and andalusite schists are shown with the same ornamentation .... since all are derived from argillaceous rocks" (Sutton and Watson, 1955, p.103). Read (1936) also commented on the boundary between the Boyndie Bay Group and the Macduff Slates; the boundary being placed at the first appearance of spotted slates, "... thus it appears that the rocks on either side of the boundary are stratigraphically the same, and differ only in their state of metamorphism" (Sutton and Watson, 1955, p.106). Similarly the boundary of the Rosehearty Beds (and the Fyvie Schists) with the Macduff Group, has very little litho-stratigraphic significance. Also, when the effects of subsequent metamorphism are ignored the boundary between the Donside and Ellon gneisses and the overlying andalusite schists becomes meaningless in a lithological sense, the sediments grading upwards without marked change.

In attempting to erect broad divisions for the Upper Dalradian in the north-east succession two facts must be considered. Firstly, the entire sequence from the Cowhythe Gneiss to the Macduff Group is gradational; there are no distinct units. Secondly, many of the stratigraphical terms reflect metamorphic grade rather than lithology. Anderson's (1948) scheme divides the succession effectively into two (assuming the Lower Psammitic Group is absent) a pelitic and calcareous group including the Cowhythe Gneiss, the Boyne Limestone and Whitehills Group, and a psammitic group including the Boyndie Bay Group, it is felt however, that Anderson was influenced by the established boundaries and that the boundary between the pelitic and calcareous group and the psammitic group should be somewhere within the Whitehills Group.

Similarly Johnstone (1967) equates his combined Upper Psammitic Group
and Pelitic Group to the combined Macduff and Whitehills Group, and
the Upper Calcareous Group to the Boyne Limestone. It is felt, however,
that the top of the Upper Calcareous Group would be more realistically
placed in the Whitehills Group. In erecting a grouping it is, therefore,
proposed to follow the principles adopted by Harte (1966) and to ignore
established stratigraphical boundaries. Three divisions will be
described. It must be stressed, however, that the lines drawn as junctions
between the units (as shown on Map 5) are arbitrary, approximating to the
position where one facies begins to predominate over another, and do not
represent marked changes of lithology. They are aids to show the trace
of lithology across the surface.

The three units in ascending stratigraphical order are:

(a) Calcareous Flag Group

Characterised by the presence of calcareous bands and the general
low proportion of grits. Inland it outcrops as quartzites and limestones
along with pelites.

On the Banffshire coast the group outcrops westwards from Whitehills.

For the purposes of this discussion the western margin of the group is
taken as the base of the Cowythe Gneiss although the group could be
extended into the Portsoy Group. As mentioned above the Cowythe Gneiss,
although now at a much higher metamorphic grade, does not differ markedly
in lithology from the overlying beds. It contains massive limestones,
calcareous bands and quartzites. Also contained in this group are the
Boyne Limestone and the lower beds of the Whitehills Group which are rich
in calcareous bands. Inland it can be traced south, outcropping to the
east of the Huntly 'Younger Gabbro' and, with slight deflections of strike,
south through the Cabrach to Donside. In Donside the group contains the
greater part of the gneiss which outcrops to the north of the Deeside
granites and also the southern edge of the andalusite schists which lie
to the north of the gneisses. Eastwards the group is represented by the calcareous rich sequence of the base of the Fraserburgh Beds, the Mormond Hill Quartzite and the calcareous rocks at the base of the Collieston Beds. The Ellon Gneiss appears to belong to this group because it contains limestones and quartzites as well as several lenses of hornblende schist which may represent calcareous bands. From Ellon the group may be traced south to Deeside where it is represented by the Glen Tannar Quartzite and Mica Schist Group, the Deeside Limestone and the Queen’s Hill Quartzite and Gneisses. Southwards to Glen Esk it becomes roughly equivalent to Harté’s (1966) Tarfside Limestone and Quartzite Group (table 1).

(b) Transition Group

Between the first and third groups there is a narrow passage or transition group characterised by the presence of grits and subordinate greywackes.

On the Banffshire coast the group outcrops from Stake Ness to the western side of Boyndie Bay and includes the top of the Whitehills group and the lowest beds of the Boyndie Bay Group. Inland it outcrops as a narrow strip running south to the Cabrach where the strike swings east to Lumsden and Old Meldrum and then north to the coast where it outcrops from Pittulie to the western edge of Fraserburgh.

(c) Greywacke Group

Characterised by the predominance of grits and greywackes with subsidiary slates and pelites.

On the coast it outcrops from Boyndie Bay to Pittulie. Inland it includes, mainly, the Macduff Group and also the western margin of the Fyvie Schists and the eastern margin of the Boyndie Bay Group. At Collieston, the Collieston Beds north of The Smithy are included in the
Greywacke Group. Re-appearing on the south side of the core of the Banff Nappe (table 1) in the area around Glen Esk, the Greywacke Group becomes roughly equivalent to Harte's Grit Group and the top half of his Pelite Group (Map 5).

With these units it is possible to draw a greatly simplified litho-stratigraphical map of N.E. Scotland (Map 5). It is now possible to reappraise several of Read's (1955, 1956) structural concepts based on stratigraphic distributions.

(a) The Banff Nappe

Read (1955) first postulated the existence of the Banff Nappe to explain the anomalous disposition of the stratigraphy in N.E. Scotland. He regarded it as a huge recumbent anticline closing eastwards, the actual closure being off the eastern coast of Aberdeenshire. The nappe Read proposed was a northward continuation of the Tay Nappe, plunging gently northwards from a culmination in Central Perthshire, such that the present erosion level represents an oblique section through the nappe. Read's main evidence was the change in younging direction at Donside, to the north the upper part of the Central Perthshire succession youngs northwards, to the south the same succession youngs southwards. Thus Read regarded the Donside gneisses just to the north of Donside as occupying the core of the nappe, the rocks to the south representing the inverted limb and those to the north the upper limb. This is shown diagrammatically in fig. 24. The disposition of the litho-stratigraphic units clearly shows the evidence for the nappe.

To the present author Read's thesis is virtually incontestable. To explain the disposition of strata by any alternative proposition would be extremely difficult and would have to account for the sudden attenuation of the Tay Nappe north of Perthshire. Most subsequent workers (Johnson,
FIGURE 24.

Diagrammatic illustration of the evidence for the Banff Nappe in the disposition of the litho-stratigraphic units and the younging directions.

The oblique cross-section through the Banff Nappe of the present day surface can also be seen.
FIGURE 25.

Cross-sections of the Banff Nappe

(a) after Read (1955)

(b) Section along 'line of section' in Map 5 showing the disposition of the major lithostatigraphic units.

(c) As (b), showing the areas of gneiss and their general relationship to the stratigraphy.
after Read, 1955

a. Lower Dalradian
   Upper Dalradian
   Gneisses

b. Faulting
   Calcareous Flag Group
   Transition Group
   Greywacke Group

c. Gneisses
1962-1963; Rast, 1963; Johnstone, 1967) have accepted the reality of
the Banff Nappe and although Sutton and Watson (1956) working on the
Banffshire coast suggest that there is no need to invoke a nappe to
explain the structures of Banffshire they admit that regional
considerations could alter their view, and it is to the south that the
main evidence is to be found. Read (1955) further argued that the
Tayvallich, Loch Tay and Deeside limestones were stratigraphically
equivalent and therefore represented a well defined massive limestone
unit stretching from the S.W. Highlands to Deeside. North of Deeside,
however, it is absent from the stratigraphical succession apart from a
small exposure in Banffshire (The Boyne Limestone). Read (1955) attributed
this absence to a large slide modifying the upper limb of the Banff Nappe.
This slide — The Boyne Line — will be discussed more fully below, but it
is considered pertinent at this point to examine the absence of large
limestones in the Banffshire and Aberdeenshire Upper Dalradian succession.

As has been discussed above the correlation of the Loch Tay, Tayvallich
and Deeside Limestones does not imply that a single massive limestone
band existed along the entire outcrop of the groups but only that a
widespread lithological assemblage existed, within which large limestones
are characteristically developed. In part, the 'Tayvallich Limestone'
consists of limestone breccias and conglomerates (Knill, 1963). Also,
the 'Loch Tay Limestone horizon' can be traced across Banffshire where
it is represented by calcareous flaggs and thin limestones. It is,
however, perhaps surprising that there are no massive limestones in
Banffshire. There is one possible sedimentological explanation for this.
The outcrop of the Loch Tay, Tayvallich and Deeside Limestones is for the
most part an outcrop along the strike but because of the plunging nature
of the Banff Nappe the outcrop in Banffshire is oblique to the strike.
Roberts (1966) suggested that the Loch Tay Limestone varies in facies more quickly normal to the strike than parallel to it. It is, therefore, not particularly anomalous that the 'Loch Tay Limestone horizon' should contain massive limestones in its trace from the south-west Highlands to Deeside and should change laterally in Banffshire to a series of calcareous grits and impure limestones, from which massive limestones are absent. This simple theory is complicated by the presence of the Boyne Limestone. That is, the series of calcareous grits and thin limestones suggested above to be the lateral equivalents of the 'Loch Tay Limestone horizon', themselves give way laterally to an assemblage containing a massive limestone (The Boyne Limestone). If the reality of the Banff Nappe is accepted, then it can be appreciated that the Boyne Limestone was laid down well to the west of the Deeside and Loch Tay Limestones, the area between being occupied by calcareous grits and thin limestones. It should be emphasised that although Read (1955) has shown the Deeside Limestone extending partially around the nose of the Banff Nappe, there is little evidence for this the easternmost outcrop of massive limestone occurring on Deeside well to the west of the conjectural position of the nappe nose.

It, therefore, seems probable that the massive limestones developed at the margins of the basin of deposition and that the lateral equivalents of these massive limestone assemblages were a series of calcareous grits and thin limestones laid down in the centre of the basin. This basin may have been one of the subsidiary NE - SW trending basins proposed by Knill (1963, p.118).

(b) The Boyne Line

Read (1923) first postulated the Boyne Line as a form of discontinuity between the Keith Series and the Banff Series, his reasons
were :-

(i) The 'cut-off' of the Boyne Limestone, Whitehills Group and Boyndie Bay Group to the east of the Huntly 'Younger Gabbro'.

(ii) The complete disappearance of the Cowhythe Gneiss and Boyne Limestone south of Huntly in the Cabrach where the Boyndie Bay beds are in contact with the rocks of the Portsoy series.

(iii) The differing metamorphic assemblages of the Banff and Keith Series.

(iv) The absence of the Banff Series from the standard Perthshire succession.

Later, Read (1955) accepted the correlation of the Banff Series with the Upper Dalradian of the Perthshire succession and came to regard the Boyne Line as a thrust or lag modifying the upper limbs of the Banff Nappe, rather than as a line separating two entirely different lithological facies.

Subsequent workers have accepted the reality of the Boyne Line although Sutton and Watson (1956) substituted the term, "zone of tectonic disturbance" for the term 'Boyne Line' which implies a single thrust. These workers accepted Read's conclusion (1952) that the metamorphism was post-kinematic. They had previously shown (1955) that the metamorphism did not follow the structures in detail, evidence which they interpreted as indicative of post kinematic metamorphism. They did not, however, consider the possibility that the metamorphism could occur between movement phases. Presuming the metamorphism to be post movement, Sutton and Watson state (1956, p. 128), "It is surprising, therefore, to find in the only satisfactory exposure of the Boyne Line (on the shore east of Cowhythe Head), that the rocks have been broken down into phyllites by movements which are clearly post-metamorphic. It would appear that
what has been taken as the outcrop of the Boyne Line at this locality is in fact the outcrop of a late structure which could not account for the pre-metamorphic disposition of the rocks in Buchan”.

Read (1952, 1955, 1956) states that the metamorphism is post-movement. Therefore, his trace of the Boyne Line south of the Coreen Hills, where it is drawn between andalusite and sillimanite bearing rocks, is even by his own arguments based on a false premise, unless the metamorphic zones were rigidly controlled by original lithology. However, it is now known that the difference between andalusite schist and sillimanite gneiss in Buchan is due to different pressure and temperature conditions during metamorphism, the junction being transitional and in no way reflecting lithological change. In fact, the stratigraphical trends as shown in Map 5 by the junction of the Calcareous Flag Group and the Transition Group are intersected by the metamorphic isograd at Cabrach, Kildrummy and Alford. Thus the Boyne Line in this area does not separate the Upper and Lower Dalradian and certainly does not represent any lithological discontinuity.

The Cowbythe Gneiss is absent from the Cabrach. It differs from the overlying and underlying rocks purely on metamorphic grade and not on lithology. Thus it’s absence in the Cabrach and the general distribution of the stratigraphy is strong evidence in favour of a post metamorphic tectonic cut out. To the east of the Huntly ‘Younger Gabbro’ the Fourman Hill andalusite schists and the calcareous flags to the east of Cornhill occupy anomalous positions in the general pattern of metamorphic zones. Again this suggests some form of post metamorphic movement. In general, therefore, the evidence seems to be in agreement with Sutton and Watson’s (1956) conclusion that the Boyne Line movements are post metamorphic in the type locality of the Boyne Line at Boyne Bay and in its
continuation south.

It is rather surprising that Read, who regarded the metamorphism as being post-tectonic, did not consider that the juxtaposition of two different grades (Read, 1923) across the Boyne Line at Boyne Bay rather anomalous. Even if the two grades had arisen from different causes at different times, their contact should have been gradational, a marked hiatus, as exists, only being possible if movements had followed the cessation of metamorphism.

It is now almost certain that the major $F_3$ movements were post-metamorphic (Johnson, 1962) and that the metamorphism occurred after the nappe forming $F_1$ movements had ceased. It is, therefore, more than tempting to equate the metamorphic cut-outs with the $F_3$ movements.

During the discussion of the basic masses of N.E. Scotland it will be (5.2) suggested that considerable NE - SW shearing took place between the Huntly and Insch masses at this time. Such shearing could easily account for the cut-out of the Cowhythe Gneiss. The anomalous position of the Fourman Hill mass etc., could have been due to faulting and shearing on the western limb of the Boyndie Syncline as it was rotated into its present steep attitude. It is interesting to note that Horne (in Read, 1923) suggested that the evidence put forward by Read for the Boyne Line could be explained by a system of normal faults possibly of late date, coupled with facies change along the strike.

In conclusion, therefore, the concept of the Boyne Line as a major pre-metamorphic thrust connected with the nappe formation is untenable; over most of its mapped trace there is no evidence for its existence, and the metamorphic cut-outs around the Huntly basic mass are post-metamorphic events.
(c) Buchan Anticline

Read and Farquhar (1956) divided the rocks of the Collieston coast into the Mormond Hill quartzite, a mixture of quartzites, pelites and calcareous bands at the base of the section, and the Collieston Beds a series of grits, greywackes, siltstones and near the base calcareous grits. Between the two divisions they recognised a ten-foot calcareous band at The Smithy which they regarded as a passage bed.

On the Fraserburgh coast section Read and Farquhar (op. cit.) divided the Fraserburgh Beds into the Kinnairds Head Group - predominantly calcareous bands and limestones - and the Rosehearty Beds - predominantly grits and greywackes. They regarded the Fraserburgh Beds as lying unconformably on the Mormond Hill Quartzite. Their evidence for this was both local and regional. If they correlated the Mormond Hill Quartzite at Fraserburgh with that at Collieston and the Collieston Beds with the Rosehearty Beds (both being predominantly greywacke assemblages), then the Kinnairds Head Group would have to be equivalent to the 'trifling calcareous band' at the base of the Collieston Beds, a correlation which Read and Farquhar found unacceptable. Also, if the Rosehearty Beds were equivalent to the Boyndie Bay Group and the Kinnairds Head Group to the Whitehills Group then the Mormond Hill Quartzite would have to be equivalent to the Boyne Limestone, again, a correlation unacceptable to Read and Farquhar. They then contrasted the Rosehearty and Collieston Beds on the grounds that the Rosehearty Beds do not show the transitional types between grits and andalusite schists seen at Collieston, i.e. the greywackes at Collieston show a range in percentage of clastic grains to matrix of 50% to 25% but those at Rosehearty show a range of only 75% to 55%. Read and Farquhar therefore came to the conclusion that, since the Collieston Beds, which lie conformably on the Mormond Hill Quartzite, are absent from
the Fraserburgh succession then a slide must separate the Mormond Hill Quartzite from the Kinnairds Head Group. It, therefore, is implied by Read and Farquhar that the Collieston Beds are cut out along the slide. The inference from Read and Farquhar's interpretation is that the Collieston Beds and the Mormond Hill Quartzite underlaid the Fraserburgh Beds, since they are stratigraphically above the Ellon Gneiss (placed by Read at the top of the Lower Dalradian) they must belong to the Upper Dalradian. However, where Read and Farquhar place them in the Upper Dalradian sequence of the Banffshire coast is unclear but it must be presumed they regard them as cut out at the Boyne Line. The structure proposed by Read and Farquhar is obviously complex, the present author believes it can be greatly simplified by the use of the broad lithostratigraphic units proposed above, and the acceptance of rapid facies change. The nature of the Boyne Limestone has already been discussed. In the Geological Memoir for sheet 87 Wilson (1886) states that the Mormond Hill Quartzite thins rapidly to the south on both the east and west limbs of the Buchan Anticline. At Collieston the massive quartzite of Mormond Hill has thinned to, at maximum, some 275 metres. Also the "Mormond Hill Quartzite" at the base of the Collieston Beds is not the massive quartzite of Fraserburgh but a succession of thin quartzites, calcareous bands, pelites and some siltstones. If the quartzite can thin and vary in facies to such a degree in a strike distance of some 35 kilometres it is to be expected that it will be absent from the Banffshire succession some 42 kilometres away, across dip, to the west. The Mormond Hill Quartzite is, therefore, most probably only a lense in the Calcareous Flag Group. If 'the difference' between the Collieston and Rosehearty Beds is dismissed as not being of any major significance, it can be easily seen that the Collieston and Fraserburgh successions are
largely equivalent - both grading from a series of quartzites, calcareous bands and pelites at the base to pelites and greywackes at the top. A sequence which can obviously be continued over the Boyndie Syncline.

Therefore, in conclusion, it may be stated that by regarding the Upper Dalradian rocks of north-east Scotland as a conformable sequence and erecting broad litho-stratigraphic groups to compensate for facies change, it is possible to simplify the stratigraphy of N.E. Scotland and in consequence to show that the major structures proposed by Read (1955, 1956) are substantially correct, but that they are not modified by slides, or major thrust planes.

4.3 Structure

The previous section dealt with the broad structural units of N.E. Scotland as implied by the disposition of the litho-stratigraphic units. It is now possible to consider the structural history correlating these broad structures with the detailed structural histories determined for the Collieston and Cabrach areas.

(a) First Fold Movements

The first major structure is the Banff Nappe. In discussion the author has found that the main criticism of the nappe structure is the absence of a root zone. Read (1936) showed that the Lower Dalradian younged consistently eastwards throughout its section and since there was no evidence of Lower Dalradian sediments to the west of their present outcrop it was impossible for the nappe to be rooted in any classical Alpine sense. However, if the nappe was generated by gravity flow the necessity for a root zone disappears. Cummins and Shackleton (1955) suggested that the Ben Lui recumbent syncline was caused by 'deep seated
Evolution of major structures in N.E. Scotland

(a) - (d) Stages in the formation of the Banff Nappe due to gravity controlled collapse of the sedimentary pile.

(e) Disposition of $S_1$ schistosity at the cessation of the first generation movements.

(f) Renewed gravity motivated folding in the upper structural zones during the third generation movements.

(g) Disposition of $S_3$ schistosity at the cessation of the third generation movements.

(h) Disposition of $S_1$ schistosity at the cessation of the third generation movements.
gravitational flow'. They cited three characteristics of the syncline in support of their view, (1) the axial plane dipped 'down' to the south-east, (2) the absence of roots, (3) the stratigraphical increase in amplitude of the folds. The Banff Nappe possesses all of these criteria, which strongly suggests that it was also generated by gravity flow. Also, since the Banff Nappe is the northward continuation of the Ben Lui synclinal structure it is a reasonable assumption that the causal mechanism should be similar in both cases. Johnson (1965, p.139) accepted that, in part at least, the Banff Nappe was due to gravity motivated flow of the sedimentary pile. A diagrammatic explanation of a possible mode of formation of the Banff Nappe is shown in figure 26,a-d. This will be described and then the various implications discussed.

(a) The Dalradian sediments were laid down in a sedimentary basin possibly on a basement of Moinian age.

(b) At the onset of the Caledonian Orogeny lateral compression folded the basement and created a slope down which the Dalradian sediments slumped forming at least two large nappes. Although the large nappes of the Central Highlands are usually considered only to effect the Dalradian there is no reason why the Moinian rocks should not have been partially involved in the slumping and the great nappes of the Dalradian may continue partially into the underlying Moine before dying out. Elucidation of this will only be found in a detailed investigation of the Moine at its junction with the Dalradian. This slumping of sediments on a regionally inclined basement is consistent with the views expressed by De Sitter (1956) in discussing gravitational tectonics in which he envisaged lateral compression folding the basement rocks of a sedimentary pile and hence producing a regional slope and trough into which the sediments could 'flow'.
(c) As the slumping and flowing continued the sediments began to pile up in front and thus creating a minor trough or embryonic syncline behind.

(d) Sediments pushed from the rear by lower sediments still sliding down the slope began to rise up from the trough and overflow on to the frontal 'hump'.

Before discussing the evidence for this frontal 'hump' it is necessary to consider the nature of the regional first schistosity. Sutton and Watson's (1956) description of the cleavage in the Macduff Slates was, "... a true slaty cleavage determined by the parallel arrangement of the minerals". Microscopic evidence of rocks throughout the Upper Dalradian shows that the first schistosity, where it has not been destroyed by later movements, dominates the whole fabric of the rock, i.e. all the component mineral grains are aligned parallel to each other, quartz grains being flattened and drawn out along the schistosity planes. The schistosity is generally, but not invariably, parallel or sub-parallel to bedding. There is no indication of discrete planes as are generally found in axial planar cleavage. It is, therefore, suggested that the first regional schistosity is a flow schistosity, the mineral grains being aligned parallel to the direction of flow of the slumping sediments. This is supported by the attitude of the cleavage in the Macduff Slates. At the present day the cleavage of the Macduff Slates in the vicinity of Banff and Macduff is a composite cleavage with \( S_1 \) and \( S_2 \) parallel or sub-parallel and in a vertical attitude. Even allowing for rotation during \( F_2 \) the \( S_1 \) planes must at the cessation of \( F_1 \) movements have had a dip of at least 30° to the west around Banff, gradually shallowing towards the east. It seems improbable that this horizontal or sub-horizontal schistosity could have formed had any lateral
compression existed. This disposition of schistosity indicates stretching normal to the Banff Nappe closure. It is suggested that the most satisfactory cause of $S_4$ is that of flow or stretching of the rocks normal to the nappe closure. A conclusion consistent with the hypothesis that the Banff Nappe formed by gravity controlled slumping of the sedimentary pile. It is however necessary to envisage that the direction of flow around Macduff and eastwards was at approximately $30^\circ$ above the horizontal. It is felt this is satisfactorily accounted for by the upsurge of sediments behind the frontal 'hump' as shown in figure 26d. The pattern of schistosity thus produced is shown in figure 26e. The concept of the regional $S_4$ as a flow schistosity also explains the close parallelism of $S_4$ and bedding in the Dalradian. There appears to be a tacit assumption amongst many workers in the Dalradian that this parallelism is due to intense isoclinal folding although fold closures and minor folds of undoubted $F_4$ age are rare. The necessity for ubiquitous isoclinal folding is lessened; although locally, as in Gabrach, isoclinal folding may be fairly common, especially in the lower structural zone. It is not difficult to envisage in the pile of slumping sediments that beds could buckle and, especially at depth, gradually tighten and be drawn out to form structures analogous to isoclinal folds. In such cases the flow schistosity was most probably also buckled with the bedding. In the nose region the folded flow schistosity would transpose itself into the direction of flow or stretching. In effect the flow schistosity would become the axial planar schistosity of the fold.

