THE GEOLOGY OF THE GEALLAIG DISTRICT,

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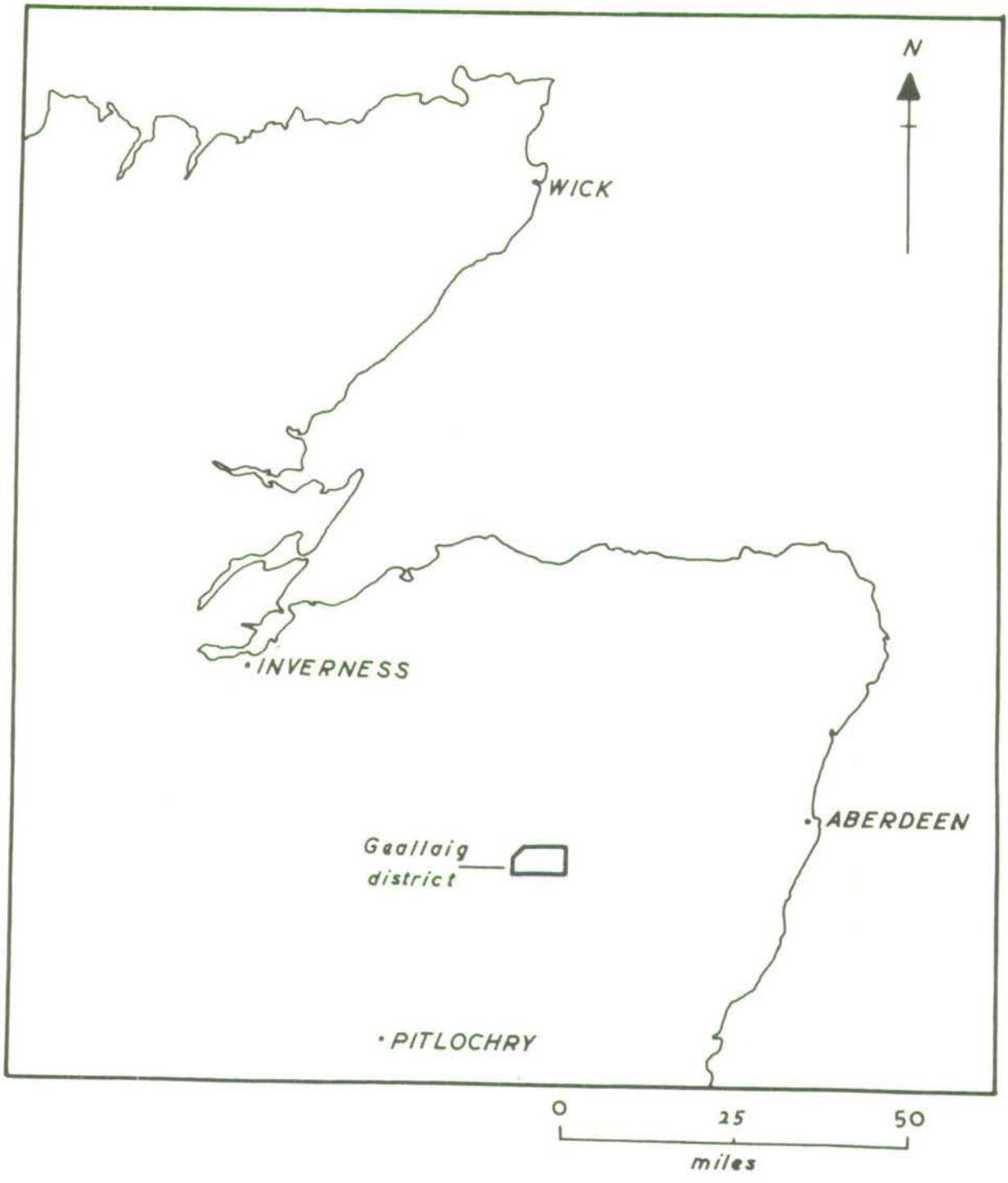
INTRODUCTION

DRAINAGE AND TOPOGRAPHY

The area considered in this thesis covers 40 square miles in the foothills of the Grampian Highlands, approximately 45 miles east of Aberdeen and 50 miles southeast of Inverness (see Fig.1). It is bounded to the south by the River Dee; to the east by the Culsten Burn whose north-south course passes roughly two miles east of Ballater. The western boundary is a north-south line from Invergelder to An Creagan, and from there northeasterly to Craig of Tullich, and the northern is an arbitrary east-west line approximately one mile to the north of Gairnshiel.

By far the greater part of the area consists of rough, heather-covered grouse moors, but narrow strips of cultivated land follow the valleys of the Dee and Gairn, and locally the northern slopes of the Dee valley carry a stand of timber. The land rises from about 800 feet in the valley of the Dee to a height of 2400 feet at the summit of Geallaig Hill, the most prominent topographic feature of the area.

High ground, culminating in Geallaig Hill, extends from the Crathie-Gairnshiel road eastwards to the Gairn valley, where the ground drops 300 feet to the valley bottom, and rises sharply again to the east of the river. Here the foothills of Morven form a plateau 1700 feet above sea level; this plateau is separated by the deep north-south cut of the Tullich burn from the craggy mass of Crannach Hill which lies close to the eastern boundary of the area mapped.



Geographical setting of the Geallaig district.

Fig. 1

The western part of the area is drained by numerous very small burns which descend the slopes of Geallaig Hill and flow northwards into the Gairn or southwards into the Dee. Of these the largest, the Torgalter Burn, is the only one which provides rock exposures, the others being sunk into alluvium. To the east of the Gairn the north-south trending Tullich and Culsten burns occupy deep cuts which mark the positions of former glacial overflow channels, whilst the hills to the south of Morven are drained radially by a number of small burns flowing into the Gairn valley to the west or into the Tullich Burn to the east.

The area is poorly exposed, the low ground being covered by glacial moraines and alluvium, whilst a large proportion of the high ground consists of heather-covered moorland. Rock exposure is generally confined to isolated patches along the shoulders of the hills.

A map showing approximate areas of exposure and the location of geographical place names referred to in the text is given in Fig. 2.

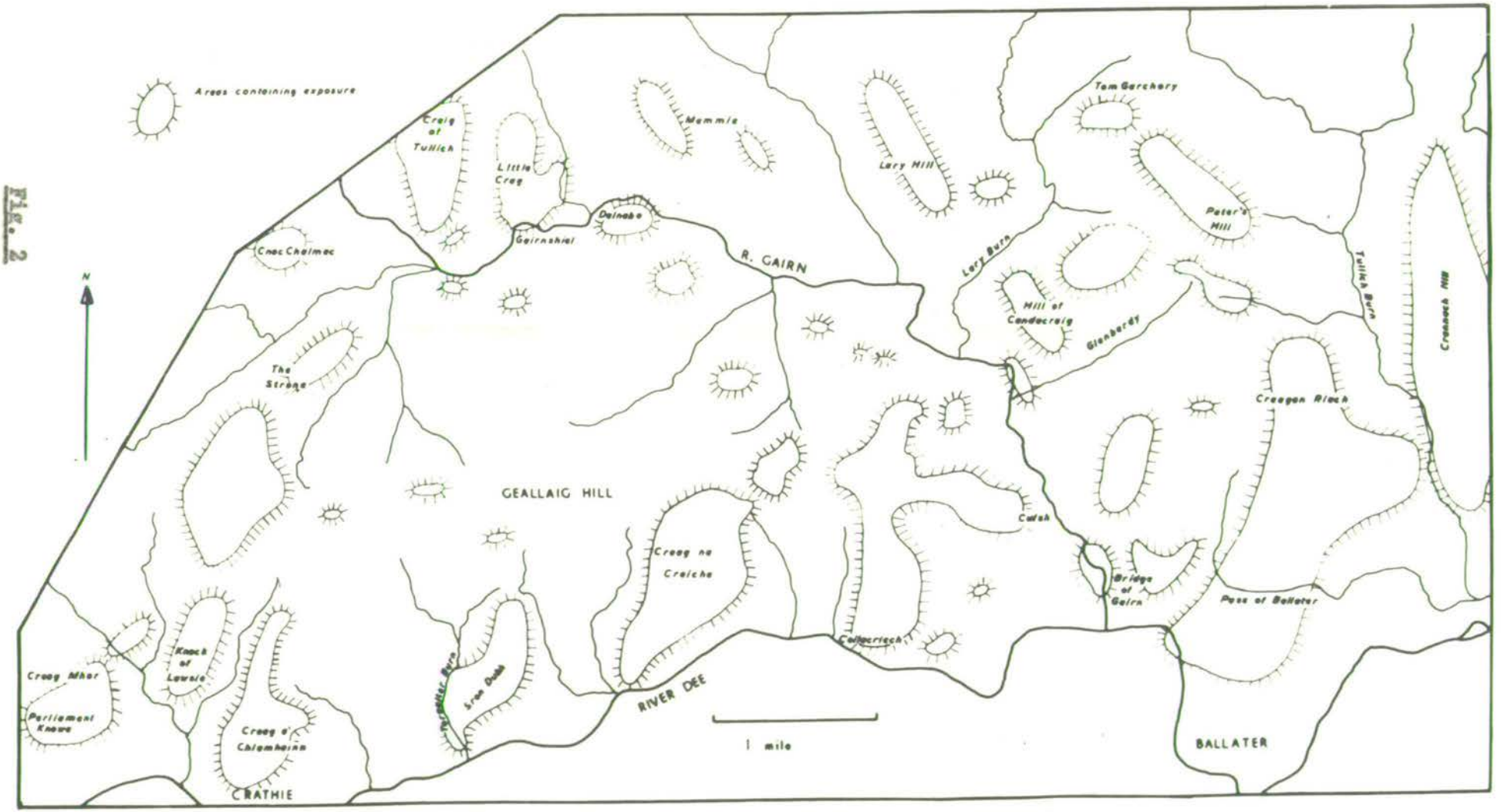
PREVIOUS WORK

Although the problems of Dalradian geology have been intensively studied in many areas, this particular part of the Highlands has so far attracted little interest. The only detailed description available is that by the Geological Survey (Barrow and Craig 1912).

Before 1860 a number of geological reports included general remarks about the geology of parts of Deeside, including the Geallaig district.

Fig. 2

Exposure and locality map of the Geallaig district.



These works include Necker (1808), Boué (1820), McKnight (1821), Nicol (1844), and Murchison (1860).

In the first works to deal specifically with Deeside, Jamieson produced a series of papers (1860, 1865, 1874) discussing the glacial phenomena of the Dee valley in which he recognised the presence of moraines and mounds of glacial debris. Soon afterwards, Heddle (1877) gave lists of minerals from various parts of the Geallaig area, reporting as many as 23 mineral species from the limestone quarry at Dalnabo. Subsequently Hamilton Bell (1833) was the first to mention the presence of lead at Abergairn, where he noted the presence of galena associated with zincblende in a vein of quartz and purple and green fluorspar.

In 1912 the Geological Survey Memoir for Braemar, Ballater and Glen Clova was published and gave the first accurate and reasonably comprehensive account of the geology of the area. Its authors, Barrow and Craig, considered the sedimentary rocks of the area to lie above the "Lower Group" of schists and gneisses found to the east and southeast in Glen Clova and Glen Muick; these they thought to be the highly metamorphosed representatives of the originally more argillaceous members of the Banffshire or Central Highland Series. The dominant strike of the sedimentary rocks was noted as NE-SW and it was considered that the rocks had been repeatedly folded although no structural detail was given. The hornfelsing of schists by the Newer Granite of Glen Gairn was systematically described, the various types being related to their non-thermally metamorphosed equivalents exposed further to the NW. The bands of schist intercalated within

the epidiorite to the west of Glen Gairn were described as "inclusions or infolds" in the basic rocks. The authors concluded that the schists first underwent regional metamorphism and were then affected by thermal metamorphism as they saw no evidence of hornfelses being broken down by later shearing.

Barrow and Craig considered that only basic representatives of the Older Igneous rocks occur in this area. These were thought to have been intruded into the sediments of the Banffshire Series in the form of a single sill previous to, or in the very early stages of, the regional metamorphism. Locally the sill has undergone contact metamorphism to varying degrees, and petrographic descriptions of the various grades are given; the intensity of shearing was thought to increase from west to east. The epidiorite was thought to be the metamorphosed representative of augite porphyrite and attention was drawn to the similar assemblage of porphyritic epidiorites found to the north, in Strathdon.

The diorites and granites of the area were assigned to the Newer Igneous group of intrusions. Almost all the diorites are at the margins of granitic masses, in particular to the west of the Glen Gairn granite and from this it was suggested that the diorites were intruded previous to the granite as a continuous mass lying beneath a now partially removed cover of schists. The diorite mass was believed to stretch beneath the Lochnagar granite from the exposures at the head of Glen Gairn southwards to those at the head of Glen Clova, the granite forming a "step feature" above the diorite. Westwards the diorites were thought to pass underneath the granite, which

further west itself passes underground and is represented at the surface only by dykes. Where foliation in the diorite is present it is unaccompanied by any crushing and was consequently recognised as a primary flow structure.

It was noted that to the north of Balmoral the diorites vary considerably in composition, the form of the intrusions in this part being sill-like. Where the biotite-granites have been intruded into and through diorite they were thought to have brought about, in nearly every case, fusion and hybridisation. Most typically a hybrid zone 50 to 100 yards wide was formed between the granite and the diorite. Where hybridisation has not taken place the granite intrusions are generally small and it was considered that they probably did not possess sufficient heat to fuse the surrounding diorite. Isolated masses of diorite occurring for a short distance into the granite of Glen Gairn were considered to be fragments of earlier consolidated diorite included in the later granitic intrusions.

It was assumed that the Glen Gairn granite is connected with the Lochnagar granite mass beneath the Dee alluvium, and it was noted that it does not differ significantly in its petrography from the ordinary Cairngorm granite. Around its margins it is fringed with small apophyses and veins but no sign of a chilled margin to the Glen Gairn granite was recognised except against the epidiorite mass at Creag a Chlamhainn. The quartz porphyries of the region were considered to represent a phase of dyke intrusion slightly later than the granite emplacement.

Since the publication of the memoir, to the best of the present author's knowledge, no comprehensive work on the solid geology of the area has been published. However Bremner, in a series of papers, dealt with the glacial features of the Dee Valley. In 1912 he discussed its physical geology including some observations on the glacial phenomena. This was followed in 1918 by a discussion of the limits of valley glaciation of the Dee basin. In this he postulated a small piedmont glacier just east of Ballater, produced by the junction of the Dee, Muick and Gairn glaciers, and the former presence of a small ice field at the southern foot of Morven, drained by small glaciers occupying the valleys of the Tullich and the Culsten Burns. In 1931 Bremner produced a further paper on the valley glaciation of the Ballater district, in which the direction of flow of the ice in the Dee and its tributaries, and occurrences of U-shaped valleys, hanging valleys, truncated spurs, moraines and glaciofluvial gravels are described.

In the most recent edition of the Regional Guide to the Grampian Highlands (1948) Read suggested that the great sill or sills of epidiorite which stretch from Portsoy to Deeside (of which the epidiorites of Glen Gairn form a part) may have been intruded between the Loch Tay Limestone and the Central Highland Quartzite, thus giving a possible stratigraphical position in the Dalradian sequence to the metasediments of Deeside. His conclusion is based upon work carried out by himself and other authors in neighbouring districts, and does not directly affect the Geallaig area other than by throwing light on its stratigraphic position in the Dalradian succession, a question treated later in the thesis.

In 1959 Moorbath, in a note on the ages of lead from some British mineral deposits, quoted an age of 470 $\pm$ 40 million years for lead from veins in the Abergairn district associated with the granite at Ballater. This confirms the Caledonian age which had been postulated for this period of igneous activity.

The orientation of hornblende crystals from an epidiorite from Geallaig Hill is discussed by Tocher (1960), but he gives no discussion of the regional significance of the orientations described. Tocher subsequently (1961) described a suite of intermediate dykes from the eastern part of the Geallaig district. He discusses their affinities, concluding that they form part of the suite of dykes of similar composition and trend found to the south of the Lochnagar granite.

Although the above list includes all those papers dealing specifically with the Geallaig district, there are a number of papers concerned with the surrounding country which may be useful in the consideration of the rocks of the Geallaig district. Read (1928) described and subdivided the schists of east Glen Muick, lying to the east of Ballater, and equated the Deeside Limestone with the Loch Tay limestone. This was followed in 1933 by a paper in which Hutchison gave a detailed description of the mineralogy of the Deeside Limestone. About the same time, Bisset (1932) described and subdivided the granitic rocks of the Skene Complex which form part of the same chain of granites as the acid rocks of the Geallaig district. These papers will be considered in greater detail when the appropriate rock types within the Geallaig district are discussed.

GEOLOGICAL HISTORY OF THE GEALLAIG AREA

Geologically the Geallaig area lies within the Central Highlands of Scotland, approximately 24 miles north of the Highland Boundary Fault. A sketch map of the geological setting of the area is given in Fig. 3, while a more detailed map of the area itself is given in Fig. 31 (end pocket). The country rocks comprise quartzites, marbles, calc-silicate rocks and pelites. These are exposed mainly towards the eastern end of the area on the eastern and western slopes of the Gairn Valley; they occur also as inclusions to the north at Gairnshiel and to the west around Crathie. These metasediments belong to the Keith Division of the Lower Dalradian of the Banffshire coast; a more detailed discussion of their stratigraphical position will be given in the succeeding section on the regional setting of the Geallaig district.

Basic igneous rocks, mainly in the form of small sheet-like bodies, were intruded into the metasediments prior to the regional metamorphism. These are now represented by epidiorites and hornblende schists. They are found mainly towards the east of the area, to the north and north-west of Ballater.

The metasediments and basic igneous rocks were involved in the regional metamorphism of the Dalradian rocks, the metasediments lying within the sillimanite grade of Barrow's metamorphic zones, and the basic rocks being amphibolised. They are folded around an axis which plunges at a moderate angle to the south-east, and now have a general NE-SW strike.

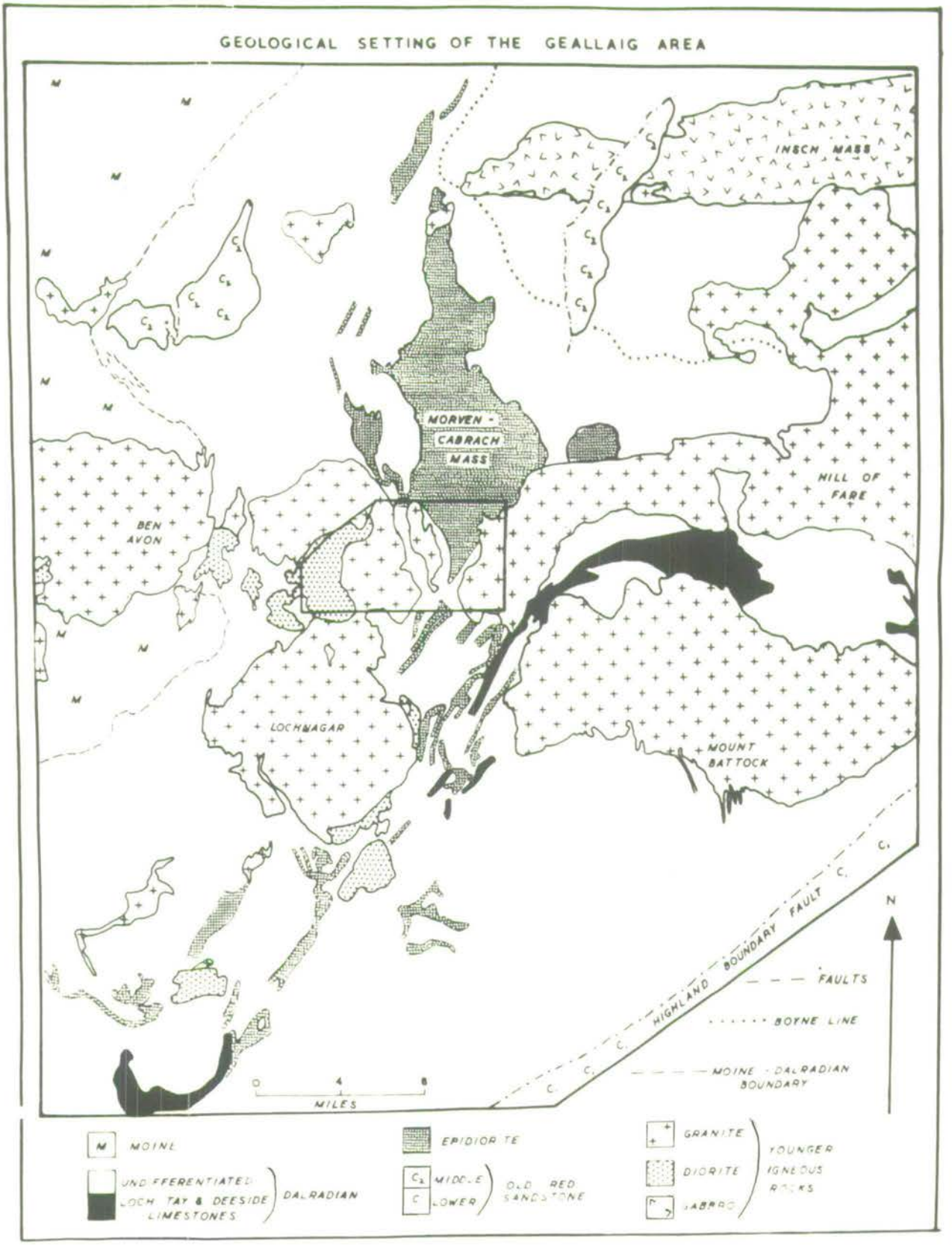

GEOLOGICAL SETTING OF THE GEALLAIG AREA
INSCH MASS
MORVEN - CABRACH MASS
HILL OF FARE
BEN AVON
LOCHNAGAR
MOUNT BATTOCK
HIGHLAND BOUNDARY FAULT
FAULTS
BOYNE LINE
MOINE - DALRADIAN BOUNDARY
N
0 4 8
MILES
M MOINE
UNDIFFERENTIATED LOCH TAY & DEESIDE LIMESTONES
DALRADIAN
EPIDIORITE
MIDDLE
LOWER
OLD RED SANDSTONE
GRANITE
DIORITE
GABBRO
YOUNGER IGNEOUS ROCKS

Fig. 3

At a time probably post-dating the regional metamorphism, the Dalradian rocks to the north of the Gairn Valley were intruded by the Morven gabbro mass, the southernmost extension of which enters the Geallaig area to the north of Ballater. This is also now largely amphibolised.

Subsequently two sets of acidic and intermediate igneous bodies were emplaced in the Geallaig district; the earlier is a heterogeneous, highly xenolithic, and often tonalitic, suite while the later is a homogeneous, non-xenolithic granite. These are separated by a dyke phase of intermediate composition. The tonalitic suite outcrops within the western half of the area mapped, while the granite is confined to the eastern half. Associated with this granite there is a suite of quartz porphyry dykes.

The relative areas of exposure of these two groups within the Geallaig district are approximately equal. The later granite forms the western extremity of the large Hill of Fare mass which extends for about 35 miles to the east, while the tonalitic suite forms part of a very much smaller series of satellitic bodies which fringe the larger granites of Deeside.

DALRADIAN METASEDIMENTS

REGIONAL SETTING

The Dalradian metasediments of Middle Deeside comprise quartzites, quartzose schists, pelites, marbles and calc-silicate rocks. They have been involved in the regional Caledonian metamorphism and affected by later thermal alteration as a result of the intrusion of the Caledonian "Newer Granites" of this region.

These metasediments clearly form part of the Lower Dalradian Keith Division of the Banffshire Coast section (Read 1936). An attempt is made here to place them more accurately within the Dalradian stratigraphical succession as they form part of the relatively uninvestigated section of the Dalradian which separates the well tabulated successions of Perthshire to the south-west, and Banffshire to the north. The difficulties of accurate correlation in such rocks, posed by the absence of fossil evidence, and areas of poor exposure, are intensified in this region by the presence of large areas of acid igneous rocks which may cut out or distort part of the sequence.

A correlation of the Perthshire, Deeside, and Banffshire Dalradian successions, based largely on Read (1955), is given in Table I.

Equating the metasediments of Deeside firstly with those of the Perthshire succession, Read (1928) has correlated the Deeside Limestone, exposed some three miles to the east of Ballater, with the Loch Tay Limestone, and the Queen's Hill Group of east Glen Muick with the Ben Lui Schists.

TABLE I

CORRELATION OF THE DAIRADIAN SUCCESSIONS OF PERTHSHIRE, DEESIDE AND BANFFSHIRE

Perthshire	Deeside	Banffshire
Loch Tay Limestone	Deeside Limestone	
Ben Lui Schists	Queen's Hill Group	
		----------Boyne Line
Ben Lawers Schists	gneisses of W. Glen Muick	Cowhythe Gneiss
Ben Eagach Schists	metasediment of Geallaig area	Portsoy Group
Central Highland Quartzite		Durn Hill Quartzite
Blair Atholl Limestone		Sandend Group

To the south-west the underlying Ben Lawers and Ben Eagach Schists of the Perthshire succession are truncated by the Lochnagar granite (Barrow and Craig, 1912, and Bailey, 1928), but would otherwise be expected to cross the Dee with the Ben Lawers Schist by-passing the Geallaig area to the east, and with the Ben Eagach Schists approximately crossing it. The Central Highland Quartzite outcrops to the west in the region of Braemar. The Lochnagar granite does not appear to distort the strike of the metasediments to any great extent.

Tracing the sequence southwards from the Banffshire coast, the Durn Hill Quartzite horizon appears to pass to the west of the Geallaig area and is equated by Read (1955) with the Central Highland Quartzite, whilst the metasediments under consideration lie approximately in the position of the Portsoy Group which overlies the Durn Hill Quartzite, and which Read correlates with the Ben Eagach Schists.

The correlation of the metasediments of the Geallaig district with the Portsoy Group is supported by a general similarity in lithology, the Portsoy Group being composed of mica-schist with thin bands of graphite-schist, limestones and calc-silicate rocks, quartzose schists and some quartzite, all interbanded with hornblende-schists (Read 1923 (b)).

The metasediments of the Geallaig area are thus considered to be stratigraphically equivalent to the Portsoy Group of the Banffshire and the Ben Eagach Group of Perthshire, or to horizons closely adjacent to these groups.

STRATIGRAPHY AND FIELD RELATIONS

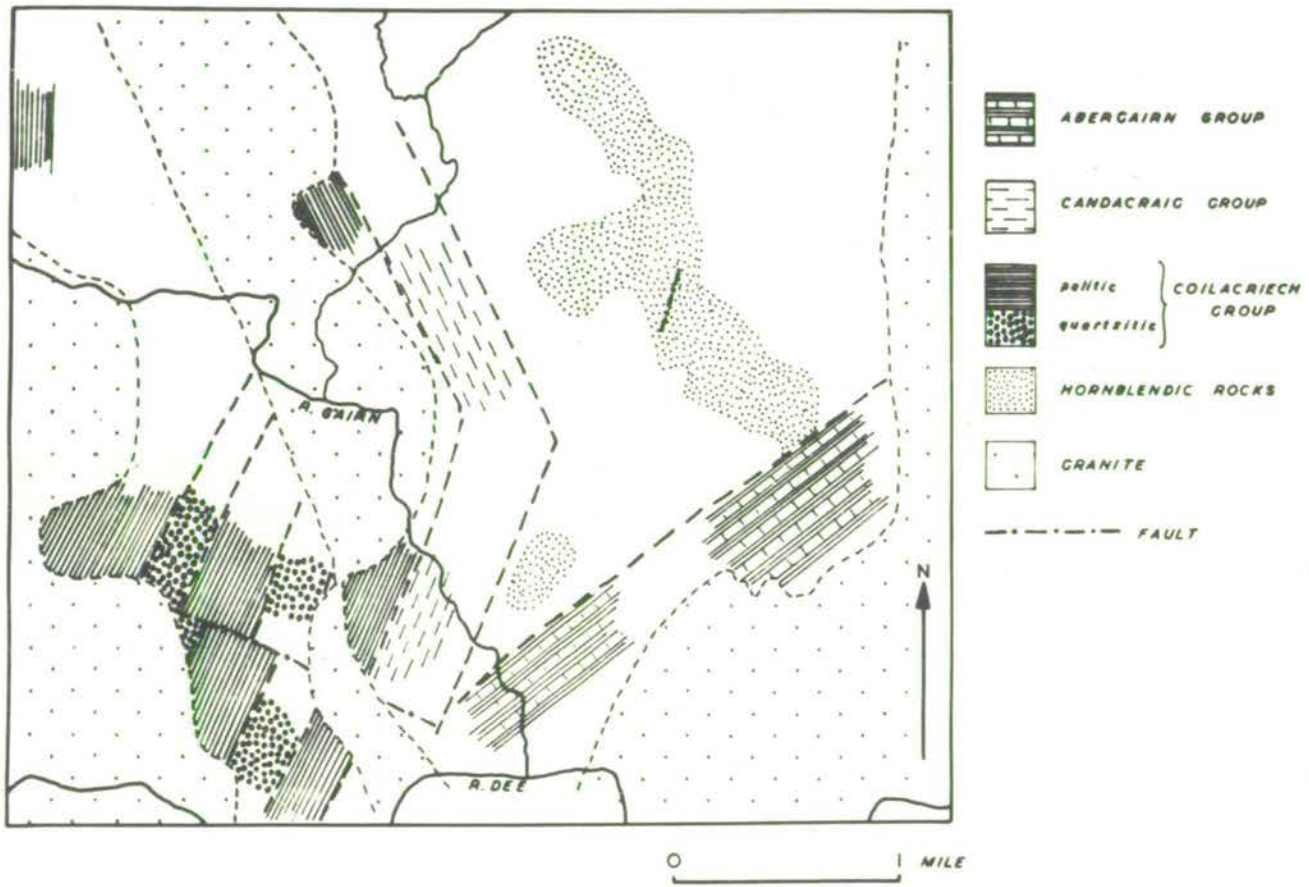
The disposition and stratigraphic divisions of the metasediments within the Geallaig district, which are not intimately associated with granitic rocks as heavily veined and fragmental inclusions, are indicated in Fig. 4. They outcrop only in the eastern half of the area mapped, being found predominantly on both sides of the Gairn Valley north of its junction with the River Dee.

This region is bounded to the south by the alluvium of the Dee Valley, and to the east and west by granite; within this the metasediment forms two independent regions of exposure, separated by a narrow, north-south trending tract of granite which narrows at one point to a width of approximately 50 yards. The western part is exposed to the north and north-east of Coilacriech, while the eastern part is found to the east of the Gairn as far as the Tullich Burn and extends northwards as far as the southern end of Lary Hill. This tract crosses the Gairn about half a mile south of Candacraig and covers the area just to the north-west of Bridge of Gairn. To the north these rocks extend beyond the limits of the area mapped.

Contacts between the metasediment and granite are very sharp and granitic veining is limited. The metamorphic rocks are also cut by numerous microdioritic dykes and occasional quartz-porphyry dykes.

Almost everywhere the metasediment contains intercalated bands of hornblende-schist which typically forms 50% or more by volume of the

Fig. 4



Stratigraphic divisions of the Geallaig district

exposed rock. Barrow and Craig (1912) in their one inch to one mile map of this area (Sheet No.65) in fact designate this metasedimentary area as consisting practically completely of hornblende schist, indicating only one or two minor sedimentary bands towards the south of the region, to the west of the Gairn. To the east of the Gairn, where a thick wedge of hornblendic rocks extends southwards from the foot of Morven penetrating into the metasediments (see Figure 4), Barrow and Craig (op.cit.) indicate no metasediment at all on their map.

Contacts between the metasediments and the intercalated hornblende-schists are sharp, and parallel to the schistosity of both rock types and to the compositional banding of the metasediments.

The metasediments of the Geallaig district have been divided into three main stratigraphic groups shown in Table II, where they are given in structural order upwards. These are penetrated by a hornblendic mass of igneous origin. Owing to the highly metamorphosed nature of these rocks it did not prove possible to distinguish way-up criteria.

The variation in thickness due to folding, and the proportion of intercalated hornblende-schist within the metasediments, cannot be accurately estimated, whilst sparse exposure makes the exact boundaries of the groups sometimes difficult to place. Thus thicknesses quoted for these groups are approximate total thicknesses, based on width of exposure on the ground.

TABLE II

STRATIGRAPHIC SUCCESSION WITHIN THE GEALLAIG DISTRICT

Abergairn Group	Marbles and Calc-silicate rocks.
Hornblendic Group	Epidiorites and hornblende schists which wedge out southwards.
Candacraig Group	Tremolite-biotite schists with subsidiary actinolite and sillimanite schists.
Coilacriech Group	Feldspathic quartzites, semi-pelites and pelites, with rare marbles.

The above succession is given structurally upwards.

All the groups are interbanded with hornblende schists.

They include the intercalated basic rocks and make no allowance for thickening of the succession as a result of folding.

Coilacriech Group - This group consists of interbedded feldspathic quartzites, semi-pelites and pelites, with at least one calcareous band a few feet wide. The pelitic rocks are now cordierite-andalusite-biotite schists with subsidiary cordierite-anthophyllite schists. The succession within the Coilacriech Group in structural order, from west to east consists of:

Pelitic rocks	900 feet
Quartzitic rocks	700 feet
Pelite and semi-pelite	1300 feet
Quartzitic rocks	1000 feet
Pelitic rocks	1000 feet

The calcareous band is found within the middle pelitic band.

With the exception of the structurally lowest pelitic band, all the above units are interbedded with hornblende schist, in variable proportion. The structurally lowest pelite, which is free from hornblende-schist, occupies the area to the north of Coilacriech and is the westernmost exposure of metasediment in the area (with the exception of metasedimentary inclusions in granite). The Geological Survey however, (Barrow and Craig, 1912, and Sheet No. 65) mapped this entire band of pelite as epidiorite.

Candacraig Group - This group structurally overlies the Coilacriech Group, the change in lithology being a rapid one. Rocks of the

Candacraig Group are exposed to the east of the Gairn, north-west of Culsh farm, and on the Hill of Candacraig to the west of the Gairn. In the Candacraig Group there is a complete absence of quartzite, the rock types consisting of tremolite-biotite schists with subsidiary sillimanite- and actinolite-schists. This group represents a transitional stage between the Coilacriech and Abergairn Groups. It contains a high proportion of intercalated hornblende-schist, probably making up over 60% of the exposure. The western margin of the Candacraig Group cannot be exactly delineated, but the thickness exceeds 850 feet.

Hornblendic Group - As can be seen in Figure 4, a wedge of hornblendic rocks, which thins rapidly towards the south, intervenes between the Candacraig and Abergairn Groups. These are of igneous origin and will be described in the section on basic rocks.

Abergairn Group - This group structurally overlies the Hornblendic Group and, to the south, the Candacraig Group, although there is a gap in exposure of about one half mile between the Candacraig and Abergairn Groups into which the wedge of hornblendic rocks may continue. The rocks of the Abergairn Group consist of marbles, and pyroxene- and amphibole-rich calc-silicate rocks. They are intercalated with a low proportion of hornblende-schists, the whole having a thickness of approximately 1000 feet.

Thus, in general, there is a decrease in the proportion of silica- and alumina-rich metasediment and an increase in the proportion of lime and magnesium from west to east. The incoming of this more calcareous horizon may represent an approach to a group equivalent to the Ben Lawers calcareous schist horizon.

STRUCTURE

STRUCTURAL SETTING OF THE GEALLAIG AREA

The general geology of the country which surrounds the Geallaig area is shown in Figure 3. On this map it can be seen that, about 15 miles to the north-west of the thesis area, there is a major swing in the regional trend of the Moine-Dalradian boundary, which for ten miles swings from the normal NE-SW Caledonoid trend to NW-SE at the southeastern margin of this region of NW-SE trend.

Descriptions of folding on all scales from the Dalradian of the Central Highlands by Bailey (1928), McIntyre (1951), King and Rast (1955), and Rast and Platt (1957) have established the existence within these rocks of two dominant fold directions. These are a main NE-SW "Caledonoid" trend, and a less widely reported NW-SE "cross-fold" trend. (The terms "Caledonoid" and "cross-fold" are used in this context purely descriptively to signify geographical trends, with no implied genetic significance.)

Rast and Platt (1957) in their discussion of "cross-folding" with special reference to the Grampian Highlands suggest the possibility of a major belt of cross-folding extending from the south-west of Tomintoul in the north, to Tarfside in the south. This belt would coincide with the major swing in strike of the Moine-Dalradian boundary to the south-west of Tomintoul. Such a cross-fold belt would include the homo-axial area, with a moderate south-easterly plunge, described by McIntyre (1951)

between Grantown and Tomintoul, and proceeding south-eastwards from this, would cross the Gairn-Dee watershed incorporating the Geallaig area.

Further support of the occurrence of folds with a "cross-fold" trend in this region is given by Matheson (1958) who describes both "Caledonoid" and "cross-fold" trending structures from Glenshee. Within the area which he discusses "Caledonoid" structures are dominant towards the west, whilst "cross-fold" trending structures become more strongly developed and assume dominance towards the east, that is in the direction of the Geallaig district.

Thus it is suggested by the literature, and has indeed been substantiated by the present work (see following section) that the major structural axis of the Geallaig district is a south-easterly trending one, situated within the postulated "cross-fold" belt of Rast and Platt.

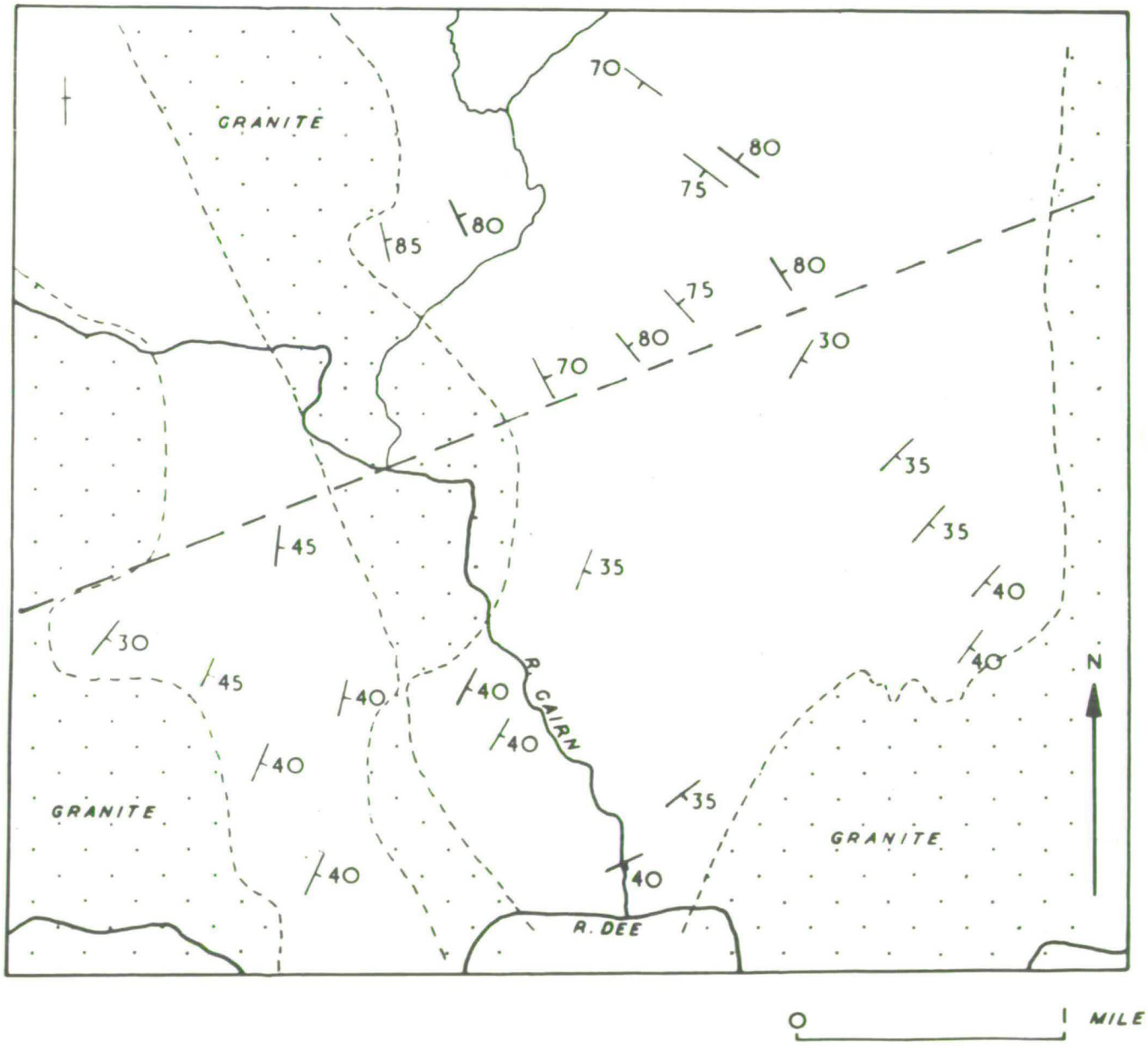
STRUCTURE OF THE GEALLAIG DISTRICT

Within the metasediments and hornblende-schists which are exposed to the north and north-west of Ballater, the most prominent structural feature is a bedding plane schistosity. This has been measured both from the metasediments, where it parallels the compositional banding of the rocks, and from the hornblende-schists, the margins of which it also parallels. Within this schistosity there occurs, in places, a lineation which is typically parallel to the dip of the schistosity plane, and which is more strongly developed in the hornblende-schists. Rarely the schistosity is cut by a later cleavage.

Structurally the Geallaig area can be divided into two units (see Figure 5). The southern and western part, to the south-west of Glenbardy, has a general south easterly dip at an angle of about 40°, while to the north and east the strike swings round and trends NW-SE with very steep dips. At the only point in the field at which the change of strike can be traced in detail, it occurs in the space of 100 yards.

The orientation of the planes of schistosity within the two units is given in Figure 6, A and B, in which the π-poles of the schistosity have been plotted on a sterographic projection and their density contoured. This diagram shows the degree of homogeneity within the individual units and the contrast between them. In the southwestern unit (Figure 6 B) the π-poles show a good maximum with a tendency to form a girdle about an axis which plunges to the southeast at approximately 40°. The spread of the maximum contour represents the variation of regional dip from east, through southeast, to south. The π-poles of the northeasterly unit (Figure 6 A) show a scatter around a NE trending vertical plane, with a tendency to form a girdle about an axis also plunging at about 40° to the southeast.

When the projections of π-poles from the two units are superimposed (Figure 6 C), a well developed great circle girdle is obtained. This dips to the northwest, indicating that the swing in strike within the area represents a major fold, its fold axis plunging to the southeast at about 40°, (for method see Weiss 1959, p.94). Also on this diagram are plotted measurements of minor folds and lineations from the southwesterly



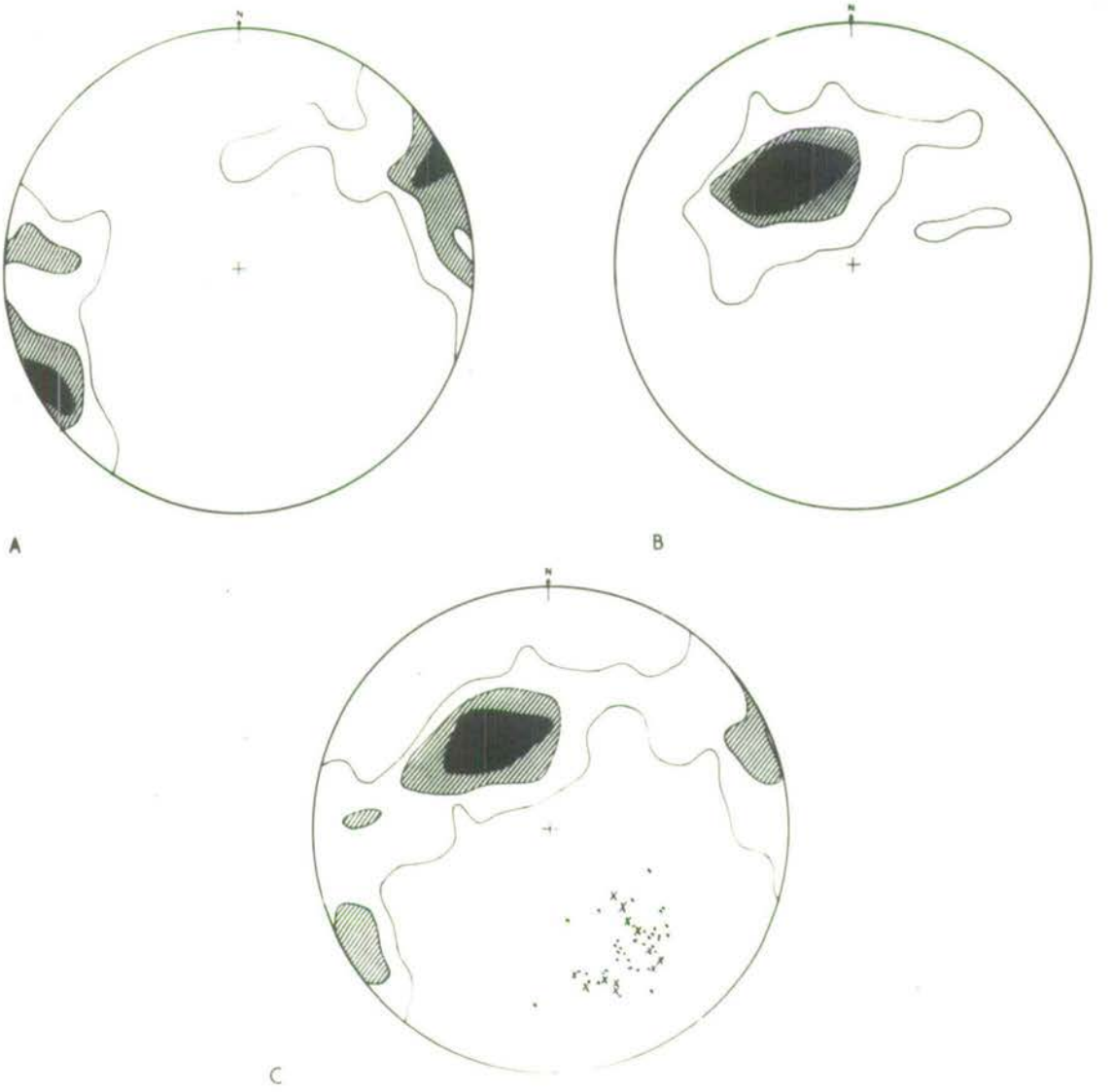
Structure of the eastern part of the Geallaig district

Fig. 5

unit, which form a scatter around the position of the fold axis suggested by the orientation of the schistosity pole girdle.

Following the method suggested by Wegmann (1929) and Sander (1948) these two units were subdivided into small areas in order to test the homogeneity of the fabric. Within these sub-areas the intersections of the schistosity planes were plotted and their densities contoured to give β-diagrams, indicating the probable position of fold axes within the sub-areas. The detailed results of this subdivision are given in Figure 30 (in end pocket). A synoptic diagram incorporating the 10% contour lines from β-diagrams of the sub-areas covering each of the two units is shown in Figure 7. That for the southwesterly unit shows a reasonable degree of homogeneity throughout the unit, giving a group of maxima which cluster around the fold axis inferred from the schistosity plane girdle and from the plots of minor fold axes and lineations. The synoptic diagram for the northeasterly unit however, gives a series of scattered contours lying on the average foliation plane. The small spread in the dip of the schistosity planes in this unit makes them rather unsatisfactory for use in β-diagrams.

Minor folds are rarely exposed in this region. Very occasionally they are seen in the southwesterly unit, especially in the pelites and quartzites at the base of the Coilacriech Group. Here the schistosity is intensely crumpled and contorted into minor folds which are rarely measurable, but where measureable, they plunge parallel to the axis of the major fold.



Structure of the eastern part of the Geallaig district.

A - poles of 113 schistosity planes in the NE unit. Contours at 1-5-10 per cent. (Incorporates sub-areas XX, XXI, XXIII, XXIV in Fig. 30).

B - poles of 170 schistosity planes in the SW unit. Contours at 1-5-10-20 per cent. (Incorporates sub-areas XV-XIX, XXII, XXV, XXVI in Fig. 30).

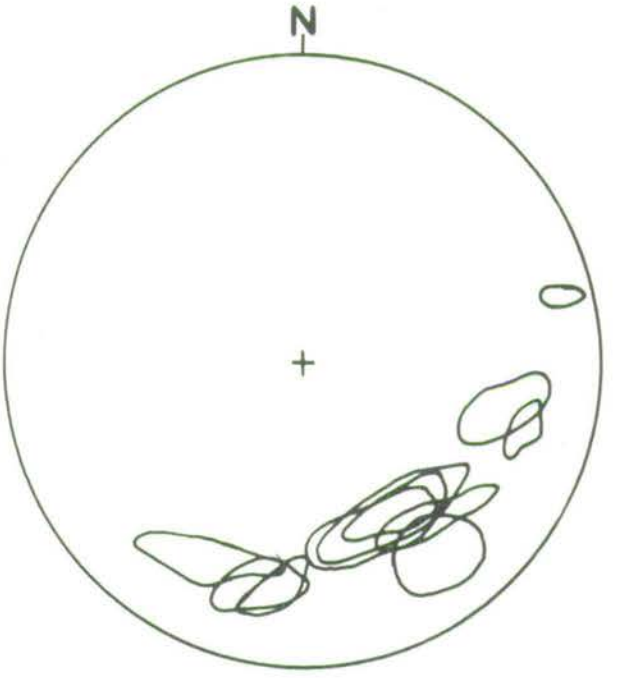
C - A and B superimposed. Contours at 1-3-7-12 per cent. x - axes of minor folds. • lineations.

Fig. 6

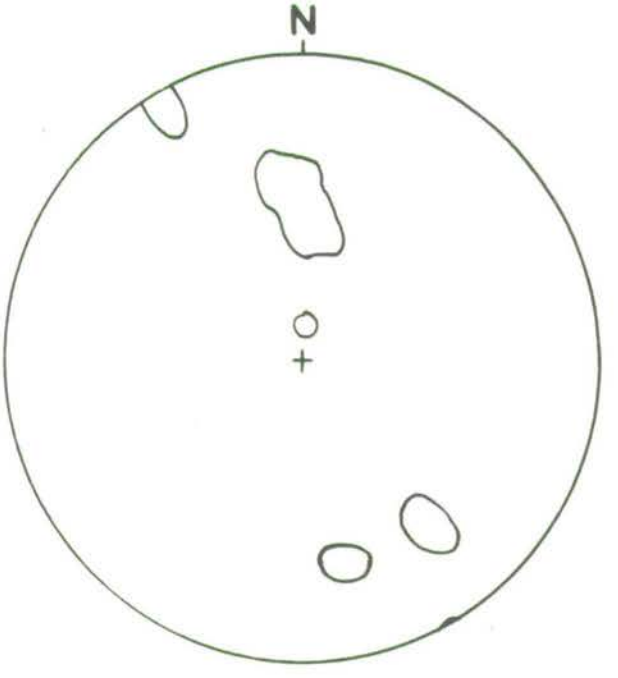
Throughout this southwest division a lineation is quite commonly developed in the hornblende-schists. This is typically oriented parallel to the dip of the schistosity and also parallels the major fold axis.

In the northeastern unit the schistosity and lineation are typically less well developed. Folding is however well developed in the rocks of the Hornblendic Group in a small area just to the south of Tom Garchory. Here the structures consist of small angular folds with limbs of six inches to one foot in length. A strongly developed strain slip cleavage parallel to the axial planes of the folds forms minute sub-angular puckers about 3 mm. in length on the limbs of the larger folds (see Pl. II). All these minor folds plunge consistently at 40° to the south-southeast, an orientation fairly close to that of the axes of the minor folds of the southwesterly unit.

The cleavage which is clearly associated with these angular folds at Tom Garchory, shows a more northerly strike than the bedding schistosity in this northeasterly unit and thus obliquely cross-cuts the trace of the axial plane of the major fold. The axes of the angular folds and associated lineations, plotted on a stereographic projection, lie on the plot of the average cleavage plane, calculated from measurements of cleavage associated with these folds (Figure 8). The trace of the axial plane of the major fold, deduced from the bisectrix of the average planes of the two limbs, is also plotted on this diagram to show the cross-cutting relationship of these angular minor folds to the axial plane cleavage. Thus, despite



A



B

Synoptic diagrams of 10 per cent contour lines from β-diagrams in Fig. 30. Area of units is as in Fig. 6, A and B.