At Collieston, however, a different fold style is evident. As was discussed in Chapter 2 the style of the Collieston folds suggests they formed by gravity collapse. It is now suggested that they formed near the nose of nappe slumping off the frontal 'hump' (fig. 26d).
Since the Collieston folds formed fairly late in the nappe formation they almost certainly buckled the flow schistosity, which is now partially destroyed by the strong axial planar cleavage ($S_1$ of Collieston) of the folds. Since these Collieston folds were not at great structural depth they were never drawn out into isoclines.

Although the concept of gravity slumping and flow schistosity implies considerable stretching and possible attenuation of the beds, critical evidence for this is difficult to find. The flattened quartz grains defining in part the flow schistosity give partial support to a stretching hypothesis but it is virtually impossible to produce stratigraphical evidence for the thinning and thickening of beds (see, however, Louzon, 1963), this is partly due to the lack of exposure. But also due to the difficulty in showing that the thinning of beds is not due to original facies variations. It is also impossible to say how much, if any, tectonic thickening of beds may have taken place due to isoclinal folding. Such stretching and attenuation of beds would provide a ready mechanism for the formation of slides and lags. Although the author has rejected Read's (1955) concept of a major slide modifying the upper limb of the Banff Nappe and also Read and Farquhar's (1956) slide cutting out the Collieston Beds and part of the Mormond Hill quartzite on the western limb of the Buchan Anticline, it is not improbable that, locally, attenuation of beds and apparent cut-outs may result partially from sliding. It is unfortunately impossible to satisfactorily determine due to lack of exposure, what tectonic effects, if any, exist. The only major slide which has been satisfactorily demonstrated in the N.E. Dalradians is that between the Banff Nappe and a lower nappe as exposed and described by Harte (1966) in Glen Esk, the Tarfside Culmination acting as a window to the underlying structures. This slide, Harte suggests,
removed most of the upper limb of the lower nappe.

The major slides of the Perthshire Dalradian as illustrated by Sturt (1961) and Rast (1963, p.138) and in particular the Iltay Boundary Slide, are absent from Banffshire. Before discussing the significance of the absence of these slides it is necessary to consider the structural cross-section of the Iltay Nappe Complex as proposed by Sturt (1961). Sturt envisaged the compression of the Perthshire sedimentary pile from which the margins rose upwards and flowed north, to give northward facing nappes and south to give southward facing nappes, the central zone between the two sets of nappes being occupied by a symmetrical syncline - The Sron Mhor Syncline. Sturt states that the northward closing nappes are of much smaller amplitude than the southward closing nappes and that much of the translation appears to be on southward dipping slides. Sturt regards this as consistent with the concept of the nappes forming by gravitational flow on an initial regional slope of the basement towards the south. In tracing this nappe complex northwards to Banffshire the slides associated with Sturt's northward closing nappes and the nappes themselves disappear. In Banffshire the Lower Dalradian forms a conformable litho-stratigraphic section with constant younging direction eastwards from the Cullen quartzite (sometimes correlated with the Central Highland Granulites or Moine) and nowhere is there evidence of a tectonic break (Read, 1936). There must, therefore, have been a lessening of the intensity of deformation from Perthshire northwards or at least a decrease in the flexure of the basement to produce the regional slope. It is possible if the basement slope was steeper in Perthshire than in Banffshire during the slumping of the sedimentary pile and that the beds could buckle in such a way as to produce northward closing nappes the lower limbs being slid on southward dipping slides, i.e. the apparent
FIGURE 27.

Cross sections of the Tay and Banff Nappe complexes.

(a) after Sturt (1961).

(b), (c) Hypothetical sections in a general traverse north-eastwards from Central Perthshire to Banffshire.

(d) Banff Nappe complex.
Diagrammatic sections across Iltay Nappe Complex from Central Perthshire to Banffshire.

1. after Shurt 1961

LTA Loch Tummel Anticline
SMS Srôdn Mhor Syncline
BS Boyndie Syncline
AA Aberfoyle Anticline
BN Banff Nappe
northward translation of the nappes is only relative to the beds which have slid under them to the south. A diagrammatic illustration of the decrease in complexity of the nappe structure from Perthshire northwards to Banffshire is shown in figure 27. Sturt (1961) suggested a tentative correlation between his central syncline - The Sron Mhor Syncline - the Boyndie Syncline of Banffshire and the Loch Awe Syncline of the S.W. Highlands. All contain a schistosity in a vertical or sub-vertical attitude and they all contain low grade rocks in the core. Rast (1963, p.152) however, stated that the axis of the Boyndie Syncline did not correspond with a change of vergence of first generation folds as is the case in the Sron Mhor Syncline. Also, if cross-sections of the Banff Nappe (fig. 25) are correct, with the axis of the Boyndie Syncline lying above and slightly west of the downbend of the Lower Dalradian, it is obvious that the slumping of the sediments producing the nappe must have originated well to the west of the syncline. This being the case it is impossible for the Boyndie Syncline to be strictly analogous to the Sron Mhor Syncline. If, however, it is possible that the northward facing nappes of Perthshire formed on a steep southward dipping slope, that is the movement direction taken regionally was southward, then the correlation of the Sron Mhor and Boyndie Synclines is possible.

If the above hypothesis of the formation of the Banff Nappe is accepted one important fact needs stressing. The disposition of flow schistosity is as depicted in figure 26e, i.e. with an upturn below the 'trough'. Thus on the present land surface which as already stated represents an oblique section through the nappe, S1 will be projected as running approximately NNE - SSW from Macduff and swinging round to trend NE - SW to the north of Insch. This is of importance in discussing the later fold movements.
It should also be stressed that the $B_1$ folds of Collieston and
associated $S_1$ cleavage although belonging to the regional $F_1$ movements
are a late phase of $F_1$ and that the Collieston $S_1$ is not strictly analogous
to the regional $S_1$.

(b) **Second Fold Movements**

It is not possible to make a detailed study of the $F_2$ folds since
they are apparently confined to the Lower Dalradian and were not found
in any of the areas studied in detail for this thesis. It is considered
relevant, however, to consider their significance in respect of the broad
structural history of N.E. Scotland. Johnson (1962) describes second
generation structures from the Banffshire coast. Due to deformation by
later movements he was unable to deduce the original trend of the second
generation folds. Their axes are, however, at high angles to the first
generation structures and this fact coupled with his tentative correlation
between the $F_2$ structures of Banffshire and Perthshire (Rast, 1958)
suggests they are 'cross-folds'. The $F_2$ folds of Banffshire have a
strong axial plane cleavage ($S_2$) which transposes $S_1$ on a strain-slip
pattern. Rast and Platt (1957) envisage the formation of cross-folds
at high angles to the main fold trend due to spatial confinements of
the folding medium during deformation. They recognise two forms of
cross-fold. Firstly, since the cross-folds develop initially by flexure
the main folds may have sufficient time to imprint an axial plane cleavage
on the rock, which will be folded by the cross-folds and disrupted on a
'strain-slip' pattern as the latter tighten. Secondly, if the cross-folds
develop before the main folds have developed a cleavage, then the two sets
of folds will have a common schistosity. If the Banffshire $F_2$ folds are
cross folds genetically related to the $F_1$ folds, then they obviously
belong to the first type. Rast and Platt also suggest that cross-folds
will develop in the zone of 'active segmentation' (Argand, 1912), i.e. in the deeper structural zones. This would perhaps account for the absence of $F_2$ structures in the Upper Dalradian.

(c) Third Fold Movements

The third fold movements occurred after the emplacement of the basic sheet and the climax of metamorphism and can, therefore, be recognised by their effects on the metamorphic fabric and on the deformation of the basic sheet.

The two major third generation fold units of north-east Scotland are the Buchan Anticline and the Boyndie Syncline. The Buchan Anticline first recognised by Wilson (1886) is an asymmetric fold with a steeply dipping eastern limb and a relatively shallow dipping western limb; the axis trends NNE - SSW through Elgin. Read and Farquhar (1956) regarded its formation as due to an uprizing and westward moving gneiss dome, concomitant with the metamorphism. To the west of the Buchan Anticline is the complementary Boyndie Syncline. Read (1923, 1936) recognised the presence of a synclinal flexure in the area and termed it the Banff Syncline. Subsequently Sutton and Watson (1956) in an extensive structural analysis of the Banffshire coast-section established the presence of a huge syncline, whose axis trended NNE - SSW through Banff, this they termed the Boyndie Syncline. The western limb of the fold is extremely steep, the eastern limb (the western limb of the Buchan Anticline) relatively shallow. Read (1955) regarded these folds as secondary, flexing the primary recumbent anticline. Read and Farquhar (1956) suggested that sediments slumping off the uprizing Buchan Anticline gave rise to the eastward facing Collieston folds and the westward facing Rosehearty - Fraserburgh folds. Johnson and Stewart (1960) believed that the axis of the Boyndie Syncline swings round to an ENE - WSW trend
in Strathbogis; this they attribute to a later anticlinal folding the
axis of which runs through Huntily and Tarves. Johnson (1962) suggested
that the Boyndie Syncline and Buchan Anticline were third generation
folds - he describes the minor third folds on the steep western limb
of the Boyndie Syncline as monoclines forming a series of steps with
nearly horizontal or flat limbs. The axial planes of the folds dipping
westwards.

In the discussion of the first folds movements it was suggested
that a 'hump' was present at the front of the nappe with a depression
behind; it is believed that these represented embryonic forms of the
Buchan Anticline and Boyndie Syncline, and that during the third fold
movements compression accentuated these features to produce the two major
third folds. In the discussion of the Collieston structures and in
4.3(a) it was suggested that the first generation folds at Collieston
($E_1$) were formed by the gravity controlled collapse of the sedimentary
pile at the nappe nose, it was also suggested that the second generation
folds ($E_2$) were formed by renewed gravity collapse possibly due to an
increase in the slope of the basement. Since the $E_2$ folds of Collieston
post-date the metamorphism it is suggested they are equivalent to the
regional third folds. It is further suggested that they formed due to
the steepening of the limbs of the Buchan anticline. In the discussion
The $E_2$ folds at Collieston on the eastern limb of the Buchan Anticline
are E-folds with an easterly vergence. The $E_2$ folds at Rosehearty and
Fraserburgh on the western limb of the Buchan Anticline are S-folds with
a westerly vergence. These opposed senses of vergence may be explained
by regarding the Buchan Anticline as a large conjugate fold. However,
from the similarity in style of the Rosehearty - Fraserburgh $E_2$ folds (2.9)
and the Collieston $E_2$ folds to gravity collapse structures, the present
author favours the hypothesis proposed by Read and Farquhar (1956) that
gravity motivated westward slumping of the rocks off the Buchan Anticline produced the $B_2$ folds of Rosehearty and gravity motivated eastward slumping produced the $B_2$ folds at Collieston. Although this hypothesis explains the opposed senses of vergence of the $B_2$ folds across the Buchan Anticline and is supported by the style of the folds, it cannot be regarded as wholly reconcilable with evidence deduced from the metamorphic state of the rocks. The $B_2$ folds of Rosehearty and Fraserburgh affect andalusite schists. Because the $B_2$ folds post-date the climax of metamorphism but affected rocks still sufficiently hot to cause recrystallisation of mica and quartz it is perhaps not unreasonable to conclude that the rocks of Fraserburgh and Rosehearty were still under approximately the same cover as they were during the climax of metamorphism. As is discussed later (p. 152) the Fraserburgh rocks most probably had a cover of some 12 km during the climax of metamorphism. Some doubt must, therefore, exist as to whether the Buchan Anticline (approximately 20 km wide across the crest at the present erosion level) was a sufficiently major structure to produce gravity motivated folding to a depth of 12 km. Before this doubt can be resolved considerable experimental work will have to be undertaken on the mechanics of such structures.

Inland, towards Strathbogie, the third folds were largely controlled by the presence of the basic sheet. The distortion of the basic sheet (4.5) shows that the Huntly mass, originally forming the western part of
the sheet, sheared off under the influence of the third fold movements, from the Insch mass which acted as a rigid horizontal strut. The Huntly mass tilted upwards in the steep limb of the Boyndie Syncline to its present steep overturned attitude. As suggested on p. 99 and p. 164 the trace of the large shear plane south of Huntly most probably paralleled the trace of $S_1$ before the third generation movements. It was also suggested that the shear plane may follow, approximately, the horizon of the Boyne Limestone. This, however, is hypothetical and cannot be proved. What is certain is that the upper part of the Calcareous Flag Group has been sheared out, that part of the group roughly equivalent to the Cowhythe Gneiss, Boyne Limestone and Whitehills Group. If the Boyne Limestone did extend as far south as Cabrach then it is certain it was removed by the shearing but whether or not it formed the locus of shearing is impossible to demonstrate. As a result of the shearing the black slates of the Lower Dalradian come into contact with andalusite schists of the Upper Dalradian. Read (1955) recognised the presence of a major tectonic break in this area, since the trace of the Boyne Line follows the trace of the shear plane. Read, however, regarded it as a first generation pre-metamorphic structure, but the fact that it also cuts out the gneisses proves it to be post-metamorphic and, therefore, most probably a third generation event (the fourth being brittle small scale folding confined to the Lower Dalradian).

The shearing off and folding of the Huntly mass and the passive nature of the Insch and Bogancloch masses has resulted in a modification of the structural elements and the isogradic surfaces between Cabrach and Strathbogie. The nature of the deformation is most easily explained by reference to Ramberg (1959, fig. 14), where he diagrammatically illustrates the effects of lateral compression on a plastic medium within which lies a
rigid non-plastic strut, the maximum compressive stress lying parallel to the long axis of the strut. Straight lines originally drawn normal to the long axis of the strut, are buckled around the end of the strut after compression. Similar phenomena are thought to have occurred south of the Huntly mass. The trace of the first schistosity, originally running south-south-westwards from Banff and swinging slightly in Strathbogie to a NE - SW trend, is strongly modified south of Huntly so that it now runs ENE - WSW to E - W from Strathbogie to Cabrach. South of Cabrach it wraps around the western end of the Bogancloch mass, and strikes NNW - SSE. The andalusite isograd which originally trended WNW - ESE has been rotated into a general strike of NE - SW to the north of the Bogancloch mass. As will be shown in the discussion of the basic masses (5.3), the isograd between the knotted schist zone and the andalusite zone runs E - W from Newmòth for about 3 kilometres and then swings round to strike ENE - WSW, it is possible that within the more rigid aureole rocks the isograd preserves its original or near original trace and that it has been rotated by the third movements outwith the aureole. As suggested in the discussion of the basic masses (5.3) and figure 38, the andalusite isograd at Cabrach and Strathbogie is essentially a compromise between the regional and thermal metamorphic gradients. Before the third fold movements the regional isograd trended NW - SE and the isotherms of the Bogancloch aureole trended E - W. The 'compromise' isograds trended approximately WNW - ESE to the north of the Bogancloch mass. Thus, the original trace of the andalusite isograd, before the third fold movements but after the intrusion and metamorphism associated with the basic sheet, ran approximately E - W north of the Insch and the extreme eastern end of the Bogancloch mass, it then swung round to a WNW - ESE trend to the north of the main part of the Bogancloch mass, and
eventually outwith the effects of the aureole, i.e. about 4 km north of the basic intrusion, into a NW–SE trend. The relationship of the isograd to the topography suggests it has a shallow dip to the west in the area of the Kirkney Water and since it most probably dipped to the east before the third fold movements (fig. 38) then it must have been rotated through the vertical during the third fold movements.

It is suggested that on the steep western limb of the Boyndie Syncline faulting and slumping caused the deformation of the metamorphic pattern and produced the phenomena quoted by Read (1923, 1955) as evidence for his Boyne Line.

In the area of Strathbogie and Gabrach the third folds are apparently unaffected by the shearing and tilting of the Huntly mass. Their trend as deduced from the rare minor folds but mainly from the trace of their axial plane schistosity and axes deduced from bedding/cleavage intersections continues on a NNE–SSW trend from Banffshire south through Strathbogie into the aureole of the Insch and Bogancloch masses. On the south side of the Bogancloch mass they also have a NNE–SSW trend. Slight fluctuations of this trend are found to the north of the Bogancloch mass. It is, therefore, suggested that at the onset of the third fold movements lateral compression induced some open minor folds in the deeper structural zones from Strathbogie southwards. As lateral compression increased or continued, the Huntly mass sheared off from the Bogancloch mass and was rotated upwards to its present steep attitude. This caused the formation of gravity slump folds in the high structural zones, and, furthermore, buckled, tightened and imprinted an axial planar schistosity on the third folds of Strathbogie, Gabrach and south of the Bogancloch mass.

The cleavage in the Macduff Slates and south of Macduff is a
composite one, with the $S_1$ slaty cleavage and the $S_3$ axial planar cleavages of the third fold Boyndie Syncline in close parallelism. The suggested causal mechanism is as follows. At the end of the first generation movements the $S_1$ slaty cleavage was dipping at about $30^\circ$ to the west, southwards from Macduff. As the Boyndie Syncline formed and the original depression of the nappe tightened as the dip of the $S_1$ cleavage steepened. As this happened folding was facilitated by the differential slip of microlithons. The boundaries of these microlithons were $S_1$ slaty cleavage planes, the slip along these planes and the consequent recrystallisation of chlorite and biotite flakes produced and define $S_3$. This produced the close parallelism of $S_1$ and $S_3$ from Macduff southwards to Strathbogie. Although this mechanism was true on a regional scale, the pattern was locally modified. In the higher structural zones gravity slump folding, buckled the $S_1$ slaty cleavage and induced an axial plane cleavage ($S_2$) oblique to $S_1$. South of Strathbogie the boundaries of the microlithons are no longer parallel to $S_1$, continuing on the NNE - SSW trend.

Johnson and Stewart (fig. 1, 1960) show the axis of the Boyndie Syncline swinging round south of Strathbogie from a NNE - SSW trend to an ENE - WSW trend. This they attribute to the effects of a fourth generation antiformal fold whose axis runs through Huntly and Tarves. The swing in the axis they deduced from the swing in the strike and in the trend of the slaty cleavage which they regarded as the axial planar cleavage of the Boyndie Syncline. It has now been shown that the true axial plane cleavage of the Boyndie Syncline and, in consequence the axis of the Boyndie Syncline, does not swing round in Strathbogie and in consequence the evidence for the Huntly - Tarves antiform is greatly reduced. Although the rocks and first generation structures are arranged
in a general antiformal pattern, it has been shown that this is due to the effects of the third movements and not to a later fold phase. The Boyndie Syncline opens radically in Strathbogie and the steep western limb becomes involved in a complex interference pattern south of Huntly. South of the Insch and Bogancloch masses the Boyndie Syncline probably reappears and begins to tighten southwards but the evidence is masked by the Newer Granites. It is unlikely, however, that it ever attained the tightness and steepness of limb, south of Insch which it exhibits on the coasts of Aberdeenshire and Banffshire. With reference to Ramberg (fig. 14, 1959) it is possible to regard the Insch mass as the "stiff plate" (Ramberg's Z axis) and Ramberg's X axis as the axis of the Boyndie Syncline and very generally, not taking account of the asymmetry of the fold, the other lines as contours on the limbs, increasing in degree outwards from the centre.

The secondary folds (B₂) of the Ithan valley are post metamorphic and, therefore, most probably third generation structures.

(d) Fourth Fold Movements

These are late stage brittle folds confined to the Lower Dalradian they trend NNE - SSW, and are described by Johnson (1962). They may be cross-folds to the third folds similar to the F₂ cross-folds on the main nappe folds (F₁) and similarly confined to the deeper structural zones.

(e) Faulting

Subsequent to the cessation of the main Caledonian movements, the granites were intruded. Subsequent to these and after the deposition of the Old Red Sandstone, NE - SW faulting occurred, giving the present day Devonian outliers scattered across N.E. Scotland.
4.4 Metamorphism

It is intended in this section to discuss the experimental evidence on the stability of various metamorphic minerals; to examine the probable genesis of some minerals and to propose a model for the metamorphism of N.E. Scotland.

(a) Cordierite

Cordierite is found associated with two types of metamorphism in N.E. Scotland; in the thermal aureoles of the Younger Gabbros and as a characteristic mineral of the Buchan type regional metamorphism. The two types of metamorphism are probably closely allied. For the purposes of this discussion only the regional cordierite, in particular those of the Collieston coast section, will be discussed. The mineralogy of the Collieston section has been discussed in 2.5 where it was shown that cordierite developed from 'knots' as the metamorphism progressed, i.e. in a north-south traverse of the section. Optically recognisable cordierite first appeared at Bottie Murlan (although as suggested cryptocrystalline cordierite may exist at lower grades) north of the first appearance of brown biotite. Since biotites have a wide range of chemical composition and since reactions producing biotite are dependent on many variables, it is extremely difficult to fix the temperature and pressure conditions of biotite formation. McNamara (1965) suggested that the biotite isograd in the S.W. Highlands represented a temperature of ca. 400°C. Hietanen (1967) from work based on field data suggests that biotite will form from chlorite at ca. 300°C. Despite the paucity of accurate information it is perhaps safe to assume that the cordierites of Collieston were first formed at maximum temperatures of 350°C. Schreyer and Yoder (1959, 1964) suggest that the lower stability boundary of Mg-cordierite was at ca. 500°C (fig. 43, curve AB). They also suggested
FIGURE 28.

A - B : Lower stability limit of Mg-cordierite
(Schreyer and Yoder, 1964)

G - E ; G - D ; G - H : Reaction curves for the
formation of cordierite from various
chlorite assemblages. (Winkler, 1965,
p. 56-57).

T - U : Upper stability limit of cordierite
derived from field data. (Hietanen, 1967).
that the presence of iron in the molecule would not significantly effect the lower stability limit of cordierite, effecting only the melting curve. In nature they envisage this lower stability boundary as represented by the reaction:

\[
\text{Mg}_4 \text{Al}_4 \text{Si}_2 \text{O}_{10} (\text{OH})_8 + 2\text{Al}_2 \text{Si}_4 \text{O}_{10} (\text{OH})_2 \rightarrow \text{chlorite} + \text{pyrophyllite} \rightarrow 2 \text{Mg}_2 \text{Al}_4 \text{Si}_5 \text{O}_{18} + 6\text{H}_2\text{O}.
\]

\text{cordierite + water} \quad (1)

Yoder (1952) and Schreyer and Yoder (op.cit.) regard excess potash as having an inhibiting effect on the formation of cordierite. Since, in the presence of excess K₂O, pyrophyllite will be inhibited by muscovite and cordierite will form by the reaction:

\[
\text{chlorite + muscovite + quartz} \rightarrow \text{cordierite + biotite + water} \quad (2)
\]

This reaction taking place at higher temperatures than (1). Yoder (op.cit.) suggests that in the presence of excess K₂O, muscovite may exist to relatively high temperatures without the formation of cordierite.

It is obvious that the cordierites of Collieston appear at temperatures well below the stability field of cordierite as determined experimentally. Fyfe, Turner and Verhoogen (1958, p.204) suggest that a deficiency of potassium in the system would allow the andalusite and cordierite of spotted slates to appear in the albite-epidote hornfels facies (with maximum temperatures of ca. 400°C (op.cit., fig.107)). It is difficult to substantiate this view, for although excess potash inhibits cordierite development there is no evidence to suggest a deficiency of potash would lower the stability field of cordierite below the curve of reaction (1). In a potash deficient system muscovite will be inhibited and pyrophyllite developed, the cordierite, however, will
still be masked by the pyrophyllite. Since reactions (1) and (2) are both in effect dehydration curves, the reaction curves could be lowered if $\mu H_2O$ was low. Although it is conceivable in high level thermal aureoles that $\mu H_2O$ was lowered considerably, it is difficult to conceive of $\mu H_2O$ being sufficiently low during the Collieston metamorphism to move the reaction curve (1) to temperatures 150 - 200°C below the curve of Schreyer and Yoder. It, therefore, appears some other factors, so far undiscovered, can influence the stability field of cordierite. It may be argued that the development of biotite was inhibited to higher temperatures than it normally appears at and therefore the Collieston cordierites although appearing below the biotite isograd were still formed at fairly high temperatures, however Winkler (1965, p. 79) gives the formation of biotite as:

$$3 \text{muscovite} + 5 \text{prochlorite} \rightarrow 3 \text{biotite} + 4 \text{Al-chlorite} + 7\text{quartz} + 4H_2O$$

This reaction is a dehydration reaction and would therefore only be inhibited by high values of $\mu H_2O$. Such conditions would of course also inhibit the formation of cordierite. Hietanen (1967) suggests the reaction:

$$\text{chlorite + muscovite + haematite} \rightarrow \text{biotite} + H_2O + O_2$$

Again conditions inhibiting this reaction would also inhibit cordierite formation.

The problem of cordierite development at temperatures below the experimentally suggested stability field must therefore be left unresolved.

(b) Sillimanite

The development of sillimanite in metamorphic rocks and in particular its association with biotite has been widely discussed in geological literature (Watson, 1948; Tozer, 1955; Francis, 1956; Chinner, 1961; Gribble, 1965).

In the north-east of Scotland sillimanite is abundantly formed in
the gneisses and in the thermal aureole of the Boganclough basic mass. It can be clearly demonstrated that the modal percentage of sillimanite increases as the percentage of andalusite decreases. The sillimanite occurs as mats of fibrolite in close association with biotite and ore, apparently connected to the breakdown of biotite, or at least, to the masking of biotite by felt of fibrolite during the progression of metamorphism. In the initial stages the boundaries of the biotite become diffuse, optically clear biotite merging with an interwoven mat of fibrolite crystals and biotite. Small fibrolite crystals are found dissociated from the biotite penetrating neighbouring quartz grains. As metamorphic grade increases the felted mass of fibrolite spreads over the biotites, and although relic cores of biotite remain in some sections, the fibrolite felt eventually masks or replaces the biotite. In the initial stages of this 'sillimanitisation' cores of andalusite can be seen in the groundmass often strongly sieved with quartz. In the higher sillimanite grades no andalusite can be seen. Although the connection between disappearing andalusite and appearing fibrolite is strong, the two polymorphs are never seen in contact. Sillimanite is often associated with cordierite that is occasionally badly altered to a yellow mineral -pinite of Deer, Howie and Zussman (1965, Vol. I, p. 284). Also associated are potash-rich feldspars, quartz and plagioclase, also, generally within the thermal aureoles, large plates of muscovite. Iron ore occurs as an accessory in some rocks but is conspicuously absent from others.

Tozer (1955) suggested that the association of fibrolite and biotite represented the breakdown of biotite to sillimanite; he regarded K, OH and Mg as being expelled from the system and the Fe constituent of the biotite precipitating out as iron ore. Tozer cited the multitude of small iron ore grains in the neighbourhood of the fibrolite in support of
his hypothesis. Francis (1956) however suggested a more probable reaction was the migration of alumina and silica from dissolved kyanite on to the biotite catalysing the breakdown of biotite and the precipitation of sillimanite, K-feldspar and iron ore, i.e.:

$$\text{Fe-biotite} + \text{kyanite} = \text{K-feldspar} + \text{sillimanite} + \text{iron ore} + \text{water}$$

Francis suggested that the decolourisation of the biotite during 'sillimanitisation' was evidence in favour of loss of iron. Chinner (1961) disagreed with this hypothesis and suggested, on the basis of an apparent constant MgO/FeO ratio in unaltered biotite and fibrolite, that dissolved kyanite migrated to the biotite as alumina + silica and because of the similarity of the sillimanite and biotite lattices was able to nucleate on the biotite and form sillimanite. He suggested the decolourisation was merely due to the dilution of the biotite colour by the overlying fibrolite. Gribble (1966) accepted Chinner's hypothesis the reaction being given as:

$$\text{biotite} + \text{kyanite} = \text{biotite} + \text{sillimanite}.$$

The present author disagrees with Chinner's hypothesis. In the highest grade rocks of the Cabrach area, long matted cords of fibrolite follow sinuous courses through the rock; no biotite can be identified. These fibrolite cords often radiate like tentacles from some central mass. Under high power magnification these cords are composed solely of a mass of small elongate fibrolite crystals without evidence of biotite. In some rocks knots of biotite are surrounded by fibrolite. These fabrics are difficult to reconcile with the hypothesis proposed by Chinner. The present author prefers the hypothesis proposed by Francis. In many rocks however there is little or no evidence of precipitated iron ore. The
ratio of precipitated iron ore to biotite is ca. 1:5, therefore for the average rock under consideration which has about 20-25% biotite, 4-5% of iron ore should be precipitated. If the assumption is made that the biotite has broken down it is necessary to postulate where the iron and magnesium have gone. Cordierite is often abundant but if it is argued that the magnesium and iron released by the biotite formed fresh cordierite then a reaction of the following type must be assumed to have occurred:

\[ 7\text{Al}_2\text{Si}_3\text{O}_5 + 2\text{KFe}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2 + 9\text{SiO}_2 = 2\text{KAlSi}_3\text{O}_8 + \text{Al}_2\text{Si}_5\text{O}_{18} + 3\text{Fe}_2\text{Al}_4\text{Si}_5\text{O}_{18} + 2\text{H}_2\text{O} \]

andalusite + biotite + silica → K-feldspar + sillimanite + cordierite + water.

This however would imply the following modal percentages:
ca. 35% andalusite + 35% biotite → 5% fibrolite + 65% cordierite.
The percentages on the right hand side of the equation are obviously unacceptable and therefore it can be assumed that the magnesium and iron did not go directly into cordierite. The most probable answer to the problem lies in the extensive pinitisation of the cordierites. That cordierites should be so altered in such high grade rocks when they are perfectly fresh at lower grades, and especially their presence in otherwise fresh rocks is certainly anomalous. It is probable that the circulating water, magnesium, iron and possibly potash from the biotite breakdown may have altered the cordierites to pinite. The term pinite is rather a catch name for cordierite alteration products. Deer, Howie and Zussman (1963, Vol. II, p. 284) suggest it is often composed of chlorite felts, muscovite, iron ore and a dark yellow isotropic mineral. It, therefore, seems probable that the magnesium and iron have been absorbed by cordierite alteration products. This hypothesis seems to
be supported by the general association of relatively fresh cordierite with the presence of iron ore in association with the fibrolite and the relative absence of iron ore in rocks containing altered cordierites.

In the breakdown of biotite, on the lines proposed by Francis, the ratio of K-feldspar produced to original biotite is ca. 1:1.5. In some rocks however staining has shown almost 60% or over of K-feldspar in the mode suggesting an original biotite content of 90%. This is excessively high. If it is assumed that biotite was going to sillimanite at fairly high temperature or in a dry environment it might be argued that muscovite in the matrix broke down to give sillimanite and K-feldspar, in the reaction:

\[ \text{muscovite} + \text{quartz} = \text{sillimanite} + \text{K-feldspar} + \text{water} \]

However, this still gives a ratio of muscovite to K-feldspar of ca. 1.3:1, still suggesting that the original mica content of the rock was 72%. This seems excessively high and suggests some form of potash introduction into the system and a reaction to produce K-feldspar as follows:

\[ K_2CO + Al_2SiO_5 + 5SiO_2 = 2KAlSi_2O_8 \]

Certain rocks contain high percentages (up to 40% of the mode) of muscovite associated with fibrolite development. Assuming higher water pressures or lower temperatures it is possible to modify Francis' equation as follows:

\[ \text{biotite} + \text{andalusite} = \text{muscovite} + \text{sillimanite} + \text{quartz} + \text{FeO} \]

It is possible that muscovite is present, initially, in the breakdown of all biotite, but itself breaks down to sillimanite and K-feldspar with increase in temperature or a fall in water pressure. The ratio of muscovite to biotite in the breakdown of biotite and andalusite to muscovite and sillimanite is ca. 1.2:1, this implies that to produce 40% of muscovite in the mode 48% of biotite must have been originally
present. Again this seems high and suggests some form of potash introduction to the system. It is possible potash released in the breakdown of biotite may have migrated to pockets, thus creating patches rich in potash. The breakdown of biotite and the production of biotite may be expressed:

\[2\text{KFe}_2\text{Si}_3\text{Al}_3\text{Si}_2\text{O}_{10}(\text{OH})_2 + \text{Al}_2\text{SiO}_5 \rightarrow 2\text{Al}_2\text{Si}_5\text{O}_{10} + 6\text{FeO} + 5\text{SiO}_2 + (\text{K}_2\text{O + 2H}_2\text{O})\]

\[2\text{biotite} + \text{andalusite} \rightarrow 2\text{sillimanite} + \text{iron ore} + 5\text{silica} + (\text{potash + water})\]

If the \((\text{K}_2\text{O + 2H}_2\text{O})\) then migrated into pockets rich in andalusite it might react to form muscovite:

\[3\text{Al}_2\text{SiO}_5 + 3\text{SiO}_2 + (\text{K}_2\text{O + 2H}_2\text{O}) \rightarrow 2\text{KAl}_2\text{Si}_3\text{O}_{10}(\text{OH})_2\]

or alternatively to produce K-feldspar (water escaping):

\[\text{Al}_2\text{SiO}_5 + 5\text{SiO}_2 + \text{K}_2\text{O} \rightarrow 2\text{KAlSi}_3\text{O}_8\]

If the potash produced in biotite breakdown does migrate into pockets, then patches must exist with a deficiency of potash and characterised by the assemblage sillimanite + quartz + cordierite. Such patches do exist, but are very small, suggesting that the production of potash and water and its subsequent migration into pockets has occurred on a fairly localised scale (ca. 20 cm.). The concept of potash and water migration from dissolving biotites to areas rich in andalusite, thereby producing muscovite or K-feldspar, is perhaps more credible than Francis' (1956) concept of alumina and silica migration from the dissolving kyanite (or andalusite) to the biotite, because potash + water is far more mobile than alumina + silica. Although it is probable that localised migration did occur, the overall modal percentages of muscovite and K-feldspar in association with the fibrolite is too great to be attributed solely to the breakdown of biotite and it is suggested that some form of regional potash metasomatism occurred; this concept will be discussed more fully when evidence from other sources can be considered.
Watson (1948) suggested that the breakdown of biotite to fibrolite was due to metasomatism from neighbouring leucocratic veins, and it would appear that circulating potash solutions might catalyse biotite breakdown.

One mineral assemblage which perhaps deserves special mention occurs in a rock from the aureole of the Bogancloch mass. A band of fibrolite (ca. 0.5 cm) apparently forming from biotite breakdown is associated with muscovite. Some distance (3 cm) from the fibrolite band there is a fairly abundant development of andalusite, these crystals are apparently stable, because they show prismatic outlines. There is no biotite associated with the andalusite. Andalusite is only unstable, apparently, in the neighbourhood of the biotite. The inference of this texture is that in the breakdown of andalusite in association with the breakdown of biotite to produce sillimanite, the reaction is initiated by the breakdown of the biotite rather than the instability of the andalusite polymorph. This solitary specimen is, however, too small on which to base general conclusions.

(c) Garnet

Garnet occurs in north-east Scotland in three different environments. Firstly it is found extensively in the Lower Dalradian where it is present in a wide range of metamorphic zones. Secondly, it occurs in the regional sillimanite gneisses and thirdly it is present in parts of the aureole of the 'Younger Gabbros'. The first environment is not unusual since garnet is a characteristic mineral of the Barrovian zones of metamorphism, the other two occurrences, however, are somewhat anomalous. In the gneisses it occurs as part of the disequilibrium assemblage andalusite - cordierite - sillimanite - garnet. In the aureoles its presence is unusual since garnet is normally considered a high pressure equivalent of cordierite (Chinner, 1962). In the gneisses garnet appears
as relatively large (ca. 1-2 mm) subhedral crystals, free of inclusions, usually in localised pockets associated generally with quartz and plagioclase. In the aureoles of the basic masses garnet is generally rare; around Belhelvie regional garnets in the gneisses have been involved in aureole metamorphism, these are described by Stewart (1942).
In the present investigation aureole garnet was only found at Den of Wraes, near Insch, but it must be added that rocks near the contact are generally obscured and the presence of garnet at the northern contact of the Insch mass may be more extensive than would appear at first. In the rock from the Den of Wraes garnet occurs as very small (ca. 0.1 mm) abundant crystals more or less confined to bands, about 4-5 mm thick.
Chinner (1962), writing on the stability of almandine in thermal aureoles, suggests two conditions where almandine may be stable outwith high pressure environments. He shows that in low pressure conditions where the complete solid solution of cordierite is stable, garnet will be limited to rocks where $FeO + MgO/Al_2O_3$ is greater than one. He also suggests that high partial water pressures will preferentially mask cordierite. The aureole rock from the Den of Wraes is only about 10m from the contact. Sadashivaiah (1950) suggested that very localised Ca, Mg, Fe, Ti, Mn and P metasomatism of the country rocks had occurred at the contact of the Insch aureole (from the presence of an olivine bearing rock). If this is true then it is possible that sufficient magnesium and iron were introduced locally into the country rock to allow the formation of garnet rather than cordierite. In the gneisses pressures were higher than in the Insch aureole. According to Chinner (op. cit.), with increasing temperature the limiting iron content on cordierite stability will become an increasingly inhibiting factor, the limiting content of iron becoming less as the pressure rises, that is to say with increasing pressure there is a corresponding increase
in the possible composition from which garnet will form preferentially
to cordierite. In the gneisses, however, the garnet appears to be a
late stage mineral, that is appearing in rocks which originally contained
stable cordierite - andalusite assemblages. As will be discussed later
in this chapter the progression of metamorphism from andalusite - cordierite
schists to sillimanite gneisses is considered to be an approximately
isobaric reaction. It is, therefore, difficult to attribute the
development of garnet as due either to original composition or to an
increase in its stability field resulting from an increase in pressure.
However, it is suggested later that the production of the gneisses was
facilitated by the introduction and mobilisation of large quantities of
water into the system and this may have raised the partial water pressure
sufficiently to bring the rocks out the stability field of cordierite
into the stability field of garnet. It will, however, be necessary to
determine the chemical composition of the garnets and co-existing
cordierites before firm conclusions can be drawn of the paragenesis of
garnet.

(d) The Alumino-silicate polymorphs and a model for the metamorphism.

The alumino-silicate polymorphs are potentially good geobarometers
and geothermometers for the conditions of metamorphism. Since the
inversion of one polymorph to another is dependent on only two variables
- pressure and temperature - they provide more realistic evidence of the
pressure - temperature conditions than mineral inversions dependent on
other variables - $\mu_2$, $\mu_{\text{CO}_2}$, $\mu_{\text{O}_2}$. In N.E. Scotland all three
polymorphs are present but before discussing how their distribution
reflects the conditions of metamorphism it is necessary to review the
experimental and field evidence for the phase diagram of the alumino-
silicates.
The first generally accepted position of the triple point was 9 Kb and 390°C based on the experimental data of Khitarov et al., (1962). This result was largely confirmed by Bell (1963). The value remained unaltered until Newton (1966) suggested that the triple point lay at 4 Kb and 500°C. Weidl (1966) placed it at ca. 2.4 Kb and 400°C. Holm and Kleppa (1966) working mainly from a thermodynamic approach plotted it at ca. 5.8 Kb and 410°C. Subsequent to this Matsushima et al., (1967) working on the Al₂O₃ - SiO₂ - H₂O and Al₂O₃ - H₂O systems largely confirmed Newton's position for the kyanite - sillimanite boundary. Newton showed during his experiments that the percentage of Fe₂O₃ in the polymorphs did not effect the phase boundaries. Before the merits of these plots can be considered it is necessary to examine the position of the hydrous phases on the diagram. The main dehydration curve is given by the reaction:

pyrophyllite → kyanite + quartz + water

This boundary has been experimentally fixed by Matsushima et al., (1967) as a smooth curve (fig. 29b) running from 15 Kb at 570°C through 5 Kb at 520°C to intersect the pressure axis at about 470°C. Winkler (1965, p.159) places the boundary at more or less the same position. Since this is a dehydration reaction it will be influenced by the value of \( \mu H₂O \) and at very low values of \( \mu H₂O \) the reaction might occur at substantially lower temperatures perhaps in the range 300 - 400°C. It is also considered pertinent at this point to examine the position where conventional metamorphism is thought to begin, that is, the upper limit of diagenesis. Fyfe, Turner and Verhoogen (1958, p.167) recognised the zeolite facies, largely on the results of Coombs (1954), as representing the transition zone between diagenesis and metamorphism, they considered the lower limit of the zeolite facies to be about 200 - 300°C at 2 to
(A) Positions of the triple point in the alumino-silicate diagram after various workers.

A - andalusite; K - kyanite; S - sillimanite
(1) after Khitarov (1962); (2) after Bell (1963);
(3) after Holm and Kleppa (1966); (4) after Newton (1966)
(5) after Weill (1966); (6) after Hietanen, (1967).

(B) Alumino-silicate diagrams after Newton (1966)

A - andalusite; K - kyanite; S - sillimanite
a - b; analcime + quartz → albite (Campbell and Fyfe, 1965)
r - s; heulandite → laumontite (Fyfe, Turner and Verhoogen,
   1958; Winkler, 1965).

C - D - E; suggested position of pyrophyllite → alumino-
silicate transition during the metamorphism of
N.E. Scotland.

h - g - f; pyrophyllite → alumino-silicate (Winkler, 1958)
x - y: minimum geothermal gradient (Birch, 1955)
i - j: possible position of geothermal gradient during
the metamorphism of N.E. Scotland (see text).

(C) As for (B); a - d - g - b possible position of geothermal
gradient during the metamorphism of N.E. Scotland
(see text).
3 Kb. The boundary being marked by the extensive albition of the plagioclase and the predominance of laumontite over heulandite.

Although Coombs (1960) subsequently extended the zeolite facies to include heulandite bearing rocks he was using the term zeolite facies to group diagenesis and the low grades of metamorphism. The albition can be equated approximately to the reaction:

\[
\text{analcime + quartz} \rightarrow \text{albite + water}
\]

The curve for this reaction is shown by Campbell and Fyfe (1965) as an isothermal line (fig. 29b) at 200°C up to 2 Kb and then curving round to intersect the pressure axis at about 4.2 Kb. The line of this reaction is shown by Fyfe, Turner and Verhoogen (1958, fig. 68) as an isothermal line at 300°C. The boundary between heulandite and laumontite is shown by Fyfe, Turner and Verhoogen (op. cit., fig. 67) as an isothermal surface at about 350°C. But the implication from Coombs (1967) is that it lies nearer 150 - 200°C. The evidence, therefore, suggests that metamorphism begins about 200°C at pressures up to 2 or 3 Kb, the temperature thereafter being controlled by the thermal gradient.

It is now possible to consider the merits of the various positions of the aluminosilicate triple point. With Bell's (1963) plot, the triple point lies well on the low temperature side of the dehydration curves. The intersection of the kyanite - sillimanite boundary and the dehydration curve is in excess of 10 Kb, suggesting that kyanite would be masked by hydrous phases at pressures less than 10 Kb, equivalent to a depth of burial of nearly 40 km! Even if the dehydration curve is taken at its lowest reasonable temperature (300 - 400°C) it still suggests that kyanite would be inhibited below about 8 Kb. With Newton's (1966) plot the dehydration curve lies just on the low temperature side of the triple point (fig. 29b) and indicates that kyanite could form at
about 4 Kb, and if the lower position of the dehydration curve is taken, at about 3 Kb. Weill's triple point lies on the low temperature side of the dehydration curve and would allow kyanite formation at 4 Kb. The lower dehydration curve allowing formation at 2.3 Kb. It is obvious that Bell's results are irreconcilable with field data since kyanite is occasionally found associated with lower greenschist minerals (e.g. Read, 1934) and also in areas where the hydrostatic pressure was probably insufficient (Read, 1962; Haller, 1962; Wenk quoted by Haller, 1962). In order to reconcile the experimental and field data a variety of arguments were proposed (see Rutland, 1965, 122-124). Newton's and Weill's results, however, are much more reconcilable with the field evidence than those of Bell and it is interesting to note that Histanen (1967) in a paper published after, but prepared before Newton's results were published, deduced purely from field data a position for the triple point at approximately 5 Kb and 500°C. Although it would be premature to assume either Newton or Weill's results to be final it is perhaps reasonable to assume future work will not change them significantly. On Weill and Newton's diagrams the kyanite - andalusite boundary intersect the temperature axis at about 150°C and thus kyanite, theoretically is stable at low pressures (> 1.5 Kb) up to 300°C. The concept of kyanite as a high pressure mineral is misleading - kyanite only appears at high pressures because it is masked by hydrous phases at lower pressures. Thus it is not unrealistic to presume that if the pyrophyllite → kyanite (and andalusite) curve is lowered due to low ν H₂O values, then kyanite could appear at 2 Kb and 350°C. This would place it in the Greenschist facies (Coombs, 1967) and would presumably imply that hydrous phases characteristic of the Greenschist facies such as chlorite might be inhibited. These are, however, extreme cases and it is more probable
that it is normally formed at minimum pressures of ca. 3 Kb. This is equivalent to a depth of burial of ca. 11.3 km.