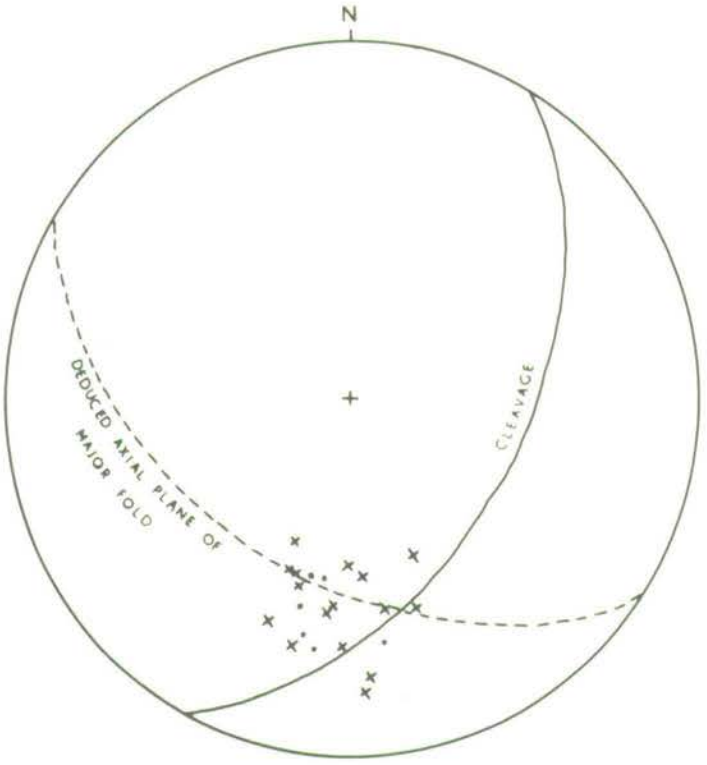
A - southwest unit. B - northeast unit.

Fig. 7

the relatively close orientation of these minor fold axes to that of the major fold, it seems likely that they were formed by a different, and probably later, stress system than that which formed the major fold.

The metasediments of the Coilacriech Group are occasionally cut by cleavages which cross cut the minor folds. These are seldom measureable, but fall into two groups, one dipping steeply to the north-east, and one dipping steeply northwest. They are sporadically developed and could not be related to any other feature.

Despite the irregular outcrop of the granite surrounding these rocks, the strike can nowhere be seen to deviate from the normal as the granite contact is approached (see fig. 29) and the major swing in strike, and fold thus formed, cannot be related to the enclosing granite. The folding falls into the regional south-easterly plunging fold pattern which was described above (p.19) and it would thus seem that the structures of the country rocks were very little disturbed by the intrusion of the granite in this part of the Geallaig district. This is in conformity with the views of McIntyre (1951, p.150) who states that "The Newer Granites appear to have but little influence on the general structural pattern" and Read (1928, p.764) who, referring to Middle Deeside, expressed the opinion that any disturbance caused by the igneous intrusions must be purely local and believed that "the dispositions of the Deeside Schists are part of a wider regional structure in which intrusions of the Younger Granite have no share."



Stereographic projection of structural elements of late stage minor folds, south of Tom Garchory.

x - fold axes

. - lineations

Fig. 8

PETROGRAPHY

COILACRIECH GROUP

Feldspathic Quartzites

A continuous gradation in mineral composition, and a certain amount of intercalation in the field, makes it difficult to draw a satisfactory dividing line between the quartzites and semi-pelitic rocks. However, two dominantly quartzitic horizons have been distinguished, and their extent is indicated in Fig. 4. It has not been possible to trace their north-eastward extension as exposure becomes poor in that direction. However such exposure as is found to the northeast consists of hornblende schist, which in all parts makes up about 70% of the exposure in the quartzitic bands.

Occasional feldspathic quartzites and more abundant quartz rich semi-pelites, also occur within the pelitic horizons of the Coilacriech Group. Within the eastern pelitic horizon, however true quartzitic rocks are absent.

The quartzites occur in beds varying from six inches to at least 30 feet in thickness. These are interbanded with the hornblende schist, which occasionally contains angular blocks of quartzite for a few inches from the margin of the quartzite. These blocks have very sharp contacts with the enclosing basic rock.

The quartzites are very distinctive in the field, weathering to a pure white rock of finely granular appearance. Where exposure is absent

the presence of belts of quartzite can be deduced from the distribution of angular quartzitic blocks. On a fresh surface the rock is pink owing to the presence of feldspar. A variation in the amount of this mineral present imparts a slight colour banding to the rock; this is paralleled in the more impure varieties by fine micaceous partings. The rock is massive and does not cleave along these planes.

The feldspathic quartzites are composed essentially of predominant quartz, and subsidiary feldspar, in varying proportions. The texture is xenomorphic granular, of varying grain size. Larger crystals of quartz, up to 1 mm. in width surround or partially enclose smaller crystals of feldspar. The quartz crystals have an irregular and often lobate habit. They are quite unstrained, but are cut by many fractures.

The feldspar occurs in small rounded crystals, generally not exceeding .25 mm. in size. It is predominantly sodic andesine, with a minor proportion of microcline. In many cases the albite twinning of the plagioclase has been sidestepped by lines of fracture.

Other mineral species are present only in accessory quantities. These are sparse pyrite, now altered to limonite, occasional small crystals of clinozoisite, small patches of a yellowish brown fibrous chlorite found within the feldspar, and very rare minute deep brown crystals of rutile.

With an increase in the pelitic constituents of the rock, minor amounts of biotite occur, and the rocks grade into the pelitic types which are described below.

Pelites and Semi-pelites

These occur on both sides of, and between, the two quartzitic bands described above. The middle and eastern horizons are interbedded with abundant hornblende schist. The pelites generally occur in bands varying in width from 3 to 40 feet, but a band approaching 100 yards in width is exposed about one-quarter mile north of the Ballater-Crathie road near Coilacriech.

Within the pelitic group there is a varied mineralogy. The most prevalent rock type is a biotite schist which with increasing alumina content, contains increasing amounts of cordierite and, in some cases, andalusite. These rocks are rarely garnetiferous. Cordierite-anthophyllite schists form a less abundant alumina-rich type, whilst there are subsidiary muscovite-bearing and tourmaline-bearing varieties. The variations in mineralogy found within this group is shown in Table III.

As the above rock types contain, to a large extent, the same minerals in varying proportions, and grade into each other with changes in the relative proportions of the constituent minerals, these minerals will be described generally as they occur in the group; individual rock types will not be described in detail.

In hand specimen the pelitic rocks are often finely banded parallel to the schistosity of the rock, particularly in the more quartz-rich varieties, the bands representing greater or lesser ferromagnesian content.

TABLE III

VARIATIONS IN THE MINERALOGY OF THE PELITIC ROCKS

OF THE COILACRIECH GROUP

	1	2	3	4	5	6
Quartz	X	X	X	X	X	X*
Feldspar	X	X	X	X	X	
Biotite	X	X	X		X*	
Muscovite	X*	X*	X*	X		X
Cordierite		X	X	X	X	
Andalusite			X			X
Tourmaline				X		
Spinel			X*			
Anthophyllite					X	
Garnet					X*	

X* = very small amounts of the mineral are present

N.B. Some of the above types occur only as bands of a few centimetres width.

The quartz-rich types have a fresh grey appearance, but with the incoming of cordierite, andalusite and anthophyllite the rock takes on a dirty brown colour and an intensely gnarled and crumpled appearance as a result of the distortion of the schistosity by these minerals. The textures present in these rocks will be described in a succeeding section.

The matrix of the pelitic rocks is a mosaic of quartz and oligoclase feldspar, of average grain size about .25 to .5 mm. The crystals are anhedral, with a generally rounded form; the quartz crystals often have embayed margins and enclose small feldspar crystals. Within this mosaic lie occasional augen of coarse quartz, individual crystals reaching a diameter of 4 mm.

Throughout this quartzo-feldspathic matrix lie crystals of biotite, patchily distributed and tending to form in elongate folia, imparting a schistosity to the rock. The biotite occurs in flakes up to .4 mm. long, and has pleochroic scheme X-pale yellow, Y, Z-reddish brown. In part it is altered to a pale green chlorite which has anomalous brown birefringence, with the production of magnetite and rutile along the cleavages of the chloritised biotite. This alteration is particularly common where the neighbouring cordierite is altered to sericitic mica. By contrast the biotite near other forms of alteration of cordierite is relatively fresh.

Cordierite is present in practically all of the pelitic rocks. It occurs in three distinct forms:-

1) in rounded crystals about 1 mm. in diameter;

2) in crystal masses elongated parallel to the schistosity and forming a reticulate network around the quartz and feldspar of the matrix;

3) in sheaf-like crystal aggregates up to 10 mm. long.

1) and 2) occur in the same rock type, namely the cordierite-andalusite (Pl XV A) schists. Such cordierite is often extensively altered. They are characterised by the presence of abundant inclusions of biotite, with subsidiary quartz, magnetite, zircon, apatite, andalusite and spinel. The included biotite occurs in short stumpy crystals about .03 mm. long, with a random orientation, in contrast to those outside the cordierite. Yellow pleochroic haloes surround the zircon inclusions. Where andalusite inclusions are present, other inclusions are rare, with the exception of tiny crystals of green spinel, which are often restricted to the interior of the andalusite inclusions themselves. Spinel is found only in andalusite-bearing rocks as inclusions within cordierite and andalusite.

3) is found in the anthophyllite-bearing rocks. A typical example is shown in Pl XV B. Such cordierite is very fresh in comparison to that of types 1) and 2), and inclusions are much less frequent, although fragmentary masses of garnet up to 3 mm. across form cores to some of the cordierite crystals (Pl XV C & D). Polysynthetic twinning is present in some crystals.

The cordierite is converted to a variety of alteration products. The most common form is a colourless, fibrous, matted, sericitic mica.

This often surrounds and reticulately veins the other alteration products. These consist of both pale and deep yellow micas, non-fibrous in habit but with high birefringence, and deep yellow to brown chlorites, also non-fibrous, which are virtually isotropic. Inclusions of other minerals within altered cordierite remain fresh. Large crystals of muscovite are often found within the patches of sericitic micas, and it is possible that in some of the muscovite-rich schists, where the muscovite is in part embedded in rounded patches of sericite that much of the mica was produced originally from the alteration of cordierite, although none is now visible.

In the pelitic rocks andalusite is almost invariably found in large fragmentary masses included within cordierite (see Pl. XIV C and D). Such masses reach 8 mm. in length and are sometimes in optical continuity. The andalusite contains rare inclusions of biotite, and in some cases abundant tiny spinel crystals. Where andalusite is not included within cordierite, it is set in a mat of muscovite and sericitic mica, which may indicate the former presence of cordierite.

The anthophyllite occurs in long fibrous needles forming radiating crystal masses up to 5 mm. across, and also in felted mats of small crystals (see Pl. XIV A and B). Both tend to have a concentration of small magnetite crystals near the centre. The anthophyllite is pale brownish green and non-pleochroic, with straight extinction and a $2V_z = 76^{\circ}$. Rarely the crystal masses are embedded in a base of indefinite biotite crystals; more commonly biotite is absent in the vicinity of anthophyllite.

The anthophyllite needles crosscut quartz and feldspar crystals, but the largest masses are associated with, and are embedded within, the sheaves of cordierite.

Muscovite, in addition to occurring within sericite as previously described, is also found in some specimens in broad flakes, associated with the biotite of the ground mass; in some bands it is developed in preference to the biotite. Muscovite is typically a minor constituent of these pelitic rocks.

Very occasional tourmaline-bearing muscovite-rich schists were found, throughout which numerous small prisms of tourmaline were scattered. These average about .5 mm. long and are pleochroic from neutral to light brown.

The typical accessory minerals of the pelites are zircon, apatite, magnetite and occasional altered pyrite. The magnetite is sometimes concentrated in bands parallel to the schistosity of the schists.

Marbles

Within the Coilacriech Group calcareous rocks are present in only two or three small exposures which cannot be traced for more than a few yards, and the contact relations of which cannot be determined. These lie within the middle pelitic horizon of the group and probably represent one horizon. They consist of pale grey marbles with bands of darker grey, relatively impure, material from one to three inches in width. These marbles are not associated with calc-silicate rocks.

The purer portions of the marbles consist of a mosaic of calcite crystals about .2 mm. in diameter. This contains scattered patches of impurity in which are found tiny granules of olivine about .05 mm. in diameter associated with a small amount of serpentinisation and a great deal of iron staining. In the same areas are abundant tiny round crystals of chondrodite, yellow in colour and strongly pleochroic (R.I. N_x 1.616, N_y 1.628, N_z 1.648). The impure patches also contain rare tiny flakes of phlogopite and occasional patches of isotropic green chlorite.

The purer portions of the marble grade into the darker impure bands with a decrease in calcite and an increase in the proportions of other minerals. In these bands calcite is present as interstitial crystals, while many of the minerals are cut across by, and include, very fine irregular stringers of calcite.

The essential minerals in the impure bands are olivine, pyroxene, phlogopite and magnetite, with minor amounts of feldspar, calcite and chlorite. The texture is very irregular. Olivine is the commonest mineral in the rock. It occurs in optically continuous relics surrounded by sinuous veinlets of colourless fibrous serpentine about .025 mm. wide. The olivines are generally about 1 mm. long, but may attain a length of 8 mm. Much magnetite is present within the veinlets and around the olivine, and magnetite is also present as irregular masses throughout the rock.

Pyroxene is much less abundant than olivine, occurring in rounded somewhat poikiloblastic crystals about 1 mm. long. These enclose magnetite crystals. Phlogopite is also common in radiating masses and bladed crystals. It is pale brown with very faint pleochroism and is uniaxial negative. The crystals typically penetrate the other rock constituents.

Andesine occurs in low proportion in this rock type, as interstitial patches penetrated by other minerals, notably phlogopite. Lamellar twinning is present but indistinct. There are also small irregularly distributed patches of deep green isotropic chlorite scattered throughout the rock.

Microstructures

In considering the textures present in the rocks of the Coilacriech Group, an attempt was made to elucidate the sequence of crystallisation of some of the minerals present. Unfortunately many of the textural relationships shown by these minerals were not suitable for this type of study.

As previously stated (p.19) the predominant structural feature of the Geallaig district is a bedding plane schistosity which has been folded around a NW-SE axis. This schistosity is distorted in places by two sets of extremely sporadically developed strain slip cleavage. In places these form a lineation on the bedding plane schistosity.

In thin section there is generally a high degree of preferred orientation of micas, forming the dominant plane of schistosity. Only in very rare cases do the secondary cleavages form the dominant plane of schistosity in the rock. More commonly they occur as a strain slip cleavage, or forming minute crinkles in the bedding schistosity. The relationships of the minerals present to the above structures will now be considered.

Biotite has grown with (001) parallel to both the bedding schistosity and the later cleavages present in the Coilacriech Group. On the bedding schistosity small biotite flakes are aligned both in biotite-rich lenses and in isolated flakes (Pl. XVI A). In some cases the biotite crystals in the biotite-rich lenses are orientated at a high angle to the elongation of the lenses (and the predominant schistosity) while isolated crystals nearby are still orientated parallel to the dominant schistosity. This may result from static recrystallisation at a late stage in the metamorphic history of the rock, the isolated crystals retaining their preferred orientation as a result of the confining pressure of the surrounding minerals.

In many cases the bedding plane schistosity is slightly crinkled. In most instances the biotite crystals in such rocks are unstrained, but occasionally they show bending and straining effects. It was not possible to relate this directly to the secondary cleavages.

When the secondary cleavages form a well marked strain slip cleavage, fresh unstrained biotite flakes are orientated along these cleavages. Such cleavages often die out over a few centimetres.

In some instances relatively large decussate porphyroblasts of biotite occur sporadically throughout the rock. These were presumably formed during a late stage of static recrystallisation.

Muscovite, although less abundant than biotite, shows the same textural relationships as the latter. However, large porphyroblasts of muscovite also occur within the sericitic alteration of cordierite. These are decussate and have probably formed at a similar time to the late decussate biotite porphyroblasts.

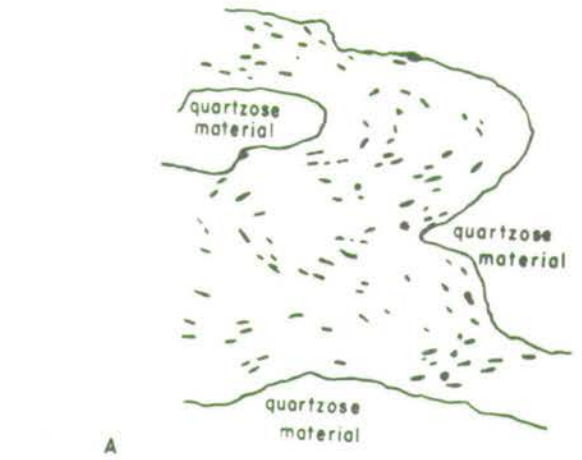
It is therefore concluded that both muscovite and biotite were stable throughout the various movement phases which affected the Geallaig district.

Cordierite. As previously described, the cordierite in these rocks occurs in three forms. The type which forms a reticulate network around the other minerals of the rock, encloses crystals of biotite and lath shaped rods of magnetite. These are of the same size as the corresponding crystals in the ground mass of the rock, and are aligned parallel to them. Thus this reticulate variety of cordierite is considered to be post-tectonic, formed during a period of static recrystallisation subsequent to the production of the bedding plane schistosity.

The rounded type of cordierite presents more difficulty in textural interpretation. Most of the crystals contain very small, equidimensional, randomly orientated, inclusions of biotite and quartz. These inclusions are very much smaller than the corresponding crystals of the groundmass. The schistosity of the rock bends around the rounded cordierite crystals leaving 'eyes' of quartz and feldspar at the sides of the crystals. (Pl. XV A). The evidence given above is taken to suggest that such cordierite is either pre- or syn-tectonic to the formation of the predominant schistosity.

In those rocks in which the schistosity is crinkled, rare porphyblasts of rounded cordierite occur which, although superficially similar to those described above, show different textural relations. These sometimes include trails of small biotite flakes which are orientated around the small crinkles within the cordierite crystals. In this case the dominant schistosity is not deflected around the porphyroblasts. (See Fig. 9B).

In other rocks, where the bedding plane schistosity is the only immediately noticeable textural feature, pelitic lenses rich in cordierite and andalusite include small magnetite laths which appear to lie around the cores of tiny isoclinal folds (see Fig. 9A). Larger isoclinal folds were not seen in these rocks, but might well be present, as the type of exposure available was not conducive to their discovery. It is interesting to note that isoclinal folds are associated with the formation of the earliest plane of schistosity (approximately parallel to the bedding) in the Dalradian rocks of Banffshire (Johnson 1962) and in Perthshire (Sturt 1961).



1·0 mm

Sketches of microstructures in rocks of the Coilacriech Group

A - distribution of magnetite rods within a pelitic band composed largely of andalusite and mica.

B - orientation of biotite crystals forming a microfold within and around a cordierite crystal.

C - trails of biotite inclusions within cordierite, orientated at a high angle to the biotite of the groundmass.

Fig. 9

The rods are partially included in cordierite which has formed subsequently to the formation of these micro-folds.

In yet other cases, where the direction of the secondary cleavage forms the dominant schistosity in the rock, porphyroblasts of cordierite are present which include straight trails of biotite inclusions. These are inclined at a high angle to the schistosity of the rock and are often of the same order of size as the biotite crystals outside the cordierite. There is no deflection of the schistosity around such cordierite (Fig. 9C). This evidence indicates that the cordierite was formed during a static phase preceding the formation of the secondary schistosity.

The third type of cordierite, which is sheaf-like in form, is elongated in the general direction of the schistosity of the rocks in which it occurs and contains small rods of magnetite which also parallel the schistosity. This cordierite is very fresh and occurs within rocks which otherwise show little development of preferred orientation. It may be taken to have formed subsequently to the development of the primary schistosity.

The majority of the cordierite crystals in these rocks are variably altered to micaceous and chloritic aggregates. This points to the operation of a period of low grade retrograde metamorphism subsequent to the formation of this mineral.

Andalusite. The porphyroblasts of andalusite are most commonly found in association with the development of the secondary cleavage, and are associated with, and often surrounded by, the cordierite. They cross cut the bedding plane schistosity, which is truncated against them, but their elongation is orientated at various angles to the secondary cleavage. Internally the andalusite crystals show no organised fabric; generally they include only tiny crystals of spinel which are equidimensional and show no clearly defined trends of any sort. In some instances the andalusite crystals appear to control the shapes of the microfolds formed by the secondary cleavages, the axes of the folds being tightly appressed around them (Pl. XIV C).

Thus, although in most cases it was difficult to obtain evidence as to the date of formation of the andalusite in these rocks, the bulk of the evidence obtained indicates that the majority of the andalusite was formed in a static phase between the formation of the bedding schistosity and the development of the secondary cleavages.

Garnet is rare in these rocks and occurs in rounded fragmental crystals. These are sometimes surrounded by cordierite which gives the only clue as to the time of formation of the garnet (Pl. XV C and D).

Anthophyllite. The anthophyllite of the Coilacriech Group shows no preferred orientation whatsoever, forming radiating masses which penetrate all other minerals in the rock, especially the cordierite (Pl. XIV A and B).

The only remnants of schistosity in the anthophyllite-rich patches are tiny laths of magnetite which show a preferred orientation parallel to the primary bedding schistosity throughout the plexus formed by cordierite, biotite and anthophyllite. Thus this mineral association was formed subsequently to the formation of the bedding schistosity.

Microstructures directly attributable to the thermal effects of the Ballater Granite are found only within a few feet of the contact. This can be traced over only a few feet of contact about 730 yards to the WNW of Culsh farm. These rocks show a typically hornfelsic texture, and practically complete recrystallisation has taken place. No trace of any schistosity is present with the exception of tiny magnetite rods in some places which show a preferred orientation parallel to the compositional banding of the rock. Very fresh cordierite is notable in this rock, while occasional crystals of much altered cordierite are also present. Tiny fresh, equidimensional, randomly orientated crystals of biotite occur throughout the rock within all the other minerals present.

CANDACRAIG GROUP

To the northwest of Culsh farm, the cordierite-andalusite schists are rapidly succeeded to the SE by tremolite and actinolite schists, with an increase in the proportion of interbedded epidiorite. The incoming of these amphibole-bearing rocks has been taken as the base of the Candacraig Group. This group extends as far to the east as the Hill of Candacraig,

on the other side of the Gairn Valley. The actinolite and tremolite schists occur in bands seldom exceeding three or four feet in width and interbanded with much epidiorite and hornblende schist.

In contrast to the gnarled and crumpled brown schists of the Coilacriech Group, these rocks outcrop as fresh grey rocks which weather with a whitish skin and which become paler as the proportion of amphibole increases. On the Hill of Candacraig the succession also includes rare sillimanite schists. The rocks of the group will be described in three sections: (1) tremolite schists
(2) actinolite schists
(3) sillimanite schists

The assemblages of the Candacraig Group, which are relatively high in calcium and magnesium with respect to the Coilacriech Group, form an intermediate variety between the alumina-rich pelitic rocks of the Coilacriech Group and the rocks of the Abergairn Group which are richer in calc-silicates and which are found further to the east.

Tremolite Schists

These rocks consist essentially of plagioclase, tremolite, and in almost every case, biotite. Minor amounts of quartz, andalusite, cordierite and garnet are found in rare instances. Apatite and magnetite occur in accessory amount. The majority of the rocks show a compositional banding parallel to the schistosity.

This reflects a variation in the relative proportions of tremolite and biotite, and also a variation in the grain sizes of the bands. The bands vary from 1 cm. to 1 mm. in width and also vary in width along their length.

The tremolite is neutral in colour, non-pleochroic, and occurs in fine needles showing typical amphibole cross sections. Radiating masses are not present, in contrast to the habit of the anthophyllite of the Coilacriech Group. The tremolite needles lie in the plane of schistosity on which they form a lineation directed down dip. The tremolite is biaxial negative ($2V_{\gamma} = 99^{\circ}$) and has a maximum extinction angle of 20° to the cleavage. The crystals are normally minute, but attain a length of 1 mm. in some coarser bands. The tremolite is set in a mosaic of small, rounded, infrequently twinned, often turbid, crystals of oligoclase. In some cases, the mosaic also contains occasional crystals of quartz.

In the majority of cases the tremolite schists also contain varying proportions of biotite. Where biotite is absent there are sparse very small flakes of muscovite. The mica shows a variably developed preferred orientation, ranging from a strict parallelism of flakes in some instances to typically decussate texture in others. The pleochroic scheme of the biotite is X-pale yellow, Y-Z-reddish brown; it is occasionally altered to penninitic chlorite. The biotite is normally subordinate in amount to the tremolite, but in rare bands it is the predominate ferromagnesian mineral and tremolite becomes sparse. In such bands the biotite becomes relatively

coarse, quartz becomes common, and occasional small patches of cordierite are found. Cordierite is absent from the tremolite-rich bands in the same rock. The cordierite ranges from fresh to completely altered to a deep yellow, virtually isotropic, chlorite. The biotite-rich bands also contain an unusually high proportion of accessory apatite, crystals up to .04 mm. across being common. These biotite-rich, cordierite bearing bands occur near the base of the Candacraig Group fairly close to the pelites of the Coilacriech Group.

Garnet has been rarely found in rocks which are tremolite-rich and biotite-free. It is colourless and occurs in clusters up to 1.6 mm. in diameter composed of a large number of tiny fragments of garnet. Rutile is a notable accessory mineral where garnet is present.

Andalusite was found in only one example from the Candacraig Group outcropping on the Hill of Candacraig. It occurs in a rock which contains a low percentage of decussate biotite and a high percentage of very tiny tremolite crystals. The average grain size of the rock was approximately .05 mm., while the andalusite forms oval 'augen' up to 1 mm. long. These augen consist in some cases almost entirely of andalusite; in other cases they comprise fragments of andalusite surrounded by crystals of quartz coarser than that of the bulk of the rock, and rare small biotite crystals. Tremolite is extremely sparse within the augen, which it tends to rim, as does the rutile which is a relatively common accessory mineral in this rock.

Actinolite Schist

Several bands of actinolite schist occur within the Candacraig Group to the west of the Gairn River. This is a light grey compact rock in hand specimen, some bands of which are characterized by a spotted appearance resulting from the presence of pink feldspar porphyroblasts. The rock is composed of abundant quartz, feldspar and actinolite, with biotite largely restricted to the porphyroblastic bands.

The matrix of the rock consists of a mosaic of rounded crystals of quartz and sodic oligoclase about .15 mm. across. Quartz forms about thirty per cent of the rock in contrast to its scarcity in the tremolite schists. The feldspar is sparsely twinned. Within this quartzo-feldspathic matrix the actinolite occurs in single crystals and in crystal masses elongated parallel to the schistosity plane of the rock. The actinolite is biaxial negative with a maximum extinction angle of 20° to the cleavage, and is distinguished from the tremolite by its colour and habit. It is pleochroic from X-neutral to Y-pale green and Z-medium bluish green, and occurs in ragged plates. The crystals often include or are rimmed by, small biotite crystals. The biotite, where it is relatively common, also tends to mass in elongate folia along the schistosity plane. Where feldspar porphyroblasts are present these actinolite and biotite folia bend around the porphyroblasts (see Pl. XIII, C and D). The biotite masses often contain a core of magnetite and sphene.

The actinolite schists contain accessory magnetite, often rimmed by sphene, subhedral pyrite often altered to hematite, occasional rutile

and zircon crystals, and in some examples relatively common anhedral masses of yellow-green epidote.

The porphyroblasts consist of large crystals of oligoclase up to 2 mm. across. These often approach a tabular form, but have finely indented margins in detail. They enclose numerous small crystals of quartz, biotite and actinolite, and fingers of the porphyroblastic feldspar penetrate between the crystals of the groundmass. The crystals are extremely turbid and show sparse albite and carlsbad-albite twinning.

Sillimanite Schist

This occurs in very occasional bands about one foot wide, interbedded with the tremolite schists on the Hill of Candacraig. It has sharp contacts with the tremolite schists. It is a silvery grey rock which breaks into elongate rods owing to the fibrous nature of the sillimanite. Sillimanite forms over 90% of the rock, with occasional small lenses of, and partings containing quartz, feldspar and sometimes biotite. The sillimanite occurs in a felt of fine needles about .5 mm. long and generally showing a very strict parallelism. In rare patches, however, the preferred orientation breaks down, and the sillimanite forms a matted felt of shorter needles. Small needles of red-brown rutile, showing geniculate twind, are relatively common and tend to parallel the sillimanite needles. There are occasional masses of magnetite and haematite.

The quartzo-feldspathic partings are generally about 15 mm. wide, lensoid in form, and contain rounded crystals of sodic oligoclase and subsidiary

quartz. Both minerals are criss crossed by decussate needles of sillimanite. Some of the partings also contain broad flakes of biotite up to 2 mm. long.

ABERGAIRN GROUP

To the east of the Gairn, in contrast to the marbles of the Coilacriech Group, relatively pure marbles, although themselves restricted in outcrop, are associated with a band of calc-silicate rocks about half a mile wide, which trends northwest-southeast. It is traceable from just north of the granite contact, half a mile north of the pass of Ballater, to the stream section just north of Bridge of Gairn. This group of rocks has been called the Abergairn Group.

The Abergairn Group comprises marbles and calc-silicate rocks which grade from pyroxene-rich rocks, through rocks containing varying proportions of pyroxene and amphibole, to rocks in which the only ferromagnesian mineral is amphibole. It is interbedded with abundant hornblende schists similar to those found within the Coilacriech and Candacraig Groups, and some confusion arises between the amphibole-bearing calc-silicate rocks and the amphibole-bearing metadoleritic rocks. However the majority of the amphibole-bearing rocks have been assigned to one or other of the two groups, on the basis of criteria which will be discussed when both groups of rocks have been described (p. 101).

Barrow and Craig (1912) did not report the presence of lime-rich rocks in this area, which they mapped as consisting entirely of hornblende

schist, the only petrographic description given being of a typical hornblende-plagioclase metadolerite.

Field relations within the Abergairn Group are obscure. This is partially due to the nature of the exposure, which consists of a series of small flat lying exposures a few feet across, usually relatively homogeneous; partially due to the similarity of the various types in the field. The pyroxene-rich rocks are pale grey in colour, and almost white on some fresh surfaces, while the amphibole-rich calc-silicate rocks are somewhat darker grey and tend to weather with a reddish brown skin. The metadoleritic rocks are darker still, and do not have this reddish weathering product. It must be emphasised however that there are all gradations between the various types.

Marbles

The marbles of the Abergairn Group are found only in two small grass covered exposures just north of the granite contact to the north of the Pass of Ballater. These are mottled rocks of typical calcareous aspect, with greenish and light and dark grey patches. A slight compositional banding parallels the schistosity of the nearby amphibolites.

The marbles consist essentially of an equigranular mosaic of calcite with subsidiary olivine and serpentine, some brucite and rare pyrite. The calcite has an average grain size of about .3 mm. with occasionally slightly coarser areas. It is rarely twinned. Olivine is

variably distributed throughout the rock, occurring as small rounded crystals about 1 mm. diameter, and occasional larger fragmentary crystals up to 2 mm. across. The latter consist of a large number of small grains in optical continuity. The olivine is partially or completely pseudomorphed by pale brown antigorite which veins the olivine along irregular fractures at right angles to which the antigorite fibres are ranged. The olivine is biaxial positive with a very high optical angle, indicating a composition very near to pure forsterite. A low proportion of brucite is distinguished from the serpentine by its colourless nature and slightly higher birefringence; it has anomalous reddish brown birefringence in the higher range of first order colours. It forms small rounded patches and narrow veinlets containing fine fibres of brucite interlayered with some calcite.

Large anhedral masses of pyrite up to 5 mm. long, enclosing crystals of calcite, occur sparsely. These are associated with rare skeletal crystals of ilmenite. Rare bladed crystals of phlogopite are also associated with the pyrite. These are virtually colourless, non-pleochroic, and uniaxial negative.

Calc-Silicate Rocks

As the pyroxene and amphibole bearing rocks grade into one another with increase and decrease of certain minerals, and since the properties of individual mineral species vary little throughout the range of rock types, the minerals from these rocks will be described in

one section. The subsidiary phlogopite and magnetite schists will be described in the following section. In some cases pyroxene-rich nodules, and irregular patches, are found within pyroxene-free amphibole bearing rocks; in other instances lenses and pods of amphibole-rich rock, ranging in size from 1" x $\frac{1}{2}$" in cross section upwards, are enclosed by pyroxene-rich types. Contacts between such segregations and the host rock are sharp, although individual crystals often penetrate for a short distance into the neighbouring rock type.

Modal analyses of typical calc-silicate rocks are given in Table IV, while the variations in mineralogy found in this rock assemblage are shown in Table V.

In thin section the calc-silicate rocks consist of pyroxene and/or amphibole set in a matrix which ranges from a freshly crystalline feldspar mosaic, through very altered feldspar, to a cryptocrystalline micaceous mat containing a little calcite.

In those rocks which contain both pyroxene and amphibole, these two minerals are sometimes equally distributed throughout the rock; more often they are very patchily distributed, and in rare cases the rock shows a fine compositional banding, the bands varying in width from a few millimetres to 10 cms. These bands are often patchy and discontinuous. The orientation of the bands parallels the schistosity of the neighbouring hornblende schists.

The pyroxene occurs in poikiloblastic crystals of very variable grain size (see Pl XIII B). Within one thin section the grain size may vary from crystals 12 mm. long to tiny grains about .01 mm. in diameter. Many of the larger crystals are formed of a mass of small interlocking xenoblasts with almost the same optical orientation. The pyroxenes enclose crystals of feldspar and patches of micaceous material. In the amphibole bearing rocks the pyroxene crystals tend to be less compact. This pyroxene is colourless: $Z \wedge C = 43 - 48^{\circ}$.

The amphibole occurs in large radiating sheaves up to 5 mm. long (see Pl XIII A). These show a rudimentary preferred orientation, and are poikiloblastic, enclosing tiny feldspar crystals. Numerous small compact amphibole crystals surround these large sheaves. The pleochroic scheme is very pale and varies from X-colourless, to Y- and Z-pale green or greenish brown. Rarely the colour is a fairly deep green. This amphibole is biaxially positive, $2V_z = 78\text{-}90^{\circ}$ (see Table VI) $Z \wedge C = 13\text{-}16^{\circ}$.

In the finely banded pyroxene-amphibole rocks the amphibole crystals contain abundant minute opaque inclusions. In some cases,

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Optic angles quoted in this thesis were measured on the Universal Stage, at least five crystals being measured from each thin section. The range of variation of optic angle from any one thin section was within a range of $\pm 2^{\circ}$.

TABLE IV

MODAL ANALYSES OF CALC-SILICATE ROCKS FROM THE ABERGAIRN GROUP

Specimen No.	18D	22Mb	21M	11Da	36D	BG5
Amphibole	-	-	45	81	39	-
Pyroxene	78	57	33	-	-	38
Phlogopite	-	-	-	-	-	33
Matrix	20*	41	21	14	48	17*
Apatite	-	-	-	-	-	6
Others	2	2	1	5	13	6

Number of points counted - 1500+

18D pyroxene-rock, 1300 yards N 40°E of Balmenach farm, east Glen Gairn.

22Mb pyroxene-rock, 1170 yards N 67°E of Balmenach farm, east Glen Gairn.

21M pyroxene-amphibole-rock, 1000 yards N 52°E of Balmenach farm, east Glen Gairn.

11Da amphibole-rock, 450 yards N 20°E of Abergairn farm, east Glen Gairn.

36D amphibole-rock, 150 yards N 72°E of Abergairn farm, east Glen Gairn.

BG5 pyroxene-phlogopite-rock, in River Gairn 75 yards upstream from Bridge of Gairn.

*the matrix in these cases consists of fresh feldspar. In the other rocks it is extensively altered to micaceous material.

TABLE V

VARIATIONS IN THE MINERALOGY

OF THE CALC-SILICATE ROCKS OF THE ABERGAIRN GROUP

	1	2	3	4	5	6
Pyroxene	X	X				X
Amphibole	X		X	X		
Feldspar	X	X	X	X		X
Idocrase		X*				
Biotite				X*	X	X'
Quartz			X*		X	
Magnetite					X	

X* - very small amounts of the mineral are present

X' - the mica is in the form of phlogopite

the feldspar is often considerably altered to micaceous material.

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notably in rocks located near the site of the old lead mine at Abergairn, the amphibole is altered along fractures in the rock to a deep green, isotropic chlorite.

The pyroxene and amphibole crystals are surrounded by a matrix which varies from a very fresh mosaic of round, anhedral feldspar crystals about .1 - .3 mm. across, to an extremely fine grained mat of tiny sericitic mica flakes. All stages are present, the amount of mica in the feldspar being variable across one thin section. It is not clear whether the feldspar is being broken down to, or crystallised from the sericitic material. The feldspar forms an equigranular mosaic showing a typical stress-free fabric, the crystal boundaries meeting in stable triple points (Voll 1960). The crystals are mostly untwinned. Refractive index determinations on cleavage flakes gave a variation in composition from An_{22} to An_{28}. The sericitic material is extremely fine grained, colourless and with fairly high birefringence.

Idocrase occurs in one of the pyroxene-plagioclase rocks examined, in large irregular masses up to 12 mm. across. These include pyroxene, epidote, and pyrite partially altered to limonite. Sparse very small flakes of biotite are present in some of the pyroxene-free amphibole bearing rocks. Sometimes the biotite occurs as very fresh flakes within the chlorite, appearing to be a late stage recrystallisation from the latter. More commonly it occurs as tiny flakes about .03 mm. across, which are fresh, reddish brown in colour and grade into the amphibole along whose cleavages it lies.

TABLE VI

DATA ON AMPHIBOLES FROM CALC-SILICATE ROCKS OF THE ABERGAIRN GROUP

Specimen No.	$2V_z$	$Z \wedge C$	Pleochroic Scheme		
			X	Y	Z
10M	87	16	very pale green	medium green	medium blue-green
19Mb	79	13	colourless	very pale brown	pale brown
21M	86	15	colourless	colourless	very pale brown
41D	90	16	colourless	colourless	very pale brownish green
22Ma	85	15	neutral	very pale brown	very pale brown

21M, 22Ma - pyroxene-amphibole rocks

10M, 19Mb, 41D - amphibole rich rocks.

Sphene and pyrite are the most abundant accessory minerals in these rocks. The sphene is faintly pleochroic from neutral to pale pink, and is often very turbid. The proportion of pyrite present is very variable; masses up to 5 mm. long are present in some specimens. Others have occasional tiny magnetite granules throughout the rock, while rare specimens have a very abundant dusting of magnetite granules throughout. Epidote is present in some of the pyroxene-bearing rocks, sometimes forming veinlets. It is biaxial negative with a high optic angle and is faintly pleochroic to pale greenish yellow. Quartz is rarely found in some of the amphibole-rich rocks, as are narrow monomineralic veinlets of prehnite.

Subsidiary Types

Within the Abergairn Group there are two rock types of very limited occurrence. These are a black schist and a phlogopite-pyroxene schist. The black schist is exposed about 200 yards NE of Abergairn farm, and is a finely fissile, dark grey rock, virtually indistinguishable in the field from the hornblende schists. However, this schist is composed essentially of quartz and magnetite with subsidiary mica. The base of the rock is a very fine grained quartz mosaic dusted throughout by very tiny granules and occasional masses of magnetite up to .1 mm. across. There is a slight banding controlled by variations in the abundance of the magnetite. Within this matrix are scattered occasional inclusion-free quartz crystals, and quartzose lenses, in which individual crystals are up to .3 mm. long. Throughout the rock there are fine needles of biotite about .15 long,

showing a preferred orientation parallel to the banding mentioned above. These are very faintly pleochroic to a yellowish brown. Occasional coarser biotite rich lenses are also present.

The phlogopite-pyroxene schist outcrops within the succession in the river bank just above Bridge of Gairn, in bands several feet wide. It is dark grey schistose rock, with lighter coloured lenses which indicate mica-free areas. It comprises phlogopite, pyroxene and feldspar with relatively abundant apatite, and exhibits a typically hornfelsic texture. A modal analysis of this rock type is given in Table IV. The phlogopite is very abundant in decussate elongate flakes, of average length 1 mm. It has a pleochroic scheme X-neutral, Y-yellowish brown, Z-medium deep reddish brown, and is uniaxial negative. Basal sections exhibit very abundant acicular inclusions of rutile arranged at 60° to each other. Inclusions of sphene, iron ore and pyroxene are also present. The pyroxene crystals are colourless, of irregular form, and sometimes poikiloblastic. They seldom exceed .5 mm. in diameter, and occasionally include crystals of phlogopite. Interstitial feldspar is irregularly distributed throughout the rock with very indefinite boundaries, a great deal of turbidity, and indistinct twinning. It thus did not prove possible to identify the composition of the feldspar. This mineral includes phlogopite, iron ore and occasional pyroxene. About six per cent of apatite is present in subhedral to anhedral crystals up to .8 mm. long. These are characterised by abundant minute and patchily distributed inclusions, which are often so abundant as to make the crystal

appear dark in plane light. A very narrow outer zone of the crystal is usually free from these inclusions. The apatite is generally found in close proximity to, or included within, the mica. Other accessory minerals include irregular masses of pyrite up to .5 mm. across, small anhedra of sphene, and sparse rounded crystals of zircon.

CHEMICAL CONSIDERATIONS

Chemical analyses were carried out on two metasediments (2CA and 8CA) with a partial analysis of a third (21M).

8CA Cordierite-biotite schist (Coilacriech Group).

A quartz-rich schist with very subsidiary feldspar. Well orientated biotite flakes are common, and elongate lenses rich in sericitised cordierite contain small amounts of andalusite, spinel and garnet. There is accessory magnetite and pyrite.

2CA Actinolite-biotite schist. (Candacraig Group).

This consists of a fine grained quartzo-felspathic matrix in which occur occasional plagioclase porphyroblasts and bands rich in actinolite and/or biotite. There is accessory epidote, magnetite and pyrite.

21M Calc-silicate rock. (Abergairn Group).

A finely banded rock, the bands consisting predominantly either of pyroxene or amphibole, both with subsidiary feldspar. These bands interdigitate with and grade into, one another. This is accessory sphene.

All chemical analyses of rocks from the Geallaig district quoted in this thesis were carried out by the Geochemical Laboratory, Grant Institute of Geology, University of Edinburgh.

The chemical analyses of the metasediments, and a comparative analysis, are shown in Table VII, while Table VIII gives the norms and modal analyses of these rocks.

Specimen 8CA is a typical example of the pelitic rocks of the Coilacriech Group. The analysis of this rock compares fairly closely with that of a sandstone from the Franciscan sandstone of Sulphur Bank, California (Talliaferro, 1943), which is given in Table VII, D. The analysis of 8CA also falls within the general group of greywacke analyses (Walton, 1955) although its alumina content is higher than the average for this group, as is its soda-potash ratio, possibly reflecting a high proportion of feldspar in the original sediment.

Specimen 2CA is an actinolite-biotite schist from the Candacraig Group. Its analysis shows a higher content of lime, magnesia and iron oxides than that of 8CA and a lower content of silica, soda and alumina. This chemical difference, which reflects the higher proportion of ferromagnesian minerals seen in the modal analysis of the rock, reflects an original deficiency in the arenaceous and argillaceous constituents of the parental sediment, their places being taken by a proportion of calcareous and dolomitic material.

Specimen 21M is an impure calcareous rock from the Abergairn Group of amphibole-pyroxene type; the specimen chosen is one of those interpreted

TABLE VII

CHEMICAL ANALYSES OF METASEDIMENTS

and

COMPARATIVE UNMETAMORPHOSED SEDIMENT

Specimen No.	8CA	2CA	D	21M (partial analysis)
SiO_2	63.4	63.5	68.5	
TiO_2	0.90	1.2	0.60	
Al_2O_3	17.2	13.7	12.8	
Fe_2O_3	0.73	1.3	1.9	4.3
FeO	5.0	5.7	3.4	
MnO	0.07	0.10	0.02	
MgO	3.1	3.8	2.2	10.2
CaO	0.94	3.7	1.8	15.3
Na_2O	4.4	3.3	6.0	
K_2O	1.5	1.7	1.3	
P_2O_5	0.18	0.13	0.16	
H_2O	1.8	1.4	0.28	
Total	99.2	99.5	98.96	

Localities:

8CA Cordierite-biotite schist (Coilacriech Group)
400 yds. N 65° W of Dalbagie farm, N bank of Dee, west of Ballater

2CA Actinolite-biotite schist (Candacraig Group)
240 yds. N 81° W of Culsh farm, west Glen Gairn.

D Franciscan sandstone, Sulphur Bank, California (Talliaferro, 1943

21M Calc-silicate rock (Abergairn Group).
1000 yds. N 52° E of Balmenach farm, east Glen Gairn.

TABLE VIII

A. CIPW NORMS OF CHEMICALLY ANALYSED METASEDIMENTS

Specimen No.		8CA	2CA
Quartz		22.5	21.2
Orthoclase		8.9	10.0
Albite		37.2	27.8
Anorthite		3.9	17.9
Corundum		6.9	-
Diopside	Ca	-	-
	Mg	-	-
	Fe	-	-
Hypersthene	Mg	7.8	9.5
	Fe	7.0	7.5
Olivene	Mg	-	-
	Fe	-	-
Magnetite		1.2	1.9
Ilmenite		1.7	2.3
Apatite		0.3	0.3
H_2O		1.8	1.4
		99.2	99.4

B. MODAL ANALYSES OF ANALYSED METASEDIMENTS

Specimen No.	8Ca	2CA	21M
Quartz	16	28	-
Feldspar	28	34	21
Cordierite*	30	-	-
Biotite	24	9	-
Actinolite	-	28	-
Amphibole	-	-	45
Pyroxene	-	-	33
Others	2#	-	1

No. of Points Counted = 1500-2000

*Almost completely altered to sericitic mica.

#Includes andalusite, garnet and spinel.

from its mineralogy as containing a fairly high proportion of non-calcareous impurity. Only a partial analysis was carried out on this rock, to determine the proportions of lime, magnesia and iron oxide. The considerable increase in the proportion of lime (15%) and of magnesia (10%) confirms the calcareous nature of the rock, and suggests that some part of the carbonate was present in the form of dolomite.

The chemical variation from the Coilacriech Group, through the Candacraig Group, to the Abergairn Group, thus confirms the change in the nature of the sediments, which was deduced from their mineralogical composition.

DISCUSSION

Dalradian Metasediments. The mineral assemblages within the Dalradian metasediments of the Geallaig district have been considered with a view to determining the grade of metamorphism which they have attained. The metasedimentary sequence can be placed within a single metamorphic facies, the hornblende-hornfels facies as defined by Fyfe, Turner, and Verhoogen (1958), the assemblages in each case being typical of this facies.

Quartzo-feldspathic Rocks. The typical assemblage of this rock type consists of quartz-microcline-oligoclase-(biotite). This assemblage may be found throughout a wide range of pressure-temperature conditions,

but Ramberg (1952, p.150) suggests that the lowest boundary of the amphibolite facies (of which the hornblende-hornfels facies was formerly a sub-facies) may be fixed by the epidote-An_{30} equilibrial assemblage, the plagioclase becoming more calcic with increasing metamorphism. Small amounts of epidote are found in these quartzo-feldspathic rocks, in apparent equilibrium with plagioclase of composition about An_{35}. This evidence indicates that the pressure-temperature conditions under which these rocks were formed were close to the lower margin of the amphibolite facies, (Ramberg, op.cit.).

Pelites and Semi-pelites. It is this group of rocks which shows assemblages particularly indicative of metamorphic grade. Typical assemblages include quartz-plagioclase-muscovite-biotite-cordierite, and quartz-plagioclase-biotite-cordierite-andalusite. These represent silica-rich and potash-poor sediments. Potash-rich sediments, which would contain microcline, are lacking in the sequence. More magnesian varieties are represented by the assemblage plagioclase-cordierite-anthophyllite-garnet-(biotite)-(quartz). These assemblages, characterised by the typical association of andalusite-cordierite and cordierite-anthophyllite are amongst the definitive assemblages given by Fyfe, Turner and Verhoogen (1958) in their erection of the hornblende-hornfels-facies, and are accepted by them as equilibrium assemblages. Such rocks however, as those which contain both quartz and spinel, the spinel being enclosed within andalusite and cordierite, show some failure to attain equilibrium as spinel is a silica deficient mineral. Garnet, which is very rarely

present in the Geallaig district, is not regarded as a normal constituent mineral in this facies, its place usually being taken by cordierite (Turner 1948, p.79).

The more basic assemblages of the Candacraig Group, transitional towards the calcareous rocks of the Abergairn Group, are typically tremolite-biotite-plagioclase-quartz. These rocks contain only a low proportion of quartz; this is to be expected in the hornblende-hornfels facies as Turner and Verhoogen (1951) state that "biotite-hornblende associations typical of the amphibolite facies contain notably less silica than the corresponding assemblages.....in the pyroxene hornfels facies."

Calcareous Rocks. The assemblages in those rocks which possess free calcite are typically calcite-forsterite-brucite, with in the more impure varieties calcite-diopside-forsterite-phlogopite. Such assemblages are also typical of the hornblende-hornfels facies. Ramberg (1952, p.150) regards the lower limit of the amphibolite facies as the point at which diopside takes the place of tremolite in the presence of calcite. The brucite in these rocks is not associated with periclase, in which connection it may be noted that Fyfe, Turner and Verhoogen (1958) suggest that brucite is not necessarily pseudomorphous after periclase at this metamorphic grade.

Calc-silicate Rocks. Typical assemblages in these rocks range from diopside-plagioclase, through diopside-amphibole-plagioclase to amphibole-plagioclase. These assemblages are intermediate between those quoted by Turner and Verhoogen (1951) for impure dolomitic limestones,

of diopside-tremolite-calcite, and those for basic rocks of hornblende-plagioclase. It is possible that, at the contacts between the calcareous rocks of the Abergairn Group and the interbedded hornblende-schists, there may have been some slight interchange of material forming an intermediate rock type. It was not possible in the field to delineate precise contacts between these two rock types.

All the metasedimentary rocks of this area thus belong to the hornblende-hornfels facies of metamorphism. In most cases where this metamorphic grade is found, it has developed as a result of close proximity to an igneous body, and its formation has been interpreted as a contact effect. However, although the metamorphic rocks of the Geallaig district are surrounded by large masses of granite, it cannot be assumed that the present metamorphic grade of the rocks has been produced as a result of the emplacement of these granites. In other parts of Aberdeenshire, and in Banffshire, rocks exhibiting similar mineral assemblages have been interpreted as resulting from regional metamorphism of an anomalous type, known as the Buchan type of metamorphism; this is considered to have taken place under lower stress conditions than normal regional metamorphism. This development of the hornblende hornfels facies on a regional scale is typically developed to the northeast of the Geallaig district in the Ythan valley (Read 1952).

In descriptions of Deeside to the east and southeast of Ballater, Read (1927 and 1928) reports no regional development of minerals of Buchan metamorphic type; cordierite and andalusite are absent except in areas of injection by Older Granite. The pelitic rocks are in the form of biotite schists with rare development of sillimanite and garnet in the vicinity of granite.

Hutchison (1933) described the mineralogy of the Deeside Limestone and, in its regionally metamorphosed sections, its mineralogical composition places it in the almandine-amphibolite facies of regional metamorphism, (Turner and Verhoogen 1960). However he (p.590) mentioned Harker's suggestion that "the anomalous characters of certain Deeside-Donside schists are departures from sillimanite grade metamorphism due to the local absence of the stress factor" and comments that, in the region of Aboyne, part of the Deeside Limestone is affected by such variable pressure-temperature conditions with the production of abnormal mineralogical associations. Chinner (1961) has reported the presence of metamorphism of Buchan type as far south as Glen Cleva about 15 miles south of the Geallaig district.

Thus, although metamorphism of Buchan type occurs both to the north and south of the Geallaig district it does not occur to the east of Ballater, with the possible exception of small areas around Aboyne. This lack of Buchan type metamorphism in the rocks east of Ballater, although they are in close proximity to large granite masses of the same general suite as those of the Geallaig district, also makes it unlikely that the

cordierite and andalusite of the latter are the result of contact metamorphism from the granites. Hutchison (op.cit) reports thermal metamorphism of the Deeside Limestone adjacent to the Newer Granites, attaining in some places the pyroxene-hornfels grade of thermal metamorphism, but this metamorphism appears to be most strongly developed against coarsely porphyritic hornblende-bearing granites such as that of Birsemore. Some, at least, of the non-porphyritic pink quartz-rich granites, such as the Mortlich Granite, mineralogically similar to the Ballater Granite, produce only mild contact metamorphism in the limestone.