It is considered worthwhile to briefly review the arguments proposed by various workers to reconcile the apparent difference in field evidence for depth of burial and the minimum pressure necessary for kyanite growth, most of these arguments were proposed when Bell’s triple point was the accepted value, and although with Newton’s value the necessity for these arguments is greatly reduced they may still be applicable in explaining certain discrepancies which still exist.

Rutland (1965, p. 129) dismissed the possibility that tectonic overpressure could raise hydrostatic pressures by 4 or 5 Kb, since at pressures of 4-5 Kb rocks would be plastic and the overpressures would be dissipated by creep or flow. He did, however, accept that tectonic effects could raise the hydrostatic pressure by small but significant amounts. Rutland also examined the possibilities of thermal effects where expansion of the rocks, due possibly to an igneous intrusion, could produce overpressures, also where the release of water or gases in certain reactions could exceed their expulsion from the system and thus create fluid or gaseous overpressures. Rutland, however, having reviewed those possibilities concluded that the most probable cause of variance between field and experimental data was the presence of foreign ions in the naturally occurring polymorphs. Pitcher (1965, pp. 327-341) accepted that the presence of foreign ions could play a significant part and proposed that the kyanite in the thermal aureole of the Donegal Granite was due to pressures created by a forcefully intruded granite. Lobjoit (1964) also attributed overpressures due to forceful intrusion to explain the presence of kyanite in the aureole of a granodiorite in Ghana.

Chinner (1966) working from experimental data on the alumino-silicate
system and the disposition of the phases in N.E. Scotland derived a pattern of isotherms and isobars which reflected the conditions of regional metamorphism. Chinner suggested that the imprinting of sillimanite was a later phase than the growth of andalusite and kyanite. This he based on textural evidence which shows that sillimanite apparently formed from the dissolution of andalusites and kyanites, and also on the presence of disequilibrium assemblages associated with sillimanite. Chinner's evidence was mainly from Glen Clova, but the present author has found similar textures in the sillimanite rocks of Donside. Chinner, therefore, proposed that the metamorphic pattern of N.E. Scotland was imprinted by two phases of metamorphism. Initially depth-controlled metamorphism gave rise to a zone of hydrous phases in the high structural levels underlain by an andalusite zone which was in turn underlain by a kyanite zone. Subsequent to this in the secondary or later phase sillimanite was produced in localised 'heat-nodes'. At the present day the andalusite - kyanite boundary is masked by sillimanite but Chinner has deduced its trace from relics of andalusite and kyanite within the sillimanite zone. However, along most of its outcrop the line is masked by the Newer Granites and their aureoles or by the 'Younger Gabbros'. Chinner's evidence is, therefore, somewhat sketchy. Then from phase evidence Chinner drew isotherms parallel to the hydrous phases boundary and from the isotherms and the position of the andalusite - kyanite boundary deduced the position of the isobars, deriving a pattern of isotherms and isobars as shown. The divergence of isotherms and isobars south of Donside Chinner explains as due to 'synmetamorphic anticlinal folding'. Chinner's hypothesis has been criticised on several points. Firstly, Johnson (in discussion of Chinner) pointed out that a synmetamorphic fold was contrary to the textural evidence which implied a static
metamorphism, also there was no known structure mapped on the ground equivalent to Chinner's hypothetical fold. Also, the trend of the fold suggested by Chinner as $F_2$ is at almost right angles to the regionally accepted $F_2$ trend, being more nearly parallel to the trends of $F_1$ and $F_3$ - an important fact, as will be revealed later. Chinner's arguments may also be criticised on the grounds of the experimental data. Chinner accepts that the experimentally derived position of the hydrous phases field, taken as the limit of stability of pyrophyllite, lies well to the high temperature side of the triple point of the alumino-silicate polymorphs - Chinner using Bell's plot. He, therefore, suggests that $\mu H_2O$ was extremely low and that the hydrous phase boundary was pushed back to 200°C. This allowed him to draw a thermal gradient to represent the depth controlled metamorphism passing from the hydrous phases through the andalusite field and directly into the kyanite field. Chinner, however, is making larger assumptions than at first appear evident. He accepts Kennedy's (1959) data for the breakdown of pyrophyllite (ca. 600°C) and therefore proposes that $\mu H_2O$ was so low that the hydrous phase boundary was driven back 400°C. He also implies, by placing the hydrous phase boundary at 200°C, that the production of most of the classical Barrovian index minerals - staurolite, garnet, biotite and chlorite - was taking place within the accepted zone of diagenesis (see above). It is, therefore, obvious that as they stand Chinner's arguments are untenable. They may, however, be re-applied to the phase diagrams of Newton and Weill and their merit re-tested. Taking the pyrophyllite upper stability limit as a roughly isothermal line (curve Hh, fig. 29b) of ca. 500°C (Matsushima et al., 1967) it is still found to lie well on the high temperature side of Weill's triple point. Even if the curve is considered to be lowered by low $\mu H_2O$ values, to
the reasonable minimum of 350 - 400°C (curve ce, fig. 29b) it still lies very close to the triple point. With Newton's plot if the dehydration curve is lowered to 350 - 400°C then it is just possible to draw a geothermal gradient (curve idgj, fig. 29b) passing from the hydrous phases through the andalusite field into the kyanite field, the line having a slope of ca. 15°/km. If the line is drawn at a shallower slope it does not pass directly from the andalusite into the kyanite slope, if it is drawn steeper it misses the hydrous phases. With this line the hydrous phases/andalusite boundary is at 2.2 Kb (equal to a depth of burial of 8 km) and the andalusite/kyanite boundary at 3.6 Kb (12.5 km). It is possible to see how these values fit the field evidence. Johnson (1963) computed the amount of cover during metamorphism to the top of the kyanite zone in Banffshire as 6.3 km, this figure he derived from the 4.3 km of existing Upper Dalradian sediment (from Sutton and Watson, 1955) above the kyanite zone to which he added the total thickness of grits (2 km) in the Highland Border succession which he regarded as equivalent to the missing cover. However, it is known from Sutton and Watson (1955) that the amount of existing cover to the andalusite isograd is 1.2 km, if therefore the assumption is made to fit in with the proposed thermal gradient that the missing cover was 6.8 km then the following results are derived:

<table>
<thead>
<tr>
<th>from experimental data</th>
<th>from field evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to andalusite zone</td>
<td>8 km</td>
</tr>
<tr>
<td>Thickness of andalusite zone to kyanite isograd</td>
<td>3.5 km</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Total thickness</td>
<td>11.5 km</td>
</tr>
</tbody>
</table>
The two values are, therefore, extremely close, it could even be suggested that the 'missing' 0.5 km of cover deduced from field evidence is due to a tectonic cut-out of part of the succession due to F3 faulting around Boyne Bay. Such a conclusion seems to support Chinner's concept of a depth controlled metamorphism. The present author feels, however, that the thermal gradient drawn is excessively low, Birch (1955) suggested that the lowest thermal gradient likely to be encountered in the earth's crust was 10°/km. Therefore in an active orogenic zone it is almost certainly considerably higher (Goombs (1967) suggests 40 - 50°/km for andalusite metamorphism in New Zealand); the only way to fit this onto the present diagram is to follow approximately the line adgb (fig. 29c). This will not affect the depth computations made above since the points of intersection (d and g, fig. 29; of the boundaries are approximately the same. Two possibilities exist to explain the nature of this curve. Firstly, the presence of tectonic overpressures in the kyanite field. Secondly, the presence of a thermal high. The first possibility will be discussed. The implication of the curve is that tectonic overpressure in the kyanite field steepens the thermal gradient of the andalusite field. The possibility of tectonic overpressure in the Dalradian has been well discussed. Rast (1962) was impressed by the association of kyanite growth with areas of intense F2 deformation and suggested, since the kyanite growth was demonstrably post F2, that F2 strain remaining in the rocks after the cessation of deformation (like a spring under compression) had produced the necessary overpressure for kyanite growth. The main argument against this theory is the lack of preferred orientations of the kyanites, an oriented fabric being expected of porphyroblasts which grew under directive stress. This criticism might be countered by arguing that
although nucleation occurred whilst remnant $F_2$ stress remained, growth occurred after the dissipation of stress. This would imply that kyanite nuclei formed at grain boundaries and were so small that they were oriented with respect to very localised stress patterns. The nuclei were then held at this stage until the stress dissipated and growth occurred. Although there is an analogy in metallurgy - Hardy and Neal (1956) showed that in recrystallising metals embryo or nuclei could exist in a state of 'steady size' for some time before commencing growth - the enormous differences in time between metallurgical recrystallisation and the dissipation of geological stresses may, however, preclude this theory. It could be argued that the remnant $F_2$ strain energy was not directive but only raised the hydrostatic pressure above the load pressure. The close equivalence in the results of the computation of the depth of the kyanite zone, however, seems to argue against this, and it is most probable that the $F_2$ deformation and kyanite growth are not directly related. Although an increase in the hydrostatic pressure above load pressure in the kyanite zone is apparently refuted, the possibility that deformation movements stressed the rocks sufficient to raise the hydrostatic pressure above the load pressure cannot be precluded. This situation would not affect the general arguments, it would merely lessen the amount of extra cover necessary to satisfy the experimental data. It, therefore, appears that the second reason - the presence of a thermal high - is the cause of the curvilinear nature of the geothermal gradient. That is, in the concept of depth controlled metamorphism with the hydrous phases, the andalusite and kyanite zones occupying successively deeper layers, then a higher temperature zone must exist near the junction of the andalusite and kyanite zones. It is possible, assuming the new geothermal gradient to apply a modified version
of Chinner's (1966) arguments on the disposition of isotherms and iso-bars. The isotherms will tend to approximate to the hydrous phases boundary. Since it has been suggested that the change of slope in the geothermal gradient was due to a thermal high and not to overpressures in the kyanite zone, then the iso-bars can be fixed from the disposition of the isotherms and the andalusite/kyanite boundary.

The pattern of isotherms and iso-bars thus deduced is similar to Chinner's (fig. 30d) but the divergence of the iso-bars and isotherms around Donside and southwards is shown to be due to a geothermal gradient of changing slope and not to a 'symmetamorphic anticline'. The significance of the thermal high must now be examined and it is perhaps best to do this approaching the argument from a different direction. If the Banff Nappe structure is accepted then the present day surface, as already stated, presents an oblique section through the nappe. Thus it is possible to project the metamorphic zones of N.E. Scotland on to the nappe structure. If the effects of the third fold movements are removed then it can be seen that the core of the nappe is occupied, at least in part, by sillimanite bearing rocks, these are overlain by an andalusite zone which is in turn overlain by a zone of hydrous phases. Below the sillimanite bearing rocks is a kyanite zone. From the author's and Chinner's textural evidence, it is known that the sillimanite is, in part at least, later than the andalusite and kyanite growth. The sillimanite zone must represent a high temperature zone. Thus it is possible on the cross section of the nappe to draw isotherms around the nappe core. Iso-bars, however, will be largely depth controlled and will therefore, be horizontal or sub-horizontal. The iso-bars will cut across the isotherms at the nappe nose. If the pattern of isotherms and iso-bars is then folded to allow for the effects of \( F_3 \) movements, and projected
FIGURE 30.

(A) Distribution of alumino-silicate polymorphs in N.E. Scotland, after Chinner (1966).

a - hydrous phases; b - andalusite; c - kyanite; d - andalusite + sillimanite; e - kyanite + sillimanite.

x-y line of section for figs. 31 and 32.

(B) Distribution of 'gneisses' in N.E. Scotland, after Chinner (1966).

a - sillimanite + potash feldspar
b - sillimanite + muscovite
c - 'Kyanite gneiss'.

(C) Distribution of isotherms (t' etc.) and isobars (p' etc.) in N.E. Scotland during metamorphism, after Chinner (1966).

(D) Distribution of isotherms and isobars in N.E. Scotland deduced from present work.
back on to the present surface, they are found to coincide very closely with the pattern of isotherms and isobars deduced from experimental evidence. The divergence of the isobars and isotherms is, therefore, due to their divergence at the nappe nose or in effect to the presence of a thermal high in the nappe core. For the above argument to be feasible it has to satisfy two points of evidence. Firstly, that the sillimanite metamorphism is allied to the kyanite - andalusite metamorphism. Secondly, that the sillimanite must at least in part overprint the andalusite and kyanite metamorphism. These two points appear at first to be rather paradoxical. It is felt, however, that a mechanism can be proposed to satisfy them both. Consider some form of heat source as welling up in the downbend of the Banff Nappe and then moving out laterally along the nappe core - in a gigantic mushroom - then in the forefront of this heat source the rocks will be warmed, andalusite will form in the higher structural zones overlain by hydrous phases, and kyanite will form in the lower structural zones. As the heat front progresses and the rocks heat up, an isobaric temperature rise carries the rocks into the sillimanite 'zone'. Sillimanite will, therefore, begin to form in a zone between andalusite and kyanite. As the heat front progresses the sillimanite zone will gradually broaden until the maximum temperatures are reached.

It is obvious that a high enough increase in temperature will lead to the production of migmatises, however a discussion of this and the association of sillimanite with muscovite or K-feldspar will be deferred meanwhile because it is not critical in this argument. The nature of the heat source is highly problematical. Pure heat could not move laterally along the nappe core since it would radiate equally from the source; it is therefore necessary to envisage some heat-carrying medium. This would
well up and move out laterally along the core, this being the direction of easiest advance, the beds effectively acting as envelopes. The occurrence of migmatites in the core of recumbent folds has been described from Greenland by Haller (1962). He attributed their presence to an upward welling of juvenile material and their subsequent lateral movement similar to salt diapir structures. He describes two geometrical forms of migmatite:

(a) "Migmatite 'foreheads': tongue shaped bodies in the cores of overturned or recumbent folds."

(b) "Migmatite sheets: large nappe like migmatitic bodies caused by extensive lateral welling. The migmatitic body which welled out horizontally, is the product of independent fluid movements initiated by granitizing agents rising vertically. The direction of expansion apparently depends on the original setting and bedding of the sedimentary mantle."

Haller also describes inverted metamorphic zoning below the migmatite sheets. It can be seen that the model proposed for the metamorphism of N.E. Scotland corresponds closely with the examples described by Haller. The nature of the heat carrying medium is however unclear but will be discussed in detail later.

Several implications of the above model for the metamorphism must be examined. The downbending of the nappe nose at the Highland Boundary Fault, figure 31, has rotated the hydrous phases zone downwards and its northward extension could easily have overturned the boundary between the hydrous phases and the kyanite zone, so that they might dip NW in the classical area of Barrovian metamorphism. The exact nature of the dip of these isograds is, however, not known as far as the present author is
I aware. Also, in the area of the downbend of the rocks in the Banff Nappe, and in the northward extrapolation of the Ben Lui recumbent syncline, the isotherms and in consequence the isograds are probably at considerable angles to the bedding. Although it has been argued from textural evidence and disequilibrium assemblages (Chinner, 1966) that the sillimanite is later than the andalusite and kyanite. It is possible that the geothermal gradient in the deeper zones could have penetrated the sillimanite field and that the sillimanite in this area is in fact contemporaneous with the andalusite and kyanite.

(e) The Sillimanite-gneiss zones

It is now necessary to examine the sillimanite gneiss zone to determine its implication on the metamorphic model proposed above. The terms 'migmatite' and 'gneiss' have been frequently used in the literature of N.E. Scotland. 'Gneiss' will be used in the following discussion to include all rocks subjected to pressures and temperatures above the minimum melting curve of granite and showing phenomena of partial melting. The term 'migmatite' has a metasomatic implication although it has been used in a purely descriptive sense (Lundgren, 1966; Shaw, 1957) in this discussion it will be restricted to 'gneisses' which have suffered some form of metasomatism.

Chinner (1966) recognised two types of gneiss in N.E. Scotland, one characterised by the assemblage sillimanite - muscovite - quartz, the other by the assemblage sillimanite - potash feldspar. The junction between these two gneisses Chinner regarded as virtually coincident with the boundary between his pre-sillimanite overprint andalusite and kyanite zones. He admits, however, this boundary is probably more apparent than real since the line is for the greater part of its trace masked by the Older Granites and their aureoles. Chinner (op.cit., fig. 4)
suggested that the sillimanite overprinting could be regarded as an isobaric adjustment on the alumino-silicate diagram. He shows andalusite rocks raised sufficiently in temperature to pass into the stability field of sillimanite + potash-feldspar whereas kyanite rocks are raised by a smaller amount and do not enter the stability field of sillimanite + potash-feldspar, thus remaining in the zone of sillimanite + muscovite. This, however, implies a negative temperature gradient, i.e. andalusite bearing rocks at high structural levels were raised to temperatures in excess of those achieved by the kyanite bearing rocks in the deeper structural levels. This would appear to be difficult to reconcile with Chinner's concept of a rising heat node as the cause of the sillimanite-gneiss overprint.

Before discussing the implication of the gneisses of N.E. Scotland further, it is necessary to consider the relevant phase work. The curve for the breakdown of muscovite may be expressed as:

(1) from Segnit and Kennedy (1961)

muscovite + quartz = orthoclase + sillimanite + water

\[ K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O + 2SiO_2 = K_2O \cdot Al_2O_3 \cdot 6SiO_2 + 2(Al_2O_3 \cdot SiO_2) + 2H_2O \]

(2) from Guidotti (1963) and Lundgren (1966)

muscovite + sodic plagioclase + quartz = sillimanite + orthoclase + plagioclase + water

\[ (K,Na) Al_3 Si_3 O_{10} (OH)_2 + (Na_x Ca_{1-x}) Al_{2-x} Si_{2-x} O_{8} + SiO_2 \]

\[ = Al_2SiO_5 + (K,Na) Al Si_3 O_8 + (Na_y Ca_{1-y}) Al_{2-y} Si_{2+y} O_8 + H_2O \]

where \( y < x \).

Segnit and Kennedy (1961) placed this curve in the range 600 - 750°C for pressures up to 5 Kb (fig. 33A). Subsequently, however, Evans (1965) put the curve about 50 - 100°C lower. Lundgren (1966) suggested the discrepancy in the results was possibly due to the methods used by Segnit
and Kennedy which may have raised the load pressure above the water vapour pressure thus inhibiting the reaction. Evans' results are remarkably well substantiated by those of Winkler (1965) who suggested that the high temperature curve of Segnit and Kennedy was due to their use of artificial instead of natural muscovites for their experiments. It, therefore, seems safe to assume that the curves of Evans and Winkler are probably correct. The minimum melting curve of granite (Tuttle and Bowen, 1958; Luth, Jahns and Tuttle, 1964) appears to be fairly well fixed at the position shown on figure 33A. The intersection point of the two curves lies at ca. 3.5 Kb. Therefore the assemblage sillimanite-muscovite-quartz gneiss can only occur in the temperature range of 600 - 700°C above about 3.5 Kb. Both these curves, however, are for water vapour pressure (Pw) equal to load pressure (Pl) and it is interesting to discuss the effects of a change in water vapour pressure. If Pw or $\mu_{H_2O}$ is low then the muscovite + quartz to sillimanite + potash feldspar curve will migrate to lower temperatures. This would obviously considerably restrict the stability field of sillimanite-muscovite-quartz gneiss and any substantial fall in Pw or $\mu_{H_2O}$ would eliminate the stability field completely. If the partial melt was undersaturated with Pw = Pl in the surrounding rocks this would most probably cause a breakdown of the muscovite below its upper stability curve (for Pw = Pl) (Lundgren, 1966) this would in effect cause the muscovite dehydration curve to migrate to lower temperatures without substantially effecting the minimum melting curve. If, however, a saturated partial melt was produced at temperatures beyond the muscovite dehydration curve, but water produced from the muscovite breakdown was slow to escape from the system, then Pw might rise above Pl - the concept of fluid overpressures described by Rutland (1965, pp. 131-2) - this in effect driving the
muscovite dehydration curve to higher temperatures, without altering the position of the minimum melting curve. This situation, however, is probably rare in nature. Thus it would appear that during the sillimanite gneiss metamorphic phase in N.E. Scotland, \( P_w \) must have been equal to, if not in excess of, \( P_l \). Otherwise the assemblage sillimanite - muscovite - quartz gneiss would not be stable. Two possibilities exist to explain the nature of the sillimanite-gneiss overprint of N.E. Scotland:

(a) That in the deeper structural zones, if sufficient water were available from an outside source a saturated partial melt could be produced without initiating muscovite breakdown, so that a sillimanite - muscovite - quartz gneiss assemblage could be produced (assuming that temperatures did not rise significantly beyond the dehydration curve of muscovite). In the higher structural zones if the rocks were raised by the same, or slightly lower, temperatures then, if a water source was available from outside, partial melting would produce an undersaturated melt which would initiate breakdown of the muscovite below the dehydration curve of muscovite (for \( P_w = P_l \)) thus giving rise to the stable assemblage sillimanite - potash feldspar gneiss.

(b) That the intermediate or high structural levels were raised to temperatures above the muscovite dehydration curve to form sillimanite - potash feldspar gneiss whereas in the deep structural levels temperatures did not pass the muscovite dehydration curve thus forming sillimanite - muscovite - quartz assemblages. This would imply a negative slope on the geothermal gradient at some point.

The first possibility - (a) above - has the following implications: (1) that sillimanite - muscovite - quartz gneiss assemblages would only occur between ca. 5 Kb and 7.5 Kb (above 7.5 Kb
(A) Distribution of isotherms \((T' < T'' < T''')\) during the gneiss metamorphism of N.E. Scotland.

stipple - sillimanite; stipple + cross hatching - sillimanite + muscovite; stipple + 'f' - sillimanite + potash feldspar.

(B) Distribution of isotherms \((t' \text{ etc.})\) and isobars \((p' \text{ etc.})\) in cross section of Banff Nappe during metamorphism.

(C) Distribution of metamorphic zones in cross section of the Banff Nappe after third generation movements.

- h - hydrous phases; a - andalusite; k - kyanite;
- s - sillimanite.

\(x - y\) - present day surface along the line of fig. 30A.

(D) Distribution of metamorphic zones in section of Banff Nappe down bent at Highland Boundary Fault.

- m - n - present day surface.

(E) Distribution of isotherms and isobars in cross-section of Banff Nappe after third generation movements.
FIGURE 32

A-C Stages in the evolution of the metamorphic pattern of N. E. Scotland.

h - hydrous phases; a - andalusite;
k - kyanite; s - sillimanite;
s + m - sillimanite + muscovite
s + f - sillimanite + potash feldspar
x-y - present day surface along the line of
fig. 30A (effects of third generation movements not shown).
FIGURE 33.

(A) Alumino-silicate diagram after Newton (1966)

A - andalusite; K - kyanite; S - sillimanite.

a - b - minimum melting curve of granite

(Tuttle and Bowen, 1958)

g - h - muscovite + quartz → sillimanite +

K-feldspar + H₂O (Segnit and Kennedy, 1961)

c - d - as g - h (Evans, 1965)

c - e - as g - h (Winkler, 1965)

(B) Alumino-silicate diagram as (A), showing the isobaric

movement of the geothermal gradient during

metamorphism (t - t' - t")

Final assemblages are given as follows ::

l - m - sillimanite muscovite gneiss

m - n - sillimanite K-feldspar gneiss

n - o - andalusite K-feldspar
the stable assemblage would be kyanite - muscovite - quartz gneiss; (2) sillimanite - muscovite - quartz gneiss assemblage could occur from 3 - 5 Kb. A straight line drawn from one zone to the other however would have a maximum slope of only a few degrees per kilometer.

It would, therefore, appear that the second possibility - (b) above - is more probable, that is a geothermal gradient with, in part, a negative slope was operative during metamorphism, This seems to fit the concept proposed above for a geothermal gradient with a 'bulge' at ca. 3 Kb, moving isobarically to higher temperatures, being responsible for the sillimanite gneiss overprinting, this is shown diagrammatically in figure 33B. In the diagram the bulge of t" is greater than t'; this is in better accord with the phase evidence and is also consistent with the proposed model. That is, as the 'heat front' causing the metamorphism advances the 'bulge' in the originally straight geothermal gradient becomes accentuated.

From figure 33B it is obvious that originally andalusite bearing rocks will go to gneisses characterised by sillimanite - potash feldspar assemblages whereas originally kyanite bearing assemblages will go to gneisses characterised by sillimanite - muscovite - quartz assemblages. Thus the coincidence of the boundary between the two gneiss groups of N.E. Scotland and the boundary between kyanite and andalusite (before the sillimanite overprint) suggested by Chinner from field evidence, appears to be borne out by the phase work. Whilst it is appreciated that large assumptions have been made in the nature of the geothermal gradient and that the close coincidence of the two lines in the phase diagrams may be partly due to chance, the approximation to coincidence must furnish strong circumstantial evidence in favour of the proposed metamorphic model.
(f) Metasomatism

Since partial melts will only form just above the minimum melting curve of granite if they are saturated (Tuttle and Bowen, 1958) some source of water must be established to explain the presence of gneisses just above the minimum melting curve. If Chinner's mapping of extensive areas of sillimanite - muscovite - quartz gneiss is correct then it must be presumed that water was entering the system from outside to allow the development of a saturated partial melt, since any extraction of water from within the system would lead to the breakdown of muscovite. Also, Lundgren (1966) mapped an isograd in S.E. Connecticut separating a sillimanite - orthoclase zone from a sillimanite - muscovite zone. The isograd being taken at the last appearance of muscovite. Lundgren suggested that partial melting was more or less concomitant with the breakdown of muscovite, however, he calculated that in a pelite with 25% muscovite, breakdown of the muscovite would give 0.4 to 1.0% by weight of water. This would allow the formation of saturated melt to a maximum ratio of 1 to 10 with the solid. It is therefore obvious that even where the assemblage sillimanite - potash feldspar gneiss occurs in the N.E. Dalradian that water must have been produced from outside the system, because much of the ground is covered by rocks with percentages of muscovites well below 25% and therefore unable to produce melt at a ratio of more than about 1:20 with solid. However, at deeper structural levels, and consequently higher temperatures, undersaturated melts could develop deriving water, perhaps in excess, from the dehydration of the surrounding rocks.

Lundgren (1966) envisages movement of such a melt: "Water in this melt would either diffuse upwards through the melt or would move with the melt if it is separated from the rocks in which it formed,"
moving upwards from them. The local separation of this melt from the 
host rocks contributes to the development of migmatites, particularly 
in the deeper levels of the sillimanite - orthoclase zone. Migmatites 
at the upper edge of the zone or in the transition zone must result 
from the intrusion of material (melt) formed at deeper levels. It is, 
therefore, possible that a similar mechanism was operative in N.E. 
Scotland. In the deep structural layers temperatures were sufficiently 
high to produce partial melts with excess water. This melt + water 
would then migrate upwards into and along the core of the Banff Nappe. 
It is not certain to what extent external melts penetrate the rocks of 
the core but it would seem essential to assume that water vapour at 
least percolated along the nappe core. As the water vapour reached 
fresh rocks it would facilitate partial melting which would in turn 
absorb water from local dehydration reactions and thus continue the 
process until the temperature of the percolating water fell below the 
temperature of the minimum melting curve. The concept of percolating 
water (and melt) lends credibility to the postulate of a heat source 
moving laterally along the nappe core. As Chinner (1966) states, 
"... once some liquid is present, diffusive processes become very rapid. 
Recrystallisation to coarser aggregates is facilitated, metamorphic 
differentiation and monomineralic segregation promoted, and the 
possibility of larger-scale metasomatic interchange, especially of 
alkalis, in response to chemical potential gradients considerably 
increased." Thus it can be seen that as a rock crosses the minimum 
melting curve and is involved in partial melting its fabric will change 
rapidly and radically, giving it the appearance of a rock of much higher 
grade than its neighbours (which may have been subjected to P/T 
conditions only slightly less than the gneiss but insufficient to
promote partial melting). This may explain why Read (1955) placed the Boyne Line between the Donside Gneisses and the northward lying andalusite schist since in hand specimen the two occasionally appear to be of widely different grades.

Although it is reasonably certain that water diffused through the rocks it is uncertain what other ions, if any, also moved. In the discussion of fibrolite genesis, it was suggested that the appearance of pockets of potash feldspar, the pinitisation of cordierite and the breakdown of biotite indicated potash mobilisation and migration, it was suggested from the high percentages of potash feldspar in the mode that large scale potash metasomatism had occurred. Chinner (1966) suggested that the presence of 'shimmer aggregate' indicate a diffusion of potash. The appearance of microcline in many rocks also strengthens this observation. The presence of cordierite and andalusite in spotted slates indicates that there was no excess of potassium in the rocks at low grade. The large amounts of potassium bearing minerals in the gneisses, therefore, suggest that potash was introduced during the partial melting of the rocks. Billings (1938) suggested that potash metasomatism in New Hampshire was due to the hydrolysis of orthoclase in a neighbouring granite and the consequent release of potash:

$$3\text{KAlSi}_3\text{O}_8 + \text{H}_2\text{O} \rightarrow \text{KAl}_2\text{Si}_3\text{O}_{10}(\text{OH})_2 + \text{K}_2\text{O} + 6\text{SiO}_2$$

The water was regarded as 'juvenile waters'.

It seems possible that granitic magma was present below the Banff Nappe at the beginning of metamorphism and that melt + potash + water migrated upwards as detailed above, potash and water being drawn from surrounding rocks. Initially muscovite formed in the migmatite from dissolving biotites and as the water percentage fell and the temperature dropped, the melt required greater quantities of water and the muscovite
was dehydrated to potash feldspar. It is probable, in the high
structural zones that 'sillimanitisation' of the biotite produced
orthoclase the water being drawn off into the melt even at temperatures
slightly below the experimentally determined curve for the reaction
muscovite + quartz to sillimanite + potash feldspar.

(g) Timing of the Metamorphism

Johnson (1962) has demonstrated that the climax of the metamorphism
was post $F_2$, pre $F_3$. There is abundant evidence (e.g. Chinner, 1961,
1966) that sillimanite grew later than andalusite and kyanite. Johnson
(1962) gave evidence apparently indicating the onset of migmatisation
after the sillimanite growth. He states with relation to the Cowhythe Gneiss,
"sillimanite has replaced the large $F_2$ biotites and is enclosed
by oligoclase crystals". It is, therefore, obvious that the three
phases of metamorphism - growth of andalusite and kyanite, growth of
sillimanite, growth of migmatitic feldspar - can be recognised as
three separate events, it would, however, be erroneous, as suggested
by Chinner (1966), to regard this as two or three phases of metamorphism,
rather they represent three stages in a progressive and continuous
metamorphism.

(h) Metamorphic Facies

The mineral assemblages of progressive Buchan metamorphism are:

(a) chlorite - 'knots'
(b) biotite - 'knots'
(c) andalusite - cordierite - staurolite
(d) andalusite - cordierite - muscovite
(e) andalusite - cordierite - sillimanite - muscovite
(f) sillimanite - cordierite - potash feldspar

In figure 34 the line xy represents the average progressive metamorphism
of Buchan type. Assemblage (1) of the curve xy corresponds to (a) above;
(2) to (d); (3) to (f).

From Fyfe, Turner and Verhoogen (1958) the above mineral assemblages correspond to facies or sub-facies as follows:

(a)  
(b)  Albite - epidote hornfels facies
(c)  
(d)  Hornblende hornfels facies
(e)  
(f)  Almandine amphibolite facies

Hietanen (1967) equates them:

(a)  
(b)  Greenschist facies
(c)  Epidote - amphibolite facies
(d)  
(e)  Amphibolite facies
(f)  

Since assemblages such as andalusite - cordierite - potash feldspar are absent from typical Buchan metamorphism it is perhaps more realistic to accept Hietanen's suggestion, and restrict the various hornfels facies to rocks where pressures never exceeded 2 Kb.

In the progressive Barrovian metamorphism the metamorphic assemblages differ from those of Buchan metamorphism by the presence of garnet and kyanite instead of cordierite and andalusite. It is obvious rocks must exist with mixed assemblages characteristic of both the Buchan and Barrovian types of metamorphism. McNamara (1965) suggested that the absence of the calcium zeolites (heulandite, laumontite etc.) from the Scottish Dalradian was due to high values of $\nu \text{CO}_2/\nu \text{H}_2\text{O}$. He shows (op.cit., fig.9) that the chlorite zone is equivalent, in part, to the zeolite facies in terms of pressure and temperature. According
to Fyfe, Turner and Verhoogen (1958, p. 219) the lowest grade rocks of
the Barrovian (and Buchan) metamorphic assemblages — quartz — albite —
chlorite — should fit into the lowest sub-facies of the greenschist
facies.

It is possible to view the facies concept in two ways:

(1) That the same mineral or chemical assemblage will always define
a particular facies under the same pressure/temperature conditions.
Therefore if $\mu H_2O$ is high, hydrated assemblages characteristic of the
greenschist facies may remain stable at pressure/temperature conditions
normally considered to be the amphibolite facies range.

(2) That the term greenschist facies defines a particular pressure/
temperature band. The mineralogy of rocks metamorphosed at pressures
and temperatures within the band would normally be that characteristic
of the greenschist facies as detailed by Fyfe, Turner and Verhoogen
(1958, pp. 166-7). It would be possible, however, under various extreme
values of $\mu H_2O$, $\mu CO_2$, $\mu O_2$ etc. that minerals normally masked by hydrous
phases could occur.

The first concept of facies — (1) above — was criticised by
Yoder (1952), but as a descriptive aid and as a guide to the areal
progression of metamorphism it is extremely valuable. It is, however,
felt that as new and more accurate phase work is forthcoming, the effects
of $\mu H_2O$ etc., becoming clearer, and the specific pressure/temperature
conditions of metamorphism sought after, that the second concept of
facies is the more desirable. Therefore, the chlorite zone assemblages
of Barrovian metamorphism (and possibly Buchan metamorphism) must, in
part, be placed in the zeolite facies, and equated with the zeolite
bearing rocks of New Zealand (Coombs, 1960) etc., since the two assemblages
suffered similar P/T conditions, differing only in the ratio $\mu CO_2/\mu H_2O$
(McNamara, 1965). This concept of facies will also effect other assemblages. If the boundary of the greenschist and almandine–amphibolite facies is taken as the dehydration curve of the aluminosilicates (i.e., the first appearance of andalusite or kyanite) then it can be fixed on a P/T diagram by the experimentally derived curve for the reaction pyrophyllite = andalusite. However, from the arguments proposed above $\mu H_2O$ was low during the andalusite–kyanite metamorphism in N.E. Scotland, therefore the first andalusite to form in N.E. Scotland did so in the greenschist facies and the assemblage (c) above spans the boundary between the greenschist and almandine–amphibolite facies.

Before this concept of facies can be properly applied to the Dalradian, work will have to be undertaken to fix the boundaries of the various facies with experimentally derived reaction curves where $P_w = F_l$.

In the almandine amphibolite facies Fyfe, Turner and Verhoogen (1958) recognised three sub-facies (1) staurolite–quartz; (2) kyanite–muscovite–quartz; (3) sillimanite–almandine–of the almandine amphibolite facies. The two sub-facies (sillimanite–muscovite–quartz and sillimanite–potash feldspar) of the sillimanite zone, as recognised by Lundgren (1966), and present in the N.E. Scotland Dalradian do not fit easily into Fyfe et al.'s scheme. Fyfe et al.'s (op.cit., p.230) second sub-facies is characterised by the absence of sillimanite, the third by the absence of muscovite. Fyfe et al. (op.cit., p.211) regard the assemblage quartz–oligoclase–cordierite–sillimanite–biotite–muscovite, as transitional from hornblende hornfels facies to the almandine–amphibolite facies. It would, therefore, seem necessary to revise the scheme of Fyfe, Turner and Verhoogen (1958) and have four sub-facies of the almandine–amphibolite facies viz:

1. staurolite–quartz;
2. kyanite–quartz–muscovite;
(3) sillimanite - quartz - muscovite; (4) sillimanite -
almandine - potash feldspar.

These sub-facies boundaries could easily be fixed on a P/T diagram by
curves for the reactions

(1) staurolite + quartz = kyanite + garnet + water

(2) kyanite = sillimanite

(3) muscovite + quartz = orthoclase + sillimanite + water

It is obvious under high values of $\mu_2$H$_2$O muscovite and quartz could
appear in the sillimanite - almandine - potash feldspar sub-facies,
also that staurolite would remain stable in the kyanite - quartz -
muscovite sub-facies. Also, at low values of $\mu_2$H$_2$O microcline could
occur in the sillimanite - quartz - muscovite sub-facies.

(i) Limitations of proposed Model

It is appreciated that in constructing the proposed model for the
metamorphism many assumptions have been made. It is felt that the model
provides the best and simplest fit for the available field and
experimental data and that the assumptions are justified. It is perhaps
relevant to examine some of the assumptions and discuss their validity.

The position of the alumino-silicate polymorph boundaries in the
field has largely been taken from Chinner (1966). As mentioned above
the trace of his andalusite/kyanite boundary south of Deeside is now
masked by Newer Granites and therefore cannot be fixed on the ground
with any degree of certainty. However, since it can be fixed fairly
accurately from the Banffshire coast down to the Dee-Don watershed and
again on the coast, the line as drawn by Chinner would appear to be
substantially correct. Also, the line separating the two gneiss zones
appears to best fit the available outcrop evidence. Within the gneiss
zones the characteristic mineral, muscovite or potash feldspar is by no
means exclusive, patches of sillimanite - muscovite gneiss appearing within the zone of sillimanite - potash feldspar gneiss, these are however sufficiently small to be regarded as localised variations in $\nu \text{H}_2\text{O}$.

It is appreciated that the nature of the geothermal gradient has been, to an extent, arbitrarily decided upon, that is although the general nature of the curve was chosen to fit experimental and field evidence, the actual slopes of the curve could vary, this would not, however, affect the pattern of isotherms and isobars postulated for the area, it would merely affect the spacing between them. It is possible that variations could occur areally in the nature of the geothermal gradient but it is not felt, within the terms of the model, that these would be significant. The pattern of isotherms and isobars has been drawn on a sufficiently small scale to provide a degree of latitude in the nature of the geothermal gradient without affecting the model.

It has been assumed that the phase work and in particular the position of the triple point in the alumino - silicate diagram is reasonably correct. Also, field data and phase data have been used in several instances to deduce similar conclusions without any significant anomalies appearing. Therefore the experimental results can be applied with reasonable confidence. Although it is assumed that the position of curves are approximately correct it is not implied that future work will not change them, it is merely thought a reasonable assumption that future work will not involve radical changes. Because future change in detail is accepted, specific values of pressure, temperature etc., have been avoided wherever possible. It is, therefore, hoped that the proposed model will be sufficiently broad and manoeuvrable to absorb new data and changes in the established position of reaction curves in
the phase chemistry of the metamorphic minerals, and as mineral reactions are confirmed and accepted they may be used to tie down the detail of the model.

It has been suggested that the rocks may have been subjected to pressures in excess of load pressure at the time of metamorphism. On the assumption that the pressure necessary for metamorphism - as deduced from the experimental evidence - was attributable solely to load pressure, it was suggested 6.8 km of cover must have existed which has subsequently been removed by erosion. It is, however, quite conceivable that after the $F_1$ and $F_2$ movements the rocks were subjected to hydrostatic stress in excess of load pressure, this would diminish the amount of 'extra' cover necessary but would not alter the arguments involved.

It is possible that during migmatization thermal overpressures or physical overpressures due to the intrusion of material were operative in the core of the nappe. Such overpressures would affect the slopes of the geothermal curve but not its overall shape, and as long as specific values are avoided, will not affect the proposed model.

The role of $\mu_{H_2O}$ and $P_w$ is difficult to ascertain accurately. It has been suggested from experimental data that $P_w$ was less than $P_l$ during the andalusite - cordierite - kyanite phase of metamorphism and that $P_w$ was equal to, or in excess of, $P_l$ during the sillimanite gneiss overprinting. A variation in the value of $P_w$ relative to $P_l$ has therefore been accepted. However it has been tacitly suggested that in the cross-sections of the Banff Nappe (fig. 32) $P_w$ does not vary very greatly relative to $P_l$ in any horizontal plane (at the same temperature of metamorphism) that is the andalusite/hydrous phases boundary has been shown as a relatively straight near horizontal line.
Variations of \( P_w \) in this sense would have the effect of forming undulations in the andalusite/hydrous phases boundary or if the change was a progressive one of causing divergence of the hydrous phases/andalusite boundary away from parallelism with the andalusite/sillimanite gneiss boundary. Yoder (1955) suggested that areal variations in \( P_w \) were to be expected. However, it is felt from the field evidence that any change in \( P_w \) relative to \( P_l \) in a horizontal plane was not sufficiently significant to affect the arguments proposed. Even if the difference in value of \( P_w \) to \( P_l \) varied to 0.5 of that proposed during staurolite-andalusite metamorphism it would not noticeably affect the arguments for the distribution of isotherms and isobars and the model for metamorphism. Water released in the dehydration reactions, at lower temperatures, migrated out of the system; at higher temperatures water released from reactions of the type muscovite + quartz to sillimanite + orthoclase was almost certainly absorbed during partial melting.

Other oxides such as \( FeO, K_2O \) etc., released during various reactions; e.g. from Hietanen (1967):

(a) \( 9 \) chloritoid \( \rightarrow \) \( 2 \) staurolite + quartz + \( 5 \) FeO + \( 8 \) H\(_2\)O

(b) \( 3 \) muscovite + \( 4 \) FeO \( \rightarrow \) \( 2 \) staurolite + \( 3 \) K\(_2\)O + \( 10 \) quartz + \( 5 \) H\(_2\)O

were almost certainly immediately re-absorbed into the system;

\( 2 \) staurolite + \( 14 \) quartz + \( 2 \) K\(_2\)O + \( 5 \) FeO + \( 14 \) H\(_2\)O \( \rightarrow \) \( 3 \) almandine + \( 2 \) muscovite

In figure 32 the sillimanite and gneiss boundaries have been shown as coincident, this of course is not strictly true since sillimanite occurs in areas where no partial melting phenomena are observable. Chinner (1966) states, using gneiss as defined above to indicate rocks subjected to pressure and temperature conditions beyond the minimum melting curve of granite; "Sillimanite-zone rocks are not however, necessarily gneissic, nor are gneisses necessarily confined to the
sillimanite zone... and some of the homogeneous Fyvie schist in the Ythan Valley near Methlick (Read, 1952) is sillimanite bearing. Nonetheless the sillimanite-gneiss association seems close enough for it to be given weight in any genetic discussion". Chinner apparently accepted that the boundary of his zone of rocks subjected to partial melting corresponds with the boundary of gneisses as shown on the Geological Survey one-inch sheets. This may not be strictly true. Large parts of the gneisses as mapped by the Survey do not exhibit partial melting phenomena. However, if the zone of gneisses as mapped by the Survey is regarded as the zone within which partial melting phenomena can be observed, although not uniformly or ubiquitously developed, then it is perhaps not unrealistic to accept Chinner's boundary.

The heat source has been depicted in the model as an upring column of saturated melt branching out along the nappe core; it might however be more realistic to envisage some form of heat dome centred around the downbend of strata in the nappe and radiating far enough to produce undersaturated melts at its centre, the melts thereafter moving out laterally along the nappe core.

(j) Summary of Metamorphism

At the cessation of the great nappe forming movements of N.E. Scotland, the metamorphic grade was largely depth controlled although biotite may have preferentially crystallised out on the S. schistosity planes. The geothermal gradient was probably about 17°/km increasing perhaps at high pressures. Such a gradient would imply the beginnings of metamorphism, with the appearance of chlorite, occurred at ca. 4 Kb (15 km); garnet would appear at 6 – 7 Kb (24 km); kyanite would only appear at 8 Kb (30 km). At depth the intrusion of a granitic magma,
FIGURE 34.

Synoptic diagram of metamorphism in N.E. Scotland.

Alumino-silicate evidence from Newton, 1966.

A - andalusite; K - kyanite; S - sillimanite

a - b: hydrous phases → aluminosilicate.

c - d: minimum melting curve of granite.

e - f: muscovite → sillimanite + K-feldspar

t', t'', t''': geothermal gradients

r - s: curve of typical Barrovian progressive

metamorphism:

(1) hydrous phases.

(2) kyanite

(3) sillimanite - muscovite

(4) sillimanite - muscovite gneiss

x - y: curve of typical Buchan progressive

metamorphism:

(1) hydrous phases

(2) andalusite

(3) sillimanite - K-feldspar gneiss
Pressure - Kb

Temperature - °C x 100
waters, or some heat-carrying medium produced a mixture of melt, K₂O and H₂O. This migrated upwards drawing water from the dehydration of the sediments. The mixture moved laterally outwards along the nappe core, at which stage the mixture was self-regenerating. As the water was absorbed in the partial melting of the sediments, and the potash reacted with alumino-silicate to form potash feldspar, so the breakdown of biotite and muscovite produced more potash and water. Metamorphism continued, with migration, migmatisation and melting, along the nappe core. As temperatures fell progressively more water was required to produce partial melts and so the amount of free water decreased until eventually temperatures fell too low to allow melting. Slight potash and water metasomatism continued for a short distance after this.

The effect of this migrating heat source was to produce, well in its fore, a 'bulge' in the geothermal gradient (t', fig.34), this produced chlorite at ca. 2.5 - 3 Kb, (ca. 8 km), garnet at ca. 6 Kb (22.5 km) and kyanite about 7 Kb (26 km), it is also probable that spots (of the spotted slates) were appearing at 2 or 3 Kb representing the beginnings of andalusite and cordierite development. As the heat source advanced so the curve t' advanced and rocks originally at conditions represented by t' rose in temperature. At t" (fig. 34) the 'bulge' is more marked and in the higher zones chlorite was going to biotite and the spots were clearing of inclusions to form clear optically recognisable cordierite and andalusite. In the deeper structural zones the garnet bearing rocks were giving way to kyanite bearing assemblages. As the heat front advanced further the curve t" advanced and rocks at conditions represented by t" rose isobarically to higher temperatures. At t"" (fig.34) a vertical cross-section shows
the following zones:

(a) chlorite - spots ('knots')
(b) biotite - andalusite - cordierite
(c) andalusite - fibrolite - biotite - weathered cordierite - potash feldspar
(d) fibrolite - potash feldspar - weathered cordierite
(e) fibrolite - muscovite - garnet ?
(f) kyanite - muscovite ?