There has been some recent work on the metamorphic history of areas both to the north and south of the Geallaig district. Johnson (1962), in a detailed study of the structural and mineralogical history of the rocks of the Banffshire coast, has described four periods of folding, and has related the date of formation of the minerals present to these fold periods. Similar studies have been carried out in Perthshire by Sturt and Harris (1961). Chinner (1961) studied the order of formation of the metamorphic minerals of Glen Clova, but did not relate this to the structural history of the rocks.

The main structures of the Geallaig area form a bedding schistosity which has been folded about a NW-SE axis. It was not possible to ascertain whether the development of the bedding schistosity was associated with a fold movement earlier than that which produced the southeasterly folds now present, as was described by Johnson (1962) from the Banffshire coast.

The only evidence in favour of earlier folds is the rare presence of isoclinal microfolds with their axes parallel to the schistosity (p.36). The NW-SE folds of the Geallaig district have a mineral lineation marked by the micas in the pelitic rocks and even more strongly by hornblendes in the basic sheets. Both Johnson (op. cit) and Sturt and Harris (1961) comment on the characteristic development of mineral lineations associated with their second fold sets in Banffshire and Perthshire, respectively.

Matheson (1958) reports that in Glen Shee the earliest folds present are dominantly isoclinal and trend on a NE-SW axis, while the second "cross-fold" set, folded more openly on a NW-SE axis, are associated with prominent mineral lineations. The second set appears to be similar to the NW-SE folds of the Geallaig district. It is thus considered that the NW-SE fold set which forms the dominant structural feature of the Geallaig district is approximately equivalent to the second fold sets described from Banffshire and Perthshire.

From textural evidence it was concluded (see pp. 33-39) that biotite, muscovite and some cordierite grew during the production of these folds, but that the main growth of cordierite, andalusite and anthophyllite took place during a static phase following the main period of folding.

During the production of the later strain slip cleavages and minor folds biotite, muscovite and quartz seem to have been the main minerals re-generated; it may have been during this time that the retrograde metamorphism

of the cordierite to chlorite and mica took place. Some late static recrystallisation of biotite and muscovite has produced relatively large, randomly orientated, porphyroblasts in parts of the rock.

This development of a high grade "Buchan" type of metamorphism after the early fold period, but preceding the late movements, is in accord with the sequence described by Johnson (op.cit.) from Banffshire where he places the metamorphic climax (with the production of andalusite and cordierite) in a $F_2 - F_3$ interval.

In the Geallaig district it is impossible to relate the later cleavages to any fold movement. It is possible that they were produced during the emplacement of the Ballater Granite. However these structures are so sporadically developed that insufficient measurements were obtained to relate their orientation to the granite margin. As the metasediments are nowhere more than half a mile from the nearest granite exposure, and there is every likelihood that granite everywhere underlies the metasediments at no great depth, any such features produced by the granite might be expected throughout the area mapped. It was thus not possible to determine the origin of the strain slip cleavages. As the development of the cordierite and andalusite precedes the development of the cleavages it is unlikely that these minerals were produced by thermal alteration from the granite. The only mineralogical reconstitution directly attributable to the granite is the largely recrystallised hornfels which occurs for a few feet from the contact.

It may thus be concluded that there are distinct similarities between the metamorphic history of the Geallaig district and that of the Banffshire coast. A fold set comparable to Johnson's F_1 in Banffshire was not recognised, but the NW-SE folds of the Geallaig area, with their accompanying mineral lineations, are taken to be roughly analagous to the F_2 set of Banffshire. In both areas this fold set is succeeded by the peak of the metamorphic grade. The later history of the rocks of the Geallaig district is not sufficiently well documented to relate it to adjacent areas. It is concluded that the Ballater Granite had a relatively limited thermal effect on the metasediments although it may have been responsible for the production of the strain slip cleavages, crystallisation of porphyroblastic micas, and retrograde metamorphism of aluminosilicates.

BASIC IGNEOUS ROCKS

INTRODUCTION

The basic rocks occurring within the Geallaig district have been divided into two groups,

1) relatively thin sill-like bodies interbedded with Dalradian metasediment; this will be referred to as the Basic Sheet Group;

2) the Hornblendic Group, which forms a relatively large mass of basic rocks intervening between the Candacraig and Abergairn Groups (see Fig. 4).

The basic rocks of the district were described by Barrow and Craig (1912) who did not distinguish between the above groups. They considered that all the basic rocks formed a sill which was affected by most of the regional metamorphism of the surrounding metasediments. They concluded that they represent the alteration of massive augitic rocks into foliated epidiorites and hornblende-schists by dynamic metamorphism. They were of the opinion that the amount of shearing increases from west to east, the converse of the conclusion reached in the present study. The porphyritic nature of some of the epidiorite xenoliths in the granitic rocks around Crathie was noted by Barrow and Craig but they made no mention of such rocks around Ballater, or of the presence of metadolerites containing relic ophitic textures to the east of the Gairn. They thus concluded that all the basic rocks formed part of one intrusion, or suite of intrusions, of pre-Caledonian metamorphism age.

In this study the division of the basic rocks into two groups was made on the basis of a number of distinctive characteristics which are considered to be sufficiently definitive to justify separate consideration of the two groups. These characteristics are listed below:

Basic Sheets	Hornblendic Group
a) occur in sill-like bodies generally from 3 - 15 feet wide	a) occurs in a large mass of surface area at least four square miles
b) do not possess small scale banding	b) possesses marked small-scale banding
c) feldsparphyric bands are relatively abundant	c) no feldsparphyric rocks seen
d) contain no pyroxene, and very rare relic textures	d) contains good relic ophitic textures and pyroxenes
e) possess a generally strong plane of schistosity.	e) schistosity fairly weak in general.

BASIC SHEET GROUP

The series of basic sheets is found throughout the Coilacriech, Candacraig and Abergairn Groups constituting, on the average, about half of the available exposure, although the proportion of metasediment to hornblende schist varies greatly from place to place. The sheets typically vary from three feet to 15 feet in width although some attain a width of at least 30 feet and may be much thicker. This could not be definitely ascertained owing to the broken nature of the exposure. These rocks are very uniform throughout the Geallaig district, typically outcropping as bands of fairly fine-grained dark green hornblende-schist. Where they can be traced towards the contact with the Ballater Granite the hornblende-schists do not change macroscopically even one foot away from the contact (Pl I B). The bands

lie parallel to the compositional banding of the metasediments with which they are intercalated. Rarely they were seen to wedge out along strike.

PETROGRAPHY

Although the majority of these hornblende-schists are medium to fine in grain size, the grain size varies within wide limits. This variation is not a consistent feature of any one band, and junctions between areas of different grain sizes are both gradational and sharp, and do not parallel the margins of the sheets.

There is a plane of schistosity which is very variably developed, and a gradation from amphibolite with no recognisable macroscopic fabric to a hornblende-schist with a very strong dimensional orientation can occur within two inches (see Pl VIII B). Where the schistosity is strongly developed the grain size of the rock is generally finer than that where the schistosity is poor or absent. Again the distribution of the highly schistose rocks is not related to the margins of the masses.

Within the plane of schistosity lies a single direction of lineation formed by the parallel alignment of hornblende crystals. This lineation typically lies parallel to the dip of the schistosity.

By far the greater part of these basic sheets consists of homogeneous amphibolites and hornblende-schists, but some of the sheets contain conspicuous white feldspathic patches (see Pl VIII A). Inthe extreme

TABLE IX

MODAL ANALYSES OF AMPHIBOLITES FROM THE BASIC SHEETS

Specimen No.	1CA	55F	26D	6F	10F	23F	41F	3CA
Plagioclase Phenocrysts	54	56*	50†	-	-	-	-	-
Groundmass Plagioclase	6	9	6	25	27	16	40	32
Amphibole	39	34	21	70	69	78	58	64
Biotite	-	-	20	-	-	-	-	2
Others	1	1	3	5	4	6	2	2
No. of Points Counted = 1500+								

1CA - feldsparphyric epidiorite, 675 yards W of Proney farm, Glen Gairn.

55F - feldsparphyric epidiorite, 1/3 mile NW of Culsh farm, Glen Gairn.

26D - feldsparphyric epidiorite, 700 yds. NE of Candacraig farm, E. Glen Gairn.

6F - amphibolite, 3 yds. W of granite margin, 1000 yards N 60°W of Culsh farm.

10F - amphibolite, 1100 yards N 74° W of Proney farm.

23F - amphibolite, 1300 yards due W of Proney farm, W. Glen Gairn.

41F - amphibolite, 900 yards due W. of Abergairn farm, W. Glen Gairn.

3CA - amphibolite, 380 yards N 65°W of Dalbagie farm, N. bank of Dee.

56* - of which 15% is replaced by micaceous alteration products

50† - virtually all replaced by micaceous alteration products.

case these patches attain a diameter of 12 mm. and constitute over 50 per cent of the rock. Generally they have a rounded form, but some approximating to a rectangular cross section were also noted. In some cases there is a decrease in their size and concentration towards the structural foot of the sheet in which they occur, although even at the base they are still abundant. In other cases they vary in abundance laterally. Modal analyses of three such feldsparphyric amphibolites are given in Table IX.

The feldsparphyric amphibolites are best developed about 200 yards south-east of the margin of the Ballater Granite to the north-east of Culsh, but they are also found throughout the succession. In the majority of cases however, the feldsparphyric rocks have been heavily sheared and a schistosity formed, within which the feldspathic patches lie as rolled out rods paralleling the lineation formed by the hornblende crystals (see Pl. I A).

The relationships between feldsparphyric and non-feldsparphyric amphibolite are variable. They both grade into each other, and have sharp contacts. These are often irregular and transgress the schistosity. In other instances irregularily shaped patches of feldsparphyric rock are enclosed within homogeneous amphibolite, and the reverse also occurs.

Thus these basic sheets comprise a group of amphibolites and hornblende schists, showing a gradation from coarse, relatively unsheared, rocks through to fine highly schistose rocks, the grain size of the rock being partially related to the amount of shear which it has undergone.

TABLE X

UNIVERSAL STAGE DATA ON HORNBLENDES FROM EPIDIORITE ROCKS

(Direct Measurements from 2 Optic Axes)

Specimen No.	$2V_z$	$Z \wedge C$	Pleochroic Scheme		
			X	Y	Z
Basic Sheets					
1CA	97	15	pale brown	moss green	blue green
22D	86	16	very pale yellow	very pale green	pale blue green
19Ma	109	18	pale yellowish green	medium moss green	medium blue green
6F	113	17	pale yellowish green	deep moss green	deep blue green
64F	109	17	pale brownish green	deep moss green	deep blue green
Hornblendic Group					
16M	101	15	neutral	medium moss green	medium blue green
30D9	106	18	pale brown	deep green	deep blue green
20M	110	15	pale green	medium moss green	medium blue green

In thin section these rocks, although somewhat variable in texture, show very little variation in mineralogy, with the exception of the presence of the feldspathic patches and rods in some cases.

The unsheared patches consist in most cases of one large crystal of feldspar, rarely they are formed by a crystal aggregate. These crystals have a maximum diameter of 12 mm. but the average size is about 8 mm. The crystals sometimes have a roughly tabular form, the edges of the crystals being invaded by a large number of small hornblende crystals. Small patches and many very tiny single hornblende crystals are also included within this feldspar. The composition of the feldspar is dominantly labradorite, showing normal zoning which ranges from An_{72} to An_{46}. Complex twinning is characteristic. In the least altered rocks the feldspar is almost completely fresh, but shows some fracturing along which occurs a fine equigranular mosaic of fresh rounded largely untwinned crystals of sodic andesine. In the next stage of alteration these small clear feldspar crystals form around the original crystals also. In the more altered, but still relatively unsheared rocks, the cores of the large feldspar crystals have been extensively altered to secondary mica, and the twin planes become irregular, individual twin members having sutured contacts. As the alteration becomes more intense, the cores of secondary mica increase at the expense of the relic rims of feldspar, and the twinning becomes almost indistinguishable. In the final stage virtually no feldspar is visible in the micaceous patches.

In those rocks which have been affected by strong shear, and show a well developed schistosity, the feldspathic patches are represented in some cases by elongate areas of secondary mica, but more commonly the feldspar has completely recrystallised into elongate patches of small feldspar crystals which are fresh, unzoned, rarely twinned and equidimensional. The average grain size of such feldspar is about .3 mm., and its composition, calculated from the refractive index of cleavage fragments, is sodic oligoclase.

The remainder of the feldspar-phyric rocks, and the homogeneous amphibolites and hornblende-schists, are composed essentially of plagioclase and hornblende in varying proportions. Other minerals are present only in accessory quantity. Modal analyses of typical examples are given in Table IX.

The typical feldspar of the basic sheets occurs in small equidimensional crystals similar to those of the recrystallised feldspathic patches. Very rarely, in rocks which show little signs of shear, in addition to the feldspar described above, there are elongate laths of feldspar of more calcic composition, sometimes showing normal zoning. Their composition ranges from An_{55} to An_{32}. These show abundant twin complexes and are often highly altered and invaded by hornblende crystals. Such feldspars are found in the least altered and practically unsheared amphibolites, and they are taken to be an earlier generation of feldspar than the small rounded untwinned crystals. It must be emphasised that such feldspar crystals are extremely rarely found in the basic sheets.

The hornblende in these rocks is deep in colour, with slightly paler varieties occurring occasionally to the east of the Gairn. Its pleochroic scheme is X-pale brownish green, Y-moss green, Z-blue green. The mineral has a variable optic axial angle, $2V_z$ varying from 86° - 113° (Table X). The optic angle is generally smaller where the amphibole is pale in colour. Biaxially positive amphiboles are extremely rare in the basic sheets, $Z \wedge C = 15^\circ$ - 18°.

The habit of the hornblendes varies according to the amount of shear which has affected the rocks. In specimens which show a very poorly developed schistosity the amphiboles form masses of poikiloblastic plates, very irregular in form, and often intergrown. These are surrounded by smaller, more compact crystals. The poikiloblastic hornblendes vary greatly in size, the average grain size in different specimens varying from .06 mm. to 1 mm. across. These crystals include small feldspar crystals and hornblende crystals. In the more schistose rocks, the hornblendes crystals form small compact, roughly elliptical crystals (Pl. XII A), often showing a very strict orientation of crystal form and pleochroic scheme. In such rocks the grain size of the hornblende and feldspar is approximately equal.

The hornblende is typically very fresh, but where the feldspar is altered to secondary mica the hornblende is often chloritised, and in some cases includes biotite.

Biotite is absent in about 90 per cent of the basic sheets, but occurs in accessory quantity in some rocks and very rarely makes up as much as 20 per cent of the rock, increasing in abundance where feldspar is

extensively altered. It forms very fresh tiny flakes, pleochroic from X-pale yellow, Y-pale orange, Z-medium reddish brown. The flakes occur within and around hornblende. Small indefinite brownish areas in the hornblende crystals may indicate incipient biotite, minute flakes of which occur along the cleavage planes of the hornblende. The biotite thus appears to be subsequent to the hornblende. In two cases where a considerable amount of such biotite is present, the specimens were collected from the close proximity of a quartz porphyry dyke. Small anhedra of quartz occur in accessory quantity in rare examples of the basic sheets. Magnetite forms small granules which are often associated with, and surrounded by, sphene. The latter is less abundant in the highly schistose rocks. Pyrite is rarely present and is often extensively altered to reddish brown haematite. Rare epidote forms small anhedra within the altered feldspar. It is patchily pleochroic to pale yellow, biaxial negative, and shows anomalous blue birefringence. Zircon and apatite occur as very rare accessory minerals.

VEINS

Epidote Veins

In the vicinity of the Ballater granite to the west of the Cairn, a few yards from the contact, the hornblende-schists are cut by occasional veins up to 2 cms. in width. In thin section these are seen to consist wholly of epidote and prehnite. The epidote is colourless and shows no pleochroism; it is biaxially positive with fairly strong birefringence.

It occurs in elongate sections up to 4 mm. in length. The prehnite occurs both interstitially to the epidote, and forming margins to the veins about 1 mm. wide. These separate the epidote from the hornblende-schist. The prehnite is colourless and shows a well developed sheaf structure. The feldspar of the surrounding hornblende-schists is completely altered to prehnite for about 3 cms. from the vein. Such veining was not found elsewhere in the hornblende-schists.

Augite Veins

Occasional veins of augite were found in the hornblende-schists within about 300 yards of the granite contact to the west of the Gairn. These are a few millimetres in width and cross cut the schistosity. They consist of a central zone of coarse augite of about 1 mm. grain size, separated from the hornblende-schist by a zone of small augites, much altered feldspars, and small granules of sphene. The feldspars are similar to those in the hornblende-schist but turbid, whilst sphene is much commoner in this zone than in the hornblende-schist. The augite is colourless and has an extinction of 45°. It is somewhat fractured along planes approximately parallel to the length of the vein, with a slight production of hornblende along the fractures. The feldspar of the margin grades into that of the hornblende-schist, but there is a sharp demarcation between the area of augite and that of the hornblende of the hornblende-schists.

Feldspathic Veins

Throughout their extent the epidiorites and hornblende-schists contain irregular, often discontinuous veins and patches of feldspathic

material. These sometimes contain quartz and orthoclase feldspar as well as the more common plagioclase. The feldspar is always much altered to fine patches of prehnite. The plagioclase is variable in composition from oligoclase, where there is free quartz, to more basic andesine where quartz is lacking. These veins are of variable grain size but are generally coarser than the enclosing epidioritic rocks. They contain some epidote and small crystals of interstitial hornblende. They are taken to represent the final stages of crystallisation of the basic magma which produced the doleritic forerunners of the epidiorites and hornblende-schists.

HORNBLENDIC GROUP

The extent of this group is shown in Figs. 4 and 31. It comprises a complete gradation from metadoleritic rocks containing relic augite and distinctive ophitic textures, through amphibolites to hornblende-schists, although the development of a well marked schistosity is not as widespread in this group as it was in the basic sheets. The Hornblendic Group extends northwards outside the area mapped but, in the northeast of that part included in this study, there is an area of finely banded hornblende-plagioclase rocks, best exposed to the south of Tom Garchory. On the northeastern shoulder of Candacraig Hill, where the representatives of this group are fine grained hornblende-schists and amphibolites, the rocks are traversed by numerous trondjhemitic veins, the intensity of the veining being very variable from place to place.

NORMAL TYPE

Many of the hornblende-schists of the Hornblendic Group are indistinguishable from those of the basic sheets, both in hand specimen and in individual small exposures. However the groups have been treated separately for the reasons given on page 70. Modal analyses of rocks from this group are given in Table XI.

In the least reconstituted rocks relic augite forms cores to many of the hornblende crystals, while two generations of feldspar are present, showing the change from early, coarse feldspar, sub-ophitic to the pyroxene, to a mosaic of relatively fine recrystallised secondary feldspar (Pl. XI C) and (Pl. IX A).

The early feldspar of such rocks is a plagioclase of andesine-labradorite composition. Normal zoning is abundant and ranges from An_{58} to An_{38}. Complex twinning is characteristic, the twin planes being indistinct in the more altered cases. In some instances the feldspar crystals are crossed by planes of fracture. The amount of alteration is variable. Some of the early feldspar crystals are altered to a fine mat of secondary mica, but more commonly they are rimmed by, and include, secondary feldspar which has the appearance of forming from the earlier feldspar by straightforward recrystallisation without an intermediate micaceous stage.

The early feldspar crystals occur in elongate, lath shaped crystals which are invaded along their margins by small hornblende crystals. These

laths may attain a length of up to 7 mm. and occur with an ophitic relationship to hornblende and pyroxene.

The late feldspar consists of a mosaic of equigranular, rounded, largely untwinned crystals, with an average grain size of approximately .25 mm. They are generally unzoned, and very fresh. Their composition is somewhat more sodic than that of the early feldspar, being andesine, about An_{40}.

Relic augite, showing all stages of replacement by hornblende, is abundant in some specimens. Textures of such a rock are seen in Pl XI. All stages are present, from a large core of augite enclosed by a narrow rim of hornblende to a few isolated optically continuous remnants of augite in hornblende, and there are always abundant crystals of hornblende lacking augite. The hornblende replaces the augite preferentially along its cleavage planes. The latter is colourless with a maximum extinction angle of 43°.

The hornblende in these rocks occurs in large ragged plates, sometimes enclosing augite as described above. The hornblende rim around augite is often optically continuous, but sometimes takes the form of a mass of small compact crystals. In the former case, the single crystal of hornblende formed shows stronger absorption peripherally than centrally. Such crystals are often intergrown with other, differently orientated, hornblende crystals. The maximum size of these crystals is 5 mm., the majority of the crystals being much smaller. Universal stage determinations gave a $2V_z$ 101°-110° and $Z \wedge C$ of 15° - 18° (Table X). The pleochroic scheme is X-pale yellowish brown, Y-green, Z-blue green. Y and Z show very deep colours.

TABLE XI

MODAL ANALYSES OF HORNBLENDIC GROUP ROCKS

Specimen No.	7M	20M	30D9	31D9(a)	31D9(b)	6D9(a)	6D9(b)	8D9
Amphibole	71	54	46	83	37	77	49	43
Plagioclase	27	27	40	15	59	20	35	52
Quartz	-	-	-	-	-	3	16	3
Pyroxene	-	15	11	-	-	-	-	-
Biotite	-	-	-	-	-	-	-	-
Others	-	4	3	2	4	-	-	2

No. of Points Counted = 1000-2000

7M - hornblende schist, 1170 yds. N 56°E of Balmenach farm, E. Glen Gairn

20M - epidiorite, 1000 yds. N 56°E of Balmenach farm, E. Glen Gairn

30D9 - epidiorite, 800 yds. S 10°W of the summit of Peter's Hill, S. of Morven

31D9 - banded hornblende schist, summit of Peter's Hill.
(a) hornblende rich band (b) hornblende poor band

6D9 - banded hornblende schist, 1 mile NE of Peter's Hill.
(a) hornblende rich band (b) hornblende poor band

8D9 - amphibolite, 1500 yds. NE of Peter's Hill
(the amphibole in this specimen is cummingtonitic.)

Sphene, magnetite and pyrite are notable accessory minerals. The sphene occurs in irregular masses and also in radiating reaction rims surrounding magnetite. The pyrite occurs in cubes, often surrounded by a deep red alteration rim of haematite.

Such rocks showing relic minerals and textures grade through those which show only relic textures, into rocks in which there has been complete mineralogical and textural reconstitution. The latter are hornblende-plagioclase rocks in which the hornblende and plagioclase are indistinguishable from those of the basic sheets, and thus no full description of these rocks will be given. Within these amphibolites and hornblende-schists lie the banded rocks and trondhjemitic veins previously mentioned which will now be described.

BANDED VARIETIES

In the northeastern part of the Hornblendic Group, extending from Tom Garchory southeast to the neighbourhood of Peter's Hill, the hornblende-schists are very finely banded. These banded rocks make up a fairly large part of the Hornblendic Group. The bands vary from light grey to dark green in colour and range from 1 mm. to several feet in thickness. In some cases they wedge out laterally, but were never seen to transgress one another. In some areas the bands break down and the rock is very patchy in nature. These banded rocks show up very well the minor folds described on page 22.

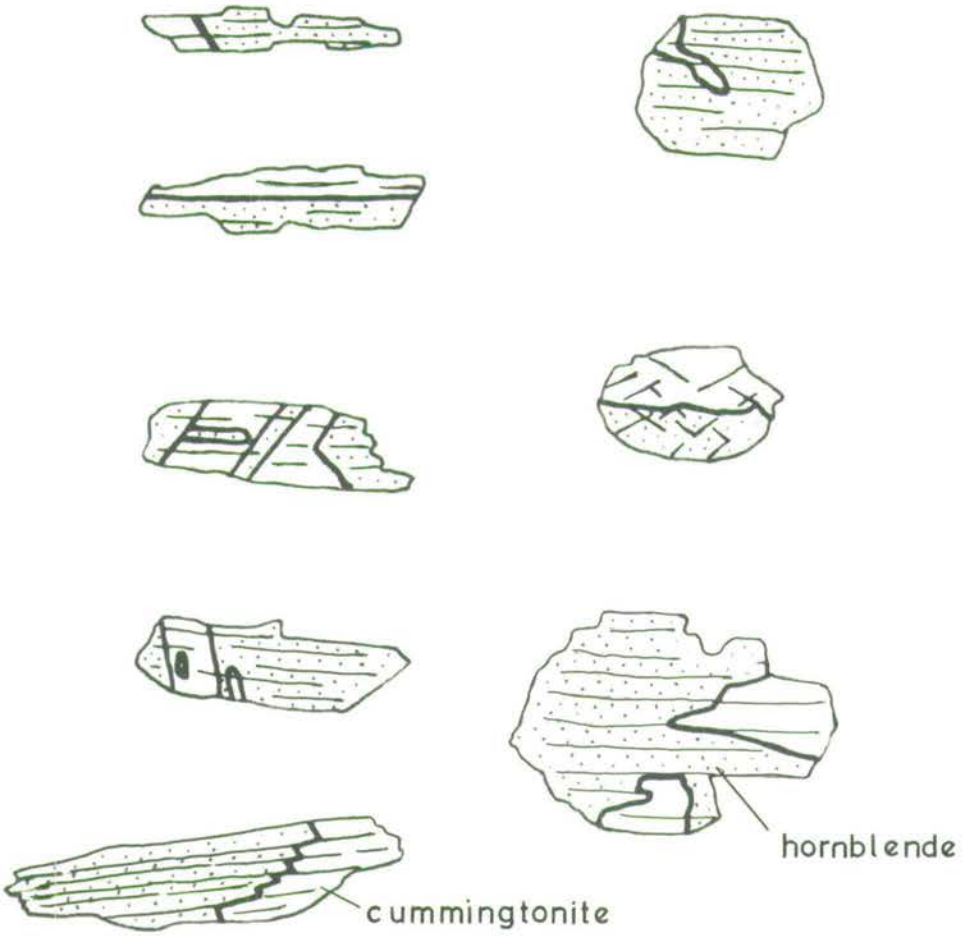
In thin section the banded hornblende schists consist essentially of amphibole and plagioclase, the different bands containing varying proportions of these minerals. Contacts may be either sharp or gradational. In the amphibole-deficient bands quartz is sometimes present in low proportion. In some cases the amphibole in both dark and light bands is a deeply coloured hornblende, in other cases it is deeply coloured only in the amphibole-rich bands, being a colourless variety where amphibole is less abundant. Occasional pyroxene-rich bands and lenses a few millimetres to two centimetres in width occur, often associated with narrow bands relatively rich in quartz. There are infrequent narrow biotite-rich bands a few millimetres in width. Modal analyses of typical bands are given in Table XI. The bands from which these analyses were taken were in the order of 2 mm. thick. The contact between two typical bands is shown in Pl. XII C and D.

As stated above, the amphibole in these banded rocks occurs in two types which differ not only in colour but also in habit and birefringence. The deeply coloured amphibole is a common hornblende with a pleochroic scheme X-pale green, Y-olive green, Z-blue green. It is biaxially negative with $Z \wedge C = 18^{\circ} - 20^{\circ}$. This hornblende occurs typically in small compact elliptical crystals of average grain size about .5 mm, the grain size increasing slightly where amphibole is more abundant. The long axes of the ellipses are orientated parallel forming a schistosity. Dark pleochroic haloes around tiny zircon crystals are common. Where the rock is crenulated the hornblende crystals lie parallel to the fold limbs,

and show excellent synchronisation of their pleochroism (see Pl. II B). No fracturing or straining of the crystals was observed.

The pale coloured amphibole never exceeds 40% - 50% of the rocks in which it occurs. It is virtually colourless; sometimes it has a very faint greenish tinge. It is biaxially positive, the optic axial angle approaches 90° and $Z \wedge C = 18^{\circ}$. The birefringence is slightly higher than that of the green hornblende and repeated twinning is occasionally present. It occurs in isolated, needle shaped crystals about 1.5 mm. long and 0.1 mm. wide. These show a very strict preferred orientation in some cases, but very little in others. These amphiboles also lie parallel to the limbs of minor folds where these are present. From the optic sign, habit and repeated twinning this is considered to be a cummingtonitic amphibole.

In those rocks which contain both cummingtonite and hornblende, the two often occur mainly in discrete bands. In other cases they are both present throughout the rock, with hornblende always predominant, and in yet other cases the distribution of the two is irregular and patchy. In every case intergrowths between the two types of amphibole are abundant. The hornblende and cummingtonite, when intergrown, are coaxial. They meet along both regular and irregular planes in the crystal. The regular planes most commonly parallel (001) and (100); the intergrowths form bands across the crystals, which are sometimes repeated, or bisect the crystal. Sometimes intergrowths parallel to both (001) and (100) occur within the same crystal (Fig.10). Where the two amphiboles meet along irregular planes, irregular patches of cummingtonite are seen in hornblende and vice versa.



Different types of hornblende-cummingtonite intergrowths in the banded rocks of the Hornblendic Group.

Fig. 10

Occasionally very thin lamellae of cummingtonite in hornblende, or the reverse, which are only distinguishable under very high power, occur. These usually parallel (001).

In the banded rocks feldspar occurs interstitially to the amphibole, in a fine grained mosaic of equigranular, rounded, fresh to slightly turbid, generally untwinned, crystals. These have an average grain size of .5 mm. and the composition of calcic oligoclase.

Quartz is absent in most of these rocks but can make up as much as 16% of the amphibole-poor bands; it is virtually absent in the amphibole-rich bands in the same rock. The quartz occurs in small rounded crystals forming part of the mosaic with feldspar.

Biotite is found in rare specimens. It forms tiny reddish brown flakes within deep coloured hornblende and appears to be forming at the expense of the hornblende. In occasional cases there are narrow bands where biotite is equal in proportion to amphibole. The pleochroic scheme of the former is X-pale yellow, Y, Z-medium reddish brown. Some chloritisation of the biotite is present.

Accessory amounts of magnetite are found throughout these rocks in small rounded grains, while pyrite occurs in some cases in larger irregular masses. Needles of apatite and small crystals of zircon are sparsely present. Sphene forms anhedral masses up to .5 mm. across and rare tiny needles of rutile are also present.

In some of the banded hornblende schists there are bands and discontinous lenses up to 5 mm. wide composed of pyroxene and sericitic mica. Scmetimes pyroxene crystals up to .8 mm. in diameter form a monomineralic core to the bands; more commonly rare crystals of pyroxene, much smaller in size, are found throughout the band. Occasionally green hornblende is intergrown with the pyroxene and appears to be replacing it. The pyroxene is set in a matrix composed of very fine flakes of sericitic mica and sparse minute crystals of epidote. In one specimen small anhedra of pale brown garnet were also present. Crystals of sphene are relatively common, while occasional cubes of pyrite also occur. In some instances quartzose lenses occur within the pyroxene-bearing bands. In such cases the quartz may form up to 40 per cent of the band in small anhedra about .25 mm. across, also set within the micaceous matrix. The quartzose lenses grade into the pyroxene-bearing part of the bands.

At the contact between the pyroxene-mica bands and the hornblende-schists there is a rapid gradation from one to the other, the feldspar of the schists becoming turbid and being replaced by sericitic mica, while the hornblende disappears. Occasional lenses of hornblende-rich material are found within the pyroxene-bearing bands.

TRONDHJEMITIC VEINS

As previously mentioned the amphibolites and hornblende-schists on the northeastern shoulder of the Hill of Candacraig are heavily veined by

trondhjemitic material. This forms an elongate tract covering at least three-quarters of a square mile and extending from NW to SE, from the eastern shoulder of Lary Hill to south of Peter's Hill (Fig. 31, end pocket). The intensity of veining and the width of individual veins is extremely variable even within a few yards. The veining varies in type from exposure to exposure, in many cases occurring as irregular masses of trondhjemitic material which enclose fragments of the surrounding rocks. In other cases the acid material forms more discrete veins with sharply defined edges. The contrast between these two types is well shown by Plates III A and III B. Even where the veins are discrete, however, they are often accompanied by discontinuous patches and veinlets of the trondhjemitic material, imparting a pseudo-porphyritic aspect to the rock. This can be seen in Plate III B. The veining, as a general rule, shows a tendency to follow the schistosity of the hornblende schists with less prominent cross-cutting veinlets. In some instances even where the veins cut across the schistosity of the host rock, a slight foliation parallel to this schistosity is visible within the vein.

The veins contain a very variable amount of basic material; all gradations are present from a vein, light pink in colour and lacking inclusions, through a slightly darker coloured rock in which very shadowy relics of inclusions remain, to a stage in which the vein material is only slightly lighter in colour than the enclosing amphibolites and hornblende-schists, and the included masses are macroscopically identical with the host rocks. In some cases the inclusions become very rich in coarse hornblende at their contacts with the vein material.

The schistosity of the rocks of the Hornblendic Group is very variably developed within this veined tract, but where it is distinguishable the inclusions show little, if any, rotation within the veins. Definite dilational features were not distinguished.

The macroscopic gradation from acid, inclusion-free veins to relatively basic veins with little altered inclusions, can also be traced in thin section, and forms a series of stages showing a progressively greater amounts of incorporation of the hornblende schists.

The most acid type of vein consists essentially of quartz and oligoclase-andesine feldspar (around An_{30}), in almost equal proportions. The absence of potash feldspar was confirmed using a staining technique (Bailey and Stevens 1960). The veins thus have the composition of a trondhjemite. They are fine grained with rounded or lobate crystals about .3 mm. in diameter; their texture is xenomorphic granular. Within this lie occasional coarser patches of quartz crystals and large feldspar crystals which have a roughly tabular form. The feldspar is generally untwinned and often turbid. Magnetite, epidote and sphene occur in accessory amount with rare irregular clusters of extremely ragged hornblende crystals extensively altered to chlorite. Such veins are sometimes cut across by irregular planes of fracture containing granulated quartzo-feldspathic material and fine chlorite.

In the next stage, where in hand specimen very shadowy inclusions of basic rock are present, the basic patches consist of hornblende and plagioclase with some quartz. Quartz is typically absent from the host rocks. The texture of the inclusions is very similar to that of the veins, the main distinction between the two being the amount and habit of the hornblende present. Within the inclusions the hornblende occurs in the small compact crystals typical of the hornblende-schists, whereas the hornblende of the veins occurs in extremely ragged and often skeletal crystals, sometimes as a number of isolated optically continuous fragments. At this stage epidote is relatively common in the vein material whilst sphene is relatively abundant in the inclusions.

In the third stage the basic inclusions are more definite in form and richer in hornblende, while the vein material, although retaining its quartzo-feldspathic nature and xenomorphic granular texture, contains a higher proportion of ferro-magnesian minerals. At this stage augite makes its first appearance, occurring in stringers through the veins and increasing in abundance towards the vein margins. The augite is very pale green in colour, and occurs in small rounded granules with occasional larger poikilitic crystals enclosing small feldspar crystals. Hornblende and augite are sometimes intergrown with coincident c-axes; rarely augite is found with a core of hornblende. Small crystals of augite are also found throughout the hornblende-rich basic inclusions, the feldspar in their vicinity being more turbid than that in the rest of the inclusion. In other cases augite crystals form stringers cutting across inclusions.

Augite crystals are also found within the surrounding host rocks in isolated centres of crystallisation. The textures of vein material and inclusions are again very similar.

In the final stage the vein material contains quite a high proportion of ferromagnesian minerals, while the composition of the inclusions is very similar to that of the host rocks, many being very hornblende-rich and lacking augite. The vein carries a variable proportion of hornblende and augite, with interrelations as described above. Augite is relatively abundant. As the hornblende approaches the augite with which it is intergrown, the pleochroism of the former becomes very patchy. The feldspar in such veins is very turbid, and often encloses small crystals of epidote. Throughout this series the composition of the feldspar remains unaltered, being still andesine-oligoclase in the most basic veins examined.

In the narrow relatively inclusion-free veins which have sharp margins, similar mineralogy and textures are found; hornblende is virtually absent. Scattered clots of augite, apparent in the field as small pinkish spots, are present in the enclosing rocks at some distance from the veins although the latter have sharply defined margins (see Pl III A). It is these clots which give the pseudo-porphyritic appearance described above (p. 89).

CHEMICAL CONSIDERATIONS

Chemical analyses were made of four amphibolites and hornblende-schists (1CA, 3CA, 4CA, 9CA) from the Basic Sheet Group. One of the hornblende-schists included in this group was taken from an inclusion within the Crathie Granite Complex at the western extremity of the Geallaig area, but is included here as it does not differ significantly from the other hornblende-schist analyses.

1CA Feldsparphyric amphibolite. This rock consists of large feldspar crystals, zoned from bytownite to andesine, set in a fine grained matrix of hornblende with some feldspar. There is accessory magnetite.

3CA Amphibolite. This is a fine grained, equigranular mosaic of anhedral feldspar and hornblende, with occasional remnant feldspar laths. There is accessory biotite and magnetite.

9CA Hornblende-Schist. A hornblende-rich rock containing subsidiary feldspar which is extensively altered, there being very occasional small fresh feldspar crystals. There is accessory magnetite, pyrite and prehnite.

4CA Hornblende-Schist. This rock is composed of hornblende, of somewhat poikiloblastic habit, and oligoclase feldspar. There are occasional feldspar-rich patches. Accessory magnetite and biotite are present.

Chemical analyses of the amphibolites and hornblende-schists with comparisons are given in Table XII, whilst their norms and modal analyses of the constituent minerals, are given in Table XIII.

TABLE XII

CHEMICAL ANALYSES OF EPIDIORITES AND HORNBLENDE SCHISTS, AND COMPARATIVE ANALYSES FROM OTHER SOURCES

Specimen No.	3CA	9CA	4CA	A	B	1CA	C
SiO_2	49.4	48.8	48.6	48.3	48.5	48.1	47.5
TiO_2	1.2	2.2	2.0	2.1	1.3	0.67	0.93
Al_2O_3	16.1	13.7	15.1	16.3	15.2	22.6	21.5
Fe_2O_3	1.7	2.0	1.7	0.8	3.2	1.3	1.7
FeO	9.1	10.4	10.2	9.3	8.9	5.4	4.8
MnO	0.16	0.20	0.20	0.29	0.21	0.11	0.15
MgO	7.5	7.4	7.5	6.5	8.1	6.2	4.6
CaO	10.4	9.4	10.1	10.6	9.4	12.3	13.2
Na_2O	2.4	2.5	2.8	2.9	2.7	2.4	2.2
K_2O	0.44	0.98	0.46	1.1	0.98	0.25	0.42
P_2O_5	0.56	0.18	0.17	0.34	0.25	0.034	0.43
H_2O	1.3	1.4	1.1	1.0	1.4	0.95	2.5
Total	99.8	99.2	99.9	99.5	100.1	100.3	99.9

Localities:

3CA Epidiorite. 380 yards N 65°W of Dalbagie farm, N bank of Dee, west of Ballater.

9CA Hornblende-schist. 2 ft. west of granite contact, 930 yards N 62° W of Culsh farm, west Glen Gairn.

4CA Hornblende-schist. 500 yards N 77° E of Ardoch farm, north of Crathie.

A Olivine-dolerite, Permian, Ayshire (Guppy and Thomas, 1931, p.67)

B Average olivine-diabase, (Daly, 1933, p.18).

1CA Feldsparphyric epidiorite. 675 yards W of Proney farm, west Glen Gairn.

C Porphyritic Centra Magma-type lava. (Bailey, Richey and Thomas, 1924 p.24)

Specimen 3CA is a typical member of the basic sheets of the Geallaig district. It is characterised by a high content of alumina, which reflects the fairly high proportion of feldspar present (32 per cent). The norm shows a higher proportion of anorthitic feldspar than do the norms for the other hornblende-schists. This is the result of the presence of remnant feldspar laths of more calcic composition than the metamorphic feldspar. Although the norm shows five per cent of olivine, this mineral does not appear in the mode; the abundance of amphibole in the rock is sufficient to explain this discrepancy between modal and normative composition, the amphibole taking the place of pyroxene + olivine.

The analysis of specimen 9CA differs little from that of specimen 3CA, although 9CA was collected from an exposure only two feet from the margin of the Ballater Granite. Its analysis shows less alumina than that of the analysis of 3CA and this probably reflects the fact that practically all the feldspar of 9CA has been altered to a fine micaceous product.

The analysis of 4CA does not differ significantly in any major constituent from either of the above two analyses; it falls between the analyses with regard to every determined oxide with the solitary exception of soda in which it is slightly richer than 3CA and 9CA. This specimen was taken from an inclusion in granodiorite near Crathie, and the signfi-cance of this lack of change in chemical composition will be discussed when the Crathie Granite Complex is dealt with. In this context it is regarded as part of a normal basic sheet.

The analyses of the above three specimens closely resemble an analysis of a Permian olivine-dolerite (A in Table XII) exposed one mile to the south of Patna, Ayrshire (Guppy and Thomas, 1931 p.67), and closely approximate to the analysis (B in Table XII) quoted by Daly (1933, p.18) for an average olivine-diabase. Thus it is clear that this group of basic sheets have the general chemical composition of typical olivine-dolerites.

The analysis of specimen 1CA differs from those of 3CA, 4CA and 9CA in that it is much richer in alumina (22 per cent) and slightly richer in lime. The modal analysis indicates that this difference is directly due to the higher proportion of calcic plagioclase which 1CA contains. This excess plagioclase is present as the patches which characterise this rock. The analysis is closely similar to that taken as typical of the highly porphyritic pillow lavas of the Porphyritic Central Magma-type of Mull (Bailey, Richey and Thomas, 1924, p.24) their specimen being taken from the south of the cairn, Cruach Choireadail, Mull (C in Table XII). 1CA also approaches identity to various members of this magma-type which have the general mineralogical composition of olivine-gabbro (Bailey, Richey and Thomas, op cit., and Richey and Thomas, 1930 p.85). Once again a considerable amount of olivine appears in the norm (6.4 per cent) but this mineral is again absent in the mode, probably being represented, along with normative pyroxene, by amphibole.

This analysis is thus consonant with derivation from an olivine-dolerite magma, as were the non-feldsparphyric basic sheets, and differs from them only in the possession of a high proportion of plagioclase phenocrysts.

TABLE XIII

A. C.I.P.W. NORMS OF CHEMICALLY ANALYSED EPIDIORITES AND HORNBLENDE SCHISTS

Specimen No.	1CA	3CA	9CA	4CA
Quartz	-	-	-	--
Orthoclase	1.7	2.8	5.6	2.8
Albite	20.4	20.4	21.0	23.6
Anorthite	50.0	31.7	23.3	27.2
Corundum	-	-	-	-
Diopside (Ca	4.6	8.4	9.4	9.2
Diopside (Mg	2.9	4.7	5.2	5.0
Diopside (Fe	1.5	3.3	3.8	3.8
Hypersthene (Mg	3.0	10.1	10.1	5.9
Hypersthene (Fe	1.6	7.3	7.4	4.6
Olivine (Mg	6.9	2.8	2.4	5.5
Olivine (Fe	3.9	2.2	2.0	4.7
Magnetite	1.9	2.6	3.0	2.6
Ilmenite	1.2	2.3	4.3	3.8
Apatite	-	-	0.3	0.3
H_2O	0.9	1.3	1.4	1.1
Total	100.5	99.8	99.1	100.0

B. MODAL ANALYSES OF EPIDIORITES AND HORNBLENDE SCHISTS

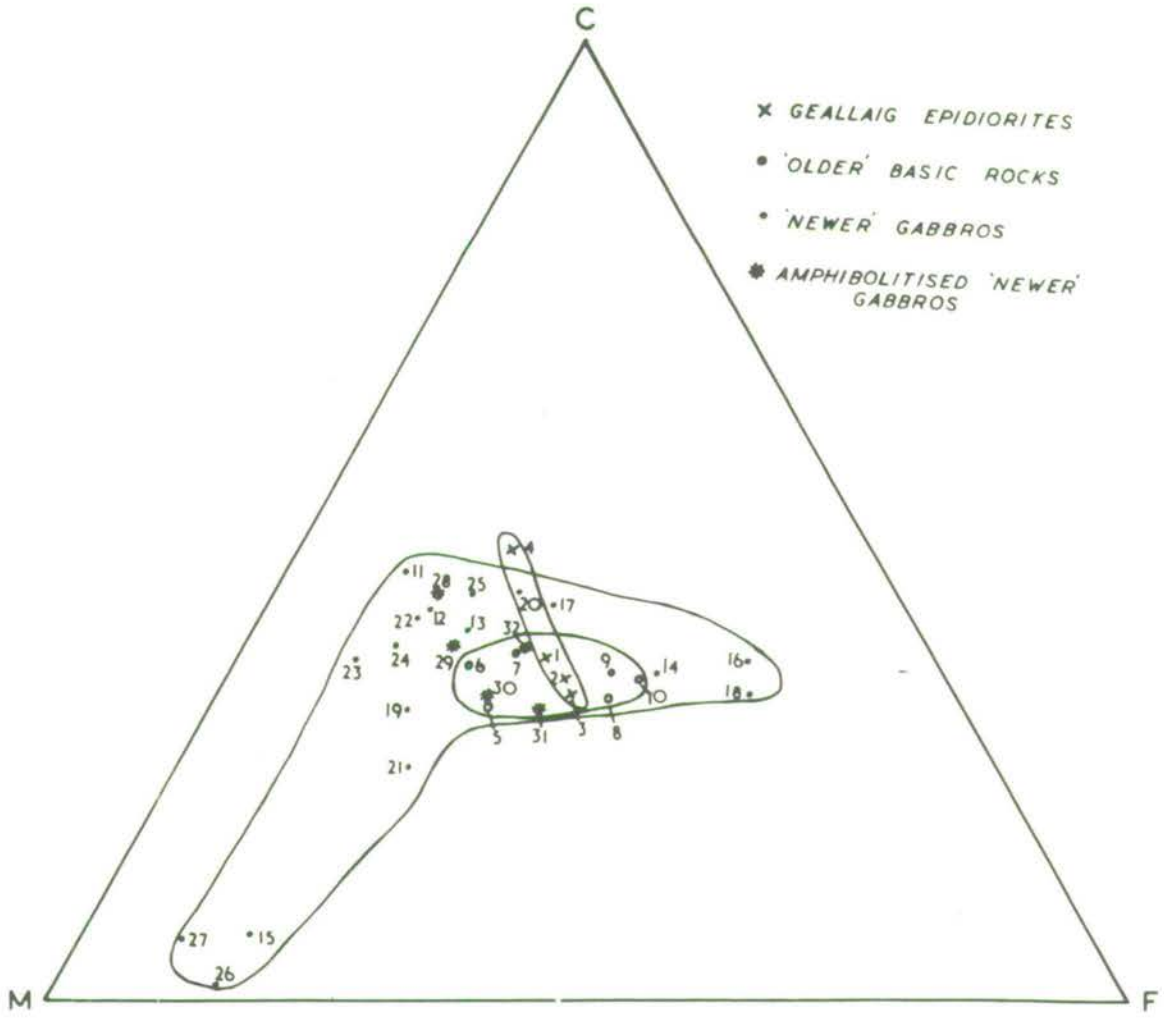
Specimen No.	1CA	3CA	9CA	4CA
Feldspar	60	32	25	32
Amphibole	39	64	70	64
Biotite	-	2	-	2
Others	1	2	5	2

Number of Points Counted - 1500 - 2000

The analyses of the basic sheets were plotted on a C-M-F triangular diagram (where C = CaO, M = MgO, F = FeO + Fe_2O_3 + MnO). On this diagram were also plotted C-M-F ratios calculated from all available chemical analyses of basic rocks from the Newer Gabbros of N. E. Scotland, and from analyses of Older Basic rocks from central and N. E. Scotland. The results obtained are shown in Figure 11, whilst the sources of the analyses are given in Table XIV.

It can be seen that the ratios obtained from both Older and Newer Gabbros plot in scattered groups which lie around the analyses of the basic sheets from the Geallaig district. A single exception is provided by the feldsparphyric amphibolite which falls slightly outside both Older and Newer groups, owing to its unusually high proportion of feldspar.

This conformity of chemical relationships shown by the Older and Newer basic rocks of N. E. Scotland including the basic sheets of the Geallaig district made it highly unlikely that chemical analyses of representatives of the Hornblendic Group would in any way clarify the problem as to whether the latter represent members of the Newer Gabbro suite which have been metamorphosed and sheared as a result of granite intrusion, or by late stage movements, or the hypothesis that they are representatives of the Older Basic suite of hypabyssal rocks which occur throughout the Dalradian metasediments. This problem will be considered when the origin



C-M-F diagram of basic rocks from northeast Scotland, where C = CaO, M = MgO, F = FeO + Fe_2O_3 + MnO

(For sources of analyses used, see Table XIV)

Fig. 11

TABLE XIV

SOURCES OF ANALYSES USED IN FIG. 11

1. Epidiorite 3CA (Table XI).
2. Hornblende schist 9CA (Table XI).
3. Hornblende schist 4CA (Table XI).
4. Feldsparphyric epidiorite 1CA (Table XI).
5. Epidiorite (Read 1923(b), p.93).
6. Amphibole schist (Farquhar 1953, p.400).
7. Epidiorite (Pantin 1955, p.91, spec.454).
8. Epidiorite (Pantin 1955, p.91, spec.366).
9. Epidiorite (Pantin 1955, p.91, spec.466).
10. Epidiorite (Pantin 1955, p.91, spec.445).
11. Troctolite (Read 1923(b),p.115, No.II).
12. Olivine gabbro (Read 1923(b), p.115, No.III).
13. Norite (Read 1923(b),p.115, No.IV).
14. Norite (Read 1923(b),p.115, No.V).
15. Picrite (Read 1923(b),p.115, No.I).
16. Olivine norite (Read 1923(b),p.124, No.I).
17. Hypersthene gabbro (Read 1923(b),p.124,No.II).
18. Olivine norite (Read 1923(b),p.127).
19. Olivine gabbro (Read 1935,p.601).
20. Quartz gabbro (Read 1935, p.603).
21. Norite (Read 1923(a), p.457).
22. Troctolite (Stewart 1946, p.474, No.D).
23. Pyroxenite (Stewart 1946, p.474, No.C).
24. Hypersthene gabbro (Stewart 1946, p.474, No.E).
25. Olivine gabbro (Stewart 1946, p.474, No.F).
26. Dunite serpentinite (Stewart 1946, p.474, No.A).
27. Augite peridotite (Stewart 1946, p.474, No.B).
28. End stage rocks (Stewart 1946, p.480, No.B).
29. End stage rocks (Stewart 1946, p.480, No.C).
30. End stage rocks (Stewart 1946, p.480, No.D).
31. End stage rocks (Stewart 1946, p.480, No.E).
32. Modified quartz-gabbro (Read 1935, p.606).

of the basic rocks is further discussed. It may however be significant that those representatives of the Newer Gabbros which are noticeably amphibolised tend to approach more closely to the composition of the Older Basic Rocks and of the basic sheets of the Geallaig District than do the majority of the non-amphibolised examples.

DISCUSSION

BASIC SHEETS

From the present mineralogy of the basic sheets, and from their chemical composition, it may be deduced that they have the general composition of a dolerite in which there is a low proportion of free olivine. The rocks have undergone practically complete mineralogical reconstitution, and in the majority of cases have been subjected to severe stress, with the development of a well defined plane of schistosity.

The feldsparphyric patches present in some of the sheets are considered to represent original phenocrysts. The other possible interpretation, namely that of metamorphosed amygdales, is less probable. In some cases the patches attain a roughly tabular form, whilst, where the patches have not been sheared, they generally consist of one single crystal. In the metamorphism of amygdales there is a high probability that an aggregate of feldspar crystals will be produced.

These rocks have the form of thin sheets concordant with the metasediments within which they are intercalated, and may thus represent

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either original sills or lava flows. In rocks which have undergone a high degree of metamorphism it is often difficult to distinguish between lavas and sills. Possible contact metamorphic effects, if present, have been obscured. Evidence which would definitely point to an extrusive origin, such as pipe vesicles, definite amygdales, or irregular tops have not been discerned. Thus, while the possibility that these sheets represent metamorphosed lava flows cannot be discounted, there is no definite evidence in favour of this hypothesis. Extrusive rocks are very rarely found in the Dalradian of Scotland apart from those in Argyllshire, while basic sills are abundant everywhere. The probability exists therefore, that the basic sheets of the Geallaig district were originally in the form of doleritic sills, which have shared in the Caledonian metamorphism and now take the form of hornblende-schists. They are taken to be representatives of the Older Basic Suite of sills found throughout the Scottish Dalradian and described by Wiseman (1934).

ABERGAIRN AMPHIBOLITES

We must now consider the criteria by which the amphibolites of the Abergairn Group have been divided into two groups — one belonging to the Basic Sheet Group and of metadoleritic origin, and the other being of calc-silicate metasedimentary origin.