The metamorphism can therefore be regarded as a continuous process as diagrammatically shown in figure 34. In figure 34 the line xy shows the general progression of rocks involved in Buchen type metamorphism; the line rs shows the general progression of rocks involved in Barrovian type metamorphism. Experimental evidence showed that values of $\rho_{H_2O}$ were low during the formation of kyanite and andalusite but rose to higher values during the higher grades of metamorphism, presumably due to either the introduction of water into the system or its accumulation during metamorphism.

Johnson (1962, 1963) has shown that garnet first appeared on the Banffshire section between $F_1$ and $F_2$. The garnet probably appeared at pressures of around 3 Kb (computing pressures from the now co-existing aluminosilicates), this implies conditions slightly below curve t" (fig. 34). This suggests that the heat source began to rise shortly after the cessation of the nappe forming movements and that by $F_2$ times the rocks of Aberdeenshire and Banffshire, now in the amphibolite facies, were up to greenschist facies and that rocks now exhibiting andalusite and cordierite contained spots or knots. Thus, for example, in the Collieston coast section the southern rocks were probably developing spots at the time of $F_2$ formation in the Lower Dalradian and
that these spots gradually developed to andalusite and cordierite; the beginnings of metamorphism - the development of spots or knots - moved progressively northwards from $F_2$ times to the climax of regional metamorphism.

Shortly after metamorphism was completed the basic sheet was intruded and as the rocks were still hot the basic masses effectively boosted the grade of the rocks and locally modified the metamorphic pattern. This is fully discussed in Chapter 5. Subsequently, localised retrogression - mainly chloritisation - occurred during the third fold movements.

(k) Possible values of Pressure and Temperature

Although, as stated above, specific values of pressure and temperature have been avoided in discussing the model for the metamorphism, for the sake of completeness certain values will be suggested in this section. It is appreciated this is the most fragile part of the argument and until the knowledge of the area and the petrology of the rocks in general are better known no real weight can be placed on these values. In particular, more detailed information would be required on the following points: (1) Accurate experimental phase work on all boundaries of the alumino - silicate diagram, and its relationship to natural occurrences; the effects of foreign ions and catalysts (biotite and possibly potash) on the reaction curves. (2) The nature and effects of changes in the value of $\varphi H_2O$, both in time and space. (3) The exact nature of stresses remnant in the rocks after deformation movements; the possible presence of directive stress and its influence on nucleation and growth; the possibility of hydrostatic stresses in excess of load pressures. (4) The accurate tying down, in the field, of all isogradic surfaces. Also, of great
benefit would be a detailed chemical analysis over the area to show which reactions were isochemical also, where and on what scale metasomatism occurred, this however may prove to be extremely difficult because, apart from the notoriously poor outcrop, the isograds tend to run parallel or sub-parallel to the strike, making it virtually impossible to show, in the gneissic areas, what the original rock composition was, and in consequence what metasomatism, if any, occurred.

With these reservations the following values are suggested more for their relative than specific values. The boundary between the Macduff Slates and the Fyvie Schist is an approximate isothermal surface at 400°C. The boundary between the assemblages sillimanite + orthoclase and sillimanite + muscovite on Donside must represent a temperature of approximately 700°C and ca. 3 Kb (10.75 km). The Collieston coast section probably represents a range in P/T conditions from 350 - 400°C and 1.5 Kb at the north end of the section to 600°C and 3.25 Kb at the south end of the section. The Rosehearty - Fraserburgh section shows a range of 600°C and 3.25 Kb at Fraserburgh to ca. 450°C and 2 Kb just to the west of Rosehearty. Read's (1952) classic section of Buchan metamorphism in the Ythan valley probably runs from 200°C and 1.25 Kb to the west of Fyvie to 700°C and 3.0 - 3.5 Kb around Ellon, the original metamorphic pattern has, however, been complicated by the intrusion of the Haddo and Arnage basic masses.
Notes on the construction of the cross-sections

Throughout the section on the metamorphism cross-sections of the Banff Nappe have been shown with the metamorphic zones superimposed. The implication of these cross-sections is that the isogradien surfaces outcropping at the present erosion level, where they run approximately parallel to the stratigraphical boundaries, can be projected in the same way as the stratigraphical boundaries. It is perhaps relevant to examine the validity of some of these projections.

Chinner (1966, pp. 173-175) has discussed the geometry of the hydrous phases / andalusite and andalusite / kyanite boundaries. He quotes evidence to show that the andalusite zone dips under the hydrous phases on the eastern limb of the Boyndie Syncline and that the kyanite zone dips under the andalusite zone and the hydrous phases on the western limb of the Boyndie Syncline. Chinner constructed, with reasonable certainty, a cross-section through N.E. Scotland (fig. 7) showing the hydrous phases overlying the andalusite zone, which in turn overlies the kyanite zone, the isogradien surfaces roughly following the major structures and stratigraphical boundaries. The attitude of the sillimanite isogradien surfaces is much more debatable.

Chinner (op. cit., p. 172) believes that the sillimanite zone transgresses the kyanite / andalusite isograd, but does not discuss the actual geometry of the sillimanite isograd. The long, roughly lenticular outcrop of the sillimanite zone on Chinner's map (op. cit., fig. 2) can be interpreted in at least two ways:

either (a) the sillimanite zone is a lenticular sheet which overlies the kyanite zone.

or (b) the sillimanite zone is a dome or 'pericline'.

It/
It is extremely difficult to decide between these two possibilities. No statement can be made about the attitude of the sillimanite isograd between upper Donside and the Highland Boundary Fault. A critical area is in Angus. If the sillimanite zone dips northwards here (i.e., the kyanite zone probably underlies the sillimanite zone) then explanation (a) is possible; if it dips southwards then (a) is improbable, unless post-metamorphic folding has distorted the sillimanite isograd. The author is impressed with the point that the sillimanite zone in N.E. Scotland occurs at roughly the same stratigraphical horizon. Although it must be admitted that this does not constitute direct evidence for the sheet-like form of the sillimanite zone it does mean that such a possibility is at least worthy of consideration. Accordingly, the sillimanite zone is shown as a sheet-like body on the cross-section, as derived by projection of the sillimanite outcrop.
5.1 Introduction

Much discussion has centred around the basic masses of N.E. Scotland. Several of the masses (Huntly, Insch and Belhelvie) exhibit rhythmic banding interpreted by Stewart (1946) and Shackleton (1948) as being due to gravity differentiation. The banding at Belhelvie has an almost vertical attitude (Stewart, 1946); at Insch it varies from 60° to the north on the southern margin of the sheet to 10°-20° to the north on the northern margin (Clarke, 1965); at Huntly (Shackleton, 1948) the banding is overturned, dipping steeply westwards. This steep attitude has led Stewart and Shackleton to suggest that the basic masses had suffered post consolidation folding or tilting. Shackleton (1956) further suggested that the basic masses were part of a continuous sheet which had been intruded before, and subsequently deformed by, the fold movements producing the Buchan Anticline and Turriff Syncline. This interpretation was unacceptable to Read who argued (Read and Farquhar, 1956) that post-consolidation folding would have destroyed the delicate igneous textures of the masses, and also that palaeomagnetic evidence (Blundell and Read, 1958) showed that the masses had cooled in their present position. These views were challenged by Stewart and Johnson (1960). Recently, detailed geophysical and magnetic surveys (McGregor and Wilson, 1967) have suggested that the masses are part of a continuous sheet and that the sheet has been deformed subsequent to its intrusion. McGregor and Wilson also suggest that the sampling carried out by Blundell and Read for their palaeomagnetic
work was inadequate to furnish reliable results.

Since most of the above arguments are based on textures within the basic masses it is intended to discuss in this section the probable conditions of the country rocks during the period of the basic intrusion and the time of intrusion. This involves a study of the effects of the basic masses on the fabric of the surrounding country rocks.

5.2 Structure

The reality of the Boyndie Syncline or Turriff Syncline is accepted in N.E. Scotland geological literature, as also is the Buchan Anticline (e.g. Johnson, 1963; Rast, 1963). If the concept of the basic masses forming a continuous sheet is accepted - from the uniformity of rock types and the geophysical evidence - then it can be readily seen that the basic sheet is symmetrically arranged around the Boyndie Syncline and Buchan Anticline. The problem of the age of the basic sheet would therefore seem to resolve itself into two possibilities.

Firstly, that the sheet was intruded after the fold movements producing the Boyndie Syncline and Buchan Anticline and that the rhythmic banding is due to successive deposition of magma on the walls of the intruded area and therefore was not gravity controlled. This negates any necessity for the banding to have been originally horizontal. This is the view accepted by Read.

Secondly, that the basic sheet was intruded before and subsequently deformed by the fold movements producing the Boyndie Syncline and Buchan Anticline, that is the rhythmic banding is due to gravity differentiation and was therefore originally horizontal or sub-horizontal. This is the view accepted by Stewart, Shackleton, Stewart and Johnson, and McGregor and Wilson.
Read (1923, p. 156-7) suggested that the cleavage of the Macduff Slates was destroyed in the aureole of the Insch basic mass. Stewart and Johnson (1960) and Johnson (1962) accepted that the cleavage of the Macduff Slates was axial planar to the Boyndie Syncline, a third generation fold, and suggested that the cleavage had failed to develop in the rigid hornfelses of the Insch aureole.

It has been shown during the present investigations that the cleavage of the Macduff Slates is composite, with $S_1$ and $S_3$ in close parallelism over much of the area studied. The $S_1$ cleavage is a true slaty or flow cleavage dominating the entire fabric of the rock. A second cleavage may also be demonstrated — it is evidenced by discrete cleavage planes marked by recrystallisation and, locally, the development of biotite flakes. It is believed that this second cleavage is the true axial plane cleavage of the Boyndie Syncline, that is $S_3$. From Macduff southwards, for some 30 km, $S_1$ and $S_3$ are found in close parallelism. They trend N - S to NNE - SSW in a vertical attitude. South of the latitude of Huntly the $S_1$ cleavage swings round and trends ENE - WSW towards Cabrach, the $S_3$ cleavage swings very slightly and intersects the thermal aureole at high angles.

In traversing through the thermal aureole towards the basic mass the $S_1$ cleavage is quickly destroyed as the fine slaty cleavage breaks up into a decussate hornfels texture. In the outer zones of the aureole spots or knots of andalusite and cordierite overgrow the $S_1$ cleavage. In the central zones of the aureole optically recognisable cordierites appear with well developed sector twinning, although the included material is sparser and coarser than that of the outer zone cordierites, it is still possible to recognise the $S_1$ fabric. In the central zone the matrix has suffered recrystallisation and the $S_1$ cleavage has become
virtually obliterated. In the inner zone of the aureole, the included fabric of the cordierite is no longer recognisable as $S_1$ and the groundmass has been completely recrystallised. It is obvious from the above textures and in particular the presence of $S_1$ included in cordierites of the central zone that the rocks now forming the thermal aureole of the Inach mass originally exhibited on $S_1$ cleavage which has been destroyed by the subsequent thermal metamorphism. The $S_2$ cleavage has a very different relationship to the thermal metamorphic fabric, for whereas the $S_1$ cleavage is overprinted by the metamorphism, $S_2$ disrupts the aureole fabric. Many thin sections from the northern aureole of the Inach and Bogansloch masses, exhibit cordierites - developed during the thermal metamorphism - broken by the $S_2$ cleavage planes. Several characteristic textures of rocks within the aureole can be referred to the disrupting effects of $S_2$ on the metamorphic fabric, viz:

(1) The $S_2$ cleavage, recognised in this area by its trend and form, can be seen running into and breaking thermal cordierites.

(2) In several thin sections, the $S_2$ cleavage can be seen abutting against and 'swinging' around the cordierites, often at high angles to the trails of included fabric which define $S_1$. From the fact that included relics of $S_1$ are usually parallel in most of the cordierites seen in thin sections, and from the orientation of the included $S_1$, it can be concluded that the cordierites have not, generally, been rotated by $S_3$.

(3) The presence of mats of mica girdling many of the cordierites suggests considerable slip and movement within the rock after the formation of the cordierites.
(a) Rose diagram showing the direction of alignment of biotite, white mica, and fibrolite (included in quartz grains) from a sillimanite hornfels near Tap o'Noth.

(b) Rose diagram showing the direction of alignment of fibrolite from the same rocks as (a).

The directions of the first ($S'$) and second ($S''$) cleavages of the area are shown.
It is therefore possible to demonstrate that the \( S_3 \) cleavage is later than the thermal metamorphism.

It is difficult, however, to demonstrate the effects of \( S_3 \) in the inner zone of the aureole and it is possible that \( S_3 \) generally failed to develop in the inner aureole. In the thermal aureole of the Bogancloch mass sillimanite has developed in the inner zone from the breakdown of biotite (q.v.) and it is possible to demonstrate in a specimen from Tap o'Noth an interesting relationship between the sillimanite and later movements. Within the rock sillimanite is represented by long matted cords of fibrolite with occasional relic cores of biotite. Within the groundmass are several plates of muscovite formed at the same time as the fibrolite from the breakdown of biotite. Crystals of fibrolite are also seen to penetrate and be contained in quartz crystals. As is discussed in 4.4b the quartz is also considered to be in part contemporaneous with the biotite breakdown.

The cords of fibrolite exhibit a weak folding which is not apparent in the rest of the rock. A series of measurements were made on the orientation of the fibrolite crystals involved in the weak folding and a series on the fibrolite included in the quartz and muscovite plates. The results of these measurements were plotted on rose diagrams. In figure 35(a) is the plot of the included fibrolite and the mica, (b) is the plot of the folded fibrolites. Also shown on the diagram are the directions of \( S_1 \) and \( S_2 \) in this area — deduced from external field evidence. \( S_2 \) of the Cabrach area is equivalent to the regional \( S_3 \). In figure 35a there is a marked alignment of crystals parallel to \( S_1 \). In figure 35b, there are two marked directions of alignment, one parallel to \( S_1 \) the other in approximate parallelism to \( S_2 \) \( (= S_3) \). Although it is appreciated that the above cannot be quoted
as firm evidence the directions of alignment suggest the following sequence of events:

1. Before the intrusion of the basic mass the fabric of the rocks was dominated by an $S_1$ planar element.

2. At the beginning of thermal metamorphism the orientation of biotite growth was governed by the orientation of the $S_1$ planes.

3. As metamorphism progressed the $S_1$ cleavage was destroyed but the large biotite flakes, and their derivative minerals - fibrolite and muscovite - retained the $S_1$ orientation.

4. Subsequent weak stresses were sufficient to fold the highly ductile cords of fibrolite but insufficient to affect the more rigid micas and included fibrolites.

Since the folds produced in the fibrolite oriented or tended to orient the fibrolite crystals parallel to the direction of $S_3$ and the trend of $F_3$ in this area, it is perhaps not unreasonable to conclude that the thermal metamorphic fabric had been subjected to the effects of the third fold movements.

In view of the evidence from the sillimanite and cordierite deformation it seems certain that the development of the thermal aureole and in consequence the intrusion of the basic sheet pre-dated the development of $S_3$. If it is accepted that the $S_3$ cleavage is the axial planar cleavage of the Boyndie Syncline, then the evidence in favour of the hypothesis which suggests that the basic sheet was intruded before and subsequently deformed by the movements producing the Boyndie Syncline, is extremely strong. It might be argued that the basic intrusion pre-dates the $S_3$ cleavage but post-dates the buckling forming the Boyndie Syncline. From regional evidence (4.30) it appears that the $S_3$ cleavage is a fracture cleavage, that is the cleavage planes were formed as active
slip planes during the folding, as opposed to slaty cleavage planes
where the orientation of the rock fabric might be due to recrystallisation
under stress after the cessation of the movements. It is therefore
difficult, if not impossible, to envisage the intrusion of the basic
sheet, and the development of a thermal aureole between the buckling
movements and the formation of $S_3$. This allied to the evidence of the
sillimanite deformation strongly suggests that the basic sheet was
intruded before and subsequently folded by the buckling movements.

With reference to Johnson's (1965) time scale it can be concluded
that the intrusion of the basic sheet post-dated the $F_1$ movements and
pre-dated the $F_2$ movements. Since the basic sheet has not suffered
retrogressive metamorphism it may be concluded that the intrusion of
the basic sheet was not before the climax of metamorphism (Johnson's $M_3$).
The intrusion of the basic sheet must therefore have occurred along
with or some time after the metamorphism, this will be discussed more
fully later but first the effects of the $F_3$ movements on the basic sheet
will be examined.

Since the present day erosion level represents an oblique section
through the Banff Nappe structure, it is possible to project any feature
or boundary from the geological map on to a cross-section. If this is
done for the basic masses it can be seen that very generally the sheet
follows the core of the nappe and that the Morven - Gabrach mass forms
a vertical column connected to the western end of the Bogancloch mass
and lying within the downbend of strata in the nappe.

In order to deduce the history of deformation of the basic sheet
several plasticine models were constructed and subjected to various
types of deformation, consistent with the structural history of N.E.
Scotland, and various geometrical projections were considered. A model
FIGURE 36.

Diagrammatic illustration of the deformation of the basic sheet.

(1) Form before third generation movements.

(2) Effects of third generation movements.

(3) Effects of forceful intrusion of Bennachie granite (broad arrow).

(4) Present day surface taken as the plane abcd through (3).

(5) General disposition of $S_1$ before third generation movements.

(6) Diagrammatic illustration of the trace of $S_1$ before the third generation movements, on the present day surface.

Arrows in (5) and (6) represent the general northward plunge of the Banff Nappe closure.
was finally deduced which seems to best fit the available field evidence and in particular the relationships of the masses to the litho-stratigraphic and metamorphic units and the attitude of the rhythmic banding in Huntly, Belhelvie and Insch.

The deformation of the basic sheet will be considered initially, as steps in the deformation of the plasticine model and the results obtained will be equated to the natural occurrences. Firstly a model was constructed in the form of a T (fig. 36,1) with the right cross limb greatly elongated, because this was regarded as the shape of the basic sheet at the time of its intrusion, the cross-bar of the T lying in the nappe core and the leg of the T lying in the downbend of the nappe. The sheet thinned towards the far side of the model and towards the ends of the cross-bars of the T consistent with thinning at Huntly and Belhelvie. The model was then deformed to simulate the effects of the $F_3$ movements (fig. 36,2). The nearside edge of the model was held rigid, in part, to correspond to the action of the Insch mass as a horizontal strut. The far edge of the model was allowed to deform normally into the present day configuration of the Boyndie Syncline and Buchan Anticline. This, in effect gave the 'Buchan Anticline' a slightly conical shape closing towards the nearside of the model. It was also considered probable that some shearing may have occurred at the right hand side of the horizontal strut. The left hand side of the model, representing in effect the Huntly mass, was sheared upwards away from the horizontal strut. The model at this stage satisfied most of the field evidence, it did not however account for the northward dip of the Insch mass, steep in the south, less steep in the north. To produce this effect the nearside margin of the mass was pushed up at the broad arrow in figure 36,3, this caused shearing which is diagrammatically shown in figure 36,3. A section
(abcd, fig. 36,3) was then taken through the model to represent the present day erosion surface and a close similarity was found between the outcrop pattern so achieved and the disposition of the basic masses (fig. 36,4). It is now possible to consider the significance of the model on the actual deformation of the basic sheet.

Within the Insh mass Read (1951, 1956) recognised several shear zones - Rothney, Ledikins and Southwest contact - marked by 'mylonites' and cataclasites and associated with acid intrusions. Read suggested (1956) that the southern aureole of the Insh mass had been removed by shearing. Clarke (1965) regarded the history of the Insh mass as essentially a three-stage process: (1) consolidation, (2) pegmatite intrusion, (3) dislocation and shearing. He suggested that the northward tilt of the Insh mass was due to the forceful intrusion of the Bennachie granite, concomitant east-west shearing exploited the pegmatites and shearing at the southern margin may have been, in part, the cause of the serpentinisation. McGregor and Wilson (1967) would appear to support Clarke's hypothesis of uplift due to the Bennachie Granite.

Since this would imply that the pressure was directed primarily on the eastern end of the Insh mass, a certain amount of torque or twisting would be induced on the western part of the Insh mass and the Bogancloch mass. It is suggested that this was relieved by shearing at Rhynie and Cabraich, such that the Insh mass was rotated uniformly to produce the 60° northward dips along its southern margin. The Bogancloch mass on the other side of the Rhynie shear was rotated uniformly but to a lesser extent than the Insh mass. This differing degree of rotation seems to explain certain of the anomalies, seen at the present day, between the Insh and Bogancloch masses. The margins of
(abcd, fig. 36,3) was then taken through the model to represent the present day erosion surface and a close similarity was found between the outcrop pattern so achieved and the disposition of the basic masses (fig. 36,4). It is now possible to consider the significance of the model on the actual deformation of the basic sheet.

Within the Insch mass Read (1951, 1956) recognised several shear zones — Rothney, Ledikins and Southwest contact — marked by 'mylonites' and cataclasites and associated with acid intrusions. Read suggested (1956) that the southern aureole of the Insch mass had been removed by shearing. Clarke (1965) regarded the history of the Insch mass as essentially a three stage process: (1) consolidation, (2) pegmatite intrusion, (3) dislocation and shearing. He suggested that the northward tilt of the Insch mass was due to the forceful intrusion of the Bennachie granite, concomitant east-west shearing exploited the pegmatites and shearing at the southern margin may have been, in part, the cause of the serpentinisation. McGregor and Wilson (1967) would appear to support Clarke's hypothesis of uplift due to the Bennachie Granite.

Since this would imply that the pressure was directed primarily on the eastern end of the Insch mass, a certain amount of torque or twisting would be induced on the western part of the Insch mass and the Bogancloch mass. It is suggested that this was relieved by shearing at Rhynie and Cabrach, such that the Insch mass was rotated uniformly to produce the 60° northward dips along its southern margin. The Bogancloch mass on the other side of the Rhynie shear was rotated uniformly but to a lesser extent than the Insch mass. This differing degree of rotation seems to explain certain of the anomalies, seen at the present day, between the Insch and Bogancloch masses. The margins of
the Insch mass are displaced northward relative to those of Bogancloch; this is due to the fact that Insch has been rotated further. Clarke (1965) demonstrated rhythmic layering in the Insch mass. He also showed that the Insch mass exhibited a well differentiated sequence from south to north — from basic to less basic gabbro. Although he regarded the Bogancloch mass as connected with the Insch mass he could not explain the apparent absence of rhythmic banding and also the fact that the Bogancloch mass was almost uniformly composed of olivine gabbro. Wadsworth et al. (1966) suggested that in the Belhelvie mass cryptic layering was apparently absent in some areas due to the flat lying nature of the rock units, that is, layering would be horizontal or sub-horizontal to the surface. It is suggested that similar phenomena are present at Bogancloch. Because the mass was rotated away from the horizontal to a lesser extent than the Insch mass, the present erosion level is contained more or less within one rock type and is near enough parallelism with cryptic layering, if present, to make it difficult to observe. It should be noted that the boundaries between rock units in the Insch mass are more or less parallel to the edges of the mass and do not vary widely in thickness, indicating that the whole of the Insch mass was rotated by the same amount.

Sadashivaiah (1951) mapped the banding in the group of ultrabasics at the eastern end of the Insch mass as trending N-S. He suggested this indicated, that both the northern and southern contacts of the mass were with roof rocks. Clarke (1965) suggested that the ultrabasics were due to anticlinal folding or a slight twist in the eastern end of the Insch mass. The second hypothesis seems to be the most consistent with the present structural interpretation. If the Insch mass was in general tilted or rotated upwards, a certain amount of
drag would be present at the extreme eastern edge due possibly to its connection with the continuation of the basic sheet saddling the Buchan Anticline, this would produce a slight downbend or twist at the eastern end of the Insch mass, as shown diagrammatically in figure 36,3.

Since the rock units are so indefinite in the Bogancloch mass the possibility must be considered that it has suffered differential rotation. If this were the case, the amount of rotation must be less to the west, implying that the mass should widen westwards, in fact it narrows considerably. Clarke (1965) computed the minimum thickness of the Insch mass as 10,000 ft. (ca. 3,000 m). The western edge of the Bogancloch mass, however, has a maximum thickness of 2,500 m. This is assuming that the present outcrop represents a section through a vertical sheet. More realistically, if the Bogancloch mass is dipping at shallow angles (10° - 20°) to the north, then the true thickness must be about 500 - 900 m. This westward thinning of the mass cannot be accounted for by differential rotation nor by, except to a minor degree, topography. It must, therefore, be presumed that the original sheet thickened rapidly from the western edge towards the centre of the Bogancloch mass and thereafter remained uniformly thick, at least until the eastern edge of the Insch mass where it probably began to thin eastwards to Belhelvie. The concept of differential rotation within the Bogancloch mass is also unlikely since, unless it sheared - and there is no evidence of this - it must have deformed plastically, and the evidence suggests conclusively that the basic masses behaved as rigid non-plastic bodies during deformation. It must, therefore, be concluded that the Bogancloch mass has been uniformly rotated due to the intrusion of the Bennachie Granite.

The shears of Rhynie and Cabrach have been subsequently exploited by faulting and are now occupied by outliers of Old Red Sandstone age.
McGregor and Wilson (1967) suggested from geophysical evidence that the covering of Old Red Sandstone is relatively thin.

The Huntly mass has been illustrated as shearing up and away from the Inach and Boganceloch masses. The form of the southern margin of the Huntly mass is consistent with this hypothesis, and the presence of a shear belt roughly along the trace of Read's (1955) Boyne Line has been discussed (3.2). It is interesting to examine the significance of this shear zone. As discussed in 4.3a, the attitude of the first schistosity was controlled by the direction of flowage of the sediments during the nappe formation. If the pattern of $S_1$ schistosity, shown in figure 36.5, is projected on to the present day surface the result is as shown in figure 36.6. The $S_1$ schistosity trends N - S southwards from the coast, swinging gradually in Strathbogie to a NE - SW trend and then curving gradually back to a N - S trend south of Cabrach. It can readily be seen that the shear zone running from Huntly to Cabrach may have been parallel to the $S_1$ cleavage. This is discussed more fully in 4.3c.

5.3 Metamorphic Effects

The relationship between the basic sheet and the metamorphism will now be considered. As stated above, it has been shown that the basic sheet was intruded during or after the metamorphism. Before the time of intrusion can be more accurately tied down it is essential to decide the state of the country rocks at the time of the intrusion, that is - were the country rocks hot or cold? Evidence on this question is best found to the north of the Boganceloch mass where regional metamorphic rocks are involved in aureole metamorphism. Sheet 86 of the one-inch Geological Survey of Scotland shows the andalusite isograd between
Distribution of metamorphic porphyroblasts around the Bogancloch mass.
DISTRIBUTION of METAMORPHIC PORPHYROBLASTS AROUND THE BOGANCLOCH MASS

- No Porphyroblasts
- Knotted Schist zone
- Andalusite zone
- Andalusite + Sillimanite zone
- Sillimanite zone

- Isograd
- Limit of thermal aureole
- Western limit of andalusite schist
- Faults
- Geological boundary

From Geol. Surv. Scotland
1" sheet 86
Drumbalg and the Bogancloch mass as a generalised line trending NE – SW. It is suggested that the two 'noses' of the isograd north of Kirkney Water are largely topographical effects, and that the isograd can be regarded as a fairly planar surface with a low dip to the west. The thermal aureole has been shown on Sheet 86 as running E – W from Newnoth to the Ealaiche Burn. Rocks in the region of Cloiche Dubh therefore lie both within the regional andalusite zone and the thermal aureole. Read (1923, p.159) states, "It is at present thought probable that the Cloiche Dubh rock represents the andalusite of the Boyndie Bay Group contact-altered within the aureoles of the Bogancloch Mass". However he does not give textural evidence to support this.

The distribution of the alumino - silicates polymorphs around the Bogancloch mass is shown in figure 37. In a traverse northwards from Bogancloch Lodge through Cloiche Dubh, the following zones are encountered: (1) sillimanite, (2) sillimanite + andalusite, (3) andalusite. The andalusite zone stretches northwards for almost 5 km – well outside the thermal aureole effects. Therefore no retrogression of the regional andalusites occurs at the extremities of the thermal aureole. This might suggest, extrapolating Watson (1964), that the country rocks were not at the time of intrusion. However, lack of retrogression cannot by itself be taken as evidence that the country rocks were hot.

Consider four traverses through the aureole:

(1) From the northern margin of the Inisch mass at Wardhouse (west end of Inisch mass), due north. The zones encountered are; (a) andalusite, 400 m; (b) knotted schist, 800 m.

(2) From the northern margin of the Bogancloch mass due north through Tap o'Noth (east end of Bogancloch mass). The zones encountered are;
(a) sillimanite, 450 m; (b) sillimanite + andalusite, 250 m; (c) andalusite, 450 m; (d) knotted schist, greater than 3,000 m.

(3) From the northern margin of the Bogancloch mass due north through Cloiche Dubh (the centre of the Bogancloch mass). The zones are: (a) sillimanite, 600 m; (b) sillimanite + andalusite, 400 m; (c) andalusite greater than 3,000 m.

(4) From the northern margin of the Bogancloch mass, due north on a line through Mount of Haddoch (the western margin of the Bogancloch mass). The zones are: (a) sillimanite, 800 m; (b) sillimanite + andalusite, 800 m; (c) andalusite, greater than 3,000 m.

It is immediately obvious that the aureole rocks of the Bogancloch mass are at a higher grade than the aureole rocks of the Insch mass. This cannot be due to differential rotation of the masses since that would only widen the zones, north of the Bogancloch mass. The higher grade must be due to one of two causes: (1) that the aureole rocks of Bogancloch were under higher pressures than those of Insch; (2) that the aureole rocks of Bogancloch were under higher temperatures than those of Insch, at the time of the basic intrusion. From the rhythmic banding and disposition of the rock units in the Insch mass (Clarke, 1965) it can be seen that the Insch mass was horizontal along its length at the time of intrusion. From the fact that the Bogancloch mass is a westward continuation of the Insch mass and from the admittedly poor evidence of the disposition of rock units within the Bogancloch mass, it seems reasonable to assume that at the time of intrusion the Bogancloch mass, or at least the eastern end of the Bogancloch mass must have been a horizontal extension of the Insch mass. This conclusion also seems to be supported by regional considerations of the relationship
of the basic sheet to the cross-section of the Banff Nappe (5,5).
Also, from regional considerations it seems improbable that the amount of overburden was significantly greater over the Bogancloch mass than over the Inisch mass. It is therefore suggested, although admittedly none of the evidence can be regarded as firm, that the Inisch and the eastern end, at least, of the Bogancloch mass were under the same pressure.

The disparity of grade between the two aureoles is therefore most probably due to different temperatures within the two aureoles at the time of the basic intrusion. It is further suggested that the increase in width of the sillimanite and sillimanite + andalusite zones between traverses (2) and (3) (150 m in both cases) is due to a general westward increase in the temperature of the country rocks at the time of the basic sheet intrusion.

It is difficult to propose any other cause for this widening of the zones apart from increases in either pressure or temperature. It cannot be ascribed to original lithology or composition since the characteristic andalusite - cordierite - biotite - quartz assemblage of the andalusite zone must be a potential sillimanite bearing rock under increased P/T conditions. Also, since the inversion of andalusite to sillimanite is a polymorphic change it must be independent of water vapour pressure etc. and only dependent on pressure and temperature. It could be argued extrapolating from the discussion of sillimanite gneiss that potash metasomatism might catalyse biotite breakdown and the formation of fibrolite; this however must be regarded as improbable, and the probability that the degree of potash metasomatism should uniformly increase along the margins of an apparently uniform olivine gabbro is most unlikely. It, therefore, seems most probable that the country rocks were subjected to a westwards increasing thermal gradient
at the time of the gabbro intrusion.

As stated above the regional andalusite isograd can be regarded as a NE - SW trending line intersecting the thermal aureole just to the east of Cloiche Dubh. Read (1923) regarded the isograd as the boundary between the Boyndie Bay Group and the Macduff Slates. However, Read (1936), and Sutton and Watson (1955) state that on the Banffshire coast the boundary between the Boyndie Bay Group and the Macduff Slates was fixed on the first appearance of andalusite and has no lithological significance. Also, it is known that the Macduff Slates in the aureole of the Bogancloch mass contain abundant andalusites. It is, therefore, possible to interpret the andalusite isograd north of the Bogancloch mass as representing a definite metamorphic reaction rather than a compositional boundary. Since the appearance of andalusite from hydrous phases is an isothermal reaction, the isograd north of Bogancloch can be regarded as an isotherm.

Isotherms at the time of the regional metamorphism can therefore be regarded at the present day as NE - SW trending lines, the temperature increasing to the west. It is suggested that the heat of the regional metamorphism was still present at the line of the basic sheet intrusion and it is this heat which produced the anomalous disposition of the alumino-silicates zones around the Bogancloch mass. It is further suggested that the shapes of the isograds reflect a compromise between the regional thermal gradient and the thermal gradient associated with the basic sheet. The suggestion that the country rocks were still hot at the time of the basic sheet intrusion is supported by two other lines of evidence. Firstly, Clarke (1965) showed that the Insh basic mass showed only a very minor degree of chilling at the margins, which he attributed to heat present in the country rocks. Secondly, Harper (1967),
in his paper on radiometric age dates in the Scottish Highlands suggests that the Dalradian rocks remained relatively warm at least until $F_2$ times.

Although it appears that the country rocks were hot at the time of the basic intrusion, a difference must be appreciated between heat retained in the country rocks after the cessation of metamorphic recrystallisation and heat in the country rocks during metamorphic recrystallisation. It is difficult to find any criteria within the metamorphic fabric which could satisfactorily differentiate between the association of the basic intrusion with one or other of the above conditions. If the basic intrusion occurred whilst the metamorphic porphyroblasts were still growing then presumably the extra heat derived from the gabbro would merely allow higher grade assemblages to develop than would otherwise have done so, and would leave no evidence of this dual heat source in the fabric. If the basic intrusion occurred after the metamorphic porphyroblasts had ceased to grow but the rocks were held at the temperatures attained during the climax of metamorphism, the extra heat of the intrusion would merely initiate further growth and the consequent development of higher grades. Although this would in effect, be 'overprinting' of the metamorphic fabric there is no obvious criterion for recognising it. One possible piece of evidence occurs in certain rocks within the andalusite and andalusite + sillimanite zone.

These rocks which contain andalusites and cordierites with a zoning of inclusions, were described in 3.5, and interpreted as evidence of two growth stages. They are confined to the aureole rocks, and it would appear reasonable to assume they represent different growth stages due to the overprinting of the thermal metamorphism on the regional
metamorphic pattern. This would, therefore, imply that the basic sheet was intruded after the cessation of the main metamorphic crystallisation, or at least after the crystallisation of the andalusite and cordierite porphyroblasts.

If the interpretation of the zoning of inclusions is correct, then a fact of especial interest emerges. If the central zones of the andalusites and cordierites represent the crystal as it was at the cessation of the main regional metamorphic crystallisation, then the rocks exhibiting these textures must have been at the same grade as spotted slates or knotted schists at the cessation of regional metamorphic crystallisation. North of the Bogancloch mass this appears to fit the hypothesis of two-stage growth in the andalusites and cordierites quite well since rocks exhibiting these textures are confined to the central and eastern part of the aureole. South of the Bogancloch mass rocks with these textures occur about 1.5 km east of The Buck and it therefore appears that in this area the regional andalusite isograd trended just to the east of The Buck swinging round to pass about 1 km south of Clayhooter Hill. This infers that the zone of regional andalusite schist was much narrower in this area than originally thought and that the Insh mass and at least the eastern half of the Bogancloch mass were intruded into spotted slates or low grade greenschist facies rocks.

Another fact emerging from the above, is the nature of the regional andalusite isograd before the basic intrusion. Before the third fold movements (q.v.) it trended approximately NW - SE north of the Bogancloch mass and probably intersected the mass north of Bogancloch Lodge. To the south of this mass, however, if the above arguments are correct, it intersects the mass to the north-east of The Buck, that is at a point west of where it intersects the northern contact. This may indicate a
displacement of the isogradic surfaces due to the basic intrusion. A diagrammatic illustration of the above concepts is shown in figure 38.

It is therefore suggested that after the climax of metamorphism the country rocks remained hot probably until the $P_3$ movements. The basic sheet, on the evidence available was intruded at some time between the cessation of the main regional metamorphic crystallisation and the third fold movements, that is, between $M_3$ and $P_3$ (Johnson, 1963). The important reservation must, however, be made that the intrusion did not necessarily post date the crystallisation of the regional sillimanite, there being no evidence to relate the age of the sillimanite growth to the basic intrusion. It is possible the regional migmatisation, sillimanite development and basic intrusion were near contemporaneous events. It is suggested, if the evidence of slight curvature of the included trails exhibited by some cordierites found within the aureole, is correctly interpreted (3, 6) then the thermal recrystallisation overlapped slightly on the third fold movements.

In the above discussions only the disposition of the alumino-silicate zones in the eastern half of the Boganclough mass have been considered. Since the Boganclough mass in its present outcrop thins rapidly westwards from its centre, it is possible that the mass may have thinned westwards at the time of intrusion. This implies that the western end of the mass was under greater overburden and therefore at higher pressures than the rest of the mass. Thus, accounting, in part, for the widening of zones between traverses (3) and (4), above. For this reason the area to the north of the western end of the Boganclough mass has been excluded from the general considerations.
5.4 Pressure and Temperature Values

It is possible from the relationships of the basic masses to the regional metamorphic pattern to deduce the conditions of the country rocks at the time of intrusion. From the above evidence it would appear reasonable that the country rocks were under approximately the same pressure and temperature conditions at the time of metamorphism as they were at the time of the basic intrusion. Absolute values of pressure and temperature will be suggested and although the values may in themselves be unrealistic at the present state of knowledge, the relative values may be of significance. The masses occur in the following country rocks.

(1) Huntly: the north end lies within the kyanite zone, immediately under a thin strip of gneiss; the south end lies approximately on the kyanite/andalusite boundary.

(2) Bogancloch and Insch: mainly at the junction of andalusite bearing rocks and hydrous phases; at the west end within the regional andalusite zone.

(3) Haddo and Arnage: at the andalusite/sillimanite + potash feldspar gneiss boundary.

(4) Belhelvie: wholly within the zone of sillimanite + potash feldspar gneiss.

This would suggest the following values.

(a) Huntly: north end, $600^\circ C$, 5 Kb (18 km)
    south end, $600^\circ C$, 4 Kb (15 km)

(b) Bogancloch and Insch: main mass, $450^\circ C$, 3 Kb (11 km)
    west end, $550^\circ C$, 3 Kb (11 km)

(c) Haddo and Arnage: $650^\circ C$, 3 Kb (11 km)
(d) Belhelvie: 650 - 700°C, 3 Kb (11 km).

These figures do not agree very well with the petrological evidence. Weedon (1965) suggested from the presence of coronas on olivine crystals within the Huntly mass that the mass was subjected to pressures equivalent to a maximum depth of burial of ca. 7 km. Weedon's evidence was, however, challenged by O'Hara and Stewart (1966) who suggested that the corona structures only indicated possible pressures less than 10 Kb (36 km). It is possible, however, that the bodily intruding basic sheet created overpressures in excess of those to which the country rocks were subjected during metamorphism. Clarke (1965) suggested from the evidence of pyroxene inversion that the Insch mass was subjected to pressures relatively greater than that of the other masses. Clarke, however, was presumably not referring to the Huntly mass, because no modern petrological work, to the present author's knowledge, has been published on it.

5.5 Age-dating evidence

Clarke (1965) quoted Rb/Sr age determinations made by Bell (1965) to prove the history of the Insch mass. Bell was unable to distinguish between the age of metamorphism and the basic intrusion, dating both events at ca. 440 m.y. Clarke quotes 400 m.y. as the age of F3 and therefore deduces that F3 post-dated the basic intrusion. Since Clarke's work several other age determinations have been made, applicable to the history of the basic sheet. Brown et al. (1965b) gave a K/Ar age of 440 m.y. to a mica schist with a strong F3 crinkle from the Banffshire coast. Brown et al. (1965a) gave K/Ar ages of 490 - 460 m.y. for various parts of the basic sheet. The spread in ages, they suggested, was due to overprinting effects during the metamorphism associated with
the third fold movements and that the age of the basic sheet was probably
greater than the figures suggest.

Recently, Harper (1967) has argued against the 'overprinting'
hypothesis in favour of a 'slow-cooling' hypothesis. He suggests
rock systems will only close to argon at relatively low temperatures,
and that Dalradian rocks remained relatively hot after metamorphism
and the spread in age determinations reflects differences in the time
of cooling. Thus during the $F_3$ uplifting rocks near the surface cooled
first and consequently will give older dates than deeper rocks which
cooled later. Harper (op.cit.) suggests 440 m.y. as the probable age
of the third fold movements and suggests the main metamorphism was
earlier than 470 m.y. Brown et al.'s (1965a) date of 460 - 490 m.y.
as the age of the gabbro must on either the 'slow-cooling' or 'over-
printing' hypothesis represent minimum ages for the basic intrusion.
Since Brown et al. (1965b) and Harper (1967) suggest 440 m.y. as the
age of $F_3$, then Bell's results of 440 m.y. for the metamorphism, and
hornfels appear, although Rb/Sr dates, to reflect the age of cooling,
uplifting or overprinting due to $F_3$. Further, Bell although allocating
the Inish mass to a 440 m.y. event quoted a date for it of 429 $\pm$ 7 m.y.
it is possible that the neighbouring Bennachie Granite (410 $\pm$ 14 m.y.)
may have influenced this date. It would, therefore, appear that the
metamorphism and the basic sheet intrusion occurred about 500 m.y. or
more, ago. Also, that the rocks remained hot until the third generation
movements.

Since the basic masses in general show no evidence of metamorphic
overprinting and also their fabric shows no evidence of internal disorder
associated with the third movements, it is perhaps simpler to explain
their spread in ages as due to 'slow-cooling' rather than 'overprinting'.
FIGURE 38.

Diagrammatic sections through the Banff Nappe to illustrate the pattern of metamorphic zones after regional metamorphism and their subsequent modification by the thermal effects of the basic sheet. See text (5.7) for explanation.

Key:
- fine stipple - hydrous phases zone
- dots - andalusite zone
- wide ruling - kyanite zone
- cross-hatching - sillimanite zone; gneisses
- close ruling - basic sheet

Heavy lines in basic sheet represent attitude of rhythmic layering. The heavy line south of Huntly represents the shear plane due to third generation movements.
5.6 Summary

The sequence of events may be given as follows:

1. The regional metamorphism of the north-east Dalradians reached a climax 500 m.y., or more, ago.

2. The basic sheet was intruded whilst the rocks were still hot, after the cessation of the regional andalusite and cordierite crystallisation, and possibly after the regional sillimanite crystallisation.

3. The heat of the basic sheet locally raised the grade of the country rocks.

4. Thermal metamorphism was in its last stages when the basic sheet was deformed by the third fold movements. These movements folded and in places sheared the basic sheet.

5. The intrusion of the Bennachie Granite tilted up the southern margin of the Insh and Bogancloch masses, shearing them in places.

5.7 Explanation of Figure 38

Several interesting facts concerning the modification of the regional metamorphic pattern, only briefly alluded to in the above text, emerge from an examination of figure 38.

Section (a): This section illustrates the pattern of metamorphic zones at the cessation of regional metamorphism, as described and diagrammatically illustrated in the section on metamorphism.

Section (b): This shows the pattern of metamorphic zones after the basic intrusion but without the thermal overprinting effects. As was shown in the discussion of the basic masses, the rocks to the south
and north of the central and eastern part of the Bogancloch mass were at the grade of 'knotted schist' at the time of the basic intrusion. It was also shown that the regional andalusite isograd intersected the southern margin of the Bogancloch mass at a point due south or slightly west of the point where it intersected the northern margin. Since the regional andalusite isograd both north and south of the mass trended from NW - SE to WNW - ESE, it is obvious the isograd 'jumps' westwards across the Bogancloch mass. This was suggested as a displacement of the isogradic surface similar to the displacement of small quartz or other veins by cross-cutting veins. Similar displacements are shown on the cross-section wherever the basic sheet cross-cuts an isogradic surface, although no field evidence has been proposed in support, it would seem logical to assume their existence.

At the time of intrusion the Belhelvie mass was entirely within the zone of gneisses. Haddo and Arnage lay near the sillimanite isograd. Insch and Bogancloch lay within spotted slates near the andalusite isograd, the eastern and western margins lay in andalusite schist. The Morven - Cabrach mass lay entirely within gneisses. Huntly had kyanite bearing rocks along its western margin, andalusite bearing rocks along its southern and south-eastern margins and sillimanite gneiss at its north-eastern margin.

When the basic sheet is plotted on the cross-section in accordance with these observations, two important facts emerge. Firstly, the part of the basic sheet now forming the central and eastern part of the Bogancloch mass, the Insch, Haddo House and Belhelvie masses must have formed a horizontal sheet. Secondly, the part of the mass now forming the Huntly mass must have cut through the gneisses in order to have kyanite bearing rocks on one side and sillimanite gneiss on the other.
This latter point is of prime importance since it shows that the cut-out of the Cowhythe Gneiss to the north of Huntly is not due to a tectonic cut-out but to the cross-cutting effect of the basic sheet.