There has been considerable discussion in recent years concerning possible distinctions between para- and ortho-amphibolites (see Engel and Engel 1951, Lapadu-Hargues 1953, Poldervaart 1953, Wilcox and Poldervaart

1958, Evans and Leake 1960). In many cases it has proved virtually impossible to differentiate the two types, in fact Yoder (in Wilcox and Poldervaart op.cit. p.1324) has stated that in his opinion "under equilibrium conditions ortho- and para-amphibolites would be indistinguishable if held at the same pressure and temperature." Lapadu-Hargues (op.cit.) argued that para- and ortho-amphibolites could be separated on the basis of their Ca, Mg and Fe content. Wilcox and Poldervaart (op.cit.) on the basis of both bulk chemical analyses, and trace element analyses, from undoubted para- and ortho-amphibolites from the Roan-Antelope area of N. Carolina, criticize and disagree with his conclusions. Engel and Engel (1951) suggested that para- and ortho-amphibolites could be separated on the basis of their Ni, Co and Cr content. However Wilcox and Poldervaart (op. cit) do not consider their criteria to be valid.

Thus a genetic distinction between such amphibolites cannot be made on chemical grounds at the present state of knowledge. In most reported cases these types are distinguished on the basis of field and textural criteria. The most widely used of these have been:-

1) the fine interlayering of para-amphibolite with metasediment, especially that of undoubted calcareous origin.

2) the presence of textures considered to be characteristic of either type, e.g. sub-ophitic textures in metadoleritic types, or the distinctive 'feather' amphiboles of para-amphibolites as described by Adams and Barlow (1910).

3) the generally homogeneous nature of ortho-amphibolites, whereas mineral proportions often vary considerably in para-amphibolites.

In this study the majority of the criteria used are based on, on one hand, the similarity between the postulated ortho-amphibolites and the basic sheets of the Coilacriech and Candacraig Groups, and on the other hand, between the para-amphibolites and the undoubted calc-silicate rocks of the Abergairn Group. The criteria used are listed below:-

Para-amphibolites	Ortho-amphibolites
a) constituent amphiboles are	a) constituent amphiboles are
(1) pale in colour	(1) deep green to blue-green in colour
(2) have $2V_z$ from 70°-90°	(2) have $2V_z$ from 90° - 113°
(3) occur in sheaf-like poikiloblastic crystals with radiating extinction.	(3) occur in relatively small and compact crystals.
b) found in close association with pyroxene-bearing rocks as lenses within, and carrying nodules of, pyroxene-feldspar calc-silicate rock.	b) lack of inclusions of, or noticeably close association with, pyroxene bearing rocks.
c) resemblance of constituent amphiboles to those of undoubted calc-silicate rocks.	c) resemblance of constituent amphiboles to those of the basic sheets.
d) contain a lower proportion of feldspar typically, which is often highly turbid.	d) contain a higher proportion of freshly crystalline feldspar.
e) show a very variable grain size and textures within individual specimens.	e) have relatively constant grain size and textures.

Although these distinctions have served to place the majority of the amphibole-bearing rocks into either the calc-silicate or metadoleritic groups there remain a small number of specimens of intermediate type which are of indeterminate origin. It is possible that these may, at least in part, represent intermediate varieties found at the junction between meta-dolerite and calc-silicate rock, as a result of some slight interchange of

material. Such a phenomenon has been described by Turner (1939) from the junction of hornblende-gneiss and marble at Doubtful Sound, New Zealand. However, the exposures within the Abergairn Group were not sufficiently good for this point to be investigated in detail.

The amphibolites of the Abergairn Group were originally divided into ortho- and para-amphibolites on the basis of examination under the single axis microscope. Subsequently a number of specimens were investigated on the Universal Stage and the values of their optic axial angles determined. The results obtained are shown graphically on Fig. 12. It can be seen that all those rocks which had been interpreted as of calc-silicate origin have amphiboles of which the $2V_z$ is less than 90°. Conversely, with one exception, the amphiboles from those rocks which had been considered to be of igneous origin have a $2V_z$ greater than 90°. It may thus prove possible, at least within the Geallaig district, to use this distinction in order to clarify the origin of amphibolites of uncertain origin. Following from this it is suggested that specimens 19Mb and 10M (see Fig. 12) may be of calc-silicate origin, whereas 24D may be of igneous origin. This is consonant with the well known correlation in calciferous amphiboles between higher 2V and Mg rich hornblendes (Winchell and Winchell, 1951, p.434).

It is of interest to note that in the actinolitic rocks of the Garron Point Group of the Banffshire coast section, described by Read (1923b) as of definite sedimentary origin, the amphibole builds radiating sheaves of practically colourless actinolite similar to those of the calc-silicate

Fig. 12

Grouping based on petrographic characteristics

Measurement of 2V from amphiboles in both metasediments and metadolerites.

rocks of the Abergairn Group. In the Garron Point Group the amphibole often makes up over 80 per cent of the rock, as it does in the Abergairn Group (Pl XIIIA). Read does not quote measurements of optic axial angles from these amphiboles.

HORNBLENDIC GROUP

Although the rocks of this group have been extensively amphibolised, they show a number of features (see p.70) which distinguish them from the basic sheets discussed above. Of these one of the most interesting is the presence of small scale banding.

The occurrence of banded basic rocks is widely known from many geological periods and many parts of the world (see for example Hess 1938 Wager and Deer 1939). In a general consideration of the nature of small scale rhythmic banding in basic rocks Hess (op.cit.) tabulates the following general characteristic features of such banding.

1) the thickness varies from a fraction of an inch to several feet.

2) the bands are traceable along strike for more than 100 times their thickness.

3) contacts between bands may be sharp or gradational, and crystals interlock across the boundaries.

4) the bands never cross each other, as dykes, although they commonly lense out along strike, or may divide to form two or more individual bands.

5) the minerals retain the same composition across a series of bands regardless of mineral proportion.

The minor-scale banding of the Hornblendic Group displays all the above features, with the exception, in some instances, of the constancy of composition of the amphibole from band to band, a feature easily disturbed during metamorphism. Over most of the area the mineral composition is constant, the occurrence of the cummingtonitic amphibole being limited.

Hornblende-cummingtonite intergrowths similar to those of the Hornblendic Group have been reported by Eskola (1950), Vernon (1962) and Asklund, Brown and Smith (1962). Eskola did not consider cummingtonite to be one of the normal products of metamorphism of basic rocks, and invoked the incoming of iron and magnesia to produce this mineral. Vernon however is of the opinion that the hornblende-cummingtonite association is an equilibrium assemblage, as are Asklund, Brown and Smith who consider that such intergrowths are the normal product of the metamorphism of some gabbroic rocks. They suggest that the coarse intergrowths are primary, while the fine lamellar intergrowths are the result of unmixing. They also suggest that the cummingtonitic areas may represent relics of hypersthene or olivine, while the hornblende-rich areas represent the former presence of augite-like pyroxene.

Cummingtonite has been reported from the northern end of the Morven-Cabrach mass by Henry (1938). However here it seems to form an intermediate stage between orthopyroxene and green hornblende. A similar occurrence has also been reported by Stewart (1946) from the Belhelvie mass.

The cummingtonite of the Geallaig area however seems to be an equilibrium assemblage similar to that of Vernon (op.cit.) and Asklund et al. (op.cit.).

Other typical features of banded basic rocks such as the planar distribution of tabular feldspar crystals, and the presence of 'graded' bands, (if originally present) might well have been obscured by the alteration.

The banding of the rocks of the Hornblendic Group is orientated approximately parallel to the margins of the mass, which also roughly parallels the strike of the metasediments to the west of the mass, as it has a roughly sill-like form. The banding is however very steeply inclined, and folded, as described above (p.22), where it was concluded that the fold set is differently orientated, and probably later, than that affecting the Dalradian metasediments.

The banding of the Hornblendic Group thus does not exhibit any features which are significantly different from that of normal banded basic rocks.

Within a few tens of miles of the Geallaig area banded basic rocks have been reported and described from Belhelvie (Stewart 1946). Huntly (Watt 1914, Shackleton 1948) and Insch (Read 1923 b, Sadashiviah 1954, Read, Sadashiviah and Haq 1961). These masses, which form a well marked

suite of pre-middle O.R.S. age, show local amphibolisation and the suggestion has been put forward (Read 1935, Stewart and Johnson 1960) that some of the more extensively amphibolised basic masses of N.E. Scotland may belong to the same petrographic suite as the banded and less amphibolised rocks.

The wedge of banded and extensively altered basic rocks under discussion lies immediately to the south of the basic rocks of the Morven mass. Henry (1938) has shown that the northern part of the Morven mass is relatively little amphibolised and shows close resemblances to the pre-middle O.R.S. "Newer Gabbros" of Aberdeenshire and Banffshire. Towards the south of the Morven mass however he states that the rocks become very extensively amphibolised.

The banded rocks of the Hornblendic Group are separated from the main exposures of the Morven mass by a tract virtually devoid of exposures. No transition can thus be directly traced between the two, but if the known southerly increase in amphibolisation in the Morven mass were continued, one would expect its southern extremity to consist largely of rocks of epidioritic composition. Such an extremity might well be represented by the southerly attenuating wedge of the rocks of the Hornblendic Group. The hypothesis that the Hornblendic Group represents the southern end of the Morven mass is thus supported by its general mineralogical composition and geographical position.

To consider whether these basic rocks may belong to the Newer Gabbro suite, the banding typical of masses belonging to that suite, may be

compared with that of the Hornblendic Group. The only detailed descriptions of the banding of the Newer Gabbros are given by Stewart (1946) in his description of the Belhelvie mass, Shackleton (1948) from Huntly and Sadashivaiah (1954) from the Insch mass. In every case the banded rocks form only a part of the total mass of gabbroic rocks. Taking the Belhelvie occurrence as fairly typical, Stewart (op.cit.) reports that the bands consist of variations in the proportions of light and dark minerals; the thickness of the bands varies from a fraction of an inch to many feet; the finer bands show greater variation in composition; the margins of the bands vary from sharp to gradational. Thus there appears to be a general similarity between the banding of the Newer Gabbros and that of the Hornblendic Group.

Although the banded gabbros of Belhelvie are relatively unaltered, a fair proportion of the rest of the mass exhibits complete amphibolisation, and the same is true of the Insch mass (Read 1951) and the Haddo House mass which Read (1935) reports as in part resembling an epidiorite. Uralitisation is also present in the Huntly mass (Watt 1914). Some of these altered rocks in both Belhelvie (Stewart 1946) and Insch (Read 1951) show pronounced schistosity. Based on this degree of alteration, and on the high angle of inclination of the banding at Belhelvie, Stewart (1946) and Stewart and Johnson (1960) are of the opinion that the Newer Gabbros have been involved in a folding phase.

It is thus possible that, as a fair proportion of the Newer Gabbro suite is considerably altered and sheared, and has possibly been involved

in a fold movement, there may be some metadoleritic rocks which, previously considered to be Older Basic rocks, may in fact be representatives of the Newer Gabbro suite. It is suggested that the Hornblendic Group of the Geallaig District may be such a mass, forming the southward continuation of the Morven mass. The features supporting such a hypothesis are:

1) its geographical position as a southward extension of the Morven mass, which has previously (Henry 1938) been attributed to the Newer Gabbros, and which is known to become much amphibolised towards its southern end.

2) the presence of small scale banding typical of basic igneous masses. Such banding is extremely rare in the sill-like masses of the Older Basic suite, but is relatively common in the Newer Gabbros.

3) the presence in parts of the Hornblendic Group of well preserved remnant pyroxene and ophitic textures.

It was stated as early as 1935 by Read that the recognition of epidioritic types definitely belonging to the Newer Gabbros may have considerable importance, and in the same paper (p.604) he mentions the Morven association of epidiorites and gabbros and suggested that this mass might have a possible association with the Newer Gabbros. The work of Henry (1938) describing the unaltered nature of the northern end of that mass supported Read's suggestion, and the work of this present study, although including only a very small part of the Morven mass, is also in accord with the above theory.

Two alternative hypotheses may be advanced for the origin of the rocks of the Hornblendic Group, namely that the banded rocks represent either an originally homogeneous sill, in which the banding has developed as the result of metamorphic differentiation, or that the bands have been produced by the metamorphism of a pile of lavas with intercalated tuffaceous bands.

Metamorphic differentiation does not appear a probable mode of origin for these rocks. There is no definite evidence in favour of such a hypothesis, whilst the banding does not show the characteristic structures of gneisses. There is also a lack of significant variation in the mineralogical composition of the constituent minerals of the individual bands.

Direct evidence that these rocks originated as a pile of lavas and tuffs is also lacking. There is no suggestion of clastic material, or of a fragmentary origin for any of the bands, while phenocrysts amygdales and other typical features of lava flows were not identified. The scale of thickness of the bands, and their low degree of variation in composition, also makes such an origin unlikely.

From all the data available in the present study, the conclusion is reached that the basic sheets of the Geallaig area are the altered representatives of sills or less probably lava flows intruded into the Dalradian metasediments prior to the Caledonian metamorphism. The rocks of the

Hornblendic Group are however considered to constitute the southern extremity of the Morven gabbro mass, which, it is tentatively suggested, may form part of the Newer Gabbro suite of N. E. Scotland. This mass has been involved in a period of alteration and folding.

TRONDHJEMITIC VEINS

Many of the characteristic features of the trondhjemitic veins indicate some degree of replacement, rather than a purely intrusive and dilational origin for these veins. Such features are:

1) the gradational nature of the vein composition
2) the partial assimilation of the included hornblendic masses
3) the irregular shape of many of the veins, and their gradational margins
4) the formation of clots of vein material within the hornblendic rocks close to the veins.

The above data indicate that the vein components were chemically active and easily diffusible when introduced; they may have had a fairly high volatile content.

The orientation of the veins in a plane generally tending to follow the schistosity of the enclosing rocks, and the slight lineation formed within the veins, suggests that they may have been introduced during the stress period which resulted in the formation of the schistosity. The texture of the veins and the enclosing rocks are very similar, which would also indicate that they had been recrystallised simultaneously.

As these trondhjemitic veins are found only within the rocks of the Hornblendic Group, it is possible that they are genetically related to the enclosing rocks. The quartz-oligoclase composition of the veins is a possible late stage differentiate of a gabbroic magma. This is suggested by Vogt (1931, p.222) where he states that an acid differentiate from gabbroic magma yields oligoclase bearing rocks as the early product of crystallisation. It is suggested that the present veining is such a differentiate which may have been intruded during, and shared in, the shearing which the mass has undergone.

ACID IGNEOUS ROCKS

INTRODUCTION

The Geallaig district lies approximately in the centre of the E-W trending belt of Younger Granites which extends for about 60 miles from Aberdeen in the east, almost to Strathspey in the west. This belt consists of a number of large bodies of granite, fringed in many places by subsidiary intermediate masses. The part of the belt in the immediate vicinity of the Geallaig district is shown in Fig. 3. No work has attempted to deal with this belt as a whole, and very little work, apart from that of the Geological Survey, has been done on individual masses.

Bisset (1932) however studied the granitic rocks of the Skene Complex which forms the eastern end of the Hill of Fare mass (as designated by Anderson 1939, p.27), and lies approximately 30 miles east of the Geallaig district. He subdivided the Skene Complex into two main units, an "Earlier Caledonian" group incorporating "acid and basic dykes, transition granites, grey granites, porphyritic granite and a dioritic series" and a "Later Caledonian" group consisting of "red granite" and "granite porphyry."

A detailed investigation of that part of the Younger Granite belt included within the Geallaig district, indicates that these acid igneous rocks may be subdivided into two groups in a similar way to that suggested by Bisset for the Skene Complex. In the Geallaig district the earlier group consists of variable grey granodiorites, tonalites, monzonites and diorites associated with white adamellites and cut by a suite of intermediate dykes; this has been termed the Crathie Granite Complex. The later

group, consisting of red granites and quartz porphyry dykes, has been termed the Ballater Granite. These two groups are thus similar in composition to those of Bisset. Their geographical distribution is shown in Fig. 31 (end pocket).

The subdivision of the Younger Granites into these two groups has been made on the basis of several criteria:-

The Crathie Granite Complex is confined to the western half of the Geallaig District in the environs of Crathie and Gairnshiel; it continues westward outwith the area considered here. The complex is characterised by an extremely variable composition both mineralogically and texturally, the average composition of the group being considerably more basic than that of the Ballater Granite. It contains numerous inclusions of varying rock types, and these show intricate and complex junction relationships with the igneous rocks.

Barrow and Craig (1912) in their description of the Younger Granites of the Geallaig district, describe the dioritic rocks in the region of Crathie and differentiate them from the granites of the area. However they do not distinguish between the more acid portions of the Crathie Granite Complex and the main Ballater Granite, although the two are of quite different character and are treated separately in the present account. Barrow and Craig also attempt to delineate boundaries between granitic and dioritic rocks in the Crathie region on their one inch to one mile map (Geol. Surv. Sheet 65). However the various members of the

Crathie Granite Complex are so intimately associated, and have such intricate and gradational contacts, that it proved quite impracticable to separate them on a six inch to one mile map.

The Ballater Granite, by contrast, is characterised by a very uniform composition and texture throughout, and by a high proportion of modal quartz. It is conspicuously lacking in inclusions of any sort, and has sharply discordant contacts with the country rocks which it veins sparsely and for very short distances from the contact.

The Ballater Granite is found to the east of the Gairn river, where it forms the western end of the Hill of Fare granite mass. This granitic mass continues eastward for 30 miles. The Ballater Granite is also found to the west of the Gairn, and here has been termed the Glen Gairn Granite by Barrow and Craig (1912). They considered this Glen Gairn Granite to be the northerly extension of the Lochnagar Granite but did not connect it with the granite to the east of the Gairn.

CRATHIE GRANITE COMPLEX

INTRODUCTION

The suite of rocks belonging to this subdivision of the "Younger Granites" of the Geallaig district outcrops on a series of low hills on the northern slopes of the Dee Valley to the east and west of Crathie, and northwards on either side of the Crathie-Gairnshiel road to the northern

boundary of the area mapped (see Fig. 31 end pocket). The exposures on these hills are reasonably good, but each group of exposures is separated from the neighbouring groups by valleys of unexposed ground. This made it difficult to interrelate the various regions of exposure, which generally exhibit slightly different ranges of rock type and field relations.

The main areas of outcrop are on Sron Dubh, Creag a' Chlamhainn, Knock of Lawsie, Parliament Knowe and Creag Mhor in the Dee Valley, and broken exposure continues northwards across the Gairn-Dee watershed to the south of the Strone. Outcrops are also found on Cnoc Chalmac in the Gairn Valley and to the south and north of Gairnshiel.

To the east the Crathie Granite Complex is bounded by the Ballater Granite, but the two groups are separated by half a mile of unexposed ground, so that their interrelations could not be ascertained. The Crathie Complex is bounded to the south by the alluvium of the Dee Valley, and to the west and north it extends outwith the limits of the area mapped.

Within the complex the mineralogical composition of the rocks is extremely variable, grading from adamellites, through granodiorites, tonalites, and monzonites to diorites. A classification of the terms used for these rocks is given in Fig. 13. Within the various petrographic types there is also considerable variation in texture and field relations. However, it is possible to make a number of broad generalisations about the rocks of the complex.

ROCK CLASSIFICATION.

LIME PLAG.	GENERALLY OLIGOCLASE OR ANDESINE *except syenogabbro with essential labradorite.					Essential labradorite
Alk felspar proportion of total felspar	> 90%	90 - 60%	60 - 40%	40 - 10%	< 10%	Not essential, always less 10%
Quartz > 10%	Alkali. Calcalkali. Granite Peralkali.		Adamellite	Granodiorite	Tonalite	
Quartz < 10% but no felspathoid.	Alkali Calcalkali Syenite Peralkali		Monzonite		Diorite	Calcalkali Gabbro
			*Syenogabbro			Alkali

Fig. 13

1) Within the Crathie Granite Complex the more acid representatives become predominant towards the east, although there are reversals of this trend on a small scale, and both acid and intermediate varieties are present throughout.

2) The more acidic varieties of the complex are, in general, richer in inclusions of metamorphic material than are the more basic types, and thus the inclusion-rich areas are more abundant towards the east.

3) A moderately strong foliation is commonly developed in the intermediate rocks, but in the acid rocks such a foliation is rudimentary or lacking. There are also abundant exposures of the intermediate rocks in which no foliation is evident.

Although this suite of rocks is varied in mineralogical composition, it has not proved possible to subdivide the various rock types precisely, owing to their intricate and gradational field relationships. However one variety which can be clearly distinguished is a monzonitic type characterised by the presence of abundant clots of hornblende crystals. This is termed the "spotted monzonite" and, as it occurs as included masses within the other rock types of the complex, it is believed to be the oldest member of the suite. The remainder of the suite has been subdivided for the purposes of description into two main groups:-

1) adamellites

2) intermediate rocks, including granodiorites, tonalites, monzonites and diorites.

The members of the Crathie Granite Complex are cut by pink aplitic veins which are probably late stage acidic segregations of endogeneous origin.

SPOTTED MONZONITES

This rock type is distinguished in the field both by its appearance, and by its relations with other rock types. It is largely restricted in occurrence to the region north of Crathie, being especially common on Parliament Knowe and Creag a' Chlamhainn, but is also found occasionally in the Torgalter Burn and further to the north in the region of the Strone. It is absent where porphyritic adamellite is the predominant rock type.

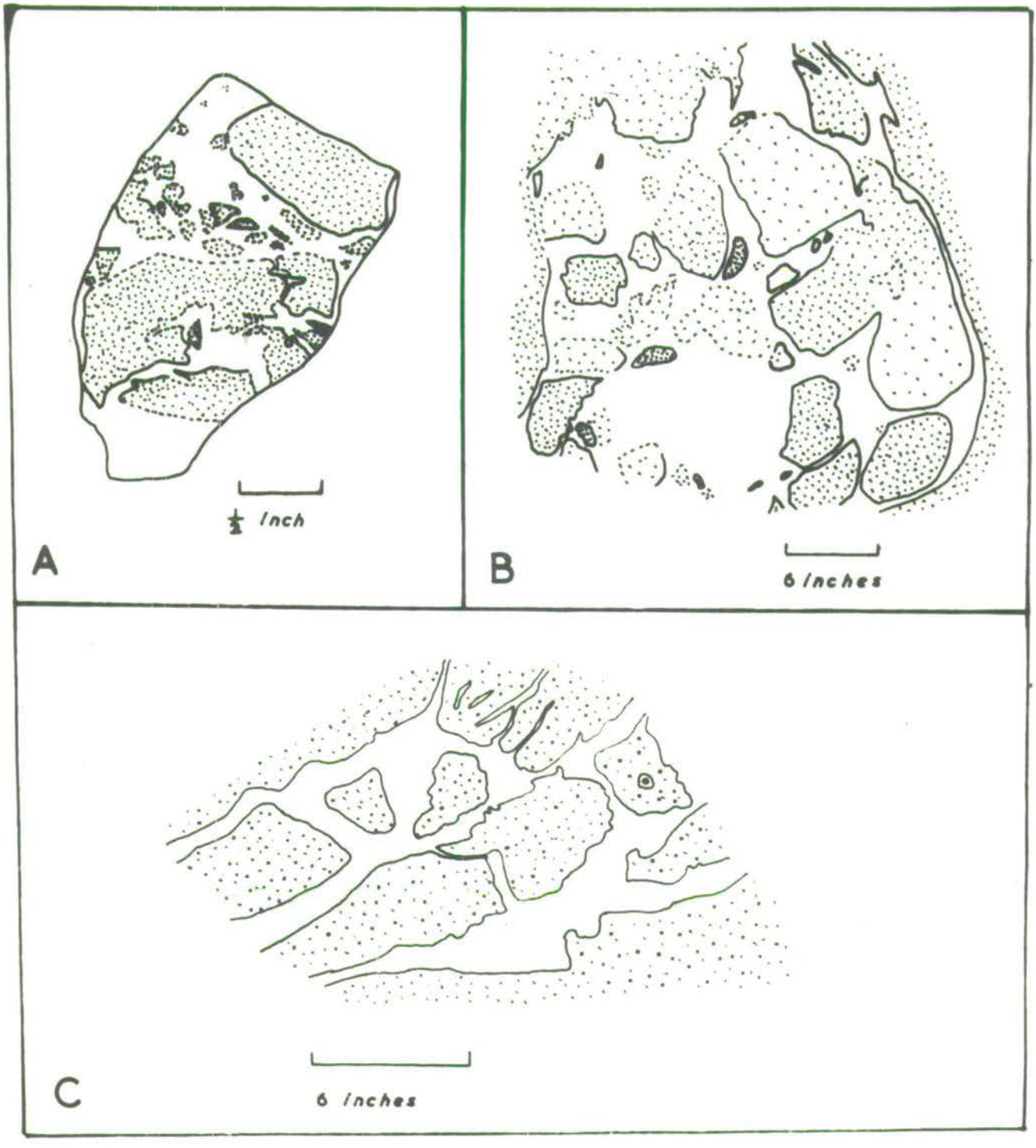
In hand specimen the monzonites are dark grey, compact rocks, lacking foliation and characterised by a spotted appearance resulting from the presence of small clots of hornblende. They occur only as inclusions within other rock types of the Crathie Granite Complex and, although they show a fairly wide variation in modal composition, they are regarded as essentially a single rock type. The modal variation ranges from rare adamellites through granodiorites and tonalites to monzonites (see Table XV). As monzonites form the most abundant petrographic type, the group name "spotted monzonites" has been chosen for convenience of reference.

The rocks containing the spotted monzonite inclusions comprise adamellites granodiorites and tonalites; in every case examined the host

rock was of more acid composition than the inclusions. As the monzonites are unfoliated, it was not possible to determine any differential rotation of adjacent inclusions. However, where the host rocks are foliated the inclusions, if assymetric, show a tendency for their long axes to be oriented approximately within the plane of the foliation.

The inclusions vary in cross-section from three inches by two inches to at least 20 feet by 30 feet. Contact relations with the host rocks are variable. In some cases these are macroscopically sharp, while in others a gradational contact across several inches is seen. In no case was any change in grain size noted in either rock type as the contact was approached. Often the inclusions are marginally broken up into a series of angular fragments by an intricate network of fine granitic veins. These monzonitic fragments vary in length from over a foot down to one-tenth of an inch, many of the smaller ones appearing as shadowy patches within the granitic veins. Sketches of typical examples are given in Fig. 14. These veined zones range up to two feet in width.

The grain size of the spotted monzonites is variable from inclusion to inclusion, and sometimes within one inclusion; the change cannot be related to the present margins of the inclusions and presumably represents an original feature of the rock. Occasionally the inclusions themselves include irregular patches of a rock which has the same texture but is considerably more basic in composition, being a true diorite.



Field sketches of marginal veining of inclusions of spotted monzonite by the surrounding members of the Crathie Granite Complex

Fig. 14

The spotted monzonite grades into this diorite across a few inches, and as the texture and general mineralogy of the diorite closely resemble that of the monzonite, it is regarded as a more basic part of the same group.

Petrography. The spotted monzonites, although variable in modal composition (Table XV) are fairly constant in textural relationships and mineral type. They are composed essentially of plagioclase feldspar, hornblende and biotite with subsidiary quartz and potash feldspar. The rocks are medium grained with a hypidiomorphic granular texture in which lie the rounded hornblendic clots.

The hornblende occurs largely in the rounded clots which give this group its name (Pl XIX A). These are almost monomineralic, about 3 - 5 mm. across, and composed of small compact randomly orientated crystals. Biotite is often incorporated within the margins of the clots and shows a slight tendency to rim them. Sometimes small crystals of biotite are found throughout the clots. The centres of the clots, especially of those composed solely of hornblende, are dusted with minute granules of magnetite. A similar dusting of magnetite within hornblendic clots is reported by Whitten (1957, p.279) from the Gola Granite. In many cases the cores of the hornblende crystals are darker in colour than the margins. This is not a compositional zoning as it does not affect the more fundamental optical properties of the mineral. Hornblende is also found throughout the rock in subhedral to anhedral crystals, often

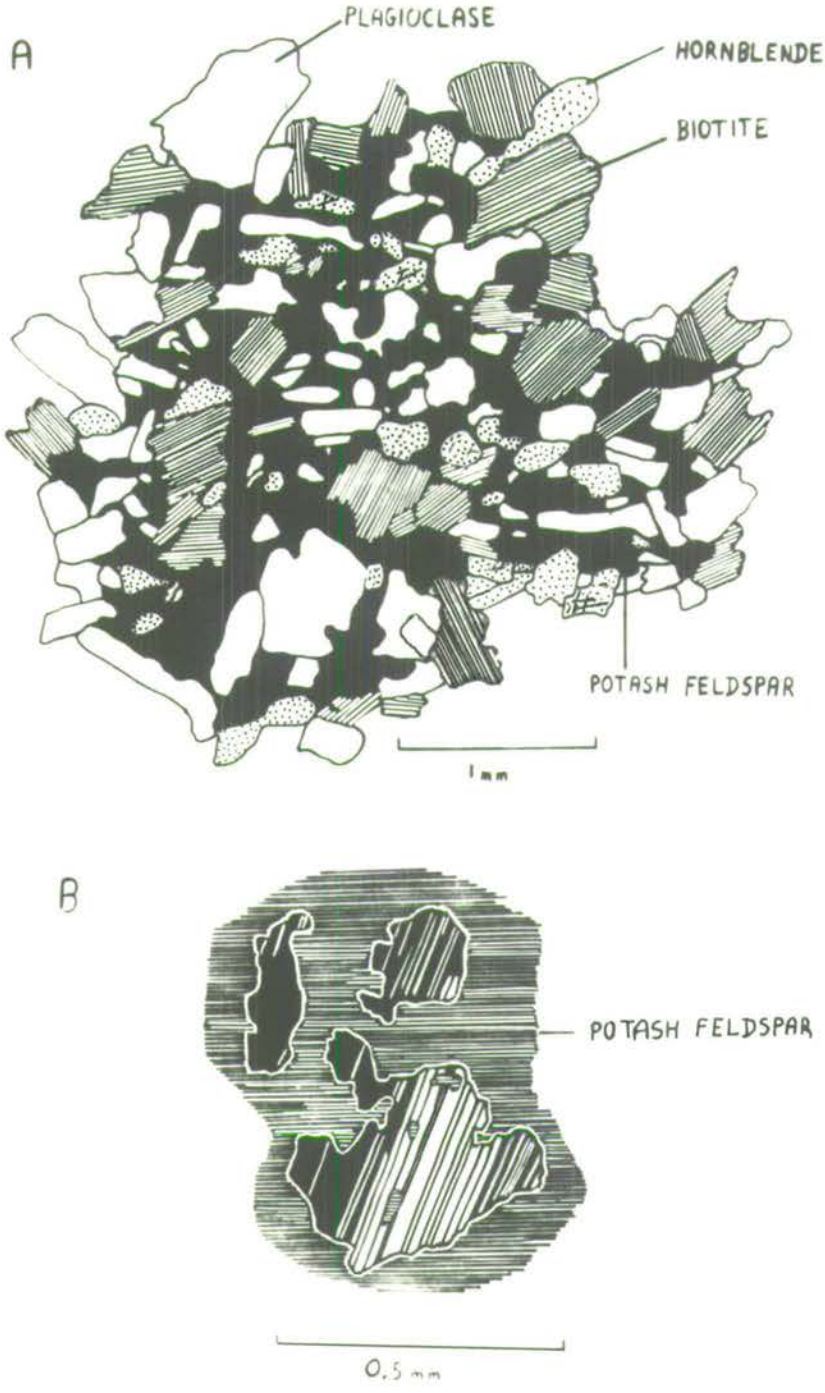
associated with biotite. The pleochroic scheme of this mineral is X-pale green, Y-medium green, Z-medium green.

One example was seen in which a few of the hornblende crystals contained corroded and serrated cores of augite. In some cases the augite and hornblende have coincident c axes. The amphibole is here clearly developed at the expense of the augite.

The biotite occurs in broad flakes, pleochroic from straw yellow to dark brown, and showing some alteration to penninitic chlorite. It often encloses small crystals of hornblende.

Plagioclase in these rocks occurs in small, very turbid, crystals, roughly tabular in habit, but with very irregular margins. The crystals are very slightly zoned and vary in composition from An_{35} to An_{30}.

The potash feldspar occurs characteristically in large optically continuous poikilitic plates which enclose numerous crystals of all the other minerals in the rock (Fig. 15A & Pl XX B). The potash feldspar is present both in the form of microcline, which is predominant, and as orthoclase. Occasionally it is slightly perthitic and is always very fresh in contrast to the highly turbid plagioclase. Although potash feldspar is common throughout the rock, and individual crystals may attain a diameter of 5 mm., the total proportion of this mineral is low as it contains an extremely high proportion of included material.



Camera lucida drawings of poikiloblastic plates of potash feldspar in spotted monzonite

A - a single crystal of potash feldspar showing the embayed nature of the included plagioclase.

B - isolated fragments of plagioclase showing coincident twinning.

Fig. 15

The plagioclase crystals within potash feldspar often have embayed margins, and in some cases several isolated fragments of plagioclase are in optical continuity, with twin lamellae parallel (Fig. 15 B). The plagioclase crystal margins are penetrated by fine interdigitations of potash feldspar, and have a corroded and turbid appearance, while the potash feldspar bordering the plagioclase contains abundant tiny inclusions with a refractive index similar to that of the plagioclase; these may represent remnants of replaced plagioclase. This textural evidence suggests that the potash feldspar replaced, in part, pre-existing plagioclase. The fairly constant ratio of modal plagioclase to potash feldspar in these rocks (see Fig. 16) supports this hypothesis. From the relatively low quartz, relatively high ferromagnesian, and constant total feldspar content, and the fact that the plagioclase composition varies little throughout the group, it seems probable that these rocks were originally all of tonalitic and monzonitic composition. They were then acidified by the introduction of the potash feldspar.

Quartz occurs as small interstitial anhedra. The accessory minerals of this rock include fairly large subhedra of faintly pleochroic sphene, small needles of apatite, and sparse grains of magnetite which often are restricted to the interior of the hornblendic clots.

Dioritic Variety. This type occurs as patches within the more acid types; in thin section it differs very little from the monzonitic rocks, apart from the change in the relative proportions of the minerals present. Quartz is less than 10 per cent, potash feldspar is absent,

Ratio of potash feldspar to plagioclase in spotted monzonites

Fig. 16

and plagioclase is relatively scarce; there is a concomitant rise in the proportion of ferromagnesian minerals (see Table XV). The spotted nature is still present in this rock type, and the same tendency for biotite to rim the clots is developed. The minerals have the same properties as in the normal type, with the exception of the plagioclase which is more calcic and more strongly zoned, ranging in composition from a core of An_{50} to a margin of An_{30}.

As this diorite shows the same texture and general mineralogy as the monzonitic rocks which enclose it, it seems probable that it is in fact an original part of the monzonitic group, possibly an original basic segregation or cognate inclusion, and it will be considered as part of the spotted monzonites in the discussion of the latter.

Contact Relationships. Marginal changes in the spotted monzonite inclusions can be traced in thin section. As the margins are approached, porphyroblasts of plagioclase become increasingly common (Pl XXI, A and B). These are slightly more sodic in composition than the normal plagioclase of the monzonites, showing normal zoning from An_{32} to An_{22}. These porphyroblasts contain very numerous small inclusions of hornblende and occasional biotite, and are dusted throughout by small crystals of magnetite. There are also rare subhedral inclusions of sphene. The inclusions are restricted to a central zone of the porphyroblasts, leaving a clear, inclusion-free marginal zone.

As the contact with the host rock is approached, and in the vicinity of granitic veinlets, the plagioclase porphyroblasts form clusters

TABLE XV

CRATHIE GRANITE COMPLEX

Modal Analyses of Spotted Monzonites

										Dioritic type
Specimen No.	26C	170F	63C	148F	55C	127C	31C	168C	114C	67C
Quartz	10	6	15	8	16	15	6	9	14	1
K-feldspar	10	8	27	18	10	5	6	8	4	-
Plagioclase	46	43	18	28	50	55	50	48	52	29
Hornblende	15	27	25	28	13	11	21	16	16	37
Biotite	18	15	13	18	10	13	17	17	13	32
Others	1	1	2	-	1	1	-	2	1	1
K-feldspar / Plagioclase	0.32	0.19	1.50	0.64	0.20	0.09	0.12	0.17	0.08	0.00
Quartz / Feldspar	0.18	0.12	0.33	0.17	0.27	0.25	0.11	0.16	0.25	0.03

No. of points counted - 1500+

of several crystals. Gradually coarser patches of the more acid, relatively ferromagnesian-free material of the host rock appear in the monzonite, while the hornblendic clots become very sparse. Simultaneously the proportion of interstitial quartz increases, and in some examples the quartz occasionally forms large poikilitic plates of similar habit to the potash feldspar.

In those cases where the contact between the spotted monzonite and its host rock is relatively sharp, plagioclase porphyroblasts are also found very close to the contact, while the biotite of the monzonite is completely chloritised although the hornblende remains fresh.

Where the spotted monzonite is intricately veined by granitic material the biotite is partially chloritised, and, where shadowy remnants of small monzonitic fragments are visible in hand specimen, patches are visible in thin section which have a texture similar to that of the monzonites, but are of more acid composition, with a low percentage of hornblende and completely chloritised biotite. These grade into the coarser, more truly granitic, material of the host rock.

MAIN BODY OF THE COMPLEX

For the purposes of field descriptions, the Crathie Granite Complex will be divided into four geographical divisions in which the field characteristics differ slightly. These are: (1) Sron Dubh (2) Parliament Knowe, Creag Mhor and northwards to Cnoc Chalmac (3) Creag a' Chlamhainn and Knock of Lawsie (4) Gairnshiel and Craig of Tullich.

1) Sron Dubh. Adamellite is the predominant representative of the Crathie Complex exposed on Sron Dubh. Typically these adamellites are coarse white porphyritic rocks, extremely rich in metasedimentary inclusions. They are typically hornblende-free and show no linear or planar structures, but they contain a higher proportion of modal biotite and have a different texture from the Ballater Granite, from which they are readily distinguished in the field or in hand specimen. Less commonly the adamellites are non-porphyritic and pink in colour with variable grain size. The adamellitic rocks are however considerably more homogeneous than the basic rocks of the complex which occur further west.

Within these adamellites lie sparsely scattered areas of more basic rock types, in the order of several yards across; these become more common towards the north end of Sron Dubh. Contacts vary from relatively sharp to a gradation over several feet, while veins of adamellite penetrate the intermediate rocks. In every case there is a complete lack of contact effects between adjacent rock types.

The relations of these adamellitic rocks with their abundant metasedimentary inclusions will be described later (p.160). Near to these inclusions the adamellites contain more basic lenses which have the appearance of shadowy schist relics, and are generally of finer grain size than is normal.

The late aplitic veins cut both the igneous rocks and the metasedimentary inclusions of this region.

2) Parliament Knowe, Creag Mhor and north to Cnoc Chalmac.

In this region the rocks of the complex are extremely variable in composition, being in general considerably more basic than those of Sron Dubh. Adamellites are comparatively sparse, and there is a complete gradation from them through granodiorites, tonalites, and monzonites to diorites, a constant mineralogical type seldom continuing for more than a few yards. Individual rock types vary greatly in grain size and proportion of basic constituents, while relatively basic types often contain irregular segregations and veinlets of more acid material. Contacts are sometimes relatively sharp in the field, although there are no visible contact effects on either side. In other instances the rock types grade into each other over a few inches, a few feet, or several yards and appear to be intermixed at the contact (Pl IV A &B). The rocks of this region practically always contain hornblende, the hornblende-bearing acid varieties tending to be pinkish rather than white, and often slightly porphyritic.

Within this complex, acid representatives commonly vein the more basic types but nowhere was the reverse seen. The veins vary from a quarter of an inch to several feet in width, and have variable contact relations with the enclosing rocks.

Across most of this region metasedimentary inclusions are sparse, but on the eastern slope of Creag Mhor a medium grained, pink, hornblende-bearing adamellite contains thousands of small inclusions seldom exceeding three inches in length. All the rocks of the region are cut by pink aplitic veins which show dilational relationships, displacing inclusions (Fig.23B).

3) Knock of Lawsie and Creag a' Chlamhainn. In the south and west of this region the rocks are very similar in composition to those in the Parliament Knowe region, while to the north of Creag a' Chlamhainn adamellites become more common, and there is an approach to the rock types found on Sron Dubh. The main characteristics of the rocks of Creag a' Chlamhainn and Knock of Lawsie, as compared with those of other areas, is the common occurrence of a relatively pronounced foliation. Foliation is in general poorly developed elsewhere. This structure is formed mainly by the parallel alignment of plagioclase crystals, less commonly by hornblende and biotite crystals. In some places it takes the form of a lineation rather than a foliation. In part the foliation is sufficiently well marked to be measureable and its orientation will be discussed later (p.171). In general the foliated varieties of the Crathie Granite Complex have the same characteristics as the unfoliated rocks, but in some cases a slight compositional banding parallels the foliation. The bands vary in width from one inch to several feet. Where inclusions of metamorphic rocks occur within these foliated rocks, their schistosity and compositional banding lies approximately within the foliation plane. However where there are relatively basic patches of igneous rock in the foliated varieties the foliation passes right through these. In some cases where a vein of igneous rock cuts across a metasedimentary inclusion the igneous rock shows a slight foliation parallel to the margins of the vein.

Throughout these rocks, and also those of the Parliament Knowe region, there is a sporadic development of large feldspar phenocrysts,

which become very common and then fade out again across a few yards. Contacts between various types are very variable; examples are shown in Pl IV B, and Pl X, A & B.

The aplitic veins transgress these rocks, cross-cutting the foliation.

4) Gairnshiel and Craig of Tullich. To the south-east of Gairnshiel, at Delnabo, non-porphyritic adamellites are the only igneous rocks exposed. These have been assigned to the Crathie Granite Complex because they are somewhat variable in composition and have intricate relationships with metasediment. They are coarse, both pink and white, rocks resembling those of Sron Dubh, but lacking the phenocrysts of the latter.

To the northeast of Gairnshiel, just east of Little Crag, a tonalitic body, rich in hornblende and biotite, is exposed over an area measuring about 200 yards N-S and 300 yards E-W. Although varying somewhat in proportion of basic constituents, this rock type does not show textural and mineralogical changes comparable to those around Crathie, but appears to consist of one coherent mass of tonalite. This mass is free from metasedimentary inclusions although the adamellite surrounding it contains abundant inclusions. A large mass of metasediment lies just south of the tonalite, but practically everywhere the metasediment is separated from the tonalite by a few feet of adamellite. At the only point at which a contact was seen between tonalite and metasediment the tonalite became somewhat more acid towards the contact. The adamellite-tonalite contact

is sharp, and the adamellite veins the tonalite for some distance from the contact. These adamellites are similar to those at Dalnabo.

On Craig of Tullich, to the west of Little Crag, more variable granodiorites, tonalites and diorites closely resemble those of the Crathie region, occasionally possessing a slight foliation. Pl IV A shows a contact between adamellite and granodiorite on Craig of Tullich. Here again metasedimentary inclusions are more abundant in the relatively acid rocks, towards the NE side of the crag.

On the western slope of Craig of Tullich there is a wedge of adamellite which bears a close resemblance mineralogically to the Ballater Granite. However, in detail, it is somewhat variable in composition, and has gradational contacts with the more normal representatives of the Crathie Granite Complex in this region. It is also cut by several of the microtonalitic dykes which were at no point seen to cut the Ballater Granite, and which are believed to have been emplaced between the time of emplacement of the Crathie Granite Complex and that of the Ballater Granite. This was therefore taken to be part of the Crathie Granite Complex.

For the purposes of description the rocks of the Crathie Granite Complex have been divided into two groups, although there is no sharp demarcation between the two. These are firstly the adamellitic group, which differs somewhat texturally, as well as mineralogically, from the more basic group of granodiorites tonalites monzonites and diorites which form the second group. The mineralogical variations found within the Crathie Granite Complex are shown in Table XVI.

Adamellites

These rocks vary from pink to white in colour, flecked with occasional dark ferromagnesian minerals. They are coarse grained and show no foliation. The white varieties in particular are often porphyritic, plagioclase forming the dominant phenocryst where there is a relatively high proportion of ferromagnesian minerals, while microcline is dominant where ferromagnesian minerals are sparse. These rocks contain abundant quartz, potash feldspar, and plagioclase feldspar, with sparse biotite; rare hornblende is present in some cases.

This group of rocks is variable texturally. The phenocrysts are often poikilitic, including many small quartz crystals marginally (Pl XX A). These phenocrysts vary from 5 to 10 mm. in length. The average grain size of the groundmass of the porphyritic rocks varies from about .1 mm. to 2 mm. The non-porphyritic rocks are somewhat coarser, varying in grain size from an average of about 1 mm. to 5 mm. The texture varies from granophyric, through allotriomorphic granular, to a hypidiomorphic rock with subhedral plagioclase crystals.

Although these rocks have a modal composition approaching that of the Ballater Granite, they are distinguished from it by their variability of texture, grain size, and mineral proportions over short distances. In general their modal proportion of quartz is slightly less than that of the Ballater Granite (c.f. Tables XVII and XXI).

TABLE XVI

MINERALOGICAL VARIATIONS IN THE CRATHIE GRANITE COMPLEX

	1	2	3	4
Quartz	x	x	x	x
K-feldspar	x	x		
Plagioclase	x	x	x	x
Hornblende		x	x	
Biotite	x	x	x	x

The potash feldspar is in the form of microcline, with abundant Carlsbad and albite-pericline twinning; both string and patch perthites are present. The microcline forms large phenocrysts which are generally rounded in form, but occasionally tabular with crenulate margins in detail. These phenocrysts have an inclusion-rich margin containing abundant small rounded quartz crystals about 1 mm. across (Pl XX A). Small tabular inclusions of oligoclase are occasionally found throughout the phenocrysts. The microcline of the equigranular rocks is sometimes surrounded by a very narrow rim of albite. It includes, and is included by, quartz, and often includes small plagioclase crystals which have embayed margins; occasionally several apparently detached fragments of plagioclase are in optical continuity, and twin lamellae may be traced across neighbouring fragments. In such cases the microline is noticeably fresher than the plagioclase in the same rock.

Plagioclase also occurs both as phenocrysts and in the groundmass. In some cases the plagioclase phenocrysts contain marginal inclusions similar to those found in the microcline; they also include sparse, randomly situated, hornblende and biotite inclusions. The composition of the phenocrysts varies little throughout the group, ranging from An_{26} to An_{33}. The crystals are virtually unzoned. The composition of the groundmass plagioclase feldspar of the porphyritic rocks is the same as that of the phenocrysts.

In the equigranular rocks however the plagioclase, although still practically unzoned, shows a wider range in composition, varying from An_{10} to An_{34}.

TABLE XVII

MODAL ANALYSES OF ADAMELLITES — CRATHIE GRANITE COMPLEX

Specimen No.	20X	19X	135C	23C	147F	30C	151F	66C	117C	100C	101C	157F
Quartz	26	33	30	32	29	31	22	21	16	28	32	10
K-feldspar	51	36	31	38	33	26	39	30	33	31	25	31
Plagioclase	10	27	36	28	33	33	34	34	43	36	37	42
Biotite	13	4	3	2	5	8	5	5	6	5	5	15
Hornblende	-	-	-	-	-	1	-	9	2	-	1	-
Others	-	-	-	-	-	1	-	1	-	-	-	2
K-feldspar / Plagioclase	5.10	1.25	0.85	1.35	1.00	0.79	1.15	0.88	0.77	0.84	0.68	0.75
Quartz / Total feldspar	0.43	0.52	0.45	0.47	0.44	0.53	0.30	0.33	0.21	0.42	0.51	0.13

No. of Points Counted 1500+

The general range is more sodic than that of the plagioclase of the Ballater Granite. The plagioclase of the equigranular rocks is generally in subhedral tabular crystals which are somewhat smaller than the microcline crystals in the same rock.

The quartz occurs typically in interstitial anhedra, often in aggregates of several crystals. In some specimens it forms rounded and lobate crystals, and in others granophyric intergrowths with microcline, up to 5 mm. across. Sparse myrmekite also rims plagioclase crystals in the groundmass of some of the porphyritic rocks.

The biotite occurs in small anhedra, occasional slightly larger crystals being found in the porphyritic rocks. The pleochroic scheme is X-pale yellow, Y-medium brown, Z-deep reddish brown. In some cases, notably in the near vicinity of metasediment, the biotite becomes very pale in colour, and pleochroic from colourless to very pale brown. Rarely the biotite of the non-porphyritic rocks has a pleochroic scheme of X-pale yellow, Y-medium brown, Z-deep greenish brown. The biotites of these rocks are thus somewhat variable in composition. Rare biotite-rich patches with a hornfelsic texture occur within the adamellite in the near vicinity of metasediment. The biotite is often partially or completely chloritised, and includes small crystals of zircon, apatite and magnetite. In the adamellites of Gairnshiel muscovite forms extremely sparse interstitial flakes.

Hornblende is only present in some specimens, forming small subhedra and anhedra. The pleochroic scheme is X-pale yellow, Y-moss green,

Z-deep greenish blue, the depth of colour varying from specimen to specimen. $Z \wedge C$ is 24°. The hornblende is usually associated with the biotite crystals, which it sometimes includes and by which it is sometimes rimmed.

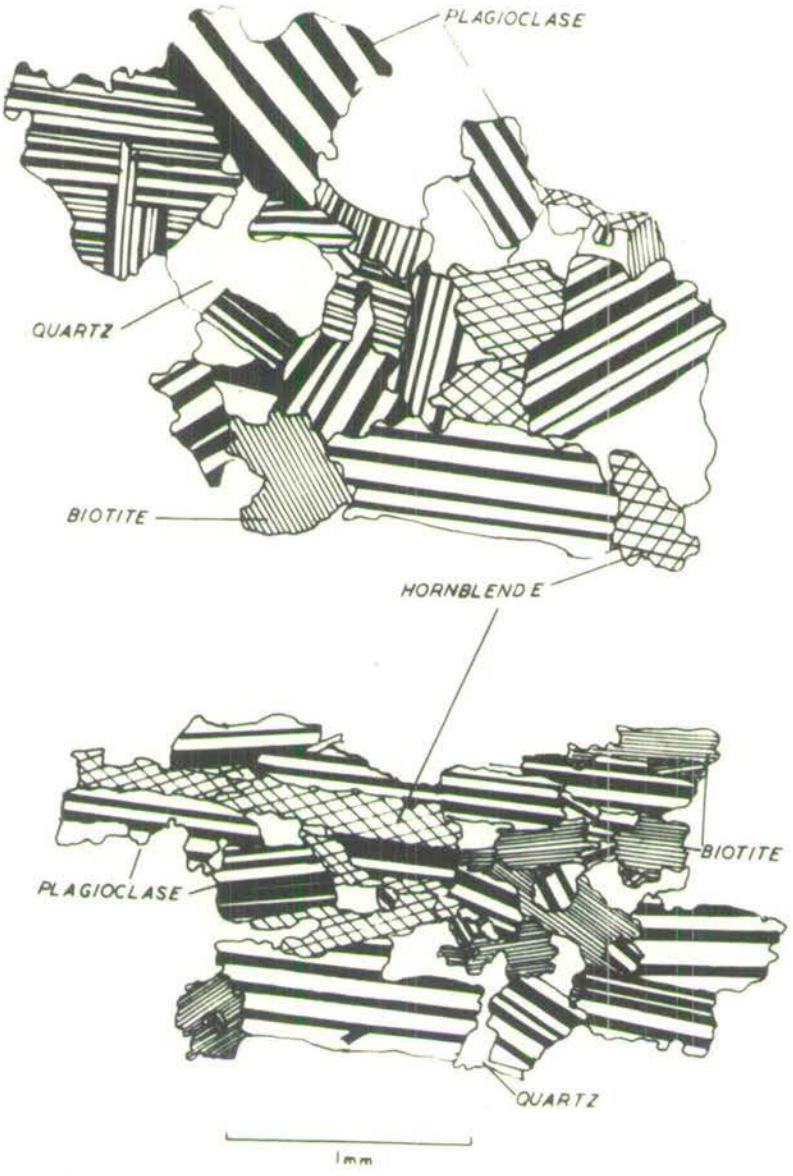
Accessory minerals include sphene which is abundant in the porphyritic rocks forming masses up to .5 mm. long, but is rare in the equigranular rocks. It is pleochroic from neutral to pinkish brown. Apatite needles are common, and often contain cores of minute opaque inclusions. Yellow pleochroic orthite is rarely found, producing dark pleochroic haloes in biotite. Zircon is relatively common, and both magnetite and pyrite also occur.

Intermediate Rock Types

This petrographic group is found throughout the Crathie Granite Complex, of which it forms the greatest part. It comprises rocks which range in modal composition from granodiorites, through tonalites and monzonites to diorites (see Tables XVIII and XIX). These various types however contain the same minerals, and similar textures throughout, and are thus considered to be one group.

In hand specimen these rocks vary from well foliated to non-foliated, from pink to white, from leucocratic to mesocratic. The grain size varies from medium to fine, the average grain size being about 1 mm.

Where there is a macroscopic foliation, this is normally formed by the parallel elongation of tabular plagioclase crystals (see Pl XVIII C



Camera lucida drawings of textures in tonalite of the Crathie Complex

A - unfoliated tonalite. B - foliated tonalite.

Fig. 17

and Fig. 17). The ferromagnesian minerals show a slight preferred orientation, but where they are present in relatively low proportion they tend to be caught interstitially between the plagioclase crystals, which may have inhibited their freedom to rotate into parallelism with the latter. In the most basic, dioritic rocks with a relatively low proportion of feldspar, the biotite and hornblende sometimes show a rude parallelism (Pl XIX C). Foliation is completely lacking in the intermediate rocks of Gairnshiel.

A number of specimens from this group are extensively altered, although in most cases this alteration could not be connected with any particular phenomenon in the field. It is noticeable that, even where every other mineral in the rock with the exception of quartz is extremely altered, the potash feldspar is extremely fresh, not even showing a slight turbidity.

The plagioclase forms tabular crystals which tend to be slightly larger than the other minerals of the rock. Occasionally they form distinct phenocrysts, which occur sporadically over a few yards in the field. The phenocrysts are relatively unzoned, consisting of andesine-oligoclase about An_{30}. They are roughly tabular, with extremely irregular margins and include crystals of biotite, hornblende and quartz; the quartz is sometimes micrographically intergrown with the enclosing plagioclase.

The plagioclase of the groundmass shows strong normal zoning; the maximum range measured was from labradorite An_{59} to oligoclase An_{18}.

TABLE XVIII

MODAL ANALYSES OF GRANODIORITES AND TONALITES — CRATHIE GRANITE COMPLEX

	Granodiorites				Tonalites							
Specimen No.	138F	71C	119C	68C	171F	142F	13C	168F	139C	108C	51X	87X
Quartz	19	18	15	17	20	23	11	10	17	15	13	14
K-feldspar	21	23	9	11	-	2	5	4	2	-	1	-
Plagioclase	49	42	38	35	59	58	54	53	53	48	51	55
Biotite	10	15	17	22	21	16	12	21	11	21	16	13
Hornblende	-	2	22	14	-	-	15	11	17	16	18	16
Others	-	1	-	1	-	1	3	1	-	-	1	2
K-feldspar / Plagioclase	0.42	0.55	0.24	0.31	0.75	0.04	0.09	0.08	0.04	0.00	0.02	0.00
Quartz / Total feldspar	0.27	0.27	0.31	0.38	0.13	0.38	0.17	0.18	0.31	0.31	0.25	0.24

Number of Points Counted 1500+

TABLE XIX

MODAL ANALYSES OF MONZONITES AND DIORITES — CRATHIE GRANITE COMPLEX

	Monzonites				Diorites				
Specimen No.	165F	160F	73X	114X	35C	109C	58C	88X	34C
Quartz	7	6	4	9	1	9	8	1	6
K-feldspar	23	8	4	8	-	-	-	5	-
Plagioclase	50	43	35	50	56	45	60	48	24
Biotite	20	15	19	13	16	18	12	14	29
Hornblende	-	27	39	19	25	28	16	29	40
Others	-	1	-	1	2	-	4	3	1
K-feldspar / Plagioclase	0.46	0.17	0.12	0.16	0.00	0.00	0.00	0.10	0.00
Quartz / Total feldspar	0.13	0.12	0.10	0.15	0.02	0.20	0.13	0.02	0.25

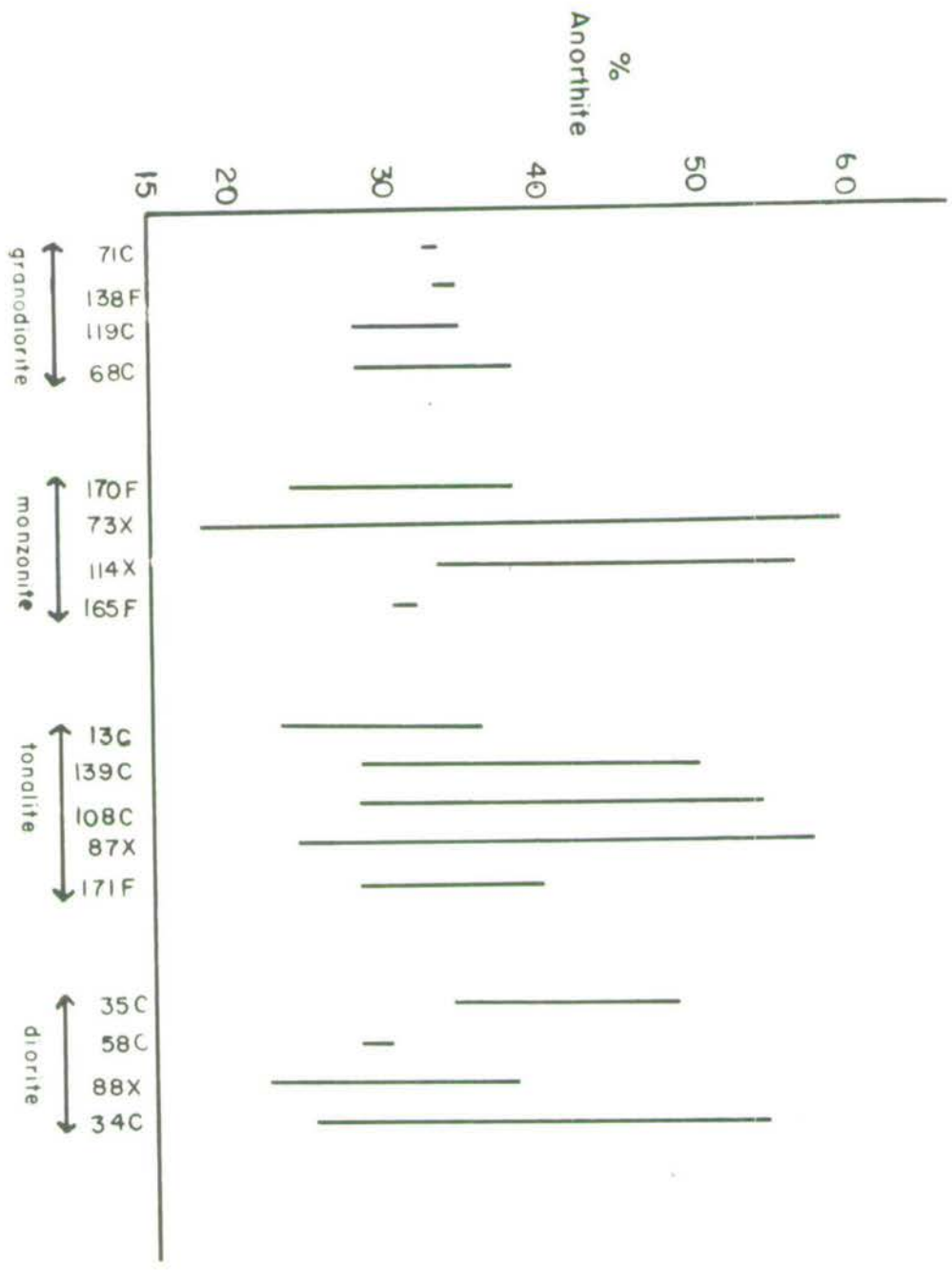
Number of Points Counted 1500+

All other measurements fell within this range, but typically the zoning within any particular rock was much less than this, for example from An_{48} to An_{34}, or from An_{36} to An_{23}. A representative sample of feldspar compositions from the various petrographic types is shown in Fig.18. Rarely, in the more quartz-rich rocks, there is a narrow border of fine myrmekite at quartz-plagioclase boundaries.

In most of the rocks the plagioclase is turbid, with alteration to sericitic mica in the relatively calcic crystal cores. In the altered rocks already mentioned, the plagioclase is completely replaced by a fine mat of colourless mica. In some specimens the twin planes of the plagioclase crystals are deformed, and occasionally fractured.

The quartz is present in small interstitial anhedra which occasionally include small plagioclase crystals, and rarely hornblende, biotite and apatite.

Potash feldspar occurs only in accessory quantity in the majority of these rocks, and is often lacking. In such cases it forms small interstitial anhedra. However, in a number of specimens from widely spaced localities, there are large poikiloblastic plates of potash feldspar up to 5 mm. across which enclose all the other minerals present. This occurrence is identical in type to the potash feldspar of the spotted monzonite, and also appears to be formed largely by replacement of the plagioclase (c.f. Fig.15). The potash feldspar rarely shows twinning, but occasionally very fine albite-pericline twins are present, and the crystals are traversed

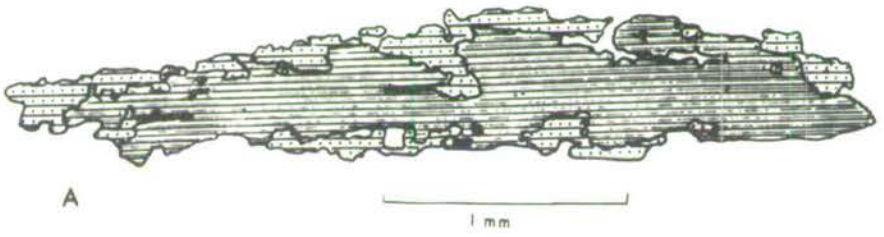


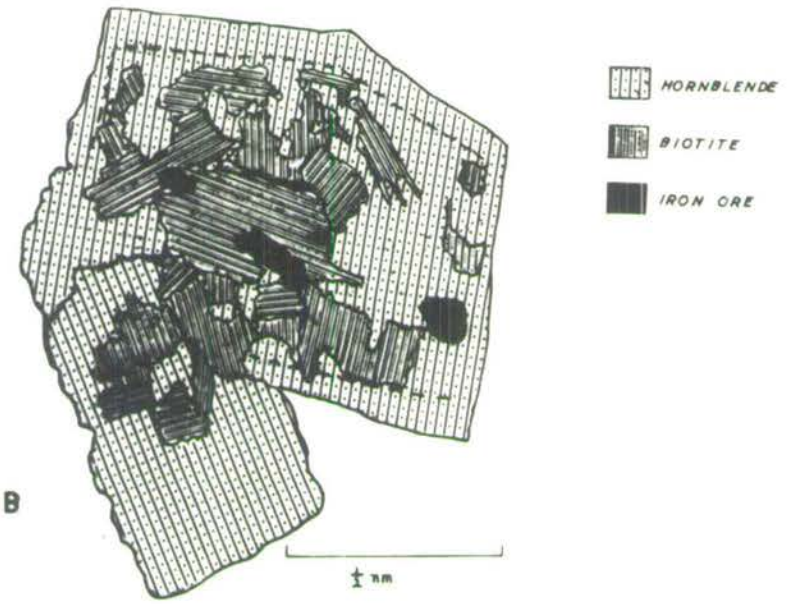
Range of composition of zoned plagioclase from modally analysed specimens of intermediate rocks from the Crathie Granite Complex

Fig. 18

by extremely fine stringers of albite. The potash feldspar is extremely fresh even where all the other minerals are highly altered, another indication that it is a late stage product.

The hornblende of these rocks forms subhedra and anhedra which are pleochroic from X-pale green to Y-moss green and Z-bluish green. These colours are pale, but the depth of colour is somewhat variable from specimen to specimen. $Z \wedge C$ varies from 17° to 25°. The hornblende tends to form aggregates of several crystals which are often intergrown with each other. It is intimately associated with biotite, which it tends to surround. This relationship is especially well developed in the diorite of Gairnshiel, but is also found around Crathie. Subhedral hornblende crystals have central zones full of small, randomly orientated, biotite crystals which are surrounded by sharply demarcated inclusion-free marginal zones (Fig. 19 B & Pl XIX B). The central zones have a brownish-green colour in plane light, while the marginal zones are a pale green. Some biotite crystals are only partially rimmed by hornblende in which case the c-axes of the two minerals are often coincident (see Fig. 19 A). It is probable that the hornblende continued to crystallise, with a slightly different composition, after the crystallisation of the biotite had ceased. In the rocks which show these textures, many of the plagioclase crystals have a very irregularily shaped core which often has embayed margins. This is surrounded by plagioclase which is optically continuous with the core, but slightly more sodic in composition (Fig.20). These two generations are presumably related to the time of change of ferromagnesian crystallisation.





Camera lucida drawings of hornblende-biotite intergrowths in diorite

A - partial overgrowth of hornblende around biotite. Note coincident c-axes.

B - biotite crystals within a single crystal of hornblende. The dotted line indicates a change in the colour of the hornblende.

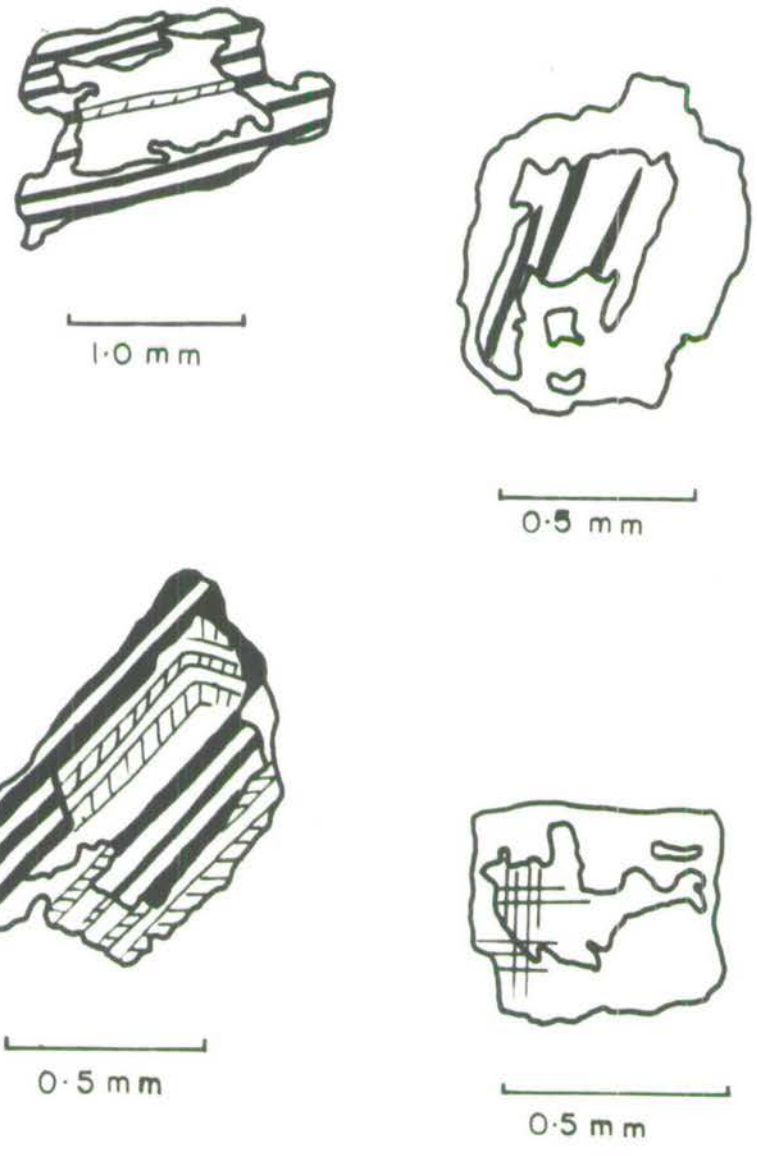
Fig. 19

Where these rocks are extensively altered, hornblende is relatively resistant to alteration in comparison to biotite, but in some cases it too is completely altered, being replaced by penninitic chlorite.

Biotite is found, as described above, enclosed within hornblende, and also as irregular flakes interstitial to the feldspar. The pleochroic scheme is X-pale yellow, Y-medium brown, Z-reddish brown. The crystals are often partially altered to penninitic chlorite, and in the highly altered rocks, are often completely pseudomorphed by this chlorite.

Accessory minerals include sphene, both in euhedra and anhedra, in crystals up to 1 mm. in length. These are pleochroic from neutral to pink, and sometimes dusted with leucoxene. Small crystals of magnetite and pyrite are sparsely present. In some specimens small needles of apatite, crowded with tiny opaque inclusions, are common. These are sometimes broken in half, the two fragments now lying closely adjacent to each other.

The hornblende-free rocks of this group occur only in small quantity, are restricted to Sron Dubh, and to the north of Creag a' Chlamhainn and occur almost exclusively as patches within adamellite. It may be significant that these rocks are found only within that part of the Crathie Granite Complex which contains a high proportion of pelitic inclusions. They grade into adamellites with increase in potash feldspar, and into the



Inclusions of plagioclase within more sodic, optically continuous, plagioclase. In diorite from the Crathie Granite Complex.

Fig. 20

normal intermediate rocks with the incoming of hornblende. These hornblende-free intermediate rocks were never found more than a few yards away from pelitic inclusions. Another notable feature is that the biotite of these rocks shows a slight preferred orientation. The proportion of quartz to potash feldspar is relatively high in comparison to that of the hornblende-bearing rocks, most of the potash feldspar occurring surrounding, or within, plagioclase, and appearing to replace the latter. It thus seems probable that these hornblende-free intermediate rocks may represent areas of adamellite which have assimilated some pelitic material.

The granodiorite of Creag Mhor, which contains abundant small inclusions of mixed type, has a hornfelsic texture, in contrast to the typically igneous textures of the majority of the intermediate rocks (Pl XIX D).

Contact Relations

These are often gradational over distances up to several yards. However in many instances the contacts are rapidly gradational over a few millimetres or centimetres. In thin section they are irregular in detail, no sharp line of demarcation being visible. Crystals of one rock type project into the other, and the only change is a rapid one in grain size and mineral proportion. Typically no contact effects are discernible in either rock type; in cases of extensive alteration both rock types are equally affected.

In other cases, where the contact consists of a ramifying and diffuse veining of finer more basic material by more acid, patches of the coarse acid material and single large feldspar crystals similar to those of the acid rock, are found within the intermediate rock for a few centimetres from the contact. As the acid rock is approached, its minerals become predominant, and irregular patches of the finer relatively ferromagnesian-rich intermediate rock are sparsely present.

At Gairnshiel, where adamellite veins penetrate tonalite, a marginal zone about half an inch wide, showing considerable enrichment in biotite, is developed. In this zone biotite makes up about 50 per cent of the rock, in contrast to the tonalite which contains only about 15 per cent of biotite and 15 per cent of hornblende. The adamellite contains only about five per cent of biotite, but has 40 per cent of potash feldspar, which is lacking in the tonalite and is present only in accessory quantity in the biotite-rich zone. Modal analyses across such a vein are given in Table XIX. The plagioclase of the tonalite in this case showed normal zoning from An_{57} to An_{24} while that of the marginal zone ranged from An_{38} to An_{24}, and that of the adamellite vein, which was only one inch wide, was unzoned, and had the composition An_{30}. Such contact relationships between adamellite and tonalite were not seen elsewhere.

Aplitic Veins

These vary from one-quarter inch to several inches in width, and cut all the other rock types of the Crathie Granite Complex. They are

TABLE XX

MODAL ANALYSES ACROSS THE CONTACT BETWEEN AN ADAMELLITE VEIN AND TONALITE, CRATHIE GRANITE COMPLEX

	Tonalite (country rock)	Marginal Zone	Adamellite (vein centre)
Quartz	14	9	21
K-feldspar	-	1	38
Plagioclase	55	48	33
Hornblende	16	-	-
Biotite	13	42	7
Others	2	-	1

Number of Points Counted - 1500+

medium to fine grained, and have sharp or very rapidly gradational contacts with the enclosing rocks. The veins consist of quartz, oligoclase, and a low proportion of potash feldspar forming an equigranular mosaic. Rare biotite is also found. Very rarely small amounts of fluorite are present. The vein constituents are often considerably altered, the biotite being replaced by penninitic chlorite, and the feldspar extremely turbid and often saussuritised, with the production of small crystals of epidote and white mica. This indicates that there was a relatively high concentration of volatiles in the material which formed these veins.

These aplitic veins produce a slight alteration in the enclosing rocks, similar in type to the changes found in the extensively altered rocks described above (p.138), and found patchily distributed throughout the Crathie Granite Complex. It thus seems likely that these altered rocks have been affected by volatiles, similar to those carried in the veins, which have percolated up joints or other fractures. This would explain the sporadic nature of these occurrences and the fact that the areas of alteration transgress rock boundaries, affecting equally all the rock types present.

METAMORPHIC INCLUSIONS

The presence of abundant inclusions of metamorphic rocks is one of the main features by which the Crathie Granite Complex is distinguished from the Ballater Granite.

The density of the inclusions can, to some extent, be related to the petrographic type of the representatives of the complex in which they are found. Inclusions are extremely abundant on Sron Dubh, the northern part of Creag a' Chlamhainn, and Knock of Lawsie, where adamellitic rocks predominate. To the west and north, on Parliament Knowe, Creag Mhor and towards the Strone, where the igneous rocks are more basic and extremely variable in composition, inclusions are of relatively sparse occurrence (with the exception of the eastern face of Creag Mhor where, again, the igneous rocks are relatively acid).

On Cnoc Chalmac, where relatively basic types also predominate, no inclusions were found, although the presence of occasional loose blocks of metasediment may indicate a low proportion of inclusions, at present unexposed. Around Gairnshiel at Little Crag and on Craig of Tullich, inclusions of metamorphic rocks are restricted to the acid rocks, none being found within the tonalitic and dioritic rocks of this region.

The inclusions embrace a wide variety of petrographic type including quartzite, semi-pelite and pelite, black schist, marble and calc-silicate rocks, and epidiorite and hornblende-schist. The assemblage is thus similar to that of the country rocks around Ballater.

The distribution of these rock types is shown in Fig. 21. It can be seen that pelitic inclusions with occasional calcareous bands predominate to the east on Sron Dubh and at Gairnshiel, while to the north of Crathie a quartzitic belt interbedded with abundant epidioritic rocks occurs.

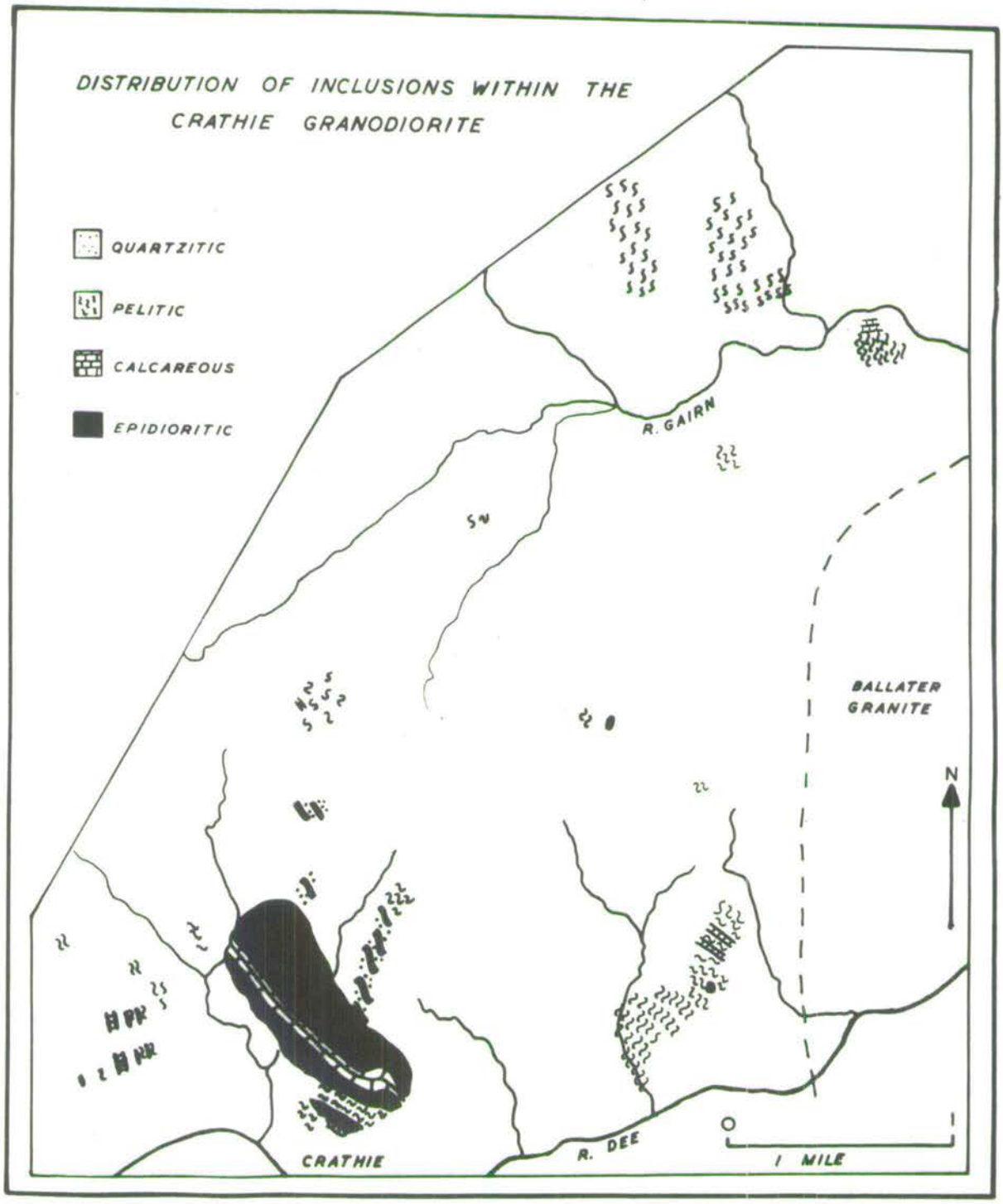

DISTRIBUTION OF INCLUSIONS WITHIN THE CRATHIE GRANODIORITE
QUARTZITIC
PELITIC
CALCAREOUS
EPIDIORITIC
R. GAIRN
SN
BALLATER GRANITE
N
CRATHIE
R. DEE
1 MILE

Fig. 21

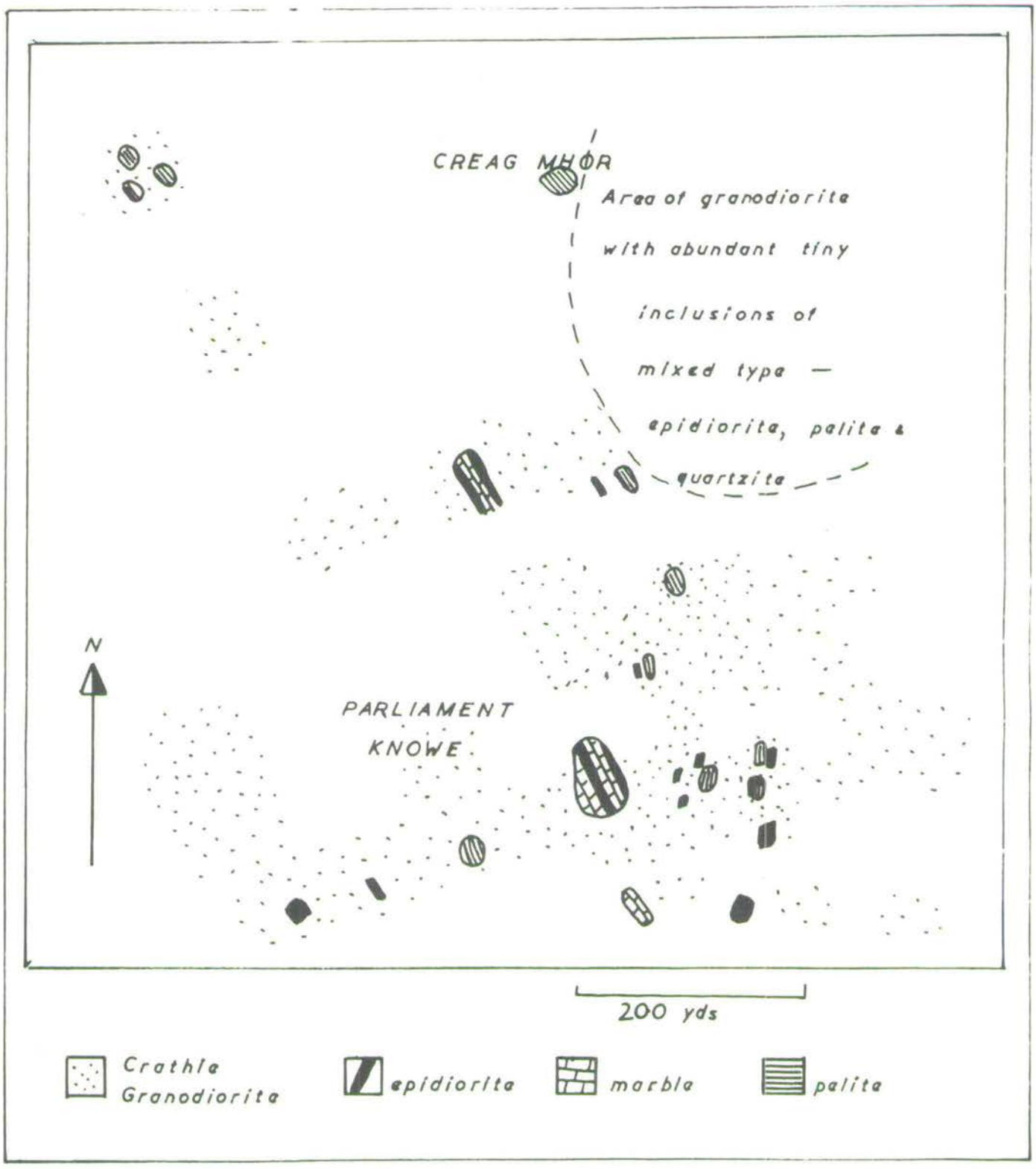
Further west pelitic rocks interbanded with epidiorite and some calcareous material are exposed. This may be a continuation of the pelite-quartzite succession of the Coilacriech Group. Some degree of stratigraphic continuity can be traced on a small scale in some parts, for example on Parliament Knowe, where the occurrence of three distinctive rock types makes such a relationship relatively easy to distinguish (Fig. 22). This stratigraphy breaks down on the east face of Creag Mhor, where abundant small inclusions of mixed petrographic type occur (Pl V A).

The size of the inclusions varies from the large epidioritic inclusion of Creag a'Chlamhainn and Knock of Lawsie, which outcrops over at least one third of a square mile, down to fragments of schist a few millimetres long. The average extent of the inclusions is in the region of a few yards.

The relations of the various metamorphic rock types to the rocks of the Crathie Granite Complex are distinctive, different petrographic types showing a different degree of alteration and assimilation. Epidiorite is the most resistant rock type, closely followed by marble and calc-silicate rocks. Quartzite is also relatively unaffected by the igneous rocks, but the metasediments show progressively greater degrees of alteration as they become increasingly pelitic in composition.

Epidiorites

Inclusions of epidiorite range from that of Creag a' Chlamhainn, one mile by one third of a mile in cross section and interbanded with pelite



STRATIGRAPHIC RELATIONSHIPS OF INCLUSIONS S. OF CREAG MHOR

Many of the inclusions indicated are generalised, representing a number of small inclusions.

Fig. 22

and marble, down to six inches in length. They are not fringed by smaller fragments as are the pelites. Contacts with the host rocks are sharp, with in some cases the development of a biotite-rich marginal zone up to one inch wide.

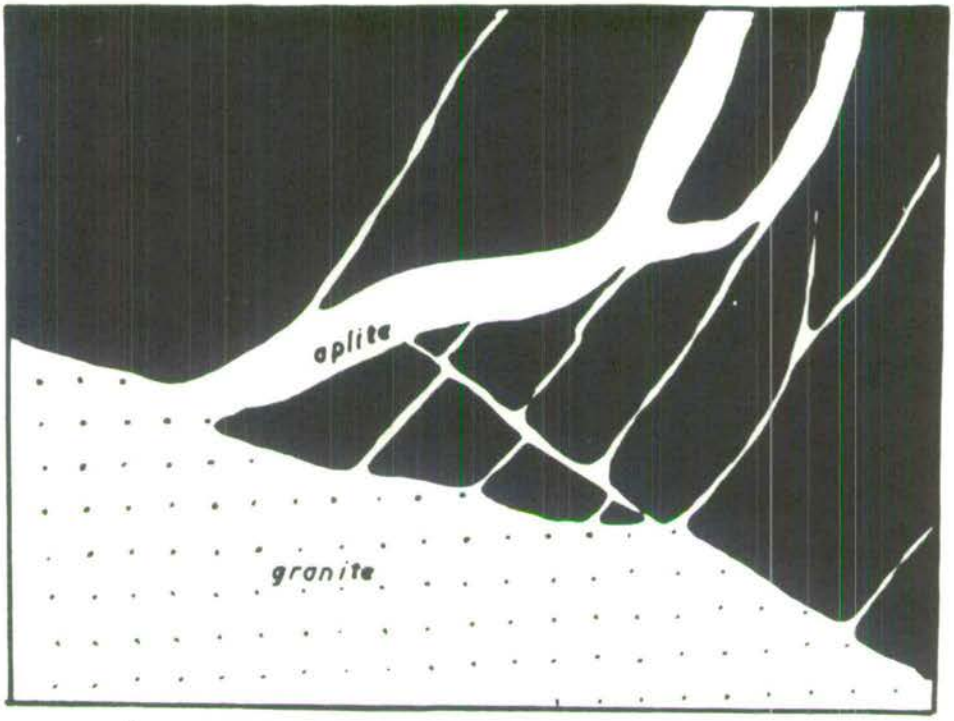
The inclusions are typically angular, occurring in aggregates of several blocks, the schistosity planes of which have a constant orientation. The epidiorite is often invaded by narrow reticulate aplitic veins, with sharp contacts and dilational characteristics (Fig. 23A).

The contact relationships of the epidiorite of Creag a' Chlamhainn are visible in the face of the crag. Here the contact runs roughly parallel to the edge of the cliff and is approximately vertical; both sill-like and cross-cutting veins of the igneous rock several feet wide cut the epidiorite. The host rocks show no textural changes towards the epidiorite.

Thus relations between epidiorite and its host are typically sharp, invading, and non-assimilative, with little evidence of reaction between the two rock types.

In thin section the epidiorites closely resemble those interbedded with the metasediments around Ballater. The inclusions range from fairly coarse rocks with feldsparphyric patches, to fine grained hornblende schist; a gradation from one to the other can occur over a few yards. The main distinction with the regional epidiorites is the relatively poor schistosity possessed by the inclusions, although this is often sufficiently marked to form a measurable plane. The hornblende of the inclusions is typically

A

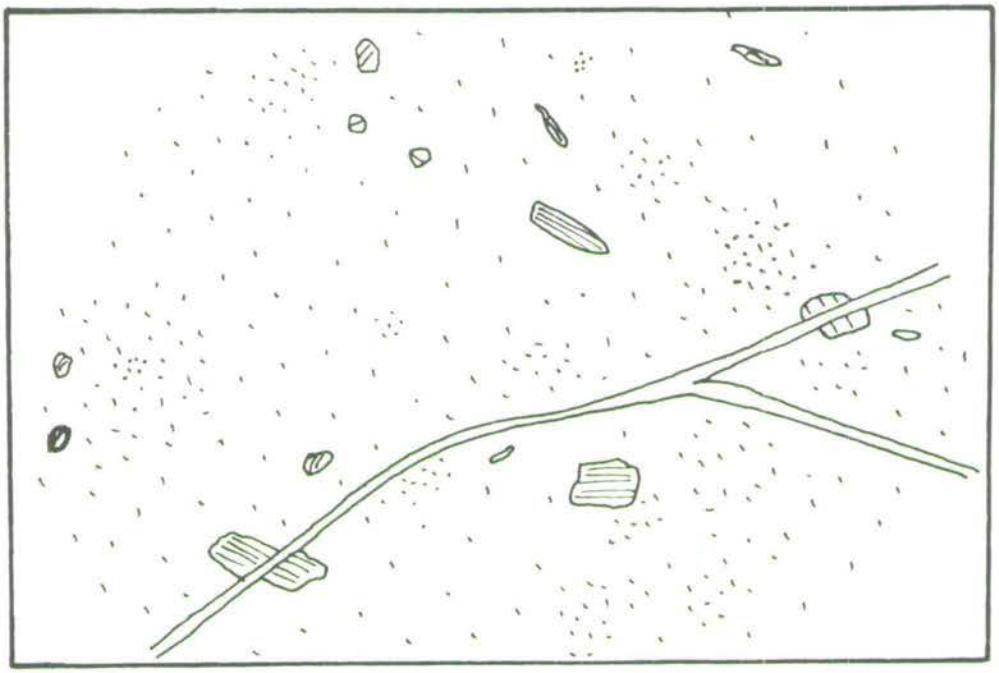


6 inches

hornblende schist veined by granite PARLIAMENT KNOWE

note dilational effects

B



6 inches

variable xenolithic granodiorite cut by later fine granitic vein which displaces xenoliths CREAG MHOR

Fig. 23

poikiloblastic, and this texture is developed throughout most of the large inclusion of Creag a' Chlamhainn, in contrast to the epidiorites around Ballater which do not show such a texture for more than a few feet from the contact with the Ballater Granite. Where feldsparphyric patches occur, these are almost always completely altered to a mass of fine sericitic mica.

In parts of the centre of the epidiorite of Creag a' Chlamhainn two generations of feldspar can be distinguished, analagous to those of the regional epidiorites (p. 76). Over most of the inclusion however the feldspar is typically metamorphic and often considerably altered, especially towards the inclusion margins.

The hornblende of the inclusions is typically fresh and poikiloblastic towards small feldspar crystals, with a pleochroic scheme X-pale brown, Y-greenish brown, Z-olive green. These show very little preferred orientation. Sometimes the hornblende becomes chloritised for a few millimetres from the contact.

In the epidiorite of Sron Dubh, which is extremely hornblende-rich, the central portions of the inclusions sometimes contain large plates of sub-ophitic hornblende invaded by tabular feldspar crystals. At the margins the hornblende is again poikiloblastic.

Quartz occurs rarely within some of the smaller inclusions, especially those which are cut by granitic veins. It is sparsely distributed in small anhedra, becoming somewhat more abundant towards the granitic rocks.

This is not a typical constituent of the epidioritic inclusions, and has probably been introduced from the igneous rock.

Biotite is absent from the central parts of the larger inclusions, but a little is found in the smaller ones, especially those which are quartz-bearing. It is patchily distributed and sometimes poikiloblastic with a pleochroic scheme X-pale yellow, Y-medium brown, Z-reddish brown.

The epidiorite inclusions are occasionally cut by monomineralic veins of prehnite about $\frac{1}{2}$ mm. wide. These are bordered by a marginal zone of chloritised biotite flakes.

The development of a biotite-rich marginal zone, or the incoming of scattered biotite towards the margins of epidiorite inclusions, is common but not ubiquitous. The biotite-rich zone often varies rapidly in width from several millimetres to less than one millimetre. In some cases the marginal biotite-rich zone is completely chloritised, admixed hornblende also being affected. In other cases the biotite is fresh with a pleochroic scheme X-pale brown, Y-yellowish brown, Z-dark brown, and hornblende is absent. In some cases where such a zone is developed along a granitic vein patches of biotite-rich material are included in the vein, and occasional large poikiloblastic biotites are scattered throughout the epidiorite for several inches from the contact.

Calcareous Rocks

The smallest calcareous inclusions found were several feet long, and in two cases, in quarries at the eastern end of Creag a' Chlamhainn and

at Dalnabo, at least 50 feet of calcareous rocks were exposed, interbedded with epidiorite. The two calcareous bands on Sron Dubh are about 25 feet wide and are cut by occasional granitic veins, Calcareous inclusions interbanded with epidiorite are also found on Parliament Knowe. These are at least 50 yards by 20 yards in cross-section. In none of these large inclusions were the contact relations visible.

At the contacts between calcareous rocks and granite, which are visible around some of the smaller inclusions, there is often a zone, about five feet wide, in which the calcareous rocks are reticulately veined by the enclosing granite (Pl VII A). Along the margins of these veins an amphibole-rich zone of variable width is formed (Pl VII B). Where there is no veined zone, an amphibole-rich layer about six inches wide is generally developed along the contact.

In every case the calcareous rocks consist of relatively pure marble which contains occasional impure bands which vary in width from one inch to one foot.

The mineralogy of the calcareous inclusions shows a higher metamorphic grade than do the corresponding rocks around Ballater. In the relatively pure marble the dominant mineral is calcite, with small proportions of diopside, feldspar and wollastonite. Olivine is not typically developed in this assemblage. As the amount of impurity increases, the proportion of diopside is greater, and in some bands there is abundant garnet and idocrase with subsidiary wollastonite and prehnite. With increasing impurity

calcite disappears and the rock consists of diopside and feldspar. A diopside-tremolite-feldspar assemblage is typically developed as a marginal phase to the calcareous rocks against quartz veins, epidiorite and granitic rocks.

In the relatively pure marbles calcite makes up about 85 per cent of the rock, occurring in a mosaic of heavily twinned equidimensional crystals. The average grain size is about 1 mm., although crystals up to 10 mm. across occur. Diopside occurs within all the calcareous inclusions. Where it is sparse the crystals are small and rounded, where it is abundant it forms masses of granular poikiloblastic crystals. It has a pale greenish tinge and is non-pleochroic. Diopside-rich bands of impurity lie parallel to the bedding planes of the rock.

Scapolite occurs rarely in some of the marbles, in association with the diopside. It forms small ragged crystals, often considerably altered to an ill-defined aggregate of fibrous material. Minor amounts of andesine occur in small fresh rounded grains sometimes enclosing diopside crystals.

Idocrase is developed in elongate lenses along the bedding planes of the rock in association with garnet and wollastonite. The crystals often attain a diameter of over 5 mm. They are pale yellowish in colour, slightly pleochroic, and show a zonary colour arrangement, the zones occurring in triangular and rectangular forms which are unrelated to the crystal outlines. The crystals of idocrase are filled with abundant

inclusions of diopside, calcite, garnet and wollastonite and aggregates and veinlets of these minerals. The garnet occurs in aggregates of pale pink anhedra several centimetres across, and as single euhedra. They are poikiloblastic, mainly towards diopside. There is much prehnite interstitial to the garnet in crystals up to 5 mm. across, showing the typical "bow-tie" structure. Prehnite also fills irregular veinlets in the garnet and it is associated with irregular masses of clinozoisite.

Wollastonite is present in small quantities in the purer marbles, but is more abundantly developed in the relatively impure bands. It occurs in elongate bladed crystals with ragged terminations which penetrate calcite crystals. Areas rich in decussate wollastonite and diopside rim the idocrase-garnet masses and in some cases the garnets are criss-crossed by abundant bladed inclusions of wollastonite.

Small masses of sphene are especially abundant in the diopside rich sections, and magnetite and pyrite are sporadically present.

The less pure calc-silicate rocks are composed essentially of patchily distributed diopside and andesine-oligoclase, with occasional patches containing some idocrase and scapolite. These diopside-plagioclase rocks are similar to those found within the Abergairn Group. The pyroxenes are variable in grain size and often poikiloblastic, while the feldspar occurs in an equigranular mosaic of rounded crystals. The pyroxene in these rocks is colourless, in contrast to the greenish tinge which characterises the diopside of the marbles.

Between the calcareous rocks and the igneous rocks an amphibole-rich zone is typically developed, which varies in width from 2 mm. to several centimetres. In one example veinlets of adamellite as narrow as 1 mm., cutting a diopside-rich calc-silicate rock, are bordered by an iron-stained zone characterised by a discontinuous band of pale-green hornblende up to 3 mm. wide. In some places the amphibole is intergrown with the diopside of the inclusion. The veins comprise quartz, potash feldspar and plagioclase, along with occasional crystals of amphibole similar to that of the marginal zone. Within the same specimen occasional patches of the diopside-rich material contain biotite which invades and criss-crosses the pyroxene in a plexus of partially chloritised flakes. The hand specimen is shown in Pl VII B.

In other examples, where veining by granitic material is absent, an amphibole-rich contact phase several inches wide is developed, in which the amphibole is very pale and typically forms large sheaf-like crystals similar to those of the rocks of the Abergairn Group. Occasional small patches of pyroxene, and interstitial areas of micaceous material, also occur within this contact zone.

Some of the contact rocks consist of amphibole, diopside and plagioclase (andesine-oligoclase) often occurring in patchy segregations. Within such rocks, in some cases, pods of potash feldspar up to 2 cms. across, composed of several inclusion-free crystals, occur. These are

surrounded by rims of pyroxene about 2 mms. wide. The average grain size of this rock is only about .5 mm. This potash feldspar has presumably been introduced from the adjacent granitic rock.

Where the calcareous inclusions are interbanded with epidiorite similar tremolitic contact effects are seen. In some cases veins of calc-silicate material, 2 - 3 cms. wide, invade the epidiorite for short distances. These consist of a core of coarse pyroxene with some pyrite, which is separated from the epidiorite by a very fine grained zone about 5 mm. wide rich in pyroxene, micaceous material and sphene. The hornblende of the epidiorite is slightly chloritised at the contact.

The calcareous rocks, although metamorphosed to a high grade by the rocks of the Crathie Granite Complex, thus show little sign of assimilation by the latter, the marginal effects being restricted to a zone a few inches wide.

Hutchison (1932) gives a description of the mineralogy of the Deeside Limestone, which extends from Glen Muick, about three miles ESE of Ballater, for 25 miles east to Banchory. Within the Deeside Limestone he distinguishes between those limestones which have been affected only by the regional metamorphism, and those which have been affected by thermal metamorphism from the adjacent Newer Granites. There is nothing in the Geallaig district which is comparable with the mineralogy of the purely regionally metamorphosed rock of the Deeside Limestone. However the

calcareous inclusions within the Crathie Granite Complex may be more closely compared with thermally metamorphosed rocks of the "inner contact zone" of Hutchison's classification of the Deeside Limestone. He divides the rocks of this zone into a number of groups on the basis of the proportion of calcite present.

Increasing $CaCo_3$ ↓

Plagioclase-diopside
Grossular-plagioclase-diopside
Grossular-diopside
Grossular-wollastonite-diopside
Grossular-idocrase-diopside
Idocrase-grossular-wollastonite-diopside

Such assemblages correspond fairly closely to the composition of the impure bands found in the marble quarries of Dalnabo, Creag a' Chlamhainn and Creag Mhor. In addition there is often an association of scapolite with grossular and wollastonite in the Geallaig rocks; such an association is also reported by Hutchison from parts of the Deeside Limestone, where he classifies such rocks as a group of unstable hornfelses formed under the relief of static pressure. He reports the presence of wollastonite needles in garnet, also found within the Geallaig marbles, and considers that the wollastonite has formed at the expense of the garnet, with the relief of pressure.

The assemblages found within the calcareous inclusions place the metamorphic grade of these rocks in the pyroxene-hornfels facies (Fyfe, Turner and Verhoogen 1958). Such assemblages are not found within the marbles of the Abergairn Group which are exposed only about 25 yards from

the margin of the Ballater Granite north of the Pass of Ballater; minerals such as wollastonite, garnet and idocrase are completely lacking in this group. Thus it would appear that some of the Newer Granites a few miles to the east of Ballater (bordering the Deeside Limestone) had more intense thermal metamorphic effects on the surrounding rocks than did the Ballater Granite.

Quartzites

These inclusions occur predominantly to the north of Creag a' Chlamhainn and range from about 50 yards by 25 yards in cross-section, down to a few inches. Typically they are several feet across, and are sometimes interbanded with epidiorite. The quartzites have very sharp contacts with the enclosing rocks and appear to be little affected by them. Rarely they are cut by granitic veins up to 18 inches wide, which finger along the bedding planes and break up into a network of narrow veins. Occasional small angular disorientated quartzite fragments are found within these veins.

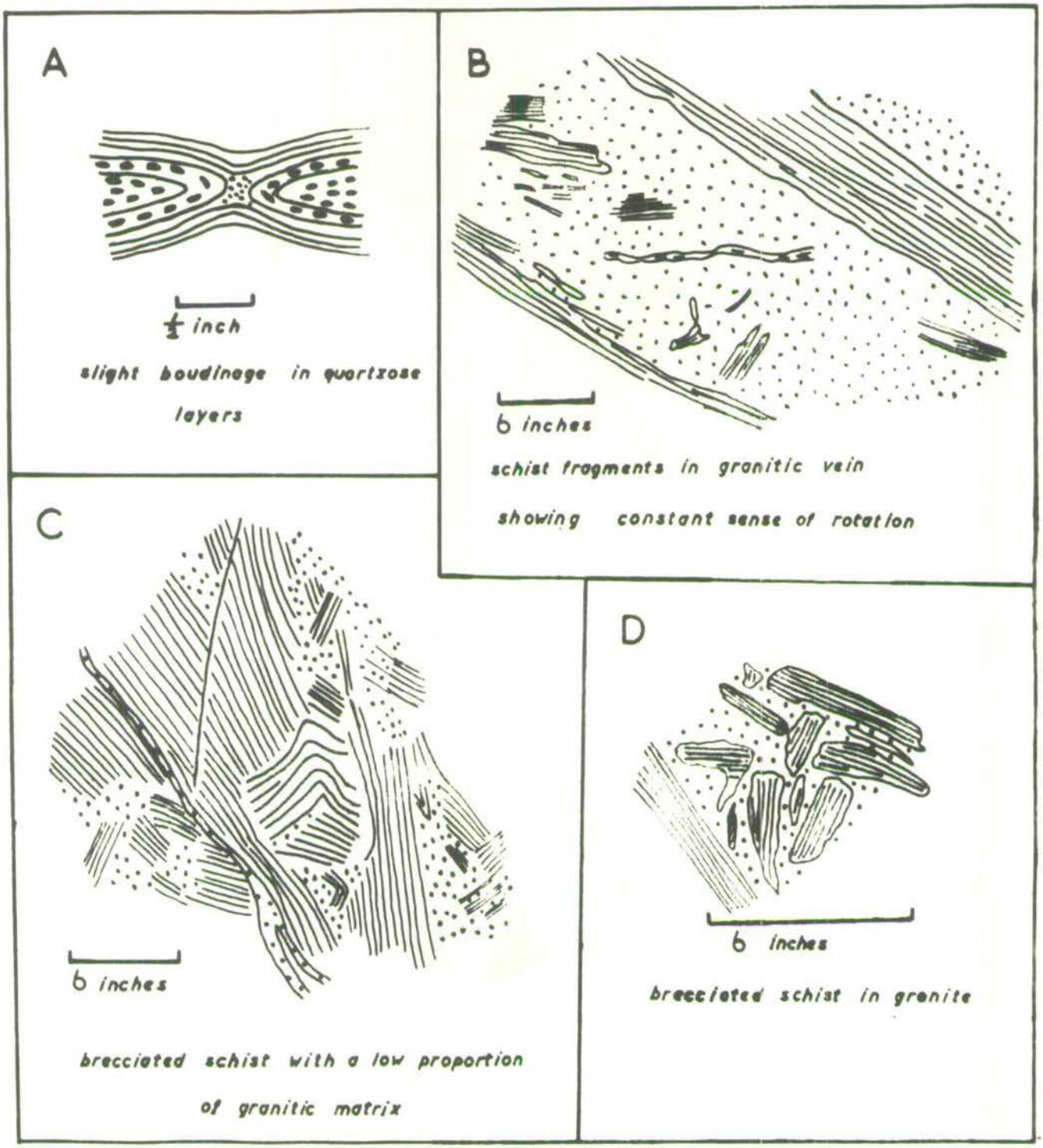
Mineralogically and texturally these quartzitic rocks closely resemble the equivalent rocks of the Coilacriech Group. They are pale pink rocks of granular aspect, which usually show a slight compositional banding. They consist essentially of variable proportions of quartz, potash feldspar and oligoclase. Rarely they become relatively coarse, and here potash feldspar is relatively abundant while the plagioclase is albite about An_{10}.

With increase in proportion of biotite, and decrease in potash feldspar, the quartzites grade into quartz-rich schists. Here the biotite occurs in small ragged, randomly orientated flakes which are often partially chloritised, and usually pleochroic from pale yellow to deep reddish brown. In occasional cases however the biotite is a rich green in colour, with a pleochroic scheme X-pale yellow, Y-medium green, Z-deep brownish green. In these schists pale pink garnet occurs sparsely in anhedral crystal aggregates.