Section (c): shows the metamorphic pattern after the thermal overprinting effects. The hydrous phases zone has been narrowed. The knotted schists, south of the Bogancloch mass, have been prograded to sillimanite (fibrolite) bearing assemblages. North of the Bogancloch mass the andalusite zone is extended and stretches right along the northern margin of the Insch mass to widen out into the regional Fyvie schists. Sillimanite bearing rocks have been formed at the northern margin of the Bogancloch mass.

Section (d): This is a block diagram showing the disposition of metamorphic zones after the third fold movements. Certain modification of the zones demonstrated on the present day surface have not been shown, viz., the disruption of the andalusite zone to the east of the Huntly mass. This has been attributed to folding and faulting on the steep western limb of the third fold movements and is a concomitant process with the formation of the Boyndie Syncline. The tilting of the Insch and Bogancloch masses by the Bennachie Granite has not been shown. It is easily seen that the shape of the andalusite isograd in Strathbogie is perfectly reconcilable with the concept of its distortion due to the third fold movements. Shear planes have cut-out the sillimanite gneiss at Cabrach and Corinacy. The pattern of zones around Bogancloch should be compared with figure 37.

Section (e): This is a cross-section through the Huntly mass. The arrow 'X' represents the direction along which successively older units of the mass come on, as indicated by gravitational sorting, that is the mass is overturned. This is consistent with Shackleton (1948).
The arrow 'Y' represents the direction along which successively older beds come on. The beds and isogradic surfaces are dipping steeply eastwards. It should be remembered that they have suffered minor third folding and distortion.

The important points may be summarised thus:

(1) The basic sheet cuts and displaces the regional isogradic surfaces.

(2) The Huntly mass cuts downwards through 'the zone of sillimanite gneiss'.

(3) The thermal overprinting effects have been locally fairly extensive, for example, the prograding of the spotted slates south of Bogancloch to a relatively wide zone (ca. 1 km) of sillimanite and andalusite rocks.

(4) The nature of the andalusite isograd in Strathbogie is due to the distorting effects of the third fold movements.

(5) The cut-out of the Cowhythe Gneiss east of Huntly is not due to a tectonic cut-out but due to the cross-cutting nature of the Huntly mass.

(6) The overturned, westward dip of the banding in Huntly is not inconsistent with the proposed deformation by the third fold movements, being due to the fact that the Huntly mass cut down through the metamorphic zones before the third fold movements.
SUMMARY OF CONCLUSIONS

The sediments of the north-east Dalradian rocks represent a gradational sequence from orthoquartzitic facies to turbidite facies. Local stratigraphic names were found to be confusing because they often refer to small impersistent units and also are often based on changes in metamorphic grade, without reflecting lithological change. Rapid facies change was suggested as the main cause of the disappearance and lensing out of quartzite and limestone units. Three broad litho-stratigraphic units were erected with characteristic lithological assemblages. They were: (a) Calcareous Flag Group, characterised by massive limestones and quartzites with calcareous and argillaceous bands. This group is roughly equivalent to the upper part of the Lower Dalradian and the lowermost part of the Upper Dalradian. (b) Transition Group, a narrow group characterised by calcareous flags, grits and greywackes. (c) Greywacke Group, characterised by the presence of greywackes and grits. The sediments were probably laid down in a NE - SW trending trough and the predominance of greywacke in the upper part of the sequence may have been due to an abundant source of detritus from an emerging landmass to the north (Sutton and Watson, 1955). It is suggested variation in facies may occur across the basin of deposition; marginal sediments of the Calcareous Flag Group developing massive limestones; medial sediments developing calcareous grits and flags.

At the beginning of the Caledonian Orogeny lateral compression folded or increased the slope of the basement on which the sediments rested, this resulted in the gravity controlled slumping of the sedimentary
pile, to produce the great nappes of the Dalradian. The Banff Nappe is a northward extension of the Tay Nappe and is characterised by a frontal 'hump' with an associated depression in the central zone of the nappe. The Iltagy Boundary Slide and other major slides of the Perthshire Dalradians are absent from Banffshire, as also are the northward facing nappes. This is interpreted as a lower degree of deformation in the north-east, possibly due to a shallower slope of the basement. The $B_1$ folds at Collieston were formed by late-stage slumping at the nappe nose. During slumping and the formation of the nappe structure, isoclinal folding occurred mainly in the lower structural zones. The slumping of the sediments and general flow of the rock resulted in the imprinting of a slaty cleavage. Locally, as at Collieston, this was folded and a secondary cleavage axial planar to the folds developed. The metamorphic grade was low, probably with slight recrystallisation and the appearance of chlorite and white mica. Locally, biotite flakes appeared on the schistosity planes (e.g. Collieston). A certain amount of tectonic cut-out or sliding may have occurred but this is on a local scale, and the major slides of Read (1955; with Farquhar, 1956) cannot be substantiated.

Consequent upon these fold movements but forming, or at least tightening at a somewhat later date were Johnson's (1963) $F_2$ folds. These disrupt the first schistosity, generally on a 'strain-slip' pattern, to produce a second cleavage. They are confined to the Lower Dalradian. It was suggested that these were cross-folds to the major nappe folds and are confined to the deeper structural zones, it was suggested this was due to their development in the deep seated 'zone of active segmentation' (Argand, 1912, quoted by East and Platt, 1957).

Sometime after, or towards the end of the nappe forming movements
migmatic intrusion or partial melting, at depth, below the nappe, produced a melt rich in potash and water which began to migrate upwards. Initially this probably acted in the form of a heat dome and radiating heat initiated metamorphic crystallisation in the surrounding rocks. In the deep seated rocks this led to the appearance of garnet and biotite (Johnson, 1963). In the higher structural zones knotted schists were developed. This heat advance continued through $F_2$ times the metamorphic front moving progressively upwards and outwards and the metamorphic grade of the rocks progressing. Actual migmatitic melt probably did not migrate far from the source and the large areas of 'migmatite' and gneiss in the Dalradian probably resulted from partial melting 'in situ'. Water and potash rich mixtures rose up and percolated along the nappe core. This hot mixture initiated partial melting in the core. Localised mobilisation of potash occurred with the breakdown of biotite to form sillimanite. The potash solutions migrated to pockets rich in aluminosilicate to form potash feldspar or muscovite. The migration and metasomatic introduction of potash along the nappe core was a self-regenerating process. Heat, carried by the percolating potash rich solutions, caused biotite breakdown and the release of potash and water. The amount of potash reacting to form feldspar and muscovite was probably in excess of the amount released by the biotite, so that the excess potash in the percolating solutions was gradually used up.

At deep levels and consequent high temperatures sufficient water was present to allow the formation of partial melts without affecting the stability of muscovite. At higher levels and consequently lower temperatures more water was required for partial melting and this was, in part, derived from muscovite breakdown. The zones of muscovite and potash feldspar are, however, more controlled by the nature of the
geothermal gradient than the requirements of partial melting.

As the potash rich solutions advanced along the nappe core, so the heat front advanced and rocks initially in the intermediate pressure greenschist facies, during \( F_2 \) times, prograded to amphibolite facies, with the appearance of staurolite and kyanite; rocks originally in the low pressure greenschist facies prograded to the amphibolite facies, with the development of andalusite and cordierite. At the same time chlorite bearing rocks of the zeolite facies prograded to the greenschist facies with the development of garnet and biotite at intermediate pressures and knotted schists at low pressures. As the heat front advanced farther, kyanite and andalusite bearing rocks in the nappe core gave way to sillimanite rocks; the consequent mobilisation of potash producing orthoclase and muscovite. Finally partial melting occurred with the formation of the characteristic oligoclase - biotite - gneiss.

After the cessation of the main metamorphic crystallisation, but whilst the rocks were still hot the basic sheet was intruded. Generally it lies parallel to the boundaries of the metamorphic zones, but locally cross-cuts the isograds. The heat of the basic intrusion locally upgraded the rocks and modified the regional metamorphic pattern.

During the last stages of thermal metamorphism a second spasm of the Caledonian Orogeny appressed the frontal hump and complementary depression of the nappe to produce the present day configuration of the Buchan Anticline and Boynie Syncline.
The folding of the basic sheet is attributed to these third fold movements. The rigidity of the sheet has imposed a tectonic control on the country rocks. The eastern part of the sheet was buckled by the Buchan Anticline. The Insch mass acted as a rigid horizontal strut. The Huntly mass was sheared off and tilted into a steep attitude on the western limb of the Boynie Syncline. The shearing south of the Huntly mass led to the cut-out of the upper part of the Calcareous Flag Group and the oligoclase–biotite gneisses around Cabrach. This resulted in the juxtaposition of Lower Dalradian black schists and Upper Dalradian andalusite schists. The trace of the shear plane follows the trace of Read's (1955) Boyne Idne in this area. Faulting on the steep western limb of the Boynie Syncline caused local lithostratigraphic cut-outs and a modification of the metamorphic pattern.

In the area south of Huntly, the tilting of the Huntly mass and the rigid nature of the Insch mass has resulted in the buckling of the first generation axial planes and isogradic surfaces. Originally NNE–SSW trending first generation structures were rotated into an E–W direction; the original NNW–SSE trending andalusite isograd was rotated into a NW–SE direction. Third generation folds cut across these structures maintaining a NNE–SSW trend throughout the area. The proposed eastward swing of the Boynie Syncline (Johnson and Stewart,
fig. 1, 1960) south of Strathbogie could not be substantiated. Although the main slaty cleavage of the Macduff Slates swings eastwards, a later cleavage - the true axial plane cleavage of the Boyndie Syncline - departs from parallelism with the slaty cleavage south of Strathbogie, continuing on a NNE - SSW trend. Therefore it was shown that the axis of the Boyndie Syncline is effectively parallel to the axis of the Buchan Anticline. Also, that the swing in trend of the slaty cleavage in Strathbogie was a result of third fold movements, and the Huntly - Tarves antiform of Johnson and Stewart (1960) was unnecessary to explain the disposition of structures.

Johnson's (1963) $F_4$ minor folds were considered to be cross-folds to the third folds analogous to the $F_2$ and $F_1$ folds.

During the last stages of the Caledonian Orogeny large scale granitic intrusions occurred. One of the masses, the Bennachie Granite, pushed up the eastern side of the southern edge of the Insch mass. This caused a general twisting of the Insch and Bogancloch masses which was relieved by shearing at Cabrach and Rhynie. The masses suffered differential rotation, the Bogancloch mass being tilted less than the Insch mass. The granites caused localised metamorphism (e.g. the Peterhead Granite on the Collieston coast section).

The present author has accepted Clarke's (1965) suggestion that the tilting of the Insch mass was due to the Bennachie Granite. This seems to be the most reasonable explanation of the structural evidence, and would also appear to be supported by McGregor and Wilson's (1967) cross-section of the Insch and Bennachie masses. It must, however, be admitted that in general the Newer Granites show no evidence of forceful intrusion; there being no demonstrable deflections of strike.
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## APPENDIX I

National Grid References for Place-names on the Collieston Section

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APPENDIX II

National Grid References for place names on the Rosehearty and Fyvie Sections

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<td>Warehouse</td>
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Rotated knot. The included grains in the knot define $S_0$ and $S_1$. Coarser grains in the matrix define $S_2$; oblique to the included trails. Collieston. x 6.
PLATE 3

Andalusite fractured by $B_2$ microfolds. Rosehearty.
Crossed nicols, $x$ 6.

PLATE 4

$B_2$ microfolds 'wrapping' around an andalusite crystal
in top right corner. Rosehearty. Crossed nicols, $x$ 6.
$S_2$ cleavage 'wrapping' around cordierite porphyroblast.
Near Tap o'Noth. Crossed nicols, $x$ 6.

$S_2$ cleavage 'wrapping' around and cutting cordierite porphyroblasts. The included grains of the cordierites define the $S_1$ slaty cleavage, oblique to $S_2$. Aureole of Bogancloch Mass. Crossed nicols, $x$ 6.
$S_2$ cleavage 'wrapping' around and cutting cordierite porphyroblasts. The included grains of the cordierites define the $S_1$ slaty cleavage, oblique to $S_2$. Aureole of Bogancloch Mass. Crossed nicols, $\times 6$.

Plate 8

As above.
$S_2$ cleavage 'wrapping' around and cutting cordierite porphyroblasts. The included grains of the cordierites define the $S_1$ slaty cleavage, oblique to $S_2$. Aureole of Bogancloch Mass. Crossed nicols, x 6.

Andalusite crystals from the spotted slate zone.
$S_2$ cleavage cuts porphyroblasts; internal trails define $S_1$ slaty cleavage oblique to $S_2$. Aureole of Bogancloch Mass. Crossed nicols, x 6.
PLATE 11

\(S_2\) cleavage 'wrapping' around and cutting cordierite porphyroblasts. The included grains of the cordierites define the \(S_1\) slaty cleavage, oblique to \(S_2\). Aureole of Bogancloch Mass. Crossed nicols, \(x\) 6.

PLATE 12

Small garnets concentrated in bands. Den of Wraes, ca 10 m from the Insch Mass. \(x\) 6.
CORDA OF FIBROLITE WITH RELIC | CORES OF BIOTITE.

TAP O'NOTH.  X 6.

FIBROLITE IN ASSOCIATION WITH BIOTITE. 'Dissolving'
andalusites can be seen in the top right and bottom
left corners. TAP O'NOTH.  X 6.
Fibrolite associated with biotite. Potash feldspar and andalusite can be seen sieved with quartz. The potash feldspar has been stained yellow. Tap o’Noth. x 6.

Cords of fibrolite mainly associated with quartz and iron ore. Tap o’Noth. x 6.
PLATE 17

Fibrolite cords, associated with muscovite, quartz and iron ore. Cloiche Dubh. x 6.

PLATE 18

As plate 17, under crossed nicols. x 6.
PLATE 19

Fibrolite crystals forming from the breakdown of biotite,
Tap o'Noth. x 15.

PLATE 20

PLATE 21


PLATE 22

Chiastolite crosses. Included material at centre of cross defines what may be $S_1$ slaty cleavage. The external cleavage is oblique to the included trails of inclusions.
Andalusite crystal with included $B_1$ cleavage. $B_2$
microfolds can be seen in top right corner. Rosehearty.
Crosed nicols, x 6.
PLATE 24

Xenoliths of andalusite schist at margin of Peterhead Granite. Whinnyfold.

PLATE 25

As plate 24.

Recumbent syncline. The closure of a large syncline can be seen on the cliffs behind. Near Pottie Murlan, Collieston.
PLATE 28

Recumbent folds. Pelitic bands surrounding the more competent grit core are pinched and pulled out along the axial planes. Fottie Murlan, Collieston.

PLATE 29

Easterly dipping $S_1$ surfaces, with $ac$ and $bc$ joints.
Looking south to Aver Hill, Collieston.
PLATE 30

Basic sill folded by $B_1$ movements, showing $S_1$ cleavage. Hell's Hole, Collieston.

PLATE 31

Basic sill (D) pinched out and disrupted by $B_1$ movements. Craig's House, Collieston.
PLATE 32

Elongated pebbles in grit band defining $L_1$, parallel to hammer shaft. Collieston.

PLATE 33

As for plate 32. Craig's House, Collieston.
PLATE 34

Elongated pebbles in grit and S₀/S₁ intersections defining L₁, parallel to hammer shaft. Collieston.

PLATE 35

Boudinage of grit band. Pottie Murlan.
PLATE 36

Recumbent fold in grit band. Pottie Murlan.

PLATE 37

Recumbent fold in grit band. The lower limb sheared by $S_2$ planes. Pottie Murlan.
Boudinage and disruption of pegmatite veins.
Craig's House, Collieston.

Pinch and swell structure in quartz veins.
Collieston.
PLATE 40

Folding and boudinage of pegmatite veins.
Collieston.

PLATE 41

As for plate 40.
PLATE 42

Boudinage of pegmatite vein. Collieston.

PLATE 43

Boudinage of quartz vein. Collieston.
Contact between schists and Peterhead Granite (G).
Block of country rock (X) can be seen within granite.

General view looking north from Aver Hill. A large 'boudin' (B) can be seen in the middle distance.
Folds can be seen in the distant cliffs.
PLATE 46

General view northwards along the Collieston coast section from Slains Castle to Whinnyfold, with the flat drift covered Buchan plateau stretching backwards from the top of the cliffs.

PLATE 47

General view southwards along the Collieston coast section from Slains Castle to Aver Hill.
PLATE 48

Rocks show general easterly dip of $S_0$ and $S_1$.
Collieston.
A structural and metamorphic history is proposed for north-east Scotland based on the detailed structural and metamorphic analyses of the Collieston coast section and the ground between Rhynie and Cabrach, and Strathbogie and Cabrach.

At Collieston two homoaxial fold movements are demonstrated one post-dating, the other pre-dating the main metamorphism. The style of folding is found to be consistent with gravity motivated slumping of the sedimentary pile. The second folds are thought to be due to the regeneration of slumping caused by an increase in the angle of slope of the sedimentary pile.

The Dalradian succession has been divided into three broad litho-stratigraphic groups. This grouping overcomes anomalies in the established stratigraphical sections caused by rapid facies change. Consideration of the disposition of these litho-stratigraphic units has led to a re-assessment of the evidence for many of the proposed structures of north-east Scotland. The concept of the Banff Nappe is accepted. However, the evidence for the Boyne Line and other slides affecting the Buchan Anticline is difficult to substantiate.

It is suggested that these slides are unlikely to exist, at least in the form postulated by H.H. Read.

The regional structural history comprises four fold episodes. It is suggested that the Banff Nappe was formed by the gravity controlled collapse of the sedimentary pile, flowage and stretching of the rocks inducing the ubiquitous regional schistosity. From various lines of evidence it is thought that the Banff Nappe possessed a frontal 'hump', with a complementary depression behind. The second fold movements are believed to be "cross folds" genetically related to the first folds and confined to the deeper structural levels of the region. During the third fold movements the frontal 'hump' and complementary depression of the Banff Nappe were appressed to form the present day configuration of the Boyndie Syncline and Buchan Anticline. Steepening of the limbs of the Buchan Anticline regenerated gravity controlled slumping at Collieston and initiated gravity controlled folding on the Rosneath-Forres-Fraochertiary section with the sediments slumping into the trough of the Boyndie Syncline. Fourth folds are believed to be "cross folds" to the third folds similar to the relationship between the first and second folds.

Metamorphism is thought to be a continuous process, beginning at or near the cessation of the first generation folding and reaching a climax, in a static phase before the third fold movements. An examination is made of the phase chemistry of the various metamorphic minerals and a model is proposed for the metamorphism. The regional metamorphism (Buchan and Barrovian type) is thought to result from the heating up, or introduction of a heat carrying medium to the rocks below the Banff Nappe, sufficient to produce a migmatic melt and/or a potash rich solution. This mixture slowly migrated, first upwards and then laterally along the nappe core, radiant heat inducing metamorphic crystallisation in the surrounding rocks. At the margins of this heat source the rocks underwent low grade metamorphism (crystallisation of chlorite, 'knots', garnet), inward from the margins the rocks underwent intermediate grade metamorphism (crystallisation of andalusite, kyanite and cordierite). In the central zone, that is where the rocks were being subjected to the metasomatic introduction of the potash rich solutions, sillimanite crystallised, partial melting occurred, and migmatic feldspars were developed.

Evidence is advanced to date the intrusion of the basic sheet (Younger Gabbros) in north-east Scotland. It is believed to have been intruded before the third fold movements, after the cessation of the main metamorphic crystallisation, but whilst the rocks were still hot. Thermal effects of the basic sheet locally/
LEGEND

A  Generalised trend of first lineations
B  Generalised trend of second lineations
C  Detailed trend of second lineations
D  Detailed trend of first lineations

Stereograms showing generalised relationship of \( S_5 \rightarrow \cdots \rightarrow S_5 \) and \( S_5 \rightarrow \cdots \rightarrow S_5 \) along the section.

Detailed analysis in text figures of Chapter 2.
AXIAL PLANE TREND OF THE FIRST AND SECOND FOLD MOVEMENTS

LEGEND

- Old Red Sandstone
- Younger Gabbro
- Newer Granite

Axial plane trend of first fold movements
Axial plane trend of second fold movements
<table>
<thead>
<tr>
<th>ZONE 1</th>
<th>ZONE 2</th>
<th>ZONE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>ZONE 1</em> — rocks now represented by sillimanite gneiss</td>
<td><em>ZONE 2</em> — rocks now represented by andalusite schist</td>
<td><em>ZONE 3</em> — rocks now represented by knotted schists</td>
</tr>
</tbody>
</table>

### Summary of the Structural and Metamorphic History of N.E. Scotland

<table>
<thead>
<tr>
<th>Structural Events</th>
<th>Metamorphic Events</th>
<th>Igneous Activity &amp; Thermal Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Deformational Movements</strong></td>
<td>Formation of Banff Nappe with frontal hump; possible localised sliding &amp; attenuation of beds; imprinting of slaty cleavage — regional $S_1$</td>
<td>Recrystallisation of micas; localised development of biotite on $S_1$ planes</td>
</tr>
<tr>
<td></td>
<td>Section across the Banff Nappe</td>
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<tr>
<td></td>
<td>Folds at Collieston</td>
<td></td>
</tr>
<tr>
<td><strong>Second Deformational Movements</strong></td>
<td>$F_2$ movements confined to deep structural zones; localised development of $S_2$</td>
<td>Continuing growth of garnet</td>
</tr>
<tr>
<td></td>
<td>$F_2$ movements; possible cross folds to $F_1$</td>
<td>Kyanite</td>
</tr>
<tr>
<td><strong>Static Phase</strong></td>
<td>$F_2$ movements</td>
<td>Silimanite gneiss</td>
</tr>
<tr>
<td></td>
<td>$S_2$ imprinted</td>
<td>Andalusite cordierite</td>
</tr>
<tr>
<td><strong>Third Deformational Movements</strong></td>
<td>Lateral compression of Banff Nappe to form present day configuration of the Buchan Anticline &amp; Boyndie Syncline</td>
<td>Localised retrogression; Recrystallisation of biotite along $S_3$ planes</td>
</tr>
<tr>
<td></td>
<td>Folding of the basic sheet and isogrades</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F_3$ movements</td>
<td>Distortion of metamorphic fabric, rotation and occasional plastic deformation of porphyroblasts</td>
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<tr>
<td></td>
<td>$B_2$ movements</td>
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</tr>
<tr>
<td></td>
<td>$B_2$ movements</td>
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<tr>
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<td>$B_2$ movements</td>
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<tr>
<td><strong>Fourth Deformational Movements</strong></td>
<td>$F_4$ movements confined to deep-structural zones; Localised development of $S_4$</td>
<td>Localised retrogression; Mainly chloritisation</td>
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<td>Tilting of Insh &amp; Bogancloch basic masses</td>
<td>Intrusion of Newer Granites; Localised thermal metamorphism</td>
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<td>Faulting</td>
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**Notes:**
- $S_1$, $S_2$, $S_3$, $S_4$ represent sets of foliations.
- $F_1$, $F_2$, $F_3$, $F_4$ represent sets of folds.