Pelitic Rocks

These inclusions are best seen on Sron Dubh, where they form over 50 per cent of the exposure in masses varying in length from 50 yards to one or two millimetres. The inclusions are tabular in form and elongated parallel to their schistosity.

The pelitic inclusions are typically intimately veined by granitic material, and numerous small fragments fringe the larger inclusions, off which they have clearly been broken (Pl V B). Many of these small fragments show considerable rotation with respect to the adjacent larger inclusions. In several cases, where veins of granite transgress inclusions, small schist fragments within the veins show a constant sense of rotation, indicating that the schists on either side of the vein have moved relative to one another (Fig. 24 B).



Field sketches of relationships between rocks of the Crathie Granite Complex, and inclusions of schist; Sron Dubh.

Fig. 24

Near the SW end of Sron Dubh there is considerable evidence of fracture of the inclusions, masses of jumbled schist fragments being separated by very little granitic matrix (Fig. 24 C). In the same area there also are indications of small scale boudinage, shown by the 'pinching-out' of quartzose layers (Fig. 24 A). In some cases the granitic veins seem to have bent the schistosity of the metasediment (Pl VI A). This plate also shows the intricate veining of schist by granite, and the irregular nature of the contacts. Contacts are often gradational, and all stages from virtually unaltered schist, to shadowy patches within granite can be seen. In some cases, where the surrounding granite is porphyritic, small feldspar porphyroblasts are visible in the margins of the pelitic inclusions. In cases where the inclusions are merely dark shadowy patches, they could be interpreted as basic patches of endogeneous origin, but their elongate shape and banded nature, and their close proximity to undoubted metasediment, makes a metasedimentary origin highly probable. Small slivers of schist in granodiorite are shown in Pl IX B.

Despite the obvious degree of displacement and rotation of pelitic fragments on a small scale, the larger inclusions retain a relatively constant orientation of strike and dip over considerable distances. The orientation of the structural elements of the inclusions will be discussed later (p.167).

Similar field relations occur within the pelites around Gairnshiel, although here there is no sign of fracture of the schists, and small fragments fringing the larger inclusions are less common. To the east of Little

Crag, and on the eastern side of Craig of Tullich, metasediment occurs in greater proportion than igneous rock. These areas may represent very large inclusions which are merely veined by the granitic rocks. These inclusions are highly contorted (Pl VI B).

Where the pelitic inclusions are not contaminated by granitic material, their mineralogy is very similar to that of the Coilacriech Group. The cordierite-anthophyllite assemblage is not found within the inclusions, while the Coilacriech Group does not include rock types equivalent to the black schist inclusions of Sron Dubh. At Gairnshiel muscovite-rich schists are relatively common. The mineralogy of the pelitic inclusions will not be described in detail, except where it differs from that of the Coilacriech Group.

The cordierite-andalusite bearing rocks differ from the country rocks only in their textures, which are much more typically hornfelsic in the inclusions (Pl XVI A & B). The compositional banding of the rocks is still visible, but in most cases very little preferred orientation of minerals is visible. The base of the rock is a mosaic of quartz and oligoclase or andesine. Within this lie reddish brown flakes of biotite which are typically decussate, and often chloritised. In general the biotite of the inclusions is redder than that of the granitic rocks. Garnet is absent in these rocks, but cordierite is abundant and andalusite fairly common.

In these inclusions the cordierite occurs both as large fresh crystals, containing few inclusions (Pl XVII C) and as irregular crystals surrounding the minerals of the groundmass. It appears to have recrystallised simultaneously with the decussate biotite. In other examples, patchy areas of the rock show poor preferred orientation of micas, often dragged into minor folds. In these cases the cordierite often contains inclusions of biotite orientated parallel to this schistosity, even where the biotite around the cordierite is decussate. This cordierite seems to have grown subsequently to the formation of the schistosity, and probably simultaneously with the decussate biotite. The cordierite of the inclusions is typically altered to a colourless sericitic mica; the deep yellow chlorite so characteristic of the altered cordierite of the Coilacriech Group is relatively rare here.

Thus the cordierite of the inclusions appears to have crystallised as a result of the incorporation of these rocks within the Crathie Granite Complex.

The muscovite-rich schists occur predominantly around Dalnabo. Here again the base of the rock consists of a fine mosaic of quartz and andesine-oligoclase. Throughout this matrix are scattered abundant muscovite and subsidiary chloritised biotite crystals. The muscovite forms about 30 per cent of the rock in large poikiloblastic flakes of very irregular habit. These often attain a length of 1 mm. and transgress the chloritised biotite.

Two distinct types of black schist occur, in close proximity, on Sron Dubh. One is biotite-rich, while the other is extremely rich in magnetite. Both contain pseudomorphed porphyroblasts which, from their form, were most probably andalusite.

The biotite-rich schist has biotite and pseudomorphed phenocrysts as its only essential constituents. The biotite forms a decussate felt of broad flakes averaging .5 mm. in length and pleochroic from neutral to Y, Z-reddish brown. In rare patches the flakes show a preferred orientation. Where porphyroblasts are scarce, minute granules of opaque iron ore are common, and the biotite is noticeably paler in colour. Tiny needles of rutile, rare apatite, and very rare tiny crystals of feldspar are found throughout the rock.

The pseudomorphed porphyroblasts form elongate patches of elliptical cross-section, up to 5 cms. long, which form clusters of crystals tending to radiate from a centre. No remnants of the original material are now present, its place being taken by a mat of very fine sericitic mica, throughout which occur occasional small pale biotite flakes, tiny needles of rutile, prisms of pale brown tourmaline, and aggregates of tiny spinel crystals. The porphyroblasts are surrounded by a narrow marginal zone of extremely small, very turbid, grains of feldspar.

By contrast, the magnetite-bearing schist consists of a very fine grained quartzo-feldspathic matrix, of average grain size about .05 mm.,

dusted throughout by extremely abundant minute granules of magnetite and tiny flakes of muscovite. Occasional larger decussate muscovites up to .4 mm. long show slightly poikiloblastic textures.

Throughout this matrix lie abundant pseudomorphed porphyroblasts occurring as rhombic cross-sections and elongate prisms of typical andalusite form. The prisms are up to 5 mm. long. The magnetite granules which are ubiquitous throughout the rest of the rock are absent within these, but form an almost continuous rim around them. The porphyroblasts are filled with abundant muscovite and patches of pale brown chlorite, cross-cut by veinlets of sericitic mica.

The contact relations of the pelites with the enclosing granitic rocks are extremely variable, but generally show an intermixing of the two rock types across distances varying from a few millimetres to several inches.

In some examples large porphyroblasts of plagioclase appear within the metasediment in the vicinity of the granite, into which the metasediment grades rapidly. In other cases an intermediate zone is formed between inclusion and granite, in which large crystals of quartz and feldspar similar to those of the granite are surrounded by a biotite-rich groundmass closely resembling the normal inclusion material The plagioclase crystals of the inclusion, intermediate zone, and granite, are all of the same composition (usually oligoclase).

In yet other cases, rounded porphyroblasts of potash feldspar appear within the pelitic inclusions for a few centimetres from the contact (Pl XXI C & D). These have very irregular margins. For a few feet from the contact the enclosing rock consists of coarse quartz, potash feldspar and plagioclase, surrounded by a low proportion of interstitial quartzo-feldspathic material with abundant biotite, not greatly different from the material of the pelitic inclusion.

A similar introduction of potash-rich material occurs along certain bands in some of the cordierite-bearing pelites, in the form of abundant rounded crystals of potash feldspar. Beside these the cordierite, which is very fresh elsewhere, is completely altered to fine sericitic mica, and the associated biotite is completely chloritised. The potash feldspar is, by contrast, extremely fresh.

In some places abundant tiny schist fragments a few millimetres long, in a granitic matrix, are associated with clots of altered cordierite also scattered throughout the granitic material. These consist of the deep yellow chlorite and sericitic mica typically formed by the alteration of cordierite. As cordierite is not a normal constituent of the Crathie Complex this is taken to indicate the partial incorporation of some pelitic material into the igneous rock. In some cases granitic rocks, which in hand specimen show no signs of pelitic material, but which always come from the close vicinity of pelite, also contain patches of altered cordierite. There would thus appear to have been at least a slight degree of mechanical comminution and incorporation of the pelitic inclusions by the enclosing granitic rocks.

Small biotite-rich elongate masses within the granite, not associated with cordierite, are also interpreted as metasedimentary relics, because of their close proximity to undoubted metasediment. They closely resemble the hornblende-free intermediate rocks of the Crathie Granite Complex, which may represent partial assimilation on a larger scale. The inclusions vary from those which are relatively biotite-rich, and lack potash feldspar, to those which contain potash feldspar and are distinguished from the enclosing granite only by a slightly greater amount of biotite, finer grain size, anhedral plagioclase and somewhat hornfelsic texture. The marginal zones of the larger inclusions often have these characteristics (Pl XVII A & B).

At Dalnabo, where muscovite-rich schists are in contact with granite, the contact is again gradational, and for some distance from the contact the granite contains radiating masses of needle-like muscovite crystals which rim and penetrate the large feldspar crystals of the granite. This granite is rich in feldspar and relatively poor in quartz, as is the schist which it encloses.

Structural Elements

Most of the metasedimentary inclusions have a hornfelsic texture, but their compositional banding is still evident and provides a measurable plane. Similarly, although the schistosity of the epidiorite inclusions is poorly developed, it forms a measurable plane sufficiently often for the orientation of the inclusions to be studied. It thus proved possible

to erect a structural picture of the orientation of the inclusions within the Crathie Granite Complex. As many small inclusions are visibly rotated with respect to adjacent larger inclusions, all the measurements used were taken from inclusions over one foot in length. It is hoped that this has eliminated, at least in part, irregular local variations which are clearly of no significance in determining the orientation of included material within the Crathie Complex as a whole.

The orientation of the large inclusions shows, over most of the complex, an ordered structural pattern, rather than one of randomly orientated, displaced and rotated, inclusions, thus confirming the general parallelism of neighbouring inclusions seen over short distances in the field.

Structurally the inclusions occurring within the Crathie Granite Complex fall into three distinct geographical groups -

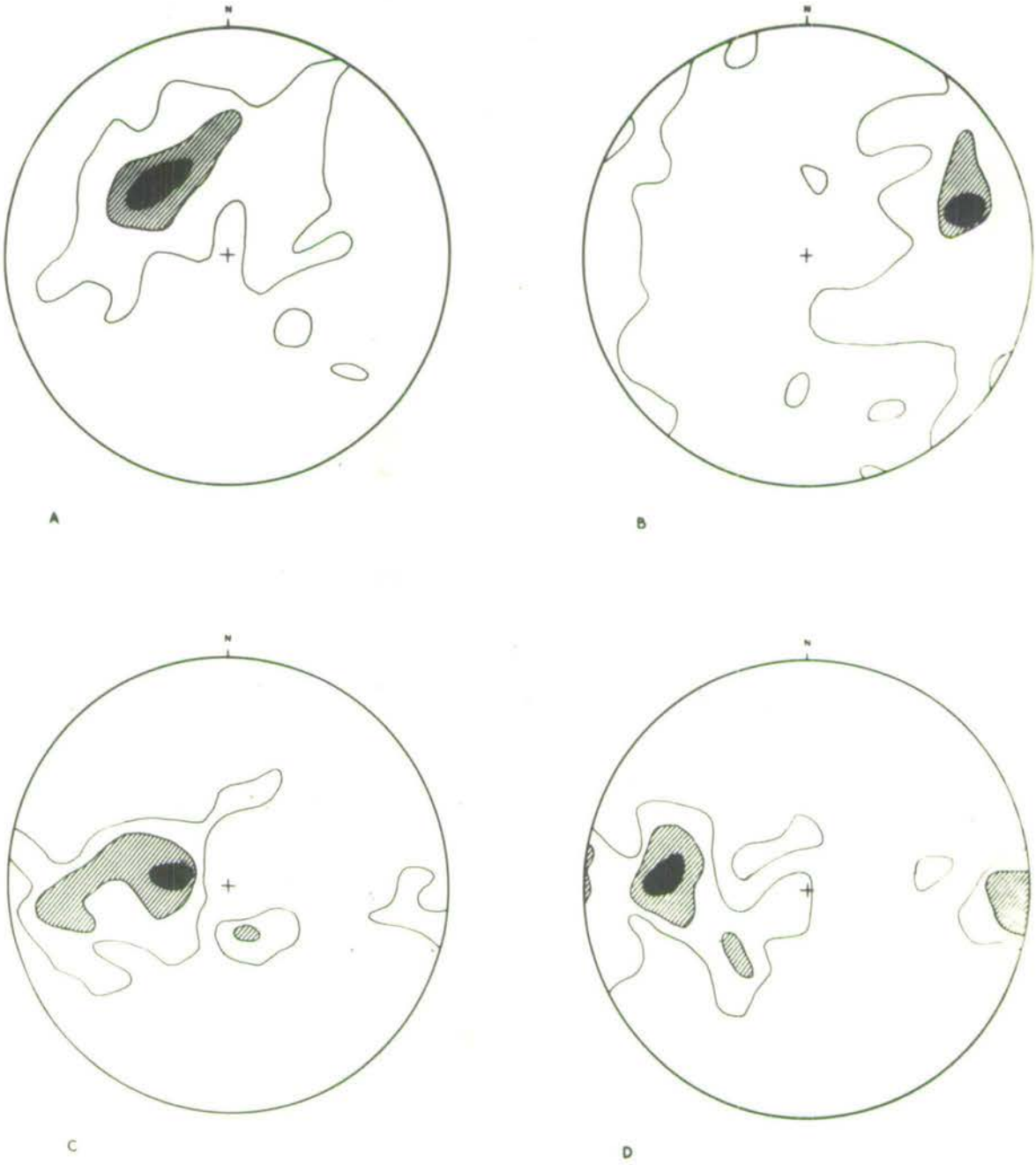
1) on Sron Dubh and the Torgalter Burn.

2) to the north of Crathie, on Creag a' Chlamhainn, Knock of Lawsie and towards the Strone.

3) at Dalnabo, Little Crag and Craig of Tullich.

In Fig. 25, A, B and C the π-poles to compositional banding of metasediments and to schistosity planes of epidiorite from the above areas have been plotted, and their densities contoured. This shows the homogeneity of each area, and the contrast between them. As these structural patterns cannot be directly related to each other, each area will be described separately.

Fig. 25



Structures within the Crathie Granite Complex.

A - poles of 182 schistosity planes in inclusions on Sron Dubh.

B - poles of 312 schistosity planes in inclusions around Cairnshiel.

C - poles of 102 schistosity planes in inclusions around Crathie.

D - poles of 41 foliation planes in igneous rocks around Crathie.

Contours at 1-5-10 per cent.

Sron Dubh. Despite the considerable amount of disorientation of small inclusions which is characteristic of this area, and is especially well developed to the SW end of Sron Dubh, the π-diagram (Fig. 25 A) shows a fairly well developed great circle girdle lying about an axis which plunges at about 40° to the SE. This girdle closely resembles that obtained from the poles of schistosity planes within the SW unit of the country rocks around Ballater (Fig. 6 B), the maxima and the orientation of the girdles in the two projections coinciding almost exactly. The greater spread of the lower contours in the π-pole diagram from Sron Dubh is probably the result of a slight degree of disorientation of some of the inclusions measured.

β-diagrams were constructed from small sub-divisions of the Sron Dubh structural region, the resulting projections being given in Fig. 30, I-VII (end pocket). These confirm the homogeneity of the fabric across Sron Dubh, all the maxima of the β-axes obtained, with one exception, plunging to the SE at a moderate angle, as suggested by the development of the bedding plane girdle.

No small folds or lineations were seen among the pelitic rocks of Sron Dubh.

The structural evidence thus strongly suggests that the larger inclusions of Sron Dubh have not been significantly rotated with respect to the country rocks which outcrop over two miles to the east, despite their inclusion within, and intensive veining by, the Crathie Granite

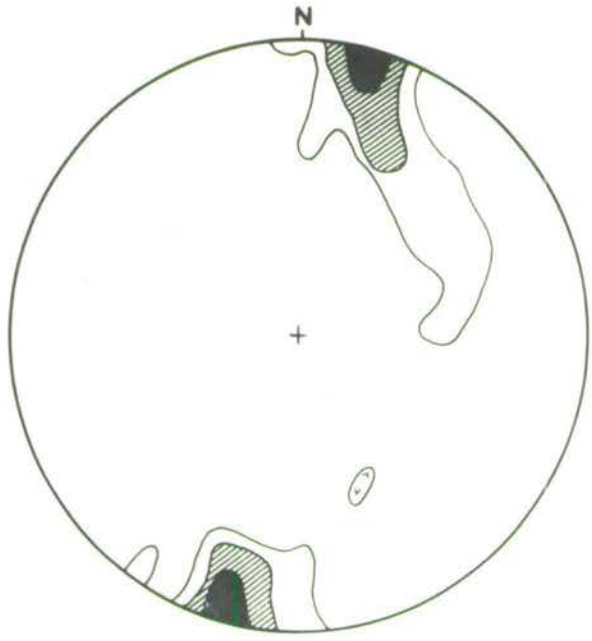
Complex, and despite visible signs of fracture of some inclusions and rotation of others.

Inclusions North of Crathie. When π-poles to schistosity and bedding from inclusions within this area are plotted and contoured, a rather poorly developed great circle girdle trending EW about an almost horizontal NS axis is obtained (Fig. 25 C). This is in complete contrast to the girdle obtained from Sron Dubh.

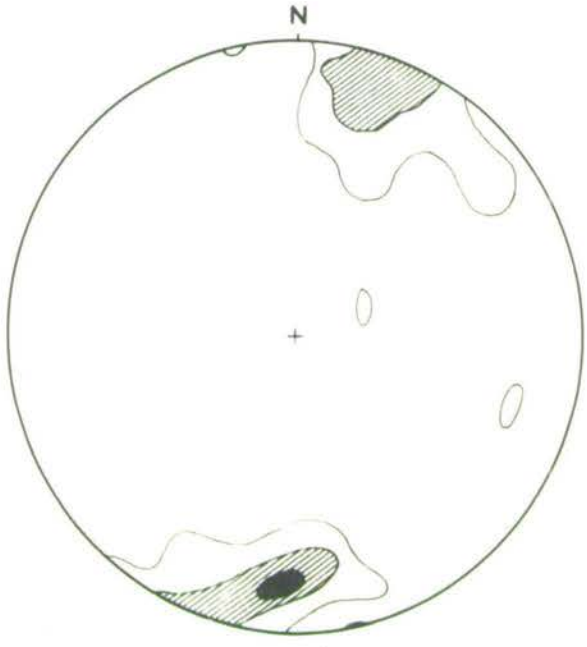
β-diagrams constructed from small sub-divisions of this area (Fig. 30, VIII - XIII) show maxima for β-axes plunging in a spread, all of which are approximately to north or south at low angles. In this case, although maxima are sometimes rather low, the approximately constant orientation of the maxima within neighbouring sub-divisions is taken to indicate that the maxima are significant and that their low value is probably the result of some degree of disorientation of the inclusions. It can be seen from the great circle girdles of the β-diagrams, which represent the average plane of schistosity and bedding, that the latter have a steep dip throughout this area with the exception of the southern part of Creag a' Chlamhainn, where the average plane dips at about 30° to the east. Although faulting is not seen, the disposition of the various rock types suggests that a zone of faulting runs across Creag a' Chlamhainn at approximately the junction of these two regions. This faulting may explain the rapid change in dip at this point.

Visible folding is not present in the pelites and epidiorites of this area, but folding is developed in the marble quarry at the SE end of Creag a' Chlamhainn. There is an early set of small similar folds with limb lengths of six inches to two feet. These plunge to the NE at low angles of varying inclination. A later set of larger monoclines, with limb length often as much as 20 feet, plunges to the south at about 30°. The presence of this later group of folds may explain the varying plunge of the earlier set.

Within this area, especially on the Knock of Lawsie and on Creag a' Chlamhainn, the foliation of the igneous rocks of the Crathie Granite Complex is sufficiently well developed to provide a measurable plane in a number of exposures. These measurements were plotted on a π-pole diagram and their densities contoured (Fig. 25 D). The result closely resembles the π-pole diagram obtained from poles to the schistosity and bedding planes from inclusions within the same area (Fig. 25 C). β-diagrams were constructed from both sets of measurements and these again show a strong similarity with maxima plunging approximately horizontal and just E of N (Fig. 26). This variation in the orientation of the foliation cannot be associated with any boundaries to the granitic rocks, nor can the variation in the dip of the foliation be traced in any particular direction. The foliation thus appears to be folded on an approximately horizontal, N by E, axis, with the inclusions lying with their structural elements parallel to this foliation.



A



B

Structure of the Crathie Granite Complex around Crathie.

A - β -diagram constructed from schistosity planes of inclusions

B - β -diagram constructed from foliation planes in igneous rocks.

Contours at 2-5-10 per cent.

Fig. 26

Assuming the possibility that the metamorphic rocks were originally orientated similarily to the country rocks and the inclusions of Sron Dubh, it would require their rotation as a block through an angle of 60° about an axis plunging at 45° to the WNW to produce their present orientation. At present it is not possible to evaluate the probability of rotation having taken place; this orientation of the metamorphic rocks may have been present before the intrusion of the igneous rocks.

Dalnabo, etc. The structures of the inclusions in this region are extremely complex, the pelites in practically every exposure being heavily contorted and cut by at least two sets of cleavages. The π-pole diagram from bedding-schistosity planes in this region shows a wide scatter of points with no significant maximum (Fig. 25 B). These rocks were not suitable for the construction of β-diagrams over most of their area of exposure, and their orientation is indicated in Fig. 30 (end pocket) by the plot of their average easterly and westerly dipping planes. Within small parts of this area however, relatively good maxima were obtained from β-diagrams, and these β-axes were confirmed by direct measurement of small folds (notably XXXIV and XXXV in Fig. 30). Over the remainder of the Dalnabo region measurements of small folds gave a wide variation of orientation. Pl VI B shows a typical well exposed contorted metasedimentary inclusion from sub-division XXXV where the minor folds plunge to the south at moderate angles. Over most of this area exposure was poor and the minor structures were not readily measurable.

The variation of orientation of the structural elements in the Dalnabo region is considerable, but as exposure did not permit a detailed statistical study of these structures, it was not possible to determine whether this variation is the result of pre-Crathie Complex structures, or the result of rotation during the emplacement of the granitic rocks.

Parliament Knowe. There were insufficient numbers of inclusions on Parliament Knowe for these to be treated statistically. However, when the inclusions are plotted on a map, the various petrographic types trace out a stratigraphy in the inclusions (Fig. 22). This would indicate that, although the inclusions are now at some distance from each other, they have probably been very little disorientated with respect to each other. The average strike of the inclusions varies from N-S to NNW-SSE.

DISCUSSION

The consideration of the origin of the Crathie Granite Complex is complicated by the fact that only part of the mass was included in this study, and no marginal relationships were exposed. The only previous description of these rocks is by Barrow and Craig (1912), in which they state that "on the north side of the Dee an extraordinary number of small patches of diorite are met with" and they consider that these represent the crests of an underlying continuous mass of diorite. From their map (Sheet 65) the intermediate rocks have an extremely complex outcrop and do not form

a coherent mass. Their descriptions of the small intermediate bodies fringing the Lochnagar mass around its eastern margin, as far south as Glen Doll, indicates that these bodies typically exhibit many of the characteristics of the Crathie Granite Complex. A regional study of these masses would thus be required in order to consider fully the origin of the Crathie Complex. However some conclusions concerning the origin of the Crathie Granite Complex can be drawn from the available evidence.

The evidence of flow in the Crathie Granite Complex, and therefore for the presence of magmatic material, will be considered first. In this context the term magma is used as defined by Scrope (1872, p.121); "a magma.....composed of crystalline or granular particles to which a certain mobility is given by an interstitial fluid."

The operation of some degree of flow in the complex is indicated by the displacement and rotation of small inclusions with respect to adjacent larger inclusions, and the differential movement of the latter. This differential movement is generally difficult to distinguish owing to the limited variety of inclusion type in many places. The invasion of earlier consolidated rocks by later, often definitely dilational, acid veins also indicates the presence of fluid material.

The foliation of the intermediate rocks is also regarded as a flow structure. Although the dip and strike of the foliation parallels that of the associated inclusions, it is considered that the latter were probably rotated into parallelism with the foliation, since their dimensions

are related to their schistosity planes. There is little evidence to suggest that the igneous foliation represents remnant bedding or schistosity; the composition of the igneous rocks bears no relationship to that of the inclusions, and no gradation from one to the other was seen. There are slight signs of fracture of feldspar crystals in the foliated rocks but the foliation is transgressed by isotropic aplitic veins; thus it does not appear to be a secondary structure of gneissose origin.

The granodiorite of Creag Mhor, containing abundant small inclusions of pelite, quartzite and epidiorite which are randomly orientated and thoroughly admixed, also indicates movement of a magma, although in thin section this granodiorite has a much more crystalloblastic texture than the majority of the igneous rocks (cf. Pl XVIII and XIX).

From the above criteria it has been concluded that the Crathie Granite Complex was intruded in a magmatic state.

Although the large inclusions of Sron Dubh do not appear to have been rotated with respect to the country rocks, those around Crathie and Gairnshiel have a distinctly different orientation. Many of these inclusions are definitely enclosed by granite both above and below, and it is considered that the metamorphic rocks have probably been incorporated into the granite in large masses; these masses at Crathie and Gairnshiel were rotated, then they were broken up into a number of smaller fragments which were spread apart but little rotated with respect to each other.

By contrast, the evidence for assimilation and replacement of country rock is limited. The constant orientation of the inclusions, especially those on Sron Dubh which are conformable with the structures of the country rocks, might be taken to indicate replacement in situ. So also might the presence of a ghost stratigraphy in some parts of the complex. The lack of supporting mineralogical and textural evidence of replacement makes a breaking up of large inclusions, as suggested above, more acceptable.

Textural evidence of replacement is limited; there is no evidence of mobilisation of sediments, and contacts between igneous and metamorphic rocks are, in the main, sharp. The majority of the rocks of the complex have typically igneous textures.

There is little sign of reaction between the more resistant country rocks and the igneous rocks. Occasionally small epidioritic inclusions show some slight introduction of quartz but, in general, reaction with the basic rocks is restricted to the development of a marginal biotite-rich zone a few millimetres wide. There is a complete lack of amphibole-rich clots and streaks showing gradual assimilation by the igneous rocks, nor is there any increase in amphibole in the rocks around the basic inclusions. Such phenomena were described by Pitcher (1952) from the Thorr Granodiorite of Donegal, in which he interpreted some assimilation of metadoleritic material. Similarly there is little evidence of incorporation of quartzose or calcareous sediments.

The pelitic inclusions however have been partially assimilated. The assimilation is probably limited in extent as pelitic inclusions are still abundant. This is in contrast to the Thorr Granodiorite (Pitcher op.cit.) where pelitic inclusions are relatively rare, in comparison to their occurrence in the country rocks. Also much of the adamellite surrounding the pelites of Sron Dubh contains very sparse biotite, which would not be expected if considerable assimilation had occurred. The pelitic inclusions show some marginal introduction of plagioclase, potash feldspar and quartz, and are invaded by sinuous, non-dilational, granitic veinlets. Many of the pelitic inclusions are associated with small shadowy basic patches showing all stages from partially assimilated pelite to biotite-rich granite. The presence of cordierite-bearing clots in the granite also indicates the incorporation of pelitic material. Although the other constituents of the pelites are readily assimilated in granite, experimental data in the system K_2O-Al_2O_3-SiO_2 show that granitic magmas, even if superheated by 200°, could not dissolve more than a small excess of Al_2O_3, (Schairer & Bowen 1955). An increase in biotite in some of the granitic rocks in the vicinity of the pelitic inclusions, forming hornblende-free rocks of intermediate composition, probably indicates that this is a contact facies of hybrid character derived by the incorporation of pelitic material. This facies is however of very restricted occurrence.

Banding in the rocks of the Crathie Granite Complex, such as might indicate the replacement of banded sediments, is found very rarely, and is restricted to the foliated and inclusion-free intermediate rocks. There is

no other evidence that these rocks have a replacement origin, and the banding more probably results from the pulling out of different fractions of a heterogeneous magma during the flow which produced the foliation.

From the above evidence it may be concluded that the rocks of the Crathie Granite Complex were intruded in the form of a magma which was formed elsewhere and travelled bodily into its present position. The degree of fluidity of this magma will now be considered.

The lack of rotation, and slight displacement, of the larger inclusions with respect to each other over any small part of the complex, indicates that the magma was on the whole very viscous. The rotation of the small fragments may have been caused by local eddying. Other criteria suggesting a high viscosity for the magma are:

1) the lack of any suggestion of gravity sorting of inclusions both dense and light rock types being found in close proximity to one another;

2) the presence of a flow foliation in places, suggesting that the magma was partially crystalline when intruded. This is supported by the occasional presence of flexured and fractured feldspar crystals in the foliated rocks;

3) the presence of a ghost stratigraphy in some areas, and the suspicion that there has been little large scale displacement of stratigraphic groups throughout the complex (Fig. 25);

4) the variation in grain size and absence of miarolitic cavities.

All of the above criteria suggest that the rocks of the Crathie Complex were in a highly viscous state at the time of intrusion. Locally the magma may have been relatively fluid, for example at Creag Mhor where the granodiorite contains a thoroughly admixed group of inclusions of variegated type.

The amount of reaction between the inclusions and the igneous rocks also throws some light on the state of the magma at the time of intrusion. The minerals of the epidiorite inclusions lie higher in the reaction series than the granitic mineral assemblage (Bowen 1928, p.60) and thus no sign of melting is to be expected. In this case the granite has not even been able to convert the epidiorites to the higher temperature pyroxene-plagioclase assemblage. The granite has however had sufficient heat to convert the calc-silicate rocks to assemblages indicative of the pyroxene-hornfels facies.

Those marbles containing free calcite are significant temperature indicators since free carbonate melts at 650°C in the presence of water at 2000 bars, and at 740°C at 1,000 bars (Wyllie and Tuttle 1959). Some granites under approximately the same conditions are almost completely molten (Goranson 1932, Tuttle and Bowen 1958). Wyllie and Tuttle suggest that the presence of water vapour and other volatile materials from the magma would produce more melting than would occur in the closed system, whilst the presence of alkalis in the natural carbonate would probably lower the melting temperature still further. These facts indicate that the granite cannot have been at a temperature much above the melting point

of most of its constituents, and probably below that of some of them, as there is no visible enrichment of lime in the vicinity of the marble inclusions, or rounding or disaggregation of the inclusions.

There are comparatively few records of reaction between acid magmas and siliceous inclusions; for rocks of granitic composition this would require considerable superheat (Turner and Verhoogen 1960, p.158). Thus it is not surprising that there is little sign of reaction between quartzose inclusions and granite in the Crathie Granite Complex.

The assimilation of small amounts of pelitic material would require comparatively little heat from the magma. This could be produced by the concomitant crystallisation from the magma of minerals similar to those which are being recrystallised in the pelite.

Thus it may be concluded that the rocks of the complex were probably emplaced at a temperature below the melting point of some of their constituents, except perhaps locally. Much of the magma probably contained a fairly high proportion of crystalline material, possibly flowing as a plastic solid rather than a true liquid. This would account for the high viscosity at the time of intrusion. The temperature of the magma at the time of intrusion was probably below 700°C. The basic rocks appear to have been more viscous than the acid types, by which they are veined. The restriction of the foliation to these rocks indicates that they probably contained a higher proportion of crystalline material than did the acid rocks.

As the inclusions have been but little moved with respect to each other, and on Sron Dubh are not moved with respect to the country rocks, it is likely that the present level of exposure is fairly close to the roof of the complex. This suggestion is supported by the low dip of the foliation. The folding of the foliation around approximately horizontal axes may have been produced by the buckling of a semi-plastic solid as the result of continued intrusion pressure. The presence of local areas of pressure is indicated by the fracture of some of the pelitic inclusions of Sron Dubh, and by the separating and pushing apart of inclusions which retain their stratigraphic continuity (e.g Fig. 22). The lack of evidence of marginal structural relations makes it impossible to evaluate further the importance of pressure during the emplacement of the complex.

The origin and relationships of the different members of the Crathie Granite Complex will now be considered. The spotted monzonite is clearly separated from the other members of the complex by virtue of its occurrence only as inclusions within the latter. However, as it differs from the other members only slightly in mineral proportions and texture, it is regarded as a consanguinous part of the complex. Like the other members of the complex the spotted monzonite is somewhat heterogeneous.

As the spotted monzonite is found only in the form of inclusions, little can be determined concerning its origin. However it must have

solidified before the other rocks of the complex, and was sufficiently brittle to be fractured into angular blocks while other members were still able to flow. The enclosing rocks are never chilled against the inclusions, so the spotted monzonite was still fairly warm at the time of incorporation.

Contacts between the spotted monzonite and the enclosing rocks vary from sharp to gradational, the latter showing some marginal introduction of quartz and sodic plagioclase. These contact relationships could be produced in different ways:-

1) if some inclusions were incorporated earlier in the sequence of events than others,

2) if the host rock varied in its ability to homogenise itself with the included material,

3) if the temperature of different parts of the spotted monzonite varied when it was broken up,

all, or any, of these mechanisms could have operated.

As the present level of exposure is probably close to the roof of the mass, and no mass of spotted monzonite is exposed in the near vicinity, it is probable that the spotted monzonite inclusions have been brought up from a level below that of the present level of erosion. The monzonite may have solidified in the conduit, and been broken up and incorporated as the later members forced their way through it.

All the later members of the complex, although varied in mineralogy, show close affinities and are clearly members of one intrusion.

Nevertheless they form a random scatter when plotted on a graph (Fig. 27) and cannot be related serially. In composition the members range through the normal series of acid differentiated rocks from diorite, through granodiorite, to adamellite and aplite (Nockolds 1946). Although the acid types appear to have been fluid at a later stage than the intermediate rocks which they vein, it is clear that this complex represents one intrusion of heterogeneous magma, rather than the staggered intrusion of a series of differentiation products. This is shown by the contact relations between the various members as listed below:-

1) the various petrographic types are intermingled in a very complicated fashion

2) there is a complete lack of chilled contacts

3) these contacts are predominantly gradational, often over several yards

4) there has been some interchange of material at the contacts, with the production of feldspar porphyroblasts in some cases.

From the contact evidence given above, it appears that some degree of homogenisation was operating. This was probably inhibited by the high viscosity of the magma. The occurrence of reversals in the normal order of crystallisation, such as the mantleing of biotite by hornblende, and plagioclase by plagioclase, indicates that the temperature did not always fall steadily after intrusion. This temperature variation may have resulted from differential movements of various parts of the complex, bringing hotter regions in contact with cooler, and raising the temperature of the latter sufficiently to reverse the crystallisation trend.

Graph of modal analyses from the Crathie Granite Complex

(Tables XVII - XIX)

Fig. 27

The origin of the heterogeneous magma must remain in doubt. The group of rock types present could be produced in one of two ways:

1) by differentiation of an originally homogeneous magma, the members of which were subsequently mixed together during intrusion

2) by melting, or granitisation and rheomorphism, of a mixed series of sediments, and subsequent intrusion of the magma produced.

The first hypothesis is perhaps supported by the fact that the more basic rocks, which would have crystallised first during differentiation, were at the time of intrusion relatively viscous compared with the acid rocks. However there is insufficient evidence available to determine the origin of the magma.

At a late stage of cooling the Crathie Granite Complex was partially affected by considerable alteration, probably caused by the action of hydrothermal fluids. This affects all the rock types of the complex, cutting across the contacts between different rock types. In places this alteration is restricted to the walls of narrow aplitic veins, which it is suggested represent the consolidated paths of these last hydrothermal solutions.

A late stage potash metasomatism, resulting in the production of large porphyroblasts of microcline, occurs in many parts of the complex. These microcline crystals are extremely fresh and are unaffected by the hydrothermal alterations. They are thus either contemporaneous with,

or later than, the hydrothermal fluids. Wahlstrom (1950, p.261) states that potash may be present in notable amounts in late hydrothermal material, although soda is more common. Late stage potash metasomatism of this type has been often reported from granodioritic rocks (Pitcher 1952, King 1947).

The conclusion reached in this study is that the Crathie Granite Complex was emplaced in the form of a highly viscous partially crystallised magma. This was of heterogeneous composition, and included fragments of an earlier consolidated portion of the magma. The complex incorporated large blocks of the roof rocks which were rotated and then broken up into a large number of small fragments. There was a limited amount of assimilation of the pelitic material. At a late stage aplitic veins cut the rocks of the complex, associated with hydrothermal alteration, and the rocks were subjected to widespread potash metasomatism.

MICRODIORITES

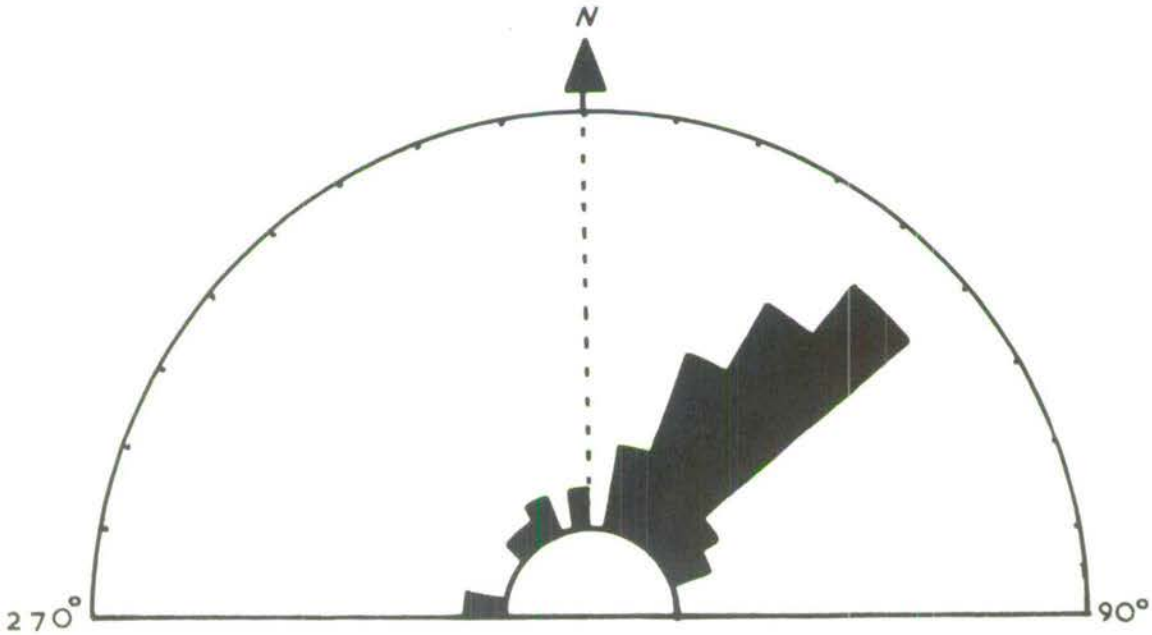
A suite of intermediate dykes occurs within the Geallaig district. These transgress, and therefore post-date, the Dalradian rocks and the Crathie Granite Complex. Nowhere were they seen to cut the Ballater Granite, although large areas of the latter are well exposed, whilst one dyke shows alteration in the vicinity of the Ballater Granite. This group was therefore intruded at some time after the emplacement of the Crathie Granite Complex, but preceding that of the Ballater Granite.

Those members of this intermediate dyke suite which occur to the north and east of Coilacriech have been described in detail by Tocher (1961). Members of this suite are however even more abundant in the region of Crathie where they tend to contain a slightly higher proportion of the more acid, orthoclase-bearing, granophyric varieties than is reported by Tocher. The dykes range in composition from microgranodiorite to microdiorite, the latter being predominant. All gradations are found between the two, and therefore only one comprehensive petrographic description will be given.

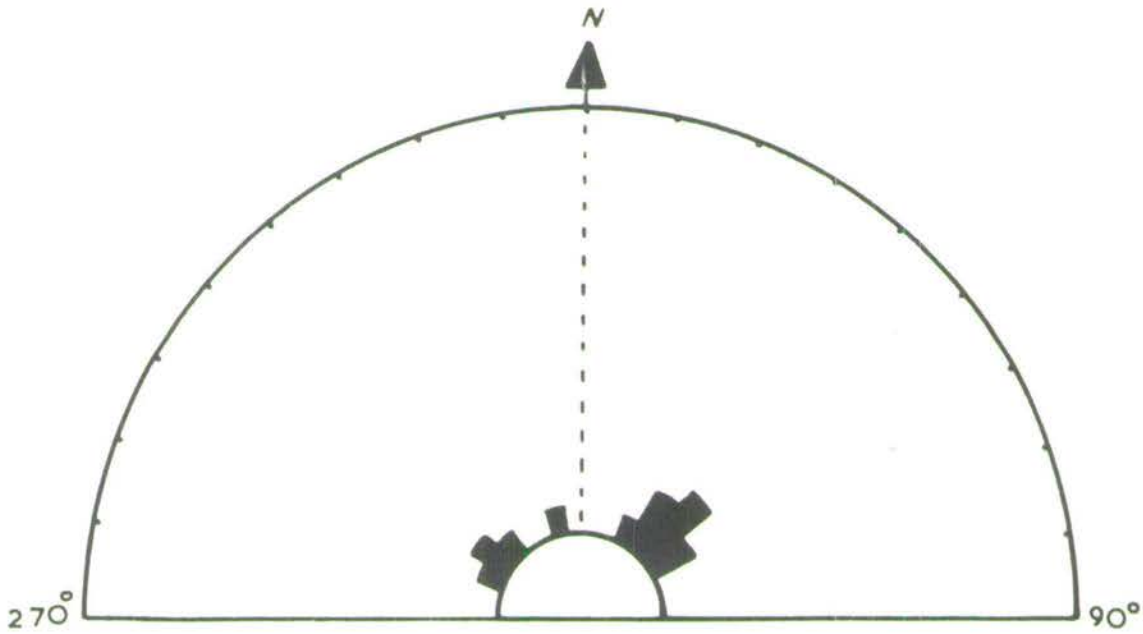
The dykes vary in width from about six inches to 30 feet, the commonest width being five - ten feet. Contacts with the country rock are sharp, and the dykes sometimes interleave the country rocks along their planes of schistosity. The dykes have very fine-grained margins, but the country rocks show little, if any, contact alteration against them. The dykes have a dominant NE-SW trend (Fig. 28); dips can rarely be measured, but where estimable are close to the vertical.

Petrography. In hand specimen these are tough, pale grey, compact rocks, with macroscopic quartz, feldspar and hornblende phenocrysts. When weathered, a pink skin which is distinctive in the field forms on the rock.

In thin section the dykes are seen to be universally porphyritic, the phenocrysts comprising quartz, orthoclase, plagioclase, hornblende and biotite. Plagioclase is dominant and the only mineral found as a phenocryst



MICROTONALITIC – 55 Dykes



QUARTZ PORPHYRIES – 15 Dykes

Rose diagram showing dyke trends within the Geallaig district.

Fig. 28

in every specimen; in a few cases it was the only phenocryst mineral. In about a third of the cases all five of the minerals listed above occur as phenocrysts within the one rock.

The groundmass is fine grained and contains all the above mentioned minerals, but apart from plagioclase their proportions vary considerably. The texture varies from somewhat granophyric in the more acid types, to a felt of randomly orientated plagioclase laths with the other minerals interstitially, in the slightly more basic varieties. A typical field from a thin section of such a rock is shown in Pl XXIII B.

Phenocrysts. Quartz occurs in rounded phenocrysts up to one mm. across which are very sparsely distributed and often absent. Where a granophyric texture is present it tends to rim the quartz crystals; in the more basic types the quartz, where present, is rimmed by crystals of hornblende. Inclusions of groundmass material and of small hornblende crystals, are often present.

Phenocrysts of orthoclase, often perthitic, are sometimes present but never abundant. They are much corroded and include small quartz crystals, often micrographically intergrown with their host; such intergrowths are restricted to an outer zone of the orthoclase crystal. The orthoclase also includes small hornblende crystals and magnetite.

Plagioclase in every case forms the predominant phenocryst mineral. It is often euhedral with somewhat corroded margins. The crystals show strong zoning which is often oscillatory, with up to four reversions.

In most of the dykes the plagioclase crystal cores have a composition of An_{30-35} while the margins are about An_{25}. In the more basic varieties the core is about An_{50} and the margin again An_{25}.

Biotite forms sparse phenocrysts in large ragged flakes with frequent small inclusions of apatite and magnetite. These are partially altered to penninitic chlorite. The pleochroic scheme is X-straw yellow, Y-medium brown, Z-reddish brown. Biotite is also found replacing hornblende as flakes and stringers along the hornblende cleavages; in some cases biotite completely pseudomorphs hornblende.

Hornblende phenocrysts, often glomeroporphyritic, occur in variable amount. They are in ragged bladed crystals with a pleochroic scheme X-greenish yellow, Y-medium green, Z-blue green. Twinning is common. In some cases the amphibole is present in the form of a fine mat of uralite pseudomorphing pyroxene phenocrysts, remnants of which are sometimes present. The uralite often shows marginal alteration to biotite and chlorite.

Groundmass. The quartz of the groundmass is ubiquitous, occurring interstitially, as granophyric intergrowths, and as inclusions within other minerals.

Orthoclase in the groundmass is often absent, and never abundant, in small interstitial crystals. Plagioclase forms the most abundant mineral in tabular crystals with irregular margins. The composition varies from slightly zoned oligoclase of An_{15-20} in the more acid types to crystals zoned from An_{45} to An_{25} in the more basic types.

The proportion of biotite in the groundmass varies greatly. Where abundant it tends to form clots associated with hornblende, apatite, magnetite and sphene. The hornblende forms ragged blades, which are never uralitic in the groundmass. Hornblende is sometimes present only in accessory proportions.

Irregular masses of sphene, pleochroic from neutral to rose-red, are present in accessory amounts. Apatite forms sparse needles, magnetite is relatively common, and sparse cubes of pyrite also occur.

In some cases there has been much introduction of carbonate, which replaces the ferromagnesian phenocrysts and patches of the groundmass. In other cases the groundmass contains patches of penninitic chlorite.

One specimen of the microdiorite which was exposed a few yards from the contact of the Ballater Granite is highly chloritised, and the feldspar considerably sericitised, thus indicating a certain amount of alteration of the dyke by the granite.

Discussion. The NE-SW trend of these dykes can be related to the jointing of the country rocks. Jointing is well developed in the Crathie Granite Complex and its enclosed masses of metasediment, the same joint sets cutting across both. Although the most prominent joint set trends NW-SW, there is a slightly weaker set running NE-SE, and it is along this plane of weakness that the dykes appear to have been intruded. Jointing is poorly and irregularly developed in the metasediments around Ballater, and here the distribution of the dykes

is less strict and their density lower. Thus the frequency of intrusion decreases where the NE-SW joint set is relatively poorly developed.

This NE-SW dyke and joint trend is a regional, rather than a local phenomenon. Throughout the Caledonian minor intrusions of Scotland typified by the linear dyke swarms of Glen Etive and Ben Nevis (Richey 1939) there is a widespread constancy of trend in this NE-SW direction, while in the same general group, nearer at hand, there is the Lochnagar dyke swarm only about 12 miles to the south of the Geallaig district. The microdiorites of this area fall lithologically within the range of these Caledonian dyke swarms which are generally of intermediate composition. Owing to their proximity to the Lochnagar dyke swarm, and the similarity of trend and composition of the two sets, it is tempting to suggest that the microdiorites of the Geallaig area form the northward extension of the Lochnagar swarm. However sufficient evidence is not yet available to draw a definite conclusion on this point.

Bisset (1933) described dykes of a similar composition and trend to the above, from the vicinity of the Skene Complex, about 30 miles east of Ballater. These transgress his "earlier Caledonian" granites and precede his "later Caledonian" granites, thus bearing the same age relationships to the igneous rocks as do the microdiorites to the igneous rocks of the Geallaig district. It thus appears likely that this intermediate dyke swarm extends eastwards almost to Aberdeen.

BALLATER GRANITE

FIELD RELATIONS

The Ballater granite is well exposed in southerly facing crags and on the shoulders of hills, and forms massive screes of large blocks on some of the steeper hillsides. However exposure is poor on the more rounded northerly facing slopes, and towards the contacts with other rock types. On some of the hill slopes the probability of underlying granite is suggested by a high proportion of granitic boulders and, owing to the lack of exposure, some proportion of the mapping had to be based on such evidence.

This homogeneous coarse pink granite outcrops in the eastern half of the Geallaig area (Fig. 31, end pocket). It completely underlies Crannach Hill at the eastern boundary of the area mapped, and extends westward from the southern end of this hill, outcropping to the north of Ballater on Craigendarroch, in the Pass of Ballater, and for three quarters of a mile to the north of the Pass. This section is continuous with the Hill of Fare granite which extends for over 30 miles to the east. It is separated by a belt of epidiorite and metasediment almost two miles wide, from a narrow strip of similar granite which broadens northwards and crosses the Gairn to the west of Candacraig. The granite of Lary Hill, further to the north, may be a continuation of this.

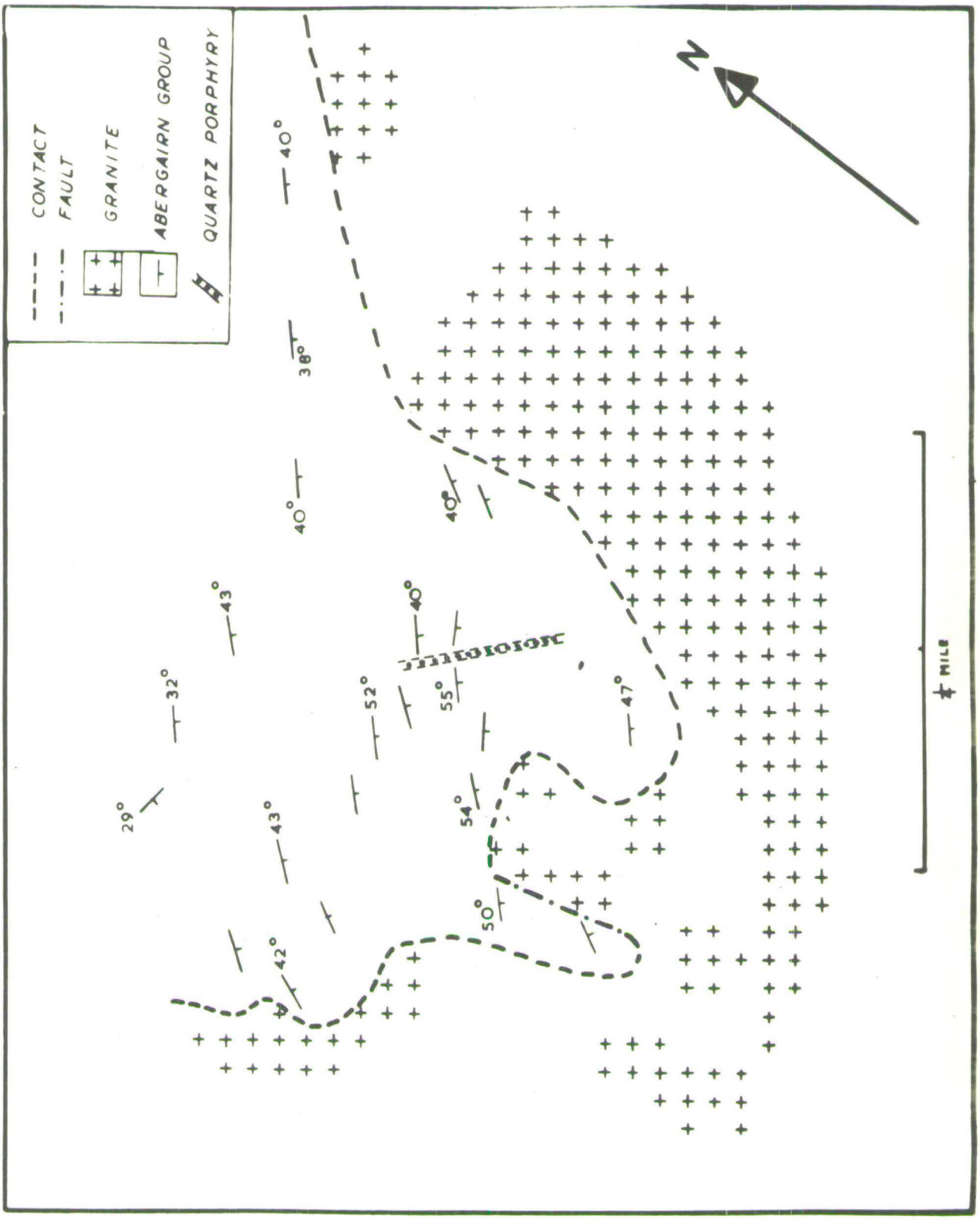
Further west, in the Dee valley, granite of Ballater type is exposed to the north of Coilacriech Inn and on the hill slopes west of this as far as Rinabaich, and can be traced northward up the eastern slopes of Geallaig Hill as far as the watershed. The northern slopes of Geallaig Hill, facing the Gairn, are however practically devoid of exposures, so the continuation of the granite cannot be determined. This granite to the west of the Gairn forms the eastern end of the "Glen Gairn Granite" as described by the Geological Survey, (Barrow and Craig 1912).

To the west of Rinabaich outcrops are absent until at Sron Dubh, the Crathie Granite Complex is exposed.

A small boss of pegmatitic granite of Ballater granite type protrudes through the epidiorite-schist assemblage to the northeast of Coilacriech.

Owing to large gaps in the available exposure, it is virtually impossible to attempt to draw boundaries to the Ballater Granite except over short distances in isolated places. The contact of the Ballater granite with its country rocks can however be traced to within a few yards at several localities.

A sketch map (Fig. 29) of the contact relations between granite and epidiorite to the north of the Pass of Ballater shows that the contact is, in detail, irregular and cross-cutting. The actual contact is not seen



Contact between the Ballater Granite and the Abergairn Group, north of the Pass of Ballater

Fig. 29

there and, as the ground surface is approximately horizontal, no estimate of its inclination can be made. In this region no aplitic veins were seen in the country rocks.

The contact between granite and the epidiorite-schist assemblage can also be locally defined to within a few feet about a mile to the north-west of Bridge of Gairn. Here again it is somewhat irregular in outcrop. The actual contact is visible over about two yards (Pl I B); it is extremely sharp, cuts across the schistosity, and consists of a series of parallel projections of granite extending into hornfelsed schist and epidiorite at an angle to the schistosity of the latter. These projections vary from six inches to three feet in width, are steeply inclined, and do not extend for more than a few yards into the country rock. Occasional aplitic veins only a few inches wide can be found cutting the country rocks for up to 150 yards from the contact.

The granite is locally cut by quartz veins which vary in width from one half inch to five feet. Rarely these consist of practically pure quartz, but more commonly they are made up of a network of quartz veinlets of varying width which ramify in an intricate plexus, enclosing angular areas of quartz-rich granite. A few of the veins are miarolitic. In some cases the granite beside these veins is apparently unaltered, but in others the feldspar is considerably replaced by gilbertite for up to four inches from the vein margin. Occasionally the veins contain a central zone composed of calcite and fluorite. These quartz veins are not very common, but are distributed throughout the granite with no apparent

relation to its margins. They are sub-vertical, with a spread in trend which shows a maximum between 350°N and 360°N.

The joints of the granite have not received detailed statistical attention, but there are three sub-vertical sets and one which is approximately horizontal. The sub-vertical sets trend roughly N-S, ENE-WSW, and NE-SW. The N-S set is approximately parallel to the maximum trend of the quartz veins.

PETROGRAPHY

The Ballater Granite is composed predominantly of adamellite (see Table XXI) but the name "Ballater Granite" is used as a general field term for the mass. This varies little throughout its outcrop within the Geallaig area. It is a coarse pink quartz-rich adamellite consisting essentially of quartz and feldspar with accessory mica. The average grain size is about 2 mm. A slight variation in grain size is almost the only change found over the large tract occupied by this rock type. The lack of variation is well seen in the Pass of Ballater, where cliffs of granite over 200 feet high are exposed.

A series of modal analyses were carried out on these rocks, (Table XXI). It was found that, in a rock of this grain size, a count of 2000 points gave an accuracy of one per cent over a particular thin section, but that a difference of up to 15 per cent in the proportions of quartz and potash feldspar was obtained from different sections taken from the same hand specimen. The plagioclase percentage was less variable. Therefore

TABLE XXI

BALLATER GRANITE — MODAL ANALYSES

Specimen No.	33M	1D	13M	1F	21D	8F	4F	3M	1M	24M	112F
Quartz	30	30	35	41	47	36	34	30	36	31	39
K-feldspar	31	38	39	26	25	45	41	31	45	26	35
Plagioclase	37	29	23	25	25	17	24	37	18	38	23
Muscovite	-	1	1	-	1	-	-	-	-	-	1
Biotite	2	2	1	6	2	2	1	2	1	5	2

Average of Counts from 2 Thin Sections from Each Specimen

No. of Points Counted per Thin Section 2000+

modal analyses were carried out on two thin sections from each specimen, and the average of the two results taken.

Normal Ballater Granite. In thin section this consists of quartz, microperthitic potash feldspar, oligoclase, a little biotite and rare muscovite. It is coarse grained with a hypidiomorphic granular texture. A typical field is shown in Pl XXII A.

The quartz occurs in anhedral crystal aggregates, individual crystals often attaining a diameter of 5 mm. Inter-quartz boundaries are often highly sutured, and the crystals show varying amounts of straining and fracture. There is a very minor development of myrmekitic intergrowths along some quartz-feldspar boundaries. The quartz contains small inclusions of potash feldspar, plagioclase, muscovite and biotite.

The microperthite is present in large anhedra up to 7 mm. across, showing simple Carlsbad twins, and rare albite-pericline twinning. In some cases the albite of the microperthite extends beyond the limits of the potash feldspar and forms a narrow rim around it. The microperthite includes small rounded quartz crystals, tabular plagioclase and occasional small mica crystals.

Plagioclase in these adamellites occurs predominantly in tabular, somewhat turbid, crystals averaging about 2 mm. in length. The composition varies from An_{32} to An_{40}. Zoning is virtually absent. Albite twinning is predominant, with a lesser development of twinning on two laws. Occasionally the twin lamellae are bent or fractured. Sparse inclusions of potash feldspar, quartz and muscovite are present.

Muscovite is present only in accessory quantity, as small anhedra often included within plagioclase. It is also found rimming, and intergrown with, biotite. The biotite is slightly more abundant, in subhedral to anhedral flakes; these seldom exceed 1 mm. in length. It occurs both interstitially and as inclusions within other minerals. The pleochroic scheme is X-straw yellow, Y-deep brown, Z-almost black, but in many cases it is almost completely pseudomorphed by penninitic chlorite. The biotite crystals enclose very small zircons, iron ore, and occasional apatite.

Accessory minerals include magnetite, in sparse irregular masses usually associated with, or included in, biotite and pyrite, much altered to haematite. Some apatite is present and very rare fluorite was found in one or two specimens. The latter is generally anhedral but occasionally euhedral. Spinel forms very rare, pale yellow crystals, while zircon is a somewhat commoner accessory mineral.

Sheared Variety of Ballater Granite. At one locality, just beside the contact with country rock (at locality F in Fig. 29) the granite has a shattered appearance and a deep orange colour. In thin section the quartz crystals are considerably strained and traversed by lines of fracture containing very finely comminuted quartz. Inter-quartz boundaries are highly sutured. The plagioclase twin lamellae are commonly bent, and often displaced by a series of shears, the displacement of individual twins being up to .03 mm (Pl XXII C). The alkali feldspar

shows strained extinction. The whole rock is cut by planes of shear which are filled by granulated quartzo-feldspathic material, while patches of epidote up to 2 mm. across are also present. From this sheared rock type, and from the shape of the granite contact at this point, a fault is inferred in Fig. 29.

Marginal Variations. As the granite is traced towards its periphery little change can be discerned until, at a distance of about 200 yards from the contact, a zone of very variable grain size is entered. The grain size, in general, tends to become finer towards the contact. This finer grained granite contains patches and lenses of pegmatitic material which have a very irregular form and grade into the surrounding rock; these become increasingly common towards the granite margin. Some of the pegmatitic segregations are miarolitic, with well formed quartz crystals bordering the cavities. In this region relatively fine grained segregations are also found within coarser granite. Often the marginal zone also contains segregations of pure quartz up to four feet across. At the contact itself the grain size is extremely irregular, and even 3 mm. from the contact some feldspar crystals attain a length of 6 mm. although the average grain size of the rock is about 1 mm.

The small boss of granite which protrudes through the country rocks to the NE of Coilacriech is very variable in grain size but, in contrast to most of the contact rocks, pegmatitic material is dominant. It is exposed on a knoll about 100 yards N-S by 25 yards E-W; the pegmatite is extremely coarse, feldspar crystals which are frequently as much as 15 cms.

long being associated with patches of granite averaging about 2 mm. in grain size. No contacts were visible around this boss.

In thin section the contact rocks show no appreciable change in mineralogy from the typical Ballater Granite, but there are slight textural changes. The grain size decreases, a myremekitic texture develops, and the quartz occurs in granophyric intergrowths with potash feldspar (Pl XXII B). Quartz inclusions in plagioclase also increase in frequency, and the crystals show less tendency to adopt crystal form. These textures are very patchily developed even within the range of one hand specimen. The composition of the plagioclase does not change towards the contact, but the biotite becomes completely chloritised.

Inclusions within the Ballater Granite. The Ballater Granite is completely devoid of undoubted xenoliths. At one place only, in the granite a few yards from the contact at the western end of Fig. 29, the granite contains a few segregations comparatively richer in biotite, and showing a well developed foliation. Apart from these characteristics the segregations are similar to the rest of the granite; only in these segregations does a linear or planar structure occur within the Ballater Granite. Whether these exceptional mafic patches are true segregations, or are xenoliths of endogeneous or exogeneous origin is not known.

Quartz-Rich Veins. The veins described above (p. 193) are, in the majority of cases, composed essentially of massive white quartz with subordinate feldspar, but occasionally they also contain traces of fluorite and very occasional cubes of galena, sometimes with associated

calcite. The calcite-fluorite combination tends to occur in a narrow central zone of the vein. Near the veins in some cases very small cubes of purple fluorite encrust the vertical joint faces of the granite. The fluorite of these rocks is often characterised by a concentric colour banding. In thin section the veins consist of very large crystals of relatively unstrained quartz, enclosing small patches of fine granitic material in which the feldspar is often much altered. Also in the vein are very large crystals of microperthite almost completely replaced by a greenish yellow mica, probably gilbertite. The biotite in this rock is completely chloritised.

The occurrence of a quartzose vein containing an unusually high degree of mineralisation is found within hornblende-schists near the granite margin, just east of Abergairn Farm. This is the site of a disused lead mine. Russell (1937) describes the presence of quartz, galena, zincblende, fluorite, cerussite, orthoclase and calcite from this locality, with minute traces of pyromorphite and chalcopyrite. No exposure is now available, and the only traces of the vein are in an overgrown and deeply weathered dump, within which blocks of quartz with some feldspar fluorite and calcite were found. These contained traces of galena and blende. Lead from this locality has been dated by radioactive methods and computed as 470 $\pm$ 40 million years old (Moorbath 1959). This vein is considered to be part of the same group as those within the granite, and these are considered to be manifestations of late stage hydrothermal activity penetrating up joints in the already largely cooled granite.

QUARTZ PORPHYRIES

The mineralogical composition of the quartz-porphyry dyke suite of the Geallaig area closely resembles that of the Ballater Granite. This, combined with the fact that this dyke suite transgresses every rock type in the area mapped (with the exception of the Ballater Granite into which it appears to merge — see below) strongly suggests that the quartz-porphyry dyke suite is related to the Ballater Granite, as apophyses of contemporaneous or slightly later age than the main granite mass. It seems likely that this suite is a minor and local phase of the neighbouring granite, in contrast to the microdiorites which probably form part of the widespread Caledonian dyke suite of Scotland.

The members of this dyke suite are found throughout the Geallaig area and, although relatively few in number, can be traced over long distances (Fig. 31, end pocket). The maximum width noted was 35 yards. The central portions of the wider dykes are, in hand specimen, massive pink rocks with macroscopic phenocrysts of quartz and feldspar up to 3 cms. in length, set in a fine grained quartzo-feldspathic matrix. Towards the contact with the country rocks the dykes become rapidly finer in grain, but are still visibly porphyritic. The country rocks show little alteration in the vicinity of the dykes.

The trend of the dykes falls into two main groups (Fig. 28), corresponding with the NE-SW and NW-SE joints of the country rocks. Although their general trend can usually be measured, the dykes deviate

slightly from their overall direction and have contacts which are irregular in detail; in places they have offshoots up to 3 inches wide which extend for several feet into the country rock.

In three cases dykes of this type may be traced towards the margin of the Ballater Granite, and in one case 150 yards to the NE of Coilacriech, as the margin of the granite is approached the dyke centre gradually changes from a very fine-grained coarsely porphyritic quartz-porphyry to a medium-grained practically non-porphyritic granite, closely resembling the Ballater Granite which is exposed only a few yards to the south. The dyke however retains its fine grained and highly porphyritic margins. It shows no signs of alteration by the neighbouring granite.

Petrography. In thin section the quartz-porphyry dykes consist of phenocrysts of quartz, plagioclase and orthoclase, often forming cumulophyric aggregates set in a quartzo-feldspathic matrix. A typical field is shown in Pl XXIII A.

The maximum length of the quartz phenocrysts is 5 mm.; these vary from euhedral to subhedral, some being partially resorbed with embayed and indistinct margins. Small inclusions of groundmass material are common, and there are also occasional small included biotite crystals.

Orthoclase phenocrysts, although subordinate to quartz, are greatly in excess of plagioclase. They form euhedra and subhedra up

to 3 cms. long in which perthitic intergrowths are common. Occasional larger tabular inclusions of plagioclase, and inclusions of groundmass material and small quartz crystals are also present . The alteration varies from a turbid dusting of kaolin to small flakes of sericitic mica.

The plagioclase phenocrysts form tabular crystals, often with embayed margins. The crystals are unzoned, show typical albite twinning, and have a composition of albite An_{5}. They are variably altered to sericitic mica.

Biotite forms small phenocrysts in some examples, occurring as aggregates of relatively small crystals often associated with apatite. The individual crystals form ragged flakes with frayed ends and are, in most cases, much altered to penninitic chlorite. They include many small zircon crystals surrounded by prominent pleochroic haloes. The biotite crystals included within the quartz are freshly pleochroic from pale to very dark brown.

The groundmass is almost entirely quartzo-feldspathic; staining has shown that it contains approximately equal proportions of orthoclase and quartz, with very little plagioclase feldspar, (for technique see Bailey and Stevens, 1960). It is normally very fine grained with a tendency towards a granophyric texture. Rarely however it is medium grained and almost completely composed of micrographic intergrowths of quartz and orthoclase. In the more altered specimens the groundmass is highly sericitised.

Accessory minerals include sparse small grains of magnetite and rare cubes of haematised pyrite. Apatite is sparse but ubiquitous, and zircon is often present. Sphene, pleochroic from neutral to rose red, is found in small amounts.

DISCUSSION

In the consideration of the origin of this granite mass, it must be remembered that it forms part of a much larger chain of granitic rocks which, from such reports as are available, appear to be somewhat variable in composition and texture. The chain is thus probably composed of a large number of individual intrusions (Hutchison 1933, Bisset 1932, Anderson 1939). The Ballater Granite continues to the east of the area mapped; its eastward termination has not been described.

The Ballater Granite is characterised by its homogeneity which, together with several of its other features, indicates that it has not been produced by metasomatic action. There is no sign of banded structures, such as might be produced by remnant bedding, the contacts are sharp with a reduction in grain size towards them, and there is a complete lack of sedimentary inclusions. In fact the remark made by Drewes (1958) concerning the granites of the Southern Snake Range of Nevada is equally applicable here. He states that "the relatively uniform composition and texture, the absence of regional alkali metasomatism, the presence of fine grained border zones and small apophyses in the host, when considered together favour a magmatic origin."

Having concluded that the Ballater Granite was probably intruded in a magmatic state, the condition of the magma at the time of intrusion must be considered. The magma from which this granite crystallised was clearly homogeneous in nature, and is characterised by an absence of included metasediment and the very rare occurrence of contact breccias and veining of the country rock. Such features might be interpreted as indicating a lack of mobility in the magma. However Buddington (1959, p.679) is of the opinion that in granitic masses a homogeneous rock of coarse grain size, with the presence of miarolite, is consistent with the possibility that the liquid phase was relatively fluid as a result of a fairly high volatile content. A relatively fluid state during intrusion would indicate that the magma contained a low proportion of crystalline material, and this would explain the lack of directional structures in the mass, which probably crystallised in situ under static conditions. This is consistent with the opinion of Gilluly (1946, p.112) who considers that a lack of lineation in a rock may indicate that there was little motion in the magma during the later stages of its crystallisation. The lack of cataclastic structures also suggests that much of the crystallisation of the mass was completed after emplacement. It is thus concluded that the Ballater Granite was probably intruded in a relatively fluid state, and may not have veined the country rocks due to a lack of intrusive pressure. Such a lack of pressure is indicated by the absence of structures induced in the country rock by the intrusion of the granite.

The amount of metamorphism directly attributable to the emplacement of the Ballater Granite is small. Although it is emplaced in rocks which have attained the hornblende-hornfels facies of metamorphism, it has already been concluded (p. 68) that this metamorphic grade is probably not related to the emplacement of the granite. Textural changes attributable to the Ballater Granite are also of very limited extent. The magma was however sufficiently hot to produce a reduction in grain size towards its margins. It may thus be concluded that the Ballater Granite, although it may have been fairly fluid as a result of a high volatile content, was not intruded at a very high temperature. The limited nature of the contact effects in the country rocks may be partly due to the lack of veining associated with the Ballater Granite along which alteration might be carried out. The hydrothermal fraction of the magma appears to have been largely restricted to within the granite mass itself, taking the form of the pegmatitic quartz-rich veins which often cut the granite but are so rarely found outside it.

Owing to the irregular altitude of the contact between the Ballater Granite and the country rocks, it seems likely that the present erosional surface is close to the upper surface of the granite mass. This is consistent with the postulated highly volatile nature of the magma, and the abundance of pegmatitic veins.

The Ballater Granite has most of the characteristics of a high level epizone granite as defined by Buddington (1959). These characteristics include a discordant nature, the presence of roof pendants, an

absence of lineation or foliation, a dominantly magmatic origin, and the presence of miarolitic cavities associated with occasional pegmatites. Buddington also states that granites of the epizone commonly have chilled margins, and have associated with them a porphyritic dyke stage. All the above features have been noted in the Ballater Granite.

It is now necessary to consider how the space was provided for this granite; this problem is intensified when we consider the vast volume of rock which comprises the belt of granites of which the Ballater Granite forms a very small part. From the structural work done during this study, and from the opinions expressed by other authors (Read 1928, McIntyre 1951) these bodies do not appear to have affected the structures of the country rocks to any noticeable extent, and have therefore not made room for themselves by shouldering apart the country rocks. The lack of foliation parallel to the contacts, and the absence of brecciation and veining of the enclosing rocks, also makes a considerable amount of intrusion pressure unlikely.

The other mechanism by which space might have been provided is that of piecemeal stoping. This is a possibility which cannot be discounted but, while there is no concrete evidence in favour of such a hypothesis, there is a certain amount of evidence of a negative type which makes this mechanism unlikely. In emplacement by this method one might expect to find an abundance of inclusions of country rocks in the granite, especially towards the roof of the intrusion, and also

considerable brecciation of the country rocks towards the contacts. Neither of these phenomena is present in the Ballater Granite which is notable for its lack of xenoliths. Even in a fairly fluid granitic magma it seems unlikely that all the xenoliths would completely disappear.

Read (1961) has suggested that the Lochnagar granite mass, just to the south of the Geallaig area, which has the same general characteristics as the Ballater Granite (Barrow and Craig 1912), may have been emplaced by subsidence similar to that of Glencoe and Ben Nevis. This was a very tentative suggestion based largely on the circular nature of the mass. There is no evidence of faulting in the Geallaig district of a type to produce subsidence, but such a mechanism would explain the lack of inclusions in the granite.

It appears that permissive intrusion of some type provides the most likely mechanism for the production of space for the Ballater Granite, but insufficient evidence is available at present for this problem to be evaluated further.

CONCLUSIONS

CONCLUSIONS

(1) The metasediments of the Geallaig district grade structurally upwards, from interbanded quartzose and pelitic rocks, through intermediate varieties, to calc-silicate rocks and marbles. All these types are interbedded with abundant metadoleritic sheets. They show the Buchan type of regional metamorphism, with mineral assemblages characteristic of the hornblende-hornfels facies. The main metamorphic events took place subsequently to the production of the dominant plane of schistosity of these rocks.

(2) The metasediments are folded in a major fold which plunges at a moderate angle to the southeast. There is sporadic occurrence of later strain slip cleavages.

(3) The basic igneous rocks may be divided into two groups. The earlier was intruded into the metasediments in the form of sills, which shared in the Dalradian metamorphism. The later, which shows fine scale banding, and is less strongly metamorphosed than the sills, forms the southern continuation of the Morven Gabbro mass, which has been tentatively associated with the "Newer Gabbro" Suite of north-east Scotland.

(4) The acid igneous rocks may be divided into two masses. An earlier suite of acid and intermediate rocks, the Crathie

Granite Complex, is of heterogeneous composition and abundantly xenolithic. It is suggested that it has been formed from a heterogeneous partially crystalline magma, intruded by piecemeal stoping, associated with very limited amounts of assimilation. This mass was affected by late stage hydrothermal fluids and late potash metasomatism.

(5) The Crathie Granite Complex was followed by the intrusion of a northeasterly trending suite of intermediate dykes, possibly a continuation of the Lochnagar dyke swarm.

(6) The final phase of igneous activity resulted in the production of the homogeneous, non-xenolithic, Ballater Granite. This has very limited contact effects on the country rocks, and has probably been intruded as a relatively fluid and highly volatile magma, of fairly low temperature. It was probably intruded by permissive means. It has, associated with it, a set of quartz-porphyry dykes.

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PLATE I

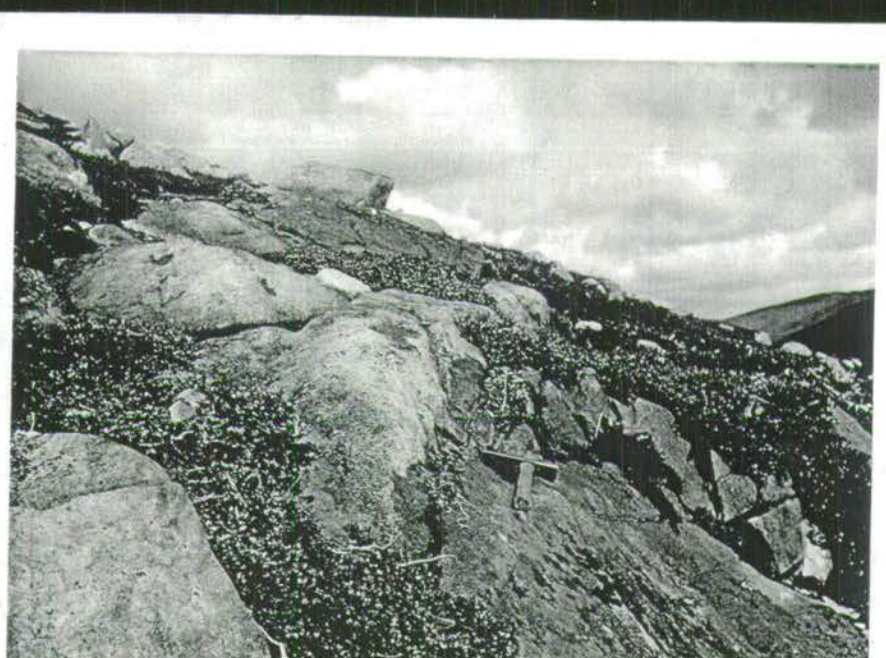
BASIC SHEET GROUP

A Typical hornblende-schist, showing a lineation formed by streaked-out feldspathic areas.
West Glen Gairn.

B Contact between Ballater Granite and hornblende-schist within the Coilacriech Group.
West Glen Gairn.

PLATE I

A



B

PLATE II

HORNBLENDIC GROUP

A Minor folding with sub-angular puckers on the fold limbs; in banded hornblende-schists, south of Tom Garchory.

B Microphotograph of puckers as above, showing the preferred orientation of amphiboles on the limbs of the puckers. Ordinary light. X 25.

PLATE II

A

B

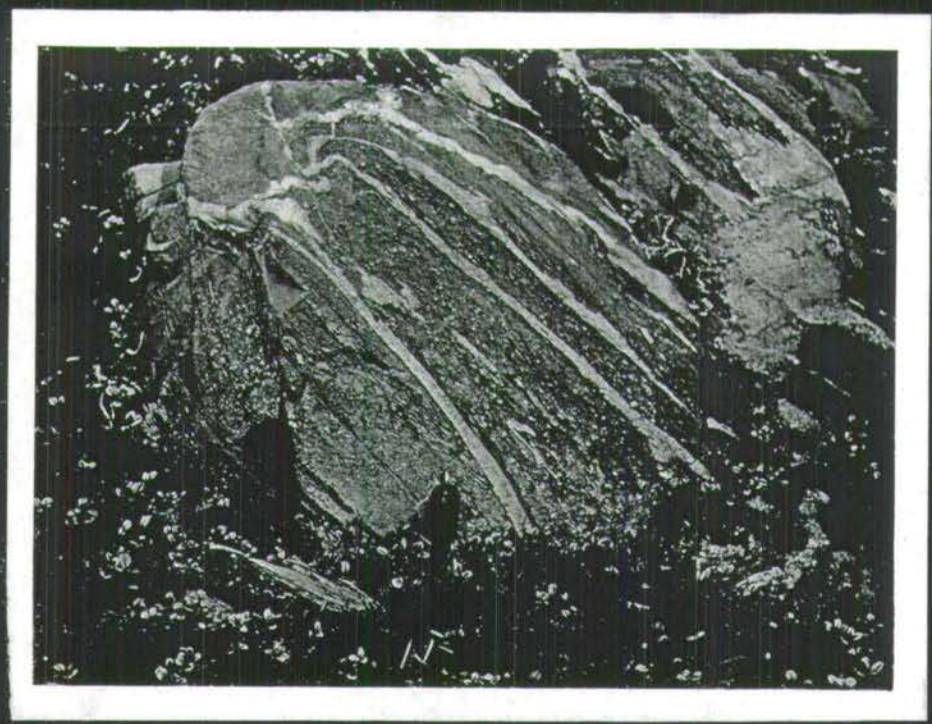
PLATE III

HORNBLENDIC GROUP

A — Relatively discrete veins of trondhjemitic material. Note the presence of spots and patches of similar material unconnected with the veins.
Hill of Candacraig.

B — Trondhjemitic veining of the more diffuse type, showing the general parallelism of the veining with the schistosity of the epidiorite.
Hill of Candacraig.

PLATE III



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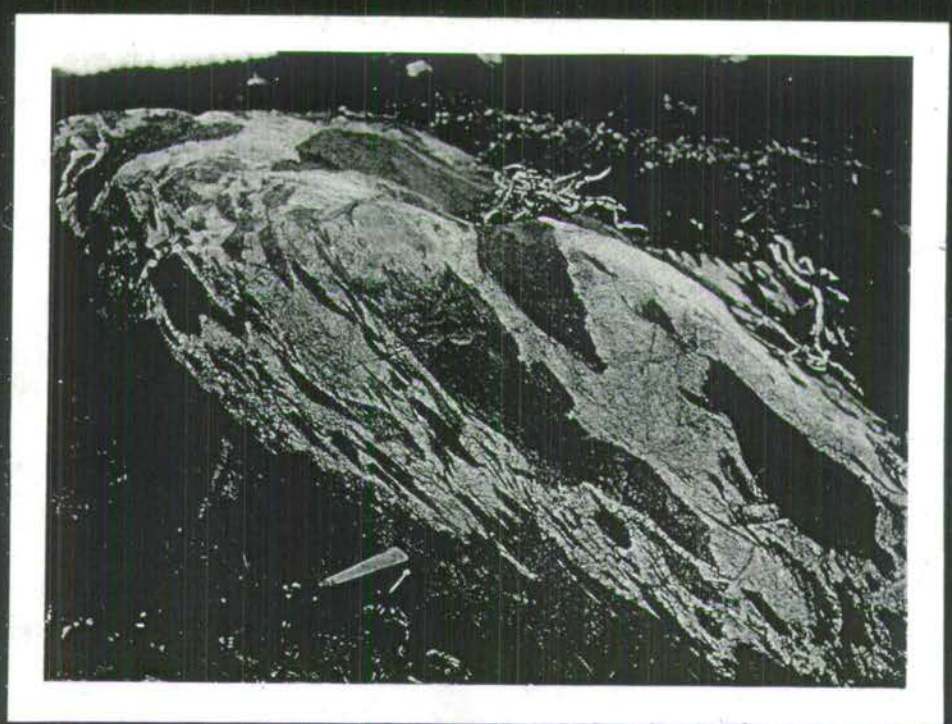


B

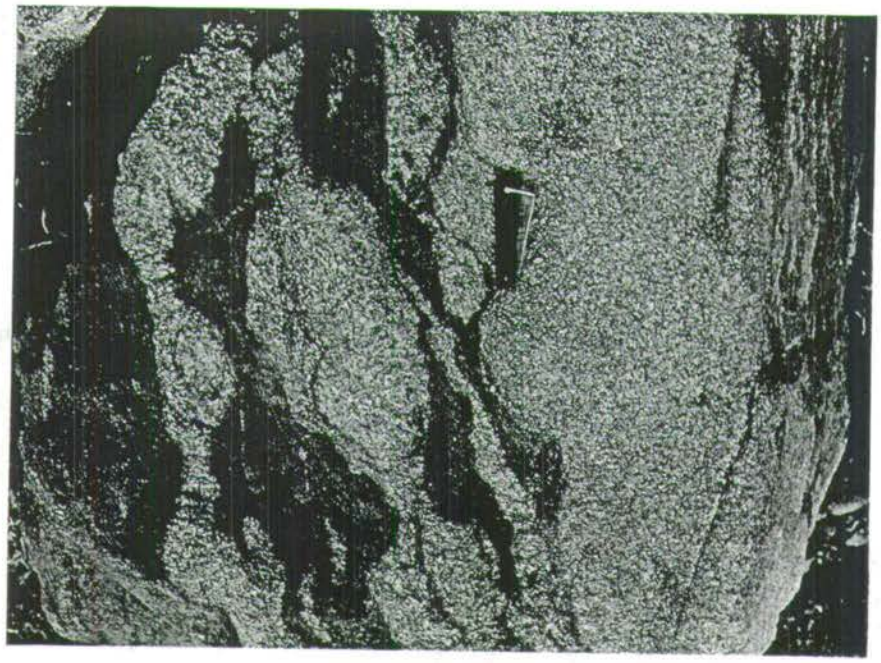
PLATE IV

CRATHIE GRANITE COMPLEX

A Contact relationships between granitic and tonalitic rocks, showing the intimately admixed nature of the two rock types.
Craig of Tullich.

B Similar relationships between porphyritic adamellite and tonalite.
Creag a' Chlamhainn.

PLATE IV



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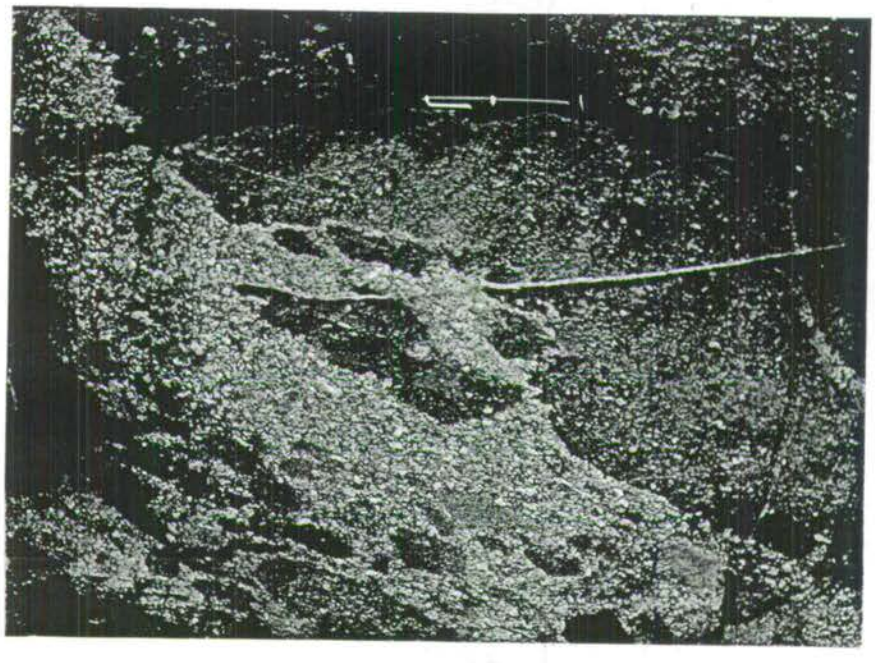


B

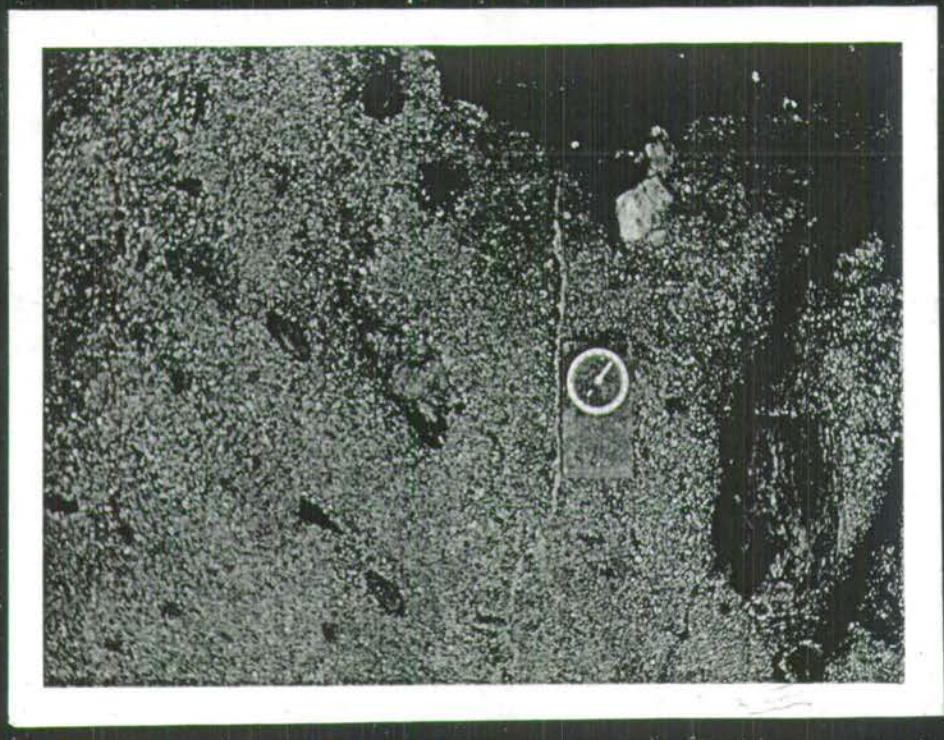
PLATE V

INCLUSIONS IN THE CRATHIE GRANITE COMPLEX

A Highly xenolithic granodiorite showing inclusions of quartzite, pelite and hornblende-schist. Creag Mhor.

B Typical adamellite-schist relationships showing the broken up nature of the inclusions. Sron Dubh.

PLATE V



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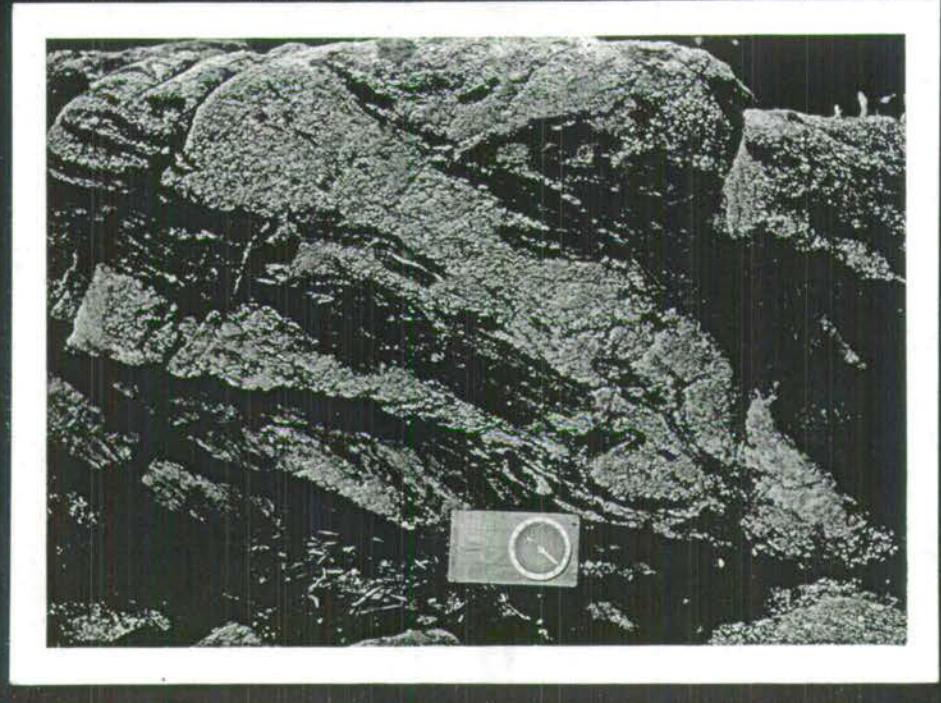


B

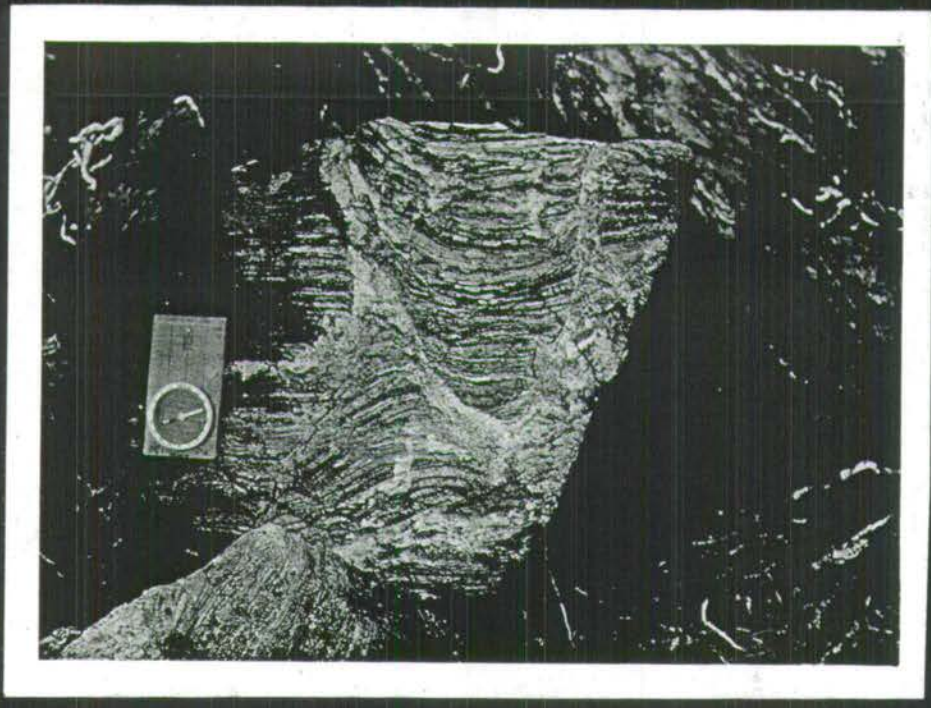
PLATE VI

INCLUSIONS IN THE CRATHIE GRANITE COMPLEX

A Schist inclusion veined by granodiorite, with resultant slight flexuring of the schistosity.
Sron Dubh.

B Highly contorted and cleaved metasedimentary inclusion.
Craig of Tullich.

PLATE VI



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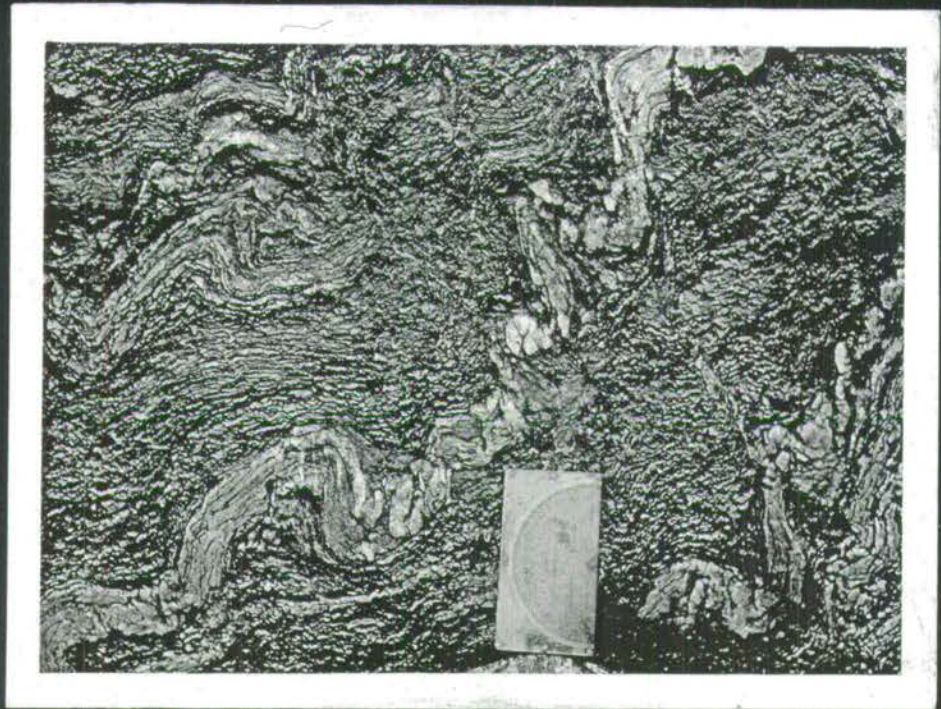


B

PLATE VII

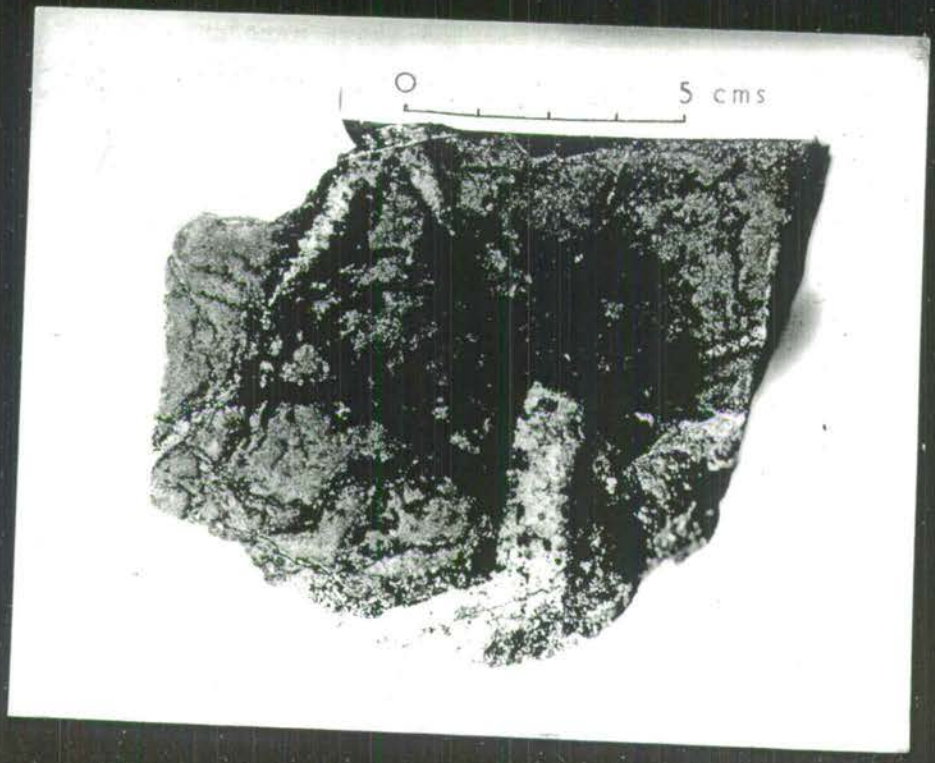
INCLUSIONS IN THE CRATHIE GRANITE COMPLEX

A Margin of calc-silicate inclusion, showing reticulate veining by the surrounding granitic material.
Creag a' Chlamhainn

B Hand specimen from the above exposure, showing the development of amphibole (dark) along the borders of the granitic veins. The remainder of the inclusion is dominantly diopsidic.

PLATE VII

A



B

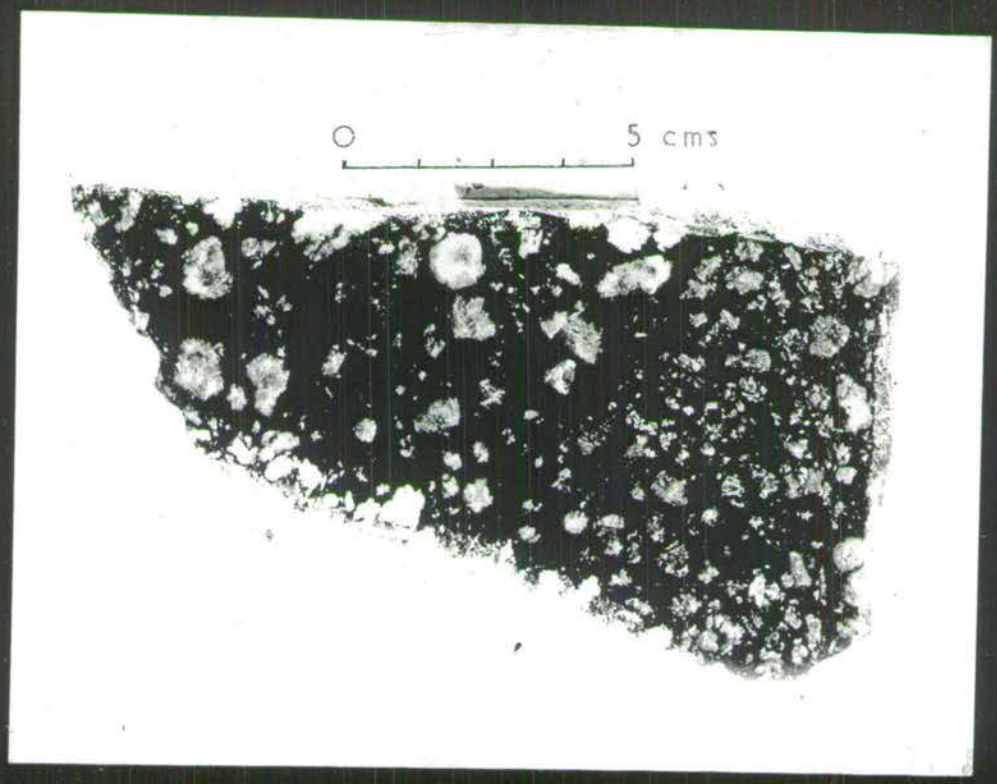
PLATE VIII

BASIC SHEET GROUP

A Epidiorite with feldsparphyric patches.
West Glen Gairn.

B Feldsparphyric epidiorite showing a rapid transition from unsheared, to highly sheared rock.
West Glen Gairn.

PLATE VIII



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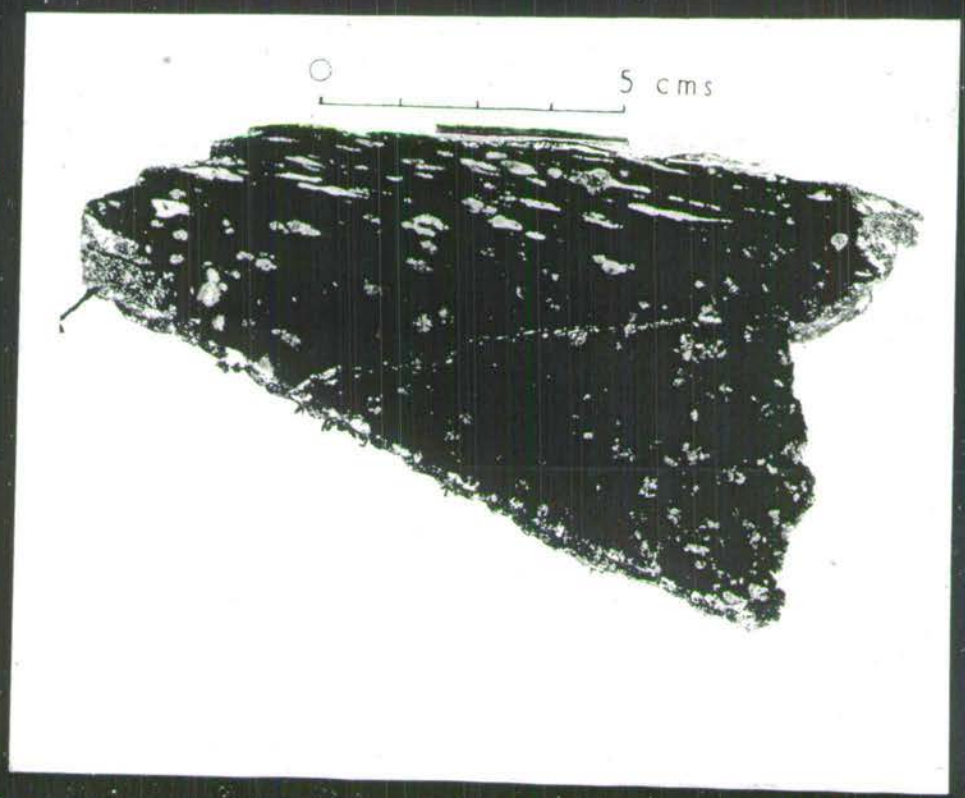


B

PLATE IX

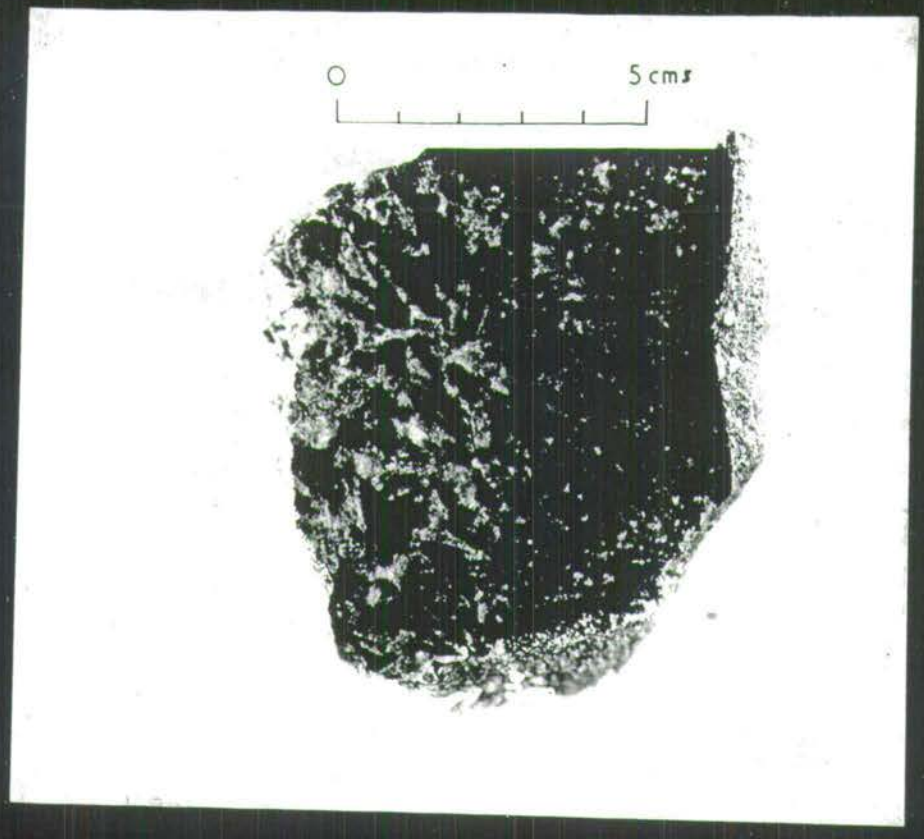
HORNBLENDIC GROUP

A Epidiorite showing remnant ophitic textures. Peter's Hill.

INCLUSIONS IN THE CRATHIE GRANITE COMPLEX

B Tonalite including fine slivers of schist. Sron Dubh.

PLATE IX



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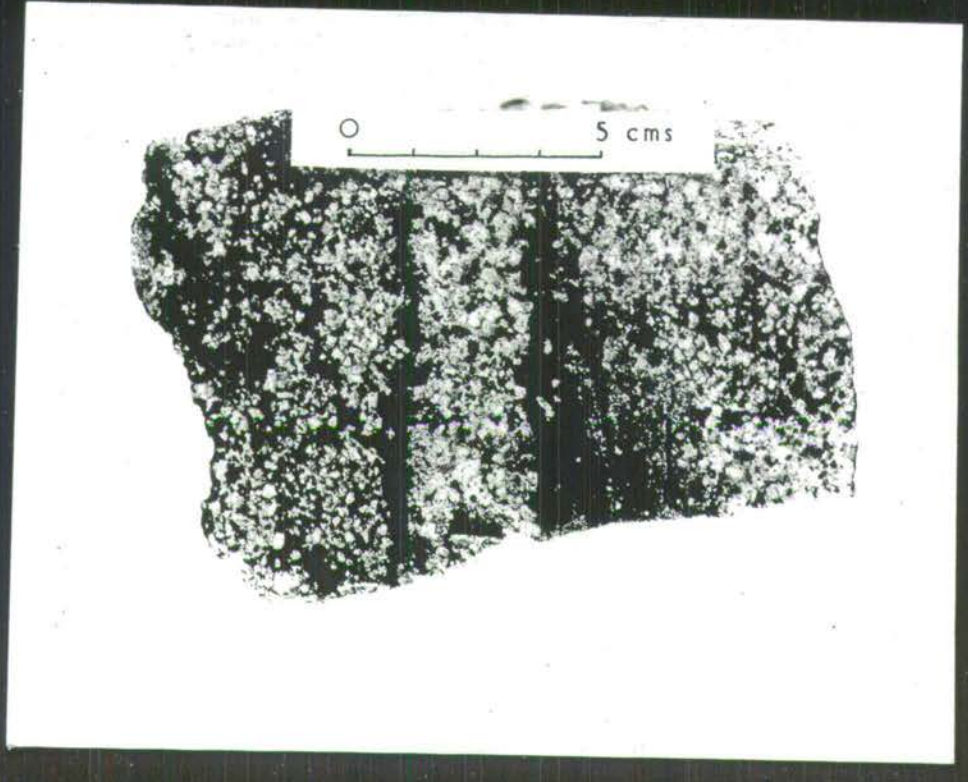


B

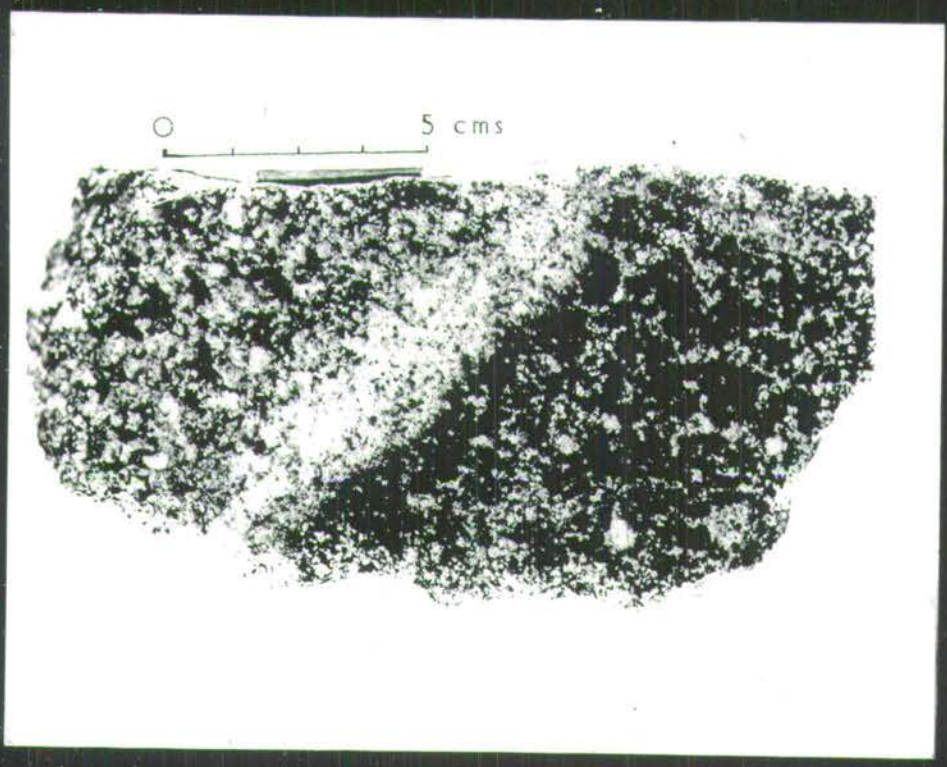
PLATE X

CRATHIE GRANITE COMPLEX

A Contact between granodiorite and tonalite, separated by a thin band of adamellite. Knock of Lawsie.

B Specimen from the Crathie Granite Complex, illustrating its tendency to rapid variations in mineralogy and texture. Creag a' Chlamhainn.

PLATE X



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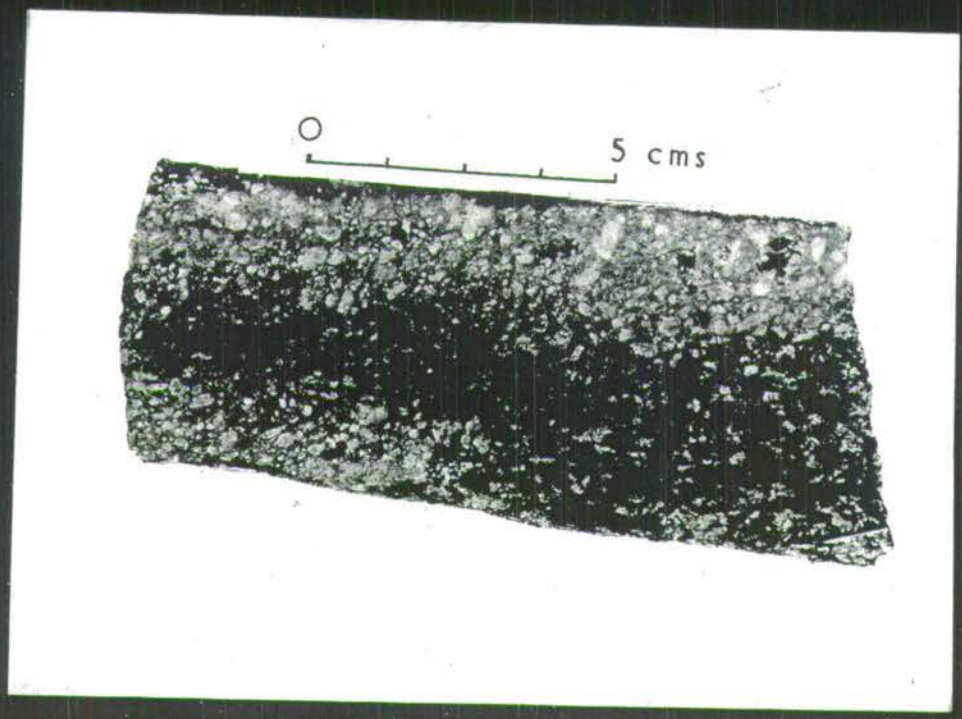


B

PLATE XI

HORNBLENDIC GROUP

A Textures suggestive of former ophitic types in epidiorite, containing relic pyroxene. The pyroxene has been largely replaced by an aggregate of hornblende crystals.
Ordinary light. X14.

B Remnant ophitic texture in epidiorite?
Crossed nicols. X14.

C Partially reconstituted epidiorite showing two feldspar generations. 1st generation (left centre) shows elongate form, indented margins and abundant lamellar twinning. 2nd generation (at top right of the 1st generation crystal) is in relatively small, equidimensional crystals, typically lacking twinning.
Crossed nicols. X14.

PLATE XI

A

B

C

PLATE XII

BASIC SHEET GROUP

A — Typical hornblende-schist.
Ordinary light. X14.

B — Same field.
Crossed nicols.

HORNBLENDIC GROUP

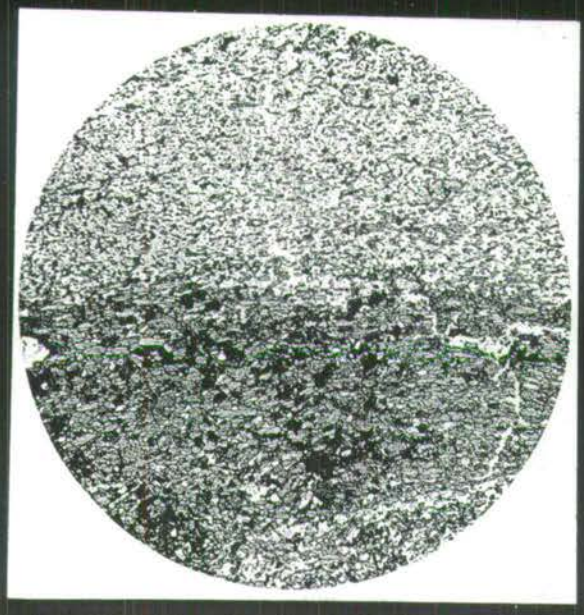
C — Typical banded hornblende-schist, showing the change in proportions of hornblende and feldspar between adjoining bands.
Ordinary light. X14.

D — Same field.
Crossed nicols.

PLATE XII

A

B



C

D

PLATE XIII

ABERCAIRN GROUP

A — Amphibole-rich calc-silicate rock. Note the sheaf-like form of the amphibole, and low proportion of feldspar in contrast to the hornblende-schists of igneous origin (Pl XII A).
Crossed nicols. X14.

B — Pyroxene-rich calc-silicate rock. Note the finely poikiloblastic nature of the pyroxene.
Crossed nicols. X14.

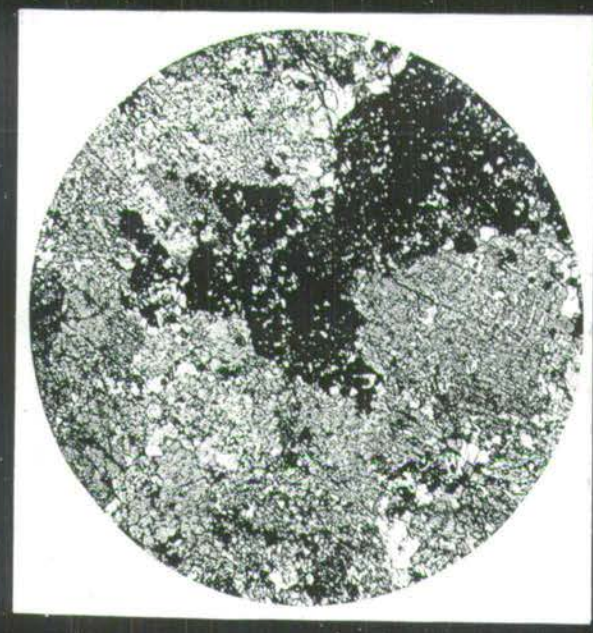
CANDACRAIG GROUP

C — Hornblende-biotite schist containing porphyroblastic plagioclase around which the schistosity is distorted.
Ordinary light. X14.

D — Same field.
Crossed nicols.

PLATE XIII

A



B

C

D

PLATE XIV

COILACRIECH GROUP

A Anthophyllite-cordierite schist, showing radiating sheaves of anthophyllite penetrating cordierite crystals.
Ordinary light. X14.

B Same field.
Crossed nicols.

C Andalusite-cordierite schist. Tiny crystals of spinel (high relief) are enclosed within andalusite (medium relief) which is in turn surrounded by cordierite (low relief). X14.

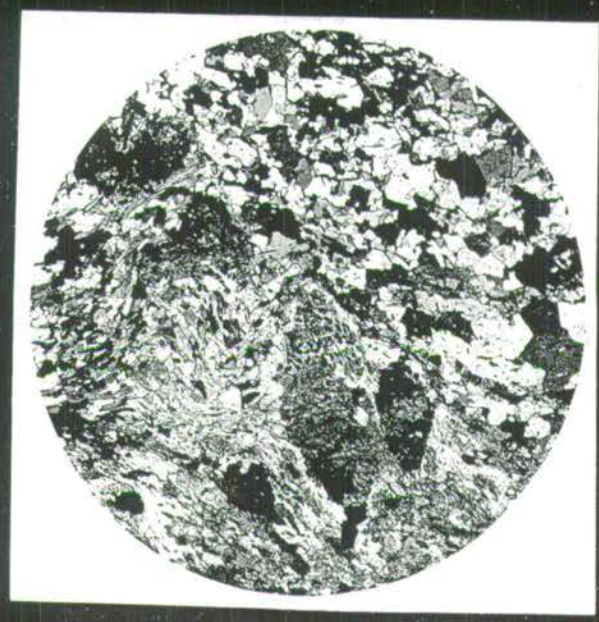
D Same field.
Crossed nicols.

PLATE XIV

A

B

C



D

PLATE XV

COILACRIECH GROUP

A Cordierite schist showing rounded cordierite, with marginal alteration and abundant inclusions, and the contrasting habit of the elongate masses of cordierite lying along the schistosity.
Ordinary light. X14.

B Cordierite-anthophyllite schist showing a sheaf like form of cordierite with inclusions of anthophyllite and biotite.
Crossed nicols. X14.

C Garnetiferous cordierite-anthophyllite schist. The garnet is surrounded by a sheath of inclusion-filled cordierite.
Ordinary light. X14.

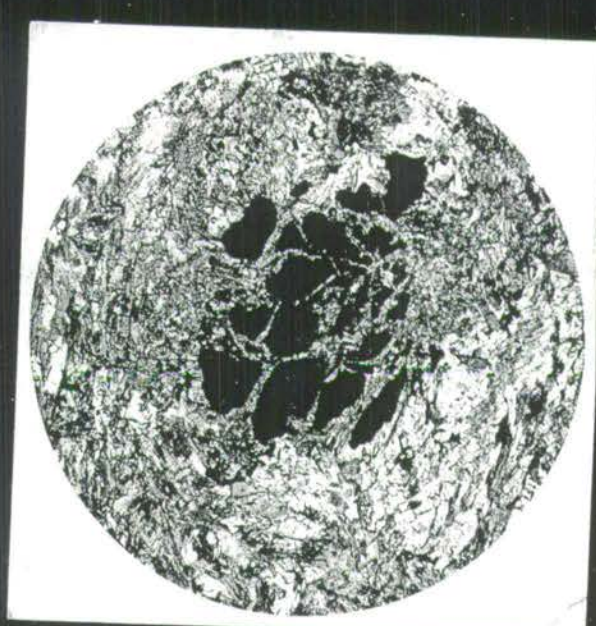
D Same field.
Crossed nicols.

PLATE XV

A

B

C



D

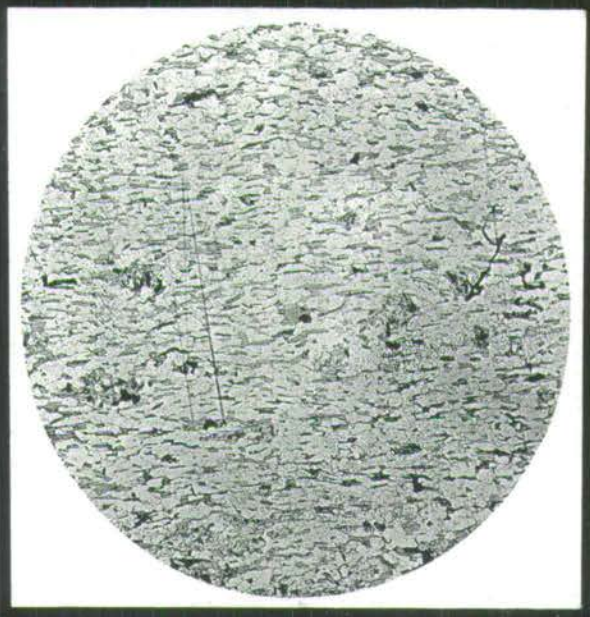
PLATE XVI

CONTRASTING SCHIST TEXTURES

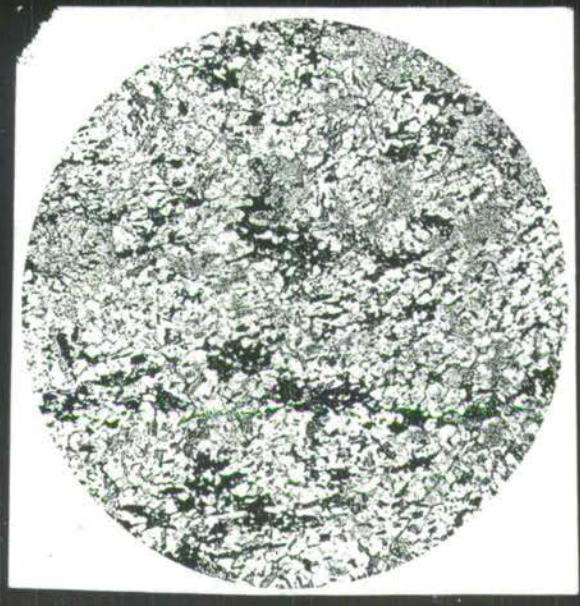
A Typical biotite schist of the Coilacriech Group near the contact with the Ballater Granite. Ordinary light. X14.

B Biotite-rich hornfels from a schist inclusion within the Crathie Granite Complex. Compare the texture with that of the above photograph (Pl XVI A).
Ordinary light. X14.

PLATE XVI



A



B

PLATE XVII

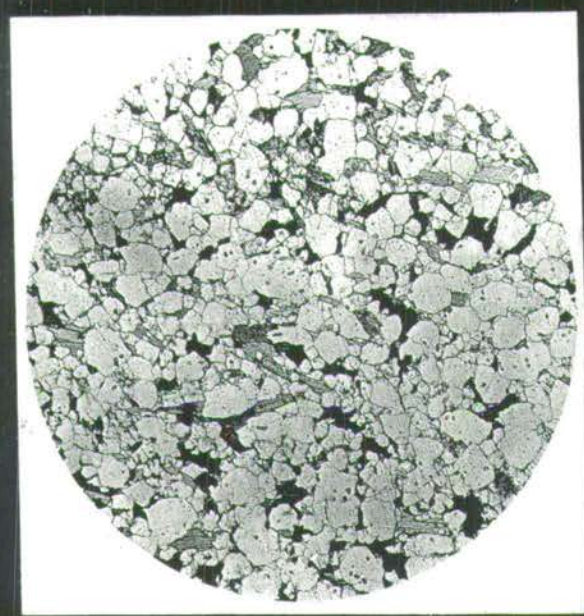
INCLUSIONS IN THE CRATHIE GRANITE COMPLEX

A Biotite schist inclusion 1 cm. from the contact with the surrounding granitic material. Note the lack of schistosity and texture in contrast with Pl XVI A & B.
Ordinary light. X14.

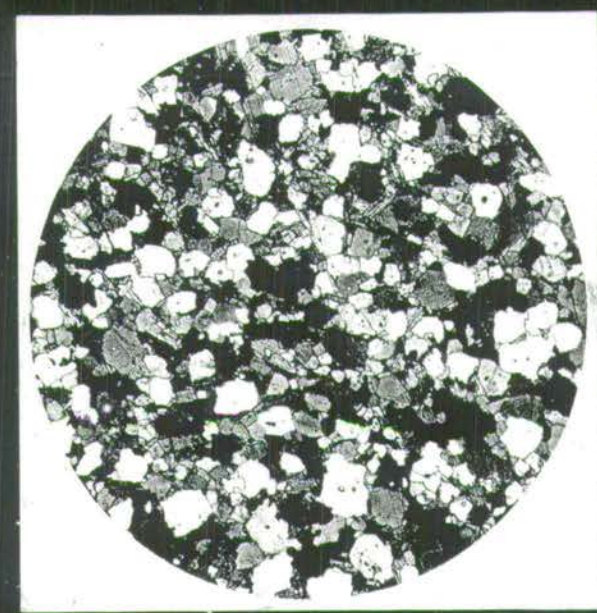
B Same field,
Crossed nicols.

C Cordierite-biotite schist inclusion showing polysynthetic twinning in the cordierite.
Crossed nicols. X14.

PLATE XVII



A



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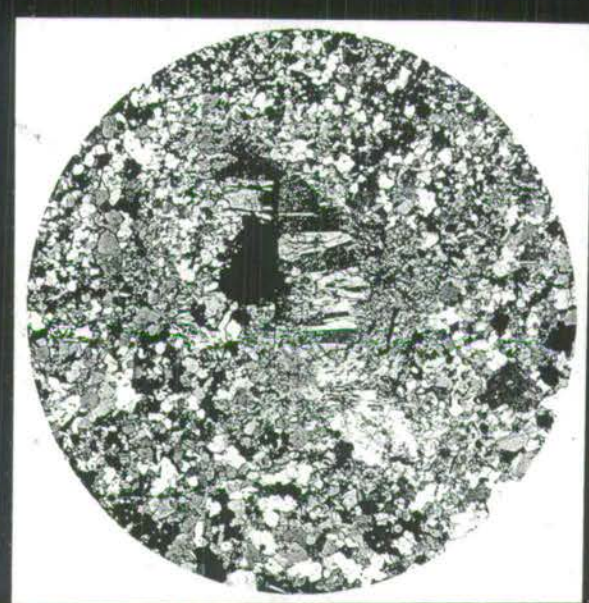


C

PLATE XVIII

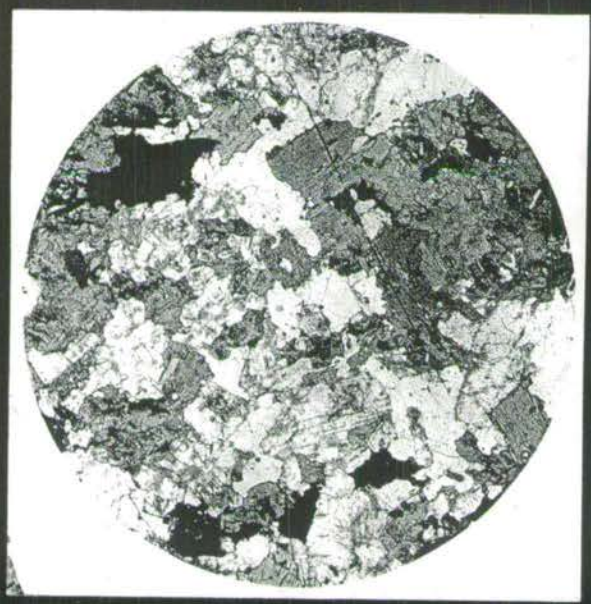
CRATHIE GRANITE COMPLEX

A Typical unfoliated hornblende-biotite granodiorite.
Ordinary light. X14.

B Same field.
Crossed nicols.

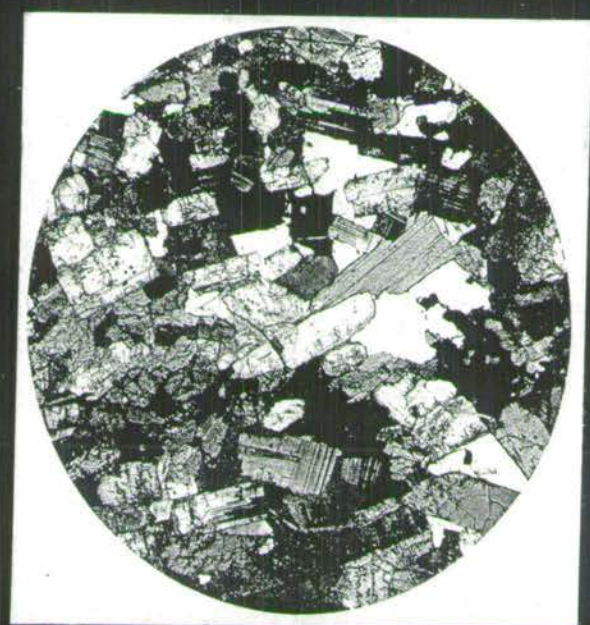
C Foliated tonalite showing rude parellelism of the tabular feldspars and biotites.
Crossed nicols. X14.

PLATE XVIII



A

B



C

PLATE XIX

CRATHIE GRANITE COMPLEX

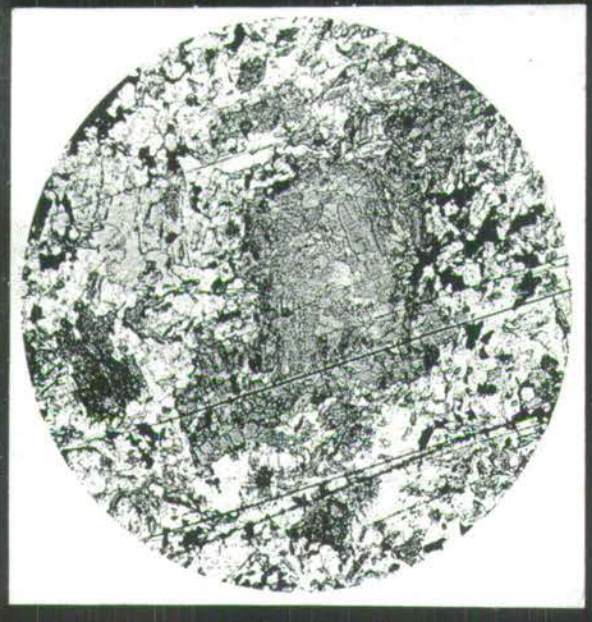
A Spotted monzonite showing a typical hornblende clot.
Ordinary light. X14.

B Hornblende-biotite diorite showing biotite inclusions within hornblende, surrounded by an inclusion-free hornblende margin.
Ordinary light. X14.

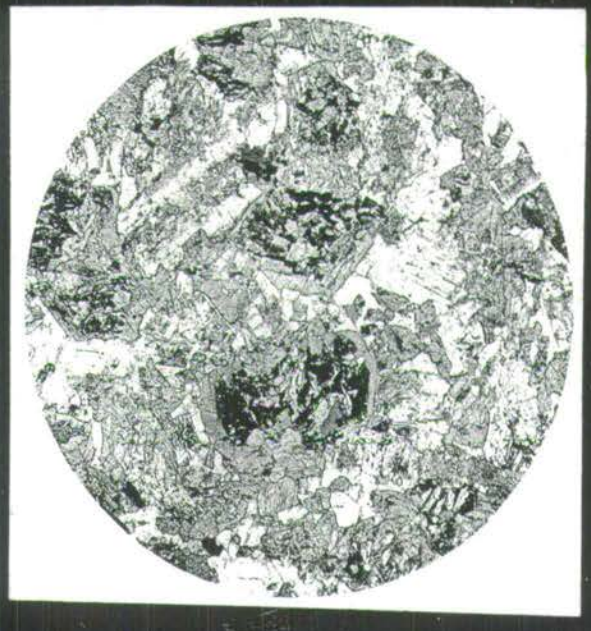
C Hornblende-biotite diorite with a rude foliation formed by the ferromagnesian minerals.
Crossed nicols. X14.

D Granodiorite typical of the inclusion-rich variety of Creag Mhor (see Pl V A). Note textures as compared with those of Pl XIX and Pl VIII which are relatively free from inclusions.
Ordinary light. X14.

PLATE XIX

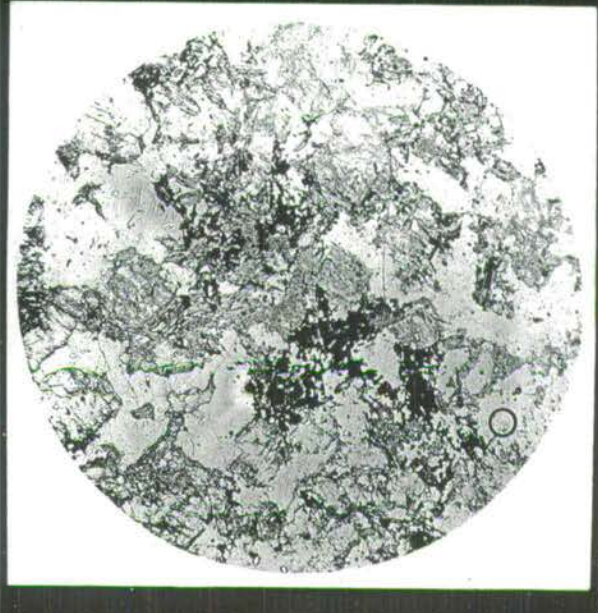


A



B

C



D

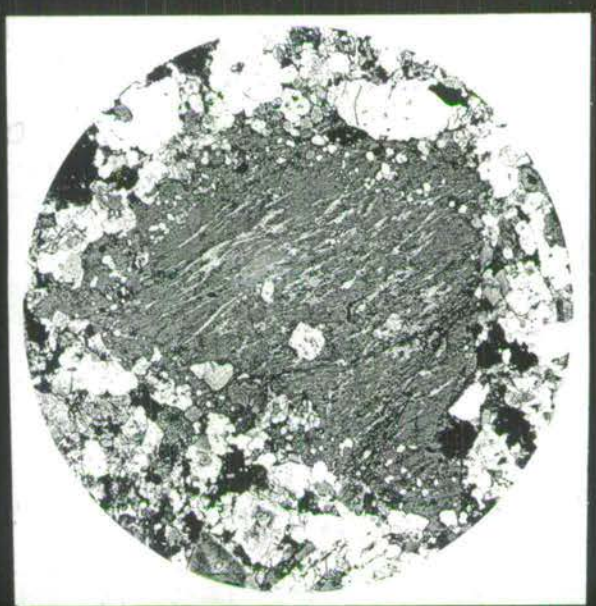
PLATE XX

CRATHIE GRANITE COMPLEX

A Porphyritic adamellite with poikilitic microcline microperthite including quartz crystals marginally.
Crossed nicols. X14.

B Spotted monzonite: large plate of poikiloblastic potash feldspar which includes all the other rock constituents and replaces the plagioclase feldspar of the rock.
Crossed nicols. X14.

PLATE XX



A

B

PLATE XXI

CRATHIE GRANITE COMPLEX — CONTACT RELATIONS

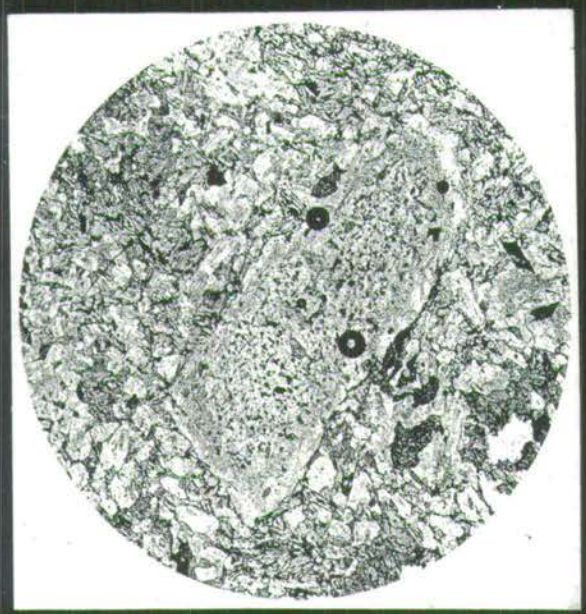
A Plagioclase porphyroblast in spotted monzonite 1.5 cms. from the contact with adamellite. Ordinary light. X14.

B Same field. Crossed nicols.

C Microperthitic potash feldspar porphyroblasts in a biotite schist inclusion a few cms. from the contact with adamellite. Ordinary light. X14.

D Same field. Crossed nicols.

PLATE XXI



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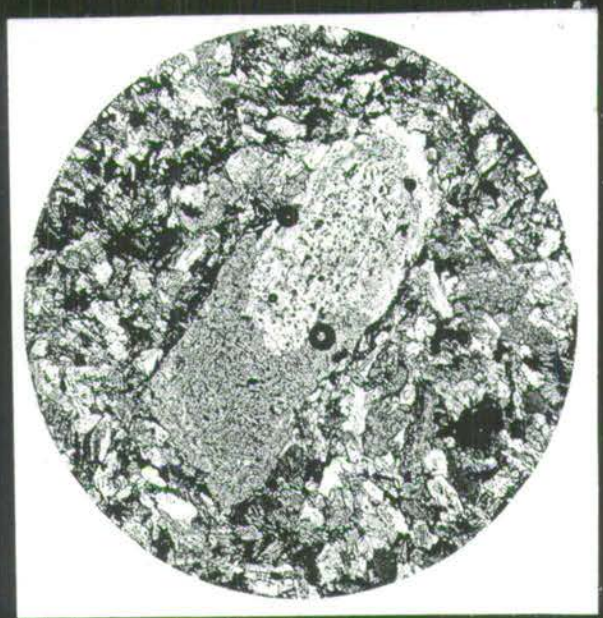

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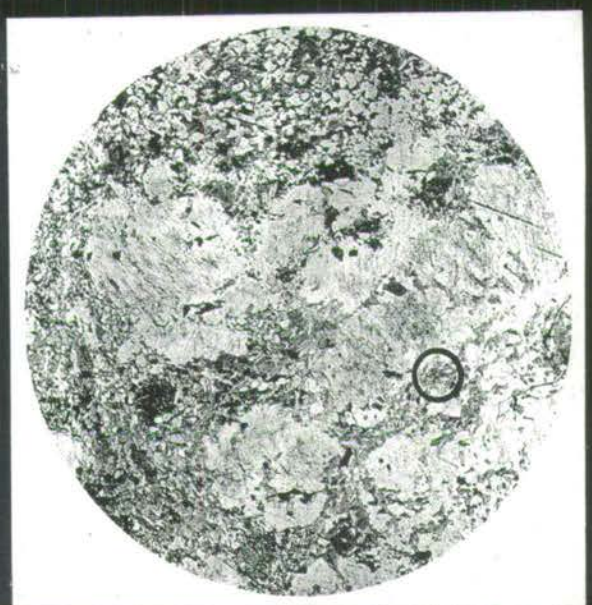

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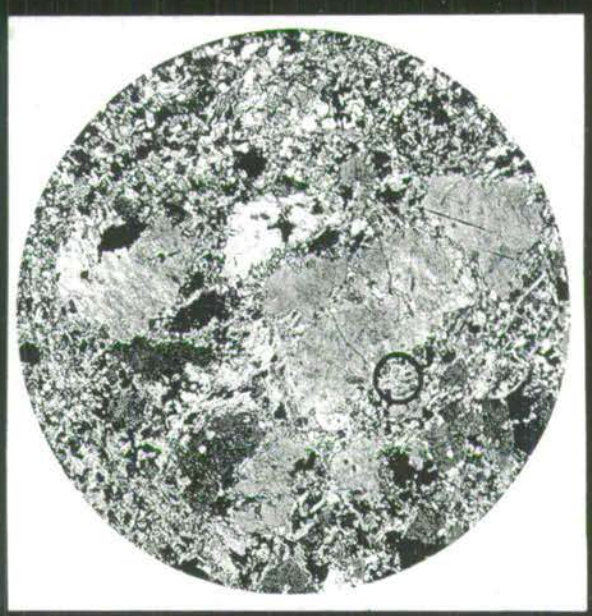


D

PLATE XXII

BALLATER GRANITE

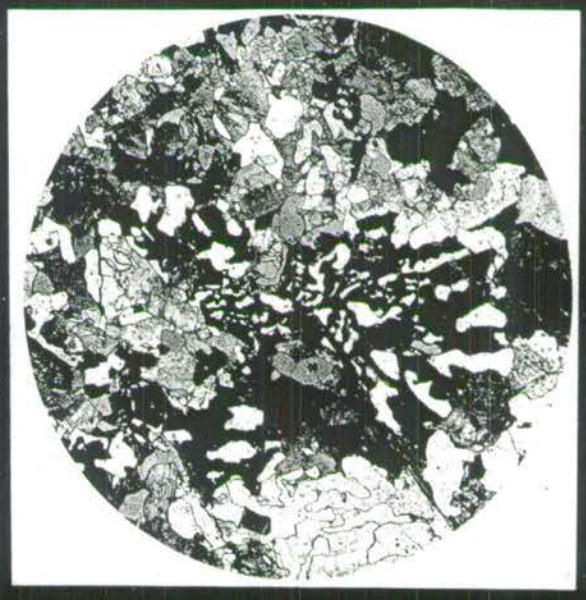
A Typical field showing quartz, potash feldspar and plagioclase.
Crossed nicols. X14.

B Marginal portion showing the development of granophyric texture.
Crossed nicols. X14.

C Sheared granite. Note the flexuring and fracture of plagioclase twin lamellae.
Crossed nicols. X14.

PLATE XXII

A



B

C

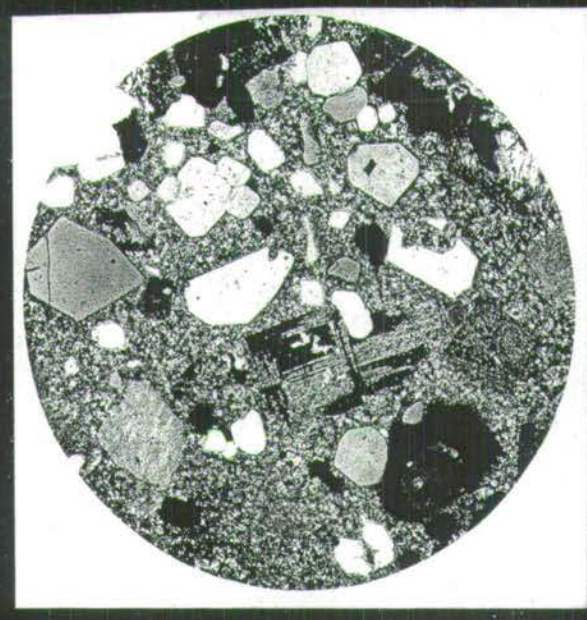
PLATE XXIII

MINOR INTRUSIONS

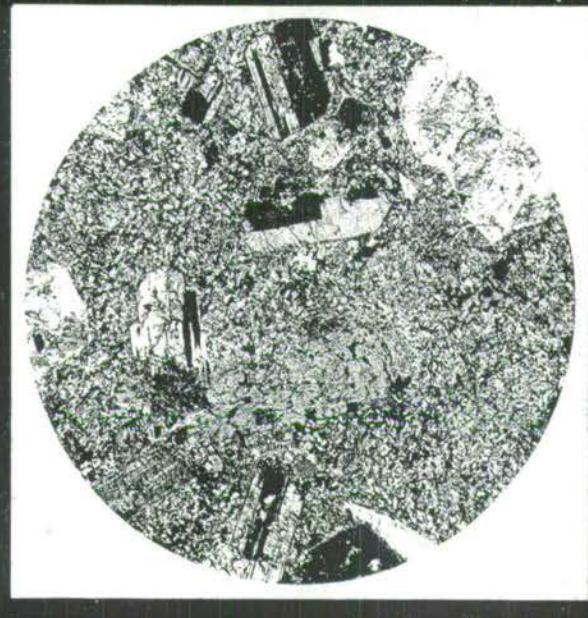
A Typical quartz-porphyry showing phenocrysts of quartz, orthoclase and plagioclase in a very fine grained acidic groundmass.
Crossed nicols. X14.

B Porphyritic microtonalite with phenocrysts of plagioclase and hornblende in a fine grained groundmass of quartz, feldspar, hornblende and biotite.
Crossed nicols. X14.

PLATE XXIII



A

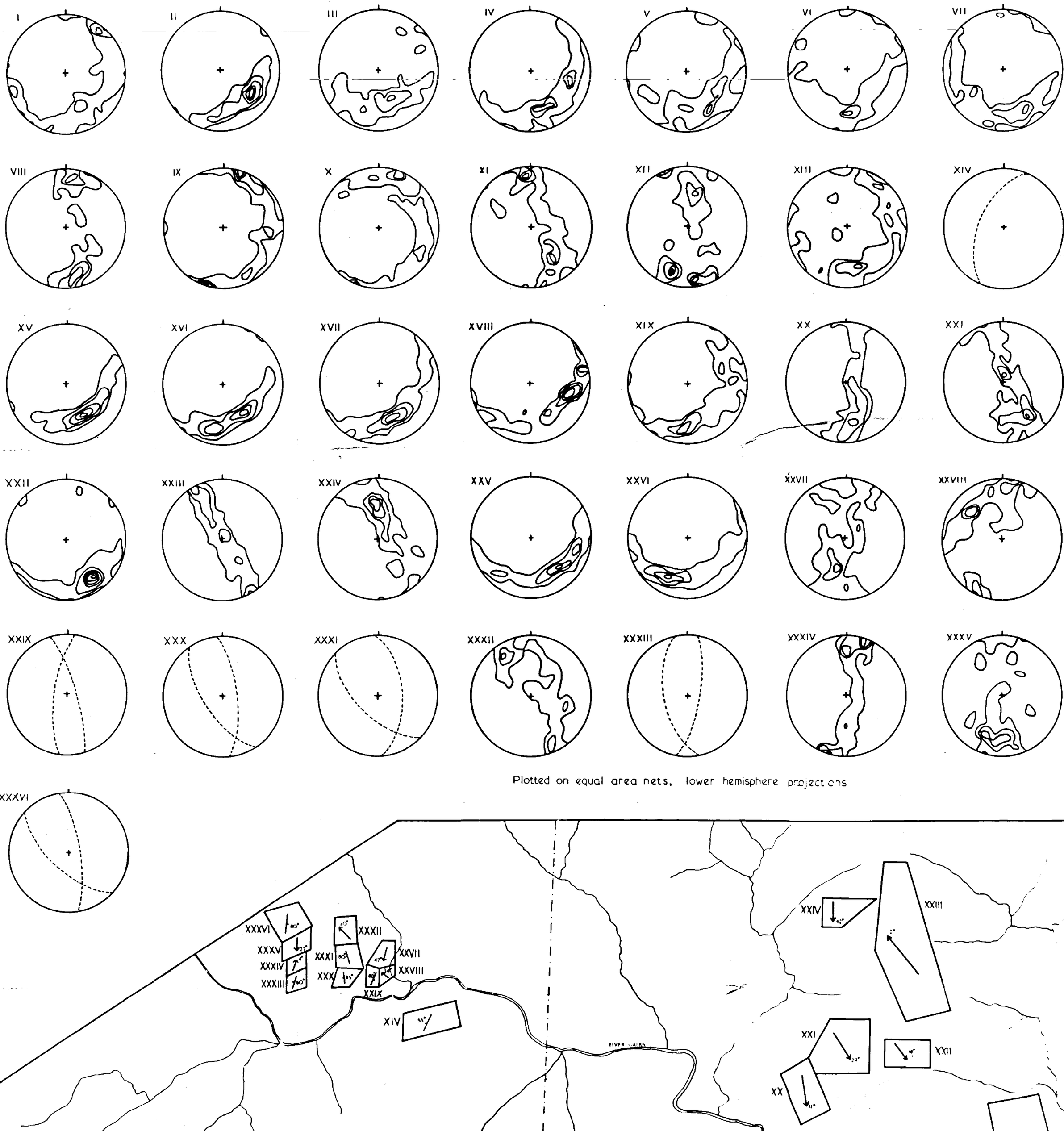


B

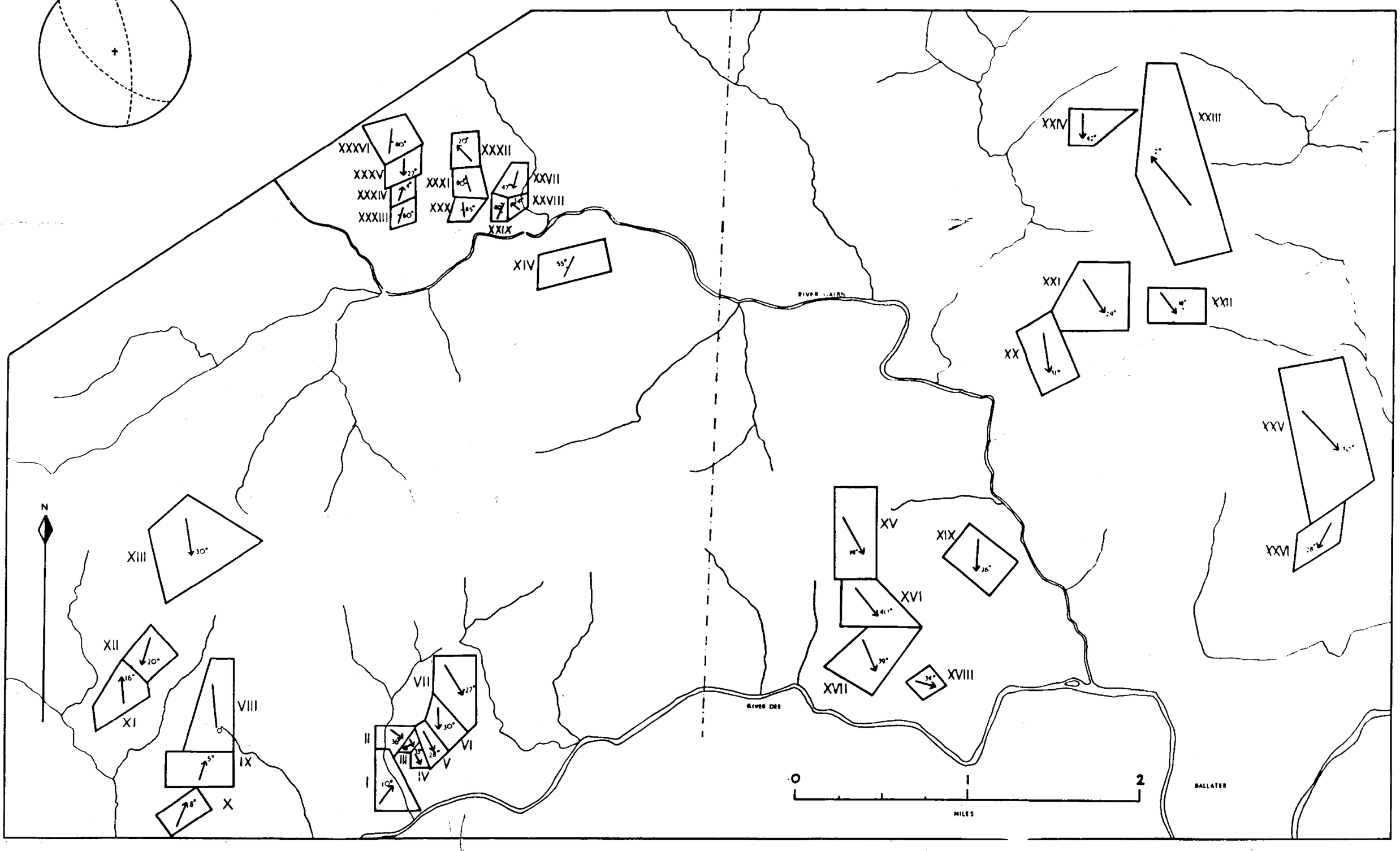
STRUCTURE OF THE GEALLAIG DISTRICT

DIAGRAMS:- β-DIAGRAMS CONSTRUCTED FROM NUMBERED SUB-AREAS (ROMAN NUMERALS). CONTOURS AT 1-5-10-15-20 % PER 1% AREA
BROKEN LINES SHOW AVERAGE EASTERLY AND WESTERLY DIPPING SCHISTOSITY IN SUB-AREAS UNSUITABLE FOR THE CONSTRUCTION OF β-AXES

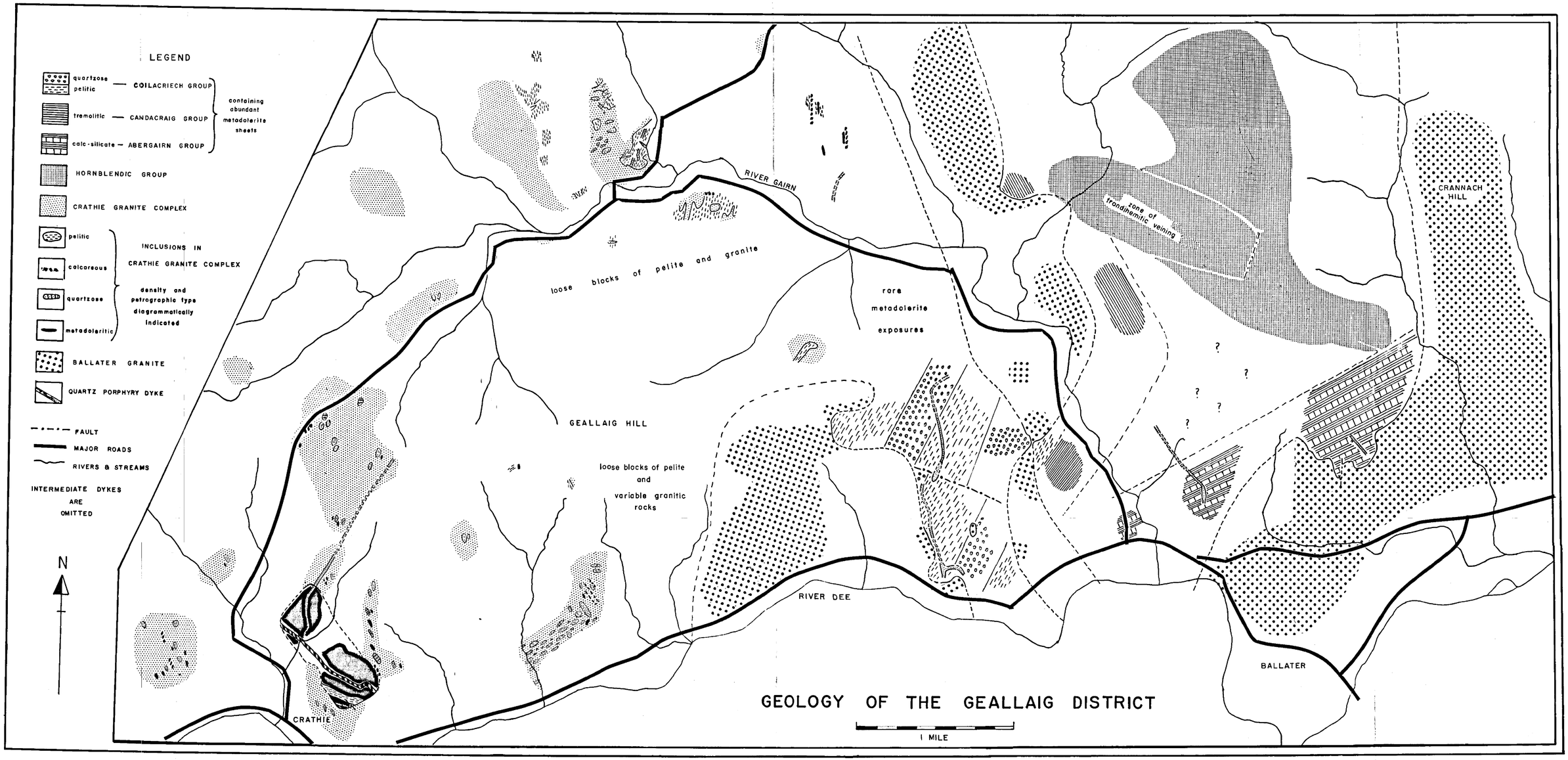
MAP:- SHOWS GEOGRAPHICAL DISTRIBUTION OF SUB-AREAS. ARROWS INDICATE MAXIMA FROM APPROPRIATE β-DIAGRAMS
AVERAGE DIP AND STRIKE OF SCHISTOSITY SHOWN IN SUB-AREAS WHERE β-DIAGRAMS WERE NOT CONSTRUCTED
-·-·-·- DIVIDES REGION OF COUNTRY ROCKS (E. OF -·-), FROM REGION OF INCLUSIONS IN CRATHIE GRANODIORITE (W. OF-·---).



Plotted on equal area nets, lower hemisphere projections



SMAM 196


LEGEND
quartzose pelitic — COILACRIECH GROUP
tremolitic — CANDACRAIG GROUP
calc-silicate — ABERGAIRN GROUP
containing abundant metadolerite sheets
HORNBLENDIC GROUP
CRATHIE GRANITE COMPLEX
pelitic
calcareous
quartzose
metadoleritic
INCLUSIONS IN CRATHIE GRANITE COMPLEX
density and petrographic type diagrammatically indicated
BALLATER GRANITE
QUARTZ PORPHYRY DYKE
FAULT
MAJOR ROADS
RIVERS & STREAMS
INTERMEDIATE DYKES ARE OMITTED
N
RIVER GAIRN
loose blocks of pelite and granite
rare metadolerite exposures
zone of frondigemitic veining
CRANNACH HILL
GEALLAIG HILL
loose blocks of pelite and variable granitic rocks
RIVER DEE
BALLATER
CRATHIE
GEOLOGY OF THE GEALLAIG DISTRICT
1 MILE